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The Sun-sor Final Paper

Introduction

Our project idea was to create a sensor that alerts the user when they are at risk of sun damage due to the UV-B wavelengths present in sunlight. Light in the UV-B range is very harmful to human epithelial tissue, with damage ranging from sunburn to skin cancer. Ninety percent of nonmelanoma skin cancers—cancers that develop in keratinocytes instead of melanocytes (6)—are caused by exposure to UV-B radiation (4). This type of skin cancer is treatable with high survival rates, but treatment is expensive and costs the United States $4.8 billion per year (4). Additionally, the cancer may metastasize to another location where it is harder to treat and may be fatal, so the high survival rates of nonmelanoma skin cancer are not entirely indicative of a patient's prognosis, and these cancers pose a serious threat to an individual's health and well-being. Melanoma skin cancers are also associated with UV-B radiation, due to mutations in the melanoma genome that are caused by UV radiation (5). These mutations are passed to an individual's children, creating an increased risk of future generations developing skin cancer. UV-B rays are clearly a very serious danger affecting many people, both directly, with 1 in 5 Americans developing skin cancer in a lifetime, and indirectly through treatment expenses and family histories (4). UV-B rays are invisible and the damage they cause is not noticeable until it is too late. Sun damage is cumulative, with only about 23% of skin damage occurring by age 18 (4). Most people are not aware of how much skin damage they already have accumulated and moreover, may not always be aware of when they are exposed to UV radiation. On a cloudy day, the warmth of the sun may be less apparent, but the UV rays still penetrate the clouds and can damage the skin. UV radiation is almost always present, posing a significant threat often without any indication of the danger. Of course, spending some time in the sun is enjoyable for most people and also comes with health benefits such as vitamin D, so total avoidance of the sun is not a practical solution. Instead, we would like to enable people to optimize their time out in the sun by informing them when they have been exposed to dangerous intensities of UV-B light for significant time intervals and are therefore at risk of skin damage. This will allow users to take necessary precautions such as moving into a shaded area or applying sunscreen.

Various companies have tried to create devices that achieve similar purposes to that of the Sun-sor before. For example, L'Oreal released a skin sensor in 2016 that has the goal of informing users of UV damage (1). Their product is a patch placed on the skin which users can take a picture of and upload to an app which will scan the patch and determine the UV damage incurred throughout the day. One major drawback of this product includes the fact that users must have their phones with them in order to determine their sun damage risk. Often, the times that people are most at risk from sun damage are situations when their phones are not easily accessible, like when swimming, gardening, or at the beach. Another company, Ultra, is making a wearable electronic product called the Violet Plus, which can be worn as a wristband or a clip-on (10). The Violet Plus, though, has the same problem as L'Oreal's skin patch in that it requires the user to look at their phone to interpret the data the device receives. Lastly, another popular idea has been one-time use paper wristbands, like UVSunSense (11). There are a number of drawbacks to disposable paper bands: they are not very accurate due to the subjectivity of the data they produce (a visually interpreted color change), they cannot be used long term, they don't take into account time spent inside or out of direct sunlight, and they are not sophisticated enough to provide potentially useful information like long term tracking of a person's sun exposure. This last point is particularly important because a person's skin damage from UV radiation is cumulative over a lifetime. Perhaps for these reasons, the UVSunSense bands fell out of favor and are no longer produced.

Our product addresses all of these concerns. First, the user is able to determine their UV risk at any moment without having their phone on them—all they have to do is look down at the LED light on the Sun-sor bracelet, and they will immediately know if they are in danger. This makes our product much more practical and easier to use. In addition, the data our product gives to the user is clear and not subjective (it's either one shade of green, one shade of yellow, or one shade of red), unlike the subtle ranging color change that the user had to interpret themselves on products like UVSunSense. And finally, our product has potential to track a user's sun exposure over the long term when used in conjunction with an app or a website, which sets it up well for further growth and development.

Our target analyte is the photons in UV-B rays that excite the photodiode. This produces a current that we convert to a voltage, amplify, and measure by reading a voltage drop between pins using an Adafruit Trinket. The Sun-sor then utilizes an algorithm to map this voltage to a UV index, and correlate this UV index to an approximate time until a sunburn will occur. The Adafruit Trinket will then blink a neopixel different colors that indicate the amount of time the user has until sunburn occurs.

There are many key engineering aspects and design choices we made in order to create the most effective, user-friendly UV sensor. One of the most important design choices was implementing the sensor as a wearable bracelet. A bracelet is comfortable for users to wear, aesthetically pleasing, more simple to put on compared to velcro arm bands, allows the photodiode to be directed at the sun and does not limit the activities the user can perform. For our prototype, we 3D printed the bracelet so we could create our own custom design. The microcontroller we decided to use is the 5V Adafruit Trinket. This board is very small, has sufficient storage, and consumes minimal power. More common boards like the Arduino Uno would have worked as well, but these boards are significantly larger and draw large amounts of current. We wanted our bracelet to be small and last for extended periods. We also went with the 5V Trinket over the 3.3V version because this gave us a larger sensing range (0-5V compared to 0-3.3V). This allowed us to make more accurate measurements over a larger ranges of UV index values.

