DIY hyperspectral imaging via polarization-induced spectral filters

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Dartmouth College

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2022
Pasadena, California

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Our Inspiration

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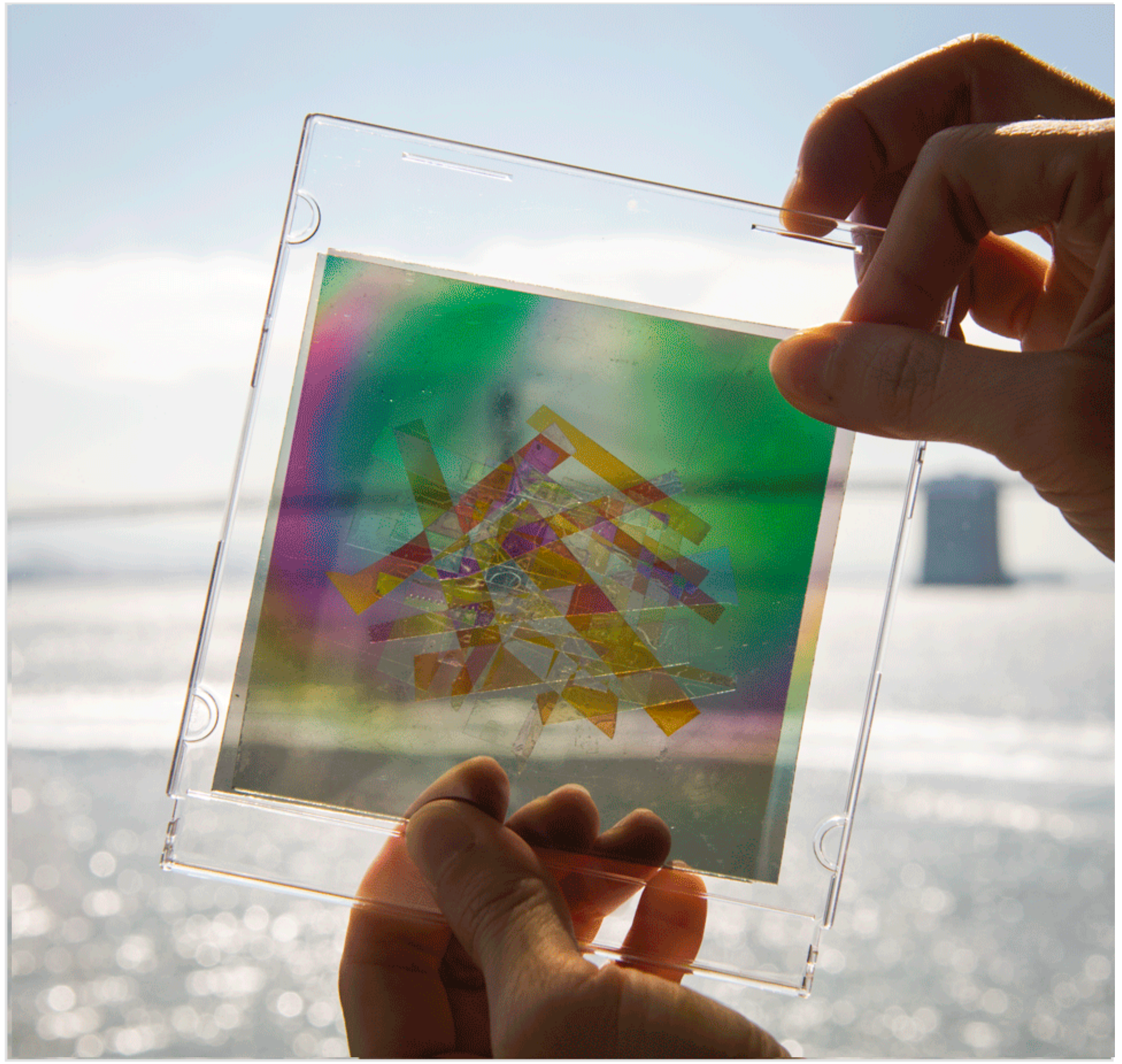

Polarized-Light Mosaic

With polarized light, you can make a stained glass window without glass.

Using transparent tape and polarizing material, you can make and project beautifully colored patterns reminiscent of abstract or geometric stained-glass windows. Rotating the polarizer as you view the patterns makes the colors change. With a little creativity, you can also create colorful renditions of objects or scenes.

Grade Bands: 6-8 9-12
Subject: Arts · Physics: Light, Waves · Social Science:
Keywords: polarized light tape color
NGSS and EP&Cs: PS: PS4 · ETS: ETS1 · CCCs: Patterns, Cause and Effect, Scale, Proportion, and Quantity, Structure and Function

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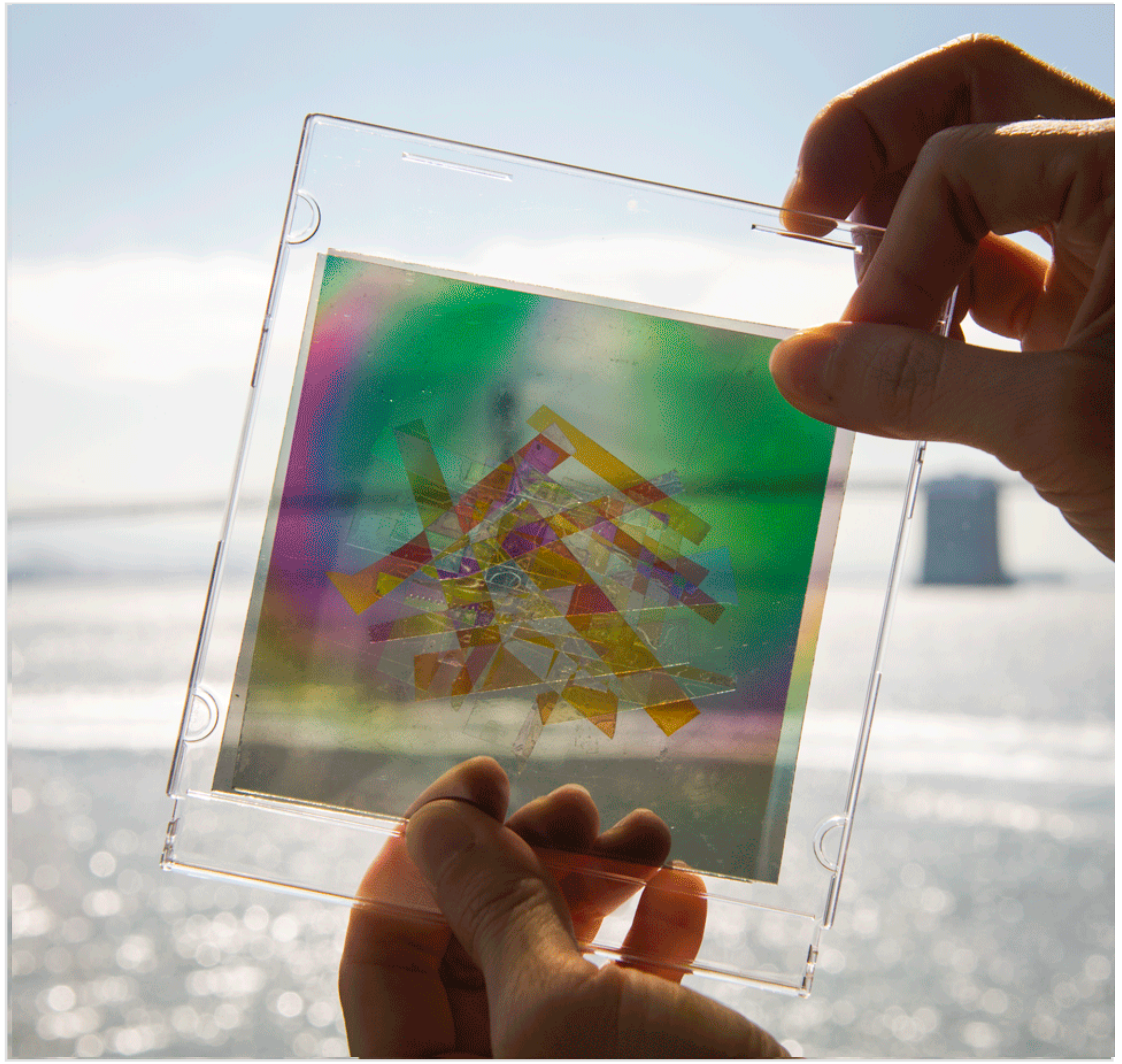

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Our Inspiration

Use this **polarization-induced color** to create a **hyperspectral camera**.

