

Report on

Plant Precept

Funded by the Kohler Fellowship
at the Wisconsin Institute for
Discovery

Meg Wilson and Tanuj
Kumar



Introduction

Our collaboration started with brainstorming a list of ideas to pursue. We started off with many ideas touching the themes of ecological art and playing with light, and we settled on two to choose from. Our first idea was connected to Tanuj's Ph.D. research on light as a force used for propulsion - there are scientific applications out there utilizing the force of light impinging on a surface, and this makes for an interesting art piece mainly because light is not something we associate feeling forces with. Further, the light itself can be invisible to humans (infrared, for example) for this piece making it even more intriguing to a viewer if an object were to move apparently with no force acting on it. However, we did not go ahead with this idea because it would require powerful sources of light. This and ensuring the safety of viewers isn't impossible to deal with, but would require a lot of engineering. We went ahead with our second idea – *Plant Precept* – portraying the color of light that plants perceive, as opposed to the familiar green we humans see all the time.

With *Plant Precept*¹, we wanted to explore the color of light perceived by plants using their absorbance/reflectance spectra, and mount an exhibition for people to experience that. We wanted to take a concept familiar to viewers and turn it on its head to make them question what goes on behind the scenes, something common to both scientists' and artists' pursuits.

The following sections talk about the science involved in this idea, the exhibit design, and some of the logistics we dealt with while working on the project.

Photosynthesis, light spectra, color calculation, and dichroic glass

Photosynthesis

Photosynthesis is the well-known process by which plants utilize mainly carbon dioxide and water (but also other components) to create carbohydrates, which plants use as food. This process generates oxygen, and very crucially requires light to run this whole process. While the process of photosynthesis is quite complex, in our project we focus on the essential role of light.

While Tanuj's Ph.D. research explores and engineers how light interacts with matter, the process of photosynthesis goes one step further in that it is literally life-giving, not only to just photosynthetic organisms but to all living things.

¹ "Plant Precept" is the title of the show that we eventually came to. "Precept," meaning something like a moral command or statute, makes this title engage the ethical question of how audiences are morally obligated to live when they consider the lives of plants and plant needs.

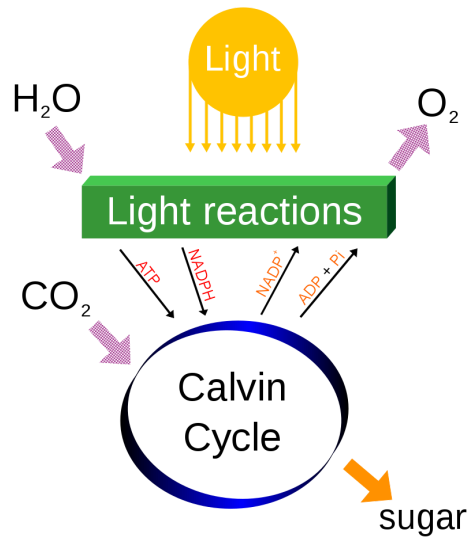


Fig. 1: A schematic of photosynthesis, wherein H_2O and CO_2 are converted to O_2 and sugar using light in photosynthetic species.

Source: By Daniel Mayer (mav) - original imageVector version by Yerpo - Own work, CC BY-SA 4.0, <https://commons.wikimedia.org/w/index.php?curid=20722530>

Further, photosynthesis is one of the most fundamental concepts taught in schools, so this is a great opportunity to get the general people thinking about the science of light. We all know and experience everyday that leaves are green in color, and that too in many shades of green. This is only more apparent in fall when the green is replaced by vibrant reds and yellows. The green color that we see is the result of daylight reflecting off of the leaves; what's interesting to note is that if daylight is white-ish yellow in color and leaves are green, then some colors are being reflected more than others.

In order to quantitatively look at the reflected and absorbed colors, we must first look at the spectrum of light.

Light spectra

Natural light sources, including the sun, are composed of a continuous spectrum of light. Humans only see wavelengths in the visible spectrum, but ultraviolet and infrared light are also of interest. Plants rely on some visible wavelengths more than others for photosynthesis, and it is this fact that gives them their characteristic green color. In broad terms, red and blue light is absorbed; green is reflected.

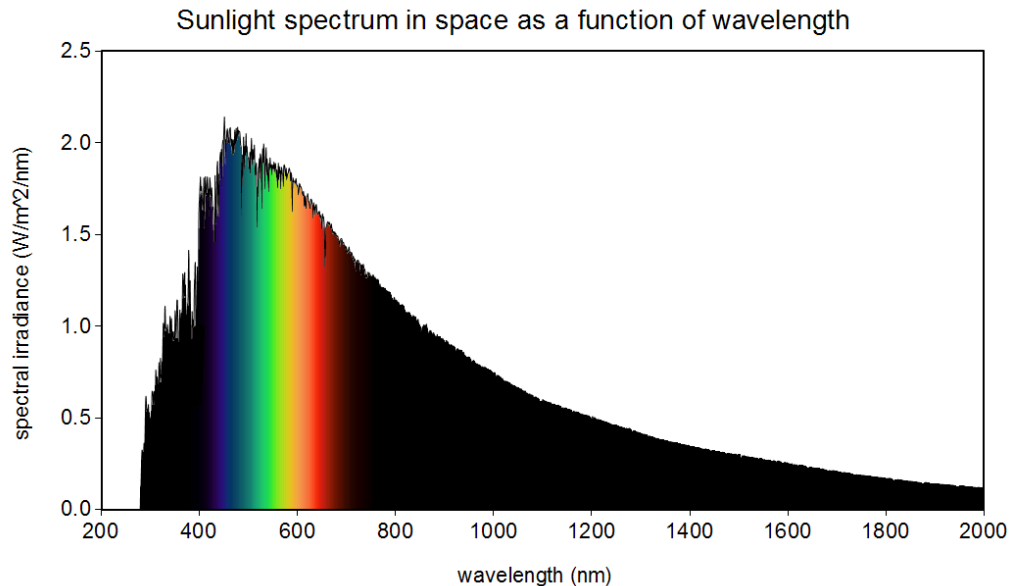


Figure 2: Spectral irradiance of sun as a function of wavelength. Wavelengths from the ultraviolet to the infrared are shown here. The colorful part of the spectrum corresponds to human vision, with a visualization of all the colors involved. Source:

<https://www.wtamu.edu/~cbaird/sq/2013/07/03/what-is-the-color-of-the-sun/>

Note that the spectral irradiance of the sun (how intense light is at a given wavelength) is not uniform across the spectrum. It peaks around 500 nm (please note that the peak changes depending on whether you look at the wavelength or the frequency or number of photons), and objects look different in daylight than under a light source that has the same spectral irradiance for all wavelengths. This is an important fact to consider when calculating the color of a given object from its reflected spectrum.