Our product senses UV-B rays and higher energy UV-A rays with a photodiode filtered to detect only waves between 220 nm and 370 nm, as these wavelengths have the most significant contributions to skin damage and skin cancer. To notify users of imminent sunburn risk, our device uses a neopixel. We used a neopixel rather than a standard LED for a few reasons. First, neopixels can be any color in the entire RGB spectrum and have options to change brightness, while LEDs have more limited color options. In addition, we wanted our device to use a single light and have it change color. Standard LEDs cannot do this, so what would have taken us three LEDs only ended up taking one neopixel. The circuitry that amplifies the signal and blinks the LED was permanently soldered to a perfboard, along with the microcontroller, to improve stability of the device. We could have left the wristband connected to a breadboarded circuit, but this is much more fragile and not aesthetically pleasing. We power the device with a 1200mAh LiPo battery. All of the components together draw less than 80mA of current, so this gives us a total battery life of more than 15 hours. The LiPo is only rated at 3.7V, so we used an Adafruit voltage booster in between the battery and the Trinket. The booster transforms 3.7V into 5.2V, which is then regulated by the Trinket to 5V. Underpowering the board could affect its ability to take accurate measurements and power elements like the neopixel and operational amplifiers. We created a circuit using two LTC-1050 chopper-stabilized operational amplifiers to boost the current from the photodiode. The currents produced by the photodiode are on the scale of nanoamperes, which is too small to create any type of reliable voltage that the Trinket can measure. These amplifiers have very low signal-to-noise ratios, high response times, operate under a wide range of temperatures, and have low input bias current. Since our photodiode creates very small currents, it is important to have amplifiers that create minimal noise as to reduce interference with the desired signal. Finally, we gave our wristband an embossed leather, velcro wrist strap. This makes the bracelet easy to take on and off, and has a very high level of swag.

Methods

The overall system of our UV sensing device is comprised of a 3D printed bracelet, a 1200 mAh LiPo battery, a voltage booster, a 5V Adafruit Trinket microcontroller, a UV filtering photodiode, an amplifying circuit, and a neopixel. The bracelet is to be worn outdoors, where the sunlight (or lack thereof) will cause the photodiode to become excited, create a current that flows through the circuit, creating a voltage which is then measured by the Trinket board. The board then blinks the neopixel different colors dependent on the intensity of UV light.

The risk of sun damage is based on the UV index calculated by the U.S. National Weather Service (2). A computer model is used to calculate the strength of UV radiation using the incident angle of the sunlight determined by latitude, day of the year and time of the day as well as a forecast for the ozone levels across the globe determined by satellite data. Shorter wavelengths, like those of light in the UV-C range, are better absorbed by the ozone layer so the UV-A and UV-B range is focused on more, with each wavelength within those ranges weighted by the McKinlay-Diffey function (3). This function assigns more weight to shorter wavelengths because shorter wavelengths are higher in energy, so are more damaging to the skin. The effective strength of UV radiation at each wavelength is integrated over the UV-A and UV-B range. This is then adjusted for elevation and cloud coverage at a particular location and then scaled by dividing by 25 and rounding to the nearest whole number to give a UV index value. A value of 0 would indicate essentially no UV radiation while a number in the mid-teens indicates extremely strong UV radiation, as shown in Figure 1. Higher UV index values mean the user has less time before skin damage begins.

UV Index Number	Risk
0-2	Minimal
3-4	Low
5-6	Moderate
7-9	High
10+	Very High

Figure 1. Correlation between UV index number and risk

Our experimental protocol has many steps of testing, debugging, and improving. The first step was to assemble a basic circuit and make sure the photodiode responds to different intensities of light. The very basic code which analyzed the voltage across the Trinket pins, and the basic circuit that converts the current into voltage was adopted from an online DIY Science blog (8). We used a handheld UV laser, the iPhone flashlight, and natural outdoor light to see if the photodiode would create different responses. The Trinket board does not have serial monitoring, because the board is optimized for efficiency. To test the device and debug, we used an Arduino UNO which has serial monitoring and also has 5V logic. All code will transfer perfectly from the Arduino to the Trinket, so the two boards are interchangeable. The next step was to then design a circuit that is parameterized for our Trinket board and gives predictable, linear voltage readings. The Trinket can read voltages between 0 and 5V, so we created a circuit