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Reflectance Spectrum
Short
Wavelengths of Visible Light
Long

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Hyperspectral Imaging

Ordinary Digital Camera

Hyperspectral Camera

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Hyperspectral Imaging

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Ordinary Digital Camera

Hyperspectral Camera

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Hyperspectral Imaging

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Ordinary Digital Camera

Hyperspectral Camera

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Hyperspectral Imaging: Our Approach

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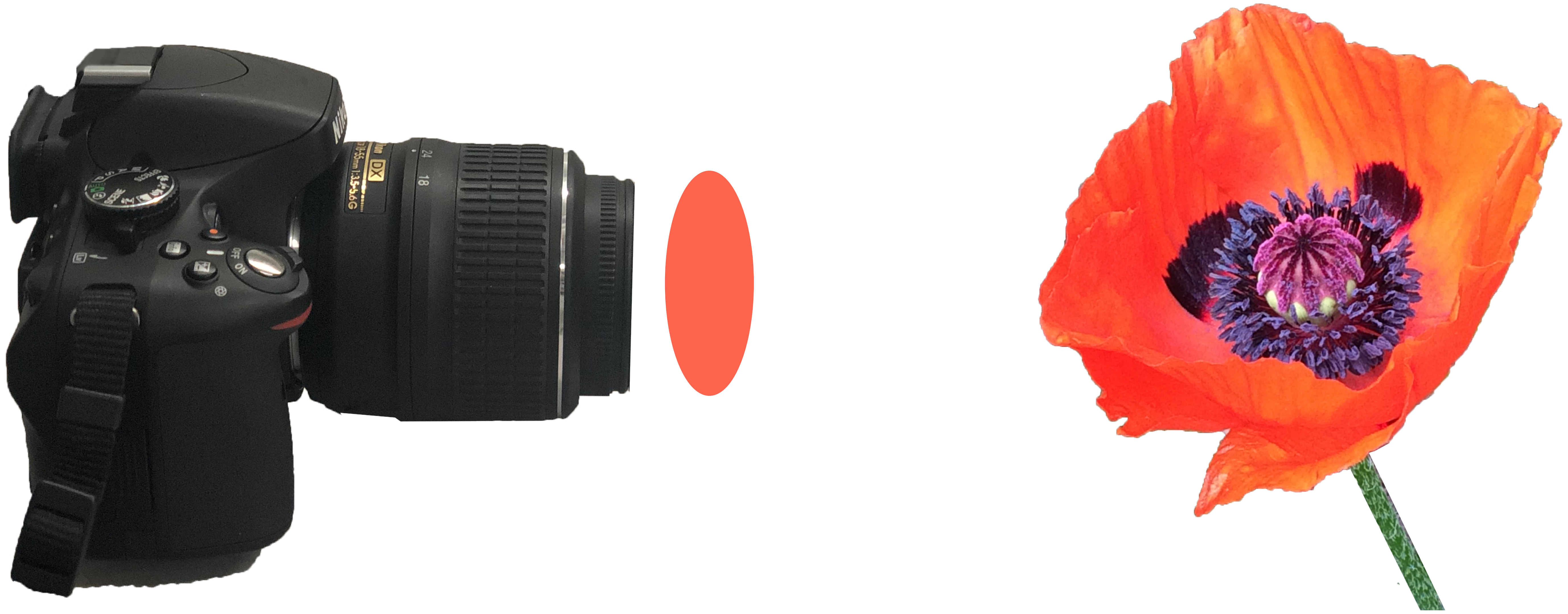
Hyperspectral Imaging: Our Approach



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Hyperspectral Imaging: Our Approach

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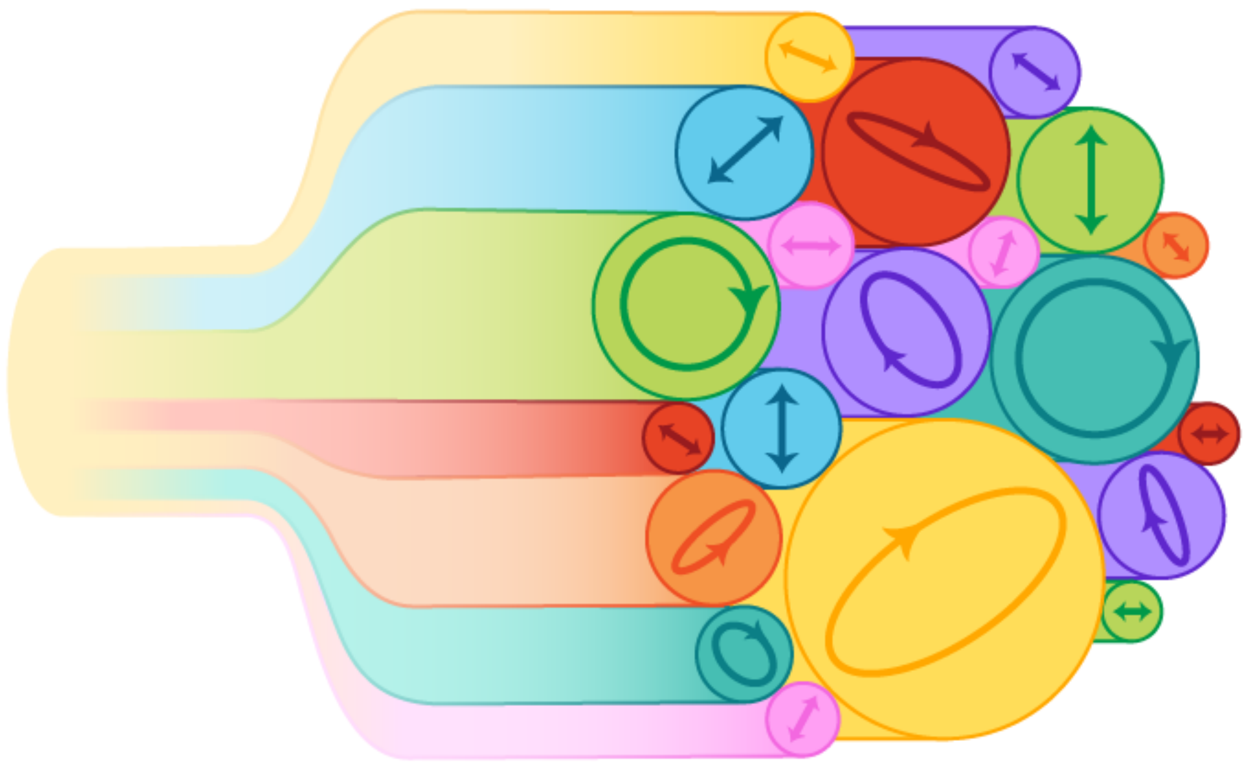

Incoming light is composed of many
wavelengths and **polarization states**

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Hyperspectral Imaging: Our Approach

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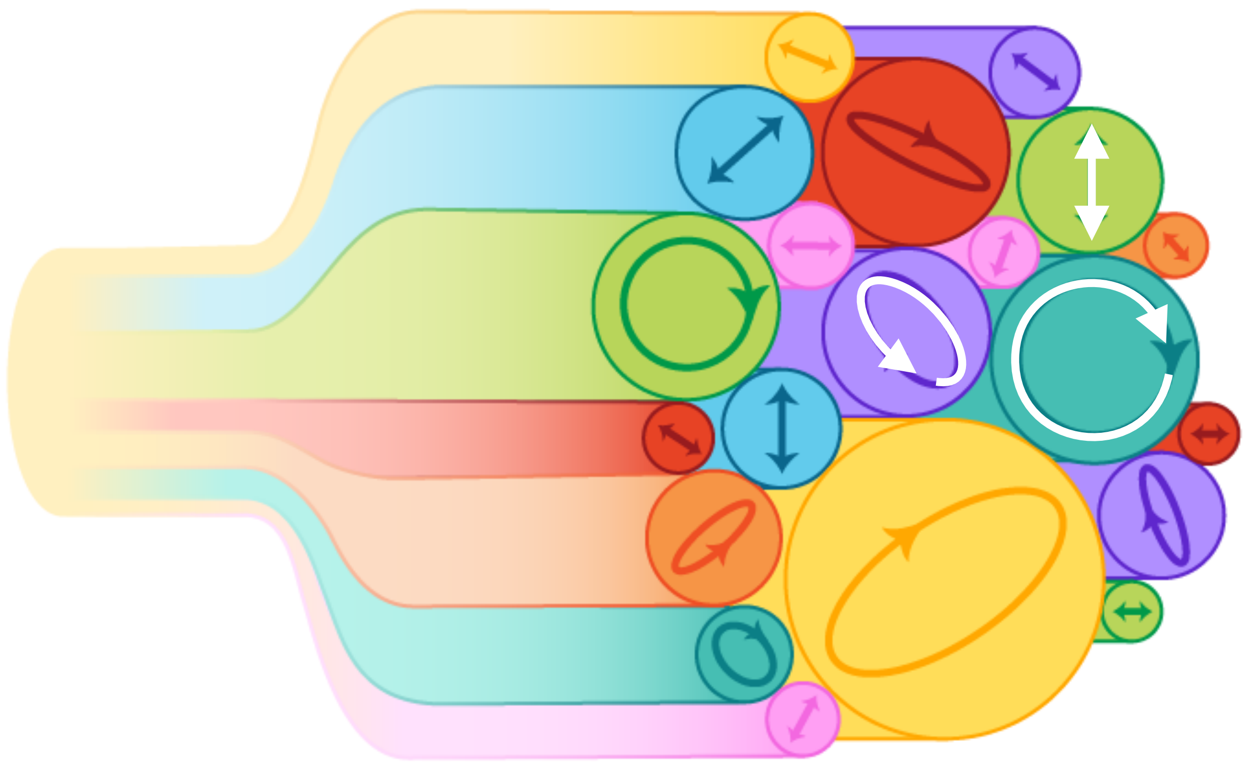

