Fabrication Methods for Polarized Light Collages

by

Laura Huang

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Abstract

In this thesis, we discuss the best methods of fabricating polarized art collages, inspired by the artwork of Austine Wood-Comarow that creates brightly colored images from cellophane, a colorless birefringent material, placed in between two polarizers. Her artwork appears alive as the colors morph between images seamlessly and invites viewers to interact with it to explore the many images hidden within. To recreate the same color and image shifting result with a more streamlined process, we created a visualization tool and tested various laser cutting settings and fabrication processes. The visualization tool takes in two vector image inputs and allows the user to play around with the color and image shifting by mimicking the rotation of the polarizers or birefringent material. The optimal fabrication process of incrementally layering cellophane sheets with water as a temporary adhesive produces quality polarized light mosaics that reliably demonstrate the image morphing behavior.

Thesis Supervisor: Stefanie Mueller
Title: Assistant Professor of Electrical Engineering and Computer Science

Acknowledgements

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I could not have found a more engaging project than this project on polarized light mosaics, so I would like to extend a huge thank you to Ticha Sethapakdi. This thesis could not have been possible without Ticha. Throughout our time working together, she always had new alternatives when I reached roadblocks, let me bounce ideas off of her, taught me Illustrator hacks, and gave me all the tools necessary to experiment on my own. She inspires me in so many ways and is a great friend and role model, and I will always remember our trip to the Museum of Science to see Austine's work in person. It has been so awesome working together with her on this project, and I could not have asked for better mentors than Professor Mueller and Ticha.

I would also like to thank everyone else in the Human Computer Interactions Engineering group for creating such a positive and creative environment even in a virtual setting.

Lastly, thank you MIT for an unforgettable four years. I have met so many wonderful people who have inspired me to be the best version of myself and encouraged me to chase after my dreams. I have learned and grown so much, and I could not have done it without the support of the friends and mentors I have found under the dome.

Publication

The visualization tool and fabrication process covered in this thesis contributed to the following publication currently in progress:
Ticha Sethapakdi, Laura Huang, Stefanie Mueller.
Polagons: Designing and Fabricating Color Changing Polarized Light Mosaics

Language and Figure Note

Throughout this thesis, I use the word "we" to signify that this work has been a group effort. However, the work that is provided in detail is my own.

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1 Introduction

Austine Wood-Comarow created a technique for creating polarized light collages, or polage, in which the colors of a birefringent material transition from transparent to saturated when sandwiched between two polarizer films. The resulting mosaics are "moving pictures" in which the images appear to shift although the physical mosaic itself does not undergo change or motion displacement. Her artwork was made by hand through trial and error to perfect color choices and the morphing behavior between images. Austine's work has great significance because her mosaics are unique in the world. Other artists and hobbyists have created polarized light mosaics out of cellophane material, but none have attempted work that remotely matches technical complexity, appearance and morphing behavior of Austine's work. Furthermore, her work is highly interactive, requiring active participation and discovery on the viewer's part. Without the physical effort of the viewer or an automated rotating polarizer, the images and colors remain static [2].

To help make this art form more accessible to others, we created a visualization tool and experimented with various fabrication methods to translate this long manual process into a simplified process. For the visualization tool, we utilized the algorithms presented in Dall'Agnol et al. [3] to predict the colors that emerge from the polarized light collages based on the thickness of the birefringent material and the relative angle of the polarizers to the birefringent layer. For the fabrication process, we tested various methods of layer and shape cutting order and various laser cutting settings under different conditions to produce collages that mimic Austine's work. This thesis will present the most promising method of fabricated polarized light collages.

2 Background

2.1 Polage Art

Austine Wood-Comarow invented polage, or polarized light collages, as an art form in 1967. Her colorful artwork was created without any pigment, using only cellulose and polarizing filters to produce each intricate image. The colors morph gently into each other, giving the viewer a continuous flow of imagery. Each piece was built by hand, testing through trial and error to control the colors and create figurative images, a time-extensive manual process to create the painting.

For each work, Austine first drew a design pattern like that of stained glass but with much more subtle gradations of color and shading. She then cut out and positioned clear, colorless cellophane arranged in a collage method to create the desired picture.In various videos of Austine working on polage artwork, she painstakingly layers sheets of clear cellophane over a light table covered with a polarized filter while wearing polarizing sunglasses to gauge the colors of the mosaic. Based on the reference image and desired colors, she plays around with the angle of the birefringent material before cutting out each shape with a knife. To control hue and intensity, Austine varies the thickness of the cellophane and the angle at which the cellophane piece is attached, respectively [4].

Other artists have used a variety of birefringent material such as film wrap, cellophane sheets, and cellophane tape to create polarized light collages, but none have achieved the complex image morphing behavior that exists in Austine's work. In this art form that she had invented, the viewer observes a sequence of changing, progressing images between two poles that have an optimal condition of stillness. In between those two poles, many unstable, incomplete stages of those two base images exist, thus as the user interacts with the light mosaics using a polarizer film, the viewer can

Figure 1: Stills of Austine's Polage-making process. In the left image, she uses a small knife to cut out cellophane pieces to match the drawn pattern. In the right image, she rotates the cellophane film to gauge the resulting color.

Figure 2: Deer Couple: mixed polage art media (a) Initial state without the front polarizer; (b) Illustration with the front polarizer to reveal the deer (c) Illustration with crossed polarizers (90 degrees to each other) (d) Demonstration of how viewers can interact with the work

observe a continuous flow of color [2].

The painstaking manual method of cutting out and layering individual shapes, experimenting with colors, and testing image morphing behavior requires extensive experience and understanding of how the materials react to light. To help make this art medium more accessible to others, we seek to develop both a visualization tool for users to observe the behavior of their artwork and a streamlined fabrication process to transform ideas into reality.

2.2 Birefringence

Birefringence is defined as the double refraction of light in a transparent, molecularly ordered material. In birefringent materials, long polymer molecules are stretched

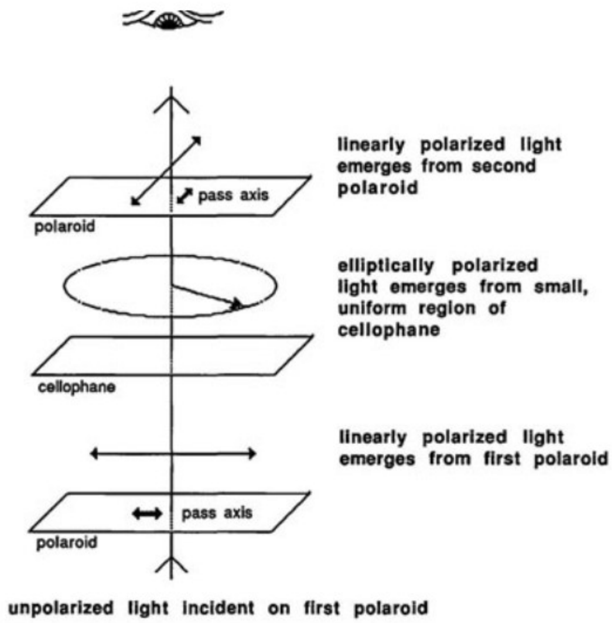


Figure 3: Illustration of light passing through birefringent material between two polarizers [1]

parallel to the length of the material. Light polarized parallel to that stretch travels through the material more slowly than light polarized perpendicular to the stretch. When light enters the material, the light refracts into two rays, the ordinary and the extraordinary ray, which are linearly polarized rays that have their electric fields vibrating in mutually perpendicular planes. The two perpendicular waves travel at different velocities since one wave will travel parallel to the length of the tape and the other perpendicular, thus building up a phase difference between the two rays [5]. This phase difference causes linearly polarized light entering the material to become elliptically polarized exiting the material. The amplitude of light of a given wavelength that emerges from the polarized light collage is dependent on the polarization ellipse [6].

In polage artwork, cellophane, or some birefringent material, is sandwiched between two polarizers. Unpolarized light enters through the first polarizer and exits as linearly polarized light. The cellophane then transforms the linearly polarized light into elliptically polarized light. The second polarizer converts the light back into linearly polarized light. For the second polarizer, when the pass direction is horizontal, the emergent light is mainly red light, and when the pass direction is vertical, the emergent light is mainly blue light [1].Thus, changing the angular position of the polarizers and the birefringent material alters the spectrum of light that emerges.

Let us define θ as the angle of the first polarizer, ϕ as the angle of the second polarizer, δn as birefringence or the difference between the two indexes of refraction,, λ_0 as the wavelength in vacuum, as the difference in wave numbers, and z as the thickness of the birefringent material. Using these variables, the transmittance can be written as

$$T_r = sin^2\theta sin^2\phi + cos^2\theta cos^2\phi + \frac{1}{2}sin2\theta sin2\phi cos(\Delta kz) \tag{1}$$

Transmittance describes how much light passes through a material unchanged without being reflected or absorbed, which gives us a method of quantifying the color of the birefringent material under different conditions. From equation 1 [3], we can observe that changing the angles of the polarizer, the thickness and birefringence of the birefringent material, and the wavelength in vacuum affects the transmittance, which in turn affects which colors are produced.

2.3 Color Theory

Given the transmittance equation (Eqn. 1), Dall'Agnol [3] discusses the method of converting the transmittance value into color coordinates by calculating the tristimulus values in the XYZ color space. According to the tristimulus theory, three numbers that quantify the stimulation of red, green, and blue cones can characterize every color that the normal sighted human eye can perceive. If two color stimuli result in the same three numbers, they produce the same color perception [7]. In the Dall'Agnol paper, color effects are simulated with a white light source that has an equal-energy spectrum and constant radiance of E0 for all wavelengths. Irradiance, I(λ), is then defined as

$$I(\lambda) = Tr(\lambda)E0 \tag{2}$$

Irradiance then gives the three tristimulus values of

$$X = \int_{380}^{780} \bar{x}(\lambda)I(\lambda)\, d\lambda \tag{3}$$

$$Y = \int_{380}^{780} \bar{y}(\lambda)I(\lambda)\, d\lambda \tag{4}$$

and

$$Z = \int_{380}^{780} \bar{z}(\lambda)I(\lambda)\, d\lambda \tag{5}$$

Where x, y, and z are the color matching functions that were determined experimentally in the 1920s and now define the CIE 1931 standard colorimetric observer (Fig. 4).

The tristimulus values define a three-dimensional color space that characterial all possible color perceptions, but for most applications, a two-dimensional color characterization is sufficient. One such representation is the CIE 1931 (x,y) chromaticity diagram in which the color coordinates are obtained by normalizing X and Y by the sum of X+Y+Z [7]. Each color coordinate maps to a specific visible color on the CIE-31 chromaticity diagram (Fig. 5) in which monochromatic colors are defined between 380 nm to 700 nm.