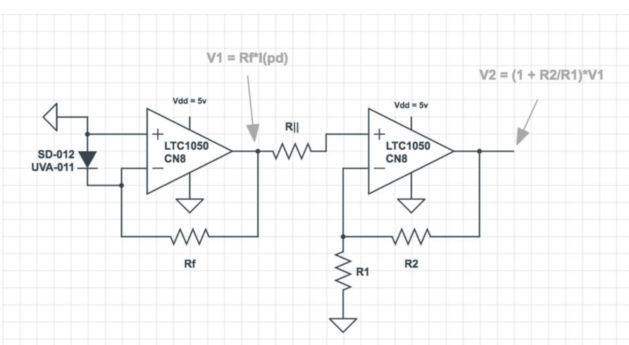

Figure 8. Amplifying Circuit

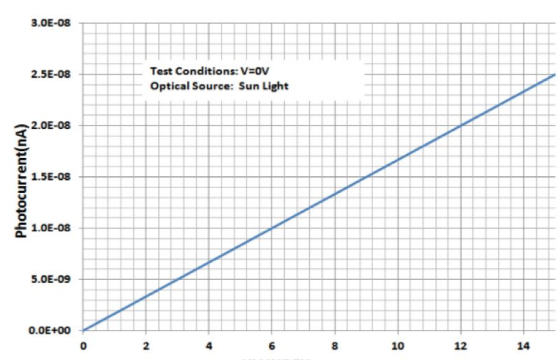

Figure 9. Current vs. UV Index

that will amplify the photodiode current to no more than 5V at the maximum UV index. We decided on UV 12 to be the maximum UV index value our device will measure, because anything above 12 is so high that the user will be able to figure out for themselves that they are going to get burned. Figure 8 is a schematic of the circuit we implemented. The voltage read by the Trinket (V2) is equal to the voltage created by the first amplifier (V1) multiplied by the gain $(1+\frac{R2}{R1})$. V1 is related to the photodiode current by the equation $V1 = R_f \times I_{photodiode}$. Combining these two equations results in the equation $V2 = gain \times R_f \times I_{photodiode}$. We set V2 to 5 volts, because this is the maximum voltage the board can read. We also set $I_{photodiode}$ to 2×10^{-8} amperes, because this is the reported current at UV index 12 (Figure 9). From here, we could then "plug and chug" different resistor values in for the gain and R_f that satisfy this equation. The resistor values we decided on are as follows: R_f = 820k, R2 = 820k, R1 = 2.7k, and $R_{||}$ = 2.7k. To ensure we did our math correctly, we again used the Arduino UNO and serial monitor to see if the board would read different voltages in response to changes in light. The board did in fact respond as expected to changes in light intensities, so the next step was to design the algorithm to correlate the voltage readings to sunburn risk.

The algorithm relies on several data sheets and UV index data. Basically, the Trinket reads the voltage from the current and then calculates the original photodiode current. The Trinket then calculates the UV index that caused that current to be made. Then, the UV index is weighted against the approximate time until sunburn occurs for the appropriate UV index. This process is repeated once every 30 seconds while the wristband is powered on. The Trinket creates a running list of the most recent 10 minutes' worth of times-until-sunburn, or 20 total data points. Every 30 seconds, the oldest data point is deleted and a new data point is added. The average time until sunburn of this 10-minute collection of data points is the metric used to inform risk. Average times between 60 and 55 minutes will result in no neopixel blinking, times between 54 and 45 minutes will result in a constant green neopixel, times between 45 and 30 minutes will result in a yellow neopixel, times between 30 and 15 minutes will result in a red neopixel, and times below 15 minutes will result in a blinking neopixel.

The circuit creates spikes in voltage, not a constant response. This is because the sensor is highly sensitive to changes in UV, resulting from UV rays reflecting off clouds in different ways, and internal noise. Although the signal is not constant, the magnitude and frequency of voltage spikes correlate directly to light intensity. To get accurate data readings, the Trinket reads 50 voltages over 5 seconds and takes the average. This means higher light intensities that have more voltage spikes, of higher magnitudes, will give larger average voltages than low light intensities. To calculate the current, the algorithm utilizes the equations displayed in Figure 8. In the equation $V2 = gain \times R_f \times I_{photodiode}$, V2 will be the measured voltage and gain and Rf are both known. The equation can be rearranged to $I_{photodiode} = \frac{V2}{gain \times Rf}$, which is used to calculate the photodiode current. The Trinket then uses the constant slope of the UV Index vs. Current graph from the photodiode datasheet (9) to determine the UV index. With this UV index, we can determine the approximate time to sunburn the user has at that moment (7). These times are collected every 30 seconds and the average of the most recent 10 minutes worth of data points is used to inform risk. This system of averaging overcomes possible spikes in voltage and provides a comprehensive risk assessment. If the circuit causes a voltage spike for one, or even a couple of the data points in the running list, the average of all data points together will still be accurate. This way, if the sun peeks through the clouds for 2 minutes but then goes back, the algorithm will inform the user that they are still okay. The algorithm would only say the user is at risk if the sun was out from behind the clouds for several minutes, or enough time that the average time to burn is high enough to make the photodiode blink.

After designing the algorithm, the next steps were to test the program in different scenarios to ensure its reliability and accuracy. We tested the sensor on a cloudy day with low UV index (zero), a partly cloudy day (UV index of 0.5), and a sunny day (UV index of 1.4). We collected data and compared the UV indices that our program calculated and compared them to the official UV indices reported on reliable online sources.

After finding that our algorithm worked as expected and gave predictable, reliable, accurate data, we created the wearable bracelet. To do this, we 3D printed a two-piece bracelet. We used a metal hinge to allow the bracelet to open and close, and used a Velcro strap to keep it closed while wearing. We also transferred the breadboarded prototype circuit onto a sturdier, permanent perfboard. We glued the LiPo battery, the booster, and the completely soldered circuit (including the Trinket) onto the bracelet. The code was transferred onto the Adafruit Trinket. The final steps were to test the wearable bracelet sensor by wearing it out in the sun.

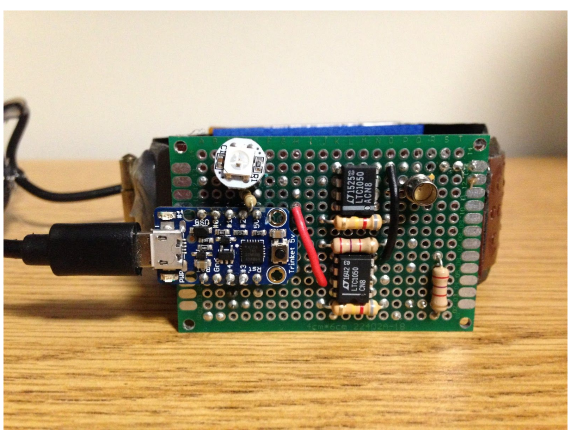

Figure 10. Final prototype UV wristband, top view. This side features the Photodiode, Trinket, and neopixel.