Color calculation and the XYZ color space

For this project, since we chose to represent the color that a plant would “see”, we needed to calculate the color the spectrum absorbed by a plant. It is possible to calculate the color a human would see for a given spectrum because we know how the human eye responds to different wavelengths of visible light.

Photoreceptor cells in the human eye are of two types - rods and cones. While rods help with low-light vision, cones are responsible for color perception in the human eye. Cones are further divided into three categories, depending upon their spectral sensitivities (short (S), medium (M) and long (L)). This means that to figure out the color that a human would see given a light source corresponding to a particular spectrum, we would have to calculate how each of the L, M and S cells respond to this light. Almost a century ago, scientists conducted experiments that found out exactly this, and thanks to those experiments it is easy to calculate color from any given spectrum.

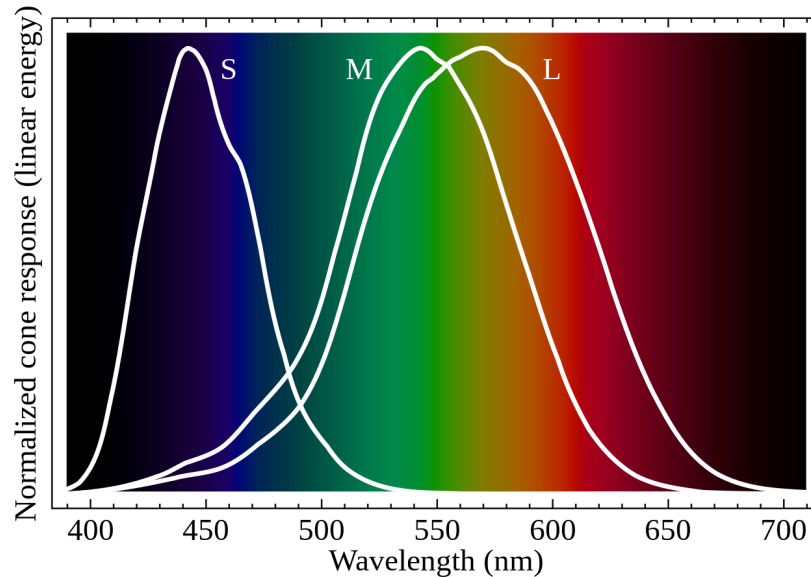


Figure 3: Responses of S, M and L cone cells to different wavelengths of visible light. Source: https://en.wikipedia.org/wiki/Cone_cell#/media/File:Cone-fundamentals-with-srgb-spectrum.svg

For this project, since we chose to find out the color that a plant would “see”, we applied what is known about the LMS response to the light that is absorbed by a plant. Loosely speaking, this would be all the light that is not reflected by a plant, although in the strictest sense we would also have to account for light transmitted through the leaf. This was thus an exercise in figuring out what is absorbed by a leaf, and what color is perceived by a human given that absorbed light.

The Red-Green-Blue (RGB) colorspace is well-known, but it is only an approximation of the possible colors perceived by humans. It works well with digital devices like the one you’re reading this on right now, but to accurately figure out the color of a given spectrum, the XYZ color space is much more appropriate (this colorspace stemmed from the experiments conducted nearly a century ago). The XYZ color space accounts for the response of each of the L, M, and S cones. Given a spectrum of light, a “multiplication” of the LMS response and the light spectrum gives an idea of the amount of stimulation given to each cone. Then, the sum of all of those stimuli describes the color an average human would see.

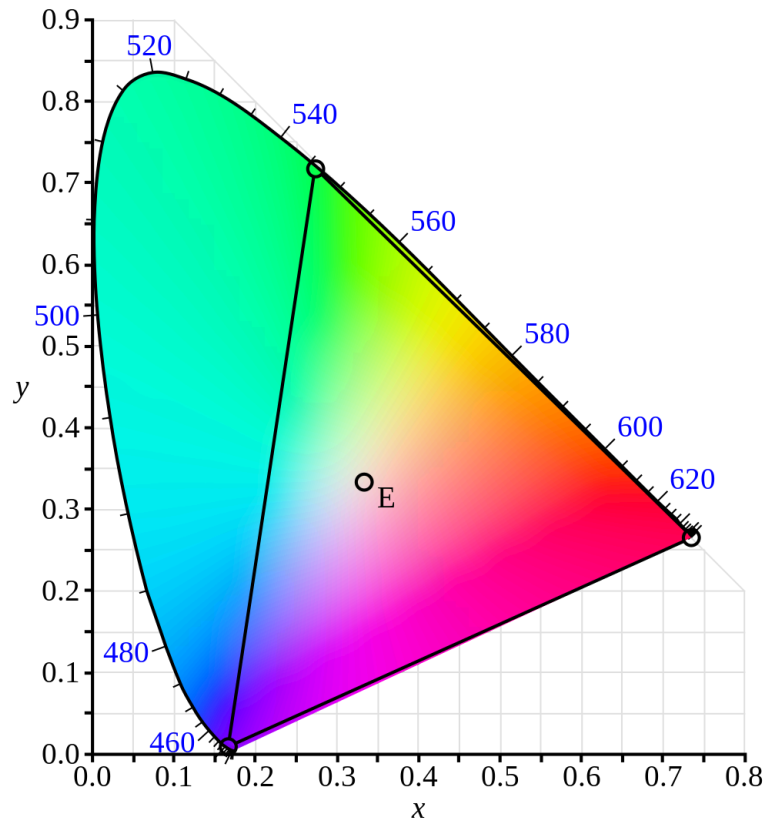


Figure 4: A representation of the XYZ color space. Note that the XYZ space is a 3D space, so it is often represented in 2D form as the xy color space, a derivative of XYZ. xy space does not account for brightness, but it presents different hues of colors. Source:

https://en.wikipedia.org/wiki/CIE_1931_color_space#/media/File:CIE1931xy_CIERGB.svg

With the help of ChatGPT, I wrote code in MATLAB (appendix 1) to calculate the color a given spectrum would produce under daylight lighting. We then used this code to calculate the color a leaf would perceive. It was first tested with reflectivity data of oak and walnut leaves from the US Geological Survey (USGS) database, and was subsequently used to find the absorbed color of Chlorophyll a, Chlorophyll b and beta-carotene.

The US Geological Survey (USGS) maintains a hyperspectral database of reflectivities in the visible and near infrared of plants, minerals, soils and other useful materials. Hyperspectral refers to a spectral resolution of 1-2 nm, from roughly 380 nm to 1000 nm. For calculating the XYZ space color, data between wavelengths of 380 nm and 780 nm is required.

The reflectance database is useful because I assumed leaves transmit very little light, which means whatever light is not reflected, must be absorbed and I could calculate the color of the absorbed light. However, this is a point of debate, because as Meg pointed out, there can be non-trivial amounts of light being transmitted through a leaf which would result in slightly different colors. This remains to be checked in the lab by me.