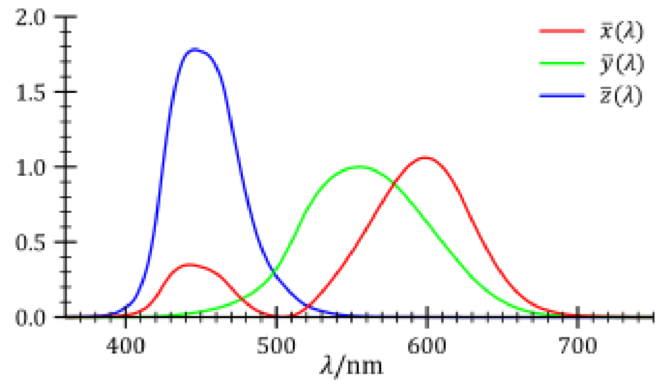


Figure 4: Color matching functions corresponding to red, green and blue [3]

$$x = \frac{X}{X + Y + Z} \tag{6}$$

$$y = \frac{Y}{X + Y + Z} \tag{7}$$

These equations were utilized in calculating the appropriate colors in the visualization tool that will be discussed in the next section. In the visualization tool, the (x,y) color coordinates are converted into RGB so that the color values can be easily compared.

2.4 Polage Color Effects

Dall'Agnol et al. [3] extensively discusses the various color effects produced by changing the variables included in the transmittance equation. In the paper, Dall'Agnol delves into the effects of varying the phase difference which is dependent on the material thickness, varying the angle of a single polarizer, and rotating the birefringent layer. Due to the way that the light is polarized, the viewer observes colors at its most opaque and luminous state when both polarizers are aligned and oriented at 45 degrees relative to the birefringent material.

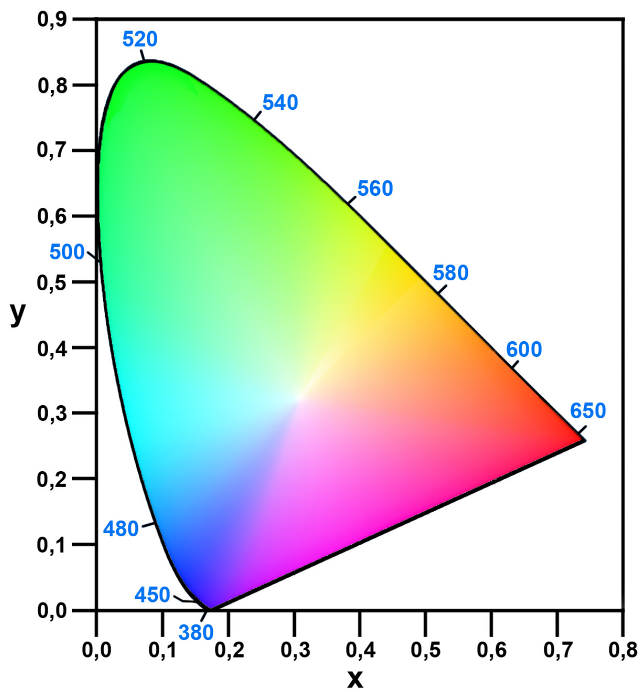


Figure 5: CIE-31 chromaticity diagram. Color coordinates of (x,y) correspond to a specific color in the visible color spectrum [3]

As the thickness of the material increases, the color of the material cycles through the visible light spectrum. Rotating a single polarizer causes a switch between complementary colors that passes through the white point, which when the birefringent material appears transparent. For example, if the artwork initially appears green, it will become magenta when one polarizer is rotated 90 degrees. As the polarizer rotates from its original configuration to 90 degrees from that, the color fades from green to transparent then to magenta. Rotating the birefringent material is equivalent to rotating both aligned polarizers at the same time. When this occurs, the colors shift from saturated to transparent every 90 degrees, but do not switch between complementary colors. This effect allows the morphing behavior between two images. As one image shifts from saturated to transparent, the other shifts from transparent to saturated.

In Austine's work, she also utilized a third polarizer to hide or reveal a third image. When the third polarizer is aligned with the other two, the third image is transparent and colorless. However, when the third polarizer is rotated 90°, the third polarizer filters out all light, so the third image is revealed as a solid black image. Consequently, the fabrication process discussed in this thesis will enable the above color and image effects to best mimic Austine's art form.

3 User Interface

3.1 Illustrator Input

The image must be a vector image with a maximum of eight colors. The number of colors is currently restricted by the number of stroke colors that the laser cutter recognizes, which are 00000 (black), FF0000 (red), 00FF00 (green), FFFF00 (yellow),

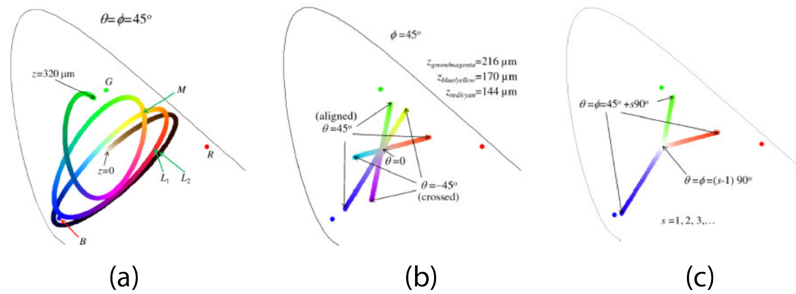


Figure 6: Polage color effects. (a) Color path as one varies the birefringent material thickness from 0 to 320 μm (b) Complementary color effect by rotating one polarizer (c) Saturated to neutral color effect by rotating the birefringent material layer [3]

0000FF (blue), FF00FF (magenta), 00FFFF (cyan), and FF6600 (orange). A theoretical limit also exists because the resulting colors become indistinguishable after a certain material thickness.

When creating the vector images, there cannot be any overlap of shapes. Each shape must be independent of others, so all shapes in layers below the current layer must be cut out of the current layer. For example, in Fig. 7, the image consists of a circle on top of a star, which is drawn inside a larger circle. Instead of creating the three basic shapes – two circles and a star – to laser cut, the shapes further back in the image must have front shapes removed to create a cut out. This effect can be easily achieved with the Shape Builder Tool in Illustrator.

Since the laser fuses the cellophane layers together, a sufficiently large gap must exist between shapes of different colors so that the shapes do not fuse together. With the Universal laser cutter, we measured the kerf width of the laser to be 0.01 in, which is approximately 1 pt. Thus, the stroke width of each shape must be at least 3 pt to ensure that the shape borders are not melted together. In Illustrator, this effect is made by setting the stroke width of the shape to at least 3 pt, converting the outline to a shape (Path → Outline Stroke), and using the Shape Builder Tool to

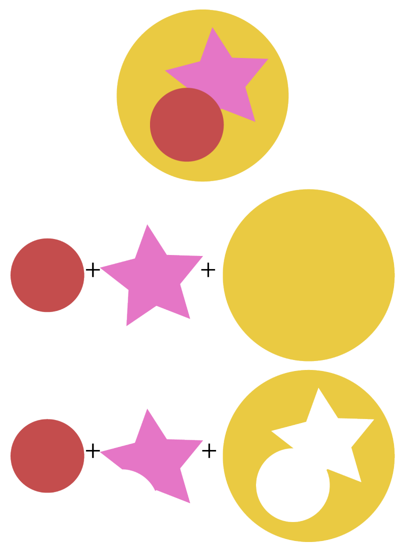


Figure 7: Example of shape cutouts for vector images. The top image is the desired vector image to be created. The middle image shows the breakdown of shapes to create the top image. The bottom image shows the necessary shape cutouts to laser cut.

keep the shapes without the stroke outlines. From initial tests, a stroke width of 3 pt is sufficient for keeping shapes of different colors separate and allowing easy removal of unwanted material.

For testing cutting order and fabrication methods, we created the two vector images shown in Fig. 8. The shapes are all independent from each other, and have a 3pt gap between neighboring shapes.

3.2 Preprocessing Program

The preprocessing program takes in two svg images as inputs and outputs a laser cutting file and separate recolored svg files corresponding to groupings of the same color for both images. Since the preprocessing code was written with the original laser cutting settings that allowed a maximum of 5 colors, the code currently processes up to 5 colors, but this can be easily scaled to incorporate more colors. The

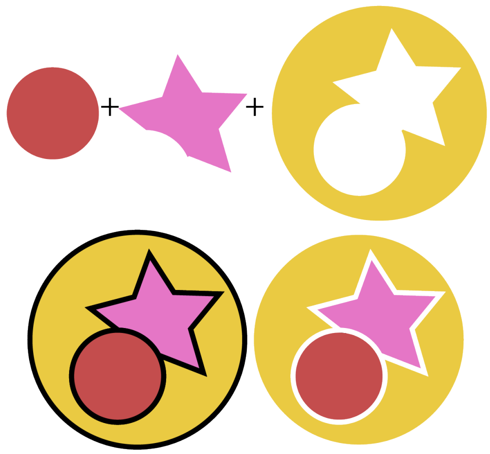


Figure 8: Vector image with sufficient gap spacing. Using the cutout shapes in the top row, we made the stroke width of each shape to be 3 pt. Each stroke was converted into a shape using Path → Outline Stroke and the Shape Building tool. The bottom right image shows the final image that will be used in the user interface and sent to the laser cutter.

Figure 9: Test vector images for fabrication testing

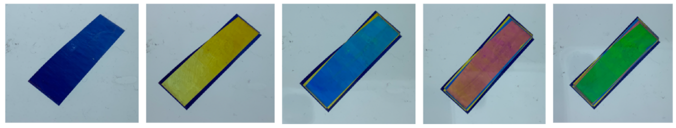


Figure 10: Available colors using 1.8 mil cellophane tape

five available birefringence-made colors using 1.8 mil cellophane tape were 081F6A, 878A2B, 035E91, 794A52, 29833B, which corresponded to one layer up to five layers of cellophane tape. The five birefringence-made colors also corresponded to the laser cutting stroke colors of red (FF0000), green (00FF00), blue (0000FF), yellow (FFFF00) and magenta (FF00FF) respectively. The five colors were determined by taking the hex color value of one layer up to five layers of cellophane tape angled at 45° between two polarizers.

After later testing, we used cellophane film with a thickness of 2.3 mil. The new colors were 2757A0, B77F32, 2DC378, 5340A9, and B0649E, corresponding to one layer up to five layers of cellophane respectively. When the front polarizer was perpendicularly crossed with the back polarizer, the five complementary colors were C8C26A, 00A3DA, D02CBE, A0CC51, and 09A679. These new birefringent-made colors are included in the newer version of the UI.

The Processing UI displays the original and recolored vector images and color palettes. The Python program running in the background recolors the images and generates the new svg files to display in the UI (as shown in Fig. 13). To recolor the image, the Python program parses through the XML of the svg file, removes the stroke if the original image has shapes with stroke, extracts the fill color of the current shape, then changes the fill color to the closest birefringence-made color using RGB distance. After the recoloring, the program groups shapes with the same fill colors and outputs svg files corresponding to each color group.

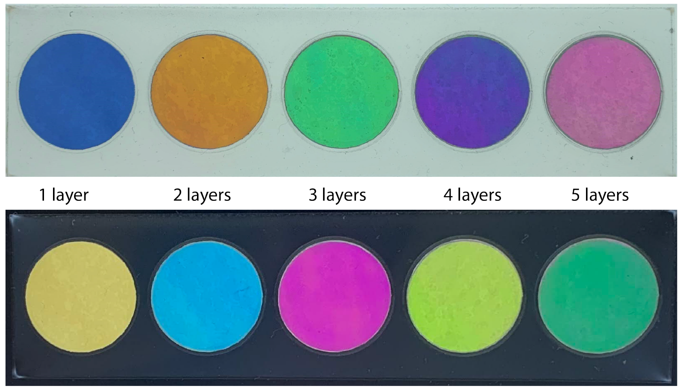


Figure 11: Available colors using 2.3 mil cellophane film. The top row of colors corresponds to the aligned polarizer configuration. The bottom row of complementary colors corresponds to the crossed polarizer configuration.

