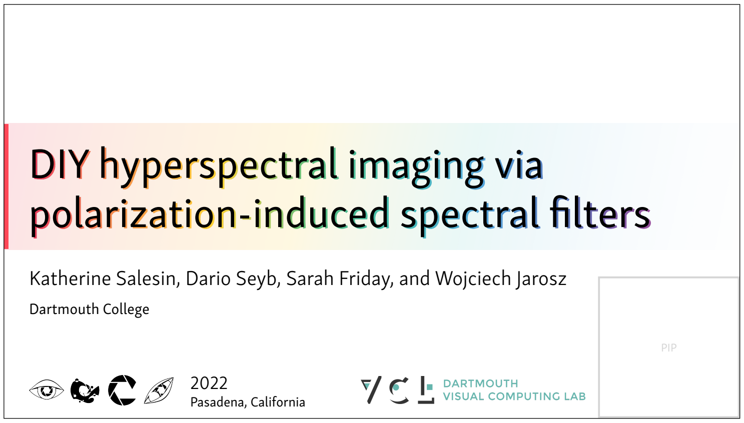
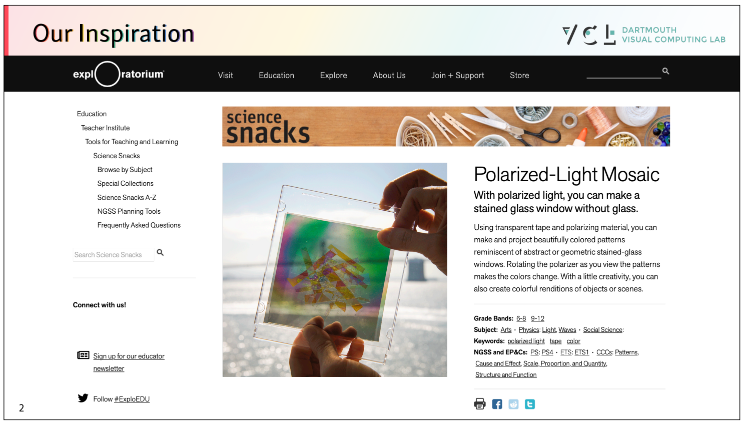
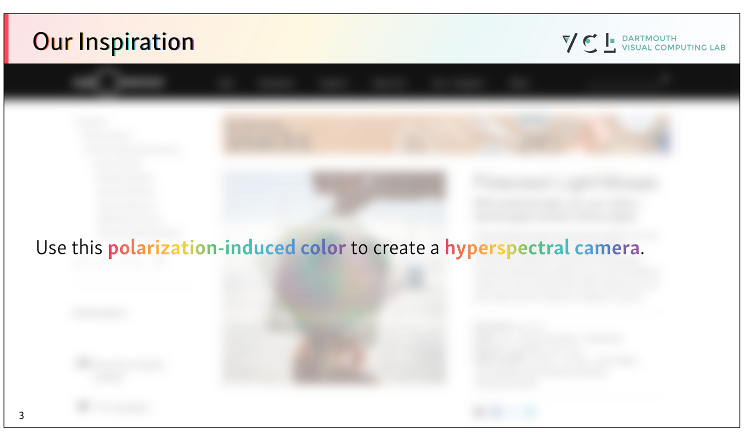


Hello! My name is Katherine Salesin, and I will be presenting our paper "DIY hyperspectral imaging via polarization-induced spectral filters", co-authored by Dario Seyb, Sarah Friday, and Wojciech Jarosz, from Dartmouth College. **[click]**

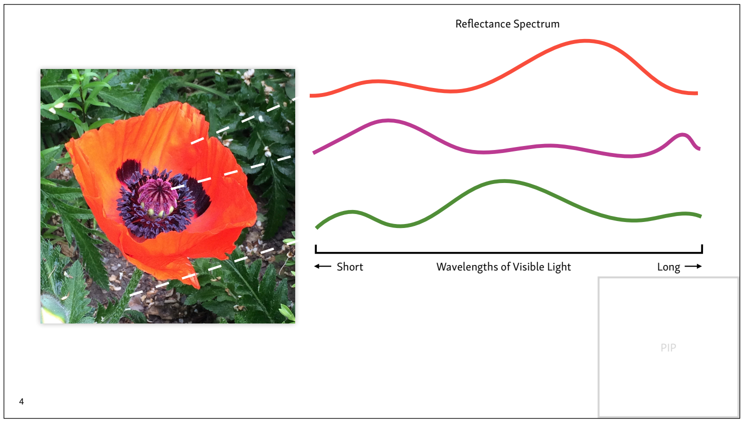


The inspiration for this project came from fun experiments like this, which show the kaleidoscope of colors you can create by placing strips of clear packing tape between two polarizers and rotating them.

