

University of Central Florida

Final Report

EEL 4915 & OSE 4952

Senior Design I

Group 1

G.E.A

Greenhouse Environmental Analyzer of Blue to Red Light,
Humidity, Temperature, and CO₂

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November 26th, 2024



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1. Executive Summary

Senior Design, the capstone class for engineering students at UCF, aims to apply our engineering knowledge gathered in our STEM classes to a real-world design project. Over the course of Senior Design I (SD1) and Senior Design II (SD2), our team will identify a marketable solution to a problem, research and investigate, budget, plan, and develop a device that solves this problem. We will gain first hand experience of project planning, goal setting, communicating in a team, and bringing an idea from the design phase all the way to implementation. These two capstone courses split our workload as follows: SD1 - Research phase. Over the course of this semester our team will complete our preliminary research into our device, looking at components, standards, specifications, budgets, and more. We will need to consider our constraints such as time, money, space, feasibility. We will learn a lot about our chosen project and the engineering behind it. This is where we will begin creating demonstrations of our ideas to show to faculty and get approved while figuring out the initial flaws in our design. By the end, we will have a 120-page document with our findings. SD2 - Building. After the research and writing phase, we will begin prototyping and buying components. There will be phases of re-designing and some changes to the initial idea. This is the core of the engineering design process that is crucial for us to learn. By the end we will have our completed project.

Our team has decided to tackle the problem of our agricultural industry. It is a problem that has always been around - food. How can we increase our food production? How can we be more effective in growing food? Our chosen solution to this aims to make growing food in greenhouses easier. We will create a greenhouse environmental monitoring system complete with humidity, temperature, CO₂, white light, as well as red and blue light ratio sensors. The goal is to aid and perhaps autonomously control the conditions within a greenhouse to ensure the maximum yield. As we know, temperature, humidity, CO₂, and light levels all directly affect crop health. Red and blue light specifically can affect the vegetation and flowering of certain plants. However, monitoring and controlling these factors one by one can be overwhelming. That is why we aim to make a portable (not necessarily handheld) device that sends all this information straight to your phone. Perhaps in the future, even control the conditions of the greenhouse based on analysis of the collected data. We believe that our device can ease the workload off of farmers while increasing crop yields and therefore food production.

This report goes over the process of designing our white light intensity, carbon-dioxide, temperature, humidity, and red-to-blue light ratio sensor. Included in this report is the background and motivation of this project, all research that was performed, standards for the technology, the proposed budget, and the prototype

design. The design, some of the research, and the bill of materials are subject to change, especially in Senior Design 2.

2. Description of Project

To understand our project more, we will dive deeper into the background of how we chose our project as well as goals and objectives we hope to achieve. We will also demonstrate how our project will work using diagrams, specifications tables, and layout images.

2.1 Background

In this high-tech and technology-dependent world, it is easy to forget the source of our foods and how important simple things like farming and the agricultural industry are in our lives. For our Senior Design project, our team aims to focus on improving this industry and coming up with an idea to aid and advance this field. We plan to create a greenhouse monitoring system utilizing photonics sensors to measure and report on key environmental factors such as relative light intensity, the ratio of blue to red light, temperature, humidity, and CO₂ levels. Our system will ideally be placed in the center of a greenhouse environment, at the canopy level of plants, and be able to monitor these parameters in real-time. The device will be capable of wireless communication and feature an accompanying mobile app that allows for remote data analysis and real-time updates. The system will also prioritize energy efficiency to ensure long-term usability. In essence, our project aims to progress the capability of environmental sensing devices and further the efficiency of greenhouses.

When choosing an idea, we needed to select a project that was going to make a positive impact on an industry and the world, as well as be challenging enough to allow us to put in a large amount of time and effort. However, the project must also not be too expensive or unrealistic for a senior design project, provided the fact that we did not secure sponsorship for our project. Our original plan was to make a portable, handheld device that would function both indoors and outdoors, but we quickly realized that we wanted our device to have a more specific use. Hence, we chose the greenhouse idea. We also realized that designing a handheld device with mounted optics would be virtually impossible for a device of this nature and that we needed plenty of optical design, which simply buying sensors would not provide. Therefore, after much research, we decided that designing both an overall light intensity sensor, designing a sensor that would quantitatively show the ratio of red to blue light, and buying a sensor that measured the humidity, temperature, and CO₂ levels would be the most reasonable. Our reasoning for building the red and blue light sensor involves our background research into the importance of these wavelengths in plant health and growth.

Specific wavelengths of light such as blue (400–500 nm) and red (600–700 nm)

have been shown to positively impact morphogenesis, metabolism, and the capacity for plants to photosynthesize [1]. With our optical light sensor, we can detect the ratio of blue and red light within the greenhouse to see when optimal light for the plants is achieved. For the future of this device, there is potential to even suggest or automatically change the lighting within the greenhouse to remotely adjust to optimal conditions.

Our project requires sufficient optical design, as one optics student needs to design a light sensor that will feed into a spectrometer, which the other optics student will build and will detect the wavelengths of the light. In conjunction with the optics students, the EE needs to design a PCB and ensure all electronic components function properly, and the CPE needs to integrate all the components with an application.

2.2 Motivation

In the very sensitive and necessarily stable environment of greenhouses, there is an increased need for reliable and easy-to-use greenhouse monitoring systems. There are many ways to define the environment of a greenhouse, but for the sake of simplicity, it is the general space in which plants would grow. Instead of measuring on a plant-by-plant basis, the “environment” described here is a broad generalization and categorization of some of the most important parameters that can be measured through the air, which will be listed later. While not a one-to-one comparison, this idea can be compared to the difference between measuring the average temperature of a single city versus measuring the temperature of the whole earth. For this project, we are focused on the “global” measurement. Keeping that in mind, modern solutions lack the combination of durability and comprehensive data collection, which is important for real-time environmental monitoring. A lot of devices tend to measure a few of these metrics at a single time. This leads to inconvenience and the purchase of multiple devices to measure metrics such as relative white light intensity, the ratio of blue to red light, temperature, humidity, and CO₂ levels. Our project aims to address these gaps by creating an all-inclusive device that not only provides accurate environmental data but is also user-friendly and adaptable to various conditions. To conclude, this project aligns with the goal of advancing greenhouse monitoring technology by making it simpler, faster, and more complete.

2.3 Goals

The goals of our project reflect what needs to be accomplished. Basic goals are what we want our device to do. Advanced goals build off of the basic goals and include specific numbers and specifications. Lastly, stretch goals are things that can be accomplished beyond Senior Design. They are uses for our device that, with enough time and research, can be implemented.

2.3.1 Basic Goals

- The device will be capable of measuring temperature, humidity, and CO₂
- The device will be capable of measuring white light and the red to blue light ratio
- The measurements of these parameters will be determined and wirelessly sent to be displayed through an application
- This device must be able to continuously collect data and update the application in real-time
- Satisfy voltage requirements aligning with SD standards

2.3.2 Advanced Goals

- The CO₂ measurement will be accurate within ± 50 ppm
- The temperature measurement will be accurate within $\pm 1^\circ\text{C}$
- The red and blue light ratio measurement will be accurate within $\pm 10\%$ of the intensity of each wavelength
- The relative humidity measurement will be accurate within $\pm 10\%$ RH
- The total dimensions of the device will not exceed 15"x15"x10"

2.3.3 Stretch Goals

- The data collected through this device will be used to predict greenhouse status dependent upon the type of plants inside
- The application will be able to analyze the data and determine parameters that must change for optimal plant health
- The data gathered by the device will be able to physically adjust to the environmental needs of the greenhouse

2.4 Objectives

In the same fashion as our goals, our objectives are split into basic, advanced, and stretch objectives. They explain how we are going to achieve our goals.

2.4.1 Basic Objectives

- Successfully calibrate the bought sensors using separate measurements to ensure reliability and accuracy.
- Successfully calibrate light sensors with lenses and other optical elements to ensure overall white light intensity measurement and the ratio of blue to red light is accurate
- Create a software structure, such as a user-friendly app, where the readings from the sensor will be displayed
- Ensure measurements are read after specified intervals of time to update app in real-time

- Determine the elements used and combined voltage to satisfy voltage requirements of 5V

2.4.2 Advanced Objectives

- Calibrate CO₂ sensor with a separate sensor to ensure accuracy.
- Calibrate temperature sensor with a separate sensor to ensure accuracy.
- Calibrate red and blue photodiodes with a lux meter to ensure accuracy of ratio
- Calibrate humidity sensor with a separate hygrometer to ensure accuracy.
- Create housing in a CAD software and specify measurements to not exceed the specifications before 3D printing housing

2.4.3 Stretch Objectives

- Create option to input type of plant within greenhouse and use data analysis of the readings to predict plant health
- Establish a firmware/hardware that allows the dispositive to understand the data and analyze it to determine the changes needed within the greenhouse
- Send signals from the device to the greenhouse itself to adjust the parameters however it determines is necessary

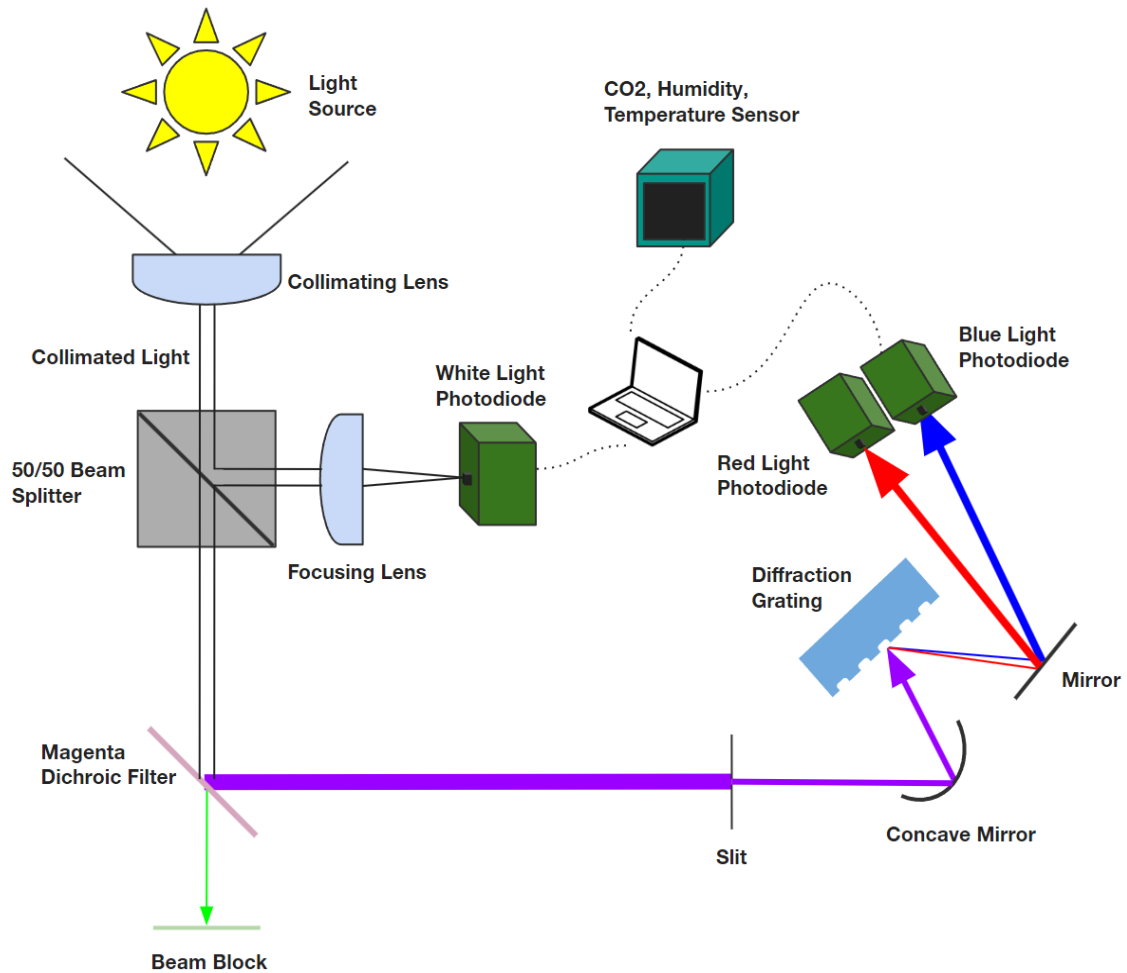
2.5 Diagrams

The diagrams shown below aim to make it easy for anyone to understand how our device will function. We will include an optics diagram, a hardware diagram, and a software diagram. To further visualize the device we will also include our prototype idea and an illustration of our app.

2.5.1 Optics Diagram

Our optics diagram shows the optical components chosen to be used and their setup. The computer represents the ECE and CpE components.

Figure 2.5.1: Diagram showing optical setup of device.



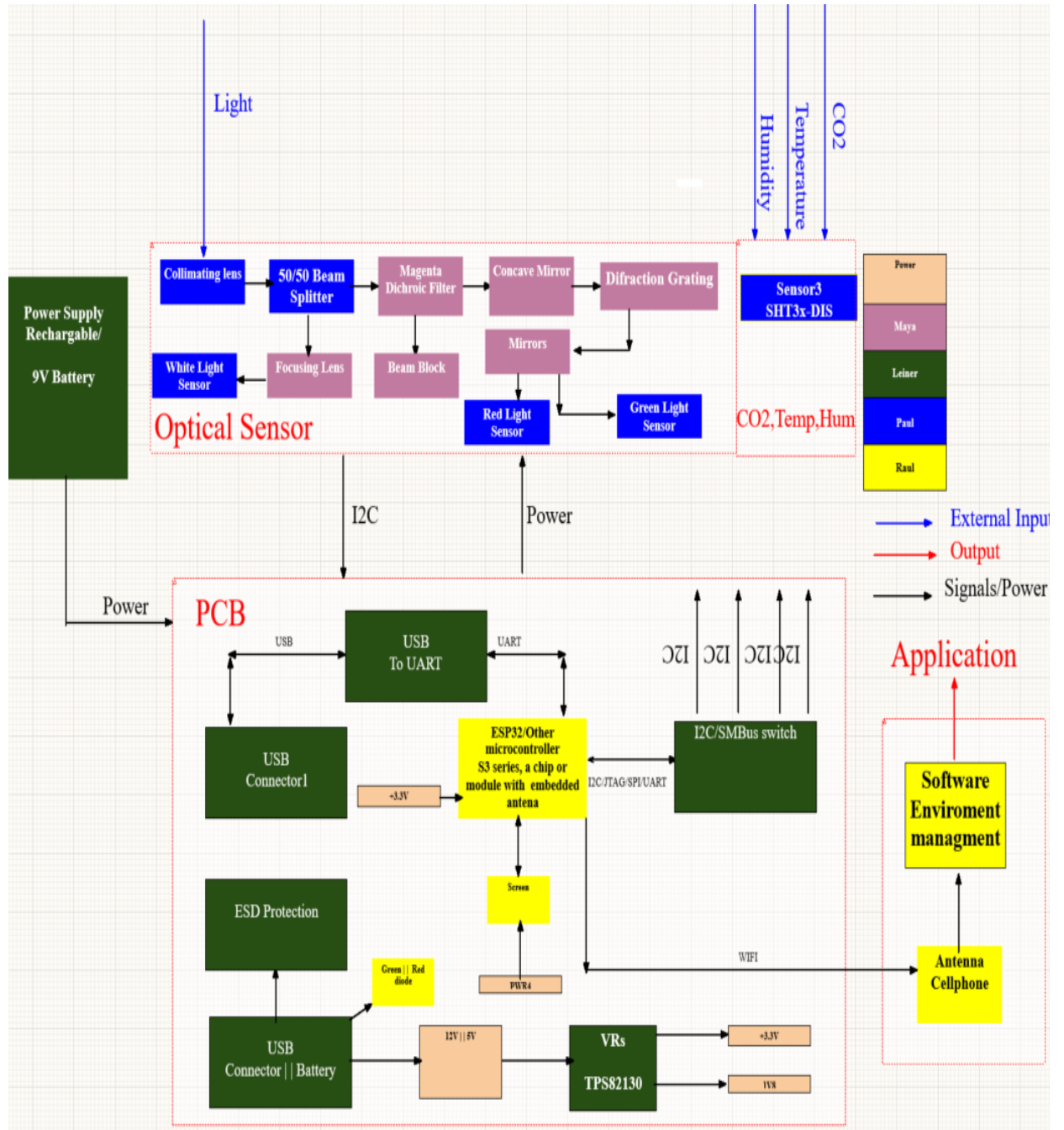
2.5.2 Hardware Diagram

The hardware diagram provides an overview of the device's key components, illustrating each team member's responsibilities and the interconnections within the system. The optical design section focuses on sensors and lenses that capture environmental data like light intensity, CO₂ levels, temperature, and humidity. This part is led by the photonics and optics team, ensuring that sensors are precisely calibrated for accurate data collection.

The PCB design section, overseen by the hardware and electrical engineering team, integrates all physical components, including power management circuitry, sensor interfaces, and connectivity modules. The PCB layout is optimized for durability and efficient power usage, ensuring seamless communication between all hardware elements. By breaking down responsibilities and detailing each team member's role, the hardware diagram captures the collaborative structure of the

project and highlights the critical components that enable effective greenhouse monitoring and management.

Figure 2.5.2: Hardware diagram showing responsibilities of each team member.

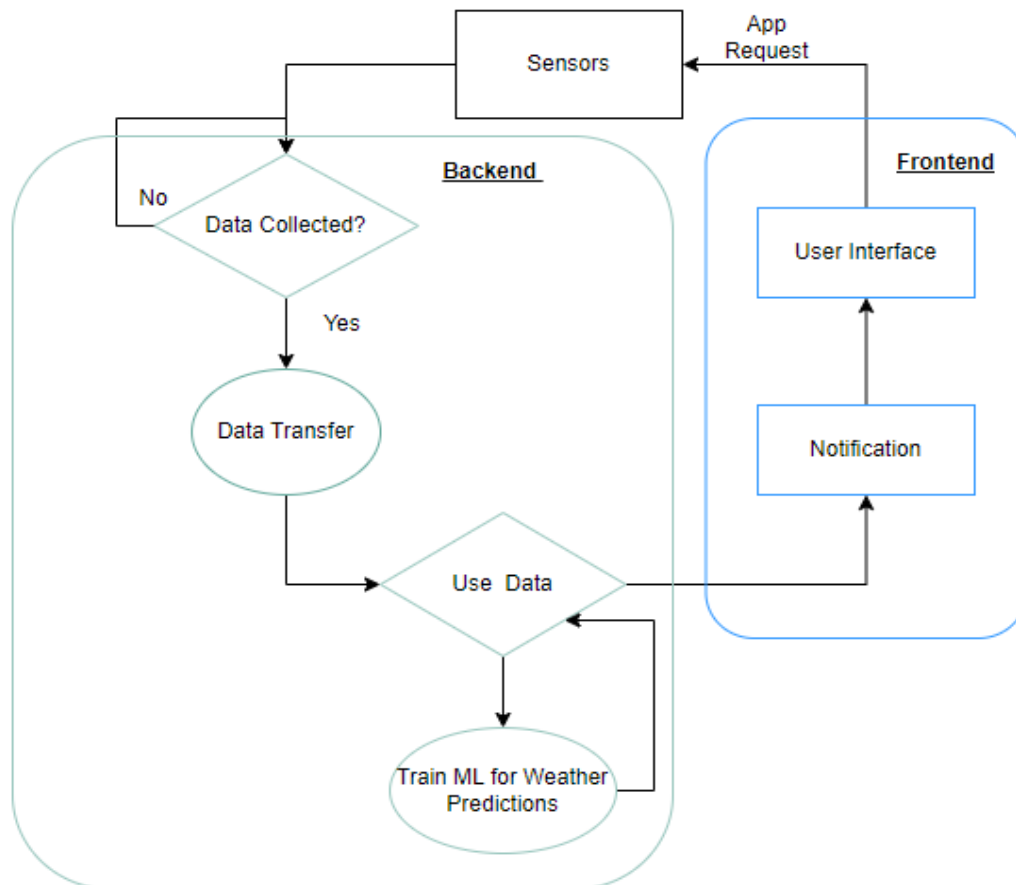


2.5.3 Software Diagram

The software diagram illustrates the data flow within the device, split into Backend and Frontend components. In the Backend, sensors gather environmental data

based on an app request, which then undergoes a Data Collection check. If data is successfully collected, it moves to Data Transfer for storage and processing. The system can either utilize this data immediately for updating the user interface or feed it into a Machine Learning (ML) module to enhance weather prediction capabilities. The Frontend includes a User Interface where users can view real-time data and interact with the device, along with a Notification system that sends alerts based on sensor readings and ML predictions. This structure enables efficient real-time data monitoring, predictive analysis, and responsive user interaction within the device.

Figure 2.5.3: Software Diagram showing data flow within the device.



2.5.4 Task Assignment Table

The Task Assignment Table below outlines the distribution of responsibilities among team members for the development of our device. Each primary task is assigned a main engineer responsible for leading it and a secondary engineer who will provide support as needed. This division ensures efficient collaboration and

allows each team member to contribute their expertise to both core and cross-functional areas.

The main assignments are categorized into four key areas: PCB design, application/website development, sensor work (including Red/Blue and Diffraction Grating), and sensor integration (for white light, humidity, temperature, and CO₂ sensors). Each of these tasks has been allocated to a lead engineer, with an additional team member designated as secondary support.

Table 2.5.4: Tasks divided up between team members.

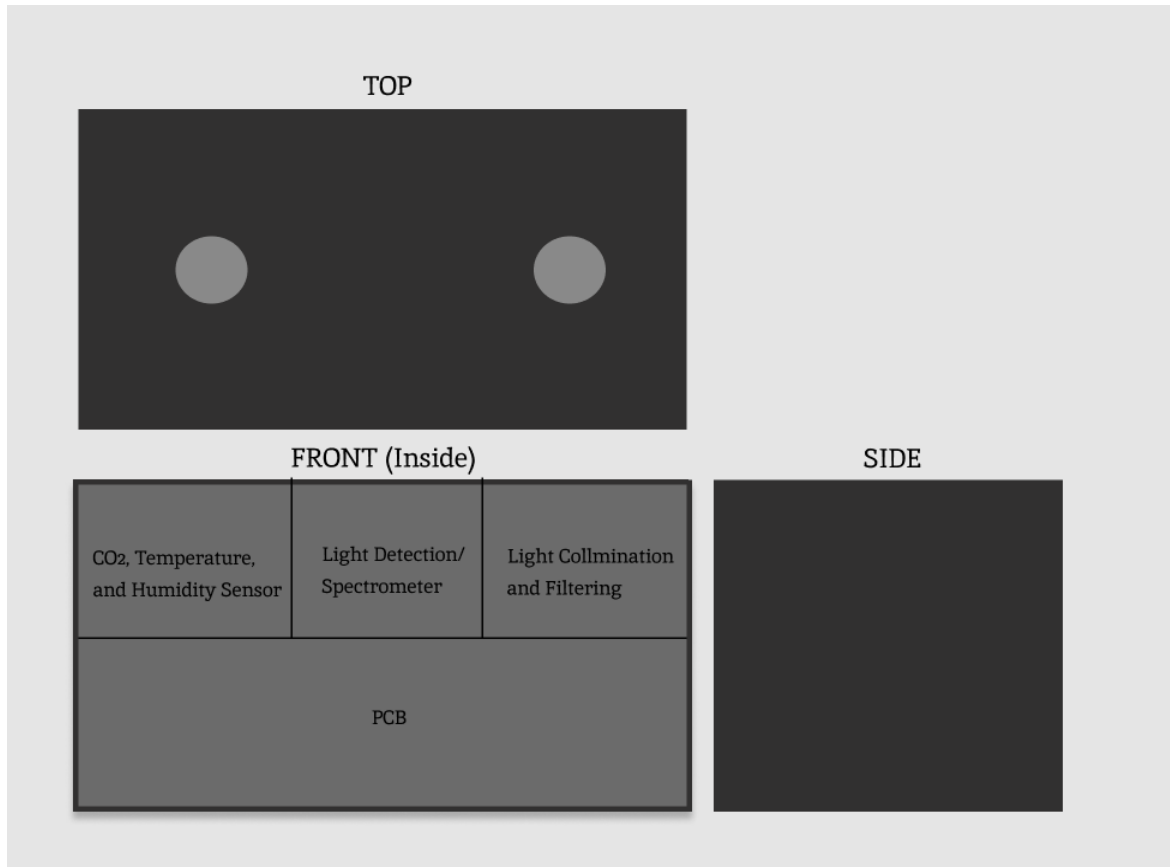
Engineer	Main Assignments Tasks							
	PCB design		Application/Website		Red and Blue Sensor/Diffraction Grating		White light sensor, Hum;Temp,CO2 Sensor	
Lead	Leiner		Raul		Maya		Paul	
Secondary	Raul		Leiner		Paul		Maya	
	ECE specific Tasks				PSE specific Tasks			
	Schematic Design	PCB layout	Microcontroller code	Application functionality	Optics Design	Optic Signal Translation	Sensor Research	Sensor Programming
Lead	Leiner	Leiner	Raul	Raul	Paul	Paul	Maya	Maya
Secondary	Raul	Raul	Leiner Paul	Maya	Maya	Maya Leiner	Paul Leiner	Raul Paul

2.5.5 Prototype Idea

The image below presents an initial prototype design for the greenhouse monitoring device, providing top, front (inside), and side views of the device's layout. The top view shows two holes in the device housing, intended to allow sunlight and air to enter. These openings facilitate measurements by permitting direct exposure to environmental factors such as light, CO₂, temperature, and humidity, essential for accurate sensor readings.

In the front (inside) view, the internal components are visible, showcasing a modular arrangement of sensors and functional parts. The CO₂, Temperature, and Humidity Sensor is positioned on the left side, ensuring it has direct access to incoming air. In the center, a light detection/spectrometer is used to capture detailed light intensity and spectral data, crucial for assessing the greenhouse's lighting conditions. On the right, a Light Collimation and Filtering component is included to enhance the accuracy and consistency of light readings by focusing and filtering the light before it reaches the spectrometer. Below these components, the PCB (Printed Circuit Board) supports the core processing functions and connections, serving as the central hub for integrating the various sensors and the ESP32-S3-WROOM-1-N8R2 microcontroller.

Figure 2.5.5: Diagram of first prototype idea showing top, front, and side views.



2.5.6 App Illustration

Below is an illustration of the proposed app design. The app will feature a secure login screen, followed by a user-friendly main dashboard displaying real-time measurements of environmental parameters such as temperature, humidity, CO₂ levels, and light intensity. The dashboard will include intuitive visualizations like graphs, and numerical displays for easy interpretation. Users will also have

access to features such as historical data analysis, customizable settings for measurement intervals. The app will integrate seamlessly with the hardware system, allowing remote monitoring and management via a Wi-Fi connection.

Figure 2.5.6: Illustration of potential app layout showing data collected from device.



2.6 Features and Functions

The device is designed with several key features and functions aimed at improving greenhouse monitoring and management. At the core, it gathers real-time data from various sensors, including those measuring light intensity, temperature, humidity, and CO₂ levels, providing a comprehensive environmental overview. This data is processed by the ESP32-S3-WROOM microcontroller, enabling responsive adjustments in the greenhouse, such as activating fans or adjusting lighting to maintain optimal conditions.

In addition to environmental monitoring, the device includes wireless communication capabilities, allowing users to remotely access data and receive notifications through a mobile app. The app interface is intuitive, providing real-time data visualization and historical trend analysis for better decision-making. To

ensure reliability, the system also includes a robust data storage and retrieval process using a cloud server, ensuring that data remains accessible even in case of power interruptions or network fluctuations.

2.6.1 Software and UI

The software and user interface (UI) components are vital to ensuring the functionality, usability, and efficiency of our environmental monitoring system. This section outlines the data collection process, including the interaction between sensors, the machine learning processor for weather predictions, and the design features of the mobile app that allows users to access both real-time and historical environmental data. The UI must be intuitive and responsive, providing users with seamless interactions while also offering advanced features for power users. The backend software will focus on robust data management, ensuring accurate and timely reporting of environmental parameters.

2.6.2 Data Collection

The sensors integrated into our system will gather environmental data, such as temperature, humidity, light intensity, CO2 levels, and UV radiation. This data will be transmitted to a central database for processing. The database will store the collected data in real-time, while historical records will also be available for comparative analysis. To enhance the accuracy of weather forecasting and improve predictions over time, the data collected by the sensors will be fed into our machine learning processor. This processor will analyze trends, patterns, and anomalies in the data to generate daily weather predictions and provide insights into environmental changes. By continuously learning from the incoming data, the system will refine its predictive models to offer more accurate forecasts and insights.

2.6.3 UI/APP

The mobile app will be designed with an emphasis on user-friendliness and accessibility. The goal is to make the app easy to navigate, with clear and concise displays of real-time environmental data such as air quality, temperature, humidity, and UV levels. Notifications will be sent to users based on predefined thresholds or significant environmental changes, helping users stay informed and take action when necessary. Additionally, as a stretch goal the app will feature a historical data section, allowing users to view and compare environmental data from previous days. Visualizations, such as graphs and charts, will be integrated to help users better understand the trends and patterns in the data. Power users will have the option to customize settings, create alerts, and export data for further analysis. The app will also include an intuitive dashboard for quick access to key metrics and trends.

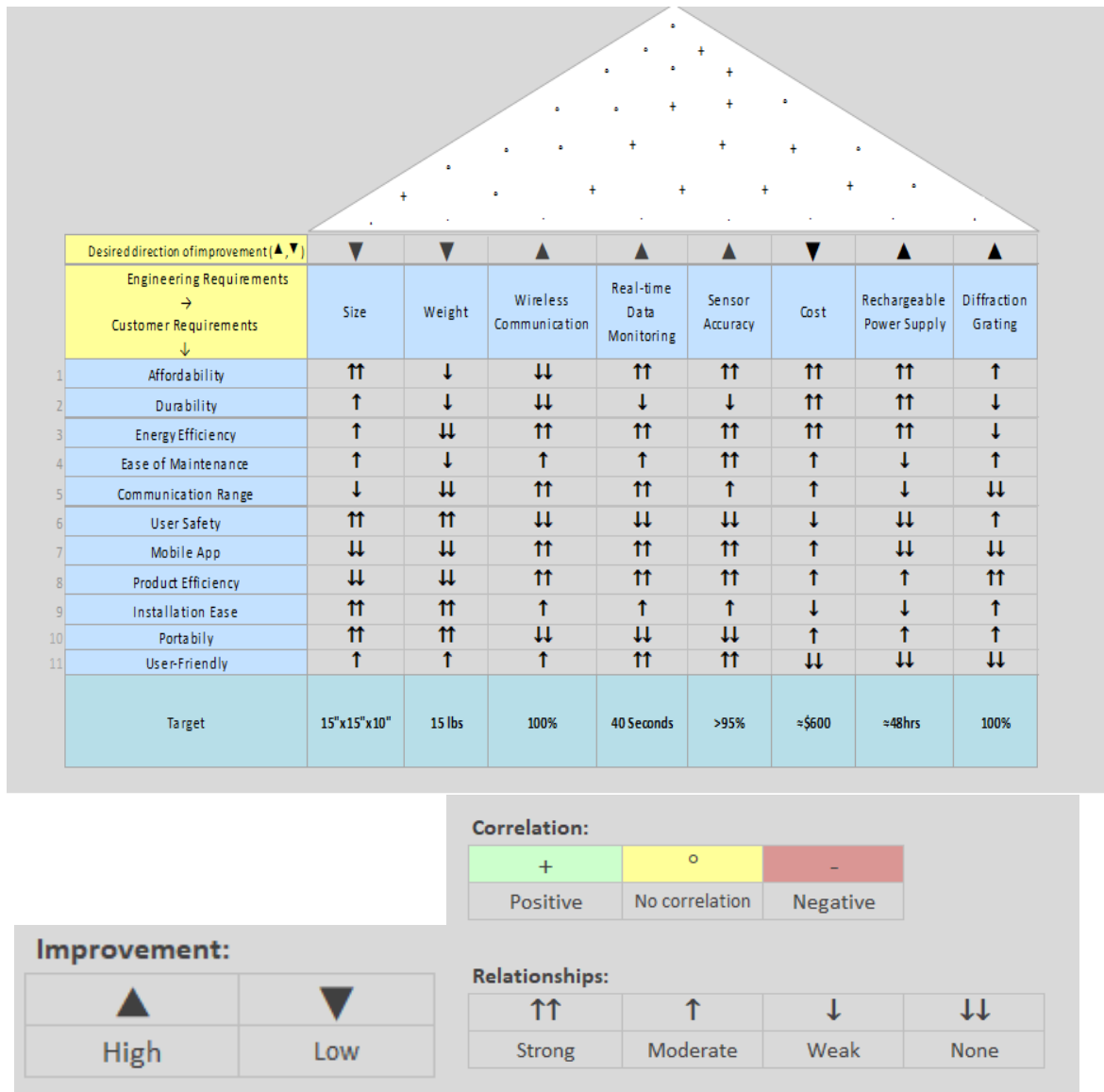
2.6.4 Wireless Connection

To ensure seamless data transmission and system connectivity, the device will incorporate wireless communication protocols such as Wi-Fi. This will allow the sensors to communicate with the central database, where the collected data will be stored and processed. In addition to data collection, the wireless connection will enable the app to send requests to the device, retrieve up-to-date information, and receive real-time notifications. The system will be designed to ensure minimal latency and maximum reliability, ensuring that users receive accurate and timely updates without delay. Additionally, the wireless communication protocols will allow for remote control and configuration of the system, enabling users to modify settings or troubleshoot issues from anywhere with an internet connection.

2.8 House of Quality

The House of Quality is a structured matrix that helps evaluate and balance customer needs with engineering requirements to guide product design. This chart visually maps the relationship between customer demands—like affordability, durability, and user-friendliness, and engineering specifications, including size, weight, wireless communication, sensor accuracy, and cost. Symbols within the matrix indicate the strength and direction of these relationships, with arrows showing desired improvement directions and icons denoting strong, moderate, weak, or no correlation. The triangular section at the top represents how different engineering requirements interact with each other, allowing for a deeper understanding of potential trade-offs. By analyzing both customer and engineering priorities in a single view, this tool ensures a balanced approach that addresses customer expectations without compromising technical feasibility, ultimately guiding us toward a well-rounded, user-centered product design.

Figure 2.8: House of Quality diagram showing correlation between engineering and customer requirements.



2.9 Specifications

Engineering specifications are crucial in the industry to explain how a product functions and what universal standards it may follow. During our research, we looked at industry standards, similar products, and made constraints, then came up with the specifications for our project. Throughout the process of prototyping and designing, our specifications may change. Currently, our project will adhere to the following engineering specifications.

2.9.1 Device Specifications

The specifications of our device govern how it operates and what metrics it operates within.

Table 2.9.1: Device specification table with requirements and the specifications of said requirements.

Requirement	Requirement Specification	Unit
The device will have sensors that measure accurately within a certain range.	± 1	Celsius
	± 50	ppm
	$\pm 10\%$	RH
	$>10,000$ & $<100,000$	lux
The time between updates of the measurements in the app will be realistic but not too much	<40	Seconds
The device shall not be so heavy that one person cannot lift it.	<15	Pounds
The device shall use the specified voltage.	9	Volts
The maximum frequency shall not exceed the specified amount.	2.4 or 5	GHz
Operating System	IOS/Android	
The idle power consumption shall not exceed the specified amount.	<1	Watt
The protective housing material for the sensors will be resistant to temperature and humidity.	ASA	
The dimensions of the device shall not be excessive and be portable.	$<15'' \times 15'' \times 10''$	Inches

2.9.2 Component Specification

The specifications of our components guide us in choosing what optic to buy. By knowing the limits of our components, we can know the quality of our setup.

Table 2.9.2: Component Specification table with requirements of the various components and the specifications of said requirement.

Optical Component	Requirement	Requirement Specification	Unit
Diffraction Grating	The diffraction grating shall diffract light at an angle that will allow us to capture the red and blue wavelengths.	1800	lines/mm
Intensity Sensors	The intensity sensors shall be able to accurately measure lux values between	10,000 to 100,000	lux
Plano-Convex Lenses	Diameter must be able to collect enough light to send light to the sensors but not too much to the point where the sensors are saturated.	Diameter: 10 — — — — — Focal Length: 20	mm
Beam Diameter	Beam size must be equal to size of active area of sensor	<25	mm

2.10 Related Work

By looking at products similar to our proposed device in the market, we can see what engineering specifications are out there and use that to create ours. We can see what is possible and also what sells and is marketable. Below are a few related products.

2.10.1 Related Products

The market for greenhouse monitoring systems includes separate sensors that usually measure either temperature, humidity, CO₂, or light levels.