XYZ (D65/2°) = 17.2 8.21 60.27				
sRGB	0-255	=	101.205	29.096 207.890
sRGB	0-1.0	=	0.39688	0.11410 0.81526
RGB	Adobe 98	=	88.265	34.582 202.846
HSL	0-1.0	=	0.73388	0.75444 0.46468
HSV	0-1.0	=	0.73388	0.86004 0.81526
HSI	0-1.0	=	0.73388	0.74190 0.44208
CMY	0-1.0	=	0.60312	0.88590 0.18474
CMYK	0-1.0	=	0.51318	0.86004 0.00000 0.18474
CMYK	0-100	=	51.318	86.004 0.000 18.474
XYZ		=	17.200	8.210 60.270
Yxy		=	8.210	0.20075 0.09582
CIE-L*a*b		=	34.416	65.501 -77.289
CIE-L*Ch(ab)		=	34.416	101.311 310.281°
CIE-L*u*v		=	34.416	7.330 -106.603
CIE-L*Ch(uv)		=	34.416	106.854 273.934°
HunterLab		=	28.653	59.469 -110.299
Pre-formatted code:				
CSS, HTML		=	#651DD0	
Java		=	new Color(101, 29, 208)	
.NET		=	Color.FromArgb(255, 101, 29, 208);	
Objective-C		=	[UIColor colorWithRed:0.39688 green:0.11410 blue:0.81526 alpha:1.00000];	
OpenGL		=	glColor3f(0.39688f, 0.11410f, 0.81526f);	
Swift		=	UIColor(red:0.39688, green:0.11410, blue:0.81526, alpha:1.00000)	
Xojo		=	rgb(101, 29, 208, 0)	

HEX CODE

xy: ■ (0.2009, 0.0958) | CCT: 1,812 K | Duv: 0.0005 | CRI (Ra): - | R9: -

Calculate CIE 1931 xy Coordinates from Spectral Power Distribution (SPD)

This online CIE 1931 xy calculator takes a spectral power distribution (SPD) input in either 1 nm or 2 nm resolution, and calculates the CIE 1931 xy coordinates. Click on "Input SPD" to load your SPD. Several notes on the SPD input:

- For best results, copy and paste irradiance data from a spreadsheet program or plain text editor, with line breaks between each wavelength data point.
- Wavelength range is 380 - 780 nm.
- Irradiance values are in arbitrary units. The calculator will automatically normalize all values.
- Need to convert from a CCT value to CIE 1931 xy instead? See our [CCT to CIE xy calculator here](#).

INPUT SPD

SPD Input

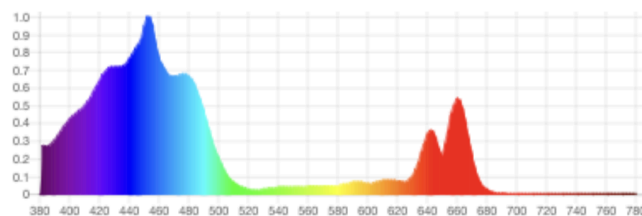


Figure 5: the results of calculations by the web calculator <https://www.waveformlighting.com/tech/spd-to-cie-xy-calculator>. For the final resulting color from this process, see the small square at the top of the image in the gray bar (next to xy coordinates (0.2009, 0.0958)).

We tested the expected color of a sample from the USGS database with both our MATLAB code as well as an online calculator², and were surprised to see different colors, though close to each other. See Fig. 5 for comparison. We reason that this discrepancy in colors was due to one or more of the following:

1. The brightness in the world of color is subjective, and the color calculated from a spectrum must manually be adjusted for brightness.
2. We do not know how the online calculator works or the light source it assumes, and that can lead to differing colors.
3. The reflection spectrum of an object, which we use to find its color (after all, every object we see is because of light reflected off of it), can be scaled up and down manually, changing its color.

Further exploration with the online calculator and different spectra for different photosynthetic pigments in leaves resulted in the following results for chlorophyll a, chlorophyll b, and beta carotene:

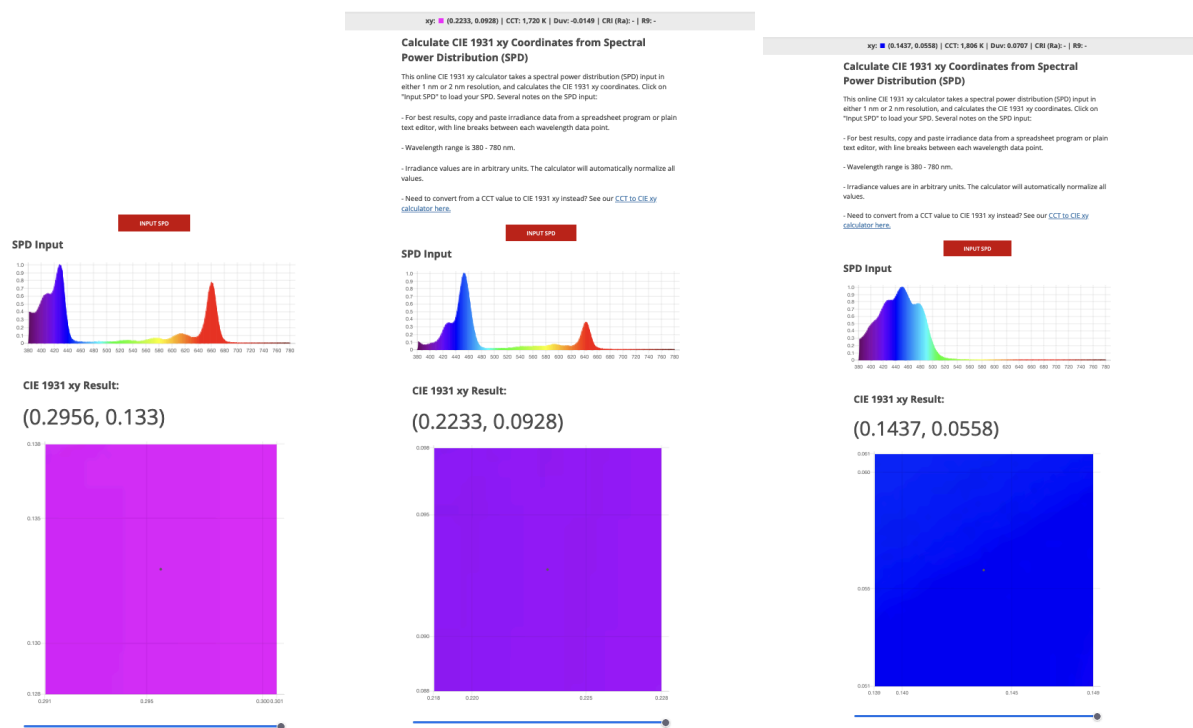


Figure 6: three separate calculations indicating the absorption spectra of chlorophyll a, chlorophyll b, and beta carotene.