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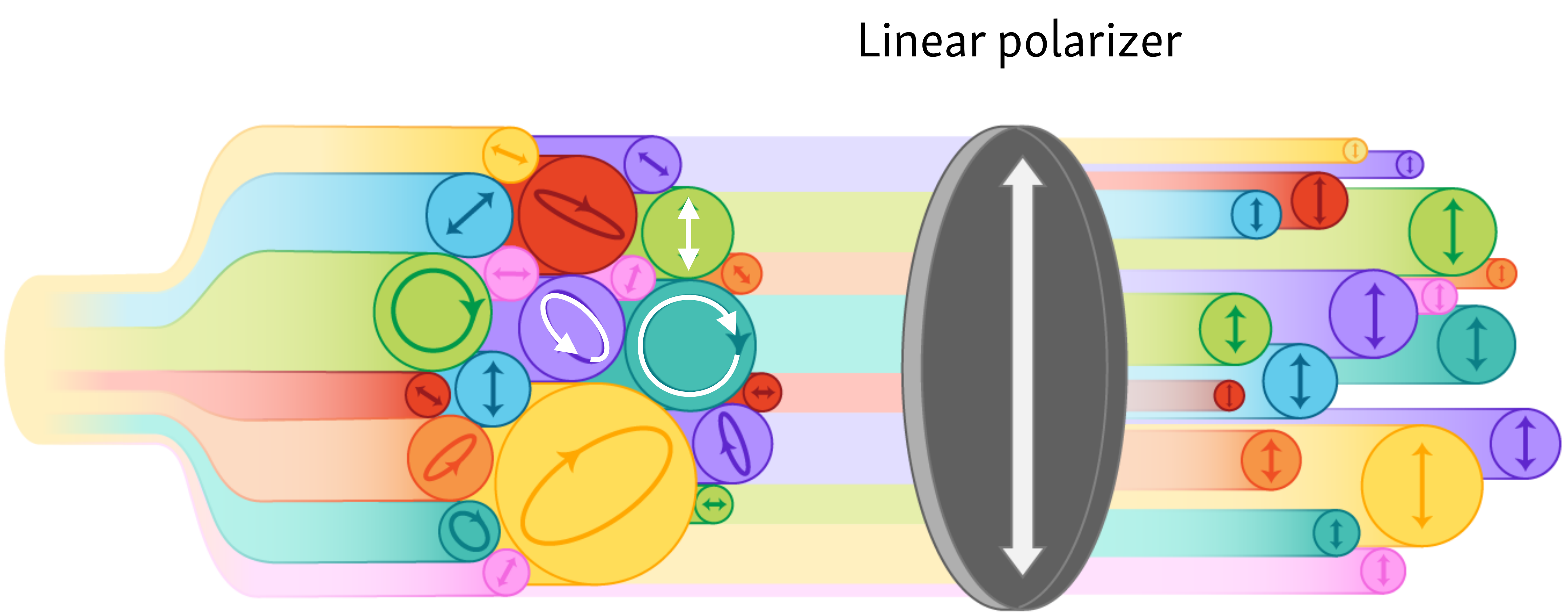

Incoming light is composed of many **wavelengths** and **polarization states**

Cuts orthogonal polarization amplitude

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Hyperspectral Imaging: Our Approach

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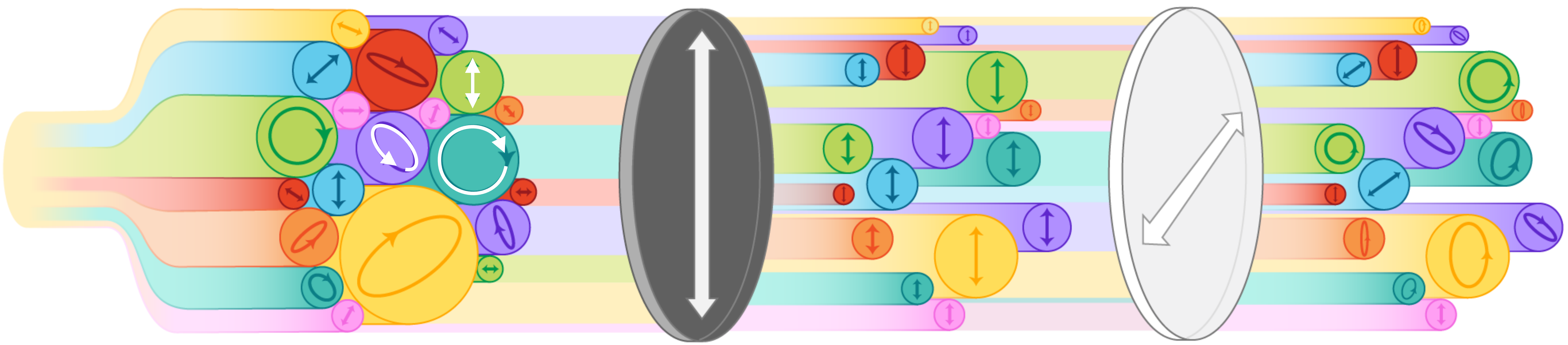

Incoming light is composed of many **wavelengths** and **polarization states**

Cuts orthogonal polarization amplitude

Causes a **wavelength-dependent** phase shift (alters polarization state)

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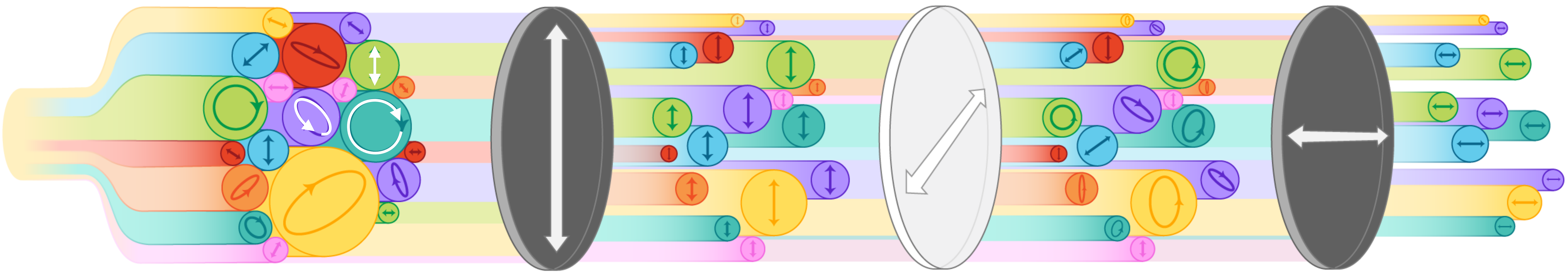
Hyperspectral Imaging: Our Approach



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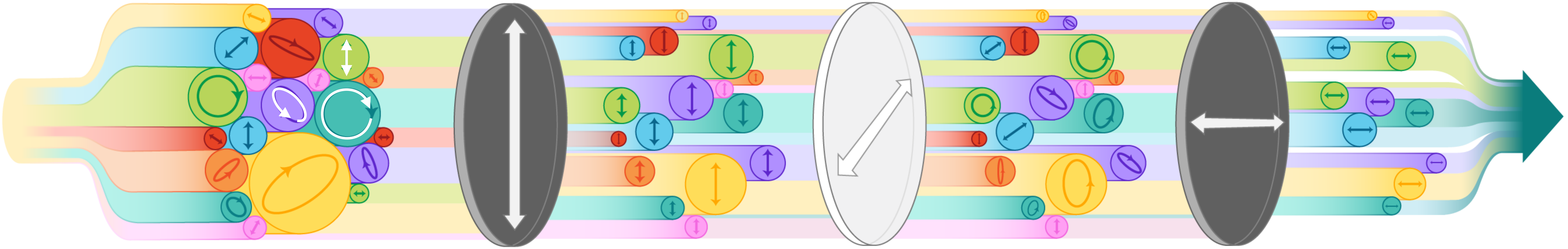

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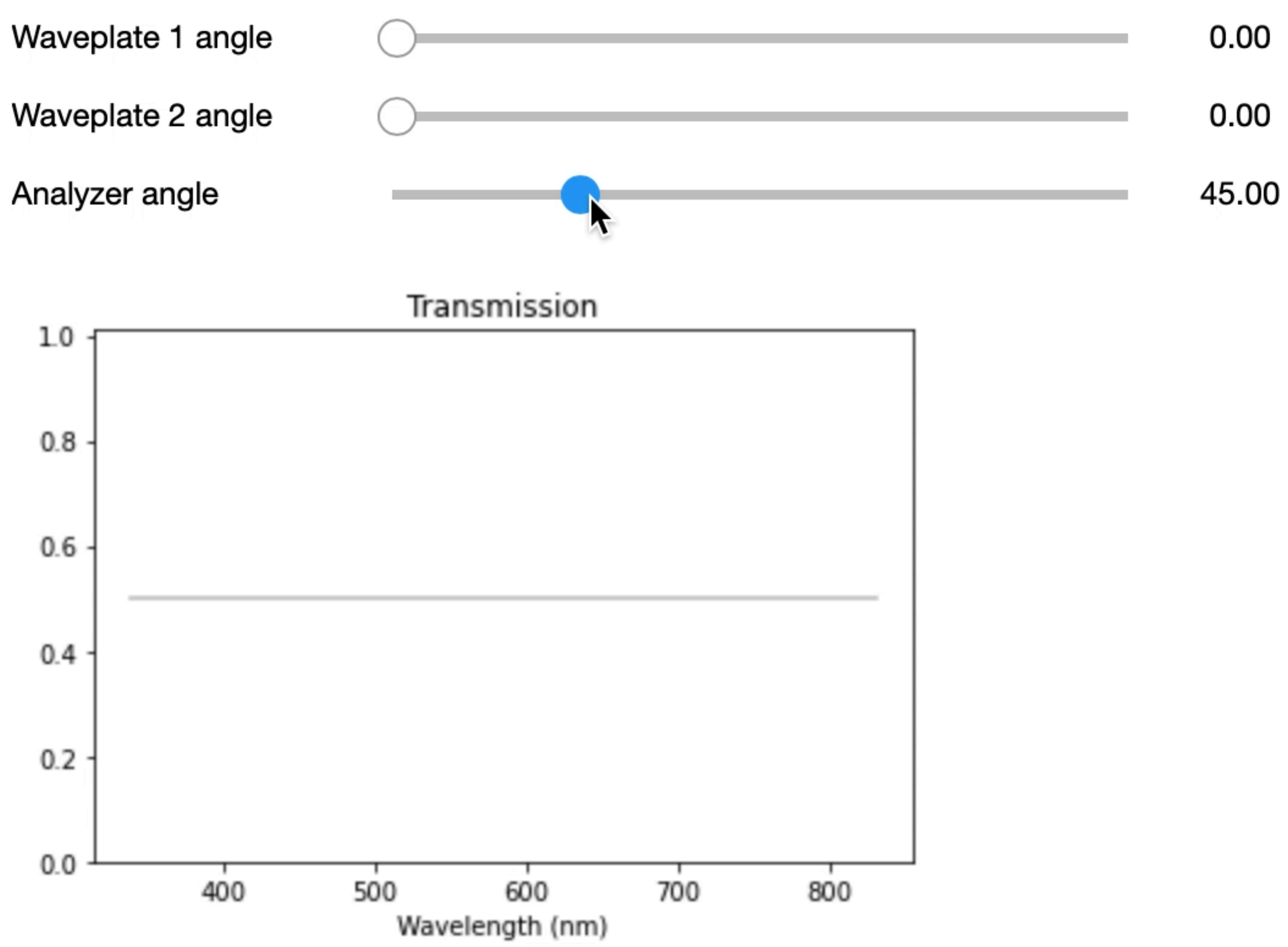

