G4G16 Gift by Eva & Ken Greenebaum February 2026

Making Color with… Birefringence

one of 15 causes of color

Introduction

We've been really excited by transparent, light changing colorful sculptures as encountered in museums and exhibits, and wanted to learn the source of this magic. While not obvious, it is possible to make vibrant dynamically changing colors using only a certain film and inexpensive plastics! We've included a small kit of parts so that you can explore this and related phenomena.

We will be walking you through simple experiments, providing both a high-level explanation of the optical physics involved, as well as references providing the much deeper theory.

Our G4G16 gift is a kit that enables you to explore how a pair of polarizers (the filters in the black holders), allow you to see hidden colors created by the birefringent filters (in the white holders), or even view hidden stress in everyday objects (such as plastic spoons).

The kit

In the kit you should find four disks:

1) Two disks in black holders, containing polarizing film
2) Two disks in white holders, containing birefringent film

Additional materials that are fun and helpful:

1) We recommend using a flashlight (we especially like the almost chapstick sized, Nitecore LA10 lantern with integrated diffusor) to better see the experiments, however a sunny window, or a well-lit room also more than suffice
2) You might want to find a protractor, and samples of transparent plastics, too

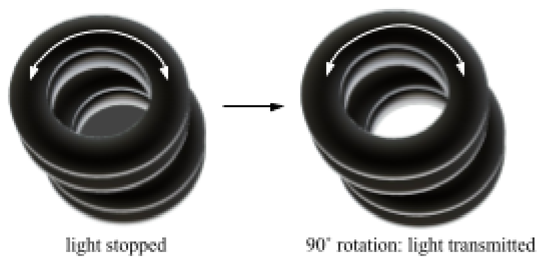
Troubleshooting

The kits were cut on a desktop mill, 3D printed on a Bambu printer, and painstakingly assembled and tested by hand. Please understand if the disks don't behave as they are supposed to it is most likely due to our accidentally failing to remove the protective plastic from one or both (?) sides of the polarizers. You should be able to achieve close to black when viewing through the stack of two polarizers by rotating the phase of one polarizer, if the polarizers are flipped arbitrarily. The protective layer will randomize the polarization (as explained later) if it is both present, and **between** the two polarizers. If flipping one of the polarizers results in a state where rotating the polarizer doesn't cause it to go black, and flipping that polarizer then allows rotation to yield black, then the errant protective layer is on the **outside** side of that filter. Either remember to use the filter in this orientation, or pry the holder apart and use your fingernail, or a dental tool, to peel the protective layer off.

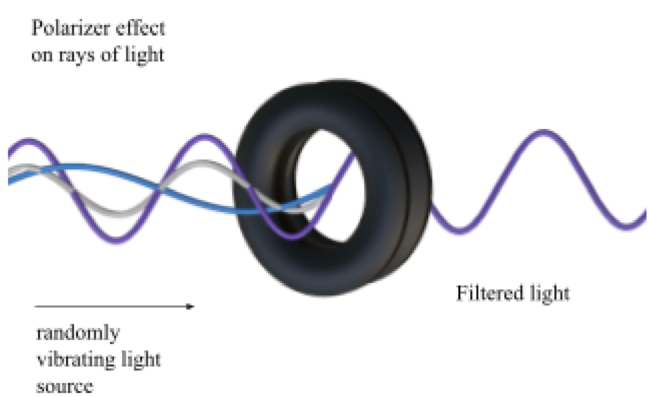
Feel free to reach out if you have any concerns and we'll try to help you resolve them.

Experimentation

The first principle to explore is polarization: Stack the pair of black linear-polarizing filters and hold them up to one eye against a bright outdoor scene or light source. Hold one filter still and rotate the other. You should notice that there is a position where most light is blocked. From this position carefully continue to rotate the filter and notice that the pattern of transparency to blocking occurs every 180 degrees.



As is commonly known, light often acts as a wave. But have you ever considered how those light waves vibrate in space? Non-polarized light vibrates in all directions. A polarizer is a filter that blocks all light except for light that vibrates in a specific direction.