² <https://www.waveformlighting.com/tech/spd-to-cie-xy-calculator>

Because the photosynthetic pigments are present in leaves in unequal amounts, utilizing common percentages of each pigment, Meg planned the wall projection to show these shades in the following manner:

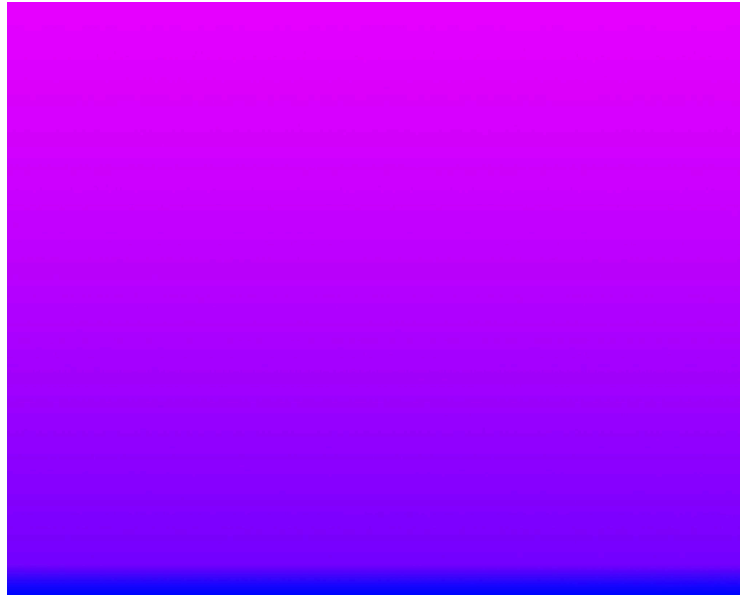


Figure 7: Planned wall projection showing the gradient of absorbed light from chlorophyll-a to chlorophyll-b to beta carotene.

Dichroic Glass

We decided to use dichroic glass to represent the reflection of green light and absorption of everything else (magenta). See figure 5 for some dichroic glass samples.. Dichroic glass is normal glass coated with alternating thin films of high and low refractive materials. For example, Schott Narima® glass uses metal oxides for this purpose.

While it is perfect for our artistic representation of the interaction between light and leaves, it also represents an important photonic concept of thin-film interference (figure 6). Stacks of thin-films close to the wavelength of light in thickness will either suppress or enhance certain wavelengths, and this can be engineered by choosing different materials and thicknesses. Further, thin-film interference is angle-dependent, meaning that dichroic glass appears to have a different color depending on the angle it's viewed from. This was an important point to consider for the exhibition design, as the mirrors could only be mounted at a certain angle to the wall to get the right colors to be transmitted (magenta) and reflected (green).

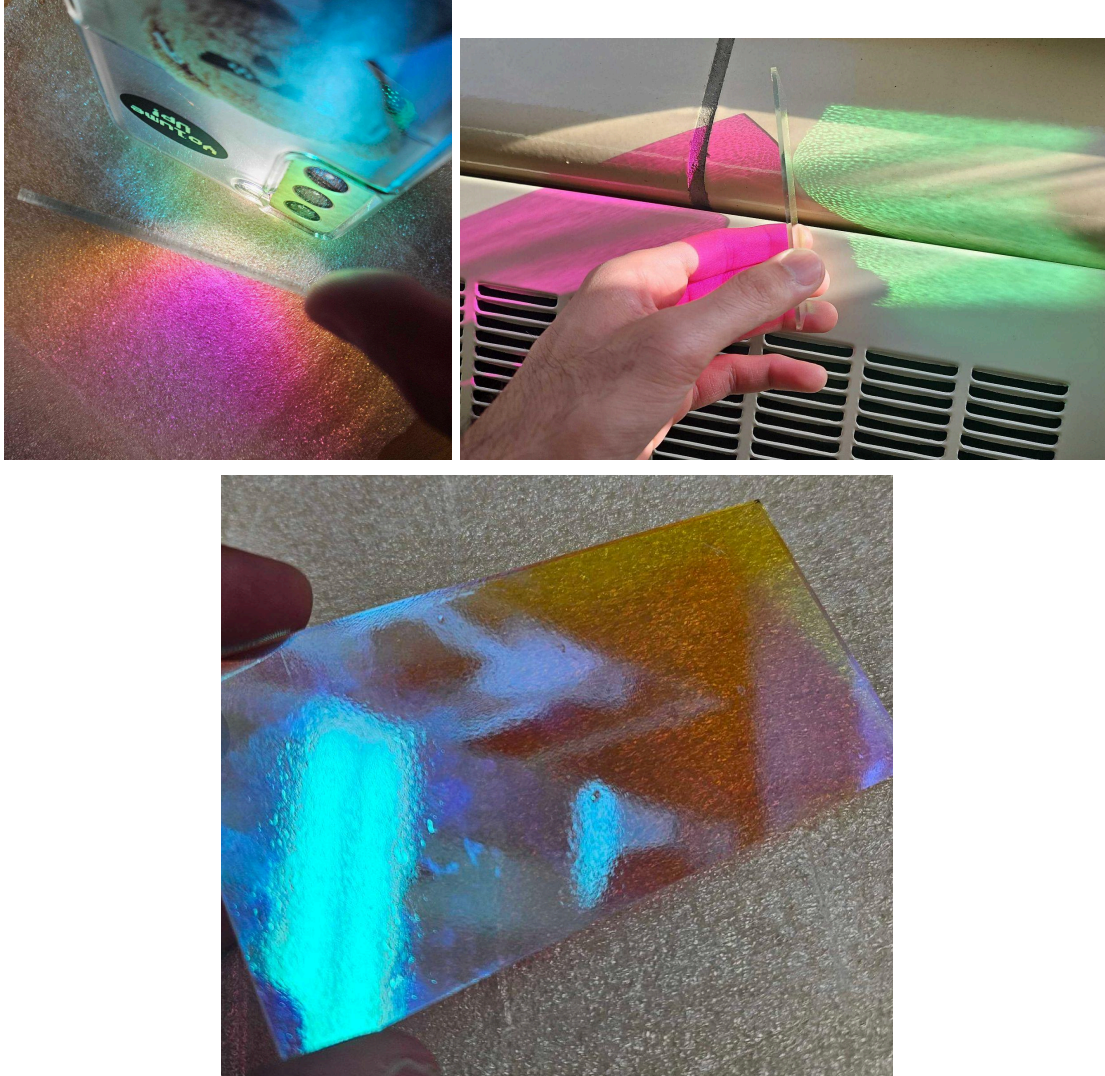


Figure 8: Some pictures showing how light interacts with dichroic glass. Note that in the third picture, the reflected light isn't exactly green due to the angle of photography.