Each grouping corresponds to one birefringence-made color and thus a certain number of cellophane layers to cut through. To create the laser cutting file, the program changes the fill of the color groupings to none and changes the stroke color to the corresponding laser cutting stroke color. Each grouping is saved as a different layer, and the layers are cut in color order corresponding to the least to greatest number of layers. Since the shapes are vector cut, the stroke width is 0.00001 pt. The laser cut svg image must also be rotated 45 degrees so that the colors are shown as fully opaque colors when placed horizontal relative to the two polarizers.

3.3 Interactive Visualization Tool

Image and color morphing represent the unique characteristics of polarized light collages, so users should be able to preview the morphing behavior before they fabricate the collages. The Processing program displays the morphing behavior and allows the user to change the birefringence of the material, the constant radiance (E0) of the light source, angle of the front polarizer to the birefringent material (θ), angle of the back polarizer to the birefringent material (ϕ), and the angle of the birefringent

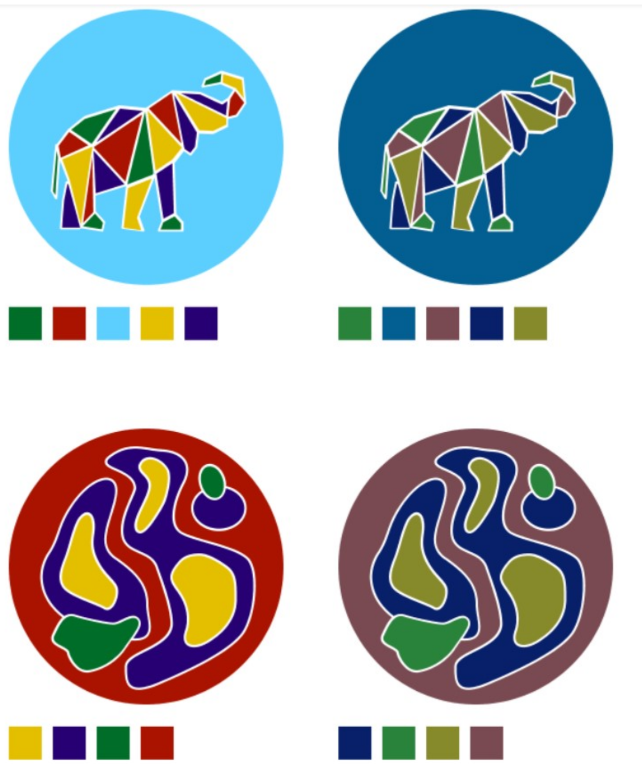


Figure 12: Processing UI of original and recolored images and color palettes. The left column displays the original images, and the right column displays the recolored images using the five available cellophane-made colors with 1.8mil tape.

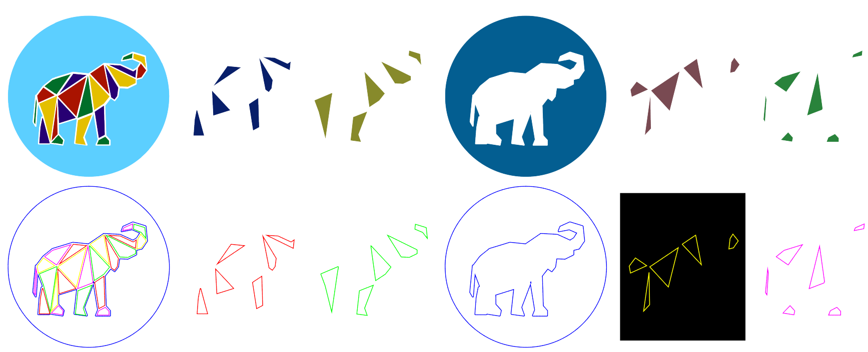


Figure 13: Illustration of the recolored image and laser cut file generation. The top left image is the original elephant design. The top row represents the recolored shape groupings according to the cellophane-made color, ordered from least to most cellophane layers. The bottom row shows the laser cutting layers that correspond to shape groupings with the same number of cellophane layers. Each color corresponds to different laser cutting settings because the thicknesses vary.

material to both polarizers (δ). The angle of the front polarizer to the birefringent material causes the colors to switch between complementary colors, and the angle of the birefringent material to both polarizers demonstrates the morphing between one image to another as one image becomes transparent and the other becomes opaque and saturated.

The Python program calculates the correct color based on the transmittance of the material using Eqn. 1-7, which depends on the material thickness and the relative angle of the polarizers to the birefringent material. Since rotating the birefringent material is equivalent to rotating the two polarizers together, delta changes both theta and phi values. The Processing program displays the color change and user interface knobs, so that the user can preview and modify the color changes. In Fig. 14, the top row demonstrates the image morphing effect as the birefringent material rotates between two fixed polarizers. In Fig 13a, the left image is saturated while the other is colorless and transparent. When the two images are rotated together at 45°, the image state switches – the left image becomes transparent and the right image becomes colorless and transparent Fig 14b. The bottom row demonstrates the appearance of Fig 14a and 14b if the front polarizer is rotated by 90°, showcasing the complementary color image.

4 Fabrication Process

4.1 Cellophane Sheet Alignment

The cellophane sheets must be aligned in the same 45° direction so that when the polarized light passes through the various layers of birefringent material, the viewer observes the most vibrant, opaque color possible. If the sheets are not aligned, some

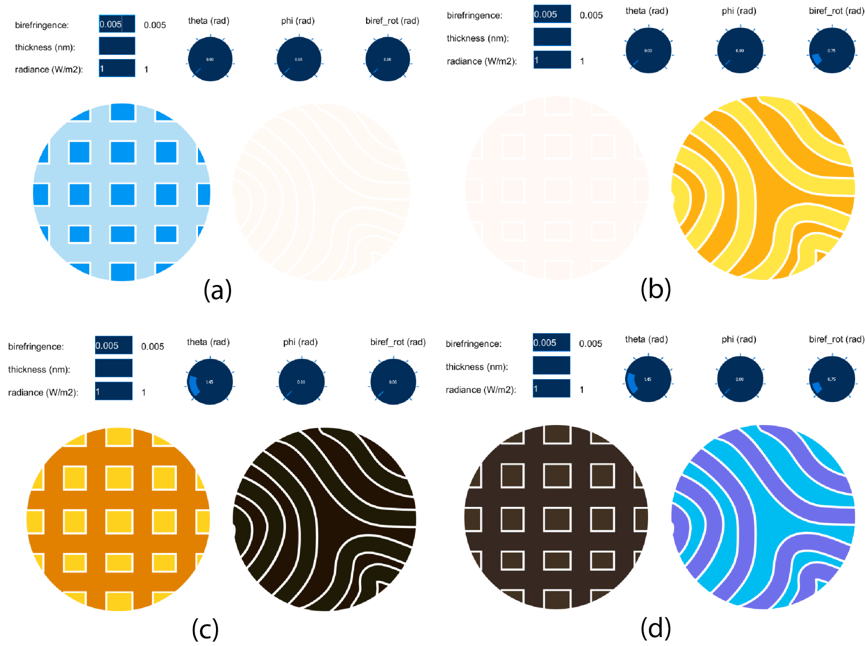


Figure 14: Polage visualization tool

layers could result in colors with different hues or intensities than what is calculated using the transmittance equation (Eqn 1).

We initially aligned the cellophane sheets by lining the top edges to a straight line on a cutting mat and taping the edges together. To ensure that the sheets did not slide off each other, each sheet was taped to the sheet below. Once the sheets were all taped together, the top edge of the cellophane stack was taped to the top edge of the machine cutting table. This process was time consuming since the clear cellophane sheets were very thin and flexible.

The next iteration on cellophane sheet alignment was inspired by peg bars used in drawing traditional animations. Peg bars are meant to hold papers in place when drawing and shooting traditional hand-drawn animations. They consist of a flat piece with one circular stub in the middle for left and right alignment and two rectangular stubs on each side for up and down alignment. This design ensures that when the

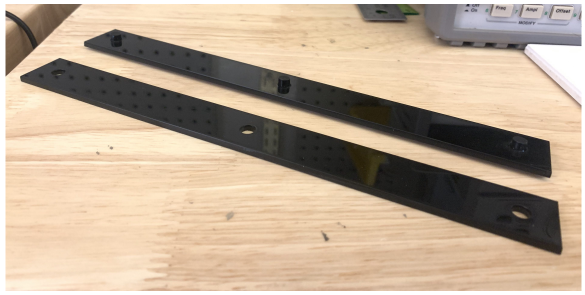


Figure 15: Peg bar pieces. The cellophane sheets are placed on the bar with the pegs, and the second piece with three holes clamps the sheets down.

papers are removed and later placed back to shoot the animation, the paper goes exactly where it was during the initial drawing so that the images stay in the correct place. Since these peg bars require a special hole punch for the square pegs, an alternative is to use a regular hole punch and a peg bar with three circular pegs [8].

To fabricate a peg bar, two 9.5" x 1" rectangular pieces of 1/8" acrylic with three 6 mm holes spaced 4.25" apart were laser cut. For the stubs, three 6 mm circles were laser cut out of 1/4" acrylic. The stubs were inserted into the three holes on one of the rectangular pieces and super glued into place. The second rectangular piece served as a clamping piece to hold the cellophane sheets in place so that the sheets do not blow away when the exhaust air is turned on. This method was cleaner and more efficient than taping the cellophane sheets to the peg bar.

The cellophane sheets needed to be hole-punched to fit onto the peg bar. Directly hole-punching the cellophane plastic caused tearing and jamming. The resulting holes either tore to the edges so that the sheet could not be used or crinkled around the edges so that the sheet would not lie flat. To fix this issue, masking tape was applied to three spots on the top edge of the cellophane that corresponded to the three holes on the hole puncher. Half of a piece of tape was attached to one side of the cellophane sheet then it was folded over the top edge to stick to the other side. Sandwiched between tape, the cellophane plastic cut cleanly, resulting in smooth circular holes

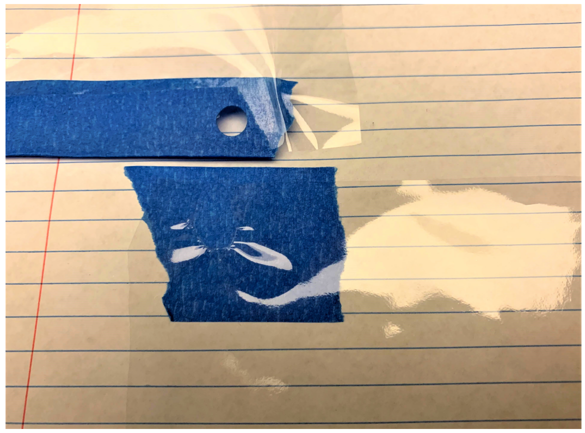


Figure 16: With the use of masking tape (top sheet), the resulting punched hole had clean edges and minimal surface texture irregularities. Without the masking tape (bottom sheet), the punched hole tore to the edge, which rendered it unusable, and had edge textural irregularities.

without tearing or wrinkling.