- *Govee Hygrometer Thermometer H5075* - A humidity and temperature sensor complete with a Bluetooth-connected app. Temperature accuracy: $\pm 0.3^{\circ}\text{C}$. Relative humidity: $\pm 3\%$. Measurement refresh rate: 2s. [2]
- *AIROASIS Air Quality Monitor Indoor* - Small screen display monitoring CO₂, TVOC, HCHO, humidity, and temperature. Used for indoors only. [3]

- *Reed LM-8000, Environmental Meter* - A handheld relative humidity, air temperature, contact temperature, and light intensity sensor. Temperature accuracy: $\pm 1.2^{\circ}\text{C}$. Relative humidity $\pm 5.2\%$ for RH $> 70\%$ & $\pm 4\%$ for RH $< 70\%$. Light intensity: $\pm 5\%$ reading. Response time: 1s. [4]
- *Temp Stick* - Small temperature and humidity sensor that can be placed anywhere and links with application. Temperature accuracy: $\pm 0.15^{\circ}\text{C}$. Humidity accuracy: $\pm 2.0\%$ RH. [5]

3. Research and Investigation

We will now dive deeper into our project and investigate the technology behind it. Our research into the various technologies and parts we are looking to implement in our device will act as a guide in how we choose these items.

3.1 Technology Comparison

Looking into the pros and cons of various similar technologies, our research can aid us in deciding on the best technology for the job.

3.1.1 Light Sensing Technologies

There are a variety of different light-sensing technologies, each with different pros and cons. For our project, we need light intensity sensors that are able to detect a wide range of light intensities across the entire visible spectrum. This is because our sensors will primarily be used in a greenhouse setting and there will be differing levels of light intensity as the day goes on. As the sun rises, the light intensity increases, and as the sun sets, the light intensity decreases. Three different technologies that can be compared for these purposes are photodiodes, phototransistors, and photoresistors.

3.1.1.1 Photodiodes

Photodiodes are a very common way to convert light energy into electrical energy. Photodiodes consist of P-N junction semiconductors, which have different properties, depending on the way they're biased. For light intensity sensing, the photodiode needs to be in the reverse-biased "photoconductive" mode. [6]

One of the biggest problems that our team might have to solve when using any type of light-sensing device is the calibration and relationships between incident light and current. One of the largest benefits of using a photodiode in photoconductive mode is that the relationship between current and incident light is linear. [6] This relationship would make the calibration and calculations on the software side much easier, as the analog signal of the current would be more easily converted into digital. If the relationships weren't linear, a more complex analysis of the signal would have to be performed.

Another one of the biggest benefits of using a photodiode is the fast response time. After a quick search on DigiKey, it was found that the response times ranged from 10 milliseconds to 16.67 picoseconds. [7] This sort of response time, while not being the only factor to determine the overall speed of the system on the application side, is still an important factor.

While there are many benefits to using photodiodes, there are some very

important disadvantages. Firstly, running a photodiode in a reverse-biased way causes something called a dark current, which is essentially noise added to the total current. Ideally, this current would not exist, but it is unavoidable. With the presence of this dark current, it is important to have an input light source with a high enough intensity to cause the overall current to increase by a readable amount. Now, that readable amount is determined by the sensitivity of the receiver. With a highly sensitive receiver, low-light-level conditions may be okay, but without one, it may be hard to distinguish between the noise and the current being produced. The dark current also increases with increasing bias, so that is something to take into account. [8]

Below are some equations showing the relationship between the overall current and the dark current, and the relationship between the overall responsivity of the system, the generated current, and the input optical power. The responsivity essentially tells us how effective the photodiode is at generating a photocurrent at a specific wavelength, given an input optical power. The lower the input power, and the higher the photocurrent, the higher the responsivity. [9]

Equation 3.1.1.1.1: Relationship Between the Output Current, Dark Current, and the Photocurrent

$$I_{Out} = I_{Dark} + I_{Photo}$$

Equation 3.1.1.1.2: Relationship Between Responsivity, Photocurrent, and Input Power

$$R(\lambda) = \frac{I_{Photo}}{Power}$$

Another issue is that the currents generated by the photodiode can be very small, even with light present. Because of this, amplifiers are typically used, which is yet another expense. [10]

3.1.1.2 Phototransistors

The next technology for consideration is the phototransistor. Phototransistors are very similar to photodiodes. In fact, it has been compared to a photodiode that has a current amplifier integrated into the part. [11] While this sounds great in theory, it brings up some interesting issues that will be discussed further down. First, we'll take a look at the benefits of using a phototransistor.

As stated above, one of the biggest benefits of a phototransistor is its current gain. This gain is quite large, with the output current being 50 to 100 times that of a photodiode. [11] This large gain would make any MCU processing much easier, as it would guarantee that there is a readable current. The equation for the current

of phototransistors are different than those of a photodiode, as the current gain, collector current, base current, and emitter current all have relationships. In a phototransistor, the base current is the photocurrent, assuming an NPN transistor. These relations are seen below:

Equation 3.1.1.2.1: Relationship Between Collector Current, Base Current, and Current Gain

$$I_C = \beta I_B [12]$$

Equation 3.1.1.2.2: Relationship Between Emitter Current, Collector Current, and Base Current

$$I_E = I_C + I_B [12]$$

The first of the potential downsides is that a current amplifier does not necessarily mean a better reading of the change in current. If the current is purely being amplified, it means that the noise of the dark current is being amplified as well. So, while the current would be easier to read, it would not necessarily get rid of the noise issue that comes from a low light level. Technically, the sensitivity of the phototransistor is greater than that of a photodiode, but that's only because of the internal processes that amplify the dark current. [11]

The second potential downside is that phototransistors have slower response times compared to photodiodes. [11] As mentioned earlier, the slower each part is, the slower the system will be overall. While the response time will likely be determined by how fast the MCU can process all the data, it would be better if change in light intensity was tracked as fast as possible, to have the most up-to-date and accurate information.

The third potential downside of phototransistors is that the response of a phototransistor is not as linear as a photodiode. [13] For our project, we want to have clear relationships between variables and equations so that we can compare our outputs to what "should" be. A mostly linear response with a slight curve could still work, but it may take more calibration and testing to make sure that we're getting the results we want.

Lastly, phototransistors are typically more expensive than photodiodes. Because of this, we'd need to justify the cost versus the benefits of this type of device.

3.1.1.3 Photoresistors

Photoresistors have a very different operating method than that of a photodiode or phototransistor. They are still semiconductor-based devices, but instead of the current and voltages changing with the increasing light intensity, the resistance and conductivity of the devices change. This change can be quite drastic, as it

can go from operating with hundreds of thousands of mega-ohms to almost nothing. [11]

Some of the benefits of photoresistors are that they do not need to be biased and that they are cheap. [14] This may benefit projects that are tight on space and budget. Also, as stated, the resistance changes with light intensity. So, with projects that aim to determine whether light intensity is changing, this may be sufficient.

Now, there are many cons to using this technology. Firstly, photoresistors are very sensitive to changes in temperature, much more than phototransistors and photodiodes. These changes in temperature affect the resistance that the photoresistor exhibits. [14] For projects that primarily need accurate light intensity readings, this is not ideal because of the chance that the change in ambient temperature messes up the readings.

The second disadvantage of using this technology is the fact that photoresistors have much slower response times to changes in light intensity than the other options. [14] Whereas the other technologies have response times that are much smaller than a second, [7] photoresistors can take as long as a second to react to a change in light intensity. [15] This would not be sufficient for projects that need very fast measurements.

Lastly, the photoresistors do not have a linear light intensity to resistance relationship. This relationship exponentially decays, [11] which makes the calculations and calibrations more complex than those of photodiodes and phototransistors.

Here is a table simplifying all the facts so we can have a clear comparison between the technologies:

Table 3.1.1.3: Comparisons between various light sensing technologies.

Technology	Cost	Response Time	Relationship	Measured
Photodiode	\$1	Very Fast	Linear	Current
Phototransistor	\$2	Fast	Linear	Current
Photoresistor	\$0.80	Slow	Non-linear	Resistance

3.1.1.4 Light Sensor Technology Choice

After analyzing the difference between photodiodes, phototransistors, and photoresistors, it's clear that photoresistors are not a reasonable choice for a light-intensity sensor that needs specific and precise measurements. The response times are too slow and the sensitivity to temperature is a factor that we'd really have to worry about, since ambient temperature is something that changes, even by a small degree, and it's hard to say how much that would affect the accuracy of readings.

The choice between photodiodes and phototransistors is a more difficult decision. While phototransistors have the benefit of not needing current amplifiers and essentially being upgraded photodiodes, their slower response times and not-quite-as-linear light intensity and current relation make them less valuable. Also, since they are more expensive than photodiodes, they would need to have much better properties to justify buying them, but they don't.

Therefore, photodiodes will be the choice for the light-intensity sensors in our project.

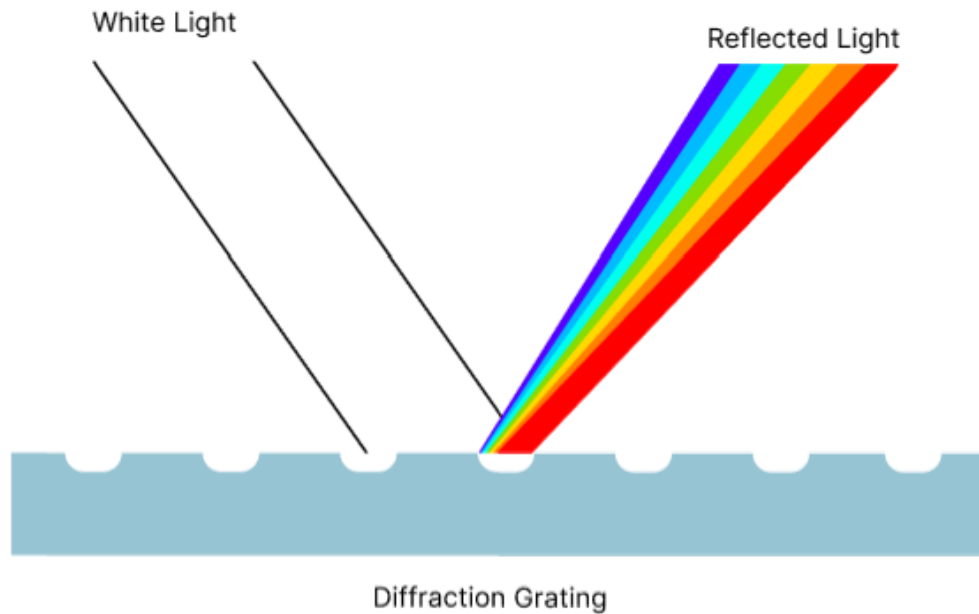
3.1.2 Diffraction Gratings

Diffraction gratings, as the name suggests, use the principle of diffraction to reflect or transmit light at an angle determined by the wavelength. Reflective gratings are the most common, however, there are transmissive, concave, ruled, holographic, and echelle gratings as well. These gratings differ in their own ways and have their own benefits and drawbacks. We will dive deeper into the pros and cons of these different grating technologies in regards to our project.

3.1.2.1 Reflective Gratings

A plane, or flat, reflective grating is an optical element that contains periodic lines, or grooves, that are made either mechanically or optically (refer to section *Ruled and Holographic Gratings*). Incident light hits these grooves and diffracts based on the light's wavelength. The reflected light then spreads due to the various angles of diffraction, allowing certain wavelengths to be captured by using a slit or other blocking device. This element provides a way to separate a light source into its components, a very useful tool in optical design.

Figure 3.1.2.1: An illustration of a plane reflective refractive grating and how it works.



The distance (d) between the grooves decides the angle of the reflected light. As the governing variable, gratings are labeled based on the frequency of d , or the number of lines per millimeter on the grating ($\frac{1}{d \text{ (mm)}}$). This is usually on the order of hundreds to thousands of lines per millimeter. We can see the dependency between the frequency, angle of incidence, angle of diffraction, and wavelength below in equation 5 [16].

Equation 3.1.2.1: Diffraction Grating Equation

$$m\lambda = d(\sin \alpha + \sin \beta)$$

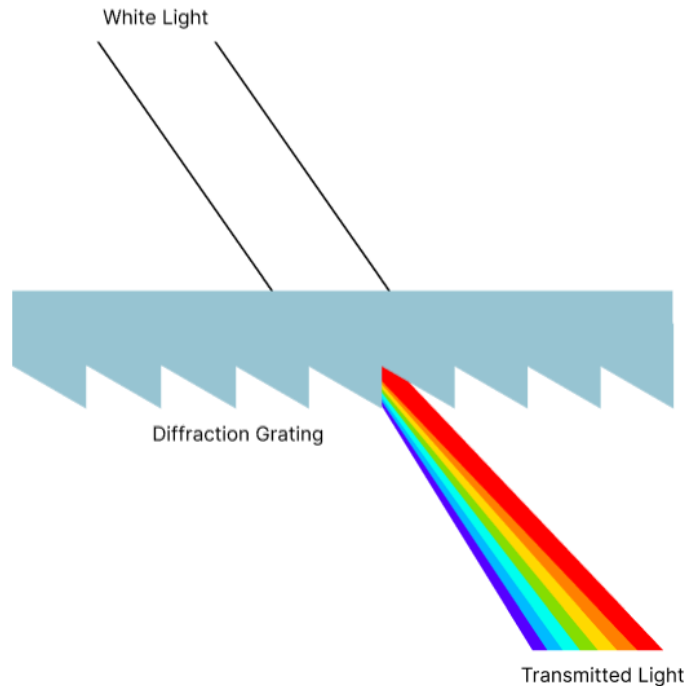
Following this formula, incident light coming in at angle α will reflect at angle β . Same wavelengths (λ) of light can reflect at various set angles based on the order (m) of the diffraction. Most of the light will diffract at the first order angle, less light at the second order angle, and so on until it is negligible [16].

Plane reflective diffraction gratings are useful due to their simple structure and lower price point. They are commonly used in applications where mirrors can be used to reflect the light back to where it needs to go. They are a solid choice in a simple optical system.

3.1.2.2 Transmissive Gratings

Transmissive gratings operate similarly to reflective gratings in regards to the equation and angle of diffraction of the light. However, the main difference comes from the fact that a transmissive grating allows the light through the element. Instead of the diffracted light being reflected, it is transmitted through.

Figure 3.1.2.2: An illustration of a plane transmissive grating and how it works.



While more expensive, benefits of a transmissive grating include ease of set up. Rather than having to account for reflection and use mirrors to get the light back on track, using a transmissive grating won't disrupt the flow of the light assuming a straight line optical setup. This is useful in applications that require a more compact optical setup [17].

3.1.2.3 Concave Gratings

A diffraction grating, whether reflective or transmissive, can be flat (plane) or concave. A concave grating will operate in the same way as the aforementioned two, dispersing the light based on incident angle and wavelength. However, the issues arise due to the shape. Concave gratings bring complexity that plane gratings don't by causing dispersion. The light will either converge or diverge after it has been diffracted [16]. This can be useful in an optical setup that needs this focusing from the dispersive element, but commonly it is not necessary when the

focusing can be done by adding another lens. Plane gratings are the common choice not only due to the lower complexity, but due to the much lower price point as well. A reflective concave grating from Edmund Optics¹ that is 25mm in diameter is about \$725 compared to a 25mm x 25mm reflective plane grating that is \$134. Due to budgeting and simplicity, we will not be considering a concave grating.

3.1.2.4 Ruled and Holographic Gratings

When talking about gratings, 'Ruled' and 'Holographic' refer to the type of groove on the optic. Ruled gratings are created mechanically, usually cut out of the glass or copper element using a diamond forming tool [17]. This creates a groove profile similar to the top element in the below figure. On the other hand, a holographic groove profile is created optically. This is done by projecting an interference pattern of two laser sources onto a material that is photosensitive. The material will then get the interference pattern of the sources "engraved" into it, resulting in a periodic groove structure similar to the bottom element in the below figure.

Figure 3.1.2.4: The groove profile of a ruled diffraction grating (above) and a holographic diffraction grating (below).



In the past, ruled gratings were more efficient and lower in price. However, with advancements in technology, holographic gratings have now come out on top. They provide no irregularities in the grooves that the mechanically created ruled gratings have, resulting in less stray light and 'ghosts' (false spectral lines) while having comparable efficiencies [18]. Additionally, holographic gratings have become relatively low in cost and simple for industry creation. The cost difference is a negligible amount when compared to the ruled gratings. Also, the process to create them can create lower groove spacings, up to 3600 lines/mm, allowing more options of angle of light dispersion [17].

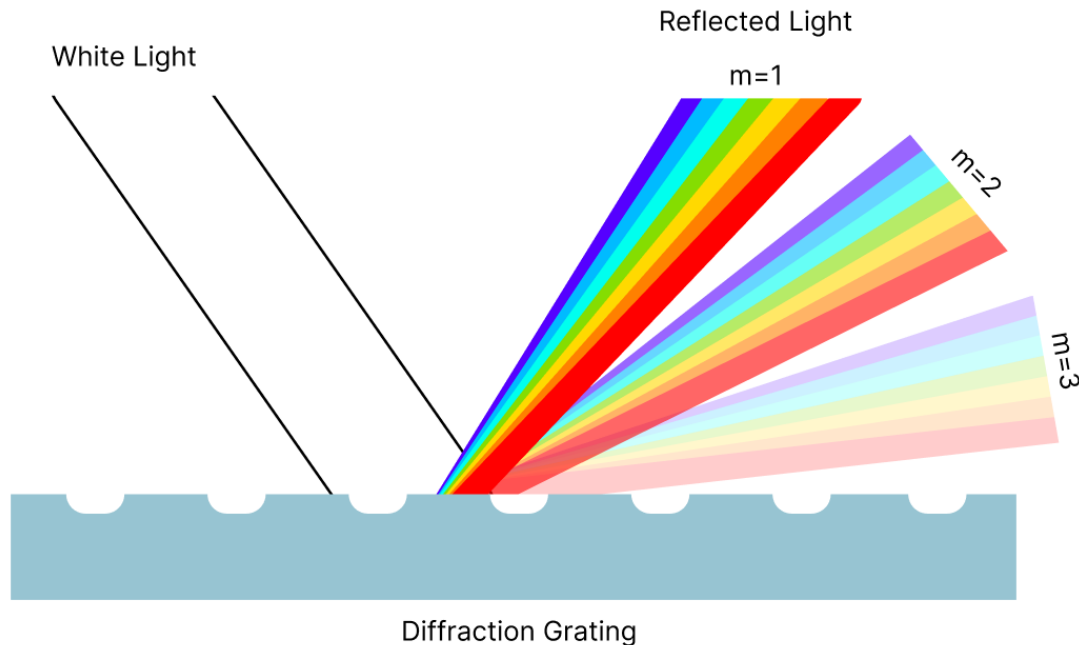
¹ Information found on Edmund Optics site, edmundoptics.com and prices are subject to change

3.1.2.5 Echelle

Echelle gratings are gratings with a low groove density, down to tens of grooves per millimeter. This higher groove spacing allows for higher diffractive orders (m) to be reached by using a high angle of incidence. This gives high dispersion, resolving power, and efficiency with a low dependence on polarization [16]. These diffractive orders are shown in figure 3.1.2.5.

At about \$100 more than a plane reflective grating, echelle gratings are more expensive. For our purposes, an echelle grating would only be needed if the dispersion we get from our chosen grating is not high enough to be able to isolate the blue and red wavelengths.

Figure 3.1.2.5: Different modes (m) of a reflective diffraction grating.



3.1.2.6 Diffraction Grating Technology Choice

Our research into the various types of diffraction gratings allows us to make an educated choice for our device. Based on multiple factors including price, efficiency, frequency of grooves, etc, we will compare these technologies and decide. For ruled and holographic gratings, they are similar enough in price and efficiency that we will not include them in the comparison but instead once the type of grating is decided, we will see what is available on the market.

Table 3.1.2.6: Comparisons of different types of diffraction gratings.

Technology	Cost	Pros	Cons
Plane Reflective	\$	Simple	Need to use mirrors to keep light on track
Plane Transmissive	\$\$	Can make optical system more compact	More expensive for similar experience of reflective grating
Concave	\$\$\$	Can converge or diverge the light	Very expensive Can make system more complicated
Echelle	\$\$\$	Can create higher diffractive orders, higher dispersion	Very expensive Not necessary for our needs

The diffraction grating we will use for our device will be a plane reflective grating. The reason for this choice is that it is simple, cheap, and effective. While other types of gratings may have more bells and whistles, that added variability ultimately just complicates the otherwise simple setup. We will stick with the basics for our project.

3.1.3 Lenses

One of the most important aspects of this optical design are the lenses. Without the lenses, there would be no way to get the light all the way through the optical system. For this particular setup, different lenses would be necessary to collect as much ambient light as possible and focus the light onto the light sensors (though, certain mirror types could be able to do this). Since we are not making an imaging system, we don't have to worry as much about any aberrations that may occur, and we only really need to consider how the collected light is focused onto the sensors. Still, there are some equations to take into account when looking for specific lenses that can tell us a lot about what the lenses do.

The first useful equation is for the $f/\#$. The f number essentially tells us how much light a lens can collect. [19] The equation for the f number is

Equation 3.1.3.1 : F -number, focal length, and lens diameter

$$f/\# = f/D, [19]$$

where f is the focal length of the lens and D is the diameter. In a similar fashion, the numerical aperture, as seen in Equation 3.1.3.2, tells us how fast light diverges after the lens.

Equation 3.1.3.2: Numerical Aperature, refractive index, and half angle of light

$$NA = n \sin(\theta), [19]$$

where n is the refractive index, and θ is the half angle of the light leaving the lens. These two parameters are related by the equation:

Equation 3.1.3.3: Relation between Numerical Aperature and F-Number

$$NA = \frac{1}{2f/\#}, [19]$$

These equations are not all that we'll need to take into account. For instance, there are many losses associated with optical components, with many of those losses coming from reflection. However, given that many of these losses will depend on angle, material, and polariation, those are things to consider later on when creating the actual optical design. We also need to take refractive index and lens radii into account as well. Some equations to help us calculate the focal length of lenses are:

Equation 3.1.3.4: Power of a thick lens of a certain thickness

$$\frac{1}{f} = (n - 1) \left(\frac{1}{R_1} - \frac{1}{R_2} + \frac{(n - 1)t}{nR_1R_2} \right)$$

Equation 3.1.3.5: Focal length of two lenses separated by a distance

$$\frac{1}{f_s} = \frac{1}{f_1} + \frac{1}{f_2} - \frac{d}{f_1f_2}$$

One good rule to take into account, is that the smaller the $f/\#$, the smaller the beam size. For this reason, the smaller the focal length, or the bigger the lens diameter, the smaller the beam size. [20]

3.1.3.1 Collector Lens

A collector lens does exactly what it sounds like, as its main goal is to collect light from a source. This collected light needs to be sufficient enough to go through the entire optical system, despite losses. This is where the $f/\#$ come in. As stated earlier, the bigger the diameter of the lens, the smaller the $f/\#$. Therefore, since we

want to collect the most amount of light possible, and we want the spot size small enough to ensure all the light falls on the sensors, we want to have a smaller $f/\#$.

A collector lens collects light, but like any lens, it can collimate light. Now, the light from the sun is generally collimated, so it wouldn't be an issue, except for the fact that any artificial lighting would not be collimated unless it was a over a focal length away. We want the light to be collimated to such a degree that the spot size doesn't grow at an outrageous rate. So, we can either use a collector lens that collimates the light, or we can have a separate collimating lens.

3.1.3.2 Focusing Lens

Focusing is one of the most vital parts of this optical setup. As light passes through the optical setup, it will focus and diverge at different points. However, we need to ensure that light focuses to a point on the light sensors. Not only do we need to ensure this, we need to ensure that the light focuses to a point that is roughly the same size as the sensor, as any point too big will read a lower intensity, and any point too small will read a higher intensity.

There are a lot of factors when choosing a focusing lens, like whether it will be able to collect all the light that is being sent in its direction and its focal length. These things will depend on the final layout of the PCB and MCU and how big our overall optical design ends up being.

3.1.3.2 Biconvex or Plano-Convex?

Now that we generally know what types of lenses we need, we need to figure out whether we are going to use biconvex or plano-convex lenses. We will not be considering any type of concave lens, as we don't want the light to diverge. Biconvex lenses are lenses that have a convex curvature on both sides of the lens, where plano-convex lenses have one flat side and one curved side. We will go over the differences between the two.

Biconvex lenses are most useful when it comes to focusing light from a small distance. Generally, that is within a couple of focal lengths of the lens: 1:1, 5:1, etc. Collecting light or imaging from images much further than this is not ideal, though it is still possible. [21] For our project, this could be useful as a focusing lens, as the distance from the beam splitters or other optical elements shouldn't be too large.

Plano-convex lenses are very similar to biconvex lenses, except they are better suited for imaging at large distances, that is, ratios like 10:1 or larger. [21] The sun is surely far enough away for this, and any ambient room light is likely to be this distance away, so these would be useful as collector lenses.

Technically, either lens can be used for both purposes, so we will have to decide when comparing lenses if both are needed or one or the other. Biconvex lenses are typically more expensive than plano-convex lenses because of the manufacturing process, so we will have to take that into account. [22] We can also consider combining lenses together, as that can change how the light focuses, but that may not be worth it considering the higher price and that we aren't worried about aberrations.

3.1.3.3 Fresnel Lenses

Previously, we talked about plano-convex lenses and biconvex lenses. These types of lenses are common in everyday optical designs, but there are also some more specialized types of lenses. One of these lenses is called a fresnel lens. Fresnel lenses differ from the previously mentioned types in that they do not have a curved side. Instead, the curved surface is replaced with a series of concentric grooves. Like conventional lenses, they can focus, collimate, and collect light. However, they tend to be produced from plastic and are much thinner. [23]

The primary uses of fresnel lenses are in light collection applications and in applications that require high magnification. The reason that this type of lens is great for light collection is that the lens has a much smaller center thickness than a conventional lens, which reduces the amount of light that is absorbed by the lens material. Also, compared to plano-convex lenses and biconvex lenses, these lenses have better focusing ability. In the same kind of way, they are great at light collimation. [23]

However, since these lenses have a non-uniform shape, they suffer from several different issues. The first issue is that they have issues with chromatic aberration, specifically when used with broadband sources, like the sun. [23] Now, this is not to say that they can't be used to collect sunlight. In fact, this is one of the common uses. This is just something to keep in mind. Fresnel lenses also have issues related to image quality and distortion, which would not be a big issue with the application of our project. [23]

Overall, a fresnel lens may be a great alternative to a plano-convex or biconvex lens for the purpose of light collection, especially considering they are thinner and cheaper than those lenses with the same focal lengths and diameters. One thing that needs to be noted is that a lower groove density is better when trying to collect light, as this means that there is less light lost to thickness overall than compared to a lens with a high groove density. [23]

3.1.4 Data Transmission

The Greenhouse Environmental Ratio Analyzer will require a communication system to effectively transmit real-time environmental data from the greenhouse to the user. The device is intended to be placed in the center of the greenhouse, where it will continuously monitor key environmental factors, such as the ratio of blue to red light, humidity, temperature, and CO₂ levels, which are essential for optimizing plant growth. These environmental conditions can vary throughout the day, and manually checking them could be disruptive, time consuming, and impractical, especially in larger greenhouses.

3.1.4.1 Wireless Connectivity

To address data transmission protocol, we considered incorporating wireless communication technology, allowing for seamless, real-time updates to be transmitted directly to a user's mobile app. This would enable growers to remotely monitor and make adjustments as necessary, without physically disturbing the greenhouse environment. Additionally, the communication setup could potentially offer alerts and notifications for critical conditions, such as out of range environmental parameters. These features are intended to enhance decision-making, improving greenhouse management precision.

As we continue our research, the finalized communication system will also aim to enable automation of certain processes, making operations more efficient. The following sections will discuss various communication technologies under consideration, examining the strengths and limitations of each. This analysis will take into account factors like signal range, energy efficiency, data transmission reliability, and scalability, ultimately guiding us toward the most suitable option for ensuring optimal performance in varying greenhouse conditions.

3.1.4.2 Wired Connectivity

While wireless communication is often used in remote monitoring, we also considered a wired solution for its reliability, especially in environments where interference might compromise signal quality. Using a wired connection would guarantee uninterrupted data flow, unaffected by signal interference or range limitations. However, it requires careful consideration of installation logistics, as laying cables could limit the flexibility of the system's placement. In the following sections, we will further analyze these wired communication technologies, examining their respective benefits in terms of reliability, guiding our final decision on the best approach for greenhouse monitoring.

3.1.4.3 Comparing Wireless and Wired Communication

When choosing between wired and wireless technologies for The Greenhouse Environmental Ratio Analyzer, we considered several factors. Wired connections offer a high level of reliability and security, providing a stable and consistent data

transmission with a low risk of interference. Wired connections also support higher bandwidth and lower latency, which can be beneficial for real time data processing. However, installation of wired connections systems would require extensive cabling that can disrupt greenhouses' environment and complicate the ease of maintenance.

In contrast, wireless technology provides notable advantages in terms of installation and flexibility. Wireless systems eliminate the need for physical cables, which simplifies the setup process. This ease of installation is particularly advantageous in a dynamic environment where running cables could be disruptive. Additionally, wireless systems are more scalable, making it easier to add or move sensors as needed without extensive modifications. Furthermore, the incorporation of a mobile app into the greenhouse monitoring system necessitates wireless communication. The mobile app requires wireless connectivity to facilitate real-time data access and interaction from any location, which wired connections would restrict.

While wireless connections do face challenges such as potential interference, security risks, and bandwidth limitations, these can be mitigated through careful design and implementation of encryption and signal optimization strategies. Given these considerations, wireless technology emerges as the preferred choice for the greenhouse monitoring system. Its benefits in terms of ease of installation, flexibility, and support for mobile app functionality align well with the project's requirements for a practical and adaptable solution. Despite the potential drawbacks, wireless technology ensures that the system remains reliable and secure, meeting the needs of modern, remote monitoring.

3.1.4.4 Exploring Wireless Communication Alternatives

After determining that wireless technologies is the optimal choice for our project, we now turn our focus to exploring and analyzing the various wireless communication alternatives available. This section will provide a comprehensive evaluation of different wireless technologies assessing their suitability in terms of range, data transfer rates, reliability, and compatibility with our system's requirements. By examining these alternatives, we aim to select the most effective wireless solution to ensure seamless integration with the mobile app and to meet the needs of real-time monitoring and data accessibility within the greenhouse environment.

3.1.4.5 Bluetooth 5.0

In evaluating communication options for our greenhouse monitoring system, Bluetooth was considered due to its low power consumption and ease of device pairing. Operating on the 2.4 GHz frequency band, Bluetooth is designed for short-range communication, typically effective up to 10 meters. This makes it

suitable for connecting devices that are in close proximity, such as linking sensors to a central hub within the greenhouse. While Bluetooth offers limited range and lower data transfer rates compared to other technologies, its efficiency and simplicity in establishing connections could be advantageous for specific applications where extensive coverage is not required. With this being said, as we are implementing a mobile app with extensive coverage, Bluetooth would not be the most suitable option for this project due to its limited range and lower data transfer rates.[24]

3.1.4.6 Wi-Fi

Wi-Fi is another significant communication option for our project, offering high-speed internet and network connectivity over greater distances. Wi-Fi operates on two primary frequency bands 2.4 GHz and 5 GHz. It uses a technology called Orthogonal Frequency-Division Multiplexing (OFDM) to transmit data, which divides the signal into multiple smaller sub-signals that are transmitted simultaneously at different frequencies. This method helps to manage higher data rates and reduce interference. Wi-Fi provides extended coverage, making it ideal for larger areas like greenhouses, and supports high data transfer rates, which is essential for real-time data streaming and integration with mobile apps. Additionally, Wi-Fi networks can accommodate multiple devices simultaneously and offer seamless internet connectivity, facilitating remote monitoring and cloud-based data management. Given the need for reliable, long-range communication and the ability to handle large amounts of real-time data, Wi-Fi might be the most suitable option for our greenhouse monitoring system, ensuring that the mobile app can function effectively and provide continuous access to critical environmental data from any location.[25]

3.1.4.7 Infrared

Infrared (IR) communication has also been considered as a potential solution for our project. IR communication uses infrared light waves to transmit data between devices. This technology operates in the infrared spectrum, which is invisible to the human eye and involves wavelengths longer than visible light. IR communication requires a direct line of sight between the transmitter and receiver, as it relies on the direct propagation of infrared light. It generally supports lower data transfer rates and operates effectively within short ranges, typically up to a few meters. This makes it suitable just for applications where devices are fixed and within close proximity, such as remote controls or basic point-to-point data exchange. With this being said, as we are implementing a mobile app, Infrared would not be the most suitable option for this project due to its line-of-sight requirement, limited range, and lower data transfer rates.[26]

3.1.4.7 NFC (Near Field Communication)

Near Field Communication (NFC) has also been considered as a potential solution for our project. NFC uses radio frequency identification (RFID) technology to enable data exchange between devices over very short distances, typically within a few centimeters. Operating in the 13.56 MHz frequency band, NFC allows for close-proximity communication and is commonly used in contactless payment systems or device pairing. Due to its extremely short range, NFC requires devices to be brought into close contact, making it suitable for specific tasks such as secure data transfer or device configuration through a simple tap. However, its limited range and lower data transfer rates may restrict its suitability for ongoing, real-time monitoring over larger areas, such as a greenhouse, where remote sensor communication and broader coverage are required.[27]

Table 3.1.4.7: Wireless Technology Comparison

Feature	Bluetooth	Wi-Fi	Infrared	NFC
Range	< 10 meters	< 100 meters	1–5 meters	< 10 cm
Frequency	2.4 GHz	2.4 GHz-5 GHz	Infrared light spectrum	13.56 MHz
Data Transfer Rate	Up to 3 Mbps	Up to 1 Gbps	< 4 Mbps	< 424 kbps
Power Consumption	1mW-100mW	210mW	10mw	15mW
Security	Utilizes E0 stream cipher for encryption	Supports WPA, WPA2, and WPA3 encryption	Does not use encryption, making it less secure	Utilizes AES encryption for secure communication
Connection complexity	Easy pairing	Requires network setup	Line of sight must be maintained	Tap/close proximity
Scalability	Limited	High (supports multiple device)	Limited	Very limited

3.1.4.8 Final Wireless Technology Decision

After evaluating the available wireless communication options, we have decided to use Wi-Fi for our greenhouse monitoring system. Wi-Fi provides an excellent range, covering distances that are suitable for large environments like greenhouses. Its dual frequency bands (2.4 GHz and 5 GHz) help manage interference while offering higher data transfer rates, which are crucial for real-time monitoring and integration with the mobile app.

While Wi-Fi consumes more power compared to alternatives like Bluetooth or Infrared, and NFC, its benefits, such as wide coverage and faster data speeds, make it a suitable choice for continuous data transmission. Wi-Fi also offers strong security encryption, such as WPA3, which protects data from unauthorized access, ensuring that the data transmitted from the sensors remains secure.

Although the connection complexity of Wi-Fi is higher than simpler technologies, once set up, it provides a reliable and stable connection. Additionally, its scalability allows for easy expansion, enabling the integration of more sensors and devices in the future. Given these advantages, Wi-Fi is the most practical and robust option for our project.[25]

3.1.5 Communication Protocols

3.1.5.1 Overview

Communication protocols are essential in engineering design as they provide structured methods for devices to exchange information effectively and reliably. They establish standardized rules and formats for data exchange, ensuring interoperability between devices from different manufacturers and reducing compatibility issues. Protocols also include error detection and correction mechanisms, which are crucial for maintaining data integrity, especially in safety-critical applications. By defining how data is formatted, transmitted, and acknowledged, protocols optimize efficiency, minimizing latency and maximizing throughput. Additionally, many protocols support multiple devices, allowing for scalability in complex systems like IoT applications. They incorporate mechanisms for managing connections and data flows, which is vital for orderly communication in multi-user environments. Security features, such as encryption and authentication, protect data during transmission, particularly in sensitive applications. Protocols also offer flexibility, enabling engineers to select the best option for specific requirements, thus optimizing performance and resource use. They simplify debugging and maintenance through standardized monitoring methods, enhancing reliability. Furthermore, protocols facilitate interfacing with legacy systems, allowing gradual upgrades without complete replacements. This modularity simplifies design, testing, and component replacement, making systems more adaptable. In summary, communication protocols are fundamental

for ensuring effective, reliable, and secure communication between devices, enabling engineers to create robust and scalable systems that meet the evolving demands of technology.