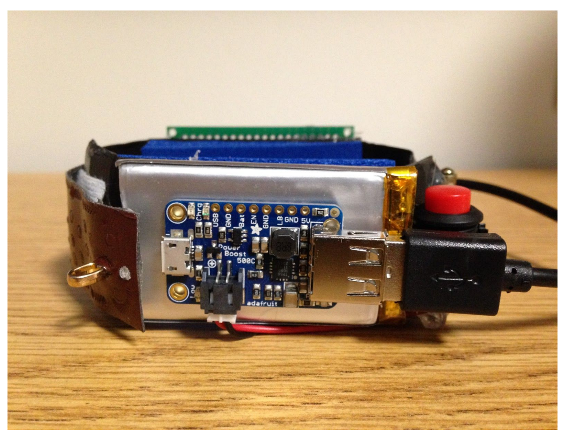

Figure 11. Final prototype UV wristband, bottom view. This side features the 1200mAh LiPo battery and the voltage booster.

Experimental Results

Cloudy Day

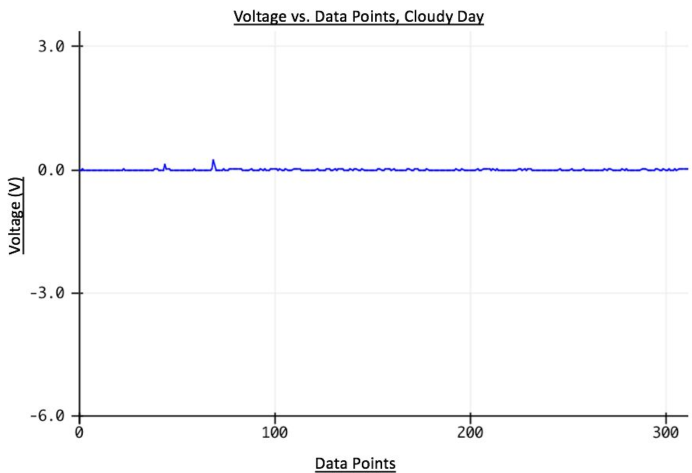

Figure 2.a. First trial of testing the device on a cloudy day (UV index of 0). Voltage read was about zero for every data point, with two small peaks around data points 45 and 70. Note: for all of the experiments, a data point was taken every 0.1 second, so 300 data points correlates to 30 seconds of using the device.

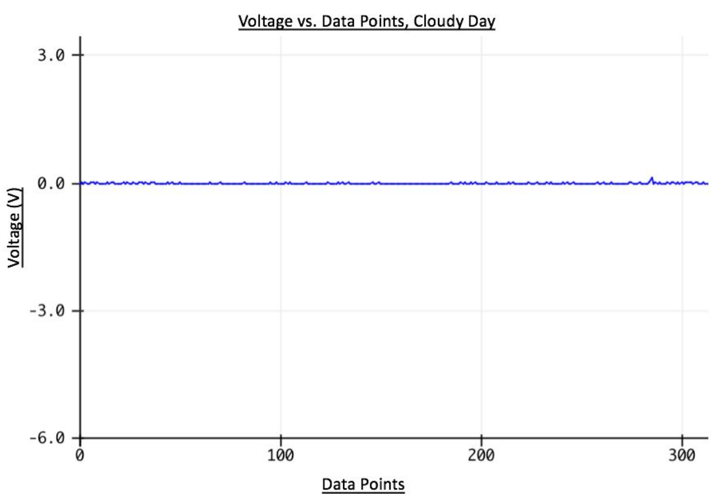

Figure 2.b. Second trial of testing the device on a cloudy day. Voltage read was about zero for every data point, with one very small peak around data point 290.

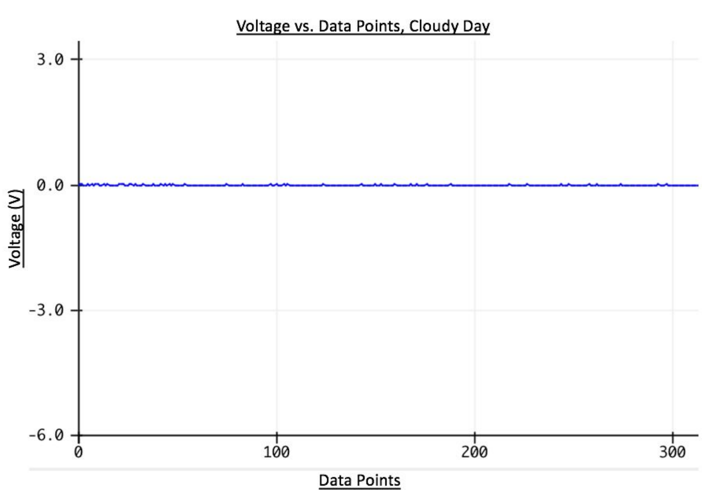

Figure 2.c. Third trial of testing the device on a cloudy day. Voltage read was about zero for every data point recorded.