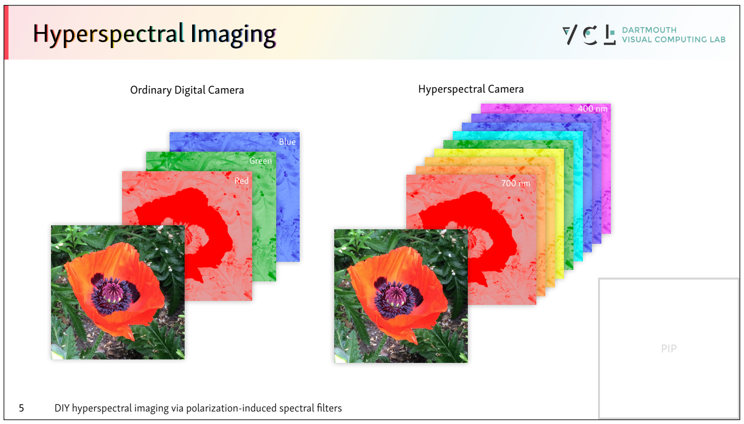
Normally, of course, this tape would appear transparent to our eyes, but we see these vivid colors because the tape is a **birefringent** material, which means that it alters the polarization state of the light in a way that depends on the light's wavelength.



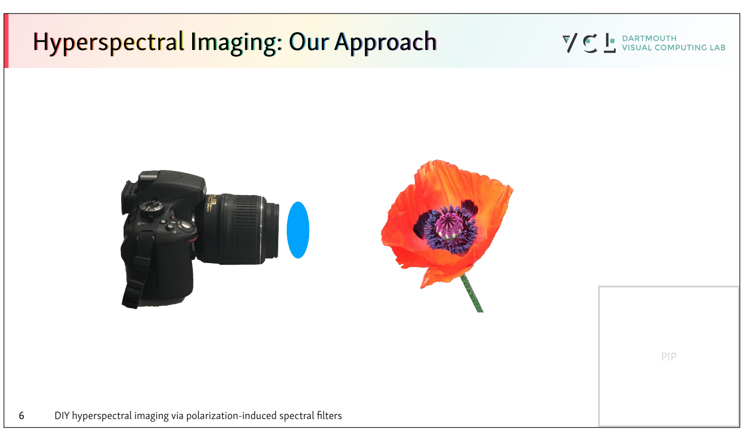
We were inspired to harness this effect to create a hyperspectral camera. But before we fill in the details of how this all fits together, let's briefly review hyperspectral imaging. **[click]**



Every color we perceive in the world consists of a spectrum in the visible wavelength range.



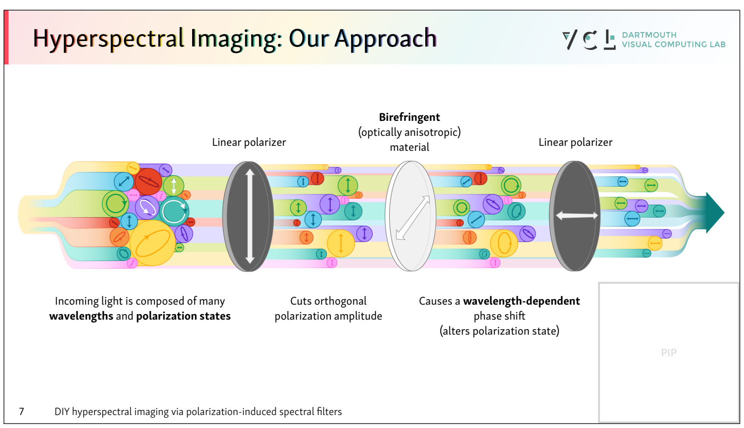
An ordinary digital camera downsamples each spectrum to just 3 values — red, green, and blue. **[click]** A hyperspectral camera, on the other hand, tries to capture a more complete representation of the original spectrum by sampling values across a larger collection of wavelengths. A typical hyperspectral camera accomplishes this by taking a series of images through a progression of filters that each have a narrow 5 to 10 nm window. These are typically expensive instruments costing thousands of dollars, which can be prohibitive. **[click]**