3.1.5.2 I2C

I2C (Inter-Integrated Circuit) is a synchronous, multi-master, multi-slave, packet-switched, single-ended serial communication bus developed by Philips (now NXP), primarily used to connect low-speed peripherals to microcontrollers. It operates using two wires: SDA (data line) and SCL (clock line), with standard modes functioning at speeds of 100 kHz (standard mode), 400 kHz (fast mode), and up to 3.4 MHz (high-speed mode). Each device on the bus has a unique address, utilizing either 7 or 10 bits for identification. I2C is widely applied in embedded systems for connecting sensors, EEPROMs, and various other peripherals. Among its advantages are the simplicity of wiring, as only two wires are required for multiple devices, and the multi-master capability, which allows several master devices to initiate communication. It also supports addressing multiple devices on the same bus. However, I2C has some drawbacks, including speed limitations that make it unsuitable for high-speed data transfers, a restricted range that typically accommodates only short distances (a few meters), and added complexity in master arbitration when multiple masters attempt to communicate simultaneously.[28]

3.1.5.4 UART

UART (Universal Asynchronous Receiver-Transmitter) is a hardware communication protocol that employs asynchronous serial communication with configurable baud rates, transmitting data as a series of bits that include start and stop bits to signify the beginning and end of transmission. It typically requires two wires for communication: TX (transmit) and RX (receive). Common baud rates range from 300 to 115200 bps, with some systems supporting even higher rates. Data is framed using start bits, a variable number of data bits (ranging from 5 to 9), optional parity bits, and stop bits. UART is frequently utilized for serial communication between microcontrollers, computers, and peripherals like GPS modules and Bluetooth devices. Its advantages include simplicity in implementation and understanding, the absence of a clock signal (which reduces complexity), and wide compatibility, as it is found in nearly all microcontrollers and communication devices. However, it also has limitations, such as restricted distance, typically accommodating only short-range communication (up to 15 meters), potential timing errors due to its asynchronous nature—especially at high speeds—and the fact that it usually supports only point-to-point communication between a single transmitter and receiver. [29]

3.1.5.5 SPI

SPI (Serial Peripheral Interface) is a synchronous serial communication protocol developed by Motorola for high-speed data transfer between a master device and one or more slave devices. It typically employs four lines: MOSI (Master Out Slave In), MISO (Master In Slave Out), SCLK (clock), and SS (slave select). SPI can operate at speeds up to several MHz, often significantly surpassing I2C, and supports full-duplex communication, allowing simultaneous transmission and reception of data. This makes SPI ideal for high-speed communication between microcontrollers and peripherals such as sensors, SD cards, and display controllers. Its advantages include higher speeds due to synchronous operation, ease of implementation and control, and the ability to transmit and receive data simultaneously. However, SPI also has disadvantages: it requires more wiring, as each slave device needs a dedicated slave select line, lacks standard addressing, and is generally limited to short-range communication, typically within a few meters.[30]

3.1.5.6 JTAG

JTAG (Joint Test Action Group) is a standard for testing and programming integrated circuits, facilitating boundary scan testing and debugging primarily used in development and manufacturing. It typically involves at least four wires: TCK (clock), TMS (mode select), TDI (data input), and TDO (data output). JTAG operates on a shift register principle, where data is shifted in and out, allowing direct access to internal registers and memory of the processor. This protocol is primarily applied for debugging, testing, and programming embedded systems, including FPGAs and microcontrollers. Its advantages include powerful debugging capabilities for both software and hardware, a widely accepted standardized interface across various platforms, and the ability to detect faults in circuit connections through boundary scan testing. However, JTAG also has drawbacks, such as the complexity of requiring specific hardware and knowledge for implementation, speed limitations that make it unsuitable for high-speed data transfer, and potential overhead that may introduce additional circuitry and costs.[31]

3.1.5.7 USB

USB (Universal Serial Bus) is a standard for connecting devices to computers and transferring data, supporting high-speed data transfer while also providing power to connected devices. It typically utilizes four wires in USB 2.0 (Vbus, D+, D-, GND), with additional data lines in higher versions such as USB 3.0. USB 2.0 supports speeds up to 480 Mbps, while USB 3.0 can reach 5 Gbps and USB 3.1/3.2 can go up to 20 Gbps. One of its key features is hot-swappability, allowing devices to be connected and disconnected without turning off the power. USB is widely used for connecting various peripherals, including keyboards, mice,

printers, and external storage devices to computers. The advantages of USB include its high-speed data transfer rates, the ability to supply power to connected devices, and the ease of connecting and disconnecting devices. However, it also has some drawbacks, such as the complexity of requiring specific drivers and software support, protocol overhead that makes it more complex than simpler protocols like UART or SPI, and cable length limitations, where longer distances can impact performance, particularly at higher speeds.[32]

3.1.5.9 Final Communication Protocol Decision

I2C is definitely the better option for communicating with our sensor. We are planning to have 4 sensors in our PCB/Device and from all the communication protocols and without stabling a big network this is the protocol which allows us to connect more devices. Since it is used inside the device the short distant constraint is not an issue and since the sensors are not high speed the not too high frequency is a constraint neither, In addition most of the sensors we have done research have I2C pinout implemented which make design easier and more feasible, if we choose other protocol we had to translate from that to I2C so it can communicate with the sensors.

For the programming connection we decided to go with a USB connection but the protocol for flashing the microcontroller will be using UART. To implement this through USB we will add a USB to UART bridge chip: CP2102N-A02-GQFN28. The reasons are: it provides power which means we can program it without the need of an external source and it is high speed plus there is a variability of connectors in the market and it makes it easy for technical support.

However we will keep other protocols in consideration, If we need higher response and higher dispositive data exchange we may have to implement SPI instead of I2C. For debugging we may want to make a small dispositive which communicates with JTAG. And UART can be used to connect to any other peripheral that we are planning to add.

3.1.6 Filters

Another important aspect of the optical design are the optical filters. Optical filters essentially allow for certain wavelengths of light to be sent through, while others are not. There are many different types of filters, each with different uses. Since we want to specifically focus on the red and blue colors and ignore the green, we want to buy a filter that can separate the green wavelengths away from the others.

First, there are many different kinds of filters including bandpass, longpass, shortpass, notch, and dichroic. Bandpass filters reject all wavelengths except for

within a specified range, longpass reject all wavelengths below a certain value, shortpass reject all wavelengths above a certain value, notch filters reject all values within a specified range, and dichroic filters reflect certain a certain range of wavelengths while transmitting another range. [33] Dichroic filters can have the properties of the other filters, the only difference is the reflection aspect, whereas other filters purely absorb. [34]

3.1.6.1 Dichroic Filters

One thing to note about these filters is the naming convention. Dichroic filters are named by the colors they reflect [34], which means that we need to decide whether the blue and red colors are to be reflected or transmitted. For example, if we get a green dichroic filter, the optical setup will need to be so that the transmitted light is input into the spectrometer. If we want blue and red to be reflected, we'd need to get a purple dichroic filter and make sure that the setup allows for the reflected light to be received.

Dichroic filters use thin-film interference to allow certain colors to pass through and others to reflect. They are essentially beam splitters, which will be covered further down, but they are different in the fact that they split the wavelengths by color and not in a general manner. [34]

One of the biggest perks of using dichroic filters is that they are greatly able to target the wanted wavelengths because of the use of interference, rather than absorbance. This property allows the cutoff between the transmitted and reflected light to be much more drastic than that of an absorption-based filter. [35] Also, the filters can be used with high-powered light sources without becoming warped. Lastly, they do not produce any fluorescence, which is a potential big advantage of this type of filter. [35] Without fluorescence, there would be no need to worry about any effects, which will be discussed in the next section.

There are some downsides to using dichroic filters. The first downside is that they are sensitive to angle. This is a result of the fact that they rely on interference to filter the light. [36] Using an angle of incidence that is different than the specified angle would change the level of interference between the layers of the filter and would cause an undesirable effect, potentially that none of the light would actually be filtered. For this reason, setting up the filter at the correct angle is critical.

The second downside is that dichroic filters are expensive compared to absorption-based filters. The reason is that absorption-based filters use dyes to absorb specific wavelengths instead of using thin-film interference to cause reflection. The production of dichroic filters is more of a technical process, and therefore it makes sense that they are more expensive. [35]

3.1.6.2 Absorption Filters

As stated above, absorption-based filters don't rely on thin-film interference to filter out light, but dyes. [35] Many of the downsides associated with dichroic mirrors are the complete opposite in absorbance filters. For instance, because these filters tend to be cheaper than dichroic filters, they differ in the filtering quality. The thickness, dye quality, and filter material are all factors to keep in mind since they all have an effect on the quality of the transmitted light.

One of the biggest benefits of using one of these filters is that they are not sensitive to the angle of incidence of the light. [35] Once again, the filtering does not use thin-film interference to transmit certain wavelengths and reflect others but instead uses dyes, which absorb at any angle. For the purposes of our project, this would ensure that our optical design is less vulnerable to failure from moving than with the dichroic filter.

Another one of the biggest benefits of using these filters is that they are more durable to normal wear and tear. Because of the materials used, they are less prone to damage, except for heat, which can warp the material. [35] While this shouldn't be a big deal, as we will take the most precautions necessary to ensure the optical elements don't get damaged, things can go wrong, and replacement parts may be necessary. So, having this safety net is a nice factor.

Lastly, related to the last note, these filters are typically cheaper than dichroic filters. [35] This provides another safety net, just in case the filters get damaged. We don't want to be spending close to \$100 on a dichroic filter and have it get damaged, whereas we can spend less money on an absorbent filter and possibly get a replacement.

We've covered a few benefits of absorbent filters, but there are a few downsides to keep note of. Firstly, as previously noted, they are prone to distortion from heat. Also, they tend to get bleached over time, which means that the filtering performance tends to decrease over time. [35] This is not ideal, as this means that the filter may need to be changed after a period.

Another downside is that the filters do not have as strong of a cutoff between the transmittance and absorbance wavelengths. [33] This means that some undesired wavelengths may get transmitted through the filter, which is not ideal. For this reason, finding high-quality filters with good cutoffs is needed.

The last downside of absorbent filters is that they are prone to producing fluorescent light. Fluorescent light is a direct result of absorbance. [35] When certain materials absorb a photon, they release another photon at a longer

wavelength. [37] This may cause an issue, depending on the intensity of the fluorescent light, as it may cause a false intensity reading or a false ratio between the blue and red light.

3.1.6.3 Filter Choice

Overall, it seems that we will most likely end up going with a dichroic filter. We need to be able to have a sharp green wavelength cutoff so that we get the maximum amount of blue and red light transmitted through the filter. The price is more expensive, but it would be worth the cost, especially since we wouldn't have to deal with fluorescence.

Table 3.1.6.3: Comparison of various types of filters.

Filter Type	Price	Mechanism	Angle Dep.	Fluorescence	Wav. Cutoff
Dichroic	\$73 to \$144	Thin-Film Int.	Highly	No	Strong
Absorption	\$19 to \$153	Absorption	None	Yes	Not as strong

3.1.7 Beam Splitters

Another piece of technology we will be using is a beam splitter. Beam splitters are often used with lasers, though they can also be used with light sources such as the sun, LED's, etc. This piece of technology splits a beam of light into two, with one beam being transmitted through, and another being reflected at an angle. They essentially are optical components with a certain ratio of transmissivity and reflectivity.

3.1.7.1 Plate Beam Splitter

Plate beam splitters are glass plates that are meant to be placed at 45 degrees to the incident beam of light. The front end of the plates are coated, such that some of the light is reflected instead of transmitted. [38] These types of beamsplitters require calibration, as the incident angles are meant to be 45 degrees, such that the transmitted and reflected beams are at 90 degrees from the incident beam. [39]

One of the benefits of this type of beam splitter is that it is easy to incorporate into any optical design. The range of sizes, and the fact that it is purely a glass plate, make it easily mountable and fittable. [40] For our project, which is tight on physical space and would preferably be as compact as possible, this is perfect.

Another benefit is the fact that it is the cheaper of the two types of beam splitters. [38]

One of the biggest downsides of using this type of beamsplitter is the tendency for a second reflection to occur off the back surface of the component. [40] This is simply an result of the fact that the second surface goes from a change of a higher refractive index to a lower refractive index. There are plate beamsplitters that have anti-reflection coatings to mitigate this, but those are more expensive. [38] Another downside is that the 45 degree incident angle may be hard to calibrate correctly. The last downside is that the transmitted beam is offset by a certain distance away from the incident beam. [40]

3.1.7.2 Cube Beam Splitter

Cube beam splitters work in a completely different fashion than plate beam splitters. Instead of a single glass plate being placed at 45 degrees from the incident beam, two prisms are joined at the hypotenuse. At the hypotenuses, there is a film added, which much like the film on the plate beam splitter, reflects some of the light. [40]

The benefit of using this type of beam splitter is that the incident angle is typically zero degrees. [38] This is because the joint hypotenuses of the prisms form a 45 degree angle already. This would be much easier to calibrate. Another benefit of this type of beam splitter is that the transmitted beam doesn't deviate from the optical path at all. [38] The ghost reflections are typically less of an issue with these types of beam splitters because the refractive indices of the prisms are the same.

One of the downsides of this type of beamsplitter is that it is typically larger and less sizeable than the plate beamsplitters. The bigger, and more important issue, is that they are generally more expensive than the plate beam splitters. [38] While overall they'd be more convenient and easier to use, their more expensive price is a harder sell.

3.1.7.3 Beam Splitter Choice

Based on the research done, a comparison table can be created based on our findings.

Table 3.1.7.3: Comparison of various types of beam splitters.

Type	Price	AOI	Ghosting	Scalable	Path Dev.
Plate	\$36 to \$640	45°	Yes	Possible	Yes
Cube	\$188 to \$565	0°	No	Limited	No

While both types of beam splitters would be able to split the light beam in our project, considering our budget, it would make more sense for us to use a plate beam splitter. While this would be more difficult to set up because of the 45 degree angle of incidence, the additional cost of a cube beam splitter doesn't justify the cost. Also, while the path will deviate by some amount with the plate beam splitter, this won't be too much of an issue and can easily be compensated for. The biggest factors to keep in mind when picking a specific plate beam splitter will be the transmission to reflection ratio and whether the beam splitter has any coatings to mitigate wavelength ranges from going through.

3.1.8 Concave Mirror vs Lens for Focusing

Both concave mirrors and lenses can be used for focusing light to the sensors. The lens equations can be used for the mirrors, it's just that the focal length of the mirrors are negative (this does not mean that the light is diverging, like it would mean with a lens). [41] In that sense, concave mirrors and convex lenses are very similar. Depending on how we decide to do our optical setup, we can use one or the other. One thing to consider is that concave mirrors are generally more expensive than convex mirrors, so we'd need to justify the use of a setup that would require them.

3.1.9 Housing Material

To protect and move around our subsystems we will need to create a portable, durable housing as shown in our prototype idea in section 2 above. The plan is to 3D print the housing to our chosen specifications (size) with our chosen material, or filament. To decide on the material, we will look into various types that are compatible with 3D printers that are accessible to us.

3.1.9.1 ABS

ABS, or acrylonitrile butadiene styrene, is a popular 3D printing filament. It is known to be durable, heat resistant, and affordable. Our device is meant to be in a greenhouse setting and needs to endure high temperatures and humidity, so heat endurance is crucial. We also need a material that can hold itself up as well

as the parts inside. This includes the PCB, optical components, sensors, etc. ABS is useful for printing functional parts such as hinges and brackets [42]. The cons of ABS are that the filament requires a heated bed (where the filament is deposited on in 3D printing), and prints at very high temperatures (220 C-250 C) [42]. ABS also produces a toxic chemical when heated that can cause damage to those inhaling [42]. To be safe, the 3D printer should be in a well-ventilated area. The price point of ABS is about \$20 per kilo.

3.1.9.2 PLA

PLA, or polylactic acid, is used in low-temperature (150C-160C) printing. It is more flexible than ABS but less durable [42]. To be exact, PLA is very brittle. This is a tradeoff that we need to consider. However, due to the low temperature printing, warping is less of an occurrence. Additionally, PLA does not emit the toxic fumes that ABS does. Another thing to look at is the environmental aspect of these different materials. PLA is biodegradable and can be made from renewable sources such as cornstarch or sugar cane [42]. PLA also sells at about \$20 per kilo.

3.1.9.3 PETG

PETG, or polyethylene terephthalate glycol, is impressive due to its moisture blocking properties. An important parameter in a humid greenhouse environment. Another thing to note is that it is chemically resistant and used for food packaging material [42]. While the device might not be in direct contact with the plants or crops being grown, this is something to consider when growing food. Some downsides of PETG are that it is clear, and it is prone to damage by UV light after an extended duration of direct contact [42]. This is a major issue for us. We want a housing material that can block out a lot of the sunlight/artificial light that may damage the inside components. We also want housing that won't be damaged by direct sunlight itself. PETG runs at about \$25 per kilo.

3.1.9.4 ASA

ASA, or acrylonitrile styrene acrylate, is an acrylic rubber that is versatile in use. Known for its excellent resistance to UV light and moisture [43], ASA meets all the requirements for weather resistance that we are looking for. ASA is also high-impact resistant and crack-resistant compared to other filaments like PLA. An important factor for a device that is to be left outside to the elements. One downside is that, like ABS, ASA needs high-temperature printing. This also means that it is prone to stringing and warping during printing [43]. These types of filaments also tend to spread toxic fumes when printing, so a ventilated area is a must. ASA sells at \$25 per kilo.

3.1.9.5 Nylon

Nylon is a filament that is both durable and flexible. Used for parts that undergo a lot of mechanical wear and tear, nylon is extremely abrasion resistant. [42] Once again, it is a filament that needs high temperatures to print and therefore is prone to warping. A big issue we see with nylon is that it is extremely moisture absorbing [42]. While this is beneficial when adding dyes to the material, in our case it is detrimental. Nylon sells at a higher price point, from \$35-50 per kilo.

3.1.9.6 Housing Material Choice

To decide on our housing material choice for 3D printing, we have to consider many parameters. This includes weather resistance, durability, price, and printing issues such as warping and toxicity. While it is important to note that all 3D printing filaments should be used in a well-ventilated area, there are some that pose more of a risk than the others. The table below serves as a quick reference guide for how the various filaments respond to our parameters.

Table 3.1.9.6: Comparison table of different 3D printing filaments based on selected parameters

Material	ABS	PLA	PETG	ASA	Nylon
Toxicity	High	Low	Low	High	High
Warping	High	Low	Low	High	High
Durability	High	Low	High	High	High
Heat Resistance	High	Low	High	High	High
UV Resistance	Low	Low	Med	High	Low
Moisture Resistance	High	Med	High	High	Low
Price	Low	Low	Med	Med	High

As we can see from the table, each material has its own pros and cons. For example, PETG has low toxicity and warping, but its UV resistance is lower than ASA. In our table some parameters have more weight than others. The weather resistance (heat, UV, and moisture) is more important than the printing issues (toxicity and warping) that we'd only experience once. Also, the Texas Instruments Lab (TI Lab) here at UCF has professionals that can aid us with printing and ensure we do it the correct and safe way. With all this in mind, the material we chose to

go with is ASA. This is due to the high weather resistance including heat, moisture, and UV resistance which is not seen in many of these materials. ASA will protect our device from the elements while mechanically protecting our subsystems.

3.2 Part Comparison

Now that our type of technology is chosen, we can dive deeper into various sellers to determine the optics that best fit our project depending on our specifications.

3.2.1 Photodiodes

There are many different ways to go about choosing our light intensity sensors. We can buy packs of photodiodes for very cheap or buy dedicated photodiode light intensity sensors. The benefit of buying photodiodes as individual entities is that we'd have total control over the circuitry and how the photodiodes react. The downside would be that we'd have no real way of being able to calibrate our light intensities accurately. We would have to use commercial products to confirm the accuracy of our data, which we do not have the budget for. There are specifications for the photodiodes, sure, but they are not calibrated to any sort of absolute.

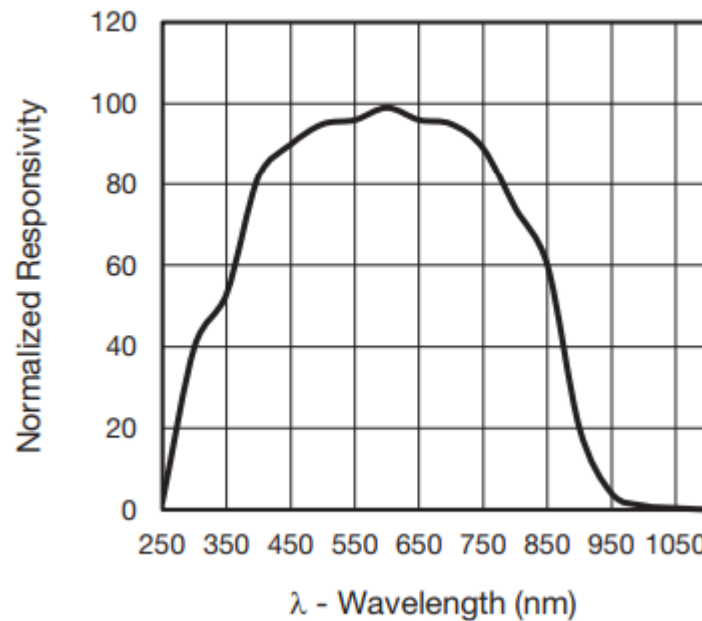
We also have to keep in mind that we'd still have to calibrate the sensors, even if we bought the photodiode light intensity sensors because of the presence of the lenses. The inclusion of lenses intrinsically changes the way that the sensors read measurements. Determination of how much light the lenses collect, how they focus it, and how the intensity changes would still need to be determined. Not to mention how other elements in the system would affect the accuracy of the readings from the sensor. Hand calculations and programs like Zemax will be necessary to ensure that all factors are taken into account and the readings are accurate. Therefore, the amount of optical design would remain the same if a photodiode sensor was bought, it would just ensure that the conversion from the electrical signal to the light intensity reading means something.

3.2.1.1 SparkFun Ambient Light Sensor - SEN-15436

The SparkFun [44], [45] evaluation board has a Vishay VEML6030 ambient light sensor integration. The VEML6030 is a 2mm x 2mm x 0.87mm sensor. The evaluation board itself is slightly bigger than a quarter. This product can read a lux range of 0 lux to 120,000 lux and boasts a 16-bit resolution. The photodiode itself can read a wavelength range of approximately 400 nm to 700 nm (assuming 25°C temperature). The nice thing about this technology is that it has a fit curve that adapts to human vision. This fit curve has a wavelength range from approximately 250 nm to 1000 nm. The center of these curves is approximately 550 nm to 600 nm. This range will ensure that we get a good measurement of the intensity of the white light. Since red and blue colors fall within this range, these

sensors will also be able to be used for the ratio of the two. This sensor also includes temperature compensation and will be able to be integrated into the existing PCB and MCU. With a cost of \$5.95, this sensor is much more affordable than some of the photodiodes found on websites like Thorlabs.

Figure 3.2.1.1: White Light Mode Responsivity Curve [45]



Unfortunately, there is some important information missing from the spec sheets and websites that leaves some doubt. For example, there is no exact specification for the temperature range or even the dimensions of the development board itself. Also, there are two I2C addresses, which isn't enough for the three that we would need.

3.2.1.2 Adafruit TSL2591 High Dynamic Range Digital Light Sensor

The Adafruit [46] photodiode sensor can detect intensities from 188 μ Lux to 88,000 Lux. This is a smaller dynamic range than the Sparkfun sensor. The sensor picks up both IR and visible spectrums and operates within temperatures of -30°C to 80°C. The physical size of the entire unit is 19mm x 16mm x 1mm. It would also be able to be integrated directly with our PCB and MCU. The data transfer rate also approaches speeds of up to 400kbits/second. The spectral response peaks around 650nm and the wavelength range goes from around 430nm to 1100nm.

There are some ways in which this sensor falls short. The responsivity curve is not as bell-shaped as the Sparkfun sensor, so it may be more difficult to calibrate the blue and red sensors for the ratio analysis. Also, the cost of the unit is \$6.95,

which is more expensive, and the detectable intensities are also less. Lastly, this unit only has one I2C address, which once again isn't enough.

3.2.1.3 Mikroe-4967

The Mikroe [47], [48] photodiode light sensor can detect up to 33,000 lux and can be used from -40°C to 85°C. This board can only be used with 3.3V input and consists of one broadband photodiode, and one infrared photodiode, with an infrared-blocking filter. The actual responsivity of the sensor goes from about 450 nm to 680 nm, with a peak around 560 nm, which is not quite the span of wavelengths we'd need to measure the light in the greenhouse. Also, there is also only one I2C address. The cost of this unit is \$14, which is much more expensive than the other two previous sensors. The data rates are up to 400kbits/second. The entire board is 1.6mm x 1.1mm.

Overall, there aren't that many advantages of using this sensor, besides the small size of the unit.

3.2.1.4 Light Sensor Choice

Now that we've determined that our light intensity sensors will use photodiode technology, we will compare a few different options.

Table 3.2.1.4: Comparison of various types of light sensors.

Sensor	Price	Wavelength	Lux
SEN-15436	\$5.95	Visible/IR	0lx-120,000lx
TSL2591	\$6.95	Visible/IR	188μlx-88,000lx
Mikroe-4967	\$14	Visible	<33,000lx

After comparing the different options for the photodiode sensors, there was only one logical choice, which was the VEML6030. The dynamic range and impressive top value of 120,000 lux makes it easily reach what can be seen in a greenhouse, as the lux value seen in direct sunlight is 100,000 lux [49], which is unlikely to be reached. Also, the sensitivity range for this sensor is exactly that of photosynthesis, and it also expands that sensitivity with its algorithm. Also, it is the cheapest option. Since this sensor, like the others, doesn't support three I2C addresses, we will have to use an I2C multiplexer.

3.2.2 CO₂, Humidity, Temperature Sensor

Since carbon-dioxide, temperature, and humidity are not measured optically, and there is no optical design behind the measurement of these parameters, we are opting to buy premade sensors that measure all three at the same time, instead of measuring them independently. These sensors are far and few, so these are the limited options that we are choosing from.

3.2.2.1 Adafruit SCD-41 - True CO₂ Temperature and Humidity Sensor

This three-in-one sensor claims to measure CO₂, humidity, and temperature at the same time. [50] According to the specifications given, it can measure 400 ppm to 5000 ppm of carbon dioxide with an accuracy of $\pm 40 \text{ ppm} + 5\%$ of the actual reading at 25 degrees Celsius and 50% relative humidity. The way that the carbon dioxide sensing works is by the photoacoustic effect. This effect is a physical effect, where the interaction of photons with a material causes the creation of very tiny sound waves. [51] In this specific case, there is most likely infrared light present in the sensor that gets absorbed by the CO₂ molecules. This photon absorption would lead to a rise in the pressure and temperature of the gas, which would cause the sound waves to be formed. The response time for this aspect of the sensor is 60 seconds, which is not fast, but should be okay for a greenhouse.

The sensor can measure with an accuracy of $\pm 9\%$ relative humidity in temperatures ranging from -10 degrees to 60 degrees Celsius and from 0% to 100% relative humidity. This is not perfect, but it is still reasonable. The response time of this aspect is 90 seconds.

The sensor can also measure the temperature with an accuracy of ± 0.8 degrees Celsius from temperatures spanning from 15 degrees to 35 degrees Celsius and with an accuracy of ± 1.5 degrees Celsius from temperatures of -10 degrees to 60 degrees Celsius. This should be fine, especially since it's unlikely anywhere near the lower end in temperature, at least in Florida. The response time for this aspect of the sensor is 120 seconds. The overall cost of this unit is \$49.95.

3.2.2.2 Adafruit BME688 - Temperature, Humidity, Pressure and Gas Sensor

This sensor, also developed by Adafruit, claims to measure temperature, humidity, pressure, and gas. [52], [53] This sensor supports AI integration to train the sensor to respond to a specific environment, but it is unlikely that we'd take advantage of this feature. The unit itself is $3 \times 3 \times 0.9 \text{ mm}^3$ and can measure gasses in the ppb (parts per billion) range. It can measure a variety of gasses like volatile organic compounds, volatile surface compounds, carbon dioxide, and hydrogen.

Given the wide range of gasses that can be detected, the device does not operate with the photoacoustic effect. Instead, it works through adsorption (adhesion of

gas to a surface). [54] This is great for the different compounds listed earlier but is not great for gases like CO₂. Also, instead of listing pure concentration, it outputs the gas data as an air quality index, which while useful, is more commonly used to say how contaminated the air is.

The humidity measurement is accurate from 0 to 65 degrees Celsius and in an environment with 10 to 90% relative humidity with an accuracy of $\pm 3\%$ RH. The response time of the humidity sensor is 8 seconds. The temperature sensor is accurate from 0 to 65 degrees Celsius. We would not be using the pressure sensor feature since that is not within the scope of our project. The price of this sensor is \$19.95.

3.2.2.3 Adafruit SCD-30 - NDIR CO₂ Temperature and Humidity Sensor

Like the first sensor we covered, this sensor is a CO₂, temperature, and humidity sensor under the SCD title. [55], [56] Though, this sensor differs in a few different ways. The first way this sensor differs is in how it operates. Unlike the SCD-41, this sensor uses NDIR to detect the CO₂ molecules instead of photoacoustics. This method allows for a gas sensitivity of range of 400 to 10,000 ppm with an accuracy of $\pm(30 \text{ ppm} + 3\% \text{ of reading})$. The temperature sensor measures between 0 and 50 degrees Celsius with an accuracy of $\pm(0.4^\circ\text{C} + 0.023 \times (T - 25^\circ\text{C}))$. As for the humidity sensing aspect, it measures $\pm 3\%$ relative humidity at 25 degrees Celsius. The cost of this sensor is \$58.95.

3.2.2.4 Humidity, Temperature, CO₂ Sensor Choice

Table 3.2.2.4: Comparison of Humidity, Temperature, CO₂ Sensors

Sensor	Cost	Measurement	Accuracy
SCD-41	\$49.95	• CO₂ • Temp. • Humidity	• 400 to 5000 ppm • $\pm 9\%$ RH • -10 to 60°C
BME688	\$19.95	• Gas (not CO₂) • Temp. • Humidity • Pressure	• $\pm 3\%$ RH • Other accuracy not considered
SCD-30	\$58.95	• CO₂ • Temp. • Humidity	• 400 to 10,000 ppm • 0 to 50°C • $\pm 3\%$ RH

Looking at all these sensors, it is clear that the BME688 is unfit for this project. The fact that it can't measure CO₂ concentrations means that a separate CO₂ sensor would need to be purchased, which is inconvenient and not what we are wanting to do. That leaves the SCD-41 and the SCD-30 as our possible choices. Now, looking at our prospective options, it is clear that the SCD-30 has better measurement ranges and accuracy. However, given the money going towards other components, we will choose to go with the SCD-41, since it is still fairly accurate and since the majority of the optical design and coding will go towards the light sensors.

3.2.3 Diffraction Gratings

Earlier, we compared various types of diffraction gratings and came to the conclusion that we will use a plane reflective grating. Now, we will look into the various parameters of this diffraction grating and use them to compare those on the market. The parameters we will look at are:

Lines per millimeter

Sometimes given as grooves per inch, lines per millimeter is an important parameter of a diffraction grating that determines the reflected angle and dispersion of the incident light. The relation of these variables and more information can be found in *Equation 3.1.2.1*.

To decide what measure of lines per millimeter we want on our diffraction grating, we will have to do the calculations. Equation 3.1.2.1 states $m\lambda = d(\sin \alpha + \sin \beta)$. The frequency is $1/d$ and for our purposes we will look at order $m = 1$. We will start with ~700 nm, or the far red portion of our spectrum. Assuming we want a 45 degree incident and exit angle to make things easy, we can do the math:

$$\begin{aligned} 0.0007 &= d(\sin 45 + \sin 45) \\ d &\approx 0.495 \mu m \\ \frac{1}{d} &\approx 2000 \text{ lines/mm} \end{aligned}$$

Plugging in that 2000 lines/mm and using the same incident angle, we can find what angle the far blue portion of our spectrum (~450 nm) will diffract to.

$$\begin{aligned} 0.00045 &= \frac{1}{2000} (\sin 45 + \sin x) \\ x &\approx 11.12^\circ \end{aligned}$$

So, now we know that our diffracted light (the wavelengths we want) will be reflected at a 11 to 45 degree angle from normal on the grating. We also know

that the grating we want will be 2000 lines/mm. Gratings of these frequencies tend to be on the more pricey end. We will decide if we have to be more relaxed on the lines/mm based on these prices.

Wavelength Range

The wavelength range gives the range of light where the grating becomes most effective. Within it there is the “blaze wavelength”. This is the wavelength of light that when incident upon the grating at the blaze angle, will reflect at the same angle. We will need a grating with a wavelength range at least from 400 nm (blue) to 700 nm (red).

Dimensions

The dimensions of the diffraction grating must be large enough to capture all the light coming through. The price of a grating will increase rapidly with its dimensions so we will want to choose the smallest grating size that will still get the job done. In our spectrometer, there will be a slit and a concave mirror to reduce the spot size of our light, making the size we need relatively small. Therefore, we will look for a diffraction grating with dimensions 1” x 1” or bigger.

Price

One of the most obvious but perhaps most important parameters of the grating is the price point. Due to our budget, we would like to keep the price as low as possible. We will need to balance the other parameters of the gratings with the price to make the most effective decision.

Keeping these parameters in mind, we will now compare the reflective gratings sold by various suppliers to decide which we will purchase.

3.2.3.1 Holographic Diffraction Grating Film - Edmund Optics

Edmund Optics is a well known supplier of all things optics, including diffraction gratings. While they have many to offer, we are looking at their “Holographic Diffraction Grating Films”, which are reflective gratings with high groove frequencies. They offer both 500 lines/mm and 1000 lines/mm options and claim that their holographic gratings “exhibit significantly sharper diffraction orders than their ruled counterparts by reducing the amount of stray light produced.” This is consistent with our analysis of ruled vs holographic gratings from earlier. The dimensions of the grating area is 1 square inch, just as we were looking for. The wavelength range is also consistent with our needs at 400nm - 700nm. The price is one of the lowest we will be looking at, at only \$24 for a pack of 15. Overall, this choice is very appealing due to hitting all of our parameters and having a low price point. One possible issue is the quality of the grating, being made of clear polyester film that is very flimsy.

3.2.3.2 Diffraction Grating Slide - Rainbow Symphony

This company is using amazon as a vendor for their diffraction gratings. This would mean quick shipping and easy returns. However, there is minimal information on amazon about the parameters of these gratings. There is no wavelength range listed. The dimensions look similar to the previous product, and they also come in 500 lines/mm and 1000 lines/mm. The price is around \$15 for a pack of 10. Similar to the previous product, they are made of a film material and might be flimsy, low quality, and easily scratched.

3.2.3.3 Plane Ruled Diffraction Grating - Newport

Newport is another widely known and trusted dealer in optical elements. Their plane ruled diffraction gratings come in numerous groove frequencies, from 150 lines/mm to 1800 lines/mm, giving more options than the previous products. Newport specifies the blaze wavelength of their gratings rather than just a range which would allow for us to use the optic to its maximum efficiency. They have gratings with blaze wavelengths at 250 nm, 300 nm, 400 nm, 500 nm, 550 nm, 600 nm, 750 nm, and more. The price point is high at about \$150 to \$200 depending on size and groove density. However, the optic is made of float glass and is of higher quality than the previous products which may make the price worth it.

3.2.3.4 Reflective Holographic Gratings - Edmund Optics

The Reflective Holographic Gratings from Edmund Optics are one step ahead of Newport's Plane Ruled Diffraction Gratings due to the groove profile. As mentioned before in 3.1.2.4 *Ruled and Holographic Gratings*, 'Ruled' gratings refer to a mechanically created imperfect groove profile, while 'Holographic' gratings refer to an optically engraved sinusoidal pattern. Holographic gratings have been known to be more expensive than ruled gratings in the past, but as we can see in the market, they now match in price or can be even lower in price than plane gratings due to the advances in technology. While still the second most expensive of the products we are looking at, this product is less expensive than the Newport product and due to the holographic aspect, it is more efficient in reducing stray reflections. The material is made out of float glass as well, a better material than the film gratings previously mentioned. The groove densities of this product ranges from 1200 lines per millimeter to 3600 lines per millimeter. This range contains the grating density we desire. They also come in various sizes. Unlike the Newport gratings, Edmund does not specify a blaze wavelength, but provides efficiency curves and wavelength ranges that can help us decide which version to choose. These ranges include the visible spectrum (400 nm - 700 nm), which is the wavelengths we would need. The price for this optic is about \$130-\$165.

3.2.3.5 Product Choice

Our choice in the diffraction grating we will buy is determined by multiple variables including vendor quality, price, and how well they fit our parameters mentioned above. The below chart gives a quick overview of what was talked about and the comparisons made between the products.