- Can calculate transmission spectra analytically using **Mueller calculus**
- Our filters produce a **continuous gamut** of transmission spectra
- The **range of achievable transmission spectra grows** as waveplates are added to the filter

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Hyperspectral Imaging: Our Approach

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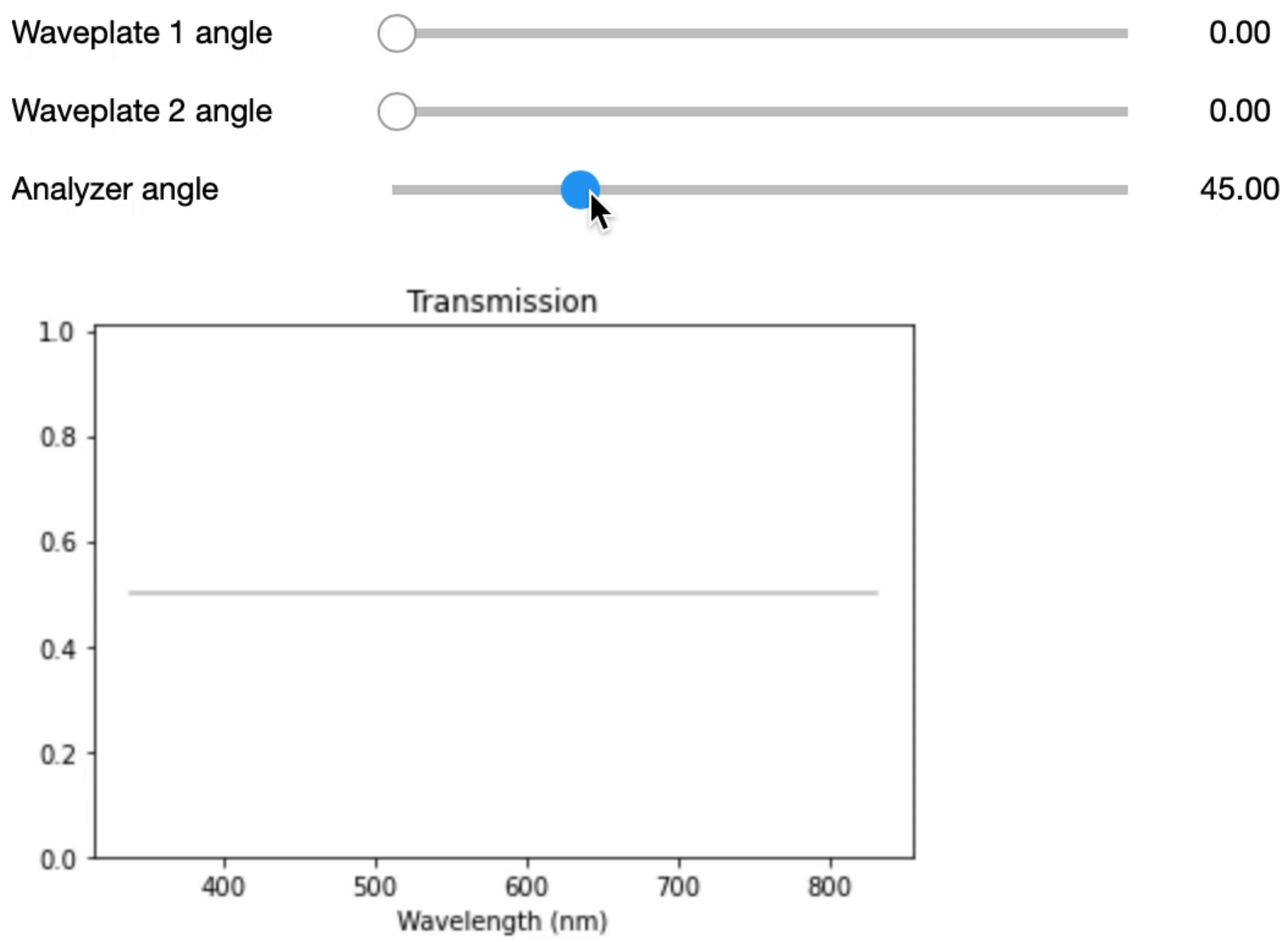

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Hyperspectral Imaging: Prior Work

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[Park et al. 2007]
[Han et al. 2010]
[Hidaka et al. 2020]
[Chi and Ben-Ezra 2007]

[Oh et al. 2016]

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Hyperspectral Imaging: Prior Work

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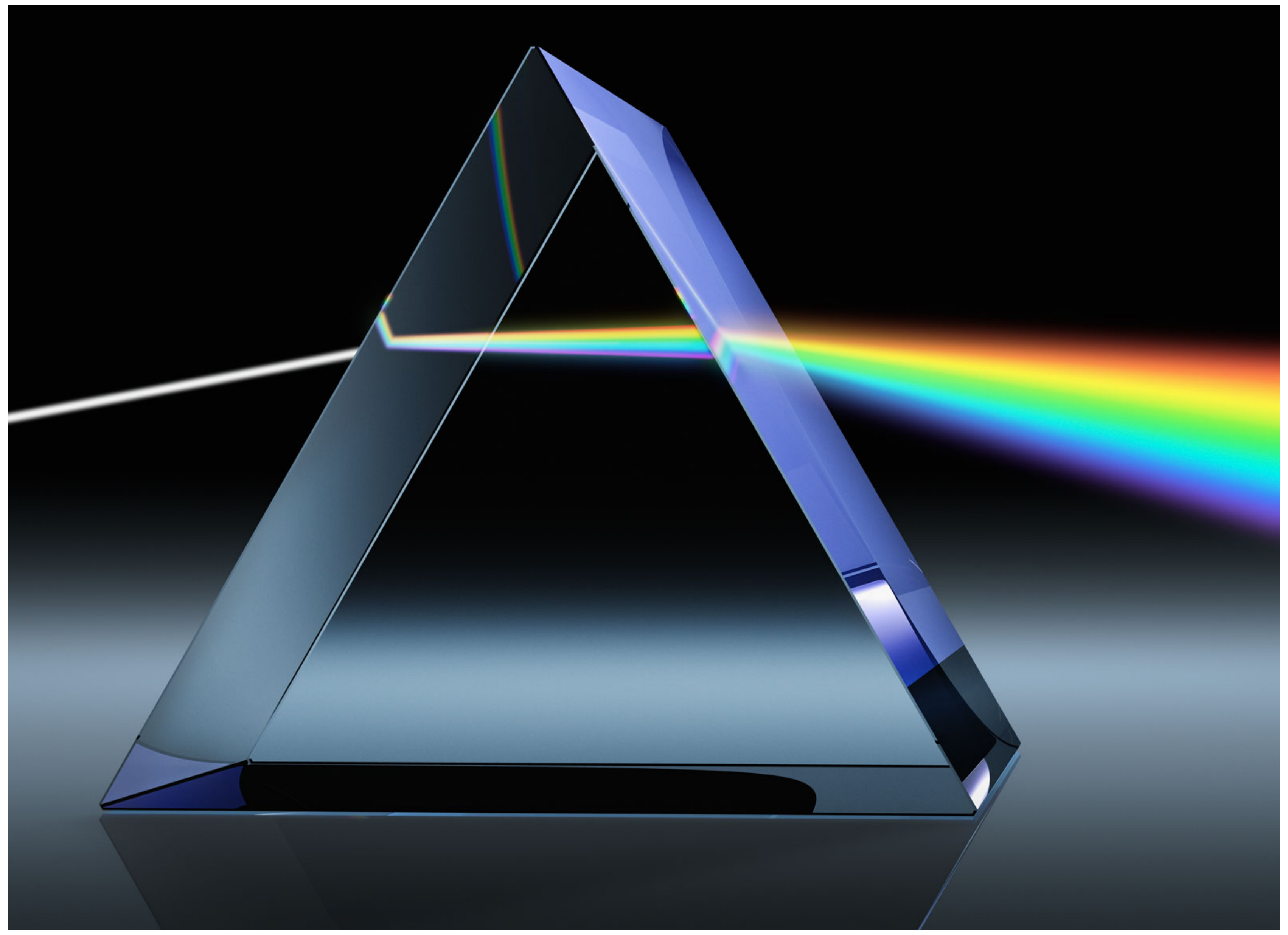
Hyperspectral Imaging: Prior Work