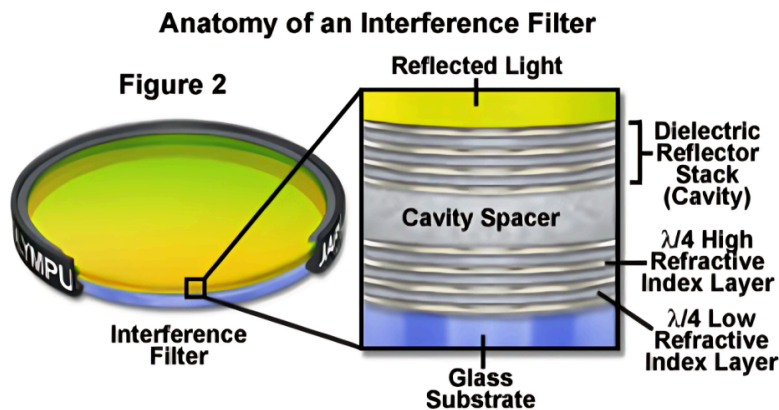
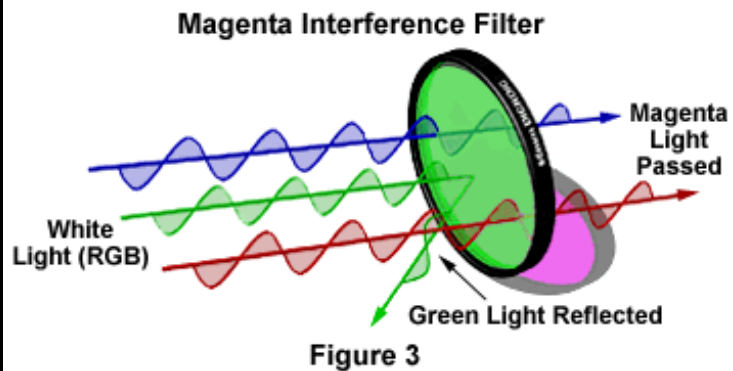
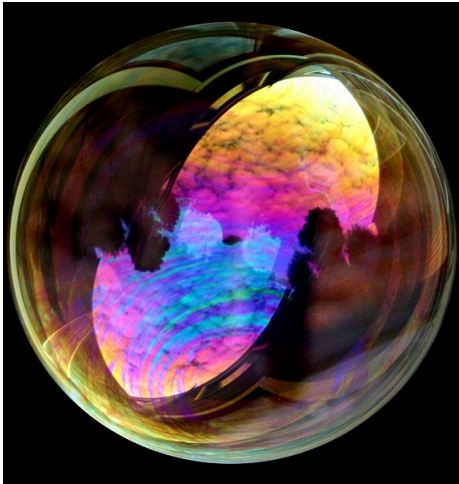


Figure 9: Vivid colors on the surface of a bubble are examples of thin-film interference that we see in everyday life. The second figure is a schematic of how green light is reflected and magenta transmitted in dichroic glass. The third figure is a close up of the thin films that cause interference to give dichroic glass its properties. Sources: https://www.physics.louisville.edu/cldavis/phys299/notes/lo_intthinfilm.html, <http://www.olympusconfocal.com/gfp/primer/lightandcolor/filter.html>, <https://www.advancedoptics.com/dichroic-filters.html>

Project logistics

Ordering dichroic glass

We tried samples from multiple vendors to make sure that the reflected and transmitted colors of their glass samples were what we wanted for the exhibit. We started with Two Way Mirrors LLC, but they only offer glass that transmits green light, the opposite of what we required. We then tried Artglasssupplies.com, who had the right kind of dichroic glass available. However, through this process we learned that ordering test samples from different vendors takes time (and there can be mistakes like when Tanuj ordered the wrong glass). There are two takeaways here -

1. Call vendors instead of waiting for them to reply over email, explain to them your requirements and understand their limitations and turnaround times.

2. Start this process early, and probe multiple vendors in parallel. In our case, January would've been a good time to try out multiple samples and settle on one comfortably before our show.

Exhibit concept

We visited several gallery spaces together, including all of the available galleries on UW campus, and multiple off-campus galleries. We decided that the Art Lofts gallery was the best option we had available, and booked it for a show.

Meg curated a selection of several additional artists to invite to participate in the show so that the large gallery would be utilized to the most striking impact. Those artists who agreed to join a group show titled Plant Precept were Anamika Singh (UW Madison), Gracie Baer (Iowa), and AJ Theirault (UNM). Meg made plans with each of these artists for the installation of their works, deinstallation, and storage of the work until it could be picked up again. Each artist creates work that engages with the politics of place and environment in the contemporary moment. Here are samples of each artist's work:

Anamika Singh

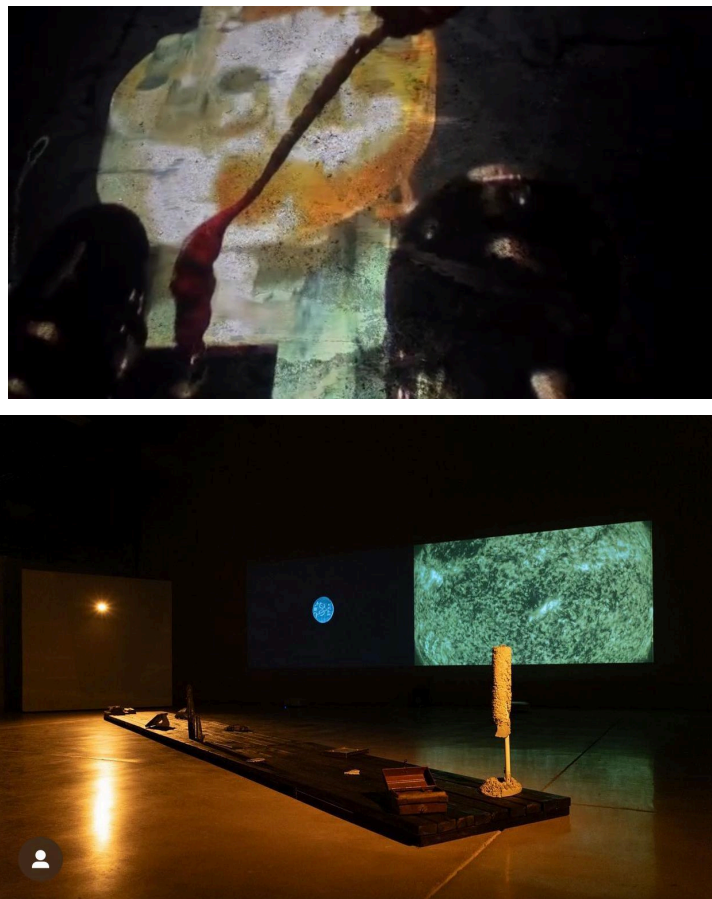


Figure 10: Samples of Anamika Singh's works involving video projection and 3D installation