Table 3.2.3.5: Comparison of various types of diffraction gratings

Diffraction Grating	Company	Comparison
Holographic Diffraction Grating Film	Edmund Optics	• Certified supplier • Film, low quality • Not the groove frequency we are aiming for • Holographic (more efficient)
Diffraction Grating Slide	Rainbow Symphony	• Cheapest option • Film, low quality • Not the groove frequency we are aiming for • Fast shipping and returns if needed
Plane Ruled Diffraction Gratings	Newport	• Most expensive • Certified supplier • Groove frequency we are aiming for • Ruled grating • Specified blaze wavelength • Higher quality material (Float Glass)
Reflective Holographic Gratings	Edmund Optics	• Certified supplier • Second most expensive • Groove frequency we are aiming for • Holographic grating (more efficient) • Higher quality material (Float Glass)

Our research draws us to the choice of the Edmund Optics Reflective Holographic Grating. It is from a certified vendor, fits the groove density we need, is of a higher quality material than the other mentioned products, and is efficient as a holographic grating. A caveat of this product is the high price point. While not the most expensive on our list, it is a bit pricey. However, for the efficiency and quality it provides, we believe it is worth it.

3.2.4 Slits

Blocking mechanisms such as slits are used to clean up beams of light. They are necessary elements in a spectrometer since they allow control over where the light enters a system while also spatially filtering it. The width of the slit can aid in better separation of light from the diffraction grating and make it easier for us to isolate the wavelengths we want. For our slit choice we will look at price, width, and quality.

Price

Slits, though simple in structure, are usually high in price due to the manufacturing aspect. Slits down to microns in width tend to be more expensive, while millimeter-wide slits are usually lower in price. We will have to find out what width slit we are looking for and then compare the prices of various manufacturers.

Width

As stated before, some slits range down to thousands or even hundreds of microns in width. In spectrometers, entrance slits are commonly in the order of 10, 25, 50, 100 and 200 μm [57]. The equation to find the proper entrance slit width is as follows:

Equation 3.2.4: Equation to find the width of the entrance slit of a spectrometer

$$w = \frac{G\Delta\lambda f}{\cos(\alpha)} \quad [58]$$

Where G is the groove density of the grating ($\frac{1}{d}$), $\Delta\lambda$ is the range of wavelengths, f is the focal length of the collimating lens, and α is the angle of incidence upon the grating. Assuming as we did before ($\alpha = 45^\circ$) and using one of our derived diffraction grating groove frequencies ($G \approx 1800 \text{ lines/mm}$), we can solve the equation for w . The range of wavelengths we are looking at include the blue and red portions of the spectrum. We will assume that we want a spectral resolution of 10 nm for both portions. Lastly, the focal length of the collimating lens will vary based on the one we decide on, however we can assume 20 mm. Therefore our equation can be solved:

$$w = \frac{(1800)(10^{-3})(20)}{\cos(45)} \approx 500 \text{ } \mu\text{m}$$

Quality

Lastly, we need to look at the quality of our slits. Not just in material, but adjustability as well. There are fixed slits of a certain width, and then ones that can adjust and will allow us to attune the light coming in to the best it could be.

3.2.4.1 Precision Optical Slits - ThorLabs

Thorlabs sells slits ranging from 5 μm to 500 μm . These products have no adjustability, so we must choose our slit size carefully. They are made of stainless steel foils and range in price from \$111 to \$135. All in all, they are basic slits at a reasonable price.

3.2.4.2 Adjustable Optical Slits - Edmund Optics

The adjustable optical slits by Edmund Optics provide the adjustability aspect that could prevent the need to buy multiple slits. The slit can be adjusted from closed to 6 mm. The material is black anodized metal and is larger in size than the previous product that was just a slit to be mounted. Since one of our goals is to have a more compact device, this is a downside. The price for this optic is \$471, which is way out of our budget.

3.2.4.3 Fixed Slit - Newport

Newport fixed slits, like Thorlabs, are simple non-adjustable slits. They have sizes from 10 μm to 1.56 mm. They are also smaller than Edmund Optics adjustable optical slit, which is good for our project. Their price range is higher than Thorlabs at \$185 to \$455. Also, unlike Thorlabs mountable slits, Newport slits are not easily mountable on an optical post. They are meant to be inserted into a spectrograph. This may cause an issue with how we incorporate it into our optical layout.

3.2.4.4 Product Choice

Table 3.2.4.4: Comparison of various products and their vendors for optical slits.

Product	Vendor	Comparison
Precision Optical Slits	ThorLabs	• Cheapest • Plenty of slit sizes • Can be mounted • Small in size • Not adjustable
Adjustable Optical Slit	Edmund Optics	• Most expensive • Adjustable • Large in size
Fixed Slit	Newport	• Second most expensive • Unable to be mounted on optical mount or adjusted • Plenty of slit sizes • Small in size

After analyzing these comparisons we chose to use ThorLabs precision optical slits. This is because its mountability gives us versatility in how we incorporate it into our system, it is more reasonable in price, and they have plenty of sizes including the one we need.

3.2.5 Microcontroller

Overview: A microcontroller is a compact integrated circuit designed to govern a specific operation in an embedded system. It typically includes a processor core, memory (both RAM and flash), and various input/output peripherals all on a single chip. Microcontrollers are widely used in applications such as automotive systems, consumer electronics, robotics, and home automation. They are programmed to execute specific tasks, often involving real-time processing, and can interface with sensors, actuators, and other hardware components. Their versatility, low power consumption, and cost-effectiveness make them ideal for a range of applications, from simple tasks like turning on lights to complex functions like controlling motors in robotics.

In this application the microcontroller will be the one who receives the data from the sensors, processes it and sends it through an antenna via wi-fi to the user which is connected and using our application.

3.2.5.1 ESP32 S3 WROM 1

The ESP32-S3 series of SoCs features an embedded Xtensa® dual-core 32-bit LX7 microprocessor with a single precision FPU, operating at speeds of up to 240 MHz. It includes 384 KB of ROM, 512 KB of SRAM, 16 KB of SRAM in RTC, and supports up to 16 MB of PSRAM. For connectivity, the module supports Wi-Fi standards 802.11 b/g/n with a bit rate of up to 150 Mbps in 802.11n, along with features like A-MPDU and A-MSDU aggregation and a guard interval of 0.4 μ s, operating in the 2412 to 2484 MHz frequency range. Additionally, it supports Bluetooth LE, including Bluetooth 5 and Bluetooth mesh, with speeds ranging from 125 Kbps to 2 Mbps and features like advertising extensions and a channel selection algorithm. The ESP32-S3 is equipped with a variety of peripherals, including GPIO, SPI, LCD and camera interfaces, UART, I2C, I2S, USB 2.0 OTG, and more. Integrated components include a 40 MHz crystal oscillator and support for up to 16 MB of Quad SPI flash. Antenna options comprise an on-board PCB antenna and an external antenna connector. The module operates within a voltage range of 3.0 to 3.6 V and has ambient temperature ratings of -40 to 65 °C for the 65 °C version, -40 to 85 °C for the 85 °C version, and -40 to 105 °C for the 105 °C version. Certifications include RF compliance and green certifications such as RoHS/REACH, along with various test methodologies like HTOL and ESD for reliability assurance. For detailed information about the module peripherals, users are advised to refer to the ESP32-S3 Series Datasheet. [59]

3.2.5.2 ATmega48A

The ATmega48A/PA/88A/PA/168A/PA/328/P is a low-power, CMOS 8-bit microcontroller from the High-Performance, Low Power AVR® family, built on an advanced RISC architecture that features 131 powerful instructions, with most executing in a single clock cycle. It offers up to 20 MIPS throughput at 20 MHz, and includes 32 general-purpose working registers along with a 2-cycle on-chip multiplier. The microcontroller supports high endurance non-volatile memory segments, including 4/8/16/32 KBytes of self-programmable Flash program memory, 256/512/512/1 KBytes of EEPROM, and 512/1 K/1 K/2 KBytes of internal SRAM, with write/erase cycles rated at 10,000 for Flash and 100,000 for EEPROM, and data retention lasting 20 years at 85°C and 100 years at 25°C. It features in-system programming via an on-chip boot program, true read-while-write operation, and a programming lock for software security. The QTouch® library supports capacitive touch buttons, sliders, and wheels, accommodating up to 64 sense channels. Peripheral capabilities include two 8-bit timer/counters, one 16-bit timer/counter, a real-time counter, six PWM channels, an 8-channel 10-bit ADC, programmable serial USART, SPI, I2C-compatible interfaces, a programmable watchdog timer, and an on-chip analog comparator. Special features include power-on reset, programmable brown-out detection, an internal calibrated oscillator, and multiple sleep modes. The microcontroller offers 23 programmable I/O lines and comes in various packages, operating at a voltage range of 1.8 to 5.5V with a temperature range of -40°C to 85°C. Power consumption is low, with active mode at 0.2 mA and power-down mode at 0.1 µA. [60]

3.2.5.3 STM32C031x4

The microcontroller features ST's state-of-the-art patented technology, powered by an Arm® 32-bit Cortex®-M0+ CPU with a frequency of up to 48 MHz, and operates effectively within a temperature range of -40°C to 85°C, 105°C, or 125°C. It includes up to 32 Kbytes of flash memory with protection and 12 Kbytes of SRAM equipped with hardware parity checks. Additional features comprise a CRC calculation unit, robust reset and power management capabilities—including a voltage range of 2.0 V to 3.6 V, power-on/power-down reset (POR/PDR), programmable brownout reset (BOR), and low-power modes such as Sleep, Stop, Standby, and Shutdown. Clock management is supported by a 4 to 48 MHz crystal oscillator, a calibrated 32 kHz crystal oscillator, and internal RC oscillators for both 48 MHz (±1%) and 32 kHz (±5%). The microcontroller offers up to 45 fast I/Os, all of which are mappable to external interrupt vectors and are 5 V-tolerant. It features a 3-channel DMA controller, a 12-bit ADC with a conversion time of 0.4 µs (supporting up to 19 external channels), and eight timers, including 16-bit timers for advanced motor control and watchdog timers. A calendar RTC with an alarm function is also included. Communication interfaces

consist of one I2C-bus supporting Fastmode Plus (1 Mbit/s) and SMBus/PMBus™ features, two USARTs with synchronous SPI capabilities, and one SPI supporting up to 24 Mbit/s with a programmable bitframe. Development support is provided through serial wire debug (SWD), and all packages are compliant with ECOPACK 2 standards.[61]

3.2.5.5 Final MCU Decision

We are choosing the ESP32-S3- wroom-1. The main reason is the embedded Wi-Fi antenna, low price and also it has an embedded flash memory which will make it more easy and feasible to design and implement plus it will save real estate on the PCB. All of them work in the same voltage range but the ESP32 can work at a higher frequency and almost 10 times higher flash memory. It has dedicated pins for USB and any GPIO pin can be used for I2C which makes it the ideal microprocessor for our application.

3.2.6 Housing Material

Earlier, ASA was chosen as our 3D printing filament for our housing. Now, we will dive deeper into various vendors of ASA to find the best quality material at the best price point. The following filaments were found on Amazon.

3.2.6.1 Polymaker ASA Filament

Listed as 'Amazon's Choice', Polymaker is a popular brand on Amazon. This brand claims its filament is UV and weather resistant. The price point is \$30 for 1kg. Reviews claim that it prints easily with minimal warping, something that ASA is known to do.

3.2.6.2 CCTREE ASA Filament

The CCTREE ASA filament is a bit lower in price at \$27 for 1kg. There are less reviews, and some say that it comes full of bubbles. However, once it is dried out it works fine. This filament is white with a glow-in-the-dark property, which might be useful in the dark greenhouse environment at night.

3.2.6.3 VOXELAB ASA Filament

VOXELAB ASA filament comes in even cheaper than the previous two at \$25 for 1kg. With plenty of positive reviews, this filament is a contender for our project. Since these filament brands are very similar, there is nothing notable to add about VOXELAB.

3.2.6.4 Housing Material Product Choice

As stated before, these filaments are all very similar. They are around the same price, are heat and UV resistant, and come in plenty of colors. This is where the reviews come in handy. Looking at the reviews and hearing from experts/those

experienced in 3D printing can help our decision. For example, the CCTREE ASA filament has reviews mentioning that it comes full of bubbles, which is something we don't want. Reviews for VOXELAB ASA filament claim that it is not of the highest of quality, some even calling it weak and brittle for an ASA filament. On the other hand, Polymaker ASA filament has plenty (1300+) reviews, each one stating their pleasure with the product. These reviews claim that Polymaker makes high quality filaments and is a well trusted name in the industry and that their ASA filament is less prone to warping, is incredibly strong, and prints very well. That is why the ASA filament choice is Polymaker.

3.2.7 Lenses

For our optical setup we are using plano-convex collector lenses and focusing lenses. There are many, many vendors out there for lenses. Some of the biggest names include ThorLabs, Edmund Optics, etc. The lenses we want are on the smaller side with smaller focal lengths to fit within our device dimension specifications. We are looking for a 10 mm diameter lens with a focal length of 20 mm. The lenses listed below are from various vendors. We will look not only for our parameters of diameter and focal length, but also price and quality of the lenses as well.

3.2.7.1 Edmund Optics VIS-NIR Coated Plano-Convex (PCX) Lenses

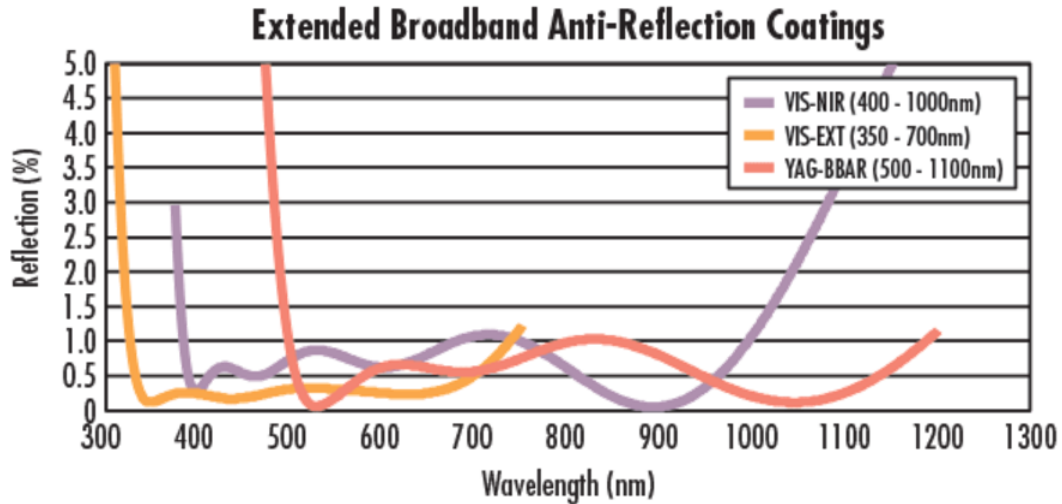
Edmund Optics has a variety of plano-convex lenses. Their VIS-NIR coated PCX lenses are AR (anti-reflective) coated at 400 nm - 1000 nm. They are designed for a zero angle of incidence, meaning the light is to hit the lens straight on. The material is N-BK7 glass, a typical lens material. Options range from a 1 mm diameter lens with a 0.6 mm EFL (effective focal length) to a 35 mm diameter lens with a 100 mm EFL. So, they have many options. This list does include what we need, a 10 mm diameter lens with a 20 mm EFL. The price for this optic is listed at \$40.50.

3.2.7.2 Edmund Optics VIS-EXT Coated Plano-Convex (PCX) Lenses

Similar to the above product, the VIS-EXT coated PCX lenses from Edmund Optics have a variety of sizes and focal lengths. They have a 10 mm diameter 20 mm EFL lens listed for \$40.50, same price as the VIS-NIR coated lens. The material, N-BK7, is the same as well. The difference between these lenses lies in the coating. The below graph from Edmund Optics shows that these two lenses have differing reflectance and different wavelengths. This is because they are meant to be used for different types of projects where different light sources (and wavelengths) are needed. As mentioned previously, the VIS-NIR coated lenses are most efficient at 400 nm - 1000 nm, with a reflectance of <1.25%. On the other hand, the VIS-EXT coated lenses have a <0.5% reflectance for 350 nm -

700 nm. This is also shown in the graph below that is directly from Edmund's website [62].

Figure 3.2.7.2: Comparison graph of reflection vs wavelength of various Edmund Optic PXC lenses [62].



3.2.7.3 Thorlabs N-BK7 Plano-Convex Lenses

The Thorlabs plano-convex lens that we are looking at has many similarities to the previously mentioned Edmund Optics lenses. Also made of N-BK7 glass, this Thorlabs lens comes in numerous sizes with various EFLs. However, when looking at the website there is not an exact match for what we are looking for. The closest lens diameter would be either the 9 mm, or if we wanted to have a slightly bigger lens the next size up is 12.7 mm. Both of these sizes do come in a focal length of 20 mm as needed. Another similarity is that Thorlabs also has various AR coatings on their lenses. “Coating A”, as they call it, is an AR coating that has a <0.5% reflectance from 300 nm - 700 nm. “Coating AB” has a <1.0% reflectance from 400 nm - 1100 nm. These are similar ranges to Edmund's filters (only difference being 400 nm - 1000 nm at Edmund Optics). The reflectance in the 300 nm - 700 nm range are the same for both, but the reflectance tolerance is lower for 400 nm - 1100 nm at Thorlabs (<1% vs <1.25%). The display of these products are also a bit different. On Edmunds website they are advertised as two separate products while on Thorlabs they are advertised as the same product but with options of “Coating A” or “Coating AB”. The price for a lens with a similar diameter and the focal length we need is around \$35 for coating A and around \$38 for coating B.

3.2.7.4 Lens Product Choice

To compare what we learned about these various products and vendors, we made a comparison table to quickly and efficiently show the research.

Table 3.2.7.4: Comparison of various products and their vendors for optical lenses.

Product	Vendor	Comparison
VIS-NIR Coated Plano-Convex (PCX) Lenses	Edmund Optics	• Has our exact specifications • Tied for most expensive • Trusted Vendor • AR coating reflectance spec is higher than Thorlabs (want lower)
VIS-EXT Coated Plano-Convex (PCX) Lenses	Edmund Optics	• Has our exact specifications • Tied for most expensive • Trusted Vendor
N-BK7 Plano-Convex Lenses	Thorlabs	• Has similar to our specifications (not exact) • Least expensive • Trusted Vendor • Lowest AR coating spec (for 400 nm - 1100 nm)

As we can see from the table, the lenses from these vendors are very similar. The only real difference is in price and AR coating specs. First thing that needs to be decided is what wavelength range the lens must be AR coated for. These lenses have the option for 300 nm- 700 nm or 400 nm - 1100 nm. Our device is being used to measure red and blue light to then determine the ratio of both of them in the greenhouse. This means that we are looking at a wavelength range of around 450 nm to 660 nm. Both of these ranges incorporate what we need. So, the next thing we can look at is the reflectivity of the AR coatings at those ranges. For both vendors, the 300 nm - 700 nm range has a reflectance of <0.5%, which is very good. For the 400 nm ~ 1000 nm range, Edmund's lenses have a reflectance of <1.25% while Thorlabs lenses are <1%, both of which are worse than the other range. Therefore, we can decide on using the 350 nm - 700 nm coatings. Next, we need to decide if our lens needs to be exactly to our calculated specifications. This is because we just narrowed down our options to Edmund Optics VIS-EXT Coated Plano-Convex (PCX) Lenses or Thorlabs N-BK7 Plano-Convex Lenses (Coating A). And while Edmund has the lens to our exact specifications, Thorlabs does not. The closest diameter lens is 1 mm smaller, or 2.7 mm bigger. Due to this, and the fact that the price difference is only about \$5, we will go with the Edmund Optics VIS-EXT Coated Plano-Convex (PCX) Lens.

4. Standards and Design Constraints

4.1 Standards

There are many different standards in engineering. These design standards essentially set a baseline for how a particular type of product should operate. These standards are made to ensure reliability and safety, both for the end user and the environment. There are many different types of “standards”, including codes, standards, and guidelines, but only the codes are legally binding. That being said, standards are sometimes referenced in codes, which would make those standards legally binding as well.

4.1.1 ESD Standard

Electrostatic Discharge is the phenomena where static charge accumulated in one body gets discharged to another body as they come in contact. Since moving charge is current, due to electrostatic discharge, there is a flow of current from one body to the other. This current is of high value and can damage sensitive components. One common example of electrostatic discharge is lightning. [63] It can lead to the failure of sensitive electronic devices, especially during manufacturing, handling, or repair. The purpose of ESD standards is to mitigate these risks by establishing proper protocols and procedures for minimizing electrostatic discharge. ESD susceptibility refers to the sensitivity of an electronic component to damage by ESD, while ESD protection encompasses techniques or materials used to shield devices from ESD. ESD standards are to ensure that electronic components are not damaged by electrostatic events, testing equipment and products. A standards to follow include ANSI/ESD S20.20, which focuses on controlling ESD in electronic manufacturing and service industries through protocols for Electrostatic Protected Areas (EPA), such as grounding, personnel handling procedures, and ESD-safe workstations with static-dissipative surfaces and equipment. [64] The IEC 61340 is an international standard covering ESD control in manufacturing, handling, and packaging of electronic devices, with IEC 61340-5-1 and 61340-5-2 focusing on control programs for ESD-sensitive devices and methods to protect them from ESD events. Since ESD is a silent IC killer, it is good to follow safe practices while working and storing them.

From Electrostatic Discharge: The hidden enemy of integrated circuits by Nirbindu Das [63]:

“Here are a few tips to protect your ICs from Electrostatic discharge:

Use antistatic workspace: Ensure you are in an antistatic workplace when working with ESD-prone devices. The table, flooring and the furniture in use should all

have anti-static properties. These are properly grounded to bypass any electrostatic discharge. One should avoid rubbing on the work surfaces, use antistatic mats on work-surfaces, walk on the floor only with ESD boots/ slippers on. Use antistatic gear: Anyone working with ESD sensitive devices should use anti-static gear. This includes (but not limited to) anti-static wrist bands, anti-static aprons and head gear. Use ESD safe storage material: All ESD prone material should be stored in proper packaging having anti ESD properties. Storage rooms should be equipped with temperature and moisture control to minimize ESD generation. The racks, cupboards etc in which the material is stored should be electrically grounded to discharge any accumulated charge.

Avoid woolen clothes and damp conditions: Personnel working with ESD prone devices should avoid woolen clothes as they tend to quickly accumulate charge. Also, moisture leads to quicken the charge accumulation. Hence the work environment in these cases should be controlled for humidity. “

4.1.1.1 Impact on our design

Our design will have a main PCB and 4 already made sensors. We will need to solder them down into our main PCB and align them to the optics hardware. In the manipulation of the sensors our product has many components which are high probable victims of electrostatic discharge.

4.1.1.2 How to follow the standard

We are going to use anti-static gear such as anti-static wrist-band, Blue Anti-Static ESD Tech Coat and anti-static bag and we are going to make sure that our soldering station is grounded and our connection to ground is proper. We will avoid woolen clothes and damp conditions. And since we will have a humidity sensor we will control the humidity of the room as well.

4.1.1.3 Equipment

This will not affect our economic constraint since we already own this equipment. Below there are images of the PPE we plan to use.

Figure 4.1.1.3: PPE We Will Use



4.1.2 IPC Standard

The IPC (Institute for Printed Circuits) standards are essential guidelines designed to regulate the electronics manufacturing industry, focusing primarily on printed circuit boards (PCBs), electronic assemblies, and related processes. These standards ensure global consistency, quality, and reliability across the electronics supply chain by providing specific requirements for everything from design and assembly to soldering, inspection, testing, and repair. IPC standards are crucial for maintaining performance and reliability in products across various sectors, including consumer electronics, aerospace, automotive, telecommunications, and defense. [65] Key standards include IPC-2221, which provides general guidelines for PCB design, covering everything from conductor widths to component placement and thermal management. IPC-6012 defines the performance requirements for rigid PCBs, ensuring the durability and reliability of boards across various environmental conditions, while IPC-A-600 sets the acceptance criteria for PCB manufacturing, focusing on quality assurance through visual inspections. IPC-A-610, one of the most widely used standards in the industry, defines the acceptability of electronic assemblies by providing detailed descriptions of workmanship for soldering and component placement, ensuring product reliability through clear visual criteria. IPC J-STD-001 focuses on soldering quality and process control, establishing the requirements for materials and techniques used in soldering, from hand soldering to reflow and wave soldering. IPC-2581 provides a standardized format for transferring design data, ensuring that critical details like trace widths, hole sizes, and layer stack-ups are conveyed consistently, improving the efficiency and accuracy of the manufacturing process. Overall, IPC standards are vital to ensuring the reliability, quality, and performance of electronic components and assemblies across a wide range of industries, guiding best practices in design, manufacturing, repair, and environmental compliance, and adapting to the evolving demands of the global electronics industry. [65]

4.1.3.1 Impact on our design

For the design of the PCB it is a good practice to follow PCB guidelines design from the IPC center to accomplish a good thermal management and set the proper rules in the software design tools such as conductor width; component placement, pad diameter, layers stack up, minimum clearance, etc. While following the IPC standards we can perform initial inspection of the PCB before plugging it to power and the support of the standards will help us to troubleshoot. Since we are planning to solder 4 sensors in our PCB is good to keep soldering quality to make sure there is not connection loose or bridged that can make us spend extra hours for a simple mistake.

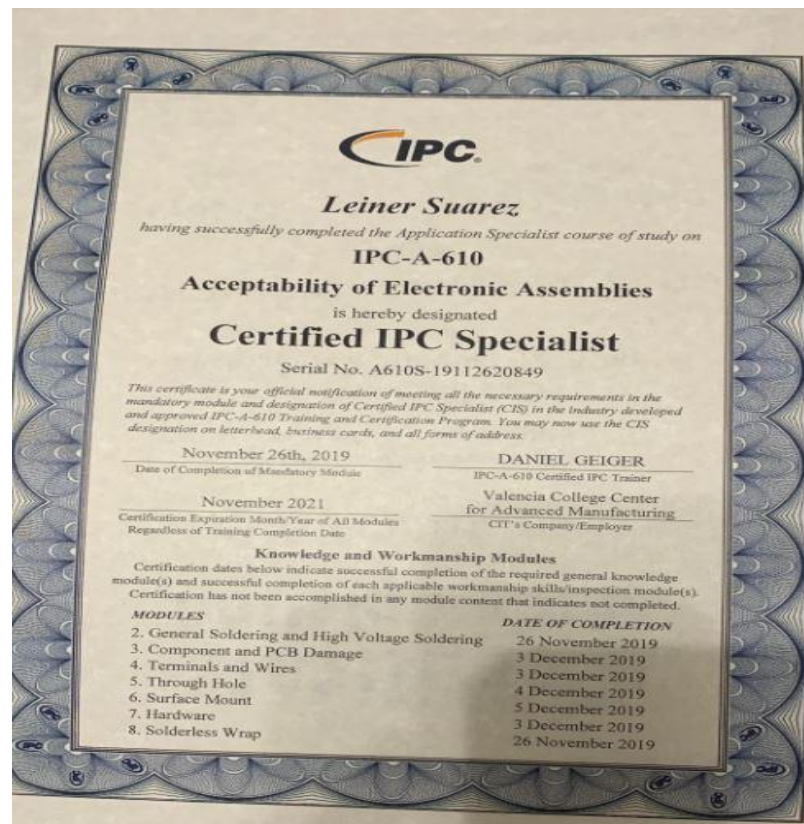
4.1.2.2 How to follow the standard

I (Leiner Suarez) am an IPC, J-Standard certified. Even though the certification is expired, I have more than 4 years of experience and the IPC J-STD-001 book to follow. We plan to make a high-quality PCB and solder it with the highest industry quality.

4.1.2.3 Equipment

The necessary equipment for the project includes soldering tools, soldering iron, sponges for cleaning the tip, cutters for wire and component trimming, tweezers for precise placement of small components, and other essential tools required for assembling and maintaining the hardware components. Additionally, we will reference the IPC standards book for guidelines on soldering quality and assembly best practices. Since we already own these tools, there will be no additional economic impact or cost associated with acquiring new equipment. This ensures that we can efficiently proceed with the assembly and prototyping phases without facing any unforeseen budgetary constraints. The availability of these tools also contributes to the quality and precision of our work, ensuring that the hardware components are correctly assembled and functional for the greenhouse monitoring system.

Figure 4.1.2.3.1: IPC Specialist Certification



[illegible]

The USB (Universal Serial Bus) standards define the protocols and specifications for communication between computers and peripheral devices, providing a standardized interface for data transfer, power delivery, and device connectivity.

4.1.3.1 Impact on our design

4.1.3.2 How to follow the standard

68

Corporation, Renesas, STMicroelectronics, and Texas Instruments. And advice design from the web such as the 5.1Kohm resistor from CC pins to ground or ESD circuit to protection.

4.1.4 I2C Standard

From “Why the Inter-Integrated Circuit (I2C) Bus Makes Connecting ICs So Easy—And How to Use It” by Art Pini and “A Basic Guide to I2C” by Joseph Wu from Texas Instruments [28], [66], the following is a summary made by ChatGpt:

The I2C (Inter-Integrated Circuit) standard, developed by Philips Semiconductors in the early 1980s, has become a fundamental communication protocol widely used for connecting integrated circuits (ICs) on a single circuit board. This versatile protocol allows multiple devices to communicate with each other using just two wires: a serial data line (SDA) for transmitting data and a serial clock line (SCL) for synchronizing the data transfer. One of the most significant advantages of I2C is its ability to support multiple master and slave devices on the same bus, which means that one or more master devices can control the bus while multiple slave devices can be connected to it. This multi-master configuration facilitates a flexible and scalable system design, enabling complex embedded systems where various components, such as sensors, memory chips, and microcontrollers, can easily communicate.

Each device on the I2C bus is assigned a unique address, typically ranging from 0 to 127, which allows the master to select specific devices for communication. The addressing scheme supports both 7-bit and 10-bit addressing, accommodating a larger number of devices in more complex applications. The protocol operates in a half-duplex mode, meaning that data can be transmitted in both directions but not simultaneously. This characteristic is particularly beneficial for low-speed peripherals, as it simplifies the design and reduces the amount of required hardware. The standard I2C bus operates at several data rates, with the most common being 100 kHz for standard mode and 400 kHz for fast mode, while newer versions of the protocol can achieve speeds up to 3.4 MHz in high-speed mode. High-speed mode is essential for applications requiring rapid data transfer, such as digital signal processing and real-time data acquisition systems.

I2C employs a well-defined protocol that includes key elements such as start and stop conditions, acknowledge bits, and clock stretching to ensure proper data transfer and synchronization between devices. A start condition is indicated by the master pulling the SDA line low while the SCL line is high, signaling the beginning of a communication sequence. Similarly, a stop condition marks the end of the communication, allowing other devices to take control of the bus. The protocol also incorporates an acknowledgment bit, which confirms successful data reception. If a device is unable to process the data immediately, it can

implement clock stretching, where the slave device holds the SCL line low, effectively pausing communication until it is ready to proceed.

The simplicity of the two-wire configuration significantly reduces the amount of required board space and the complexity of wiring, making I2C a popular choice for connecting low-speed peripherals in microcontroller-based systems. This feature is particularly advantageous in applications where space is limited, such as mobile devices, automotive electronics, and consumer products. Furthermore, I2C supports a daisy-chain configuration, allowing multiple devices to be connected in series without requiring additional wiring, which enhances the scalability of the system. The protocol's flexibility also allows for easy integration with other communication standards, such as SPI (Serial Peripheral Interface) and UART (Universal Asynchronous Receiver-Transmitter), providing designers with a range of options for inter-device communication.

In terms of electrical specifications, I2C operates at a voltage level typically between 1.8V and 5.5V, accommodating a wide range of devices and ensuring compatibility across various components. The bus is designed to function in various environmental conditions, ensuring reliable communication in both noisy and stable electrical environments. I2C also includes specifications for signal integrity and timing, which are critical for maintaining effective communication, especially in systems with long wire lengths or multiple connected devices.

4.1.4.1 Impact on our design

I2C has a great impact in our design since it will be the main communication protocol to the microcontroller to talk with the 4 sensors we will use. We are going to use two different types of sensors: the Adafruit TSL2591 High Dynamic Range Digital Light Sensor and the (SCD-41) for measuring temperature, CO₂ and humidity. And we might use I2C for other peripherals and indication diodes.

4.1.4.2 How to follow the standard

Because we are using the same sensor three times we had to implement an extra IC chip to use them due to the fact that they have the same address. To do this function we choose TCA9546ADR from Texas Instruments. We will have the main data and clock signal I2C going to this device and then this device will make 4 extra channels for each sensor.

4.1.5 Photonic Standards

Standards in the photonics industry are continuously emerging. Due to the nature of photonics and optics as an ever-growing field, there is an ever-growing need for continuous improvement. New technology means new standards needed for safety and precision. Current standards, such as ANSI Z136.1 that governs the safe use of lasers, are essential in preventing physical injuries. [67] However some

standards, like ISO 9211, explain more technical specifications. ISO 9211 is the standard for the type of optical coatings used and testing methods for lenses, mirrors, filters, etc. as well as their tolerances. [68] The latter are the standards we will mostly be working with, as we are not using laser light in our device, but we will be using optical components. Adhering to these standards is essential to ensure the precision and performance of our optical components.

There are some other standards that will have an impact on our design, such as ISO/CIE 19476:2014, which standardizes light-intensity sensing devices and their calibration techniques. [69] ISO 9845-1:2022 provides different solar spectral irradiance levels at the ground under different conditions. [70] ISO 9022 and IEC 60068 both provide methods for testing optical components under a variety of different environments. [71], [72] Lastly, ISO 15368:2021 provides rules for measuring reflectance and transmission for things like beamsplitters. [73]

4.1.5.1 Impact on our design

Although we are not creating these optical components directly, we can follow ISO standards by ensuring the vendors we buy from follow them, and that we use them to inform the design and calibration of our product. We will need to ensure vendor credibility throughout our research, so that we will know that our optics are ISO certified and standardized. All of the optical components in our system should follow these standards.

4.1.5.2 How to follow the standard

We will use these standards as the guidelines for the optical components we design, buy, and incorporate into our system. This means we will have to look closer at the specifications of the optics we buy. We somewhat did this earlier in our research and investigation section where we analyzed all of our components and compared various products to find the best fit into our design. We will need to be sure that these also follow the ISO standards. We will also take the spectrum of the light that reaches Earth into account and ensure that we follow the proper techniques for light sensor calibration.

4.1.6 C and C++ Language Standards

The greenhouse monitoring system's embedded software, developed for the ESP32-S3-WROOM-1-N8R2 microcontroller, utilizes both C and C++ languages. While C is used primarily for its efficiency and portability in handling low-level hardware interactions, C++ is employed for managing more complex data structures and higher-level functionalities, such as organizing sensor data and managing communication protocols. Adherence to international standards ISO/IEC 9899 for C and ISO/IEC 14882 for C++ ensures that our code remains

robust, maintainable, and compatible across different development environments and platforms. [74]

The C language standard (ISO/IEC 9899) defines core syntax, constraints, and semantics, creating a predictable framework essential for embedded systems, which need reliable, consistent performance. For instance, the standardization allows our code to handle critical operations, such as processing environmental readings and performing arithmetic calculations, with precision, directly influencing the accuracy of our temperature, humidity, and CO₂ monitoring.[74]

ISO/IEC 14882, the international standard for C++, extends the basic capabilities of C by adding object-oriented features and templates, which allow for more organized and reusable code. In our system, C++ is used for higher-level tasks, including data management, organizing modules within the mobile app, and facilitating efficient communication with the Heroku server. Using C++ also makes it easier to modularize the code, allowing us to refine specific functionalities like sensor calibration or error handling without impacting the core operations of the embedded software. [74]

While these standards define key elements of program behavior, they do not impose restrictions on hardware-specific implementations, giving us flexibility to optimize code for energy efficiency and response time. For instance, C++ features such as classes and inheritance help streamline the code, enhancing maintainability and enabling us to implement efficient, scalable solutions for data transmission and user interface elements. [74]

4.1.6.1 Impact on our design

The adoption of ISO/IEC 9899 (C) and ISO/IEC 14882 (C++) standards will significantly influence our design decisions. In particular, using C ensures that the embedded software maintains low memory usage and high performance for real-time data processing, which is essential for monitoring the greenhouse's environmental factors efficiently. The modularity and organization provided by C++ allow us to build clean, scalable software for higher-level functions, such as data logging, communication with the Heroku server, and the mobile app's user interface.[74]

By following these standards, we can ensure that our design remains flexible, maintainable, and compatible with various hardware platforms and future updates. The standards also promote portability, enabling the software to run reliably across different systems or be adapted to future versions of the ESP32 or similar microcontrollers. Moreover, they encourage the development of robust error handling and debugging techniques, which are crucial for maintaining system reliability in the long run.

4.1.6.2 How to follow the standard

To comply with ISO/IEC 9899 (C) and ISO/IEC 14882 (C++) standards, we will follow their syntax and semantics, ensuring the code is correctly written and interpretable across compilers. We will structure the code modularly using object-oriented principles in C++, allowing for reusable and scalable components. This approach ensures clear separation of concerns and easier future updates.