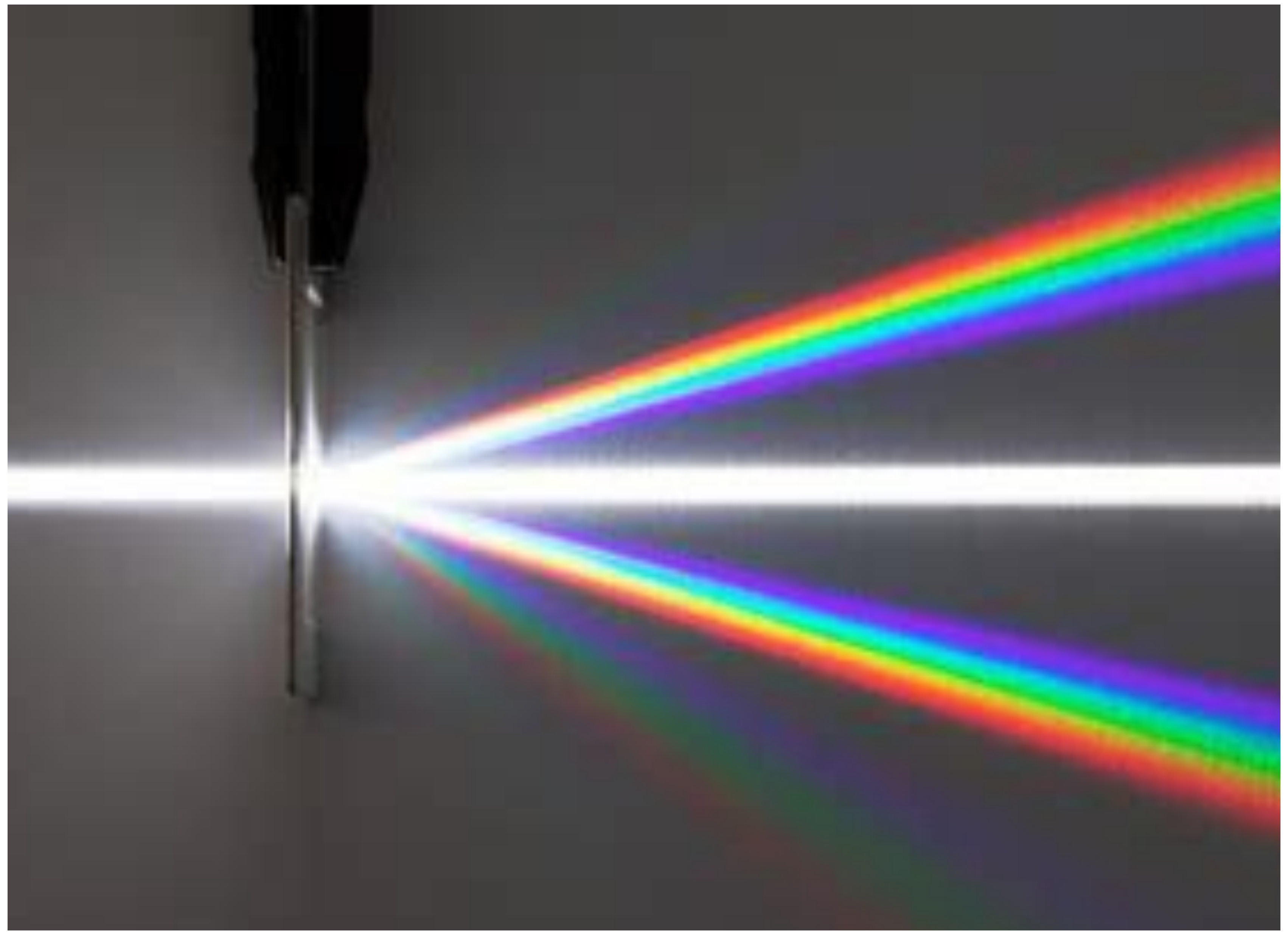
- Use **dispersion** or **diffraction**
  - e.g. CASSI, computed tomography, [Du et al. 2009], [Baek et al. 2017],[Habel et al. 2012], [Jeon et al. 2019]
  - Transform **spectral** into **spatial** information → trade off **spectral resolution** for **spatial resolution**

Dispersion



https://www.britannica.com/technology/prism-optics

Diffraction



https://pixels.com/featured/light-dispersed-by-diffraction-grating-giphotostock.html

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Image Model

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$$p_k = \int_\Lambda c_k(\lambda)\, e(\lambda)\, r(\lambda)\, \mathrm{d}\lambda$$

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Image Model

Pixel Value (for channel k) $$p_k = \int_\Lambda c_k(\lambda)\, e(\lambda)\, r(\lambda)\, \mathrm{d}\lambda$$

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Image Model

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Camera Response (for channel k)

Pixel Value (for channel k)

$$p_k = \int_\Lambda c_k(\lambda)\, e(\lambda)\, r(\lambda)\, \mathrm{d}\lambda$$

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Image Model

Illuminant spectrum

Pixel Value (for channel k) $$p_k = \int_\Lambda c_k(\lambda)\, e(\lambda)\, r(\lambda)\, \mathrm{d}\lambda$$

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Image Model

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Reflectance spectrum (unknown)

Pixel Value (for channel k) $$p_k = \int_\Lambda c_k(\lambda)\, e(\lambda)\, r(\lambda)\, \mathrm{d}\lambda$$

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Image Model

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Pixel Value (for channel k) $$p_k = \underbrace{\int_\Lambda}_{\text{All Visible Wavelengths}} c_k(\lambda)\, e(\lambda)\, r(\lambda)\, \mathrm{d}\lambda$$

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Image Model

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$$p_k = \int_{\Lambda} c_k(\lambda)\, t(\lambda)\, e(\lambda)\, r(\lambda)\, \mathrm{d}\lambda$$

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Image Model

Filter Transmission Spectrum

$$p_k = \int_\Lambda c_k(\lambda)\, t(\lambda)\, e(\lambda)\, r(\lambda)\, \mathrm{d}\lambda$$

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Image Model

Convert continuous functions to discrete vectors by sampling *N* wavelengths:

(also determines the **spectral resolution** of the system)

$$p_k = \int_\Lambda c_k(\lambda)\ t(\lambda)\ e(\lambda)\ r(\lambda)\ \mathrm{d}\lambda$$

($\odot$ is component-wise multiplication)

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Image Model

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Convert continuous functions to discrete vectors by sampling *N* wavelengths:

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$$p_k = \mathbf{c}_k \odot \mathbf{t} \odot \mathbf{e} \odot \mathbf{r}$$

($\odot$ is component-wise multiplication)

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Image Model

If we take measurements of the spectrum through a set of M **filters** with **transmission spectra** $t_1, \ldots, t_M$:

$$\begin{bmatrix} p_1 \\ p_2 \\ p_3 \\ \vdots \\ p_M \end{bmatrix} = \begin{bmatrix} \mathbf{c}_k \odot \mathbf{t}_1 \odot \mathbf{e} \\ \mathbf{c}_k \odot \mathbf{t}_2 \odot \mathbf{e} \\ \mathbf{c}_k \odot \mathbf{t}_3 \odot \mathbf{e} \\ \vdots \\ \mathbf{c}_k \odot \mathbf{t}_M \odot \mathbf{e} \end{bmatrix} \begin{bmatrix} \mathbf{r} \end{bmatrix}$$

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Can use a least squares solver with constraints (smoothness, positive, etc.) to solve for **r**!

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Can use a least squares solver with constraints (smoothness, positive, etc.) to solve for **r**!

The more filters, the more overconstrained the system

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Physical Capture Setup

Linear polarizer

Waveplate =
Clear Filter + Clear Tape

Linear polarizer

Tape entirely covers clear filter

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Physical Capture Process

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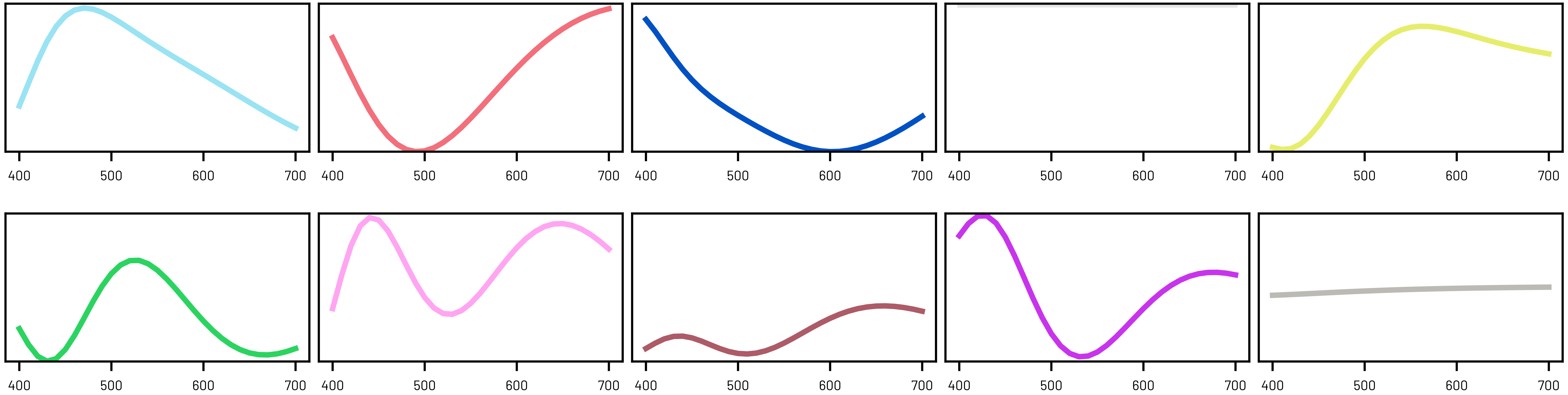

Filter transmission spectrum
(color = sRGB projection)