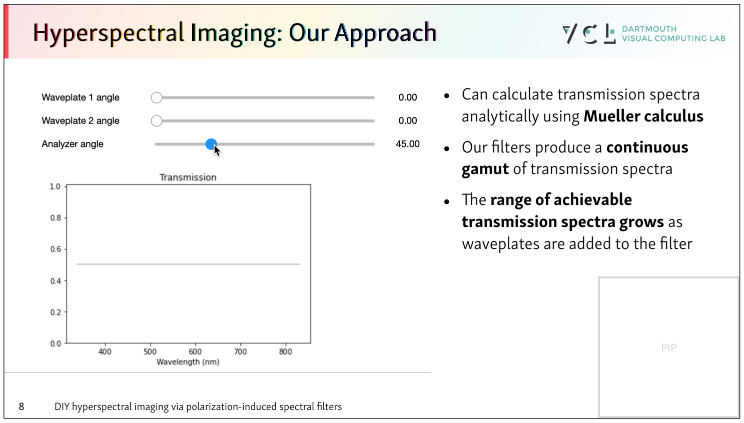
Our approach is to use the less expensive, ordinary digital camera **[click]** augmented with low-cost, broadband spectral filters placed on its lens. The greater the variety of transmission spectra that these filters can achieve, the more useful spectral information can be gathered about the subject.

We bring this concept to fruition by using the polarization-induced color that was our inspiration for this project. We use this polarizer-waveplate sandwich to create spectral filters that have several desirable properties, including the capability to produce a huge variety of transmission spectra.

Let’s take a look at the transformations of light that produce these colors… **[click]**



[click] If we were to look at a beam of light as a bundle of individual waves, each would have their own wavelength, amplitude, and polarization state, **[click]** which could be vertical, circular, or elliptical. **[click]** This light passes through a linear polarizer, which cuts the polarization orthogonal to its transmission axis, **[click]** then passes through the birefringent material, which causes a wavelength-dependent phase shift that alters the polarization state of the light. **[click]** It then passes through a second linear polarizer, which again cuts the polarization orthogonal to its axis. **[click]** The cumulative effect is wavelength-dependent transmission. **[click]**

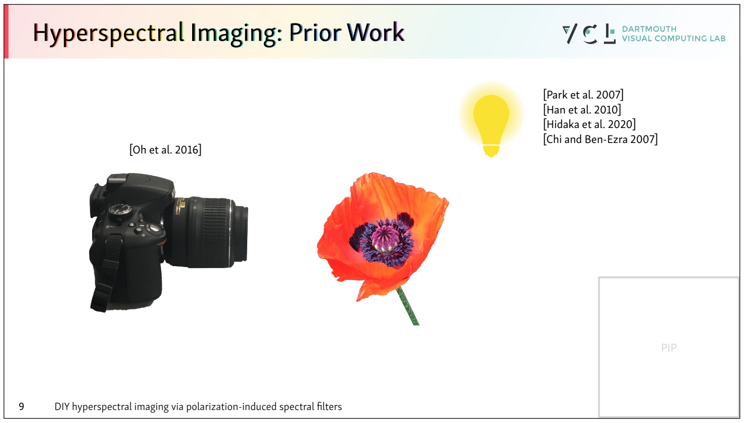


The transmission spectrum of a filter can be calculated analytically using Mueller calculus, a mathematical framework for describing polarized light, given the rotation angle of each element as well as the birefringence value and thickness of each type of waveplate.

Since rotation angles are continuous, our spectral filters can produce a continuous gamut of spectra, whose range of expressiveness grows as waveplates are added to the filter. We describe an algorithm for choosing a discrete set of filters from this continuous gamut in the main paper.

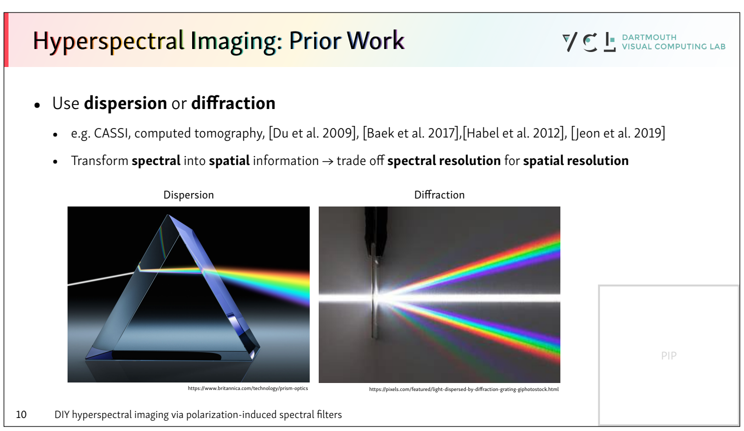
We show here some examples of how easy it is to produce a wide variety of filter transmission spectra by just rotating either the waveplates or linear polarizers in a two-waveplate system.