Partly Cloudy Day

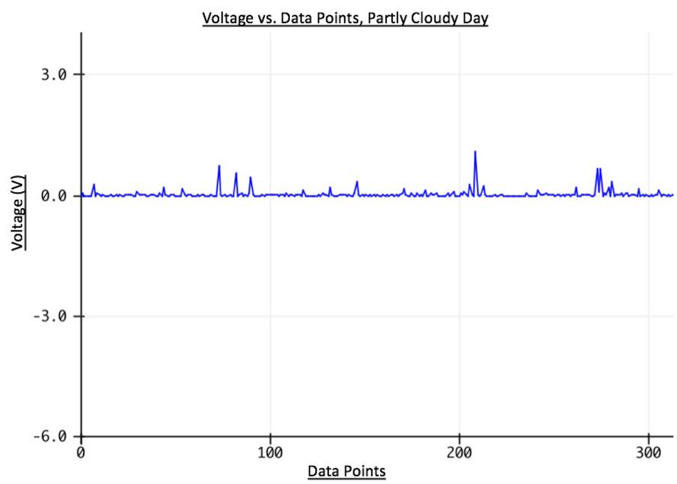

Figure 3.a. First trial of testing the device on a partly cloudy day with some sunlight coming through (UV index of 0.5). The voltage read peaked variably, with a few medium size peaks (around 1.0 V) and many small peaks.

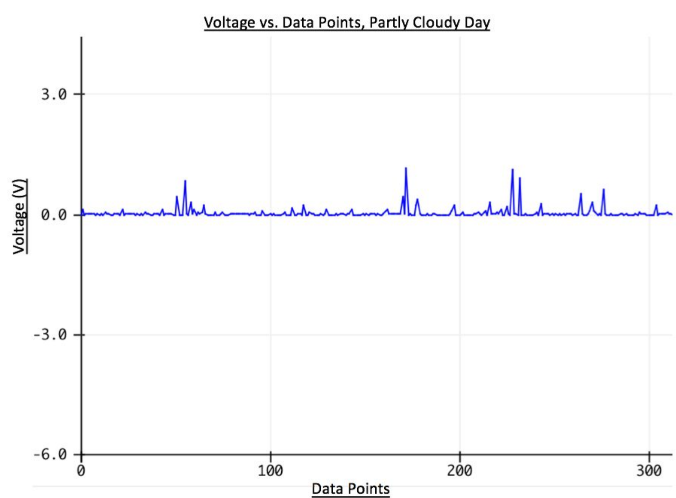

Figure 3.b. Second trial of testing the device on a partly cloudy day with some sunlight coming through. Again, a few medium size peaks were observed around 1.0 V, along with many small peaks.

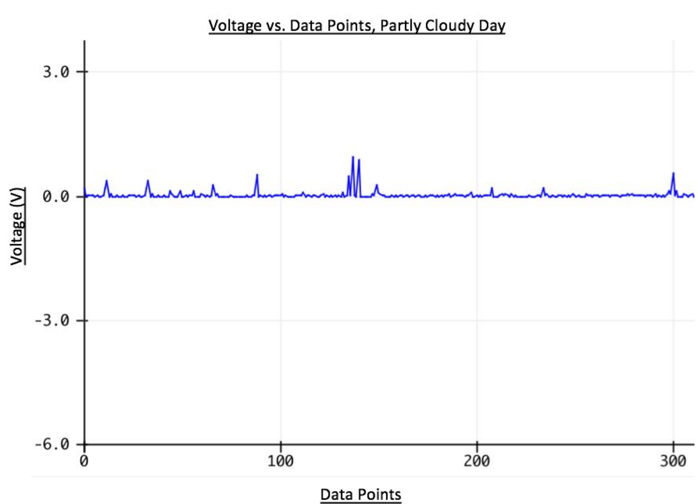

Figure 3.c. Third trial of testing the device on a partly cloudy day with some sunlight coming through. On this graph, one grouping of peaks reached medium height (around 1.0 V), and the number of small peaks was fewer.

Sunny Day

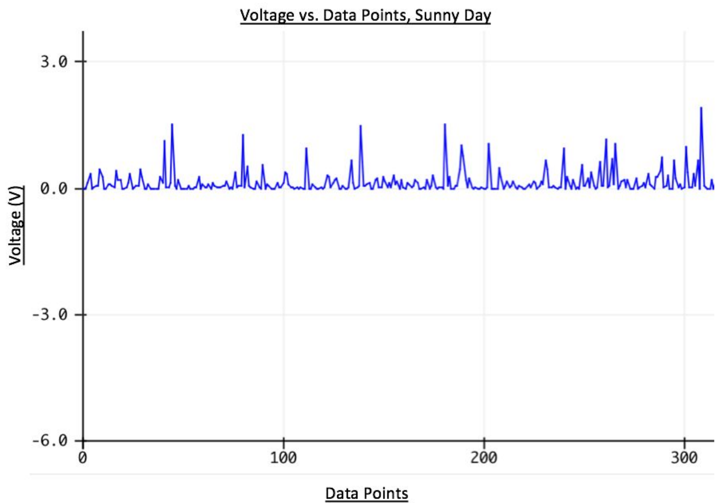

Figure 4.a. First trial of testing the device on a sunny day (UV index of 1.4). Many medium size peaks were observed, with some reaching about 2.0 V. At almost no points did the device record a reading of zero.