Hold a single black polarizer to your light source. Notice how the filter slightly dims the light? This is due to it blocking half of the light's vibration direction. Does this seem to be brighter than the expectation of having ½ the light blocked? That is because our perception of brightness is not linearly proportional to light intensity. While perception is a topic for a different G4G, please refer to Reinhard et. al. for more details.

Next hold a single black polarizer to your eye and view a sunlit object (an object illuminated by a lightbulb might also work). Rotate the polarizer and notice that while most of the object will remain the same regardless of filter rotation, specular reflections might grow brighter and dimmer. Compare that specular at min brightness to not having the filter in place at all.

The polarizer attenuates reflections, which is why sunglasses are often polarized!

We have already experienced rotating a polarizer will attenuate polarized light, so we might intuit that somehow the reflection has taken on polarization.

While you might enjoy reading more about the interaction the electromagnetic wave that is light as it interacts with surfaces suffice it to say that the electric field can be split into two components, and one of those components, the parallel polarization, can not radiate energy back in the direction of the reflection when close to a special angle called Brewster's angle (itself dependent on the densities of the materials (e.g. approximately 53 degrees for light in air reflecting off water), thus leaving primarily the other component (call the perpendicular component), thus leaving the reflected light polarized in one direction.

If you are feeling intrepid, and have a protractor, you can find Brewster's angle for a given material in air by reflecting light off the object, rotating the polarizer until the reflection is minimized, then change the incident angle of the light source to the surface until the reflection viewed through the polarizer is minimized. Measure the angle using the protractor.

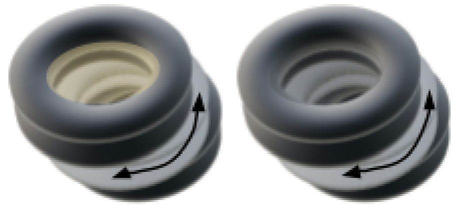
Let's see some colors!

Start by stacking the two black polarizing filters and rotating one until essentially no light is passed.

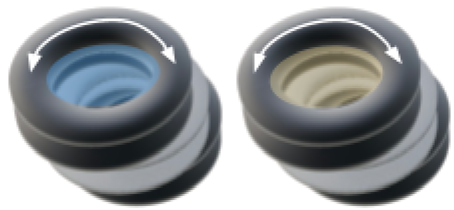
Next hold the polarizing filters apart so there is room for a filter (or two!) between (should still be dark when viewing). We like to hold the filters between our thumb and forefingers, then add or rotate the fingers using my other hand. It is best to hold the stack toward a white target, light, or a brightly illuminated wall to more easily identify the colors produced.

Now, partially slide a white birefringent filter between the two black polarizers. Depending on the rotation of the white filter, you will probably see the overlapping area become a transparent yellow instead of the black of just the two 180 degree phased polarizers.

Rotate the white birefringent filter and you should see the color shift between a bright yellowish hue to black, and back to bright yellowish again every 90 degrees of rotation.



Don’t worry if you see a blue-ish tint instead of a yellow-ish tint, this just means that your polarizers slipped out of the 180 degree orientation. To this point, try rotating the black polarizing filter closest to your eyes (called the analyzer) and you should see a shift between the most saturated yellow, and most saturated blue tint every 90 degrees you rotate the analyzer.



For more fun, add the second white birefringent filter to the stack between the black polarizer, and the second black polarizer (analyzer). Have fun changing the rotational phase relationships between the individual birefringent filters and the analyzer. What colors can you find?

You should be able to create saturated magenta, blue, cyan, yellow, green, red, and some other colors in-between. In terms of additive color, these are the primary colors, red, green, and blue, as well as the secondary colors yellow red + green), cyan (green + blue), and magenta (blue + red).

What is happening?