Clearly, this spectra are broadband in that they span the full visible spectrum, in contrast to a typical hyperspectral camera that uses many narrowband filters to isolate a tiny wavelength range. We cannot use our filters to isolate a single wavelength in the same way.



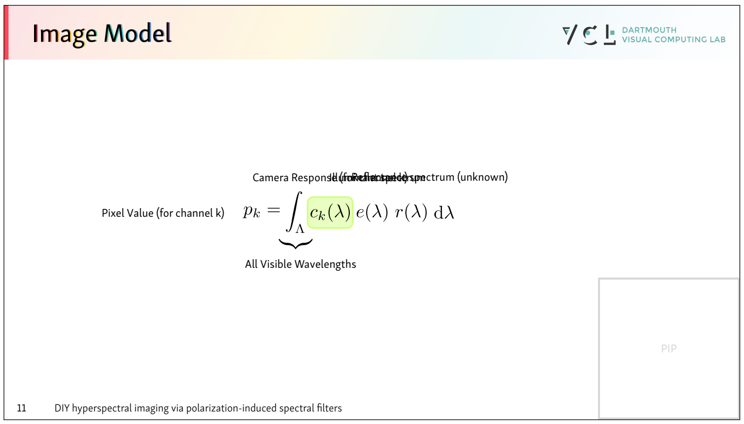
Instead, we pose this as an optimization problem. There are several prior methods that take a number of measurements of a scene by varying the lighting or sensors, and then using those measurements to solve for the measurement signal. We share the same underlying methodology as these prior works.

However, these approaches all choose spectral variants from an existing discrete set, whereas our spectral filters can produce a continuous gamut of spectra and therefore can take many more useful measurements. We also do not need to physically swap in or out any elements of the system between measurements — taking more measurements is as easy as rotating the filter.

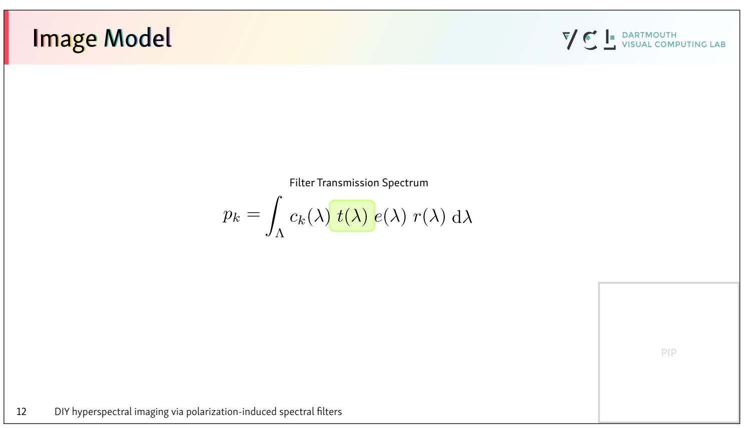


Another class of approaches to hyperspectral imaging use dispersion or diffraction

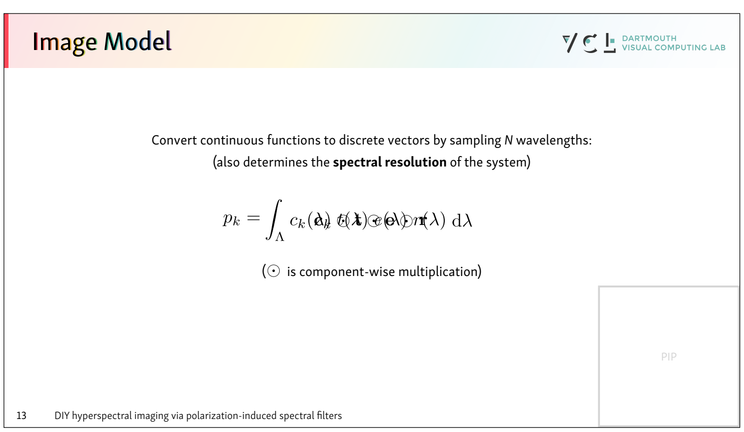
Both of these methods bend light rays to spread spectral information over a spatial area, which in turn lowers the spatial resolution of the system. In our approach, we use temporal multiplexing to obtain spectral measurements, allowing us to retain the full spatial resolution of the image