AJ Theriault

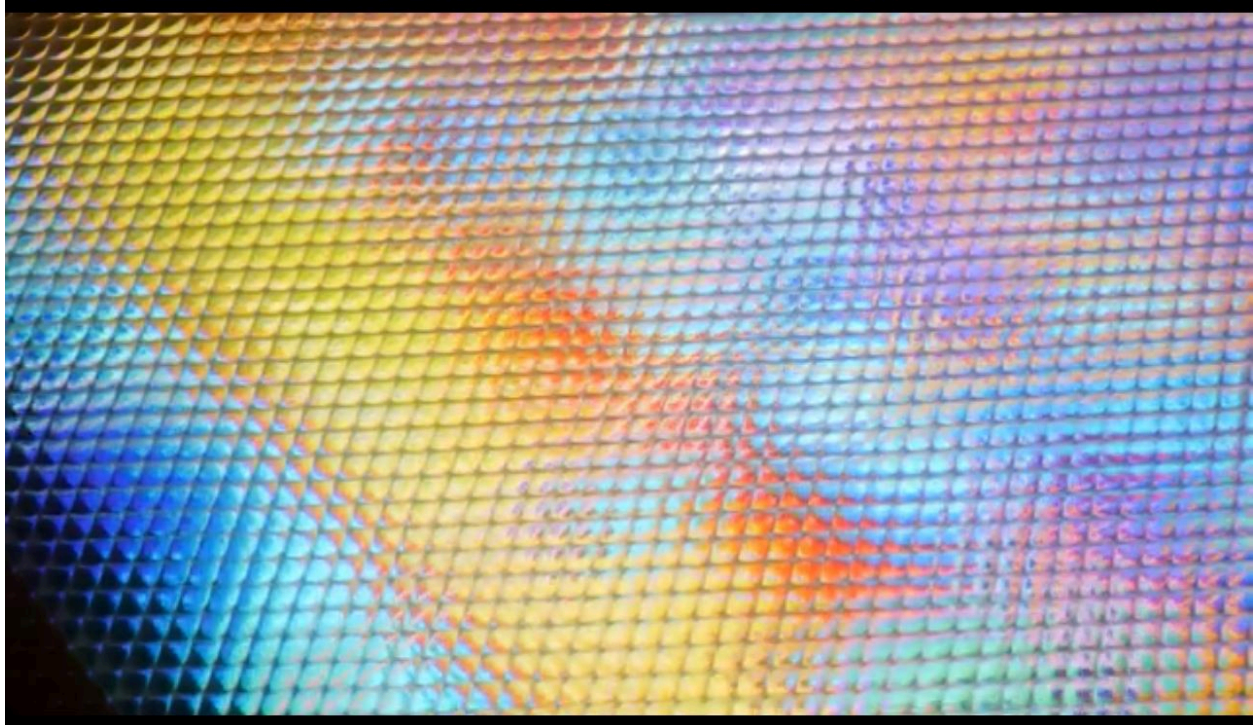
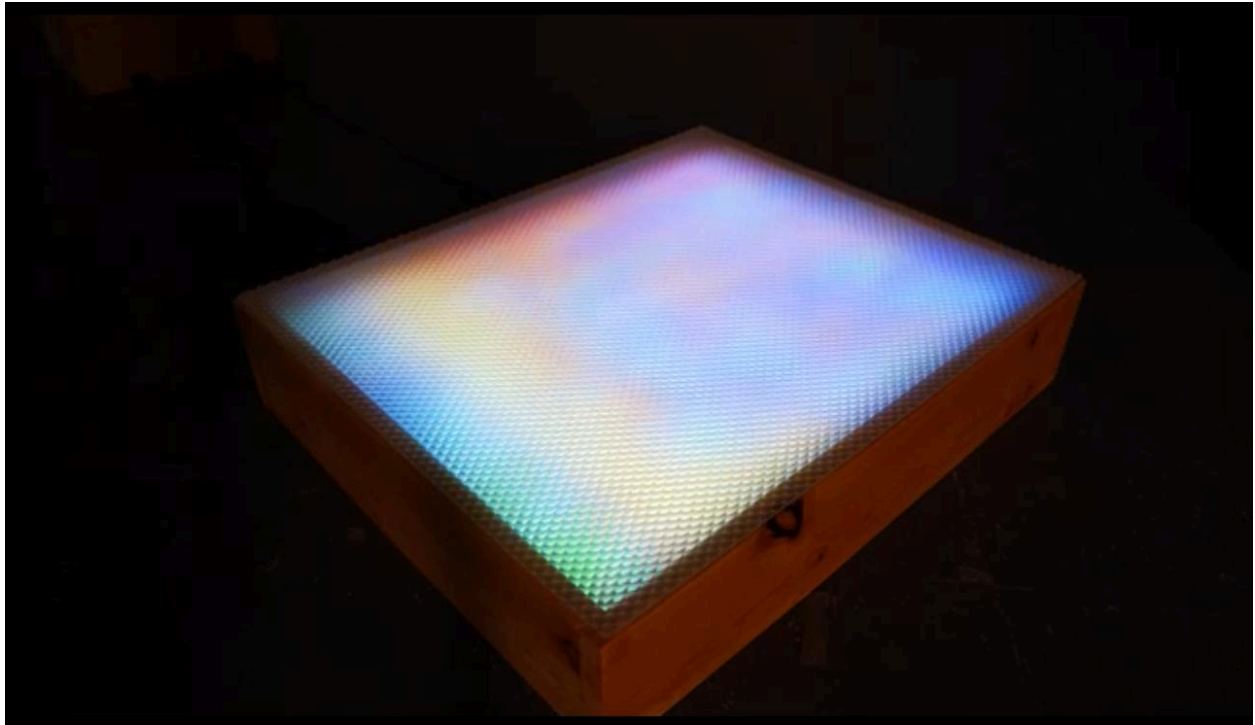


Figure 11: AJ Theriault: biomimicry and the cyclical inter-functioning of living systems
Here is a Sculptural Video Floor Piece titled "Supercell". Theriault would show two of these pieces:
<https://youtu.be/wUZqoYkBiR8?feature=shared>

Gracie Baer



Figure 12: Gracie Baer: sculpture, lens-based media, sound, and environmental installation., video playing on a screen mounted on the wall:

The show description is as follows:

“Plant Precept is a group exhibition of ecologically-concerned work. Not to be confused with Nature Art, the ecologically concerned works in this show recognize the more-than-human living beings in urban contexts and consider the porous imaginary borders between *urban* and *rural*. Acknowledging human entanglements with other forms of nature, and the complex land ethics that result when other perspectives are given as much weight as the human, the included artworks will be challenging and create new possibilities for becoming response-able to our others. Themes addressed by the works include migration, assisted migration, queer ecologies, plant senses, and the space of possibility that exists in art/science and science/art.

Art media will include light projection, sculpture, and 2D pieces (photographs and painting).