At the highest level. white light is made up of all frequencies of light in roughly equal brightness. Objects like walls that we actually perceive as white are illuminated by what is known as a black body radiator (literally the spectrum an object emits when heated to a given temperature commonly measured in Kelvin, e.g. metal heated to 5000K glows blueish white, and old-school tungsten light bulbs cause their filaments to be heated to 2700K and produce an orange-ish glow). Objects that we perceive as being diffuse white have the property of reflecting the illuminator’s spectrum evenly at least across the range of electro-magnetic frequencies that we perceive as light, roughly 650nm red, to 400nm violet when the frequency is described in terms of wavelength in nanometers. Just longer wavelength electro-magnetic radiation can not be seen and is called ultra-violet, just shorter wavelength light also can not be seen but can be felt as heat and is called infra-red.

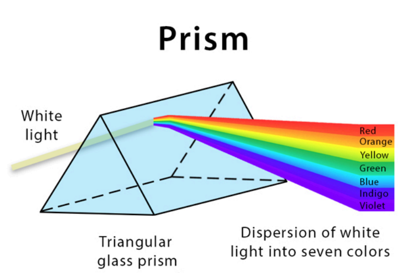
Our filter stack is attenuating the brightness of some frequencies of light more than others causing a net change in perception. When the stack is configured to produce a saturated red, it is actually acting to significantly attenuate the frequencies of light outside of a narrow region of frequencies associated with the color red.

With one birefringent filter we only produced yellow-ish, and not a more saturated yellow, because we were not able to produce a narrow pass-band. The narrower the pass-band of the filter (also called the emissivity of the filter) the more saturated the colors produced. By extension the most saturated perceivable colors require a single wavelength of light. This almost always requires a laser light source, and LED's, and even quantum dots don't produce single wavelengths.

How light spectra are perceived as color is based on the physiology of the eye including the response of the three photopigments in the human cones, as well as the photopigment of the human rod cells, however this, too, is the subject of a different G4G (curious readers might want to consult Color Imaging Fundamentals and Applications by Erik Reinhard, et. al.)

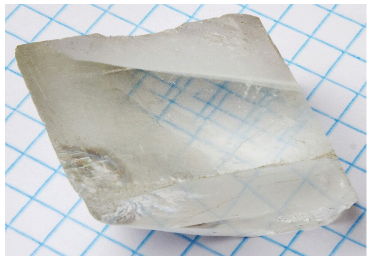
The details

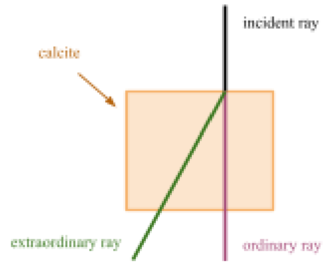
Birefringence is a fancy way to say bi (or two) refractive indices (from the Latin refringere). Refraction, of course, is the bending of light usually induced by the speed change as light passes between materials of different densities (e.g. when passing from low-density air to high-density glass/water, causing the common example of straw in a glass of water appears bent where the straw is submerged). A prism is constructed with a triangular cross section creating two refracting surfaces such that light enters the prism through one surface, causing the light to slow due to the air to glass transition, bending inside the prism (with each wavelength of light moving at slightly different speeds). Then, the light is bent again on the other refracting surface's interface to air, causing the light of different frequencies to emerge at a different angle. Essentially a prism has a different refractive index for each wavelength of light.



science facts website

Calcite is an example of a naturally occurring birefringent material (one with exactly two indices of refraction) as can be seen in the photo below.





wikipedia commons

Essentially, the first polarizer changes the unpolarized light vibrating randomly into light vibrating in the same direction, the birefringent material induces a phase change between the light that passes through each of its two distinct refractive indices, and the second polarizer acts like a detector causing the polarization phase changes to combine causing some frequencies to be added, and some attenuated, thus inducing spectral changes we see as color.

The phase difference between the two polarization components passing through the birefringent material changes with the material's thickness. Thicker birefringent material (or the more slices of the material that are present as in our case) the more change, leading to more saturation.