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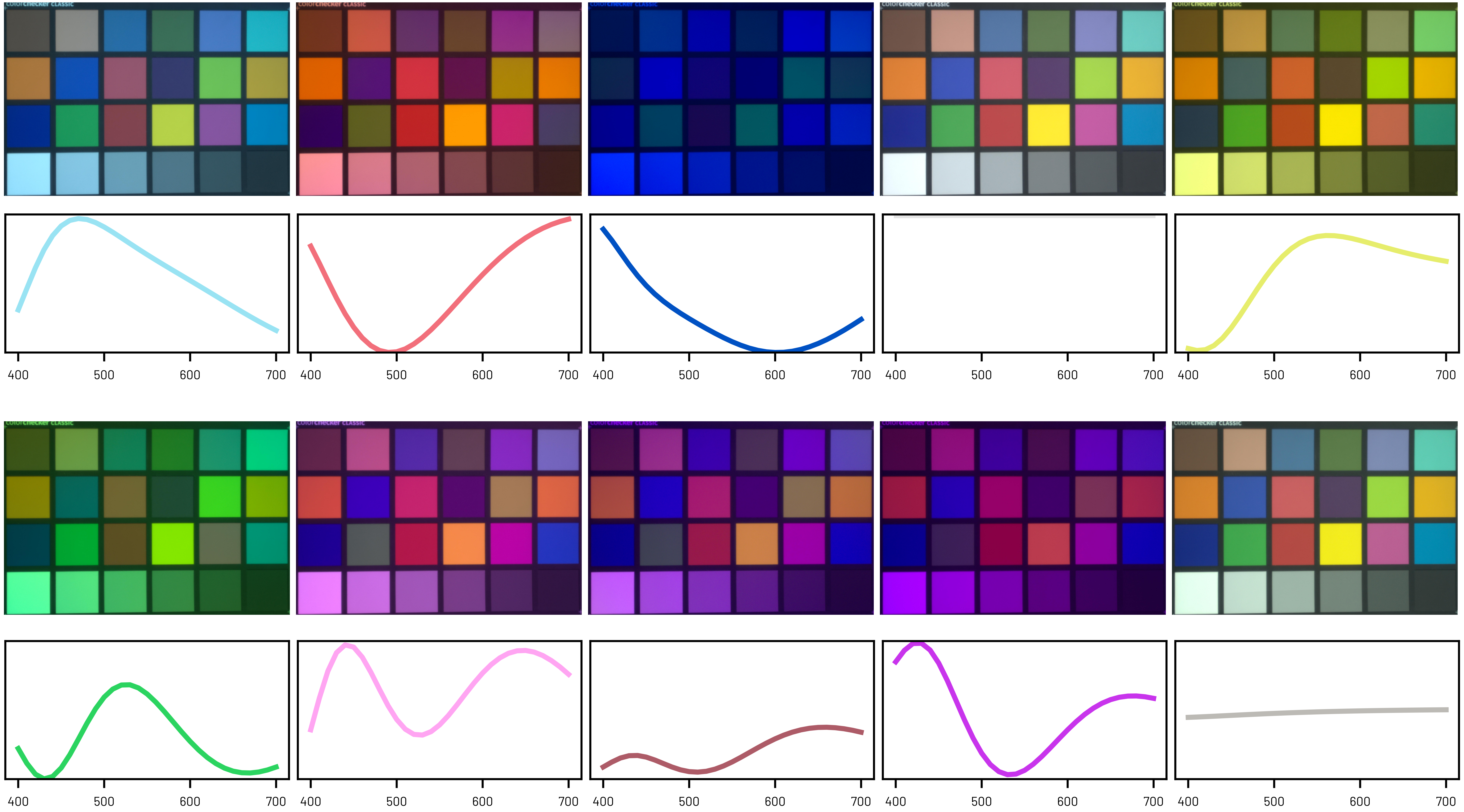
Physical Capture Process



ColorChecker
viewed through filter

Filter transmission spectrum
(color = sRGB projection)

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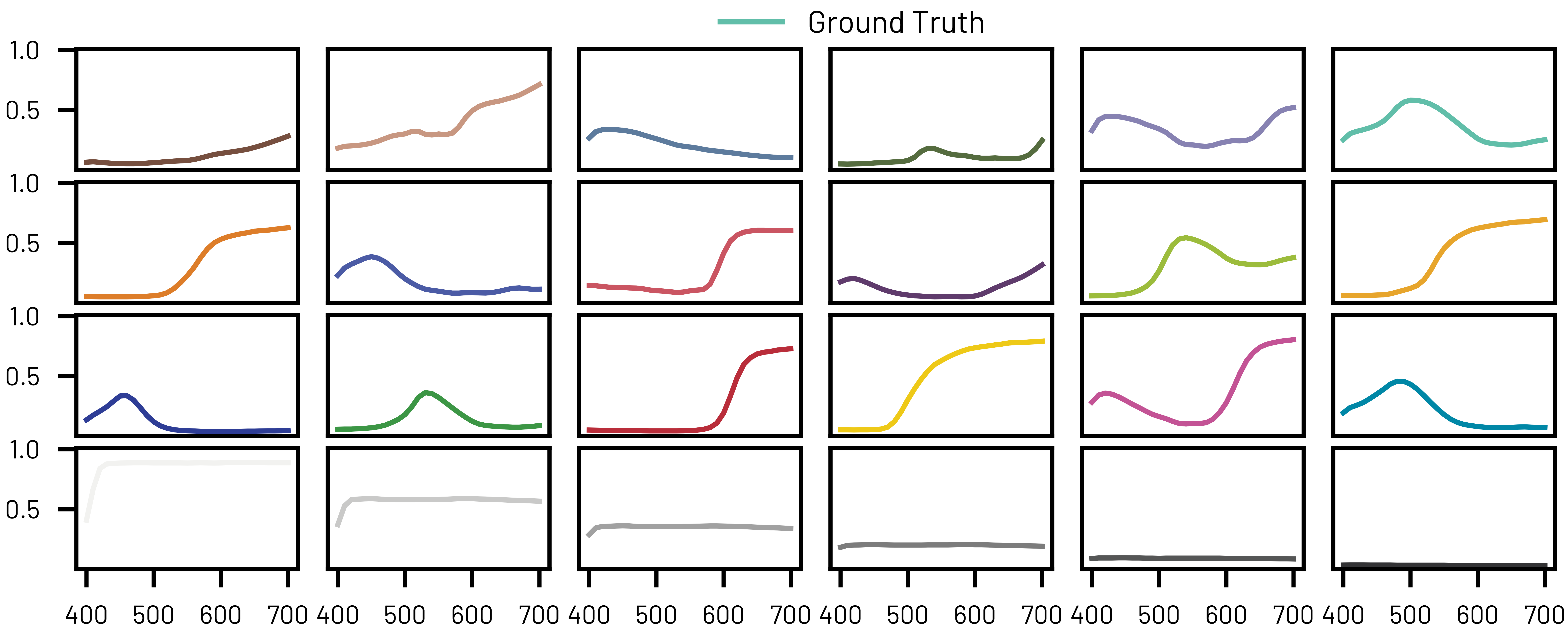
Results



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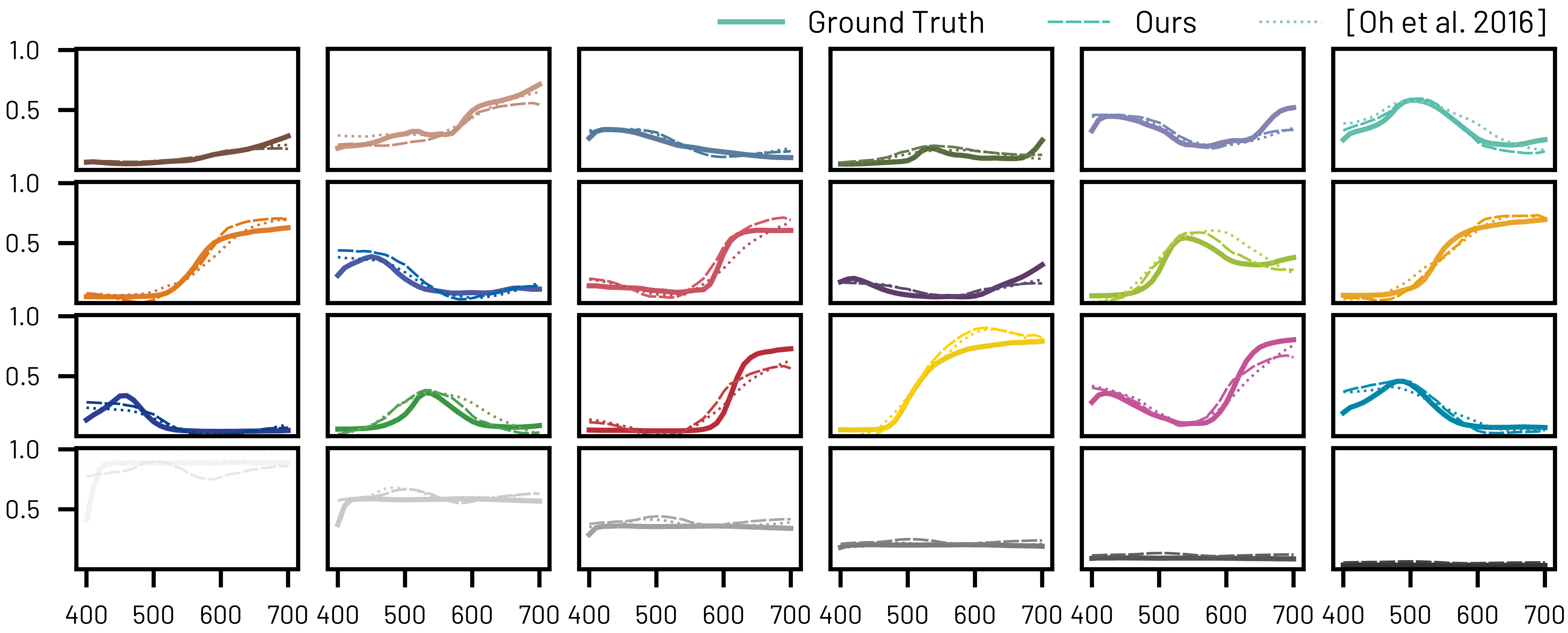
Results