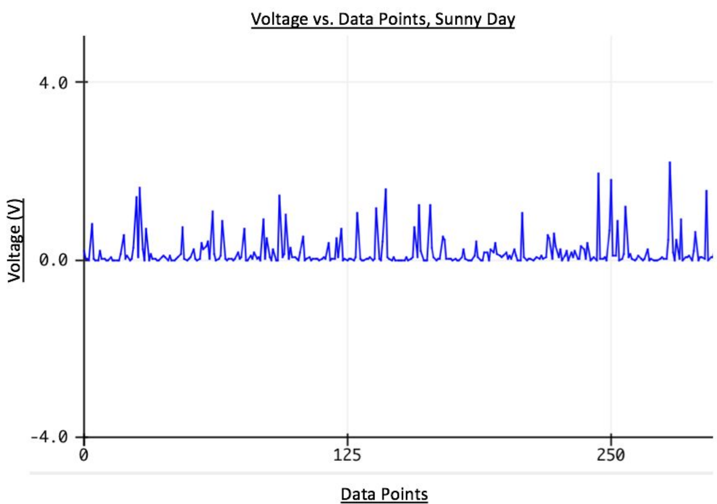

Figure 4.b. Second trial of testing the device on a sunny day. Again, many medium size peaks ranging from 1.0-2.0 V were observed, and small peaks filled the areas between larger peaks.

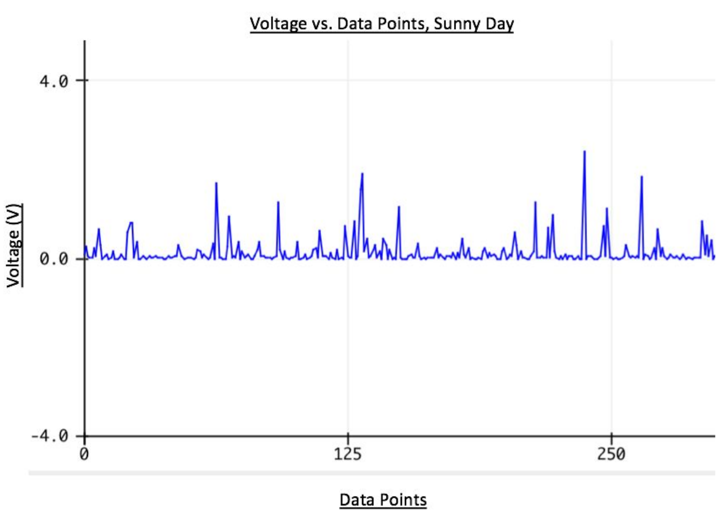

Figure 4.c. Third trial of testing the device on a sunny day. Many medium size peaks between 1.0 and 2.0 V, though slightly fewer than in the first and second trials.

Device Responsivity

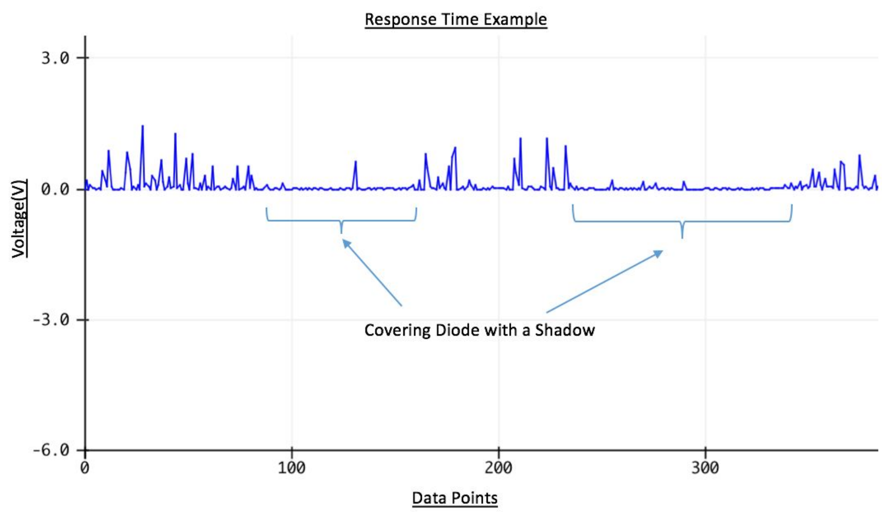

Figure 5. This data demonstrates the sensor's ability to respond in real time. Data was taken outdoors on a sunny day. The shadow was caused by placing a hand over the diode to block the sun, making sure not to touch the metal casing.

Note: the nature of our data was not conducive to evaluating standard deviation or including error bars. The averages are incorporated into our code and are reflected in the average calculated times to burn.