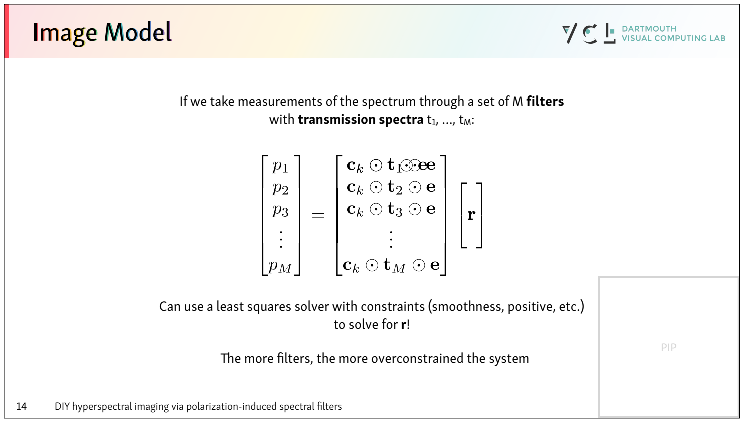
The image model for our approach defines the **[click]** pixel value recorded by the digital camera as the product of several terms: **[click]** the camera's spectral response, **[click]** the light source's emission spectrum, **[click]** and the surface's reflectance spectrum, which is the unknown that we wish to acquire, integrated over all



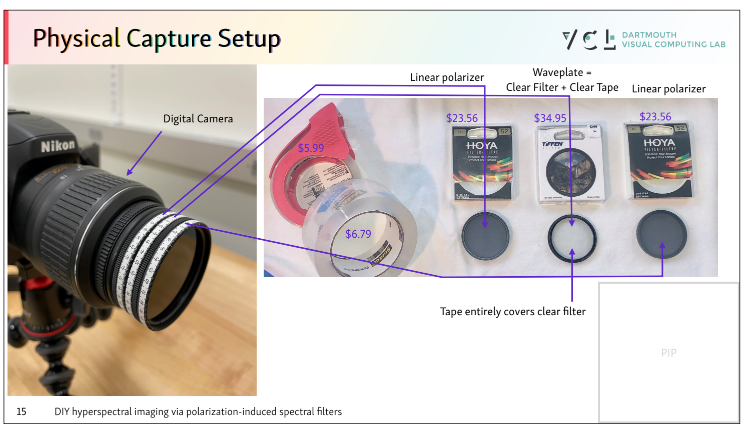
When we place our filter over the camera lens, the filter's transmission spectrum becomes part of this product. **[click]**



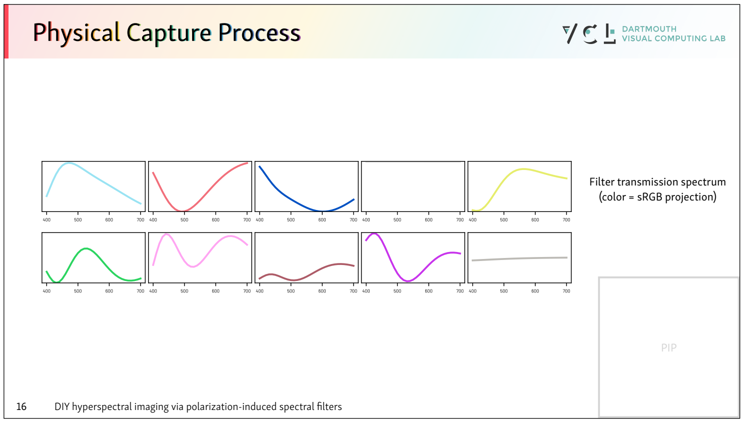
In order to solve for r, the reflectance spectrum, we convert these continuous functions to discrete vectors by sampling a set of N wavelengths, which also determines the spectral resolution of the system.



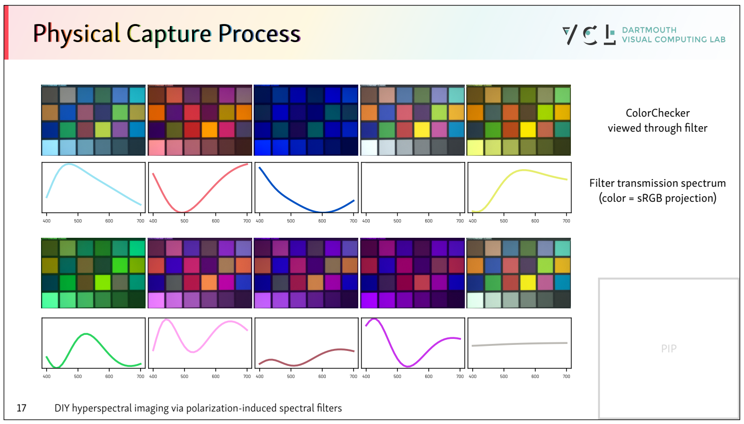
If we then take measurements through our filters in various configurations with distinct transmission spectra, we can arrange all those measurements into one matrix and separate the unknown r from the rest of the knowns. **[click]** This is now in the basic form of a linear system, which we can solve using a least squares solver with various constraints. **[click]** The key idea here is that the more measurements are taken with distinct filters, the more overconstrained this system will be, which makes our filter design that can produce an arbitrary number of distinct transmission spectra especially powerful.