Art/science collaboration duo Meg Wilson (MFA 2024, PhD Art History 2026) and Tanuj Kumar (PhD Engineering, 2026), Kohler Science/Art Fellows 2023-2024, will curate the exhibition and will mount an installation of their project that uses projected magenta light and living plants (in

containers) to create an environment that reproduces the color of light absorbed by leaves (which do not absorb the green light) as they utilize sunlight to make our worlds liveable.

If our proposal is accepted, we issue invitations to a select group of Madison artists whose work participates in the same conversations.”



Figure 13: Meg Wilson and Tanuj Kumar: Wall projection with plant installation, freestanding wall piece with dichroic glass.

Gallery layout plan:

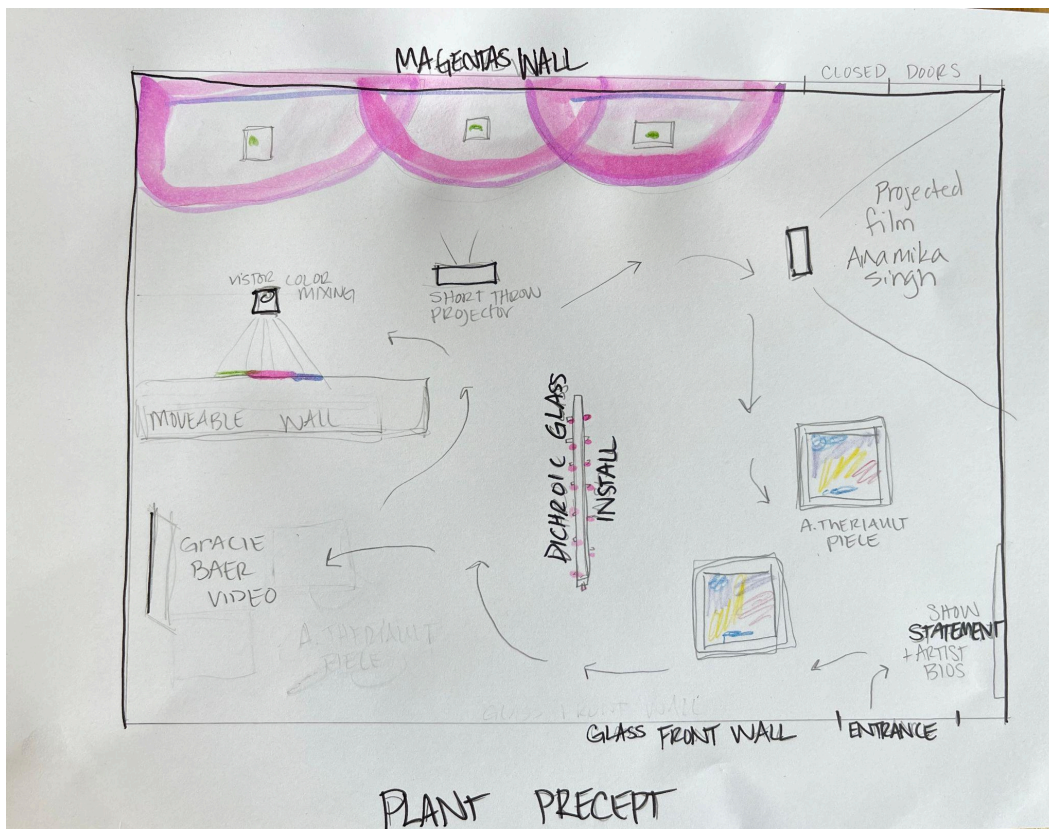
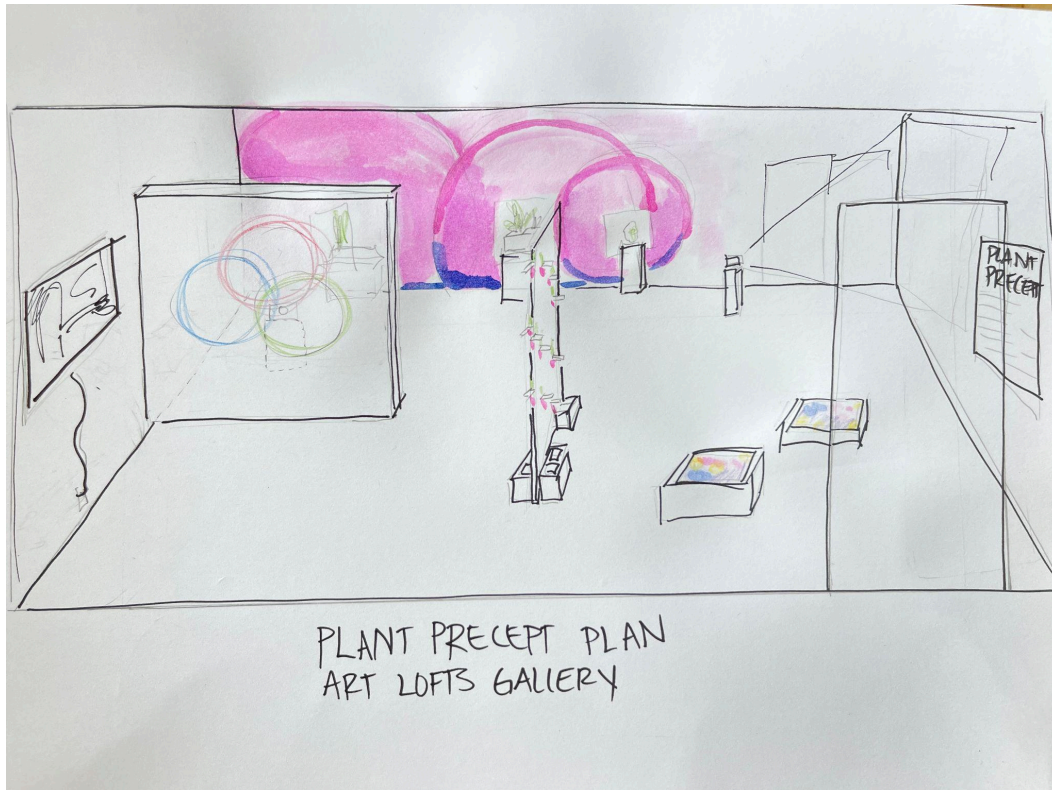


Figure 14: gallery layout plan for Plant Precept

In the week in which we were going to finalize catering for the reception and were going to start promoting the show, the artists involved agreed together that with the protests on campus and the climate of campus at the time, we could not reasonably promote a show about ethical relation to land and ask people to come celebrate with finger foods, no matter how deeply political the pieces individually and the statement of the show as a whole were. Without everyone able to commit to the show, we instead put a collaboratively-written statement on our show poster (which was designed by Singh, in collaboration with Wilson), removed the mention of the Kohler program (as per our conversation with Andrew), and posted this on social media, around campus, and on the windows of the gallery.