In the laser cutter, the bottom peg bar was taped to the border of the laser cutter cutting board so that the top edge of the peg bar was aligned with the top edge of the border. Since the border is at a greater height than the acrylic base board, the cellophane does not lie flat at the edges as shown in Fig. 17. To minimize surface irregularities and air bubbles in the finished mosaic, the vector images should be placed a few centimeters away from the side edges.

For the cellophane sheets, the optimal alignment method was to first cut a piece of cellophane that was at most as wide as the hole puncher work area. Then masking tape was applied to three spots corresponding to the three hole puncher holes. The cellophane sheet was hole punched then placed onto the peg bar. After the desired number of prepped cellophane sheets were stacked on the peg bar, the top clamping piece was placed on top of the peg bar stubs to hold the cellophane layers in place during the laser cutting (Fig. 18).

Figure 17: Air gaps in the cellophane at the top and left border of the cutting table. Since the cellophane sheet does not lie flat at the edges of the cutting table, those areas should be avoided to minimize surface irregularities and maximize cellophane adhesion to the acrylic base board.

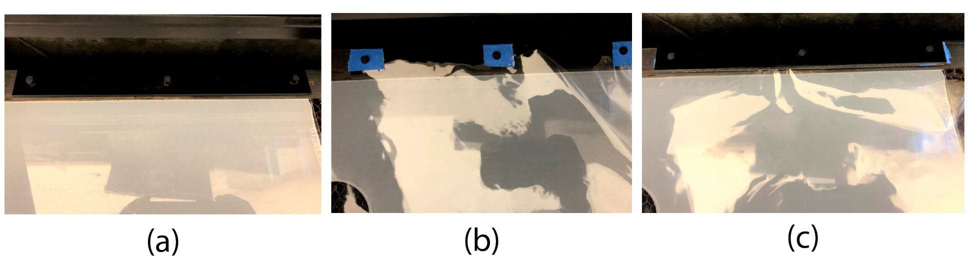


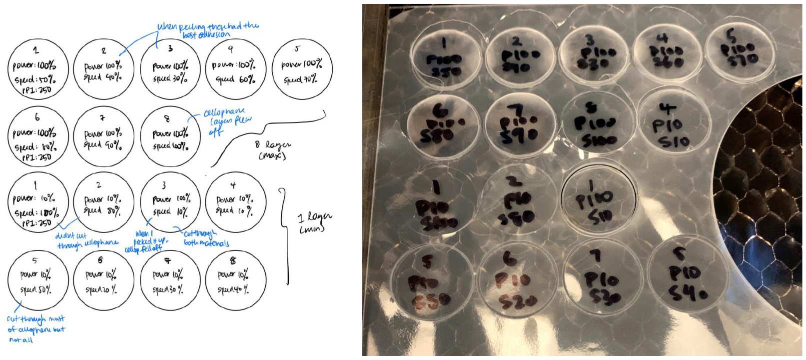
Figure 18: Process of aligning cellophane sheets in the laser cutter. (a) Bottom peg bar is taped to the cutting table top border (b) Hole-punched cellophane sheet is placed over the pegs (c) Top clamping piece is placed down to hold the sheet in place during the cutting process

4.2 Testing of Laser Cutting Settings

Since no previous studies on the laser cutting settings for cellophane film existed, especially for this application, tests were conducted to find the optimal settings for creating polarized light collages. The settings must allow the cellophane sheets to melt enough to adhere to both each other and the bottom clear acrylic layer but to not distort the laser cut shapes. The resulting shapes must also lie smoothly without surface irregularities so that the colors are uniform and that neighboring shapes are not distorted. The two setting combinations tested were high power high speed and low power low speed. High power high speed allows for quicker fabrication time and prevents melting distortions, but the shapes may not adhere well to each other or cut through on the first pass. Low power low speed may ensure better adhesion between layers but may result in melting distortions. The optimal balance must be found between power and speed so that the resulting artwork can be made quickly with good adhesion and minimal blemishes or distortions. The laser cutting settings should also scale with and have a simple mathematical relationship with the number of stacked layers.

4.2.1 Settings for Minimum and Maximum Number of Layers

For the initial runs, we used the settings of $20x\%$ power, 41% speed, and 250 PPI where x represents the number of cellophane sheets stacked to produce a certain color. When shapes were cut with these settings, smaller shapes would not adhere to the acrylic base layer very well and would often blow away during subsequent cuts. To find some baseline settings, different settings were tested on single cellophane sheets and stacks of 8 cellophane layers since the laser cutting machine recognizes 8 different line colors. For the single cellophane sheets, lower power and higher speeds would



(a) (b)

Figure 19: Laser cutting test results for 1 layer and 8 layers of cellophane. (a) Power and speed settings and observations (b) Resulting cellophane cutouts

be ideal for the minimum baseline setting so that there are more setting possibilities for stacks with more cellophane layers. To get a sense of the quality of the resulting cut, we tested a minimum power of 10% since the most common power setting for thin polypropylene film, which is the plastic in cellophane, is 10%. So when we tested 10% power at various speeds, the cellophane did not cut completely through with 10% power until a speed of 40%. This marks the lowest baseline setting for one cellophane layer. Any greater power setting may allow the layer to adhere to the base acrylic sheet better.

For a stack of eight cellophane layers, high power and low speeds were first tested to make sure that the laser could cut through the thick stack completely. At 100% power and 100% speed, the cellophane layers cut through but did not adhere to the acrylic base. The settings of 100% power and 30% or 40% speed resulted in the best adhesion to the acrylic base. This marks the highest baseline setting for the maximum number of cellophane layers because any higher speed will result in poorer adhesion to the acrylic base.

4.2.2 Settings with a Top Wood Layer

From previous tests, the cellophane material often wrinkles, resulting in uneven surfaces which cause uneven colors. In test images, uneven surfaces cause the appearance of a color gradient instead of a single solid color for a certain shape. One possible solution is to place a top layer of material such as wood to hold down the cellophane. Tests were run with one cellophane sheet under both 1/8” wood, which has more mass to flatten the cellophane but has more material to cut through, and 1/16” wood, which has less material to cut through but may not hold down the cellophane. High power high speed settings resulted in cleaner edges and minimal melting, but did not adhere to the acrylic base and required multiple passes to cut all the way through. High power low speed settings resulted in better adhesion but much more edge distortion, material melting, and wood burn marks on the shape edges. Low power high speed settings required multiple passes to cut through and had minimal adhesion to the base plate. Low power low speed settings resulted in edge melting and wood burn marks.

Both 1/8” and 1/16” wood as a layer on top of the cellophane did not produce promising results since all combinations of speeds and powers resulted in a variety of problems – low adhesion, wood burn marks, cellophane edge melting, surface irregularities, or multiple passes to cut. For 1/8” wood, the settings of 100% power and 15% speed with 2 passes resulted in the best results. As a reference, the common vector cut settings for 1/8” wood is 50% power, 3.1% speed and 500 PPI. For 1/16” wood, the settings of 40% power and 10% speed for the first pass and 40% power and 20% speed for the second pass or settings of 90% power and 40% speed for 4 passes worked best. Surface irregularities and minimal adhesion persisted as an issue, and since optimal settings for one cellophane sheet under wood was not found, multiple

Figure 20: Test settings and observations with a 1/8" wood top layer.

cellophane sheet settings were not tested.

4.2.3 Settings with Water Spray

Another method of reducing surface irregularities without the need of an extra cutting material is to use water as a temporary adhesive between cellophane sheets and the acrylic base. To prepare the sheets for cutting, we sprayed water onto the acrylic base

Figure 21: Cellophane cutouts resulting from the varied laser cutter settings. Many have edge discoloration and melting, and some blew off the surface due to low adhesion.

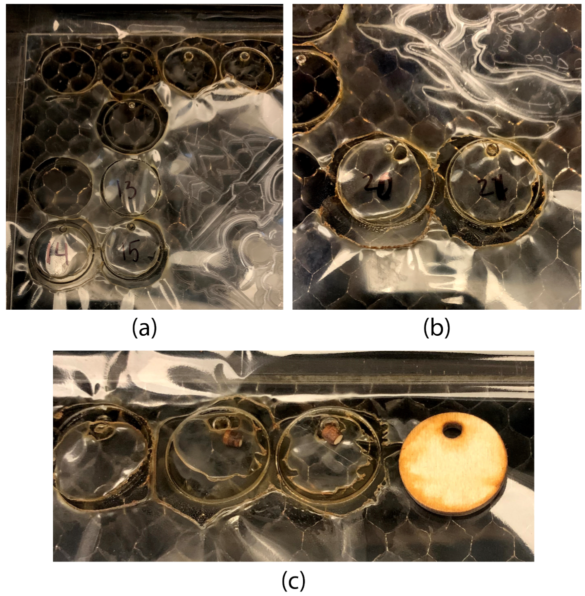


Figure 22: Cellophane burn marks and surface irregularities with " wood top layer. (a) Cellophane melting and surface irregularities (b) Edge discoloration of the cellophane and the almost burnt edges (c) Edge discoloration and distortion of the cellophane and the cellophane marks were imprinted onto the wood cutout

Figure 23: High power test settings and observations with a 1/16" wood top layer

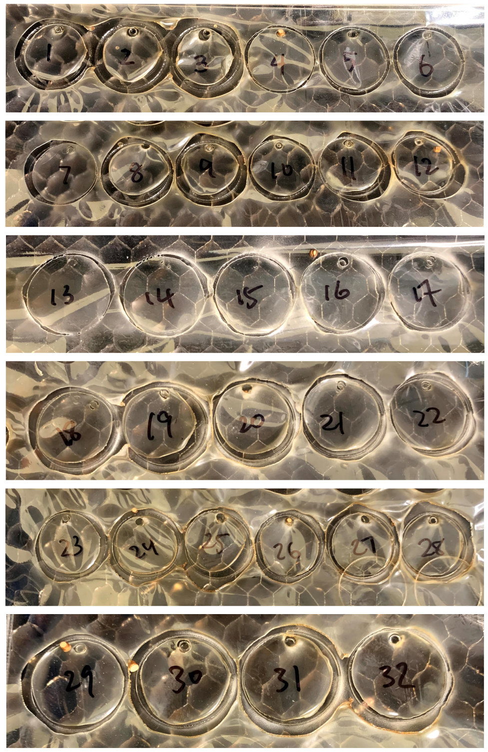


Figure 24: Cut results for high power test settings at various speeds with a 1/16" wood top layer. Row 2 was cut at high power and low speed settings, which resulted in edge melting and discoloration. Row 3 provided the cleanest results with minimal surface irregularities and burn marks, but the circles required multiple passes to cut and had low adhesion to the base acrylic surface.

Figure 25: Low power test settings and observations with a 1/16" wood top layer

Figure 26: Cut results for lower power test settings at various speeds with a 1/16” wood top layer. Low power high speed settings did not cut through the cellophane on the first pass, and low power low speed settings caused edge melting and discoloration.