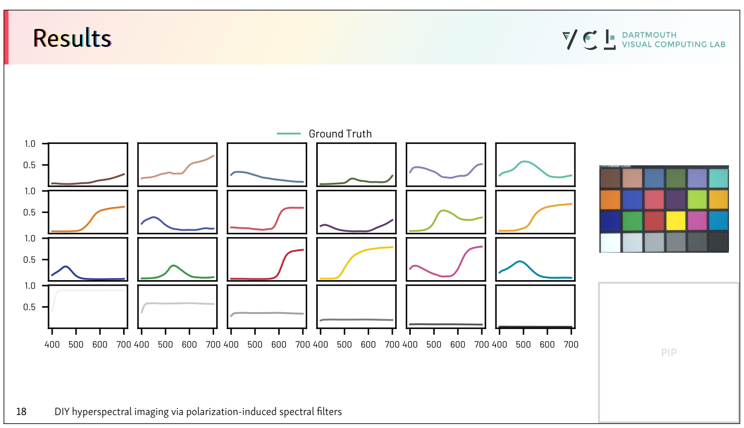
Now that we have covered the theory behind our system, let's take a look at our prototype. To build our spectral filters, we use linear polarizers designed for casual photography that screw into a camera lens, and for our waveplates we use clear packing tapes that are taped onto a clear lens filter. We labeled the angles around the edges of the filters since estimating rotation angles precisely is important to the accuracy of our method. Aside from the digital camera, the total cost of these components comes in around $100.



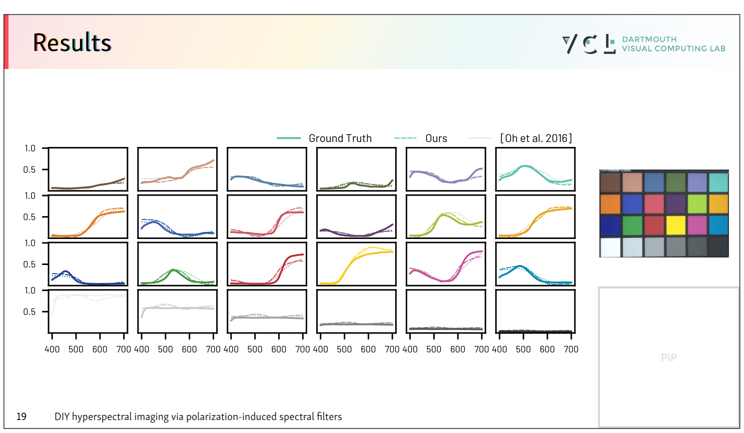
These are the simulated transmission spectra of 10 filters chosen by our filter choice algorithm from a two-waveplate system, and their sRGB projection.



These real-world measurements of a ColorChecker through these 10 filters shows that the tint of the ColorChecker does appear to match the predicted color of the filters very closely.



We reconstruct the reflectance spectra of the ColorChecker squares using these 10 measurements, and achieve reconstructions that mirror ground truth quite closely, and are also comparable to recent prior work.