Rotating the birefringent filter changes how it interacts with the polarized light essentially controlling which wavelengths are enhanced, and which are suppressed.

Stress testing with polarizers

Another fascinating application of birefringence is stress detection. We are going to use our kit to visually inspect transparent materials for the presence of hidden stress.

Most transparent materials such as glass, or plastics, are manufactured such that they are isotrophic, meaning that they provide the same response across all angles. This is both for optical properties, but also, as we will see, to limit internal stressors that can lead failures (although ironically, some materials are pre-stressed to provide enhanced strength).

For example, again set-up two black polarizing filters 180 degrees out of phase such that they block most light, but this time with a gap between them. As you insert a high quality plastic, such as acrylic (branded as Plexiglass), the observed black will be replaced by potentially perfectly clear (no color shift). Essentially the isotropic high-quality plastic randomizes the polarization negating the effect of the first polarizer.

Next, take the lower quality plastic we mentioned earlier (possibly that protractor, a clear plastic spoon, or even the ziploc baggie this kit came in) and place it between the 180 degree offset black polarizing filters. Once again the black will give way to transparency, although this time with rainbow fringes around some features (often sharp features in the cast part where latent stress is present).

Essentially, internal stresses, as well as deformations, locally induce birefringence in otherwise isotropic materials.

For the intrepid, try heating the material showing birefringent stress to its glass transition temperature (not hot enough to melt, and careful, not hot enough to catch on fire!). Allow to slowly cool again, and observe using our 180 degree polarizer configuration to determine if the internal stresses were reduced as would be evidenced by less color! This process is called annealing, and is correcting for the permanent stresses that may have been "frozen" into a piece of material.

Also try using our apparatus to examine stresses within engineered materials like automotive glass that are pre-stressed to both facilitate strength, as well as particular properties like shattering into tiny pieces when broken.

Applications of birefringence

A hidden, but super common use of birefringence is in the now ubiquitous Liquid-crystal displays (LCDs) which use a polarized stack similar to ours, and a liquid-crystal whose birefringent properties may be electrostatically manipulated to form an electronically controlled light valve to modulate the amount of light transmitted from the backlight. Birefringence in this case is not used to create color. Rather for every pixel there are individually controlled red, green, and blue sub-pixels such that the relative brightness of the R, G, and B sub-pixels produce a spectrum that is perceived as grey (when R==G==B), or any color between the R, G, and B primaries. Please refer to Reinhard et. al. for more information on how the ratio of the brightness of three colors can produce the perception of any color in between!

Assembling the kit

To assemble the kit we visited TAP Plastics, and other sources searching for birefringent materials that would produce beautiful and clear examples. Ironically many of the materials they sold were too high quality to produce birefringence.

One of the first plastics that we tried was polyethylene, commonly used for plastic wrap. This worked pretty well, but we found the material to be non-uniform, and very difficult to work with. We also tried clear packing tape, which when put under stress made decent colors. Again, due to its self-clinging nature, it was tricky to work with.

We finally settled on using pre-cut sheets of cellophane from Amazon.

Similarly, we sourced our linear polarizer material from Amazon sold in sheets, unfortunately with one adhesive side. We tried to assemble the filters with the adhesive side deeper in the carrier to make it more difficult to fingerprint, but be careful not to fingerprint or get other material stuck to it.

We used a drag knife on a small CNC milling machine to cut the 1" filters, and a 3D printer to create the carriers (which may be pried apart to remove or replace the filter material).

We initially intended to incorporate the filters into a circular tube to make it easier to more precisely manipulate the phase, but ran out of time!

Learn more about birefringence, color, and perception

Kurt Nassau's *The Physics and Chemistry of Color*, 1983
Erik Reinhard, et al's *Color Imaging: Fundamentals and Applications*, 2008
Douglas Murphy, et al's article *Principles of Birefringence* via Microscopy U by Nikon
Rüdiger Paschotta's article on Birefringence through the RP Photonics Encyclopedia

All illustrations are original unless cited.

Contact us

Please reach out if you have questions, corrections, or suggestions!