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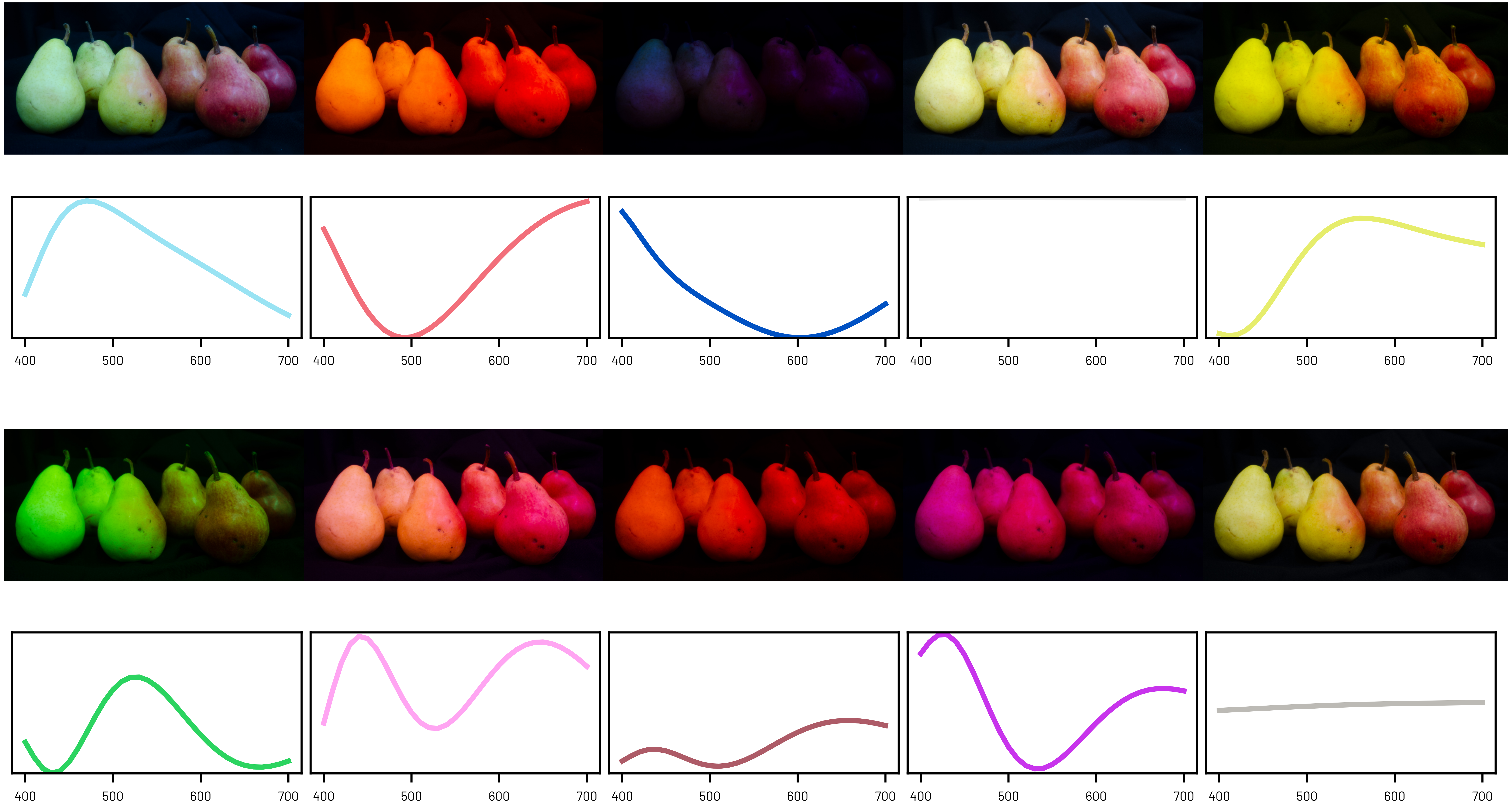
Results



Pear scene viewed through filter

Filter transmission spectrum (color = sRGB projection)

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Results

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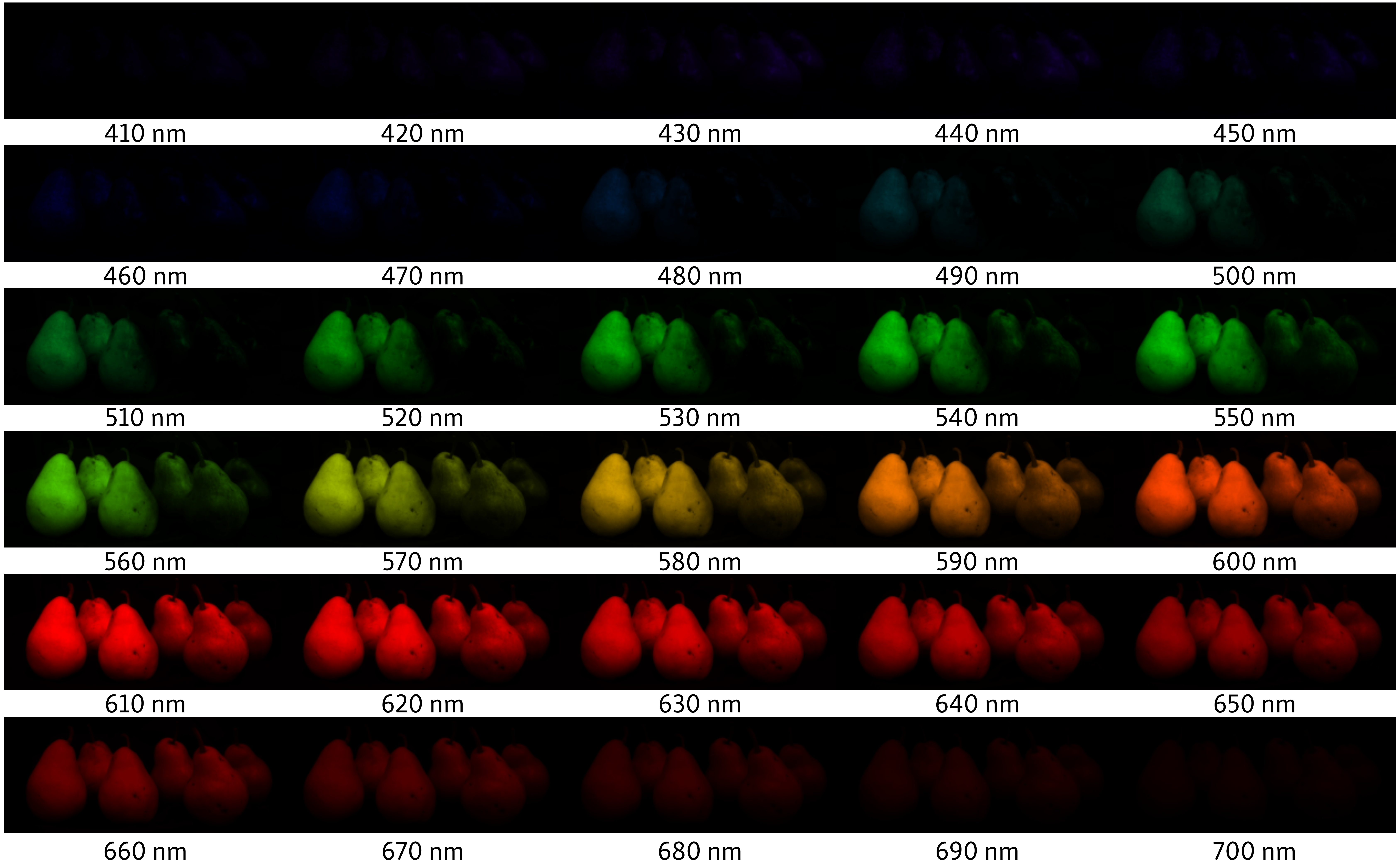
Recovered reflectance spectra