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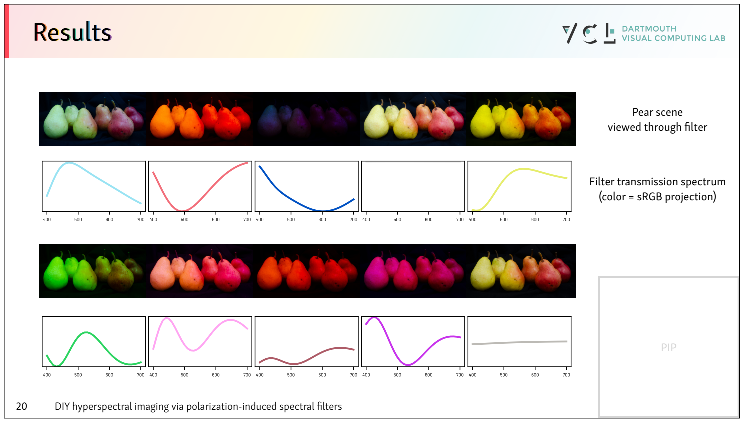
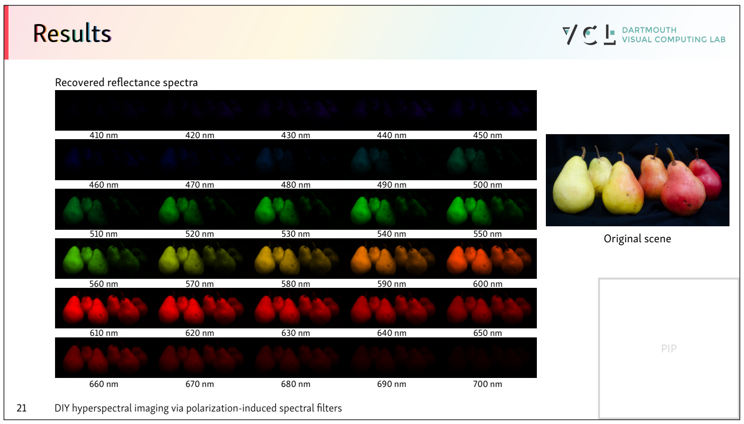
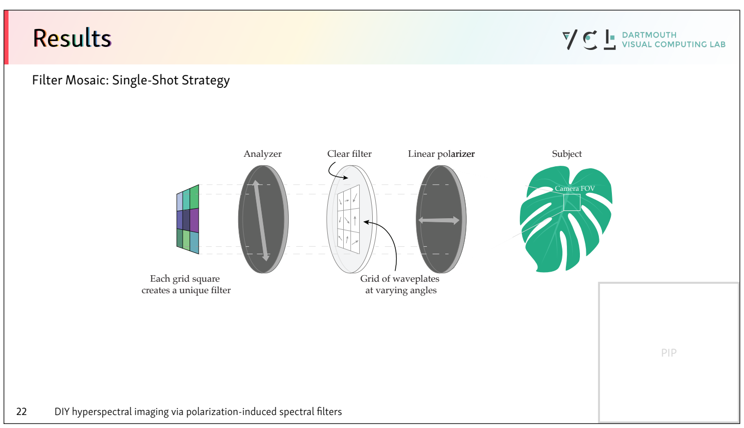


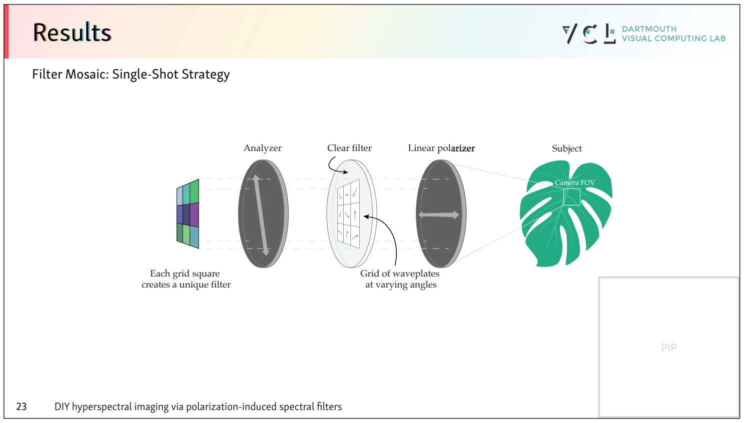
We also tested our system on more complex scenes like this one, again taking a set of 10 measurements through the same 10 filters.

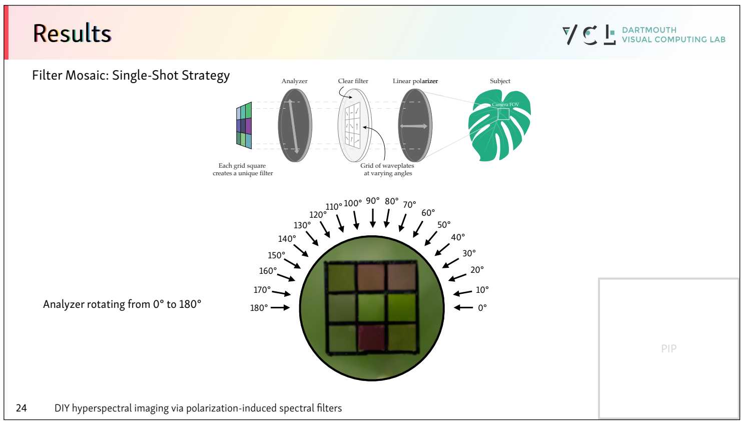


And our system is able to successfully capture a hyperspectral image of this scene. We show further validation comparing real-world and virtual relighting of this scene in our main paper.