We will optimize memory usage and performance by utilizing C's low-level capabilities and minimizing C++ overhead where necessary. Robust error handling and debugging mechanisms will be implemented to ensure reliable operation under various conditions. Testing, including unit, integration, and stress testing, will confirm compliance with the standards and the correct performance of the system. By following these practices, we ensure our software is robust, reliable, and maintainable while adhering to the C and C++ standards.

4.2 Design Constraints

There are many different types of design constraints that affect the potential quality of our project. These constraints do not all have to do with physical qualities of the project, but also with external circumstances or pressures that could potentially impact the design. These are monetary, size-related, time-related, mental-health related, and regulatory.

4.2.1 Monetary Constraint

One of the most important constraints of our project has to do with money. With everything that we design, consider, buy, and do has to do with money. Firstly, we need to think of how much money we are willing to spend as a group to do our project. Since we have no sponsors, all parts will either come from the senior design lab or be purchased. Because we are college students, we would prefer to spend as little money as possible. While it's hard to give an exact cap to how much we are willing to spend, preferably we would like to spend less than \$100 a person. This most likely is not a budget we can stick to, as optical components tend to be expensive, but it is a good general estimate for the amount of money we want to spend.

The money constraint inside PCB design is a huge factor. We want to make a PCB as less expensive as possible. To do this we need to follow Fabrication Houses guidelines for standard and cheaper designs capability which mean we have to make a set up of rule in our software tool capable of reduce the price; example of this are layer counts, laminate materials, clearance on traces, pad and vias, via through hole tolerances, types of vias, solder mask, etc.

While there is the design's monetary constraint, we need to think about the potential consumer's willingness to buy our product at a certain price. Ideally, our product would be priced reasonably enough that we would make some sort of net financial gain, but not too high, as to scare off buyers. An interesting thing to keep in mind is that if we were to go full-scale into production, we'd find ways to cheapen our expenses and still provide a reasonably-priced, yet well-functioning final product. Therefore, we would make things simple and say that we'll look for our net gain to be zero dollars and that a product priced around \$600 is reasonable for a device of this functionality and nature.

4.2.2 Size Constraint

The next type of constraint that we need to keep in mind is the size of our design. While ideally our product would be as small as possible, it wouldn't be reasonable to have our sensor to be at a handheld size. This is a result of the amount of optical elements we are incorporating into our assembly and the size of the PCB and MCU. We also need to make sure our design isn't too big as to take up too much space in a greenhouse and potentially block out light from reaching plants. In the same sort of vein, the sensor needs to be either placed high enough that it receives light at plant canopy level, or it needs to be tall enough that the sensor is inherently at the canopy level. For this reason, we aim to keep the dimensions of the entire device less than 15 inches x 15 inches x 10 inches.

Size constraint inside PCB design is a huge factor, that is why it is really important to choose small components against larger components when they accomplish the same goal and the cost is less or relatively similar. Component placement is a great factor in our design since we have 4 sensors that will be measuring light and they have to be separated and need to be isolated from other signal or component noise. But not only components made a constraint here, also the signal routing will be a factor, and we want to make a PCB with as few layers as possible meaning less space for routing or placement which make size constraint highly relevant.

Another type of size constraint that we need to keep in mind is the weight of the part. Ideally, the design needs to be light enough for a single person to carry and place in an ideal location in the greenhouse. There isn't much of a concern of the part being too light, as there is not likely to be any sort of factor in the greenhouse that would cause it to be knocked over easily. However, it needs to be able to be carried by the vast majority of people. Therefore, we should aim to keep the weight under 15 pounds.

4.2.3 Time Constraint

Perhaps the most long-term constraint is time. From the beginning of senior design to the end, we have nine months. This may seem like plenty of time, but life gets busy. Some people have work, others have multiple classes, and some have all of the above. For these reasons, this is also perhaps the most flexible, yet most risky constraint.

One of the most interesting aspects of this project and this course is that we have to come up with our own schedules, work on our own hours, and have very little day-to-day submissions or supervision. On the optics side, we meet weekly to discuss different aspects of our project. Other than that, there is no other feedback besides on demo days, meetings with advisors, or the mandatory page deadlines. Because of these factors, we need to work together to make sure that our project is on track. We decided to meet every Monday to review progress and make sure that the project is where it needs to be.

Time constraint is a common issue when designing PCB. In our project we need to be realistic and create a PCB as good as possible in the time given. We might be able to make it better but we will need to do extra research and spend time on gaining knowledge to apply for a better design. For example choosing USB 3.0 instead of USB 2.0 will technically improve the speed of the PCB connection with computers but in order to route this high speed signal against USB 2.0 will need extra investigation and time consumption.

As we work on this project, we will, and have run into problems along the way. These issues take time to resolve and can sometimes impact multiple parts of the project, causing an overall stall. This is not a good thing, and needs to be resolved as quick as possible. Whatever the case, errors and issues will be encountered, and we are constrained to the sixteen weeks of Senior Design 1 and the sixteen weeks of Senior Design 2. There is no way around this.

4.2.4 Manpower/Personal Constraint

One of the more unique and probably less talked about constraints is in manpower or personal willingness. While this can be considered a time constraint, it is different enough that it is worth being talked about.

With any sort of major task, like this project, it is almost guaranteed that some sort of stress and pressure will be felt by the individuals performing the task. While with proper support systems and coping mechanisms, someone can be less prone to feeling overwhelming effects of stress, it is common for people to feel burnout, anxiety, depression, and other sorts of mental qualms. These symptoms may lead to a lowered motivation, lowered self-discipline, and lowered work

quality. There are more serious symptoms on the more individual level that will not be discussed here, but the point is that the element of stress can negatively impact the progress, even if not directly tied to a time element.

In the same vein, the small number of individuals building this project severely limits how fast and efficiently the project can be done. With a group of 50 or more people, tasks would be able to be divided out more equally, and it would be easier for others to pick up slack if one person is falling behind. In a group of four, this is much harder to do.

4.2.5 Material Constraint

Another physical constraint, alongside the size and weight, is the material. The device will be comprised of many different components. Some of these components will be electronic and some will be purely light-based. However, they all need to work in an environment like a greenhouse. Greenhouses are humid, warm, and light-heavy. Therefore, any housing for our optical and electronic components need to be able to withstand the heat, humidity, and light intensity present. Thankfully, datasheets often provide operating ranges for components to work in, which takes out the guesswork of whether a component is appropriate for the environment that it is going to be placed in.

4.2.6 Scope Constraint

One of the more tricky constraints we have to deal with is the scope of the project. By this point, we have already considered the scope, which entails all the functions that the device will include. This constraint is informed by our goals and essentially forms our goals. For example, the scope of our project is to make a device that is meant to measure the environment of a greenhouse. It is not without the scope of this project to make a device that detects the environment and changes light sources, accordingly. While this is a stretch goal, that is not within the scope of our project within the timeframe of senior design.

This is a constraint that can be slightly changed, but not by much. As the project goes on, we'll most likely have to make some compromises, but we can't change them too much to the point that each individual doesn't do enough work. As it stands, the scope of our project is plenty, with two optical subsystems, multiple electronic components, plenty of coding, and the design of a program. It is tricky, but should not be too much for the number of people we have.

4.2.7 Regulatory Constraints

As discussed previously, there are many different engineering standards for a variety of different components and types of devices. These standards inform

what is normal in the industry and should be kept in mind for what level of precision and quality is appropriate for our project.

As seen, there are many different standards, such as ESD, I2C, USB, and a variety of optical standards. Each of these standards must inform the components that we buy and the way that our device operates. Thankfully, there does not seem to be many standards on how light sensors or temperature, humidity, or CO2 sensors should be used or operated, but rather how the technology behind them should work. Since we are putting a variety of these sensors together, we shouldn't have to worry about operating them in a way that goes against standards. All we have to make sure of is that we are using these devices effectively and according to their datasheets.

5. Use of LLMs

In recent years, artificial intelligence has become a major aspect in everyday life. A vast majority of companies have incorporated some sort of artificial intelligence into their services. Even making a quick Google search will result in some sort of AI summary being shown to the user before any website search results. In this section, we see the pros and cons of large language models (LLMs) and show examples of how different LLMs might answer the same prompt. These prompts were relevant to our project and provided us with some necessary information.

5.1 Pros and Cons

As mentioned before, LLMs can be very useful to not just big companies but to individual users. Companies use AI to automate customer service, cutting down the hours humans need to work and ensuring around the clock help for customers. Industries such as finance, IT, software development, and more use AI to aid in their main tasks. On an individual scale, doing background research or finding a quick answer are things that are now very simple thanks to AI. If you have questions that you cannot find the answer to, LLMs can scour the internet to put bits and pieces together from articles and come up with an answer. It is then up to the user then to do more research and ensure that the information is correct.

While artificial intelligence, or LLMs, can be useful tools in research, they are not foolproof or perfect. In fact, there is no real intelligence, as humans would know, if at all. Instead, these tools use both internet results and data gathered from human input to put together its results. Unfortunately, there are many websites on the internet that do not provide correct or accurate information, and it is possible for LLMs to pull data from these. For example, websites like Reddit or Quora let users ask and answer questions on the internet. While some of these

answers may be accurate, they are not the best sources to gather information from in general, as many answers will be incorrect. Therefore, the fact that LLMs gather information from these websites needs to be kept in mind while using them. Another thing to note is that some LLMs, like ChatGPT, are not connected to the web and pull facts from stored data that might be outdated.

Keeping this in mind, the next few sections will compare responses from OpenAI ChatGPT, Microsoft Copilot, and Google Gemini, three of the most popular LLMs on the market. The correctness of the responses, the ethicalness of the responses, and the format of the responses will be reviewed.

5.1 Example 1

5.1.1 ChatGPT

For this example, I asked the LLM the benefits of using a plano-convex lens versus a biconvex lens for focusing. This was something that we covered earlier on, so it will be easy to determine if the answer is correct. The LLM answered in a very conversational tone and listed reduced spherical aberrations of collimated light, the lower cost, and the better use with longer focal lengths as benefits of using plano-convex lenses. It listed increased aberrations for uncollimated light and lens orientation sensitivity as downsides of using this type of lens. [75]

The benefits of using a biconvex lens were listed as the reduction of aberrations with noncollimated light, better performance with shorter focal lengths, and better focusing of non-collimated light. The downsides were listed as higher cost, higher aberrations with collimated light, and the reduction of effectiveness with longer focal lengths. [75]

In the end, the LLM output a table summarizing the benefits and disadvantages of each type of lens and stated the main takeaways at the end. It is worth noting that it did not provide any sources to back up its claims.

As for the information we can see and previous research, it's clear that the shape of the lenses provides different pros and cons depending on the desired focal length. Since we are not imaging, we are not too concerned with the details about the aberrations, but it is worth noting that ChatGPT did provide incorrect information. Without searching additional information about aberrations than that provided from previous sources, it is clear that plano-convex lenses perform best when the convex side faces the collimated light. [22] ChatGPT claimed that the plano side should face the collimated light to reduce aberrations (which would make the light focus better), which is incorrect. [75]

5.1.2 Gemini

I asked the same question for this example as I did for ChatGPT. In its response Gemini listed the benefits of a plano-convex lens as reduced spherical aberration with collimated light (that faces the convex side), cheaper cost, and use with objects at infinity. It listed the cons as shorter focal length and the sensitivity to orientation. [76]

For the biconvex lens, it listed the pros as a longer focal length, performance when the object is not at infinity, and the symmetry of the lens. The cons were listed as increased spherical aberrations with collimated light and the more expensive cost. [76]

The response itself was not as conversational as ChatGPT, but it did correctly state that the collimated light should face the curved part of the lens, as opposed to the flat side. [76] The other claims seem to match up with previous research and what ChatGPT stated. A great feature that comes with Gemini is the ability to see exactly where the response pulled its information from. Most of the information seemed to be confirmed within these sources, but Gemini kept note as to when no sources could be found to support its claims. In this case, it couldn't find sources to confirm that biconvex lenses have larger focal lengths with the same material and curvature. Just by the lens equation seen earlier on in this report, it is clear that this claim is false, so it makes sense that there were no sources to support it.

5.1.3 Copilot

When it came to answering the prompt, Copilot was much more concise than the previous models. It listed the benefits of using plano-convex lenses as being cost-effective, good at focusing collimated beams, and collimating divergent beams. It also said that the curved side should face the incoming light. For the cons, it said that the lenses don't have as much focusing power as biconvex lenses and that they are more prone to alignment errors. [77]

As for biconvex lenses, it listed the pros as the symmetric design, high focusing power, and wide range of applications. It specifically stated the fact that the symmetric design of the lenses make them ideal for situations where the image and object distances are equal. The cons of these lenses were listed as being higher cost and having an increased circular aberration. [77]

For this prompt, Copilot seemed the least conversational of all but the most concise. However, it listed key pros and cons of plano-convex lenses and provided sources at the bottom of the page. Unlike the previous LLMs, Copilot

did not make any mistakes when providing information, which was a great thing to see. [77]

5.2 Example 2

5.2.1 ChatGPT

The prompt I asked ChatGPT was: What are the benefits when trying to create a mobile app using Flutter versus MERN stack? Since I have used both technologies, this gives me a good reference to see how well the AI synthesizes and contrasts them.[78]

ChatGPT first discussed the strength of Flutter. It emphasized that Flutter is known for its cross-platform capabilities, meaning that apps built using Flutter can run on both iOS and Android with the same codebase. According to ChatGPT, this can save developers considerable time and resources, which would otherwise be spent on creating separate applications for each platform (iOS and Android). ChatGPT highlighted Flutter's fast development cycles due to its "hot reload" feature, which allows developers to see changes in real-time without having to fully compile the app. The AI also pointed out that since Flutter uses Dart, a language that compiles natively, performance is generally optimized, making it have less overhead compared to using web-based frameworks. Overall, ChatGPT seemed to favor Flutter when it comes to achieving a better user experience across different platforms reducing the workload.

ChatGPT also provided a comparison with MERN stack which is MongoDB, Express.js, React, and Node.js. ChatGPT pointed out that while MERN is primarily used for web development, it can still be used for mobile app development through React Native, which allows for the development of mobile apps using JavaScript. However, ChatGPT cautioned that using MERN or React Native for mobile apps might require more customization and separate codebases for Android and iOS features, leading to a more complex development process compared to Flutter.

To conclude, MERN offers versatility, Flutter's focus on mobile app development and its use of a single codebase for both iOS and Android platforms can provide advantages in terms of performance and development efficiency. Ultimately, the best choice for our project is Flutter because of the development timeline, and the need for web and mobile compatibility.

5.2.2 Gemini

Gemini's response to the prompt: What are the benefits when trying to create a mobile app using Flutter versus MERN stack? was that both Flutter and MERN

Stack have their own unique advantages when it comes to mobile app development. However, those primarily focused on creating mobile apps might find Flutter to be a better choice.[79]

Gemini weighed the decision based on what would be most efficient for developers. Flutter's native performance and cross-platform support were seen as significant advantages over the MERN stack for strictly mobile needs. While MERN is versatile and can serve both web and mobile applications, Flutter's specialization in mobile development can lead to a more streamlined and efficient development process. However, Gemini did not completely discredit the MERN stack. It acknowledged that MERN can be a valuable choice for projects that require both web and mobile components. In such cases, MERN's ability to handle both platforms can simplify development and maintenance.

Overall, Gemini's response highlighted the strengths of both Flutter and MERN Stack and suggested that the best choice depends on the specific needs and priorities of the mobile app project.[79]

5.2.3 Copilot

Copilot responded in a conversational tone, explaining that Flutter offers a single codebase for both iOS and Android, which can significantly reduce development time and costs. It also highlighted Flutter's rich set of pre-designed widgets and its ability to deliver high-performance apps with a native look and feel. However, Copilot noted that Flutter might have a steeper learning curve for those unfamiliar with Dart, the language it uses, and that it might not be as suitable for complex web applications.

On the other hand, Copilot described the MERN Stack as a powerful combination of MongoDB, Express.js, React, and Node.js, which is well-suited for building full-stack web applications. It emphasized that the MERN Stack allows for a more modular and scalable approach, with React providing a robust framework for building dynamic user interfaces. The use of JavaScript across the entire stack can streamline the development process. However, Copilot pointed out that the MERN Stack might require more effort to optimize for mobile performance and that it could involve more complex setup and configuration compared to Flutter.

In summary, Copilot provided a detailed comparison, noting that Flutter is ideal for those looking to quickly develop high-performance mobile apps with a unified codebase, while the MERN Stack offers a more flexible and scalable solution for full-stack web applications. It concluded that the choice between Flutter and the MERN Stack depends on the specific needs and goals of the project, as well as the developer's familiarity with the respective technologies. This response was

thorough and aligned well with the information we have on these technologies, although it did not provide specific sources to back up its claims.

In summary, all three LLMs ChatGPT, Gemini, and Copilo agree that Flutter is better suited for mobile app development due to its cross-platform capabilities and single codebase for iOS and Android, which reduces complexity and enhances performance. MERN, on the other hand, is more versatile, especially for full-stack web development, but requires more effort for mobile optimization. While Flutter excels in mobile-specific projects, MERN's flexibility makes it a strong choice for apps needing both web and mobile components. The final choice depends on the project's specific goals and requirements.

5.3 Example 3

5.3.1 ChatGPT

The prompt I asked to ChatGPT was: What are the benefits of building a budget server using an old laptop compared to paying for a server? This is a topic that we have been considering, and ChatGPT's might be useful when deciding.[80]

ChatGPT first focused on the advantages of repurposing an old laptop as a server. It noted that using an old laptop can be a cost effective solution since you are essentially utilizing hardware you already own, eliminating the need for ongoing payments to a hosting provider. ChatGPT mentioned that this option gives you complete control over your server's configuration, operating system, and software, which can be an advantage for users with specific customization needs. ChatGPT also pointed out that laptops are portable and often come with built-in battery backups, providing some resilience in case of power outages. However, it also acknowledged that while this approach may work for small projects or personal use, the hardware of an old laptop is usually not optimized for sustained, high demand server workloads. It could struggle with performance issues, cooling problems, or limited storage, which may ultimately hinder scalability.

On the other hand, ChatGPT contrasted this with the benefits of paying for a server through a cloud provider or dedicated hosting service. It noted that while this option involves recurring costs, it typically offers superior performance, reliability, and scalability. Paid services usually come with technical support, regular backups, and security updates, reducing the risk of downtime or data loss. According to ChatGPT, the infrastructure provided by cloud services is far more robust, designed for high availability and fast load times, which would be especially critical for businesses or high traffic websites. ChatGPT seemed to lean towards paid hosting as the better option when long-term reliability, uptime, and technical support are essential, though it did acknowledge that for small-scale,

personal projects, an old laptop server could be a reasonable choice if budget constraints are a priority.

5.3.2 Gemini

Gemini's response to the prompt explored the advantages and disadvantages of both building your own server using an old laptop and paying for one.[81]

On the one hand, building your own server using an old laptop can be a cost-effective option. By repurposing existing hardware, you can significantly reduce the upfront costs associated with purchasing a new server. Additionally, building your own server can provide a greater sense of control and customization, as you can configure the hardware and software to meet your specific needs. However, building your own server also comes with certain challenges. Older laptops may have limitations in terms of processing power, storage capacity, and reliability. Additionally, maintaining and managing a self-built server can require technical expertise and time commitment.[81]

On the other hand, Gemini said that paying for a server can offer several benefits, including higher performance, reliability, and professional support. Commercial servers are typically designed to handle demanding workloads and are often equipped with advanced features such as redundancy and automatic backups. Additionally, paying for a server can alleviate the burden of maintenance and troubleshooting, as these tasks are typically handled by the service provider.

5.3.3 Copilot

I asked Copilot about the benefits of building your own cheap server using an old laptop versus paying for a server. Copilot highlighted that this approach allows for complete control over the hardware and software, enabling customization to meet specific needs. Additionally, it mentioned that repurposing an old laptop is environmentally friendly, as it reduces electronic waste. However, Copilot also pointed out that this option might come with limitations in terms of performance and reliability, especially if the laptop is outdated or not designed for continuous operation.

On the other hand, Copilot discussed the benefits of paying for a server, emphasizing the reliability and performance that come with professional hosting services. It noted that paid servers often come with robust support, regular maintenance, and security features that ensure uptime and data protection. Copilot also mentioned that while this option might be more expensive, it can save time and effort in the long run, as the hosting provider handles most of the technical aspects. This can be particularly advantageous for those who may not have the technical expertise or time to manage their own server.

To conclude, all three responses provided insights into the benefits and drawbacks of building a cheap server using an old laptop versus paying for one. ChatGPT and Copilot focused on the cost-effectiveness and customization benefits of using an old laptop but also highlighted the potential limitations in terms of performance and reliability. Gemini emphasized the higher performance, reliability, and professional support offered by paid servers but also acknowledged the upfront costs involved.

While all three responses discussed similar advantages and disadvantages, there were some nuances in their emphases. ChatGPT and Copilot seemed to lean slightly towards the DIY (Do It Yourself) approach for smaller projects, while Gemini favored paid servers for larger or more critical applications. Copilot also highlighted the environmental benefits of repurposing an old laptop. Overall, the responses provided a comprehensive comparison of the two options, allowing users to weigh the pros and cons based on their specific needs and priorities.

5.4 Example 4

Next, we will ask the LLMs about the importance of adding a slit to any spectrometer. The question asked was as follows: “Explain to me why adding a slit to a spectrometer is necessary. Is it necessary? What does it do?”

5.4.1 ChatGPT

To summarize, ChatGPT answered yes, adding a slit to a spectrometer is necessary and serves a few crucial purposes. These crucial purposes are 1) Controls spectral resolution (ability of spectrometers to distinguish between wavelengths). 2) Limits stray light and improves accuracy. 3) Controls the optical throughput (signal intensity). 4) Shapes the image of the spectrum. For each list item the LLM gives a paragraph explanation. Then, it answers a question that wasn't in the prompt but is still applicable: Is the slit always necessary? To this it answers that while it is essential in most spectrometers, some of them, such as fiber-optic spectrometers, use other techniques that make a slit unnecessary. ChatGPT then gives a conclusion paragraph wrapping up its thoughts, that a slit is a critical component in most spectrometers. [75]

As we can see ChatGPT gave a very in-depth and long response. It listed multiple reasons to answer my question with explanations under each one. We did not specify a detailed answer, yet it gave one. It explains to us why slits are usually necessary and when they may not be, which is something that wasn't asked. Yet, it knew that it would be helpful information to us based on our question. The information is accurate, and therefore ChatGPT seems like a reliable source to get this information from.

5.4.2 Gemini

Gemini answered that “Yes, slits are generally necessary in spectrometers.” Gemini claims that they serve a crucial function in controlling the light entering the instrument and determining the resolution of the spectrum, a similar answer to ChatGPT. It then goes on to tell us the primary function of slits with 3 main bullet points followed by a sentence or two explanation. These points were collimation, resolution enhancement, and intensity control. Again, this is similar, though not as detailed, as the previous LLMs response. Another similarity is that Gemini also gives us the answer to a question that was not asked by explaining entrance and exit slits as types of slits. Gemini seemed to assume that this information is in some way relevant, and while it is, it did not help answer the question and was unnecessary. Then, the LLM gives a quick summary explaining what was said. [76]

While not as long, Gemini also gave an in depth response. The few sentences were adequate in answering the prompt while ChatGPT’s paragraphs were perhaps a bit too long. Same as ChatGPT, the information seems accurate. It also almost has the same structure, which is interesting. The paragraph answer as an introduction, the list of reasons with explanations, and then the concluding paragraph make it seem like these two LLMs were following the same structure. One key difference though is that Gemini stated that slits were necessary with no caveats. On the other hand, we know ChatGPT said slits were often, however not always, necessary. [76] Other than that, it seems that these two LLMs are similar. Therefore, Gemini is also a good source to gain background information from while researching and/or writing a paper.

5.4.3 Copilot

Copilot response was short and can be put in full: Adding a slit to a spectrometer is like putting a spotlight on the main act. It's necessary for increasing the instrument's resolution and precision. By narrowing the slit, you limit the light entering, which helps isolate specific wavelengths more accurately. Think of it as controlling the stream of light, so the spectrometer can do its thing with fewer distractions—resulting in clearer, sharper data. [77]

Copilot responded in an interesting manner. In contrast to the last two LLMs that were very lengthy and scientific in response, Copilot gave a short, simple response full of analogies. For our purposes, this is not what we want. The analogies given were confusing. The detail was minimal. Perhaps for a quick answer - yes or no - this response would be good. However, for writing a paper and doing research, Copilot does not seem like the way to go.

5.5 Example 5

We will now ask the LLMs about fresnel lenses for light collection. The prompt will be: “How do fresnel lenses compare to collector lenses? Which is more efficient?”

5.5.1 ChatGPT

ChatGPT’s response stated that both fresnel lenses and collector lenses serve similar purposes. This is collecting, focusing, and directing light. But they differ in design, performance, and efficiency. The LLM then goes on to list the design and structure, optical efficiency, and applications of both fresnel lenses and collector lenses. For each section and each lens it gives two or three sentences and then ends with a paragraph conclusion. Essentially, ChatGPT answered that “fresnel lenses are more efficient for large-area light collection while collector lenses are more efficient when optical precision and minimal aberration are essential”. [75]

Once again ChatGPT gave a very long, though detailed and accurate, explanation. The structure of the response goes into depth answering our questions. This is good for an in-depth answer, however not for getting a quick answer for background research. ChatGPT also did not directly answer the question, but instead gave benefits to both. Therefore using ChatGPT would depend on what you are aiming to do.

5.5.2 Gemini

Gemini compared the lenses by listing the structure, efficiency, and applications. It gave about two sentences for each parameter for each lens. The explanations were similar to ChatGPT’s, however Gemini gave a direct answer, that fresnel lenses are considered more effective. [76]

Gemini’s response differed in structure from ChatGPT’s due to it listing the lenses first and then the parameters (structure, efficiency, applications) under each lens. ChatGPT instead listed the parameters and then explained how they differed for each lens under them. In a comparative explanation, I believe ChatGPT’s structure is more beneficial and easier to read. However, Gemini’s explanation overall is a bit more short and to the point than ChatGPT’s which makes it faster to get the answer we are looking for.

5.5.3 Copilot

Copilot’s response, like the previous two LLMs, listed the design, applications, and efficiency of both lenses. Copilot provided about a sentence each for these items.

In contrast to the previous example, Copilot gave a lengthy and descriptive comparison. The response is comparable to Gemini’s, with both lenses listed and

their design, applications, and efficiency being explained. Another thing to note is that Copilot had references (links to websites where the information is from) at the end of its sentences. This is very interesting and something that I have not seen ChatGPT or Gemini do. It is very beneficial to have these sources and to be able to quickly fact-check the LLM. It makes doing background research a lot more efficient. [77]

One con about Copilot's response is the repetitiveness. The fact that fresnel lenses are more suited towards "light-gathering" while collector lenses are more suited towards "solar applications" seems repeated multiple times. The response definitely could have been summarized a bit more efficiently to avoid those repetitions. Also, the response never distinctly answered which lens was more efficient, like ChatGPT's response. However, it seems to claim that they are both efficient in their own ways, so perhaps their answer is a more well-rounded one anyways. [77] Other than those issues, it seems that Copilot gave a solid response.

5.6 LLM Conclusion

Overall, there are many different pros and cons to the different LLMs. For a more conversational approach, ChatGPT was definitely the way to go. However its lack of citations and its verbosity were large downsides. Copilot was the least verbose in its responses, almost to a fault. There were moments where it would have been beneficial if things were elaborated a bit more. Unlike ChatGPT, it did provide its sources. Gemini was probably the best option, as it struck a delicate balance between being conversational and being good for research. It was more concise than ChatGPT, but it also provided citations and even admitted when it had no sources for things it was claiming. It was verbose enough that there was enough detail, but concise enough that it wasn't overwhelming.

As for the information given by all the LLMs, it's clear that they are great research tools. They help reduce the burden of jumping from website to website trying to find information, and most of the information given can be found to be true. Still it is still vital to double check claims. That is why it is so great that Gemini and Copilot provide sources. In conclusion, the LLMs would best be used as initial "consultants" that gave good initial indications of what the answers should look like. From there, it is best to find corroborating sources and evidence.

6. Hardware Design

6.1 Selecting the CAD software

We researched the main CAD software to design our PCB. Fortunately there are many out there but the ones that really caught our attention and we gave them a try were OrCAD/Allegro, Altium Designer , and EAGLE.

EAGLE: The main advantage of Eagle is that it is provided by UCF and it is the Software that we used in Senior Design 1, it has simple schematic and PCB implementation but it does not provide a detailed good rule setting system , also is missing some simulation capabilities and has technical constraint at the time to design. Teaching support on the web is not bad but it is not better than other tools.

OrCAD/Allegro: OrCAD//Allegro is a really advanced software that provides many tools while designing the PCB and schematic but it's not easy to link them since they work on different programs. It is not provided by UCF but there is a 6 month free deal for students and 30 hours for the really advanced allegro. There is teaching support on the web enough to understand the basics but it becomes a little hard to try to use more advanced features. We have not used it before which will make us spend a long time just learning how to use the tool without even starting designing.

Altium Designer: is also an advanced software that provides a really good set of rules. The tools for designing PCB and Schematic are advanced and it is easy to link since they operate under the same software just using different windows. It is not provided by UCF but there is a free deal for students for 1 year full access to all its capabilities. There is much support on the web with the whole series and the Altium Academic channel that make everything accessible and understandable. We have used it before at work and we have experience with the tool.

Conclusion: Since Altium is Advanced, it provides a good set of rules and tools that Eagle does not have. We have experience on using it more than Eagle where we had used it for just a little period of time during senior design 1 and more than OrCAD that we have never used. Implementation of schematic and PCB is easy, there are plenty of sources where we can learn from and their youtube channel is really good at teaching. The only disadvantage that it has is that it is too expensive but with the student deal it allows us to use it for free for one year while OrCAD that it is only for 6 months, we can lose access before the end of senior design 2.

This is clear that the CAD software that feels this project the most is Altium Designer and it is the one we are choosing for the PCB design.

6.2 Power Structure

6.2.1 Power Supply Structure 1

This product will have 3 different power supplies which will allow the device to work properly in different situations. Only one will provide power if more than one supplier is being used. It will follow the logic structure in picture *Figure 6.2.1*.

We will have AC/DC Voltage, Battery and USB. Direct input voltage is the highest hierarchy, if it is in the other suppliers will be in open circuit and they will not provide power to the system. Second is the Battery and the last is the USB port. This is to make sure that the device can work for unlimited time if connected to a standard AC 110V source. It also can work for a limited time by a battery without the need of a standard AC 110V source. And it can work through USB connections for technical and troubleshooting reasons

AC/DC Voltage:

It will be 12 volts provided by a transformer, in amazon or Walmart there are many and we will use connector PJ-002BH. This connector will be used because it can hold 24VDC and support 5A, which is enough for our application. Also, its datasheet, footprint and schematic are easily accessible.

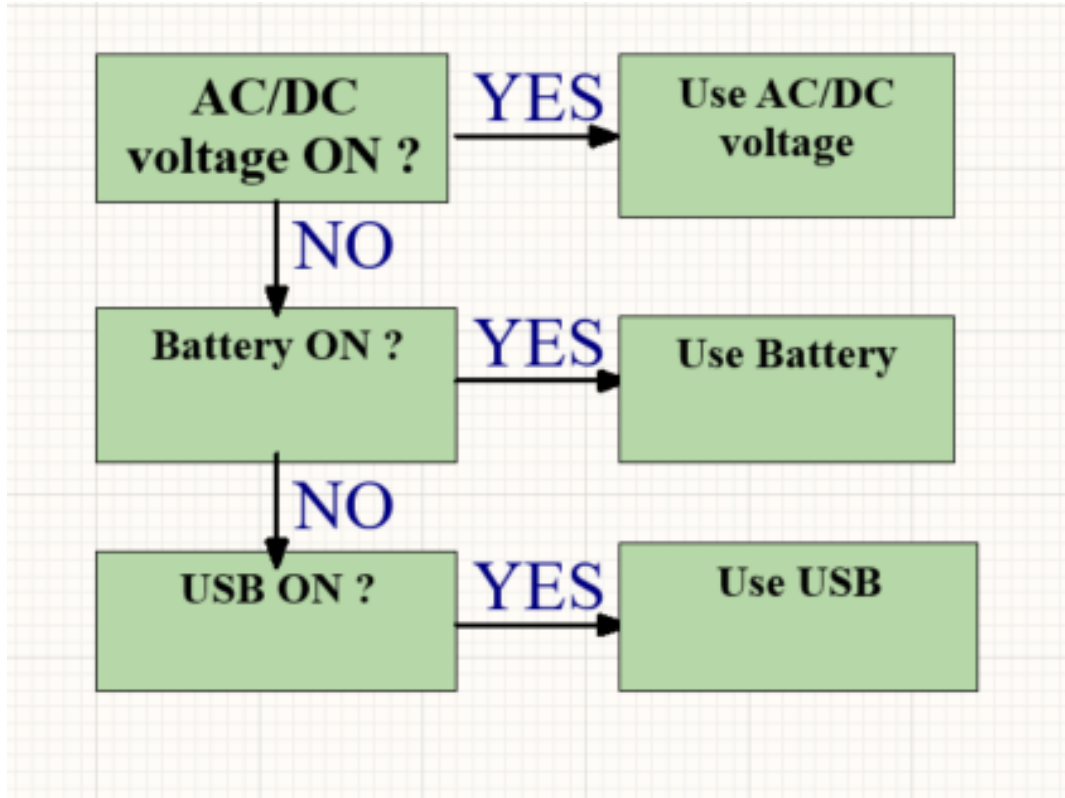
Battery:

The battery will be a standard 9V that will be used as a supporter of a BC9VPC. This connector will be used because its footprint is SMT and that provides better mechanical features.

USB Type B:

A USB Type B connector (2169900002) will be used on the board. We decided to use USB to program the microcontroller ESP32 because we are very familiar with ESP32 development boards, and its USB provides 5 volts that can be used through a voltage regulator to originate the 3.3V that the microcontroller needs. Also, USB is one of the most common interfaces and providing support through it will make the product more feasible.

Figure 6.2.1: Power Supply structure 1 logic block diagram



6.2.2 Power Supply Structure 2

This product will have 2 different sources of power which will allow the device to work properly in different situations. We will call it the programmable mode and the functional mode. It cannot be on both modes at the same time and the modes will be chosen through a mechanical switch.

Programmable mode:

This mode is implemented in order to program the device. When it is in this mode the power supply to the device will be through USB line (5V) and a RED LED will be on. The device should be completely functional. We will use Battery explained above.

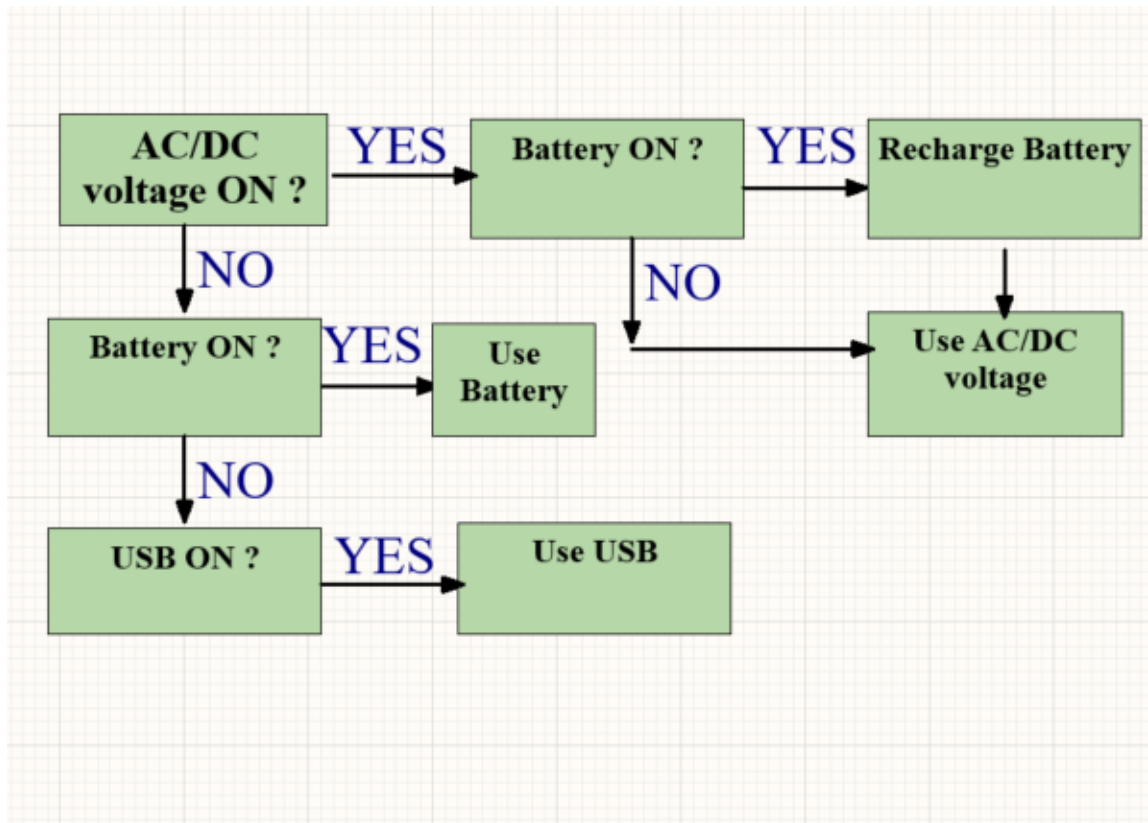
Functional mode:

This mode is implemented in order to use the battery power from the device (9V) and a GREEN LED will be on. The device should be completely functional. We will use USB Type C explained above.