UV Index Calculation

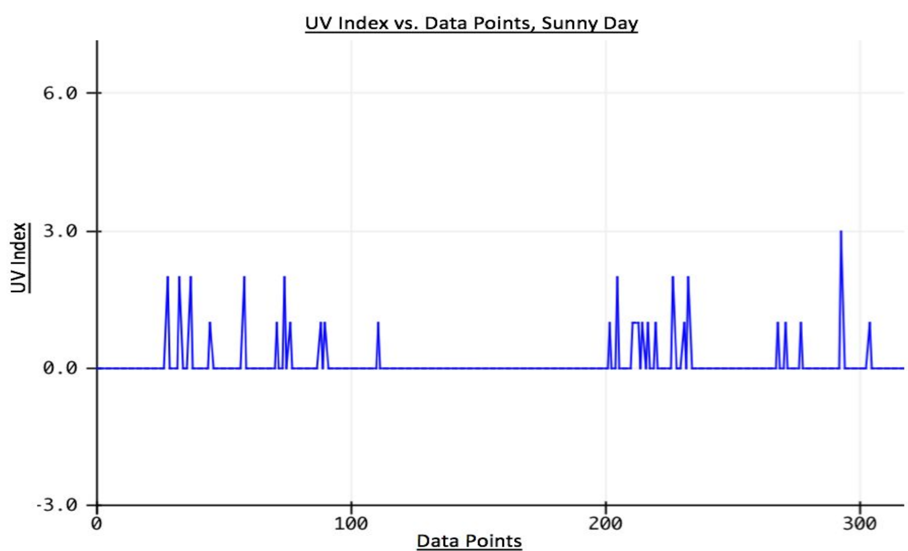

Figure 6. This graph demonstrates the algorithm's ability to calculate UV indices from voltage readings. The officially reported UV Index on this day was 1.4. The algorithm rounds UV indices up and down to the nearest integer value (i.e. UV 1.6 → UV 2).

Average Calculated Times To Burn

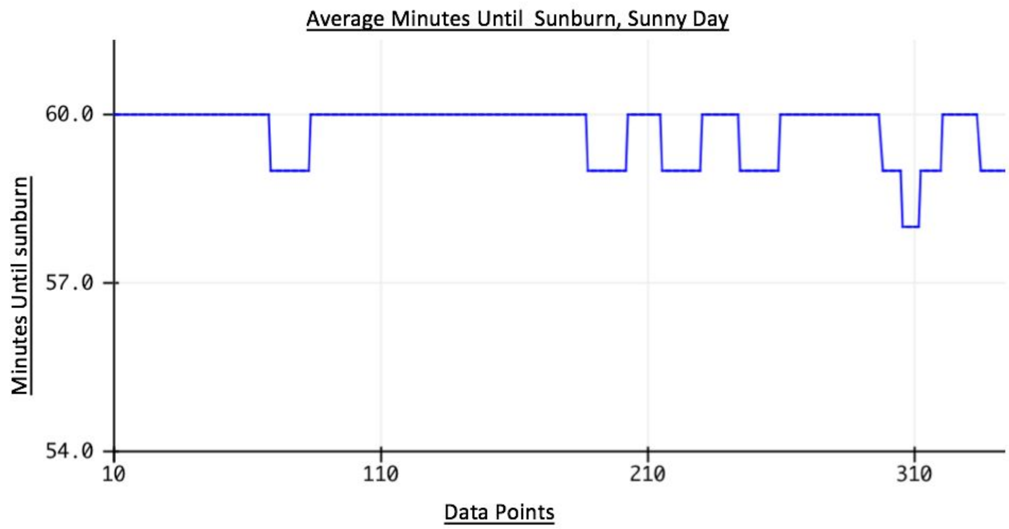

Figure 7. The calculated average time until sunburn occurs, data points taken every 100 ms. The algorithm calculated the average time to burn of the 10 most recent data point. On this day, the official UV Index was 1.4 which correlates to approximately 60 minutes until sunburn.

Discussion

The results of our experimental data using the Sun-sor circuit were consistent with our expectations, and were consistent over several trials. On a cloudy day, when the UV index forecast was 0 according to the US National Weather Service, the Adafruit Trinket consistently read a voltage of approximately 0 (Figure 2.a-c). On the partly cloudy day, when the UV index was reported to be 0.5, the Adafruit Trinket read voltages between 0.0 and 1.0 volts (Figure 3.a-c). On the sunny day, when the UV index was officially reported as 1.4, the Trinket read voltages between 0.0 and 2.0 volts (Figure 4.a-c). The amount of UV-B radiation coming from the sun directly correlates to the magnitude and frequency of voltage spikes read by the Trinket. There are many possible factors that could result in the Trinket reading a varying, spiking voltage. The circuit is very sensitive to changes in UV light intensity. Although the sun does emit an ultimately constant intensity of light, variances in the atmospheric particles the rays pass through can lead to a change in UV-B intensities from moment to moment. Also, light reflecting off moving clouds could cause the UV-B to have varying intensities. The circuit itself also produces noise that could amplify sudden small changes in UV-B radiation.

The Trinket is still able to calculate accurate UV indices even with these sometimes very large voltage spikes. By taking the average of voltage values over a period of five seconds, the algorithm still finds a relevant voltage. The average voltage of a 0 UV index day, with almost no voltage spikes at all, will be lower than a sunny day with a high frequency of large voltage spikes. In these ways, the intensity of UV-B light still directly results in accurate risk diagnosis.

The photodiode also responds quickly enough to measure sudden changes in UV intensity. Looking at Figure 5, one can see that the average voltage is substantially lower when the diode was covered with a shadow compared to open light. Data points are taken once every 100 milliseconds, so the photodiode responds in at least 100 milliseconds.