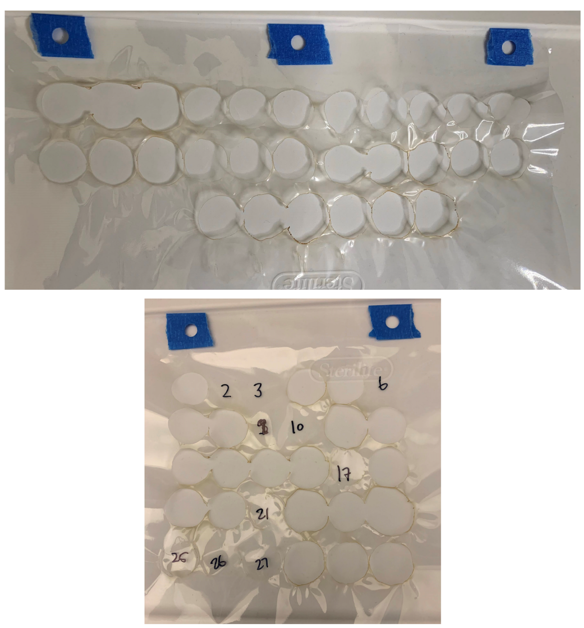


Figure 27: Remaining cellophane sheets for 1/16” wood tests. For both low power and high power settings at a variety of speeds, most cuts resulted in edge melting and discoloration, uneven surface textures, and minimal adhesion.

then smoothed down the first cellophane layer on top. Subsequent layers of cellophane also required a spraying water treatment to temporarily adhere the layers together to minimize the appearance of surface irregularities and air gaps. Speed values were kept low so that there was room to adjust the power setting based on the number of cellophane sheets to cut.

Since there are a maximum of 8 laser cutting settings, each additional layer of cellophane adds an additional 12.5% power. After some testing, the optimal laser cutting settings were $12.5x\%$ power, 30% speed, and 500 PPI where x represents the number of cellophane layers to create a specific color. Since power increased with the number of layers, lower speeds such as 10% caused the laser to cut through both the cellophane layers and base acrylic layer. This water spraying method produced the best results – good adhesion, smooth surfaces without any surface irregularities, and clean edges. After the initial cut, the cellophane had a slight opaque white color due to the minuscule water droplets trapped between the layers, but after some time the water evaporated and the finished polarized light collage became transparent.

4.2.4 Settings Summary

Method	Advantages	Disadvantages	Optimal Settings

Cellophane only	• No need for additional cutting materials	• No method of preventing surface irregularities and air gaps between layers	• For 1 layer: 10% power, 40% speed, 500 PPI • For 8 layers: 100% power, 40% speed, 500 PPI
Cellophane with wood top layer	• None	• Requirement of additional cutting material • Edge melting and discoloration • Surface irregularities • Low adhesion	• For 1 layer and 1/16" wood: 40% power and 10% speed for the first pass and 40% power and 20% speed for the second pass

Cellophane with water spray	• Smooth shape surface • Consistent results • Simple implementation process	• Need for a misting bottle	• For x layers up to $x = 8$: $12.5x\%$ power, 30% speed, 500 PPI

Settings Summary

4.3 Laser Cutting Methods

Various methods of sheet placement and shape cutting order were tested to determine which method produced the best results. For sheet placement, cellophane sheets could be layered one at a time between shape groupings by color so that the image is built up by layers similar to the process of a filament 3D printer. Another method would be to place in stacks of cellophane sheets that correspond to the number of layers needed to produce the desired color. For shape cutting order, results were compared for cutting the outside shapes then inside shapes and cutting the inside shapes then outside shapes. Outside shapes are shapes that completely surround or enclose other shapes within so that when the excess cellophane is removed, the inner enclosed shapes are made with extra layers of cellophane. The extra layers change the colors of those shapes so that they no longer match the desired colors from the visualization

Figure 28: Water spray test settings and observations for a variety of cellophane layers to find the optimal power and speed settings

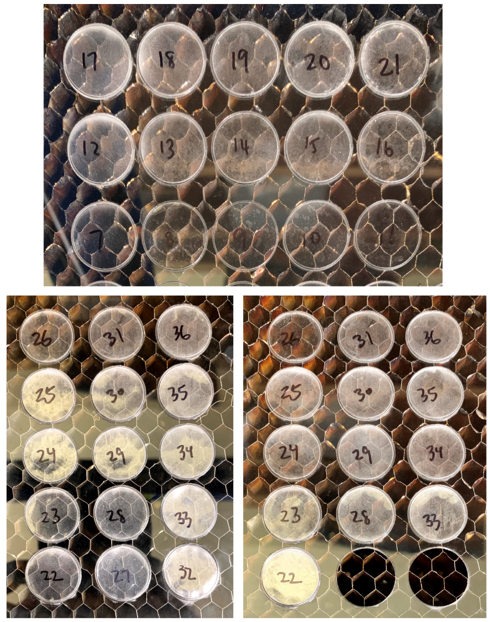


Figure 29: Cut results with water spray test settings. The speed setting of 30% for each number of cellophane layers provided optimal results. At higher powers and a speed of 10%, the laser cut through both the cellophane layers and the base acrylic board, which is not desired.

tool.

4.3.1 Order of Outside to Inside Shapes

The undesired cellophane must be removed between each cut of shape groupings since each cut corresponds to shapes with the same color. For the group layering by color method, the order of outside to inside shapes does not matter since all unwanted cellophane can be easily removed between cuts. For the incremental layer placement method, the order of shapes matters for creating a simple, straightforward fabrication process. In the case where inner shapes must be removed, having a sufficiently large gap or kerf width between the shapes increases the ease of removal.

After the shapes are cut, taking the cellophane sheet off the peg bar only removes the cellophane outside of that boundary. If the unwanted cellophane material inside the boundary is not removed, the remaining cellophane may alter the final color of subsequent shapes cut inside the boundary since there are now more layers than expected. Testing determined that outside shapes, which have other shapes inscribed in them, should be cut first if possible to reduce the complexity of picking out unwanted pieces of cellophane as the sheets are layered on top of each other between cuts.

For example, if the desired image is a circle inside of an annulus shape, the annulus should be cut out first. This means that the annulus shape is cut out of the first layer of cellophane, which corresponds to the color that is created with one cellophane sheet. The inner circle will have the color corresponding to two cellophane sheets. When the annulus shape is cut using one sheet and the cellophane material is lifted off the peg bar, the material inside the inner circle remains, which allows layering when the second sheet is added. When the circle is cut, the laser now cuts through two layers of cellophane, and produces the desired design.

If the inner circle is cut first using one cellophane sheet, only the circle remains adhered to the acrylic base when the cellophane is removed. However, when the annulus shape is cut after layering on the second sheet, only the cellophane material outside the outer ring boundary is removed, thus the inner circle now has a second layer of cellophane laying over it, which alters its final color to be that made with two cellophane sheets instead of one sheet. To produce the desired design, the material inside the inner ring of the annulus must be removed. This extra processing step can become more difficult as the designs become more complex and require extra processing time.

An illustration of cutting outside to inside shapes versus inside to outside shapes is shown in Fig. 30. This theory was tested using a design with a circle surrounded by three concentric rings. For the design in which the inner shapes were cut before the outer rings, post processing was required by removing the extra circle shapes.

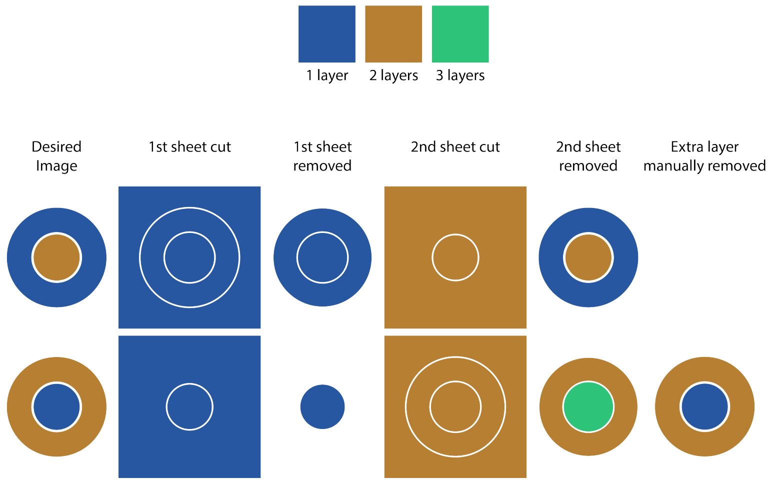


Figure 30: Comparison illustration between cutting outside then inside shapes versus inside then outside shapes. As shown, cutting inside then outside shapes requires post processing to remove the extra, undesired layers.

Since the gap between the shapes were sufficiently large, the extra circles were picked off easily.

One possible solution for removing the post processing step is to create the designs with a thin gap in surrounding or outside shapes so that the material outside and inside the shape are connected by a thin strip of cellophane. Thus, when the leftover cellophane sheets are removed, all the undesired material is connected and can be removed together in one motion. We tested gap sizes of 3pt, 5pt, and 7pt for the design shown in Fig. 32, and a gap size of 3pt was sufficient to connect the excess material both inside and outside the cut-out shapes. For the sample design, we determined which shapes needed a gap slit by starting at the inner shape and moving outwards. If the surrounding or outside shape had a higher layer count, that outer shape had a slit to allow for ease of excess material removal.

For the following tests, we used two vector images (Fig. 34) to compare the effectiveness and quality of three fabrication methods – group layering by color, incremental layering without water, and incremental layering with water. Both images

Figure 31: As shown in the top image, the design in which the color layers were ordered from inside to outside shapes required post processing to achieve the desired colors. The design in which surrounding (outside) shapes were cut before enclosed (inside) shapes, the desired colors were achieved without any post processing. The middle and bottom images show the designs with aligned and crossed polarizers, respectively.

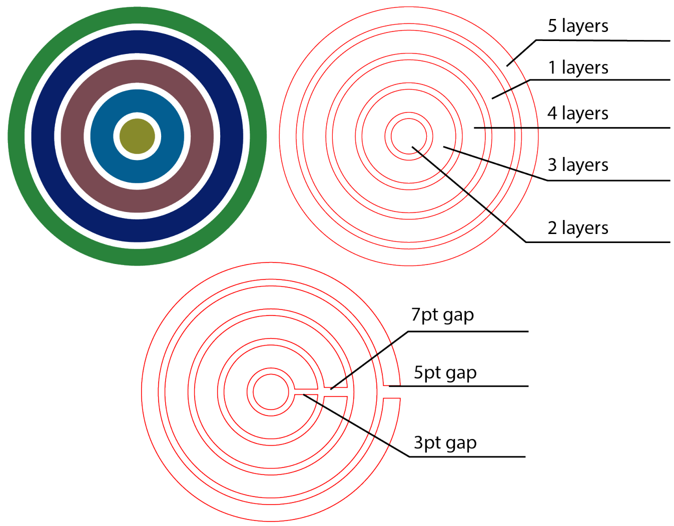


Figure 32: Gap solution test with 3pt, 5pt, and 7pt gaps. The top row shows the desired design and the corresponding number of layers to create each color. The bottom image shows the altered design to test the viability of differently sized gaps in removing the need for post processing.

Figure 33: Gap solution test results. The top image shows the image cutout and the leftover cellophane sheets. The thin strips of cellophane connect the leftover material both inside and outside the ring shape so that no post processing is required. The bottom images from left to right show the design between aligned and crossed polarizers, respectively.