6.2.3 Power Supply Structure 3:

This product will have 3 different power supplies which will allow the device to work properly in different situations. Only one will provide power if more than one supplier is being used. It will follow the logic structure in picture *Figure 6.2.3*. We will have AC/DC Voltage, Battery and USB. This will consist in 2 modes functional and programmable that can be chosen by a mechanical switch.

Figure 6.2.3: Power Supply structure 3 logic block diagram



Functional mode:

This mode is implemented in order to use the battery power from the device (9V) or the AC/DC connector. If there is a battery and AC/DC connector both connected, the battery will be charged and the power will be provided by the AC/DC source, if there is only one of them the circuit will work depending on the connected source and a GREEN LED will be on. We will use LTC4412 because it has a wide range for voltage in and for batteries capacities and also provides all the circuit logic, we will need to add a couple of extra electrical component. The device should be completely functional.

Programmable mode:

Same as explained in power structure 2.

Conclusion:

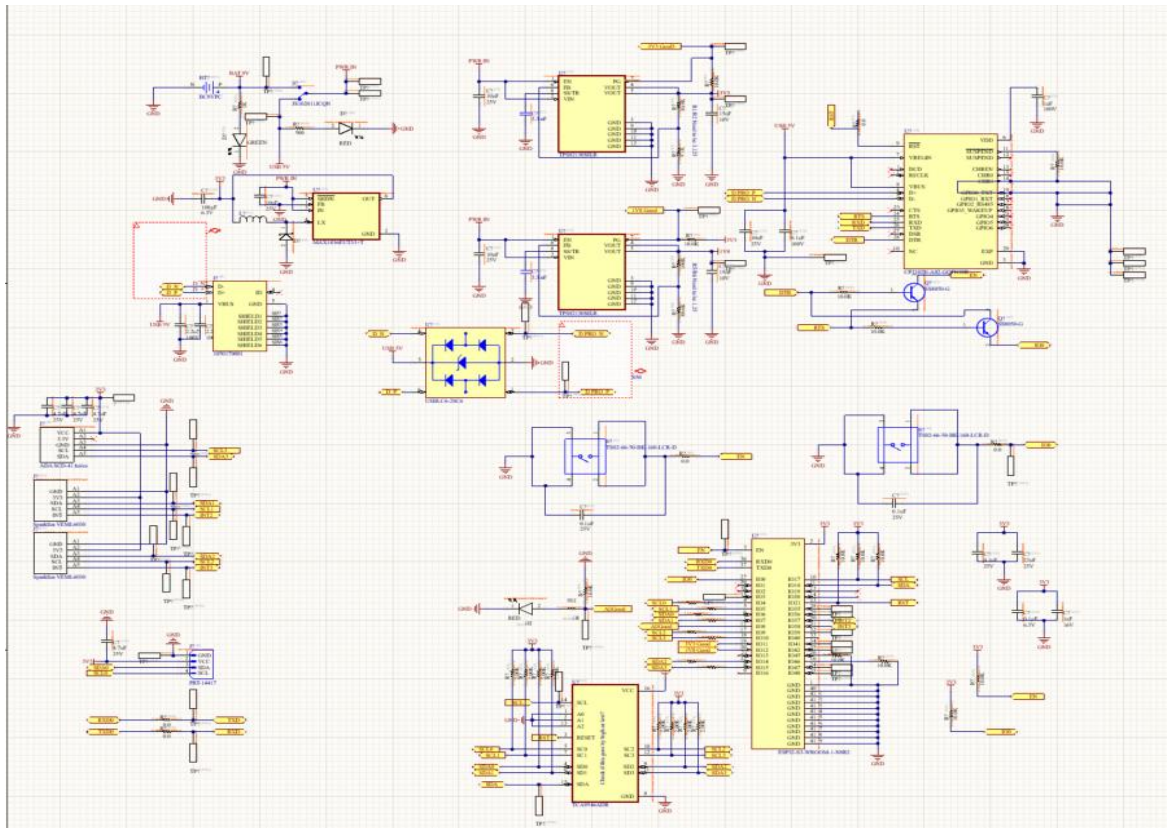
The preferable power structure is number 3 which is a mix of number 2 and number 1. It is capable of providing 3 different power sources and able to recharge the battery. This will be easy to sell in the market. But it is complicated to implement and most costly, it will also take more time while number 2 can be implemented in 30 minutes; 3 will take around 10 hours. Depending on the peace of Senior Design 2 we will consider. Number one we will keep it as a draft since it is really hard to implement without a mechanical switch and only by electric logic, but it can be another project in the future since I found that there is not an IC capable of multiplexing 3 input voltages without a voltage supply. For now we think number 2 is the right option.

Implementing Power Supply Structure 2:

Depending on the mode established by a mechanical switch the board will receive its main power supply PWR IN (9V or 5V). PWR IN will be stepped down by two voltage regulators to provide 3V3 which will be used by the microcontroller and peripherals and 1V8 which will be used for other peripherals.

6.3 Schematic Explanation

Figure 6.3: Overall Schematic



6.3.1 Power Sources and Mechanical Switch

As stated before this device will use two power sources: a 9 volts battery that will be held by a 9V battery holder *BC9VPC* capable of providing 500 to 600 mAh and the USB VBUS which can provide a constant 5 Volt. The use of these sources will be selected by the user depending on which mode he needs the device to be, programmable or functional. This will be accessible by a switch *JS102011JCQN* [82] which can provide contact rating of 0.3 A at 6 VDC or 0.1 A at 30 VDC, with an electrical life of 5,000 make-and-break cycles. It features a maximum contact resistance of 70 mΩ and a minimum insulation resistance of 100 MΩ at 500 V. This works in our application since our major IC draws a maximum of 240mA if using full wifi and bluetooth capacity which will not be used, and has less than 10uA at sleep mode. If the battery is on the device will light a green *LED HSMG-C197* which DC forward current is rated at 20 mA, which should be derated linearly for temperatures above 25°C. The maximum power dissipation is 65 mW, with a reverse voltage rating of 5 V at 100 μA. The LED junction temperature should not exceed 95°C. It operates within a temperature range of -40°C to +85°C and can be stored in the same temperature range. We placed a 1kohm resistor for reducing the current going through the diode to 9mV and 5mV depending on the source which is less than the 20mA maximum. For the USB there is a *RED LED HSMS-C197* [83] surfainstead of green so it will be easy to debug. Each diode is then connected to ground. Then the switch will select the power source and that source will become PWR IN.

Equation 6.3.1: Current Through the Diode

$$\begin{aligned} & PWR/1k \\ \text{Battery: } & 9V/1K = 9mA \\ \text{USB: } & 5V/1K = 1mA \end{aligned}$$

The consumption in the standby mode by the major ICs:

Equation 6.3.2: Consumption while standby mode

$$\begin{aligned} & 2 \times V_{rQ} + ESP32_{SM} + 4 \times (Sensors_{SM}) + I2C_{SM} \\ & = 2 \times 20 + 10 + 4 \times 2.3 + 1.3 \mu A \\ & = 60.5 \mu A \end{aligned}$$

Assuming all small components consume 10 uA in the standby mode the device will consume 70.5uA.

Equation 6.3.3: Hours of battery life in standby mode

$$\text{Battery } mA H / SM \text{ consumption} = 500 / 0.0605 = 8264 \text{ hours}$$

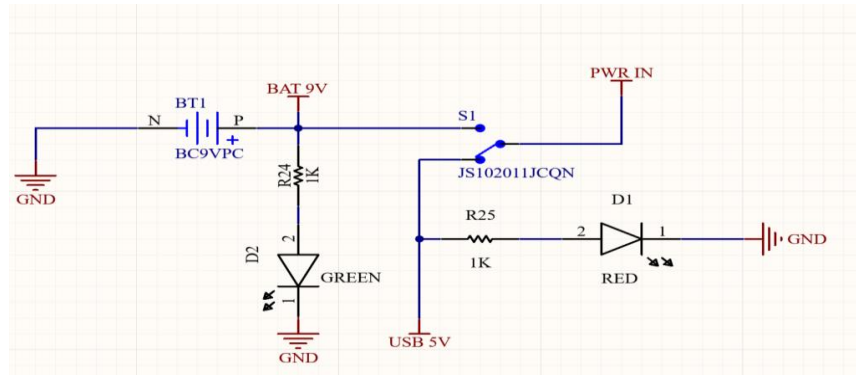
Equation 6.3.4: Consumption while active mode:

$$2 \times V_{rQ} + ESP32 \text{ AM} + 4 \times (\text{SensorsAM}) + I2C \text{ AM} \\ = 2 \times 0.02 + 150\text{mA} + 0.0023 \times 4 + 0.02 = 150.1\text{mA}$$

Equation 6.3.4: Hours of battery life in active mode

$$\text{Battery mA}H / \text{AM consumption} = 600 / 150.1 = 4 \text{ hours}$$

Figure 6.3.1: Battery and switch schematic



6.3.2 Voltage Regulators

The PWR IN reels which will be the source selected will go to pin 1 EN of the voltage regulator TPS821309 MicroSiP package [84], measuring 3 mm × 2.8 mm × 1.5 mm, supports an input voltage range of 3 V to 17 V and delivers a continuous output current of 3 A. Featuring DCS-Control topology and a power save mode for enhanced efficiency under light loads, it has a low quiescent current of 20 μA. The output voltage is adjustable from 0.9 V to 6 V, with a 100% duty cycle ensuring minimal dropout. Additional features include a power-good output, programmable soft start-up with tracking, thermal shutdown protection, and an operating temperature range of −40°C to 125°C. Between PWR IN and ground will be a 10uF capacitor for and between Vout and GND will be a 22uF capacitor as recommended by the datasheet “for the best output and input voltage filtering, low-ESR ceramic capacitors are required. The input capacitor minimizes input voltage ripple, suppresses input voltage spikes, and provides a stable system rail for the device. A 10-μF or larger input capacitor is required. The output capacitor value can range from 22 μF up to more than 400 μF. Higher values are possible as well and can be evaluated through the transient response. TI recommends larger soft start times for higher output capacitances. High capacitance ceramic capacitors have a DC bias effect, which have a strong influence on the final effective capacitance. Therefore the right capacitor value has to be chosen carefully. Package size and voltage rating in combination with dielectric material

are responsible for differences between the rated capacitor value and the effective capacitance. “ Between FB and Vout we have R1 and R5 respectively and between FB and GND there are R2 and R6, these resistor set Vout as explained below:

Equation 6.3.2 Calculation of Vout

$$V_{OUT} = V_{FB} \times \left(1 + \frac{R1}{R2} \right) = 0.8 \text{ V} \times \left(1 + \frac{R1}{R2} \right)$$

FOR 3V3

$$V_{out} = 3.3\text{V}; V_{fb} = 0.8\text{V}$$

$$R1/R2 = V_{out}/V_{fb} - 1$$

$$R1/R2 = 3.3/0.8 - 1 = 3.125$$

Ideal: R1=31.25Kohm ; R2=10Kohm

Real R1=30.9Kohm ; R2=9.1Kohm.

FOR 1V8

$$V_{out} = 1.8\text{V}; V_{fb} = 0.8\text{V}$$

$$R1/R2 = V_{out}/V_{fb} - 1$$

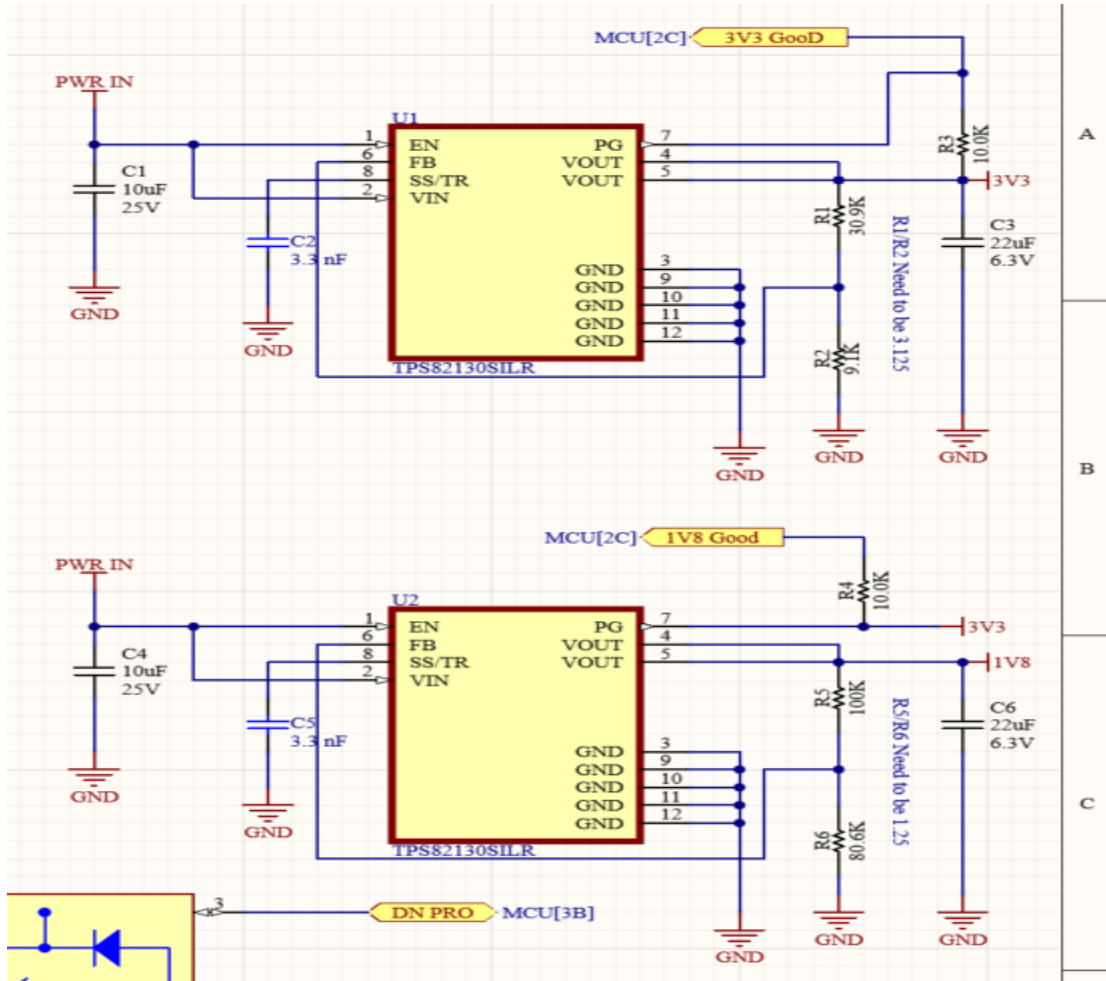
$$R1/R2 = 1.8/0.8 - 1 = 1.25$$

Ideal: R1=12.5Kohm ; R2=10Kohm

Real R1=100k Ohm ; R2=80.6Kohm

Vin is also connected to the PWR IN pin which works as the VCC of the VR. SS/TR pin is set as recommended in the data sheet typical application since we do not have a turn on sequence for the microcontroller or other main ICs. In case we need to set up a sequence we can vary these capacitors. The PGOOD signals on both VRs will be used for the microcontroller to implement some logic and for testing objectives. We may have to inverse the signal, not explore that yet. The PGOOD are pulled up by a 10K resistor to avoid high current and the 3.3V source. Vout will be 1.8V for some peripheral and 3.3V for the microcontroller.

Figure 6.3.2.1: Voltage Regulator



Voltage regulator comparison

Voltage regulator technology	Efficiency	Noise	Heat disipation	Power Conservation
Switching	80%to 95%	EMI noise. Our application is low speed	Do not need heatsing or any mechanical solution	Good power conservation. Suitable for batteries supplied circuits
Linear	40% to 60%	Low noise.	Need Heatsink.	Lower switching than regulators.

We chose the switching regulator because it is the best technology for our application. It provides high efficiency, which is important for the MCU, and it also has good power conservation, which is perfect since we are using a battery. However, the linear regulator provides low noise, but our device will be working at low frequencies and interferences, which will not be a problem. And finally for linear regulator we might have to implement heatsink and since we do not have any mechanical engineer, we decided to avoid this. For all these reasons we decided to use switching regulators. Here below is a more in-depth comparison.

TLV700 series:

This was the first one we took a look on because it is easy to implement, highly efficient, low cost and small size but was discarded because its input voltage is in a range which will not fit our battery application which provides 9 volts. We can use it for other peripherals and not for the main application.[85]

LD29150DT18R :

This is also a fixed voltage regulator which provides 1.5A and works up to 30V vin. STMicroelectronics also has a configurable Vout version. It is small and efficient in our design. But we need to choose different part numbers for each of the series since they are fixed output voltage.[86]

LMS1585A:

This is also a fixed voltage regulator which provides from 3A to 5A, which may be good but may be too much for our application and works up to 13V vin. They have adjustable modules and fixed ones that provide only 1.5V or 3.3V.[87]

LTM4623:

This is an adjustable voltage regulator that can set up Vout in a range of 0.6 to 5.5V and accept Vin from 4 to 20V which really matches our application. Also it has Power Good indicator and CLKin and CLKout logic implementation which can help us with many different configurations in our application. We can also control rise time by hardware, It provides 3A which may be too much for our circuit and it is a little big.[88]LTM

TPS82130:

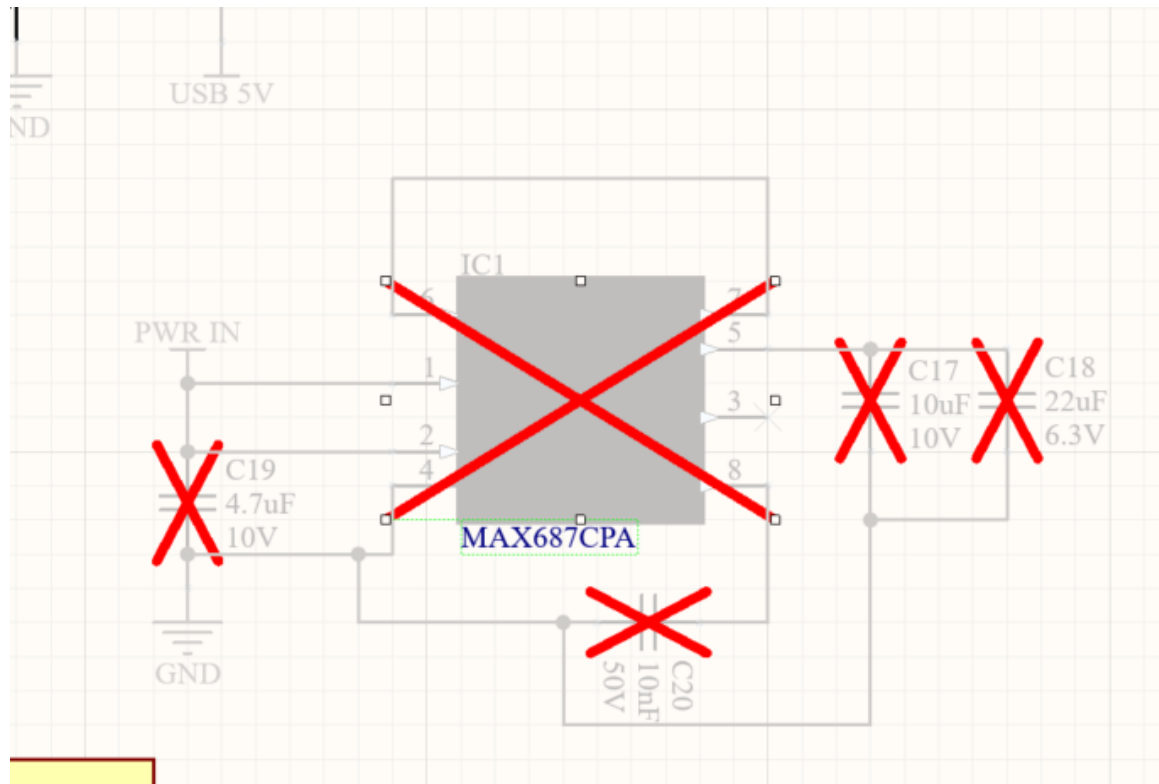
This is an adjustable voltage regulator that can set up Vout in a range of 0.9 to 6V and accept Vin from 3 to 17V, which really matches our application. We can control rise time by hardware. It provides 3A that may be too much. It has a 100% duty cycle for lowest dropout and Power Good output. And I have used it before for other designs.

Conclusion:

The preferable power supply is TPS82130. It has a perfect V_{in} range and V_{out} range as LTM462 and 3LD29150DT18R. It is better than 3LD29150DT18R because we do not have to choose different part number and getting fix V_{out} , 3LD29150DT18R does not provide PGOOD capabilities and controllable rise time, however 3LD29150DT18R has a lower current output to the load which may be better for us. TPS82130 also overpass LTM462 because is smaller and has a 100% duty cycle for lowest dropout as we I have used it on other designs. For now we have decided to use TPS82130.

However since it is a really small chip and can be difficult to troubleshoot we will have a do not place component for troubleshooting , in case the voltage regulators are not providing the expected voltage we can solder down a MAX687CPA MAX [89].

Figure 6.3.2.2: MAX687CPA troubleshooting option



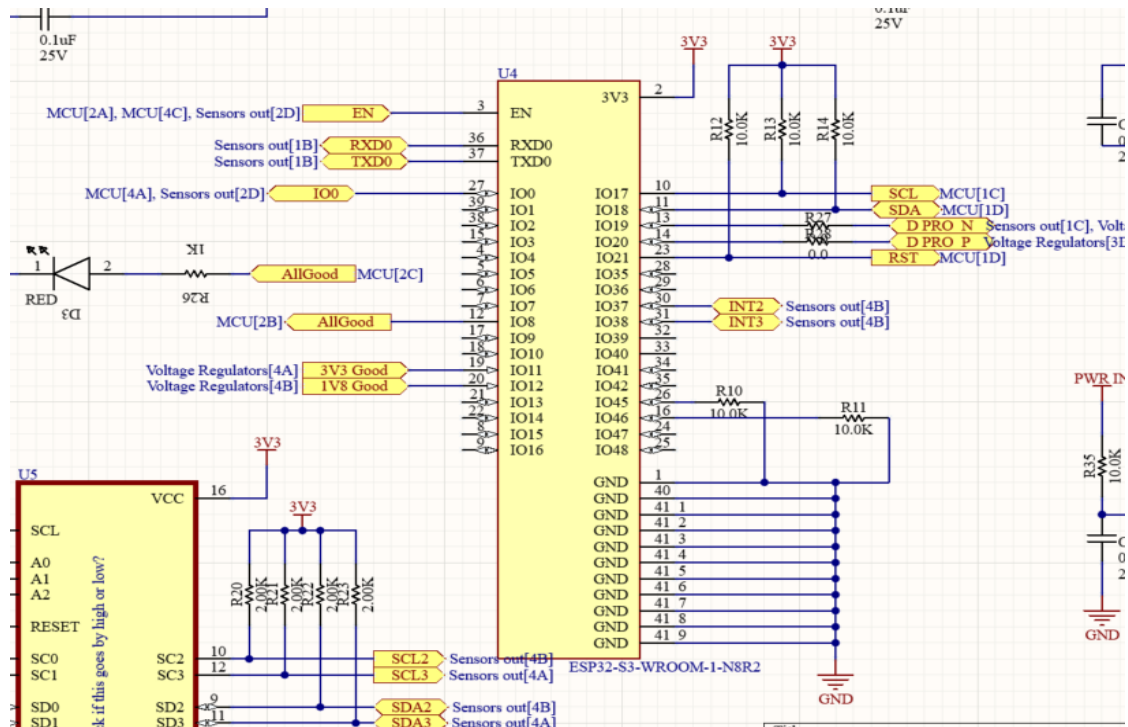
6.3.3 The USB Connector and ESD Protection

USB schematic:

We used the connector USB4510-03-1-A_REVA to implement our USB port. This will allow us to program the microcontroller from a computer or any device with a USB port. To power up the board we will use the V_{bus} equal to 5V while programming. As recommended by the datasheet and reference design we pull

Microcontroller will be enabled by PWR_IN, any source available either battery or the USB connection. And will receive 3.3V from the voltage regulators. We will have both Power Good signals from the Voltage regulators to indicate to the ESP32 that both voltages are working properly in range. We will have the I2C line SCL and SDA on pins 10 and 11 as suggested in the datasheet and will receive the USB communication through pin 14 and 13. We also implement an RST signal to control the reset of the I2C multiplexer. And added 2 signals INT2 and INT3 for extra communication with the sensors. We will implement a signal call All good that will light up a LED if the microcontroller is receiving everything it should.

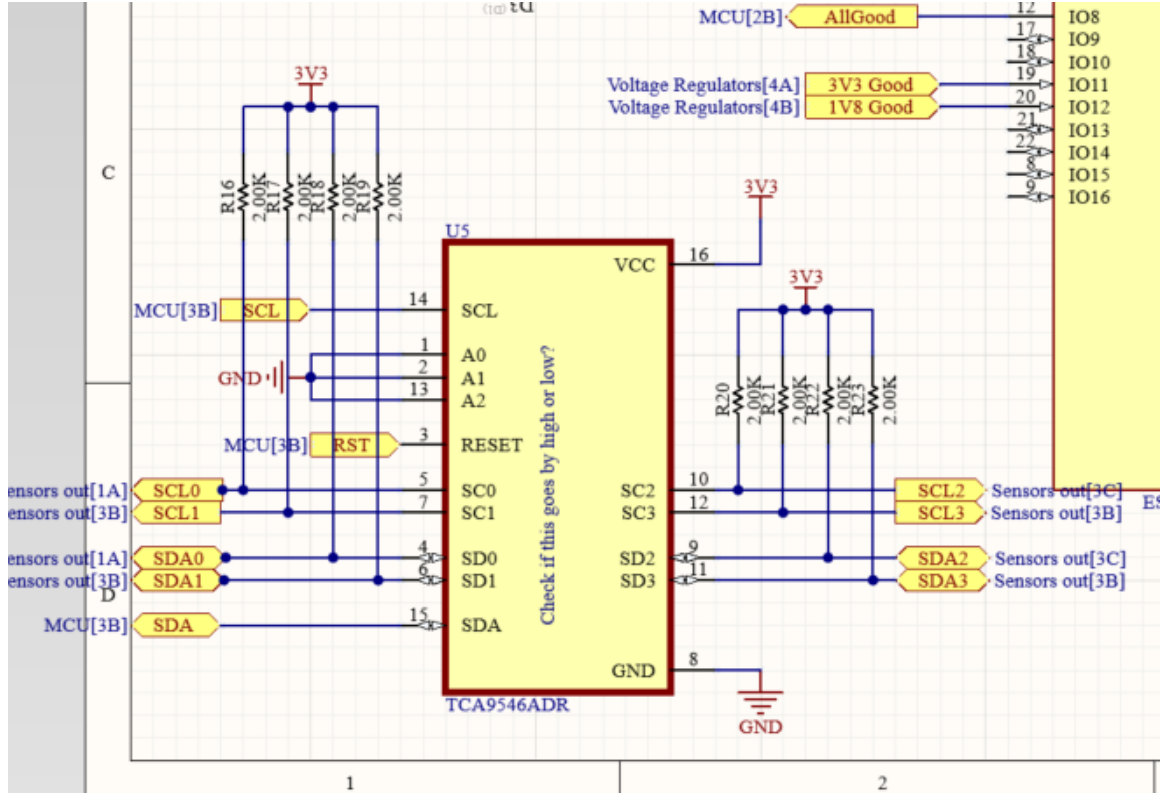
Figure 6.3.4.2: Microcontroller



6.3.5 I2C Multiplexer

Since we are going to use the same sensor 3 times we faced a problem with the I2C protocol, those 3 sensors will have the same address. As a solution we decided to implement an I2C multiplexer. It will receive the main I2C signal from the microcontroller and then splitted to 4 I2C lines all of them with their own clock which will go through each sensor. All these lines have to be pulled high since I2C is open drain and we use 3.3V same as the microcontroller. We also have the RST signal that we will be good to use for controlling this IC. [91]

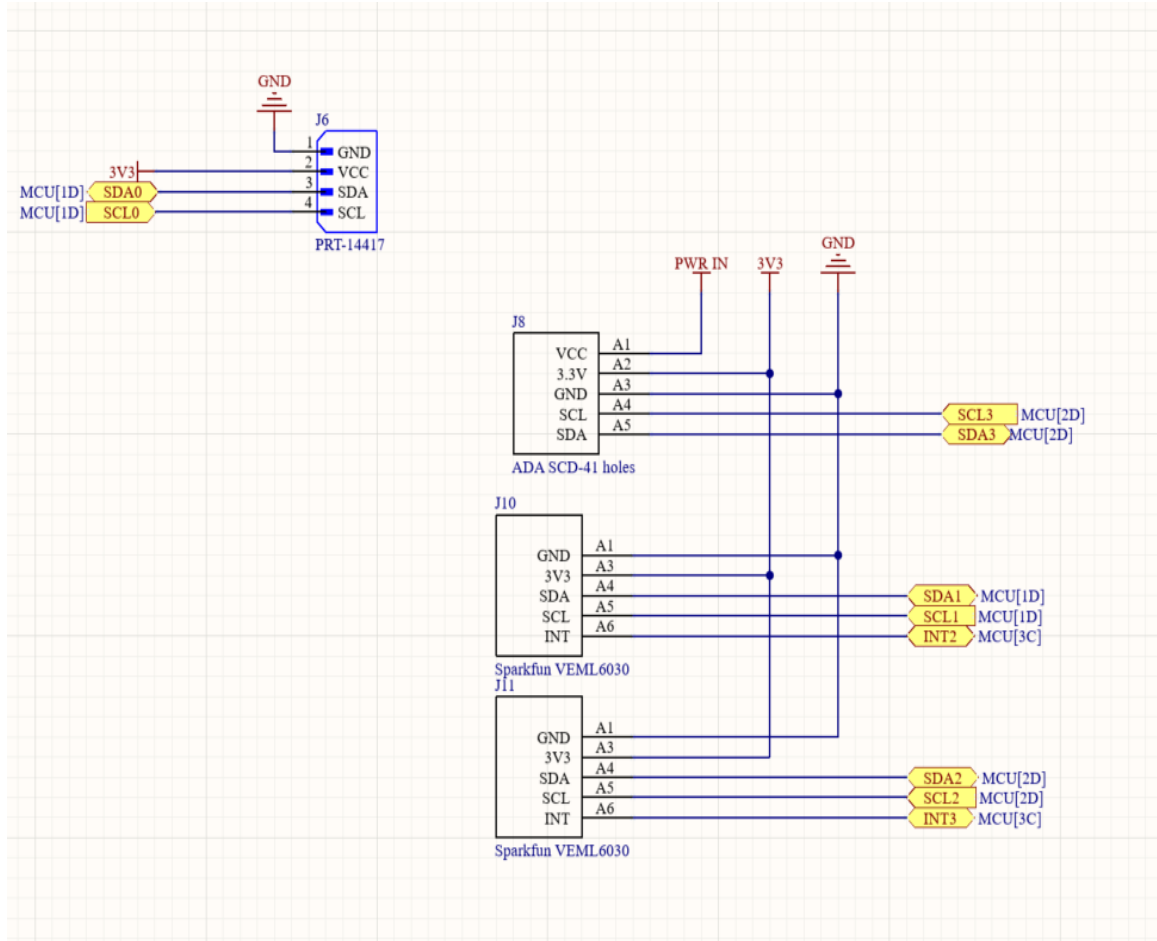
Figure 6.3.5: I2C Multiplexer



6.3.6 Sensors

Sensors will be soldered into the main PCB so I created schematic symbols for them that will be on the PCB only as through holes where we can solder the sensors. I follow sensor footprints to make it compilable. They will have GND,3v3,SDA,SCL and INT. We will also be adding a single connector just for troubleshooting.

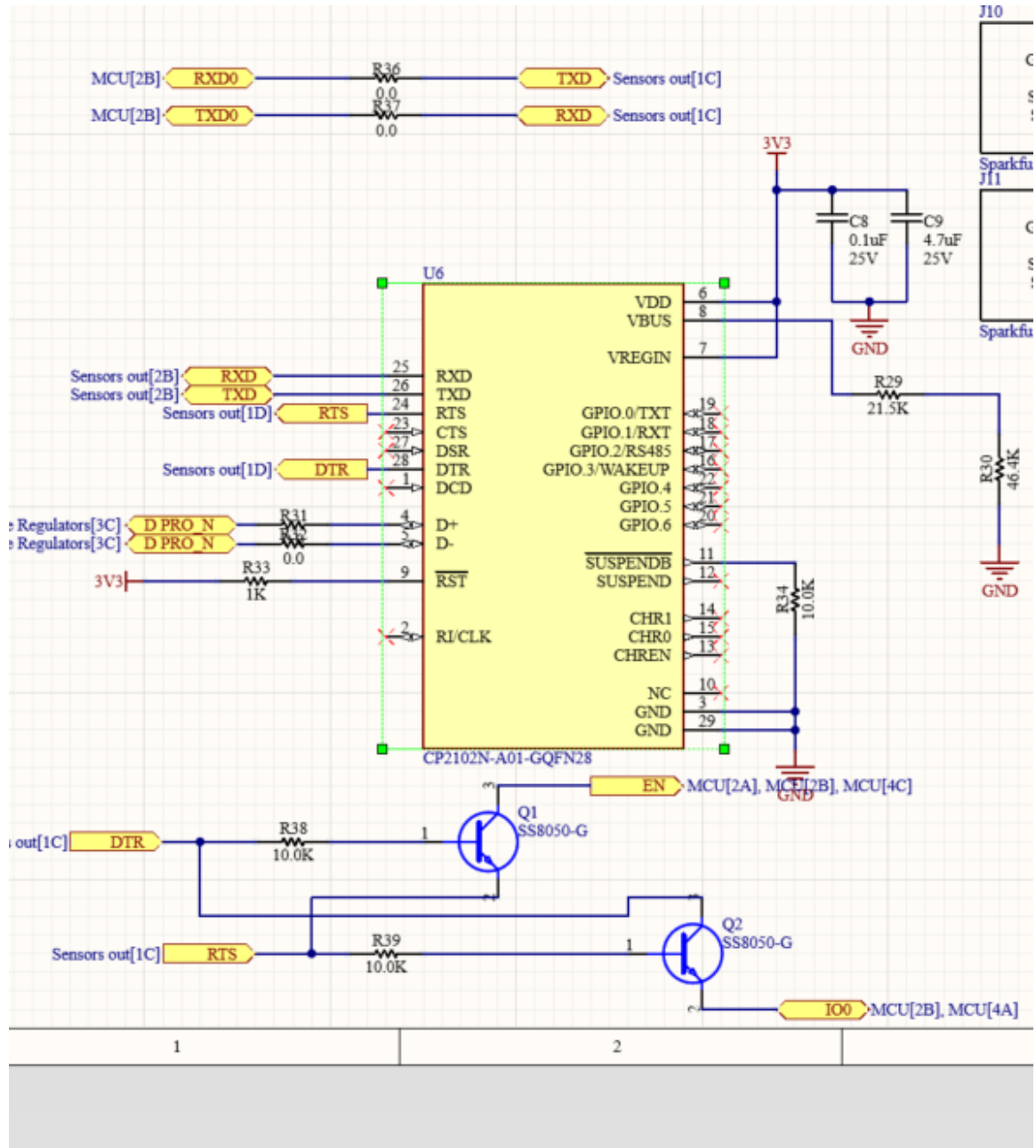
Figure 6.3.6 Holes for sensors



6.3.7 USB to UART Bridge:

The ESP32 has to be programmed through UART. To accomplish this we had to implement a USB to UART translator, we used the same suggested in the DevKit provided by professor Weeks CP2102N-A01-GQFN28. Here we connected the diff pair from usb D+ and D- to pin 4 and 5 and then submitted UART signals RXD and TXD to the microcontroller. We also provide logic protection and states for EN and IO0 pins in the microcontroller. We are not using batteries or clock capacities on this chip and set up Vbus as a variant version. [92]

Figure 6.3.7: USB to UART



It is important to specify that the test points are not present on the schematic picture provided but we have plenty of them in almost every signal/pin for troubleshooting.