Looking at Figure 6, the photodiode measured UV indices between 0 and 3 on a day when the officially reported index was 1.4. The average of these UV index values was approximately 0.9. Even though the photodiode did not measure the exact reported UV index on this day, the nature of the UV index scale allows room for error and approximates. UV indices 0 through 2 all correlate to 60 minutes until sunburn, UV indices 3-4 correlate to 45 minutes until sunburn, and the trend continues for multiple UV indices having the same times until burning (7). The damage that UV-B rays cause to skin at UV index 3 will be very similar to the damage UV-B rays at UV index 4 will cause to skin. Additionally, the times until sunburn may occur are calculated for the group at highest risk of skin damage by assuming the user is light-skinned with very little melanin in their skin cells. For this reason, calculating a UV index within +/- 0.5 of the actual UV index will still result in accurate times until burning. Taking the average of many data points over several minutes assists in accuracy as well. If the Trinket reads a UV index of 3 and puts 45 minutes until burning in the list, due to a spike in voltage, when the actual UV index is only 1.4, taking the list average will make the spike negligible. Most of the other UV index values in the list will be times for UV indices of 0 and 1, so the weighted average of many 60 minutes data points and a few 45 minute data points result in times still very close to 60. Figure 7, which shows the times until sunburn from the sunny day voltage and UV index data, indicates that the average time until sunburn ranges from 60 minutes to 58 minutes. The neopixel will remain unlit for any times between 60 and 55 minutes, so the occasional spikes in reading will have no effect on informing the user of risk. Likewise, the Trinket will show the same color for times to burn between 54-45 minutes, 44-30 minutes, 29-15 minutes, and 15-0 minutes. Taking the average of the averages and informing risk using scales of values both make the algorithm both consistent and accurate.

Overall, our readings had a strong correlation to the actual UV index values and the resulting times until sunburn. These results support our initial target, as the photodiode successfully converted the photons in the incident UV-B rays into a current which was amplified and measured as a voltage drop by the Adafruit trinket, with values that are accurate for the expected current for each UV index value provided on the data sheet (9). The algorithm then converted the UV index into a correct approximate time until burning. The average of a running list of these times created an accurate and reasonable time until sunburning occurs, which made the neopixel blink different colors accordingly.

The device could be improved in many ways. One of the best improvements would be to use a photodiode with a wider viewing angle. This would allow the sensor to detect more of the

UV rays that are present and cause the voltage readings to be more consistent instead of spiking. The photodiode currently has a 55˚ viewing angle, meaning that rays that approach at a wider incident angle are not detected. If the user is wearing their bracelet with their arm down to the side, or not directly facing the sun, the photodiode will likely record lower than normal voltages and higher resulting times until burning values. Another improvement would be to power the bracelet with a solar battery cell. This makes perfect sense as the bracelet will most likely be worn outdoors most of the time. The overall bracelet design could be improved, with a rubber material and some type of clip system to secure the bracelet instead of velcro. The bracelet should also be smaller/thinner. To accomplish this, we would need to make the circuit smaller as well. The bracelet would then be sleek and fashionable as well as small enough to not interfere with any daily activity. Another amendment to the bracelet would be to enclose the circuit completely so that the bracelet could be waterproof. This is crucial to the success of the product because users need to be able to wear the bracelet while performing any outdoor activity they desire. The bracelet would be resistant to sweat and rain, and could even be completely submerged in water during swimming or other water activities. Finally, we would connect our device to an app that allows users to track their long term UV exposure on their phone. The neopixel would still alert users in real time when they are in danger, so users do not need to have their phones on them during outdoor activity. However, the Adafruit trinket will send data to the app so the total exposure over many days could be stored. The user would also be able to input data on their specific skin type and family history of skin cancer. The app would then provide cumulative data on the user's skin damage that is personalized and specific. This would provide the benefits of a phone app combined with the crucial alerting of the user in real time, before the damage has already occurred.

Branding

Our company name is The Sun-sor™. Our logo is shown below:

The name of our first product is "The Sun-sor 1.0." We do not yet have a website, but plan to incorporate a phone app to collect and store the data from each use to provide data on cumulative UV exposure. Our company's mission is to provide all people with information that allows an individual to optimize their time outdoors by knowing the exact risks they face from the sun's rays at any given time. Our vision is to be a worldwide leader in the fight against bodily damage from the sun. Some of our principles include providing clear information and instructions for users to follow, warning users before damage occurs, providing highly accurate data, and listening to feedback from customers to ensure satisfaction with our product is high. In a sentence, our company is the future of skin protection from the sun for people around the world.

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Acknowledgements

For this project, Noah was in charge of the electronics. He determined the setup of the circuit, soldered the components together, and wrote the code in the Arduino IDE to make the device run. Two lines of code were copied from an online DIY Science blog (8) to read the voltage across the Trinket pins. Three libraries were utilized as well, including two standard libraries, “math” by Arduino and “Adafruit Neopixel” by Adafruit, and a user-created linked list library called “Linked List” found on github (12). A breadboard, Arduino, wires, and soldering instruments were used courtesy of the Tufts Crafts Center, and various resistors were used from Bray Laboratory. The Adafruit Trinket, voltage booster, lithium-polymer battery, photodiode, and amplifiers were provided by Tufts University in a supplies budget for this project. Allie was responsible for the physical backbone of the bracelet. She took measurements and, with the rest of the team, determined the desired aesthetics of the product. She then designed the schematics for the bracelet using online CAD software, and 3D printed the result using the 3D printers in the Silk Lab. Emily performed much of the background research, including the exact mathematical relationship between UV intensity and skin damage risk, as well as the biological association between UV radiation and skin cancer. Emily and Allie worked together on the branding for the company, and the entire team worked together to create the algorithm for determining an individual’s time to burn. The entire team additionally collaborated on writing and preparing all presentations and papers. The entire algorithm and more detailed images can be seen at https://github.com/nhill03/UV-Light-Sensor/issues/1.