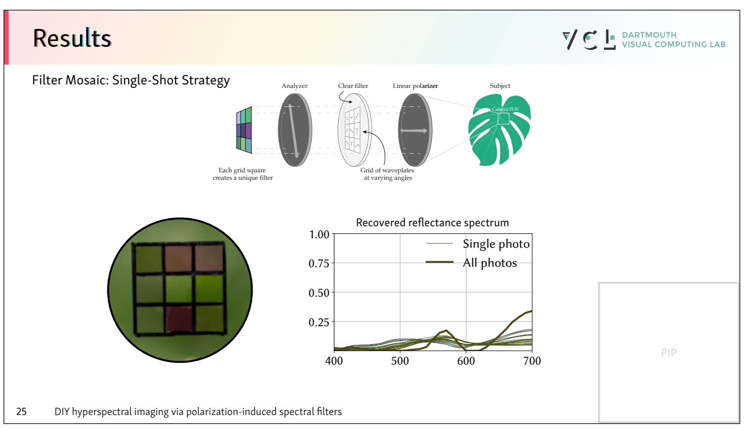


Lastly, we show a variation our system that trades off temporal multiplexing of our filters for spatial multiplexing, allowing our approach to become a single-shot strategy at the cost of spatial resolution. For this experiment, we cut out small squares of packing tape at varying angles and create a grid of them on the clear filter, allowing every grid square to become a separate filter. **[click]** We then took measurements of a Monstera leaf, allowing the leaf to occupy the camera's field of view.

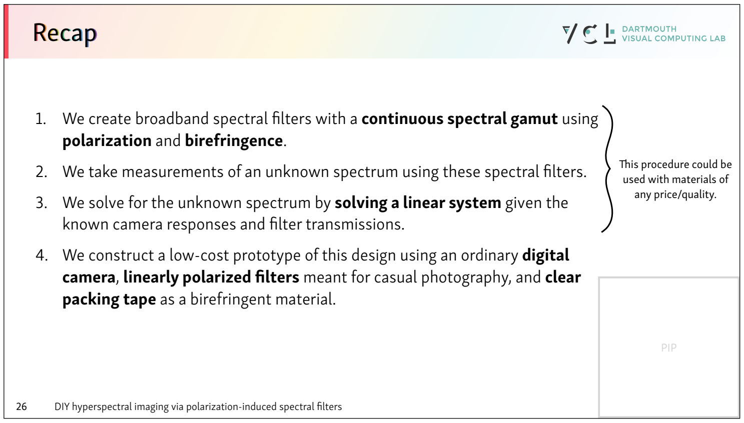




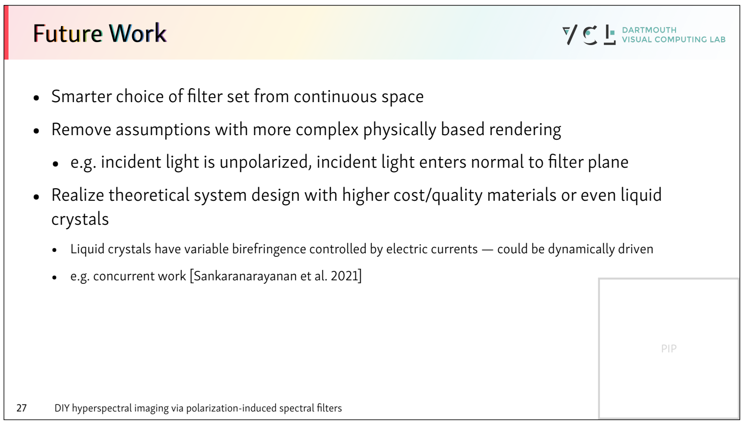
When we rotate the analyzer, we can see the mosaic of morphing colors that are produced by the waveplate grid.



If we use a single one of these photos consisting of 9 measurements for reconstruction, we get consistent but smoother results than if we use all 9 measurements from all photos together for reconstruction, suggesting that as more measurements are added to the system, the relative importance of the smoothness term in the solver decreases. In all cases, the RGB color of the reconstructed spectra match each other and the leaf, and show a clear reflectance peak where one would expect for a leaf full of chlorophyll.



To recap…



In the future, one could develop a more optimal algorithm for choosing a set of filters from this continuous space,
we could remove some assumptions of our light model using advanced physically based rendering,
for example, we assume that incident light is unpolarized and also that it enters normal to the filter plane.
Lastly, we could build a prototype of our system with higher quality materials or even liquid crystals. One could imagine shrinking our filter mosaic down and placing it directly onto the sensor like a Bayer mosaic. If liquid crystals were used, their birefringence could by dynamically controlled and many measurements could be taken at an extremely high rate, which concurrent work has begun to investigate.

Visit: dartgo.org/hyperspectral

for a **tutorial** on how to build your own hyperspectral camera!

PIP

For more information and a detailed tutorial on how to build your own hyperspectral camera, visit dartgo.org/hyperspectral

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