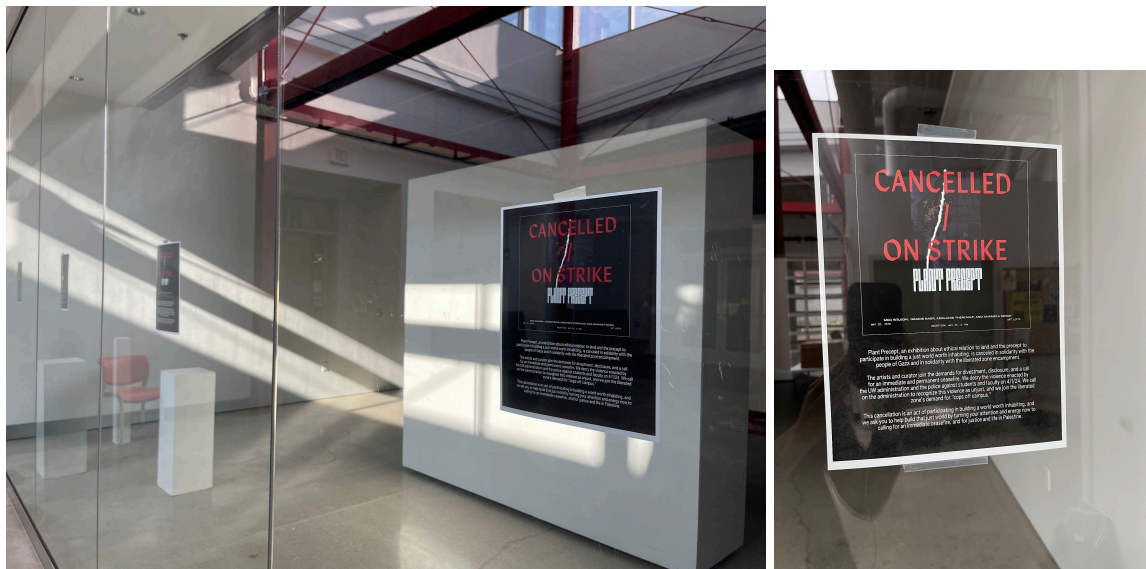


Figure 15: Posters in the gallery where the show was supposed to be exhibited

Conclusion & Acknowledgements

In Plant Precept, we explored the intersection of science and art by looking at how plants perceive the very light that gives them their characteristic green color. This process took us through color theory, photosynthesis, color spaces, human vision and perception, dichroic glass as an art material that also demonstrates many photonic concepts, and the broader theme of more-than-human living beings in urban contexts.

This project challenged our understanding of science and art and we quickly found out that science-art fusion is its own subject worth exploring, drawing from both science and art but being its own thing entirely.

We would like to acknowledge funding from the Kohler fellowship at the Wisconsin Institute of Discovery. We would also like to thank Andrew Hanus, Dr. John Yin, and Angela Richardson for running the program and mentoring us throughout the fellowship. A special thank you to Janine Harrison and the purchasing staff at the Wisconsin Institute of Discovery for helping us with purchasing.

Appendix 1: MATLAB code to calculate XYZ colorspace coordinates

```
clear all;
close all;

% xyz2rgb = [3.2406, -1.5372, -0.4986; -0.9689, 1.8758, 0.0415; 0.0557, -0.2040,
1.0570];

% wavelength_file = 'splib07a_Wavelengths_ASD_0.35-2.5_microns_2151_ch.txt';
% reflectance_file = 'splib07a_Oak_Oak-Leaf-1_fresh_ASDFRa_AREF.txt';
% wavelength_file = 'wavelengths_chlorophyll_a'; %0.2 to 3 microns
% reflectance_file = 'absorbance_chlorophyll_a';
% wavelength_file = 'wavelengths_walnut';
% reflectance_file = 'reflectance_walnut';
wavelength_file = 'Meg combined peaks wavelengths.txt';
reflectance_file = 'Meg combined peaks absorbance.txt';
d65_file = 'CIE_std_illum_D65.csv';
cmf_file = 'cixyz31_1.txt';

% Load the wavelength and reflectance data from the files, skipping the first row
%MULTIPLY wavelength BY 1000 FOR USGS
%MULTIPLY wavelength BY 1000 FOR USGS
%MULTIPLY wavelength BY 1000 FOR USGS

wavelengths_nm = readmatrix(wavelength_file, 'NumHeaderLines', 1);
reflectances = readmatrix(reflectance_file, 'NumHeaderLines', 1);

% Load the D65 illuminant data from a CSV file
d65_data = readtable(d65_file);
d65_wavelengths_nm = d65_data(:, 1); % Assuming the first column is wavelengths in
nanometers
d65_values = d65_data(:, 2); % Assuming the second column is the D65 values

% Load the CIE 1931 color matching functions from the txt file
cmf_data = readmatrix(cmf_file);
cmf_wavelengths_nm = cmf_data(21:421, 1); % First column is wavelengths in nanometers
x_bar = cmf_data(21:421, 2); % Second column is x_bar
y_bar = cmf_data(21:421, 3); % Third column is y_bar
z_bar = cmf_data(21:421, 4); % Fourth column is z_bar

% Interpolate the D65 illuminant and the reflectance data to match the CMF wavelengths
d65_interp = interp1(d65_wavelengths_nm, d65_values, cmf_wavelengths_nm);
% SCALE UP REFLECTANCE HERE
reflectance_interp = interp1(wavelengths_nm, reflectances,
cmf_wavelengths_nm)/20000000;
```

```

% Calculate the XYZ values
N = trapz(cmf_wavelengths_nm, d65_interp .* y_bar);
disp('XYZ');
% X = (100/N)*trapz(cmf_wavelengths_nm, reflectance_interp .* x_bar)
% Y = (100/N)*trapz(cmf_wavelengths_nm, reflectance_interp .* y_bar)
% Z = (100/N)*trapz(cmf_wavelengths_nm, reflectance_interp .* z_bar)

X = trapz(cmf_wavelengths_nm, reflectance_interp .* x_bar)
Y = trapz(cmf_wavelengths_nm, reflectance_interp .* y_bar)
Z = trapz(cmf_wavelengths_nm, reflectance_interp .* z_bar)
%
% disp('xyz');
% x = X/(X + Y + Z)
% y = Y/(X + Y + Z)
% z = Z/(X + Y + Z)
%
xyz2rgb([X, Y, Z])
figure();
rectangle('Position',[0 0 7 7], 'FaceColor', xyz2rgb([X, Y, Z]));
axis([0 7 0 7]);
% plot(cmf_wavelengths_nm, reflectance_interp, 'linewidth', 150, 'color', [0.4772 0
0.5537]);
% xyz2rgb*([x, y, z])
% xyz_values =
calculate_cie_xyz('splib07a_Wavelengths_ASD_0.35-2.5_microns_2151_ch.txt',...
%      'splib07a_Oak_Oak-Leaf-1_fresh_ASDFRa_AREF.txt', 'CIE_std_illum_D65.csv',...
%      'ciexyz31_1.txt');
% disp(xyz_values);

```