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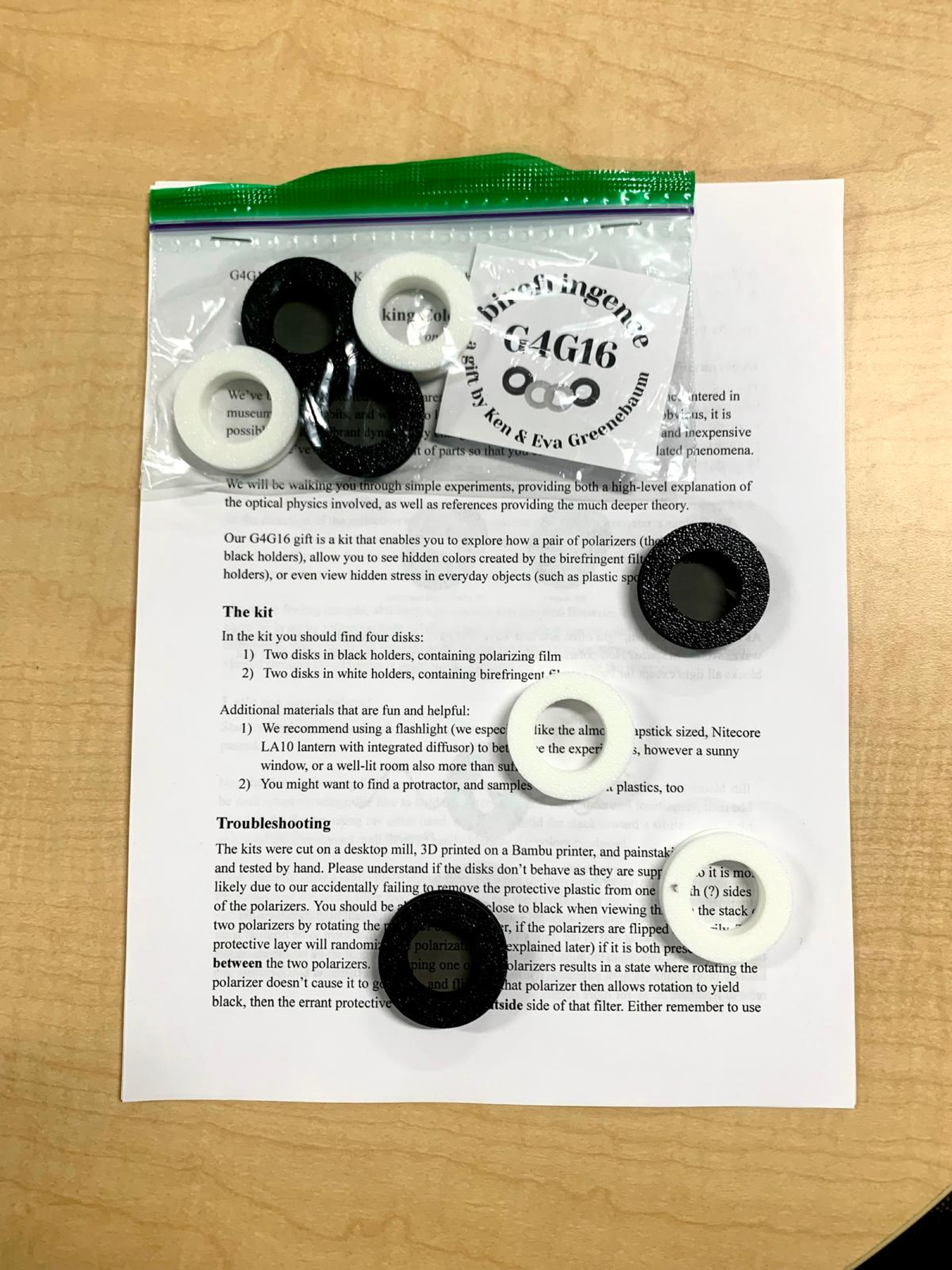

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