6.3.8 Capacitors and Resistor selection

We selected a capacitor basing us in the voltage they will be on it. If they are at 3.3V we choose a capacitor of 10V which is more than twice higher than the

maximum voltage in the reel. We try to select the biggest size but since we are using a texas instruments voltage regulator we prefer to select small footprints and make sure they are close to the voltage pin for proper decoupling.

The resistor selection was highly based on their temperature rating and their tolerance. Also the size was considered but since we are not building our PCB for ourselves only troubleshooting it we agreed that 402 footprints are not wrong in specific parts. We tried to use 0805 as much as we could.

6.4 Zemax Design

When it comes to designing the optical portion of the project, there are two ways to approach it. The first way is to physically buy components and test them directly in the lab. This way is convenient because it means directly seeing how the optics will behave in real life. There is no guesswork or approximation here, there is purely observing. The downside of this approach is that the optics need to be physically bought. Before you do this, you'd need to ensure that your calculations are exact and that you are sure of the components you want to use. Otherwise, you'd be spending a lot of money, only to realize that the components you bought aren't working.

The other approach is to simulate the optics. While this approach is not as precise as real life, it is very useful, if you know what you are doing. Simulating optics is free, and you are free to change components as you please. As such, you don't have to worry about needlessly spending money. This approach is more feasible for our project, and makes more sense overall, as money is the biggest personal constraint for all of us. To simulate the optical design, we will use Zemax.

6.4.1 Design #1

When it comes to designing the optical setup and ray-tracing of the lenses, we had to ensure that sufficient ambient light was collected by the first lens. For this reason, we needed to choose a lens with a sufficient diameter. We decided to start the design by incorporating a 50 mm diameter lens with a focal length of 100 mm, which makes it an $f/2$ lens. This lens would take in the incoming collimated light and focus it to a point. From this point, we decided to use a 10mm diameter $f/2$ lens to pick up the light and recollimate it. This came with a cost, as some of the light was lost. We thought it might be worth the sacrifice, as having 50 mm lenses throughout the system would be hard to mount all the way through and they are much more expensive. However, we still kept this option open.

Now that the light was collimated, but some of the light was vignetted, we placed a plate beam splitter into the design. It did matter much how far away from the (mostly) collimated source we placed it, as ideally the light would travel in a straight line. There were some issues with getting the beam splitter to work, as

even though the surface was prescribed a mirror material, the light was still going through. It was discovered that a negative thickness was needed to get the light to be reflected, which matches up with conventional optics coordinates.

Still, there was an issue with getting the transmitted light to go through. Since we are using Zemax in sequential mode, the rays follow a single optical path, and therefore can't be split, like a beamsplitter would do. However, there is a feature that allows for multiple configurations to be set, which allows for different optical paths to be defined. Using these paths, and changing the material seen on that path (as the mirror is just a coating), we were able to show both the transmitted and reflected beams.

Now that we had both paths that the beam takes, we used the first configuration to place a focusing lens above the beam splitter. Since the light was collimated, we theoretically could place the focusing lens anywhere in the ray path to be picked up by the focusing lens. We used the same collimating lens as the focusing lens. With this lens, we focused onto a 0.5mm image plane that represented the active area of the light sensor. By deleting the vignetted rays, we could see that only 46% of the light sent into the optical system actually hit the first sensor. This is a big issue, as that doesn't even take into account the light lost at the beam splitter interface, or the light reflected off the optical materials themselves.

Now that we had the transmitted light, we had to choose between using a dichroic filter or purely capturing the blue and red light with lenses, while ignoring the green. With the advice given during the midterm demo, we chose to model the optical setup without the dichroic filter to see if it could be done. We set the diffraction grating to 1.800 lines/ μm and to show the first mode. Doing this part of the design took much trial and error, as Zemax did not want to diffract the beams when we placed the diffraction grating at 45 degrees. It turned out that all we had to do was rotate the diffraction grating by 45 degrees in the other direction. Since we are planning on using a reflective grating, we set the thickness to a negative value.

Now that we had the rays diffracting, we had to create new image surfaces for each of these diffracted beams. Unfortunately, Zemax does not allow for more than one image plane in sequential mode, so new surfaces had to be created in the paths of each of these ray bundles with coordinate breaks and multiple configurations. The resulting design had the red and blue rays focusing onto the sensor, which is what we wanted.

6.4.2 Design #2

After further consideration, we realized that the intensity focused onto the sensors would be too high if we were to try to focus the light to 0.5mm. For example, calculations shown at the first sensor indicate that the intensity at the white light sensor would reach 1.3×10^{12} lux with an input of 100,000 lux. To redo these calculations, we needed to take into account that the lux that the collimating lens received would be the same, no matter the size of the lens itself. We also needed equations to relate lux after a lens to the lux received on the sensors. The equations are as follows:

Equation 6.4.2.1: Conservation of Lux

$$\text{Lux at lens} \times \text{lens area} = \text{lux at spot} \times \text{spot area}$$

Equation 6.4.2.2: Distance from lens that lux is equal to input

$$\text{Distance from lens} = \text{Spot diameter} / \text{lens diameter}$$

Equation 6.4.2.3: Distance from focus that lux is equal to input

$$\text{Distance from Focus} = \text{Focal length} - \text{Distance from Lens}$$

Using these equations, we determined the component specifications, as seen in section 2.9.2. We were able to simulate the distances and parameters found with these calculations to see if they were accurate.

The distance from the focus wasn't exact, since the focus isn't truly 20 mm from the backside of the lens. The perfect distance was found to be 33 mm from the back of the focusing lens, which is very different from the calculated distance. However, we were able to get 40% of the incoming light through the entire system, which means that 40,000 lux made it to the white light focusing lens. Since we got a spot diameter of 6.4 mm, that means that the intensity seen at the white light sensor is 97,656 lux. This is very close to our expected value.

For the blue and red light sensors, we have to take into account that any intensity that is reported by zemax needs to be split in 3, since the program is not aware that we assume the intensity of light splits in 3 at the diffraction grating. Zemax says that the overall intensity at the blue sensor focusing lens is 37,000 lux, which means that the actual transmitted blue light intensity is about 12,000 lux. The calculated value at the lens was 12,824 lux, which is very close to the simulated value. Moving the lens a distance to where the spot diameter is about 3.6 mm, which is about 9 mm from the focusing lens, we find that the lux value is about

91,257 lux. With the equal light assumption, we can say that the red sensor will have the same values.

6.4.3 Design #3

Now that we know that the calculations we did are very similar to what is found within Zemax, we can do away with some of our assumptions. The first thing we can correct is that the ratio of red, blue, and green light is 33% each. Instead, due to atmospheric absorption, it may be more accurate to assume that the light is 30% blue, 30% green, and 40% red. This is not completely accurate, as conditions change and it is a general estimate, but it is still more accurate than each color sharing the same percentage of the sun's light that reaches the surface of the earth. The second thing we need to account for is the 500 micron slit that goes before the diffraction grating. This slit allows for a better diffraction resolution.

None of the values associated with the white light sensor will change, as the beam splitter ratio has not changed. The biggest thing we have to now consider is that the intensities of light seen at the blue and red sensors will be different from one another, that the beam will no longer be circular, and that the overall intensity of light received at the blue and red sensors will be much lower. Therefore, a smaller incident beam area will be necessary for both.

Initially, when putting the slit exactly between the beam splitter and diffraction grating, the resulting blue light footprint diagram looked biconcave instead of slit-like. We ruled out aberrations, since this was unlike anything we've seen before. After much troubleshooting, changing the diffraction grating ruling, and playing around with the distance between the focusing lens and the sensor, we were able to get the slit shape to completely take form, and we were able to get the width of the pattern to completely cover the width of the sensor.

Determining the intensity read by the sensor is a completely different issue. Unlike with the design that had no slit, the intensity seen at the sensor is not intuitive. This is because now a lot of light is being cut off at the sides, but the light going directly through the slit without diffracting remains at the same intensity (ideally, but diffraction will decrease it).

From looking at the footprint diagram of the blue sensor, it is clear that the height of the beam becomes much taller than the active area of the sensor. Unfortunately, the width of the beam becomes smaller than the .5 mm of the active area of the sensor. While we could increase the sensor distance to compensate for the fact the beam width decreases, this would only lead to a reading less than the actual intensity. While this could all be fixed by

postprocessing, it would be better to increase the size of the slit, change the location of the slit, or to eliminate the slit altogether.

6.4.4 Zemax Design Conclusion

Given that we know that Design #2 will most likely work, we will try this for our final demo this semester. We are not yet certain whether we will have enough space between colors to only catch the light that we need, and it will most likely be better to have a slit somewhere before the focusing lenses to guarantee that we are receiving the specific wavelengths that we want. By increasing the slit to a 1 mm width, the sensor would be entirely covered. Still, it's not certain if this will be necessary, or how the actual intensity will be distributed across the sensor, so we will have to test this as well. For now, Design #2 will be good.

The system will work in sleep mode while using a battery for as long as 8264 hours and it will work in active mode for 4 hours. The strategy to make the best out of these 4 hours and planning the dispositive to work for 1 month without changing battery is to do an automatic update every 15 minutes(assuming it takes 15 seconds, to send the update, it should be less). Also we should implement a code that when the reading from the sensor is bad for the plants it should send an extra update, we can save one active hour for this as well. Which will give the user the ability to check the app at any time and request an update for a maximum of 1 hours during the month which is 240 updates. I think that is enough.

Equation 6.4.5 total minutes can be fully operating per hour

Monthly daytime hours in florida = $13 * 31 = 403$ hours

Active minutes per hour = $403/240 \approx 2$ minutes

7. Software Design

This section provides an overview of the software architecture, detailing the components within the mobile application and the embedded software on the monitoring device. Beginning with the design goals for the dashboard, this section illustrates how users can view real-time metrics for temperature, humidity, CO₂ levels, and light intensity at a glance. Following this, we dive into the data logging and retrieval mechanisms, allowing users to access historical environmental data for tracking and analysis. Subsequent subsections describe the functionality of the alert system, designed to notify users when environmental parameters reach preset thresholds. This is complemented by an explanation of the app's login and account setup, which enhances secure access.

7.1 User Interface (UI)

Our app will be designed for ease of use, ensuring that navigating through the app is intuitive and straightforward. Accessibility is a core priority in our design process, and we are committed to making the app usable for a diverse range of users. We aim to use clear, descriptive text labels alongside visual elements, making each feature's purpose immediately understandable.

Each section of the app will have a defined function to help users efficiently manage greenhouse conditions. Pages such as the login/logout screen and dashboard. Transitions between these sections should feel natural, enhancing the flow of the user experience.

This design approach prioritizes simplicity and usability, helping users quickly grasp the state of their greenhouse. By keeping elements intuitive and organized, the app ensures that greenhouse management remains efficient, focused, and stress-free.

7.2 Signup Page

The Signup Page will provide an easy to use form where new users can create an account by entering essential information such as email, username, password, and a confirmation of their password to avoid entry errors. Once submitted, the entered information (email, username, and password) is stored temporarily in our MongoDB database until the account is verified. A confirmation email is then sent to the user, containing a link to verify the account. Using MongoDB Compass, we can view and manage this process, ensuring secure and organized temporary storage. Upon successful confirmation, the user's information is transferred from the temporary database to a secure, permanent storage table, establishing their account for future access.

7.3 Login Page

The login page is designed to offer a secure and user-friendly login experience. Users can log in by entering their registered email and password, with built-in checks to handle incorrect details and guide users with prompts. A Forgot Password option is available for easy recovery. Upon successful login, credentials are verified against the securely stored data in the permanent MongoDB table, ensuring data integrity and access security. MongoDB Compass allows us to manage and monitor user data effectively, reinforcing robust security and a seamless login process.

7.4 Home Page

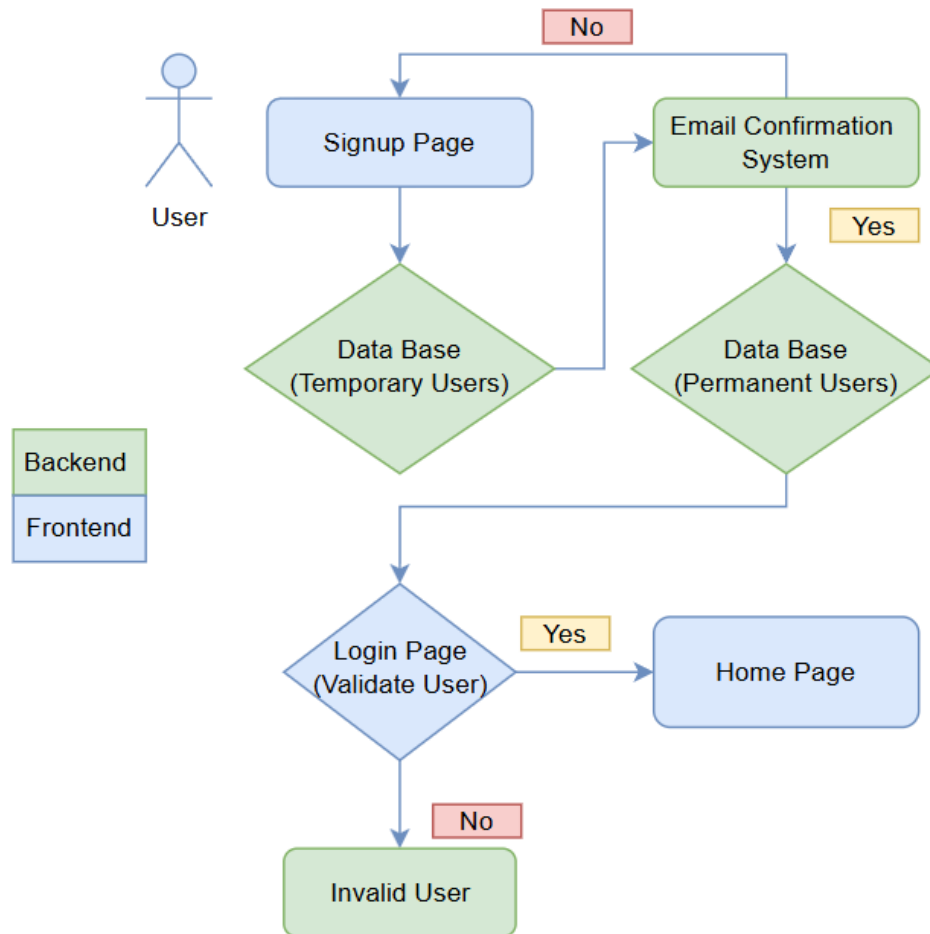
The Home Page serves as the primary dashboard for users, providing an organized and clear overview of key greenhouse metrics, such as temperature, humidity, CO2 levels, and light intensity. Real-time data is displayed in a user-friendly format, allowing users to monitor environmental conditions at a glance. Each metric is updated, ensuring accurate and timely information for effective greenhouse management.

This page also includes quick-access links to other key features, such as the Data History section for reviewing past trends, the Alerts page for notifications on critical conditions, and the Settings menu where users can adjust preferences.

All Data retrieval and interaction with the app's backend will be facilitated through Heroku, which will act as the server, ensuring smooth communication between the app and the MongoDB database. Heroku's platform provides reliable cloud hosting, enabling the app to handle real-time data-updates and user-requests efficiently. The MongoDB database, managed through MongoDB Compass, will store and retrieve user data and greenhouse metrics securely, while Heroku ensures that the server connection remains stable and scalable.

With MongoDB and Heroku working together, the Home Page will offer a seamless user experience, providing up-to-date environmental data while maintaining fast and reliable backend operations. The page is designed to be both visually engaging and highly practical, acting as the central hub for all essential greenhouse monitoring features.

Figure 7.4: Software Diagram showing Sign Up/Login process.



7.5 ESP32-S3-WROOM-1-N8R2

The ESP32-S3-WROOM-1-N8R2 module will be programmed using both the Arduino IDE and the ESP-IDF frameworks. The Arduino IDE will facilitate rapid prototyping and initial code testing, while the ESP-IDF provides access to advanced features optimized for the ESP32 architecture, allowing us to maximize performance in our greenhouse monitoring system.

The program, written in C/C++, will enable the ESP32 module to carry out several critical functions. It will gather data from photonic sensors to monitor environmental factors such as light intensity, temperature, humidity, and CO₂ levels. The module will then transmit this information wirelessly to a mobile application, allowing users to view real-time data. Additionally, as a stretch goal the ESP32 will control various greenhouse devices, such lighting, based on the environmental conditions detected by the sensors. The following sections provide

a detailed overview of the development process for each component and the software functions required for effective integration with the microcontroller. [59]

7.6 ESP32-S3-WROOM-1-N8R2 and Server Connection

To connect my ESP32-S3-WROOM-1-N8R2 to a Heroku server, the first step will be to set up a server-side application on Heroku to handle requests from my ESP32 device. Once the server application is created, I will deploy it to Heroku by initializing a Git repository, committing the code, and pushing it to Heroku's remote repository. After deployment, I will receive a Heroku URL which will serve as the endpoint where my ESP32 will send data.

Next, we will program the ESP32 to connect to a Wi-Fi network and send HTTP POST requests to the Heroku server using the WiFi.h and HTTPClient.h libraries in the Arduino IDE. The ESP32 will collect sensor data, like temperature and humidity, and send it as a JSON payload to the Heroku server at an endpoint like <https://app-name.herokuapp.com/sensor-data>. The server-side application will receive the data, process it, and potentially store or forward it for further analysis.[93]

By periodically sending the sensor data, the ESP32 will communicate with the Heroku server, which will respond with either a success or failure message depending on the status of the data transfer. This setup will enable real-time data monitoring from my ESP32 device to the Heroku server, facilitating remote tracking and analysis.

8. Prototype Construction

This section documents the physical procedure of what we did to start prototyping our project. By this point, we've already done research, some design, and are purely starting to put things together. Now, this is not final, and it is not fully functional, but it gives somewhat of an idea of what the end product will look like. For example, our demos allow us to demonstrate our concept in a physical sense. They may not work to specification, and many of the final parts may not be present, but they provide good representation.

8.1 PCB Layout

This section will go into details inside PCB layout. We will cover from material selection in the stack up to quoting and manufacturing.

8.1.1 Stack up and dimensions

After research in material selection we realize that we are good on using FR370HR which provide some advantage for high speed signal and at the same time is not too expensive. As in the PCB Material Selection Guide from San Francisco Circuits says: FR370HR this offer higher performing thermal characteristics than a general purpose FR4. 370HR has a thermal conductivity of $0.4[W/m^{\circ}K]$, a T_g of $180^{\circ}C$, and a CTE for Z-axis of $45 [ppm/C]$. The D_k is about 4.2 and D_f is 0.016. The higher glass transition temperature of this material means it can hold its mechanical structure better at higher temperatures. If a PCB is exposed to a temperature higher than its specified T_g , then it can lose its solid form. This can cause complete failure of an electrical system or product. However, short exposure to a higher temperature is generally ok. In fact, most reflow profiles exceed the T_g of PCBs. This generally will have little effect on the PCB as long as it is not repeatedly exposed to these higher temps. [94]

Then we used the Sierra circuits tool to generate our stack up of 4 layers on a 15cm by 15 cm.

Why 15 by 15 cm? It is because of two main reasons. We have not yet found out what will be the minimum and maximum distance required from our sensor to be spaced from each other in order to properly measure the different light spectrums. And as it was suggested by Dr Weeks we want to have wide traces and big footprints components for easy troubleshooting. Having a big area makes everything simple. Maybe the area will be reduced after the first revision.

Figure 8.1.1: Altium Stackup Manager

#	Name	Material	Type	Weight	Thickness	Dk
	Top Overlay		Overlay			
	Top Solder	Solder Resist	Solder Mask		0.5mil	4.2
1	Top Layer	Foil	Signal	1/4oz	1.45mil	
	Dielectric 2	FR370HR	Prepreg		3.348mil	3.63
2	GND	Copper	Plane	1/2oz	0.689mil	
	Dielectric 4	FR370HR	Core		14.9mil	4.14
	Dielectric 1	FR370HR	Dielectric		21mil	4.14
	Dielectric 5	FR370HR	Core		14.9mil	4.14
3	PWR	Copper	Plane	1/2oz	0.689mil	
	Dielectric 3	FR370HR	Prepreg		3.348mil	3.63
4	Bottom Layer	Foil	Signal	1/4oz	1.45mil	
	Bottom Solder	Solder Resist	Solder Mask		0.5mil	4.2
	Bottom Overlay		Overlay			

8.1.2 Design Rules

We follow the design rules provided by sierra circuits when we generate the stack up and the suggestion from professor weeks to generate our design rules. Everything else we just let it set up by default in Altium. These rules will change as the design advances.

Figure 8.1.2.1: Design Rules Clearance

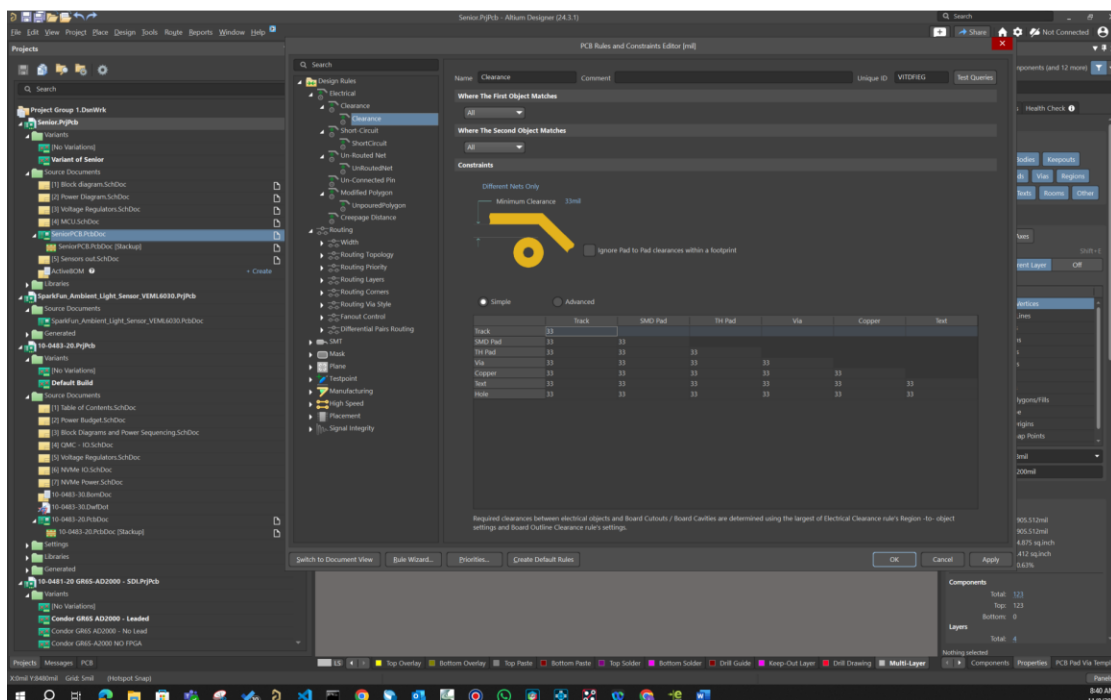
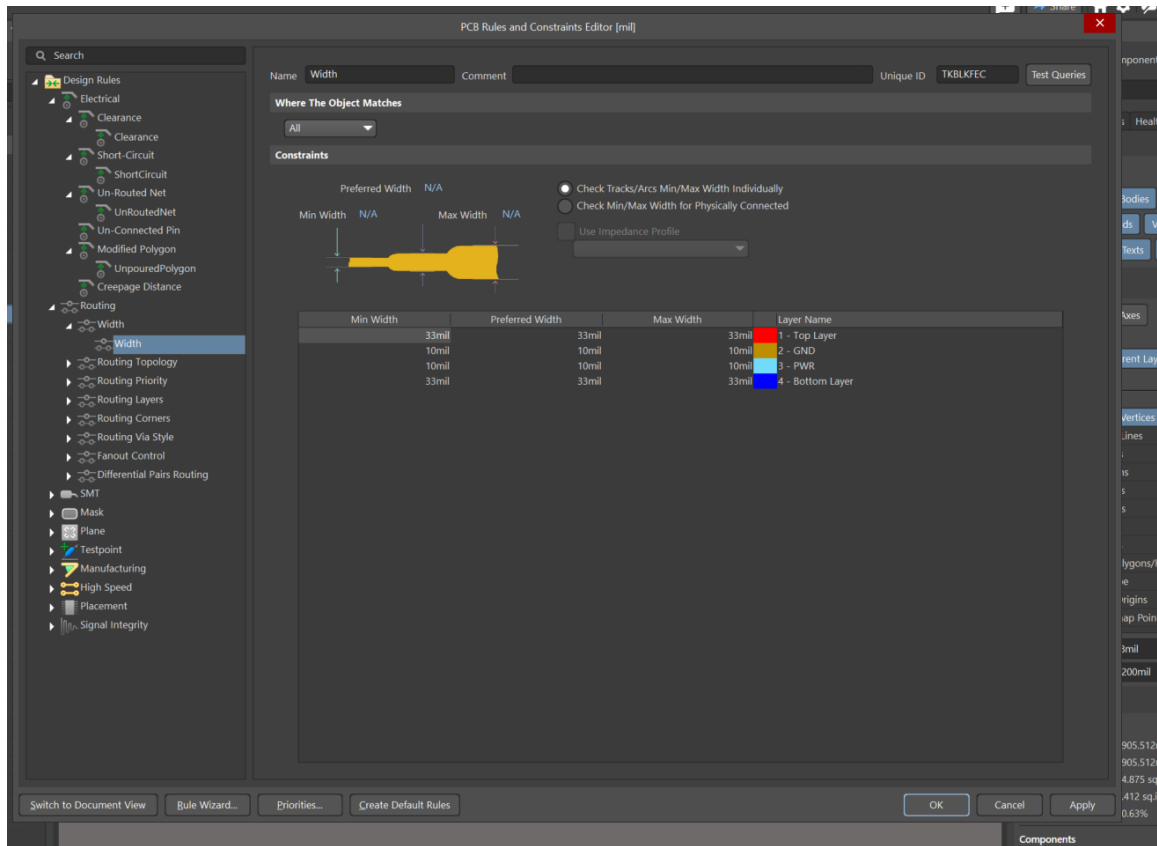


Figure 8.1.2.2: Design Rules Routing



8.2 Optics Midterm Demo

For our midterm demo, we chose to display the red/blue subsystem of the design. Given the fact that we hadn't finished the Zemax design and that we had not ordered any parts yet, we were limited to what was in the senior design lab and the undergraduate lab.

Since we did not have the path leading up to the diffraction grating set up, we chose to use a fiber light collimator, a 6.35 mm diameter lens with an 88.3 mm focal length, a reflective 1200 lines/mm holographic diffraction grating, and two optical fiber holders. We did not have any sensors present, as they had not arrived yet.

The overall aim of our demo was to show that we could successfully collect and isolate the light that was diffracted by the grating. Unlike our final design most likely will have, we did not have any lenses to isolate the light. This was due to the fact that we had designed our demo prior to deciding to isolate the diffracted light with lenses rather than an aperture. Also missing from our demo was the slit that

is commonly seen in spectrometers. Still, we were able to demonstrate our capability to isolate the light, and it was successful.

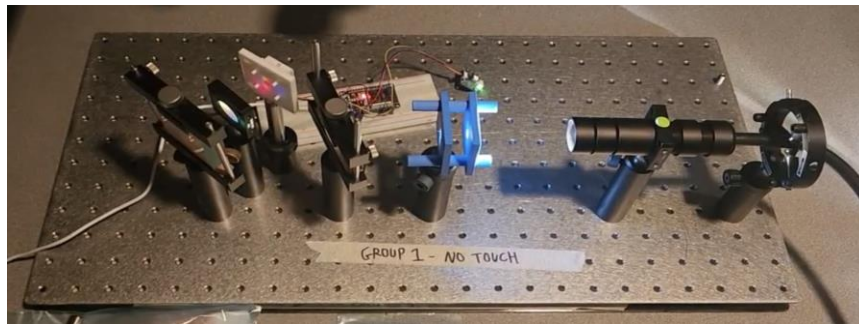
Now, there were interesting questions that were brought up, such as whether a dichroic filter is necessary to separate the green light from the red and blue. We still believe it is necessary, as the distance between the diffracted colors will most likely be much smaller in our final design, as our idea was for the sensors to be placed onto a single PCB, which would significantly reduce the amount of space that we can allow the light to diffract. Using a dichroic filter would give us the best chance to eliminate the overlap of wavelengths present in such a small diffracted length.

8.3 Optics Final Demo

For our final optics demo, we decided that we'd attempt to build the complete optical system so that we could determine any major issues that would lead to major setbacks in Senior Design 2. We did not have any of the actual components besides the light sensor, and we only had one ready to use. For this demo, we had 8mm diameter plano-convex lenses with a focal length of 10mm, a transmissive diffraction grating with an unknown ruling number, a fiber light source, and a cube beam splitter with an unknown transmission/reflection ratio.

Since our lenses were so small, we had to 3D print our own lens holders. These lens holders went through many different iterations, as we had major difficulty getting the lenses to collimate the light at the beginning of the optical system, since the optical table has posts that are too far apart. We ended up settling on a design that allowed two lens holders to be connected by rods, which allowed for only one post to be used. We also used a collimating lens for the light source, since we were losing too much light intensity before the light even reached the beginning of the actual lens system. Lastly, we used a rectangular aperture before the focusing lens to isolate the red light.

Figure 8.3: Final Demo Design



9. System Testing and Evaluation

In this section, we provide details on the testing we have done on our components and how we plan to further develop our design in Senior Design 2. Unlike Chapter 8, this section goes more into the actual working nature of the design than the physical building and look of it. Here, we test some of our chosen components and see if we have to make any improvements.

9.1 Hardware Testing Procedure

For hardware testing we are going to measure the voltage points through test pads. We implement many test pads to also check the signals. In addition, we have diodes that will tell us if certain parts, components, are behaving as expected. We are going to have the sensors under different conditions to see how they react and if the data is accurate we are going to compare with other similar sensor devices. More specific testing will be posted. Since we still do not have the right components we will be testing prototype components. We are planning to use an ESP32 Devkit and the real sensors with optical lab components.

9.3 Software Testing Procedure

Our software testing will focus on ensuring that both the microcontroller and server operate smoothly and reliably. A key part of this process is verifying that the idle-time algorithm is working as intended to conserve battery life. We'll test this feature under different scenarios to make sure the system efficiently enters a low-power state when idle and quickly resumes full functionality when activity is detected.

We will also be examining Wi-Fi connectivity closely to confirm that the system maintains a stable link with the online application. This involves testing its ability to reconnect automatically if the signal drops, as well as evaluating performance under varying signal strengths to understand how network conditions might impact data transmission and responsiveness.

To ensure that the microcontroller and server communicate effectively, we will monitor data synchronization and timing. We will check that data flows smoothly between the device and the server without delays or errors, so the system can handle real-time input accurately and reliably. This will allow us to confirm that the device is ready to support the precise, real-time monitoring that is essential to the project's goals.

9.4 Humidity, CO₂, Temperature Sensor Testing

As for testing our humidity, temperature, and carbon-dioxide sensor, we created a circuit and plugged our sensor into a laptop. From this laptop, we could see

temperature readings, humidity readings, and carbon-dioxide readings. Now, we really could not determine if any of the readings were correct. For instance, there were no units listed on the readouts, so we were only assuming what they meant. The only real feature of the sensor we could test was the carbon dioxide. The temperature of the room and the humidity stay relatively the same, with only a slight variation. However, with the carbon-dioxide feature, we were able to breathe on the sensor and see that the number increased.

For the testing of this sensor, we may buy complementary sensors that measure the same things. While this does not seem especially important at the moment, especially since it's not optical design, it would be great if we could confirm the values. This will play a higher role later on, as all the sensors will be placed inside of the device's housing, which may affect the accuracy of the sensor.

9.5 Optics Final Demo

With this demo, we were able to display the entire design of our optical system in a mostly accurate way. Though we did not have many of the final components, we were able to prove that our light sensors measured an increase in light intensity. We had no way of knowing whether the readings were accurate, as there is a gain built into the code that we need to play around with, and we were not able to collimate the light that went into the system.

We did receive some feedback that made a big impact on our project. Firstly, we were told that we needed to make sure our photodiode was biased correctly. While this would make sense if we biased our photodiodes by ourselves, our light sensor is on a breakout board and doesn't need to be biased by us. This was done beforehand, and all we had to do was plug it into our MCU.

The second piece of feedback was much more impactful. Attention was brought up to the fact that the pattern formed by the diffraction grating would not remain constant on the light sensors. We were thinking that the ambient light level would change based on the weather conditions and the time of day, but we didn't take the fact that the sun physically moves through the sky into account. This causes the diffraction pattern to move, which would cause our design to fail. It was recommended that we simply put filters in front of our sensor instead of relying on the diffraction pattern to fall in the correct place. This would make our product simpler, which didn't seem like an issue from the reviewers, since they recommended it.

However, because of this simplified approach, we may have to consider changing our goals or make one of our stretch goals into one of our actual goals.

9.6 Overall Integration

The PCB will supply power and the Microcontroller communication between the sensors and the online server/mobile application. The sensors will gather the data that the optical design will translate into useful data (separate natural light into red and blue to measure intensity needed by the plants) for our application, and the microcontroller in the PCB will send the data collected through Wi-Fi to an own cloud server we will provide all the information to the User app.

9.7 Overall Plan for SD2

Much work has gone into researching, prototyping, and revising our project idea in Senior Design 1. We have run simulations, put together demos, and have seen what has worked and what has not. In Senior Design 2, we will have the opportunity to finalize our design and showcase our design in front of a panel of judges.

Even though we have made a lot of progress during Senior Design 1, there is still much work to do. We still don't have many of our components. We have received our sensors, since they are some of the most vital components in our project. We have also acquired beam splitters and MCU's. Given the time from the end of Senior Design 1 to the start of Senior Design 2, we will have roughly a month to acquire all our components. Ideally, we will have the PCB sent to the Fab House and back by early January, so that we can start connecting all our subsystems.

Given that we have prototyped and simulated our optical components, we have a very good idea of how the optical system should behave. We received very useful feedback from the final demo in Senior Design 1. We will need to redo some calculations and part of the design to take this feedback into account. Putting our first attempt at our final design should flow relatively easy from there. Still, real life isn't a computer simulation and there are many mistakes that can be made while simulating. We will have to be very vigilant in our setup to ensure we are measuring distances correctly and are seeing expected results.

We may have to go back to the design stage if we aren't seeing our expected results and we realize that they are unachievable. So, we have to start building as soon as possible to compensate for this, as well as the possibility that components may break or stop working.

One of the other major focuses of Senior Design 2 will be in implementing the codes for the microcontroller, as well as maintaining the server and continuing to develop the application. As the semester goes on, we will slowly integrate all the subsystems together.

Another major factor in Senior Design 2 will be in creating the housing for our device. So far, we have only designed the subsystems, but have not finalized or even prototyped any sort of design for our device. This will be important, as our device needs to be marketable and portable, which would be very hard to do if it had no housing.

Lastly, we really need to consider how we are going to show off the capabilities of our device. Our device has specifications that are meant to fit the lux requirements and commonalities of a greenhouse. However, our project will need to be showcased indoors, and definitely will not be showcased in a greenhouse. We need to find a way to showcase the accuracy of our sensors, as well as their ranges. We have considered using solar lamps, as well as separate lux meters, hygrometers, thermometers, and carbon dioxide sensors to confirm our results. Still, showcasing temperature change, humidity, 10,000 to 100,000 lux light intensity, and carbon dioxide levels will be a challenge to do indoors. So, we need to be creative.

10. Administrative Content

This section covers the administrative and logistical aspects essential to the project's successful execution. It includes a detailed breakdown of the project budget, financial considerations, and scheduling of key milestones. Each part ensures that the team remains organized, financially responsible, and aligned with project deadlines.

10.1 Budget and Financing

Below we have our predicted budget as well as bill of materials, which show the actual cost of our project.

Table 10.1: Budget and Bill of Materials

Item	Price per unit	Quantity	Budget Price	BOM
Server	\$5	1	\$5	-
Rechargeable Power Supply	\$100	1	\$100	-
Batteries	\$15	1	\$15	-
Mic (ESP32 s3 with antenna)	\$10	1	\$10	-
Voltage regulators (TPS82130)	\$5	2-4	\$20	-
Screen (NHD-C12864A1Z-FSW-FBW-HTT)	\$25	1	\$25	-
Humidity, Temp, & CO ₂ Sensor (SCD-41)	\$49	1	\$49	\$0
Mirrors	\$11	2	\$22	-
Intensity Sensors	\$6	3	\$18	\$44
Diffraction Grating	\$100	1	\$100	-
Beam Splitter	\$2	1	\$25	\$57
PCB manufacturing	\$50	1	\$50	-
Plano-Convex Lens	\$27	5	\$135	-
Total			\$574	\$101

Our current budget includes all the elements needed for the CPE, EE, and PSE sides of the project. While there are miscellaneous parts that will be needed, we put together a budget for the main components. As can be seen above, the estimated cost is \$583. This price is a few hundred dollars more than the devices listed earlier in the document. However, as stated in the motivation behind this project, none of these devices carry all the features that our device aims to. Also, considering the prototype nature of our project, this price is higher than would be expected if this were to be produced on a mass-scale, like the devices seen earlier in the paper. Therefore, this budget seems completely reasonable and not excessive for this project.