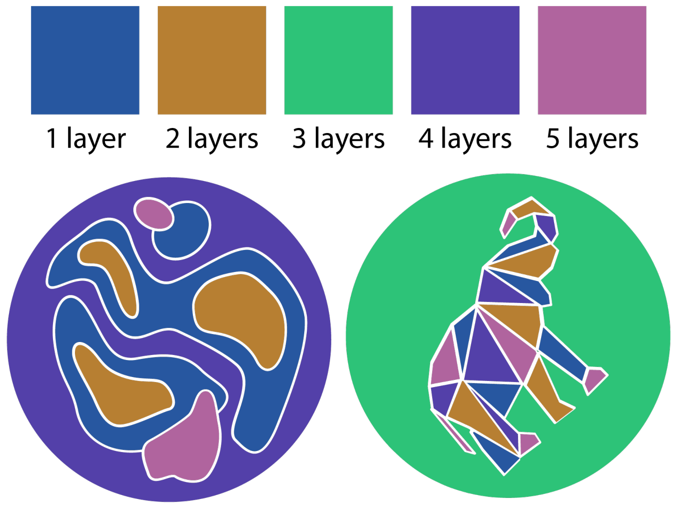


Figure 34: Vector images to test the various fabrication methods.

utilized multiple colors and had shapes enclosed in others.

4.3.2 Group Layering By Color

Prior to laser cutting, the user must prepare and group sheets together so that there are groupings of 1 sheet, 2 sheets, up to N sheets where N represents the number of sheets corresponding to the color that requires the maximum number of layers. The benefit of this method is that the user can choose which shapes to cut first, and thus can control cutting the outside shapes before the inside shapes for ease of material removal. During tests, when each grouping of sheets was removed after a cut, the desired shapes adhered to the acrylic base and the undesired cellophane material easily peeled off. Although this method worked well with larger shapes since those shapes had a larger perimeter for the cellophane to bond to the acrylic, it did not work well for smaller shapes. During later cuts, the smaller shapes tended to fly off due to the exhaust stream and poor adhesion to the acrylic base plate. Furthermore, this method had a longer setup since the sheet groupings must be made before so if we used N colors, the user must prepare $\frac{N(N+1)}{2}$ sheets. Stacking sheets over already cut shapes caused an uneven surface texture that affected the final color of the polarized light mosaic. For instance, if shapes made with 5 layers were cut first followed by shapes made with 1 layer, the single sheet of cellophane would have an uneven surface since some areas would be raised above others. Consequently, if a shape was cut next to a raised bump, that shape would not adhere well to the base plate and would likely fall off.

Fig. 35 exhibits the results of this method. Since this method was tested using the starter settings pror to setting testing, we used $20x\%$ power, 41% speed, and 250 PPI where x represents the number of cellophane sheets stacked to produce a certain color. In the top row with the abstract image, there was a shape irregularity since a layer of cellophane did not adhere properly to the base board and created an extra shape. The resulting mosaic still required postprocessing to remove extra layers, as seen in the top middle image where two pink-purple shapes, corresponding to 4 layers of cellophane, Enclosed shapes with the same color as the surrounding shape served as an indication that post processing was required to remove extra layers. In the bottom row with the geometric elephant image, each shape was relatively small, which led to poor adhesion, so many shapes fell off. Furthermore, the images have surface texture irregularities with various bumps and air gaps as seen in surfaces of the colorless images and the color gradients in the colored images.

4.3.3 Incremental Layering Without Water

We tested incremental layering with two different methods – with and without water. In the method without water, sheets were added then removed after each cut. So, the shapes corresponding to the color with the maximum number of layers (N) were cut in the first run so that the image could be built up layer by layer. After each cut, the unwanted cellophane material was removed. For the next layer, a single cellophane

Figure 35: Fabrication result using the group layering by color method. From left to right, the columns exhibit the colorless mosaics, colored mosaics under aligned polarizers, and complementary colored mosaics under crossed polarizers.

layer was placed in the laser cutter, and the shapes corresponding to N and N-1 layers were cut. This process was repeated done until N, N-1, ... 1 layer shapes were cut out. In summary, a cellophane sheet was placed in then removed between passes, and the laser cut the shapes in repeated passes to build up the final mosaic similar to how a 3D printer deposits material on the same area to build the final structure.

This method performed better than the group layering by color method since the repeated passes better adhered the shapes to each other and the acrylic base plate. One drawback was that if the image was more complicated and had many small shapes, picking out the unwanted cellophane material could be difficult. However, if the spacing between the shapes was sufficiently large, a small string of cellophane, the width of the spacing, connected the unwanted material together. Furthermore, since the shapes were repeatedly cut until the number of sheets corresponding to the desired shape color is cut, the power settings cannot be too high because the laser may cut through all the layers including the base acrylic layer.

Figure 36: Fabrication result using the incremental layering without water method. From left to right: the colorless mosaic, mosaic between aligned polarizers, and the mosaic between crossed polarizers.

Fig. 36 exhibits the fabrication result using this method. Since we tested this method before our extensive laser testing settings, the settings were difference. For the elephant, we used 40% power, 41% speed, and 250 PPI for each pass. Power was increased to improve adhesion. As shown, the shapes adhered to the base plate better than the previous method. For the abstract image, we tested 100% power, but this power was too strong, so the shapes with higher layer counts cut all the way through the base acrylic material.

4.3.4 Incremental Layering With Water

The second method of adding sheets after each cut then removing all the sheets at the end of the fabrication process with water spray produced the best results. To add layers, we placed the punched cellophane sheet to the peg bar, sprayed the previous layer surface or acrylic base sheet with water, then smoothed the cellophane sheet down to remove air bubbles. Fig. 37 demonstrates the process of layering in sheets between passes. The bottom layer was first sprayed with water, followed by adding and clamping down a cellophane sheet taking care to not release the sheet onto the base plate yet. Once the sheet was clamped, we ran a finger along the top edge before laying the sheet down and smoothing out the air gaps in a downwards motion. The process shares similarities with that of applying a phone screen protector to a phone

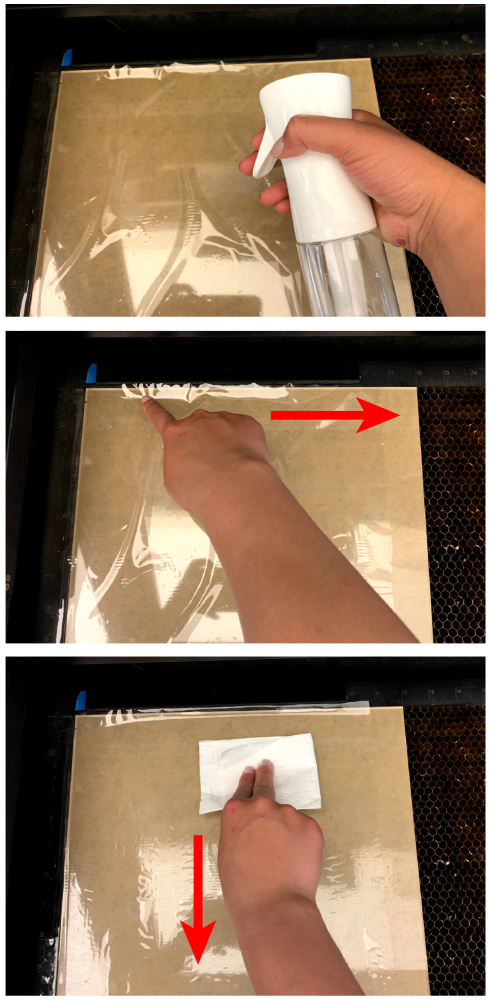


Figure 37: Water spray layering method

screen.

The shapes corresponding to 1 layer were cut first, then shapes corresponding to 2 layers, and so on until the image was complete. Between each pass corresponding to shape groupings with the same number of layers, another cellophane sheet was added. Once all the shapes had been cut out, all layers were removed at once since the unwanted material was also fused together due to the laser heat.

This method produced the cleanest results without minimal surface irregularities, strong adhesion to the acrylic base layer, clear colors, and fast fabrication time since

Figure 38: Fabrication results using the incremental layering method with water for the elephant image. In the colorless image, the white powdery dust was easily wiped off, and in the colored images, the shapes adhered well to the base board, had clear solid colors, and had minimal surface texture irregularities.

Figure 39: Since the outer shape was cut after the inside shapes, post processing was required. The missing gap of material exists because the shape was accidentally removed during fabrication.

the only peeling of unwanted material occurred at the very end. One drawback was that more considerations were required in creating the image to cut since the outside to inside cutting order of shapes mattered more. If there were an inside shape cut out, followed by a surrounding outside shape in the next layer, the resulting collage would require some post-processing of manually removing the inside unwanted material. However, if a small slit were placed in the surrounding shapes as described in the cutting order section, this method would produce the desired images with a single action of material removal and no post processing.

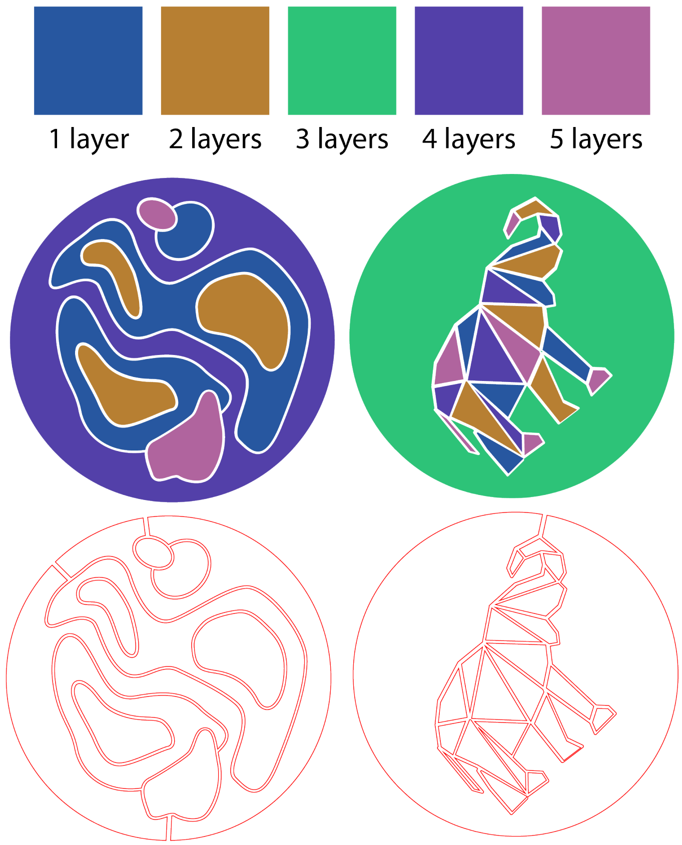


Figure 40: Altered designs with slits in shapes that enclose other shapes with a lower layer count. The bottom row of images shows the new shapes to be cut. The shapes with a slit cutout have a higher layer count than the shapes inside of them.

Figure 41: Fabrication results using the incremental layering method with water and slits in shapes enclosing other shapes.