10.3 Project Milestones

To ensure our team stayed on time and met all the due dates, we put together a schedule for both SD1 and SD2. These schedules told us what milestones we should have been working on during the semester as well as when they should have been finished by. Though we were initially hesitant about setting up a schedule, it proved to be a very useful reference and guide to what we needed to get done.

10.3.1 Senior Design I Schedule

The schedule shown here was meant to give us a rough estimate and deadline for each task in our project. It was very useful early on, as there were many different moving parts and submissions necessary. As the semester went on, it became harder to follow the schedule in a precise manner, but it was still a great indicator of where we should have been in the project.

Table 10.3.1: Schedule for completing milestones in SD1

Week(s)	Milestone	Finish By
1	Brainstorming Project Idea and Forming Group	8/23/2024
2-3	Divide & Conquer Document/Committee Formation	9/6/2024
4-5	Individual Research & Finalize Idea	9/18/2024
5	Order Optical Components	9/20/2024
6-8	Continue Research/Prepare for Midterm Demo	10/7/2024
8	Midterm Demo (1 Optical Subsystem)	10/8/2024
7-10	Setting up and Testing Optical Sensor	10/25/2024
8	PCB Schematic	10/25/2024
8-15	PCB Design	11/30/2024

8-10	60-page Draft Report	10/25/2024
10-12	60-page Report Revision	11/8/2024
13-15	Mini Demo Video/Final Report	11/26/2024

We completed most of these milestones by the end of SD1. However, some tasks were significantly pushed back for a variety of different reasons. For example, setting up the optical sensor and ordering the PCB will most likely be completed at the beginning of Senior Design 2 and during the holiday break, respectively.

10.3.2 Senior Design II Schedule

Our Senior Design II schedule outlines our intended completion dates for each milestone, providing a structured timeline that allows us to manage the project effectively. We have carefully spaced out and organized each phase, ensuring ample time for troubleshooting, testing, and making any necessary adjustments. This approach is designed to keep us on track and allow flexibility for any challenges that may arise during the build phase.

The timeframes and deadlines in this schedule are both achievable and reasonable, as we will have finalized most aspects of our design by the start of Senior Design II. This positions us to transition smoothly into the building phase with a clear focus on implementing, testing, and refining the prototype. By establishing realistic goals and accounting for potential setbacks, we are confident that this schedule will support the successful completion of our project while maintaining high standards in design and functionality.

Week(s)	Milestone	Finish By
1	Order PCB	1/10/2025
1-2	Order the Rest of Materials	1/10/2025
1-5	Application Design/Coding	2/7/2025
3-5	Building Prototype	2/7/2025
6-7	Testing Prototype	2/21/2025
8-9	Evaluation/Redesign	3/5/2025
10-12	Building Final Design	3/28/2025
13-14	Final Testing	4/11/2025
15	SD Showcase	4/17/2025

Table 10.3.2: Schedule for completing milestones in SD

11. Conclusion

Our chosen project aims to simplify the complications of monitoring and improving greenhouse systems. By making a remote, all-inclusive measurement system, the future of greenhouses stands to improve tremendously. Throughout the composition of this paper and the process of senior design 1, we have learned critical skills that will ensure future success in our professional careers. Not only have we had to come together as a team and use the knowledge that we have acquired in our time in college, but we have also needed to be our own bosses and ensure that we are each doing our collective parts for the progress of the project.

We have learned the importance of identifying a problem (or even just something that has not been done yet), and understanding technologies that have been used in similar ways. It is really in this way that one can determine if their project is going to be purposeful, or if it is purely meant to be a copycat product. For us, the idea of the red and blue light ratio was what set us apart from other products, along with the package deal of the white light intensity sensor and the humidity, temperature, and carbon dioxide sensor.

Once we had an idea of what kind of product we wanted to develop, we went through the process of defining our goals and researching for the project. Though we initially had some idea of what components we'd need, this process did not turn out to be short, or linear. We were encouraged to research different types of technologies that could be used to fulfill a certain function. Once we chose one of those technologies to go with, we were to research across different companies and individual parts to determine what part we'd get. This taught us the importance of researching deeply, learning new things, and determining what parts to go with based on any set of different constraints we had.

Researching standards taught us the importance of ensuring that technologies and parts met industry expectations and sometimes even federal law. These standards, along with the limits of the devices we compared and researched, informed the values of our device specifications and the values seen in our advanced goals.

Next, we used ChatGPT, Gemini, and Copilot to test different LLMs by asking relevant project questions, determining their usefulness, truthfulness, and ease of use. Considering how prevalent LLMs are becoming, it was vital for us to understand the limitations of these technologies and truly get an understanding of how they perform.

We then started the hardware and software design processes. These processes were where we took our research and started applying it. All plans for PCB, MCU, I2C, software, power supply, optical design, etc. were created here. We expanded upon our initial prototype idea and designed a layout with actual dimensions instead of a quick drawing with arbitrary distances. These processes coincided with the midterm demos and the end of semester mini demo, along with the continuing research.

Our prototypes and demos let us find errors without design and helped us determine our next steps and what we plan to do in Senior Design 2. Overall, the process of building this product has been difficult, but rewarding. Further development will be needed to finalize the product, but we are ready to take on this challenge.

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13. Appendix

LLM Comparison Prompts and Responses

Example 1-

Prompt: “What are the pros and cons of using plano-convex vs biconvex lenses for focusing?”

ChatGPT: “When choosing between plano-convex and biconvex lenses for focusing applications, the decision depends on factors such as aberration correction, focal length, and light intensity. Here’s a breakdown of the pros and cons of each:

Plano-Convex Lens

A plano-convex lens has one flat (plano) side and one convex side.

Pros:

1. *Reduced Spherical Aberration (for collimated light):*
 - When the flat side faces the object (incoming collimated light), plano-convex lenses are highly effective in minimizing spherical aberration. This makes them ideal for focusing collimated beams of light, like from lasers, into a small point.
2. *Less Expensive:*
 - Due to their simpler design compared to biconvex lenses, plano-convex lenses are often more affordable.
3. *Efficient for Single-Element Systems:*
 - When only one lens is needed, plano-convex lenses are generally more efficient at focusing collimated light onto a detector or focal plane, making them a preferred choice in basic optical setups.
4. *Better for Longer Focal Lengths:*
 - They tend to provide better performance in systems requiring longer focal lengths.

Cons:

1. *Increased Aberrations for Diverging or Converging Light:*
 - When light is diverging or converging (not collimated), plano-convex lenses introduce more spherical aberrations compared to biconvex lenses.
2. *Direction-Sensitive:*
 - To achieve optimal performance, the orientation of the lens matters. The plano side should face the collimated light. If this

orientation is reversed, it can worsen image quality and focusing precision.

3. Limited to Certain Applications:

- They are less suitable for imaging or focusing light from a diverging source without additional correction.*

Biconvex Lens

A biconvex lens has two outward-curving convex surfaces.

Pros:

1. Symmetry Reduces Aberrations:

- Biconvex lenses exhibit more symmetry, which helps reduce spherical aberration, especially when focusing light from a divergent or converging source. This makes them ideal for imaging applications where light paths are complex.*

2. Better for Shorter Focal Lengths:

- For applications where a shorter focal length is required, biconvex lenses tend to offer better performance and are preferred over plano-convex lenses.*

3. More Versatile for Non-Collimated Light:

- They are generally more versatile than plano-convex lenses for handling light that is not collimated, such as from point sources or diverging beams.*

Cons:

1. More Expensive:

- The double curvature makes biconvex lenses more complex to manufacture, which can make them more expensive.*

2. Higher Aberrations for Collimated Light:

- When focusing collimated light, biconvex lenses can introduce more spherical aberration compared to plano-convex lenses, especially in single-element systems.*

3. Less Optimal for Long Focal Lengths:

- Biconvex lenses tend to be less effective in applications requiring long focal lengths, where plano-convex lenses would perform better.*

Comparison Summary:

<i>Factor</i>	<i>Plano-Convex Lens</i>	<i>Biconvex Lens</i>
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<i>Best Use</i>	<i>Collimated light, longer focal lengths</i>	<i>Diverging/converging light, shorter focal lengths</i>
<i>Spherical Aberration</i>	<i>Less for collimated light, more for diverging/converging light</i>	<i>More balanced for non-collimated light</i>
<i>Cost</i>	<i>Less expensive</i>	<i>More expensive</i>
<i>Versatility</i>	<i>Less versatile for non-collimated light</i>	<i>More versatile for various light sources</i>
<i>Focal Length</i>	<i>Better for longer focal lengths</i>	<i>Better for shorter focal lengths</i>
<i>Aberration Reduction</i>	<i>Needs proper orientation (plano side toward collimated light)</i>	<i>Symmetrical, reducing aberrations for complex light paths</i>

In summary, plano-convex lenses are optimal when focusing collimated light (like lasers) and when long focal lengths are needed. Biconvex lenses are more suitable for divergent or convergent light, imaging systems, and shorter focal lengths. The choice depends on the specifics of your optical setup, light source, and desired focal properties.”

Gemini: *“Plano-convex and biconvex lenses are both converging lenses, meaning they focus parallel rays of light to a single point. However, their shapes lead to some differences in how they focus light. Here's a breakdown of the pros and cons:*

Plano-Convex Lenses

- *Pros:*
 - *Less spherical aberration: When used to focus a collimated beam (parallel rays of light) into a point, a plano-convex lens minimizes spherical aberration when the curved side faces the collimated source. This means light rays converge to a more precise focal point.*
 - *Easier to manufacture: Generally simpler and cheaper to produce than biconvex lenses.*
 - *Good for infinite conjugate ratios: Well-suited for situations where the object is very far away (effectively at infinity), like focusing light from a distant star.*

- *Cons:*
 - *Shorter focal length: For a given material and curvature, a plano-convex lens will have a shorter focal length than a biconvex lens.*
 - *More sensitive to orientation: Flipping the lens the wrong way can significantly increase spherical aberration.*

Biconvex Lenses

- *Pros:*
 - *Longer focal length: Offers a longer focal length compared to a plano-convex lens with the same material and curvature.*
 - *Symmetrical: Less sensitive to orientation and performs well when the object and image are at similar distances from the lens.*
 - *Minimizes spherical aberration for finite conjugates: Performs best when focusing light from a relatively nearby object to another point a similar distance away.*
- *Cons:*
 - *More spherical aberration for collimated light: Introduces more spherical aberration than a plano-convex lens when focusing collimated light to a point.*
 - *More complex to manufacture: Typically more difficult and expensive to produce.*

In Summary

The best choice depends on your specific application:

- *Collimated light to a point: Plano-convex with the curved side facing the source.*
- *Object and image at similar distances: Biconvex.*
- *Object very far away: Plano-convex.*

It's also important to consider factors like cost, ease of manufacturing, and the specific level of precision required in your optical system."

Copilot: *"Great question! Both plano-convex and biconvex lenses have their own advantages and disadvantages when it comes to focusing light. Here's a comparison to help you understand their differences:*

****Plano-Convex Lenses****

****Pros:****

- **Cost-Effective:** Generally easier and cheaper to manufacture compared to biconvex lenses¹(<https://www.physicsforums.com/threads/difference-between-plano-convex-and-biconvex-lens.318310/>).
- **Ideal for Asymmetric Applications:** Best suited for focusing collimated beams or collimating divergent beams²(<https://www.sycco-optics.com/resources/biconvex-plano-convex-biconcave-plano-concave-and-meniscus-lenses.html>).
- **Reduced Spherical Aberration:** When used correctly (with the curved side facing the incoming light), they can minimize spherical aberration³(<https://www.edmundoptics.com/knowledge-center/application-notes/optics/lens-geometry-performance-comparison/>).

Cons:

- **Limited Focusing Power:** Less effective for applications requiring high focusing power compared to biconvex lenses²(<https://www.sycco-optics.com/resources/biconvex-plano-convex-biconcave-plano-concave-and-meniscus-lenses.html>).
- **Alignment Sensitivity:** More sensitive to alignment errors, which can affect performance³(<https://www.edmundoptics.com/knowledge-center/application-notes/optics/lens-geometry-performance-comparison/>).

Biconvex Lenses

Pros:

- **Symmetric Design:** Ideal for imaging applications where the object and image distances are equal²(<https://www.sycco-optics.com/resources/biconvex-plano-convex-biconcave-plano-concave-and-meniscus-lenses.html>).
- **Higher Focusing Power:** Can focus light more effectively due to their symmetric curvature¹(<https://www.physicsforums.com/threads/difference-between-plano-convex-and-biconvex-lens.318310/>).
- **Versatile:** Suitable for a wider range of applications, including imaging and beam focusing²(<https://www.sycco-optics.com/resources/biconvex-plano-convex-biconcave-plano-concave-and-meniscus-lenses.html>).

Cons:

- **Higher Cost:** More complex to manufacture, leading to higher costs¹(<https://www.physicsforums.com/threads/difference-between-plano-convex-and-biconvex-lens.318310/>).
- **Increased Aberrations:** More prone to spherical aberrations if not used in optimal conditions³(<https://www.edmundoptics.com/knowledge-center/application-notes/optics/lens-geometry-performance-comparison/>).

In summary, the choice between plano-convex and biconvex lenses depends on your specific application needs. Plano-convex lenses are great for cost-effective, asymmetric focusing tasks, while biconvex lenses offer better performance for symmetric imaging and higher focusing power.

Do you have a specific application in mind for these lenses?

Source: Conversation with Copilot, 11/25/2024

(1) Difference between plano-convex and biconvex lens - Physics Forums.

<https://www.physicsforums.com/threads/difference-between-plano-convex-and-biconvex-lens.318310/>.

(2) Biconvex, Plano-convex, Biconcave, Plano-Concave and Meniscus Lenses.

<https://www.sycco-optics.com/resources/biconvex-plano-convex-biconcave-plano-concave-and-meniscus-lenses.html>.

(3) Lens Geometry Performance Comparison | Edmund Optics.

<https://www.edmundoptics.com/knowledge-center/application-notes/optics/lens-geometry-performance-comparison/>."

Example 2-

Prompt: What are the benefits when trying to create a mobile app using Flutter versus MERN stack?

ChatGPT: "Creating a mobile app using Flutter and the MERN stack both have their unique advantages, depending on the project's needs. Here's a breakdown of the benefits of each:

Benefits of Using Flutter

1. Cross-Platform Development:

- *Flutter allows you to create apps for iOS, Android, and web from a single codebase, reducing development time and effort.*
- *Ensures a consistent UI and performance across platforms.*

2. Rich UI/UX:

- *Flutter uses its own rendering engine (Skia), enabling custom, visually rich designs without depending on platform-specific components.*
- *Pre-designed widgets make it easy to create intuitive, polished interfaces.*

3. High Performance:

- *Flutter apps are compiled to native code (ARM), resulting in faster performance compared to web-based apps built with MERN.*
- *Eliminates the need for a JavaScript bridge, which improves runtime speed.*

4. *Hot Reload:*
 - *Developers can see changes in the app instantly without restarting the app, enhancing productivity during development.*
5. *Unified Language (Dart):*
 - *Using Dart simplifies development as both front-end and logic are written in the same language, avoiding context switching.*
6. *Strong Ecosystem:*
 - *A rich package library provides ready-made solutions for common tasks like authentication, database integration, and state management.*

Benefits of Using the MERN Stack

1. *Full-Stack Development:*
 - *The MERN stack enables you to build end-to-end applications (frontend, backend, and database) using JavaScript.*
 - *If your app requires significant server-side logic, the MERN stack is ideal as it integrates backend services natively.*
2. *Flexibility:*
 - *You have complete control over the architecture, allowing you to build both web and mobile apps using frameworks like React Native for mobile interfaces.*
3. *Scalability:*
 - *MERN is a better choice for apps that are heavily data-driven or require robust server-side features.*
 - *MongoDB offers flexible schema design, making it suitable for evolving projects.*
4. *Mature Ecosystem:*
 - *The JavaScript ecosystem is vast, with countless libraries and tools to handle any requirement.*
5. *Separate Frontend and Backend:*
 - *You can independently scale the front-end and back-end, especially in microservices-oriented architectures.*
6. *Reusable Components:*
 - *React allows for reusable UI components, which speeds up development and ensures consistency.*

Choosing Between Flutter and MERN

- *Choose Flutter if:*
 - *Your primary goal is a mobile-first application with a rich, uniform UI across platforms.*
 - *Performance and native-like behavior are critical.*

- You want to focus on rapid development with minimal platform-specific adjustments.
- Choose MERN if:
 - Your app requires complex server-side functionality or needs to interact heavily with a database.
 - You want the flexibility to create a full-stack web and mobile application (possibly integrating with React Native).
 - You already have a web-first focus and plan to expand into mobile later.

For a hybrid approach, you can also combine Flutter with a MERN backend (e.g., Node.js/Express API for server logic and MongoDB for database needs)."

Gemini: *"Flutter vs. MERN Stack: A Comparative Analysis for Mobile App Development"*

When considering the development of a mobile app, Flutter and MERN stack are two popular choices. Each has its unique strengths and weaknesses. Here's a breakdown of the benefits of using Flutter over MERN stack for mobile app development:

Flutter's Advantages:

1. Cross-Platform Development:

- *Single Codebase:* Write a single codebase for both iOS and Android, significantly reducing development time and effort.
- *Consistent UI/UX:* Ensure a consistent look and feel across both platforms.

2. Faster Development:

- *Hot Reload:* Quickly see changes in real-time, accelerating the development process.
- *Rich Widget Library:* Utilize a vast library of pre-built UI components to speed up development.

3. Excellent Performance:

- *Native Performance:* Achieve near-native performance thanks to Flutter's rendering engine.
- *Smooth Animations:* Deliver fluid and responsive user experiences.

4. Expressive UI:

- *Customizable Widgets: Create highly customized and visually appealing user interfaces.*
 - *Rich Motion API: Implement stunning animations and transitions.*
5. *Strong Community and Support:*

- *Active Community: Benefit from a large and growing community of developers.*
- *Official Documentation and Tutorials: Access comprehensive resources for learning and troubleshooting.*

MERN Stack's Advantages:

While MERN stack is primarily used for web development, it can be used for mobile app development with frameworks like React Native. Here are its benefits:

1. Full-Stack Development:

- *Unified Technology Stack: Use a single technology stack for both frontend and backend development.*
- *Seamless Integration: Easily integrate frontend and backend components.*

2. Large Community and Ecosystem:

- *Extensive Resources: Access a wealth of libraries, frameworks, and tools.*
- *Strong Community Support: Get help from a large and active community of developers.*

When to Choose Flutter:

- *Prioritizing Performance and User Experience: Flutter's native-like performance and smooth animations can significantly enhance the user experience.*
- *Developing Cross-Platform Apps: If you need to target both iOS and Android, Flutter's single codebase approach can save time and resources.*
- *Creating Custom UI Designs: Flutter's flexible widget system allows for highly customized and visually appealing interfaces.*

When to Consider MERN Stack:

- *Building Web and Mobile Apps Simultaneously: If you're already familiar with the MERN stack and want to extend your web application to mobile, React Native can be a good option.*
- *Leveraging Existing Web Development Skills: If your team has strong web development skills, particularly in JavaScript, React Native can be a more familiar and efficient choice.*

Ultimately, the best choice for your project depends on your specific requirements, team expertise, and project timeline. Carefully consider the factors mentioned above to make an informed decision.”

Copilot: *“Both Flutter and the MERN stack offer unique advantages for mobile app development. Here's a comparison to help you decide which might be better suited for your project:*

Flutter

1. *Cross-Platform Development: Flutter allows you to create apps for iOS, Android, web, and desktop from a single codebase. This can significantly reduce development time and costs.*
2. *Hot Reload: This feature lets developers see changes in real-time without restarting the app. It speeds up the development process and makes it easier to experiment and fix bugs.*
3. *Consistent UI and Business Logic: Flutter ensures that the UI and business logic remain consistent across all platforms. This can simplify maintenance and updates.*
4. *Rich Widgets and Customizable UI: Flutter provides a wide variety of widgets that can be customized to create highly attractive and functional UIs.*
5. *High Performance: Flutter uses the Dart programming language and the Skia graphics engine, which allows for smooth and fast performance.*

MERN Stack (MongoDB, Express.js, React.js, Node.js)

1. *Full-Stack Development: MERN stack covers both front-end and back-end development, making it a comprehensive solution for building web and mobile applications.*
2. *JavaScript Everywhere: Since all components of the MERN stack use JavaScript, developers can work more efficiently without switching between languages.*
3. *Scalability: The MERN stack is highly scalable, making it suitable for applications that need to handle a large number of users and data.*

4. *Strong Community Support: With popular applications like Walmart and Airbnb using the MERN stack, there is a robust community and plenty of resources available.*
5. *Flexibility and Customization: The MERN stack allows for high levels of customization and flexibility, enabling developers to tailor applications to specific needs.*

Choosing Between Flutter and MERN Stack

- *Use Flutter if: You need a cross-platform solution with a single codebase, want to leverage fast development cycles with hot reload, and prioritize a consistent and customizable UI across platforms.*
- *Use MERN Stack if: You need a full-stack solution that handles both front-end and back-end development, prefer working entirely in JavaScript, and require a scalable and flexible architecture.*

Which aspects of your project are most important to you? This might help narrow down the best choice for your needs!

Example 3-

Prompt: “What are the benefits of building a budget server using an old laptop compared to paying for a server?”

ChatGPT: “Using an old laptop to build a budget server offers several benefits compared to paying for a dedicated or cloud server. Here's a breakdown of the advantages:

Cost Savings

- *Zero Initial Investment: If you already have an old laptop, you avoid the upfront costs associated with purchasing new hardware or subscribing to a server plan.*
- *No Subscription Fees: Self-hosting eliminates recurring costs for cloud services or rental fees for dedicated servers.*

Portability

- *Compact Design: Laptops are lightweight and portable, making them easy to relocate if needed.*
- *Integrated Components: Laptops come with a built-in display, keyboard, and battery backup, which simplifies setup and provides resilience against power outages.*

Energy Efficiency

- *Lower Power Consumption: Laptops are designed to be energy-efficient, using far less electricity compared to traditional desktop servers or some dedicated server setups.*

Customization and Control

- *Full Access to the System: With an old laptop, you have complete control over the operating system, software, and configuration without restrictions imposed by a hosting provider.*
- *Privacy and Security: Hosting your own server gives you greater control over data privacy, reducing the risks of breaches in third-party hosting environments.*

Learning Opportunity

- *Hands-On Experience: Setting up and maintaining a server on an old laptop is an excellent way to gain hands-on experience with networking, operating systems, and server management.*
- *Skill Development: You'll learn valuable skills, such as configuring web servers, managing databases, and optimizing hardware for performance.*

Versatility

- *Multi-Purpose Use: You can repurpose the laptop to host websites, run a personal cloud (like Nextcloud), serve as a media server, or handle development/testing tasks.*
- *Upgradability: It's easy to start small and scale up by upgrading the laptop (e.g., adding RAM or swapping in an SSD).*

Environmental Impact

- *Reusing Hardware: Extending the life of an old laptop reduces electronic waste and minimizes the environmental footprint compared to buying new hardware.*

Performance for Light Workloads

- *Sufficient for Small Applications: An old laptop is often powerful enough for small-scale applications like hosting personal websites, blogs, or low-traffic servers.*

Offline Availability

- *Local Hosting: Unlike cloud servers, a locally hosted laptop server can operate even without an active internet connection, which is beneficial for private or local network tasks.*

While using an old laptop as a server offers many benefits, it's important to consider limitations such as hardware lifespan, potential thermal issues, and limited performance for demanding tasks. For small-scale projects or personal use, it can be a practical and economical solution."

Gemini: *"Benefits of Building a Budget Server with an Old Laptop*

Building a server using an old laptop offers several advantages over renting a server:

Cost-effectiveness:

- *Zero upfront cost: If you already have an old laptop, the initial investment is minimal.*
- *Lower ongoing costs: You'll only need to pay for electricity and potentially internet connectivity.*

Control and Customization:

- *Full control: You have complete control over the hardware and software, allowing you to tailor the server to your specific needs.*
- *Flexibility: You can easily install and configure various services and applications.*
- *Open-source options: Many powerful open-source server solutions are available, further reducing costs.*

Learning Opportunity:

- *Hands-on experience: Building and managing a server provides valuable technical skills and knowledge.*
- *Experimentation: You can experiment with different configurations and technologies without significant financial risk.*

Privacy and Security:

- *Data privacy: By hosting your server locally, you have greater control over your data and can implement robust security measures.*
- *Reduced latency: Local hosting can lead to faster response times and improved performance for applications.*

Considerations and Potential Drawbacks:

- *Power Consumption:* Older laptops might consume more power than modern servers, increasing electricity costs.
- *Limited Resources:* The performance of an old laptop may be limited compared to a dedicated server, especially for resource-intensive tasks.
- *Maintenance:* You'll need to maintain the hardware and software, including updates and security patches.
- *Reliability:* Older hardware may be less reliable, potentially leading to downtime.
- *Noise:* Laptops can be noisy, especially when under load.

Ideal Use Cases:

- *Home media server:* Streaming media files, running a Plex server, or hosting personal photos and videos.
- *Personal cloud storage:* Storing files and backing up data.
- *Web server:* Hosting personal websites or blogs.
- *Home automation:* Controlling smart devices and home systems.
- *Virtualization:* Running multiple virtual machines for testing or development purposes.

By carefully considering your specific needs and the limitations of an old laptop, you can build a cost-effective and functional server for various purposes.”

Copilot: “What are the benefits of building a budget server using an old laptop compared to paying for a server?”

Here are some additional benefits of building a budget server using an old laptop:

7. *Backup and Redundancy:* You can use the laptop server as a backup for important files and data, providing an extra layer of redundancy in case your primary storage fails.
8. *Home Automation:* An old laptop server can be used to control and manage smart home devices, acting as a central hub for home automation systems.
9. *Media Server:* You can set up a media server to stream movies, music, and photos to other devices in your home, making your media library accessible from anywhere.
10. *Web Hosting:* Host your own website or blog without the need for a third-party hosting service. This can be a great way to learn about web development and server management.

11. *Game Server: Use the laptop to host multiplayer game servers for games that support it, providing a private gaming environment for you and your friends.*
12. *Development Environment: Create a dedicated environment for software development and testing, isolating it from your main computer to avoid conflicts and maintain a clean workspace.*
13. *Network Attached Storage (NAS): Convert the laptop into a NAS device to provide centralized storage accessible over your home network.*
14. *Virtual Private Network (VPN): Set up a VPN server to securely access your home network from remote locations, enhancing your privacy and security.*
15. *Learning and Experimentation: Experiment with different operating systems, server software, and configurations without the risk of disrupting your main computer. This hands-on experience can be invaluable for learning and skill development.*
16. *Security Camera System: Use the laptop to manage and store footage from security cameras, creating a DIY surveillance system.*
17. *IoT Projects: Integrate the laptop server with Internet of Things (IoT) devices for various projects, such as environmental monitoring or home automation.*
18. *Email Server: Set up your own email server to have complete control over your email communications and data.*
19. *File Sharing: Facilitate easy file sharing between devices on your network, making it simple to transfer files without using external services.*
20. *Print Server: Use the laptop to manage and share printers across your network, making it easier to print from multiple devices.*
21. *Database Server: Host databases for personal or small business use, providing a centralized location for data storage and management.*
22. *Continuous Integration/Continuous Deployment (CI/CD): Set up a CI/CD pipeline to automate the testing and deployment of your software projects.*
23. *Educational Purposes: Use the server to teach others about server management, networking, and other IT skills, providing a practical learning environment.*
24. *Community Projects: Collaborate with others on community projects, such as hosting a local forum or resource site.*
25. *Personal Cloud Storage: Create your own cloud storage solution, giving you access to your files from anywhere without relying on third-party services.*

These additional uses highlight the versatility and potential of repurposing an old laptop into a budget server. Each use case can provide unique benefits and

learning opportunities, making it a valuable project for tech enthusiasts and beginners alike.

Do any of these additional ideas resonate with what you have in mind for your server?”

Example 4-

Prompt: *“Explain to me why adding a slit to a spectrometer is necessary. Is it necessary? What does it do?”*

ChatGPT: *“Yes, adding a slit to a spectrometer is often necessary and serves several crucial purposes. It directly influences the performance, resolution, and signal intensity of the system. Below are the key reasons why slits are important:*

1. Controls Spectral Resolution

The entrance slit determines how finely the spectrometer can distinguish between wavelengths (spectral resolution). A narrow slit improves resolution by reducing the range of angles and wavelengths reaching the dispersive element (e.g., a diffraction grating or prism). This ensures that closely spaced wavelengths appear as distinct peaks instead of overlapping.

Trade-off: A very narrow slit provides higher resolution but allows less light through, reducing the signal intensity.

2. Limits Stray Light and Improves Accuracy

The slit defines a specific path for incoming light, ensuring only a focused beam enters the spectrometer. This helps minimize stray light that could scatter and degrade measurement accuracy. Without a well-defined slit, light from multiple angles or sources could mix, reducing the precision of the spectral output.

3. Controls the Optical Throughput (Signal Intensity)

The width of the slit determines how much light enters the spectrometer. A wider slit allows more light, increasing the signal intensity (important for weak light sources or fast measurements). However, wider slits reduce the spectral resolution by blurring wavelength separation.

4. Shapes the Image of the Spectrum

The entrance slit, in combination with the spectrometer’s optics, controls the size and shape of the image of the spectrum on the detector. A narrow, well-defined slit ensures that each wavelength is accurately focused and mapped to a specific position on the detector, such as a CCD.

Is the Slit Always Necessary?

While a slit is essential in most spectrometers, some systems (like Fourier-transform infrared (FTIR) spectrometers or fiber-optic spectrometers) may not use slits in the traditional sense. In these cases, the design compensates for the absence of slits using other techniques (e.g., interferometry or spatial filtering). However, for traditional grating-based spectrometers, a slit is usually necessary to balance resolution and light throughput.

Conclusion

In most spectrometers, the entrance slit is a critical component that ensures accurate, high-resolution measurements by limiting the incoming light's angles and wavelengths. While necessary for good performance, the slit width must be carefully optimized to balance spectral resolution and signal intensity for the specific application."

Gemini: *"Yes, slits are generally necessary in spectrometers. They serve a crucial function in controlling the light entering the instrument and determining the resolution of the spectrum.*

Primary Functions of Slits:

Collimation: Slits help to ensure that the light entering the spectrometer is parallel. This is essential for accurate measurements, as parallel light rays are easier to focus and analyze.

Resolution Enhancement: By limiting the width of the slit, the spectrometer can achieve higher spectral resolution. This means that it can distinguish between wavelengths of light that are very close together. A narrower slit results in a narrower beam of light, which leads to a more focused image on the detector.

Intensity Control: The width of the slit can also be used to control the intensity of the light entering the spectrometer. A wider slit allows more light to pass through, while a narrower slit reduces the intensity.

Types of Slits:

Entrance Slit: Located at the front of the spectrometer, this slit controls the amount of light entering the instrument.

Exit Slit: Located at the back of the spectrometer, this slit determines the specific wavelength of light that is detected.

In summary, slits are essential components of spectrometers because they:

Ensure parallel light rays.

Improve spectral resolution.

Control light intensity.

The choice of slit width depends on the specific application and the desired level of resolution. For example, a narrower slit is often used for high-resolution spectroscopy, while a wider slit may be used for applications where higher light intensity is required.”

Copilot: *“Adding a slit to a spectrometer is like putting a spotlight on the main act. It's necessary for increasing the instrument's resolution and precision. By narrowing the slit, you limit the light entering, which helps isolate specific wavelengths more accurately. Think of it as controlling the stream of light, so the spectrometer can do its thing with fewer distractions—resulting in clearer, sharper data.”*

Example 5-

Prompt: *“How do fresnel lenses compare to collector lenses? Which is more efficient?”*

ChatGPT: *“Both Fresnel lenses and collector lenses serve similar purposes in optical systems—collecting, focusing, or directing light. However, they differ in design, performance, and efficiency. Here’s a breakdown of their key characteristics and a comparison of their efficiency:*

1. Design and Structure

Fresnel Lens:

*Made of concentric rings, each approximating a section of a conventional lens.
Much thinner and lighter than traditional lenses.
Can be flat or flexible, making them suitable for lightweight applications (e.g., solar concentrators, overhead projectors).*

Collector Lens:

*Usually a traditional thick, curved lens (e.g., plano-convex or biconvex).
Designed to gather light from a source and focus it at a point (such as in LEDs, lasers, or solar cells).
Heavier and bulkier, but provides better imaging quality.*

2. Optical Efficiency

Fresnel Lens Efficiency:

*High efficiency in focusing large areas of light (e.g., sunlight).
Slightly lower optical quality due to the segmented design, which can introduce chromatic aberrations and diffraction losses.*

Efficiency depends on the material and precision of the grooves but typically ranges between 85-90% for high-quality plastic Fresnel lenses.

Collector Lens Efficiency:

Typically offers higher optical clarity and better imaging performance with fewer optical losses (less diffraction and scattering).

Collector lenses may achieve up to 95-98% efficiency under ideal conditions but are less practical for large-scale applications due to their size and weight.

3. Applications

Fresnel Lenses:

Used in solar concentrators, projectors, VR headsets, and lighthouse beacons. Ideal for applications where weight, thickness, or large aperture sizes are a concern.

Collector Lenses:

Common in optical instruments, lasers, LEDs, microscopes, and cameras. Better suited for applications requiring high-quality imaging or precise focusing over smaller areas.

4. Which is More Efficient?

Energy Efficiency:

For applications like solar energy concentration, Fresnel lenses are generally more efficient because they can focus light over a large area while remaining lightweight and compact.

However, collector lenses offer better efficiency for optical systems requiring high precision, where optical losses (such as diffraction) need to be minimized.

Conclusion

The choice between a Fresnel lens and a collector lens depends on the application:

Fresnel lenses are more efficient for large-area light collection (like solar concentrators) and when weight or size is a concern.

Collector lenses are more efficient when optical precision and minimal aberration are essential (e.g., microscopes or laser systems).

In summary, Fresnel lenses are better for large-scale light collection and weight-sensitive applications, while collector lenses excel in optical precision.”

Gemini: *“Fresnel vs. Collector Lenses: A Comparison*

Both Fresnel and collector lenses are used to focus light, but they operate on different principles and have distinct advantages.

Fresnel Lenses

Structure: Fresnel lenses are composed of a series of concentric rings, each with a different thickness. This design allows them to be much thinner than traditional convex lenses while maintaining the same focal length.

Efficiency: Fresnel lenses are generally considered more efficient than traditional lenses in terms of light transmission. This is because they have fewer surfaces through which light must pass, reducing the potential for reflection and absorption losses.

Applications: Fresnel lenses are commonly used in lighthouses, projectors, and solar panels due to their efficiency and lightweight design.

Collector Lenses

Structure: Collector lenses are typically convex lenses with a simple, curved surface.

Efficiency: While collector lenses can be efficient, they may experience more reflection and absorption losses compared to Fresnel lenses, especially when made of thicker materials.

Applications: Collector lenses are widely used in various optical instruments, including cameras, microscopes, and telescopes.

In general, Fresnel lenses are often considered more efficient than collector lenses due to their reduced surface area and lower potential for light loss. However, the specific choice between the two depends on factors such as the required focal length, the desired level of light transmission, and the overall design constraints of the optical system.”

Copilot: *“Fresnel Lenses*

Design: These lenses are made up of concentric grooves etched into plastic or glass, making them much thinner and lighter than traditional lenses

Applications: Commonly used in lighthouses, traffic lights, and solar power systems

Efficiency: They are highly efficient in light-gathering applications due to their design, but they can suffer from optical losses like absorption and diffraction

Collector Lenses

Design: These lenses are typically used in solar collectors and are designed to focus sunlight onto a small area to generate heat or electricity³

Applications: Mainly used in solar power systems to concentrate sunlight onto a receiver.

Efficiency: Collector lenses can achieve high temperatures and are efficient in converting solar energy into usable heat or electricity

Comparison

Efficiency: Fresnel lenses are generally more efficient in light-gathering applications due to their thin, lightweight design. Collector lenses, on the other hand, are more efficient in concentrating solar energy for heating or power generation.

Applications: Fresnel lenses are versatile and used in various fields, while collector lenses are specialized for solar energy applications.

In summary, the efficiency of each lens depends on its specific application. Fresnel lenses excel in light-gathering and projection, while collector lenses are more efficient in solar energy concentration.”