4.3.5 Methods Summary

Method	Advantages	Disadvantages	Used Settings
Group layering by color	• Control over cutting order to minimize post processing	• Surface texture irregularities • Poor adhesion • Time consuming • Uses more cellophane material • Layer removal per pass	• For x layers: $20x\%$ power, 41% speed, 250 PPI

Incremental layering without water	• Less surface texture irregularities • Uses less cellophane material • Better adhesion	• No control over cutting order* • Laser may cut through acrylic for shapes with a high layer count if power is too high • Layer removal per pass	• For the elephant image: 40% power, 41% speed, 250 PPI • For the abstract image: 40% power, 41% speed, 250 PPI
Incremental layering with water	• Best adhesion • One time layer removal • Clear, solid colors • Minimal surface texture irregularities	• No control over cutting order*	• For x layers: $12.5x$% power, 30% speed, 500 PPI**

Methods Summary

Figure 42: Comparison of the three methods between aligned and crossed polarizers. In the images going clockwise: group layering by color method, incremental layering without water method, and incremental layering with water method

* If a gap slit is added to surrounding shapes that enclose others, cutting order no longer matters, and post processing is no longer needed.

** In later incremental method layering with water tests, 25% speed produced better adhesion because it ensured that the shapes cut out of the cellophane entirely and could adhere to the layers below.

5 Discussion

5.1 Optimal Fabrication Method

The best results are produced if the image is cut away from the edges of the cutting table due to the unevenness of the cellophane at the edges even with the use of water spray. Since the borders of the cutting table are at a taller height than the acrylic base sheet, the cellophane material does not lie flat. To prevent the cellophane edges from flying up and ruining the cut, the bottom free edge should be weighed down with some small object. The incremental layering method with water should be used. To remove the need for post processing, shapes that enclose or surround other shapes with a lower layer count should have a small slit that is at least 3pt wide. The optimal laser cutting settings are $10x\%$ power, 25% speed, and 500 PPI where x corresponds to the number of sheets for that specific color. The procedure is as follows:

1. Set up the peg bar on the top border of the cutting table
2. Lay down the acrylic base plate
3. Place and clamp down the first cellophane sheet
4. Spray the acrylic base plate then lower and smooth down the cellophane sheet onto the acrylic
5. Laser cut the shapes corresponding to the color made with one cellophane layer
6. Clamp down another cellophane sheet on top of the first
7. Spray the bottom cellophane layer and smooth down the top sheets
8. Laser cut the shapes corresponding to the color made with the current number of cellophane layers
9. Repeat steps 6-8 until all layers have been added and all shapes have been cut
10. Remove all the unwanted cellophane, taking care to not move the bottom acrylic plate
11. Laser cut out the finished polarize light collage out of the acrylic base plate. Make sure that the acrylic cutout is at least 3pt away from the outmost edge of the cellophane shapes to prevent edge melting and distortion.

With this current process, placing a cellophane sheet and cutting the shapes for a certain color takes approximately 5 minutes. So, if the user wishes to fabricate a polarized light mosaic with N colors, the process will take approximately $5N$ minutes.

For instance, a 5 layer image like the elephant example shown in previous sections takes about 25 minutes to fabricate.

5.2 Applications

Polarized light mosaics have the potential for a wide variety of applications. Cellophane is commonly found in everyday items, which makes it cost effective and widely available for large scale mosaics. Since the cellophane is a plastic film, the material is flexible, formable, lightweight, colorless, waterproof, and durable. As a colorless, transparent material, cellophane removes the need for pigments or electronics to create color. Instead of mixing pigments, users can control the hue by the thickness and angle of the cellophane material.

With the use of two viewing polarizers, two vector image designs, and a third intermediate polarizer with a separate design, eight unique images can be created – the two original designs, the complementary color versions of the original designs, and the previous four with the third polarizer design visible. Although only one image can be saturated or visible at a time, there could be multiple images aligned with both each other and the two viewing polarizers since all will be transparent and colorless, This opens up the possiblity of multiple image morphing combinations to easily create interactive displays, personalizable items, and more visually appealing everyday objects. For example, one could create a clock with twelve different faces corresponding to each hour, and the images morph from one to the next.

Since the mosaics are easy to control manually, personalized objects can be easily made. Some examples include color- and image-changing earrings, book covers, and phone cases. Cellophane film is also transparent, which allows the possibilities of see-through displays that can also block out all light if the polarizers are crossed properly.

Some applications could be sunglasses, face shields, windows, or other objects that benefit from having the ability to transition between transparent and opaque states. Since plastic film is durable and water-resistant, polarized mosaics could be used outdoors in different weather conditions and with objects that are direct contact with water. Some examples are umbrellas, outdoor furniture, aquarium displays, shower curtains, and plant pots. Large scale items and structures can also be made since cellophane is widely available in a variety of sizes, and the designs are fabricated with a laser cutter and require no manual input. Thus, large color changing posters, murals, and building faces could also be made.

Furthermore, cellophane is a flexible and formable material, which allows integration with other soft objects or materials. Some possible applications are color changing face masks, tablecloths, shoes, clothing items, cup covers, and curtains. One interesting application is combining polarized light mosaics with origami. Instead of creating a design to adhere to the base acrylic plate, one could create a design so that the desired image is cut on the cellophane layers that are removed from the acrylic plate and normally discarded. The plastic film with the desired image could be formed around an object or folded like origami into another shape. However, folding the sheet alters the angle of the birefringent material to the polarizers, which may affect the perceived colors. Another limitation is the polarizer itself. Although the polarizer film can bend, it is not as flexible or formable as cellophane, which limits the types of origami shapes that can be made.

5.3 Examples

To laser cut the polarizer film, we used settings of 20% power, 20% speed, 250 PPI, and a thickness of 1.00 mm. For 1/16" colorless acrylic base plates, the final work was cut out using 100% power, 8.6% speed, and 1000 PPI. For 1/8” colorless acrylic base plates, the final work was cut out using 100% power, 4.7% speed, and 1000 PPI.

5.3.1 Image Morphing Behavior

This example demonstrates the ability the create eight unique images from two vector images and a design cut out of a third polarizer. When the third polarizer is aligned with the two viewing polarizers, the design is colorless and transparent. When the front polarizer is rotated 90°, the front and third polarizer are now crossed, which causes the design to turn black and visible. Fig. 43 exhibits the resulting eight images. In the top row, the elephant is visible while the abstract design is transparent in the first two images and the reverse is visible in the last two images. The images with a black background signify crossed polarizers, revealing the complementary set of colors. The bottom row creates the same images as in the top row, but the polarizer design is now visible.

Since three designs can generate eight unique images, many sets of designs can be combined together in which all designs except the desired image are aligned with the two viewing polarizers and thus are colorless and transparent.

5.3.2 3D Lantern

Instead of creating 2D objects or mosaics, the mosaics can be combined together to create 3D objects. One such example is a color changing lantern that requires active participation by the viewer to reveal the pattern. Opposing sides of the lantern were created with the same pattern as shown in Fig. 44, and the lantern was assembled by fitting the wall pieces, made with 1/8” acrylic, together with a polarizer film inside three faces with shared edges. Polarizer film could have been adhered to the outside of the other walls to view the colors statically, but doing so would have limited the

Figure 43: Eight unique images generated from two vector designs and a third polarizer

number of resulting color configurations since the polarizer shape would not cover the desired area if rotated. Fig. 45 demonstrates the resulting color pattern if a single polarizer is held aligned or crossed with the polarizer inside the lantern. Fig. 46 exhibits the assembled lantern box viewed without a polarizer as well as with aligned and crossed polarizers. Different color patterns were generated by holding one polarizer sheet in front of the lantern and another directly behind the lantern (Fig. 47). When the two polarizers were both aligned or both crossed with the polarizer inside the lantern, the visible patterns on wall faces across from each other were the same color. When the two polarizers were crossed with each other, one wall face had one set of colors, and the other wall face had the complementary color set.

This lantern example only had two wall designs, but another could be made with different designs for each wall face for greater personalization, more viewer participation, and visual appeal. The lantern could be placed outdoors since the material is durable and water resistant, and many more could be easily replicated and produced with this fabrication method.

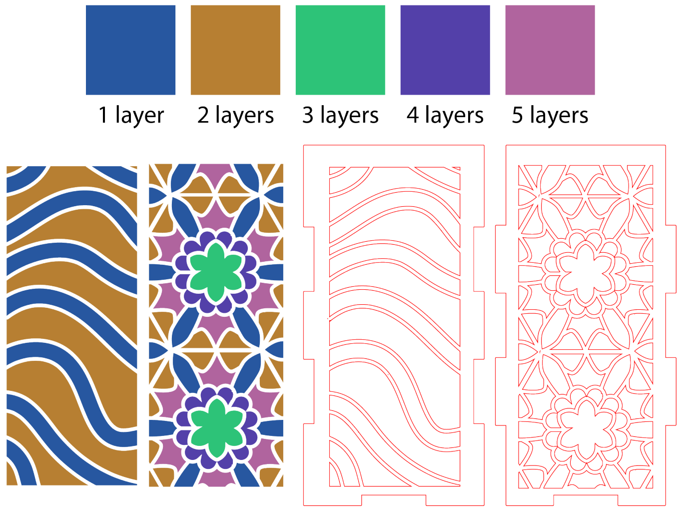


Figure 44: Illustrator design of lantern walls.

Figure 45: Color pattern of lantern walls with one outside polarizer. The left column shows the results of an aligned polarizer outside the lantern, and the right column shows the results of a crossed polarizer.

Figure 46: Lantern with no outside polarizer, aligned polarizer, and crossed polarizer.

Figure 47: Different wall color configurations made with two outside polarizers. From left to right: aligned outside polarizers that are both aligned with the inner polarizer, aligned outside polarizers that are both crossed with the ineer polarizer, and crossed outside polarizers.

5.3.3 Sunglasses

Since cellophane is transparent, polarized light mosaics could be used as personalizable sunglass lenses. Users can choose which designs are visible based on the positioning of the cellophane layers or a third polarizer relative to two other polarizers. Two different sunglasses were created – one with image morphing between two designs and another with a single design and a third polarizer.

For the image morphing sunglasses, the lens design is illustrated in Fig. 48, and the wood frame design with living hinges is included in Fig. 49. Two tabs were added to the mosaic lens so that the wearer can shift the angle of the birefringent material to choose which design is visible. The notches on the sunglass frame are 45° apart so that moving the tab between the two notch areas switches the image that is visible. When the tab is aligned between the notches near the hinges, the kaleidoscope pattern is visible and the ring design is transparent. When the tab is aligned between the notches closer to the bridge, the ring design is visible and the kaleidoscope pattern is not. The individual and overlapping mosaic lens are shown in Fig. 50 and Fig. 51 respectively. Since the polarizer circles are pressfit into the lens holes without any adhesive, the wearer can rotate one to achieve the complementary color set. The final sunglass result is shown in Fig. 52.

The other set of sunglasses contained one fixed image with the ability to reveal or hide the pattern made with the third polarizer. The lens and frame design are included in Fig. 53 and Fig. 54 respectively. The individual lenses, overlapping lenses with the third polarizer, and the final sunglass results are shown in Fig. 55, Fig. 56, and Fig. 57 respectively.

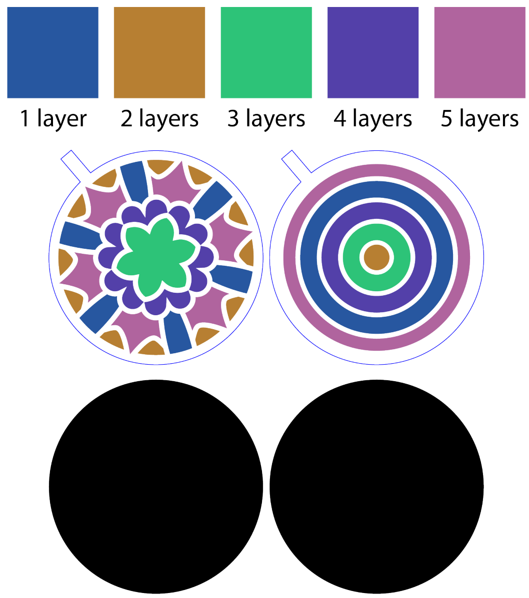


Figure 48: Lens design for the two image morphing sunglasses. The designs shown create one mosaic lens, so two must be made. The black circles represent the polarizer cutouts that sandwich the birefringent material.

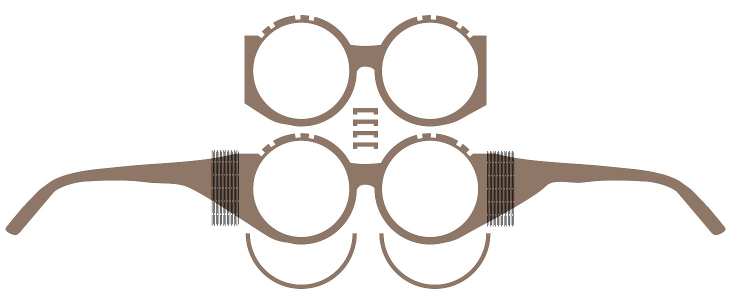


Figure 49: Wood frame design for the two image morphing sunglasses. The notches mark the correct tab position of the lenses so that the one image is visible and the other is not at that specific location. The smaller wood pieces fit into the notches to hold the lens tab in place. For this example, the frame pieces were made of 1/8" wood with a living hinge.

Figure 50: Individual lens mosaics for both designs. Left: aligned polarizers. Right: crossed polarizers.

Figure 51: Demonstration of image visibility configurations. Top row: ring design is visible and the kaleidoscope pattern is not. Bottom row: kaleidoscope pattern is visible and the ring design is not. Left column: aligned polarizers. Right column: crossed polarizers.

Figure 52: Sunglasses result with two morphing images. Top image: no mosaic lens. Top row: ring design is visible and the kaleidoscope pattern is not. Bottom row: kaleidoscope pattern is visible and the ring design is not. Left column: aligned polarizers. Right column: crossed polarizers.

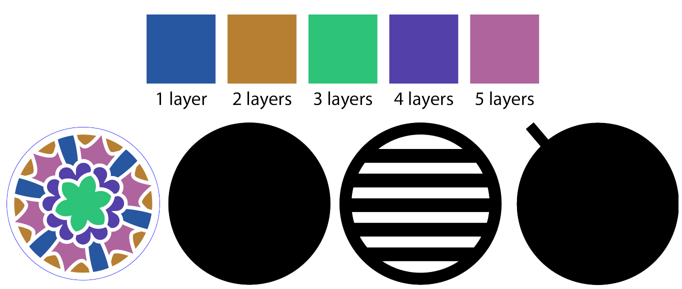


Figure 53: Lens design for sunglasses with a third polarizer. The designs shown create one mosaic lens, so two must be made. The black circles represent the polarizer cutouts that sandwich the birefringent material. The orientation of the polarizer film when cutting out the striped polarizer design matters depending on the wearers preference for viewing the design in the original or complementary color palette without the third polarizer design.

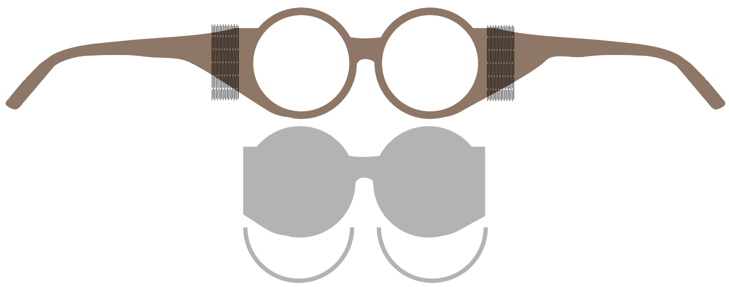


Figure 54: Wood frame design for the sunglasses with a third polarizer. The brown represents 1/8" wood, and gray represents 1/16" acrylic.

Figure 55: Individual lens mosaics without the third polarizer. Top: aligned polarizers. Bottom: crossed polarizers.

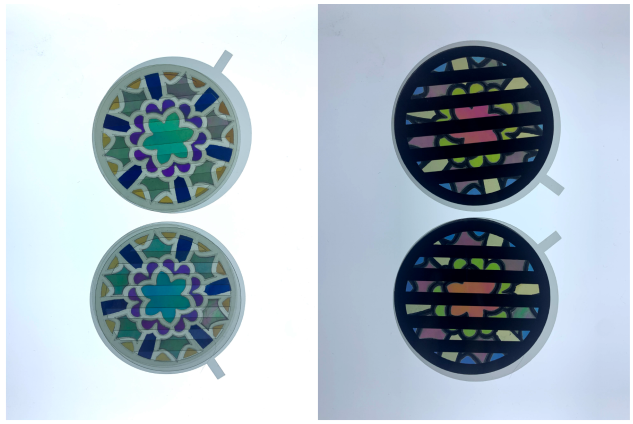


Figure 56: Polarizer-mosaic stack effect of third polarizer. Top: aligned polarizers so the design not visible. Bottom: crossed polarizers so the design is visible.

Figure 57: Sunglasses result with a fixed image and a third polarizer. Left: aligned third polarizer so that the design is not visible. Right: crossed third polarizer so that the design is visible.

Figure 58: Visible pattern on the excess cellophane sheets. The leftover material that is typically discarded has a visible pattern that could be wrapped around a non-flat surface or object since cellophane is flexible and formable.

5.3.4 Excess Cellophane Sheets

As shown in Fig. 58, the excess cellophane sheets that are typically discarded after the fabrication of a mosaic on a base plate still contain a colorful pattern that can be wrapped around non-flat objects or shaped into another form. Since the pattern is not fixed to a rigid base plate, many more possibilities exist for color-changing objects as long as the material can be sandwiched between two polarizers.

5.4 Limitations

The current fabrication process can only utilize a discrete color palette since we experimented with single thickness cellophane. If the material thickness could be controlled in a continuous manner, we would have access to a continuous range of colors, which is consistent with theoretical results. The current fabrication process also places constraints on the design of the svg images that are fed into the visualization tool. The current design tool does not account for overlapping shapes, which requires the user to create the appropriate non-overlapping shapes with a sufficient gap between neighboring shapes. If there are shapes that enclose other shapes made with a smaller thickness of cellophane, the user would need to add slits to remove the need for post-processing, but it may alter the user's desired pattern or image.

Regarding the physical fabrication method, all shapes are cut at a 45° angle so that the resulting colors are as vibrant and opaque as possible. Since all the shapes must be cut first before cutting out the acrylic base layer to ensure the correct shape positioning, the material cannot change angle between passes, so colors cannot be produced at different hues or intensities. In Austine's manual process, she angled the cellophane sheets at a variety of angles to achieve different hues and intensities. In our process, all the shapes are cut at the same angle, which limits the amount of colors that can be produced with the single thickness cellophane. For instance, the current process cannot cut one cellophane sheet at a 30° angle and the next at a 45° angle.

Another limitation is that the polarizer is less flexible and formable than the cellophane material, which limits the types of objects that can be made via polarized light mosaics since the birefringent material must be sandwiched between two polarizers to perceive the colors. Bending or folding the cellophane may also alter the expected color since angle of the cellophane relative to the polarizers has changed. Furthermore, this process only accounts for two birefringent layers as discussed in Dall'Agnol et al., so we currently do not have a method of visualizing three birefringent layers. This behavior is more complex and may require a different model than the algorithm proposed by Dall'Agnol et al. [3].

6 Conclusion

We presented a custom visualization tool that allows users to view and interact with their designs before fabrication and a simplified fabrication process that produces quality polarized light collages. On the visualization side, images can have up to 8 colors, and the designs must have non-overlapping shapes and adequate spacing between neighboring shapes. On the fabrication side, the optimal laser settings are $12.5x\%$ power, 25% speed, and 500 PPI for x cellophane layers, and the optimal fabrication method is incremental sheet layering with water. Designs should include slits in shapes that enclose other shapes with a lower layer count to remove the need for post-processing. This art medium has several benefits over other art forms or displays in terms of scalability, durability, and flexibility, which allows for a wide variety of applications. With a streamlined process, more people can access and utilize this art form for either aesthetic or practical uses. We hope to build upon the art technique that Austine invented decades ago and increase its presence in our daily lives.

6.1 Future Work

For the visualization tool, the UI can be improved to become more intuitive to users and better mimic real-life behavior. Currently in the UI, the images are do not rotate or change opacity to mimic the saturated to colorless behavior as the birefringent material rotates relative to the polarizers. For next steps, the images should appear stacked, rotate, and change opacity to accurately demonstrate the image and color morphing. The program should also demonstrate the effects of adding a third polarizer that displays another image based on its relative angular position to the front and back polarizer.

Since shapes that enclose other shapes with a lower layer count give rise to the need for postprocessing, the original image must be modified. The visualization tool should either indicate which shapes should be modified or directly modify those shapes automatically. To give the user more control over the fabrication process, they can choose whether or not to implement those slits.

On the fabrication side, we can improve the current method by reducing the amount of user involvement such as layering sheets, changing laser settings between passes, or removing the need for slits in outside shapes. We can explore loading all the sheets at once and rastering away undesired layers, so that the user only needs to load sheets once and remove the final finished image at the end. Regarding the laser settings, increasing cutting power improves cellophane adhesion to the base acrylic plate, but it also increases the opacity of the cut border, which can affect the transparency of the end result. The tradeoff between better adhesion and greater transparency may be explored.

For polarized light mosaic applications, we can explore different light sources to determine their effect on the birefringent colors and on the types of objects that can be made with these mosaics since a large white backlight may not be needed anymore. The light mosaics can also be applied to other 3D geometries to better understand which structures and geometries work well with this art medium.

References

[1] Lyons, D., 1987. The physics of polage. Tech. rep., University of Massachusetts/Boston, Boston, MA, March. See also URL `https://www.austine.com/physics`.

[2] Mann, J., 2005. *Austine Wood Comarow: Paintings in Polarized Light.* Wasabi Publishing, Las Vegas, NV.

[3] Dall'Agnol, F., and Engelsen, D., 2012. "Colors from polarizers and birefringent films". *Revista Brasileira de Ensino de Fisica,* **34**(3), June. See also URL `http://dx.doi.org/10.1590/S1806-11172012000200005`.

[4] Comarow, A. About the polage art medium. On the WWW. URL `https://www.austine.com/medium`.

[5] Institute, E. T. Polarized-light mosaic. On the WWW. URL `https://www.exploratorium.edu/snacks/polarized-light-mosaic`.

[6] D. Murphy, K. Spring, T. F., and Davidson, M. Principles of birefringence. On MicroscopyU. URL `https://www.microscopyu.com/techniques/polarized-light/principles-of-birefringence`

[7] Gigahertz-Optik. Colorimetry. On the WWW. URL `https://light-measurement.com/colorimetry/`.

[8] Chew, J., 2021. Learn about peg bar in animation and how it is used. On the WWW, March. URL `https://www.lifewire.com/what-is-a-peg-bar-4066653`.