Original scene

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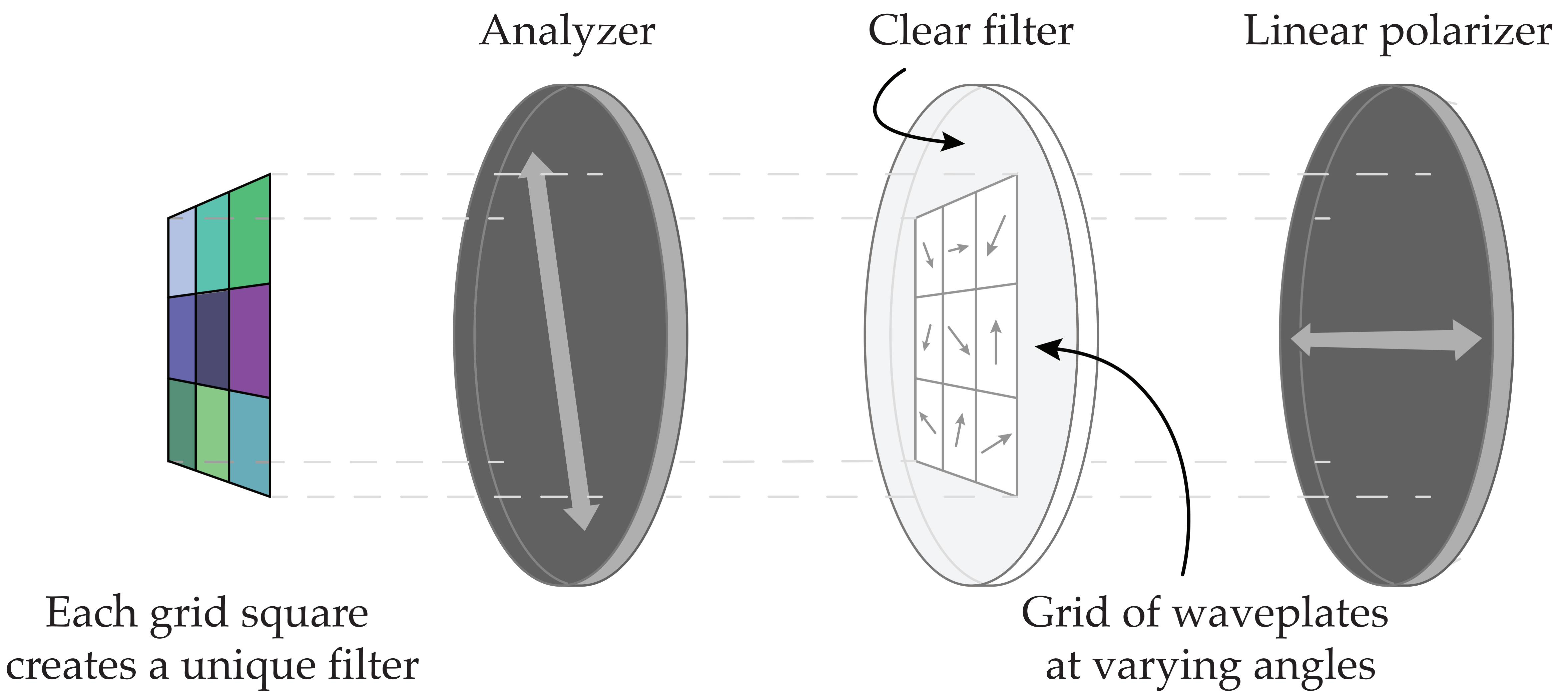
Results

Filter Mosaic: Single-Shot Strategy



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Results

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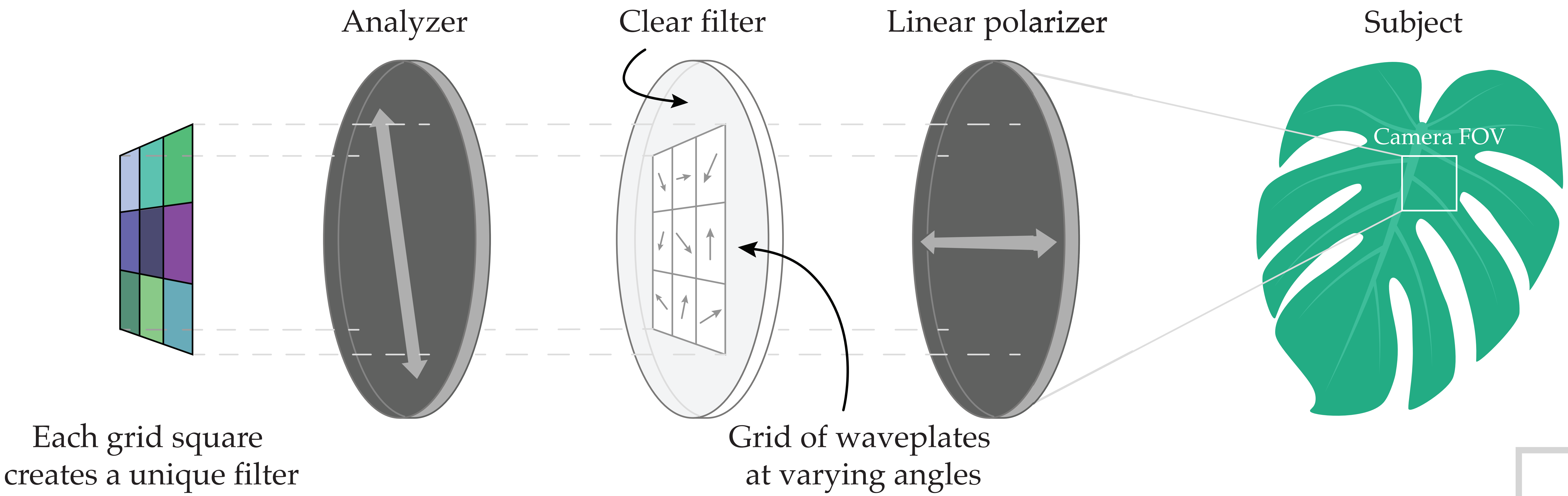

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Results

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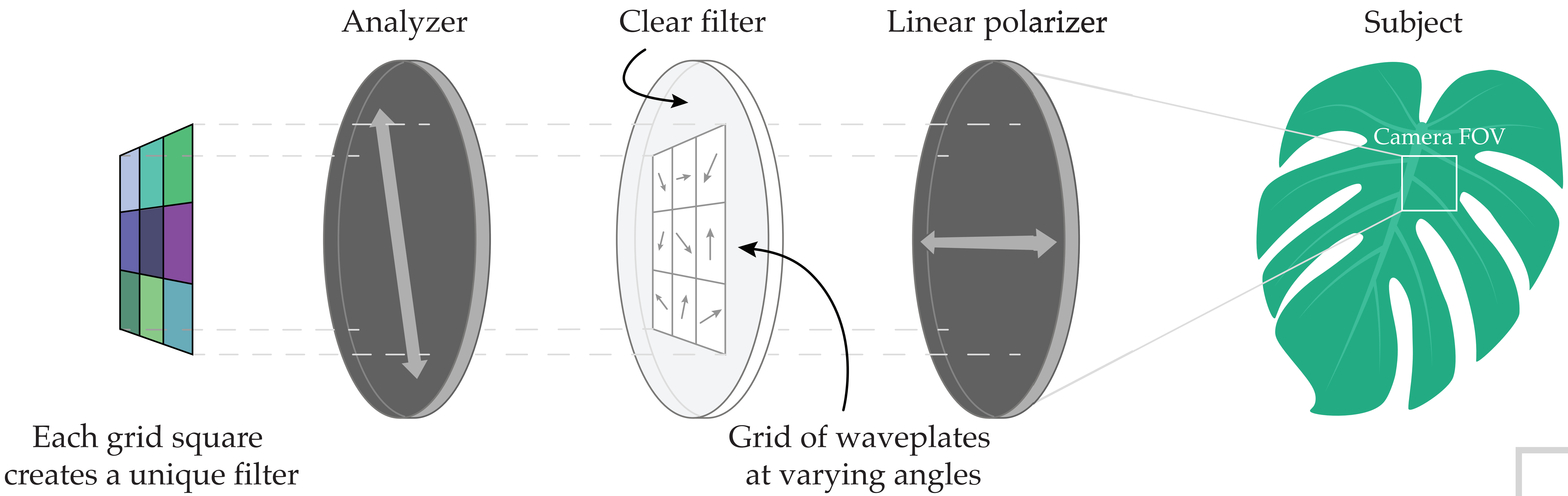

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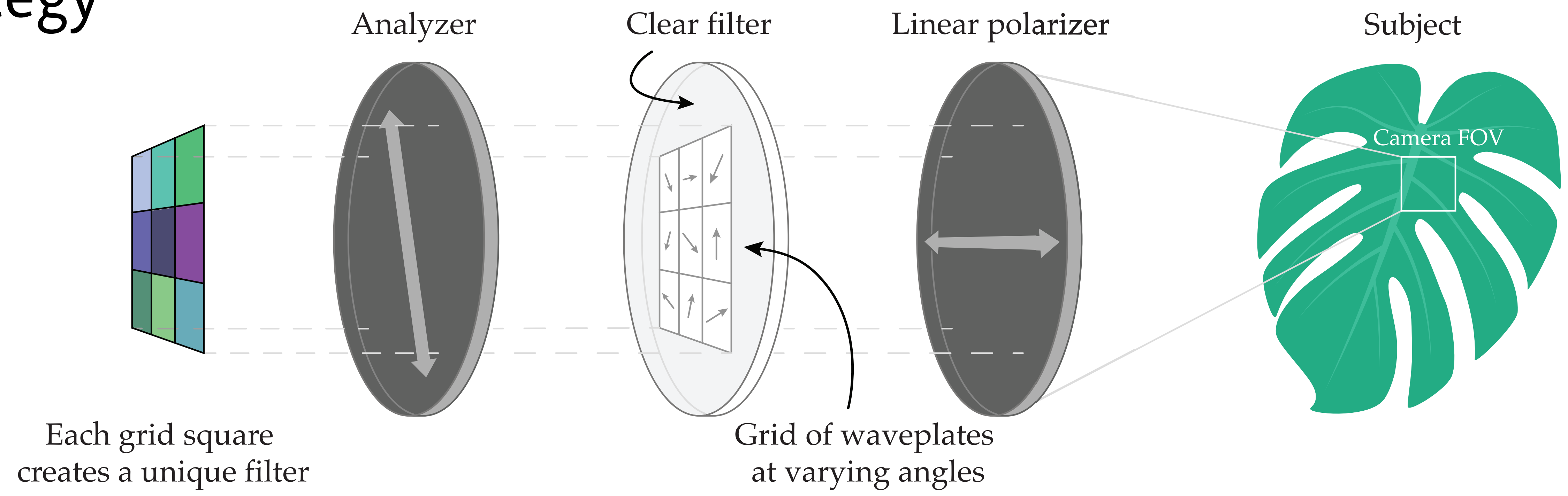

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Results

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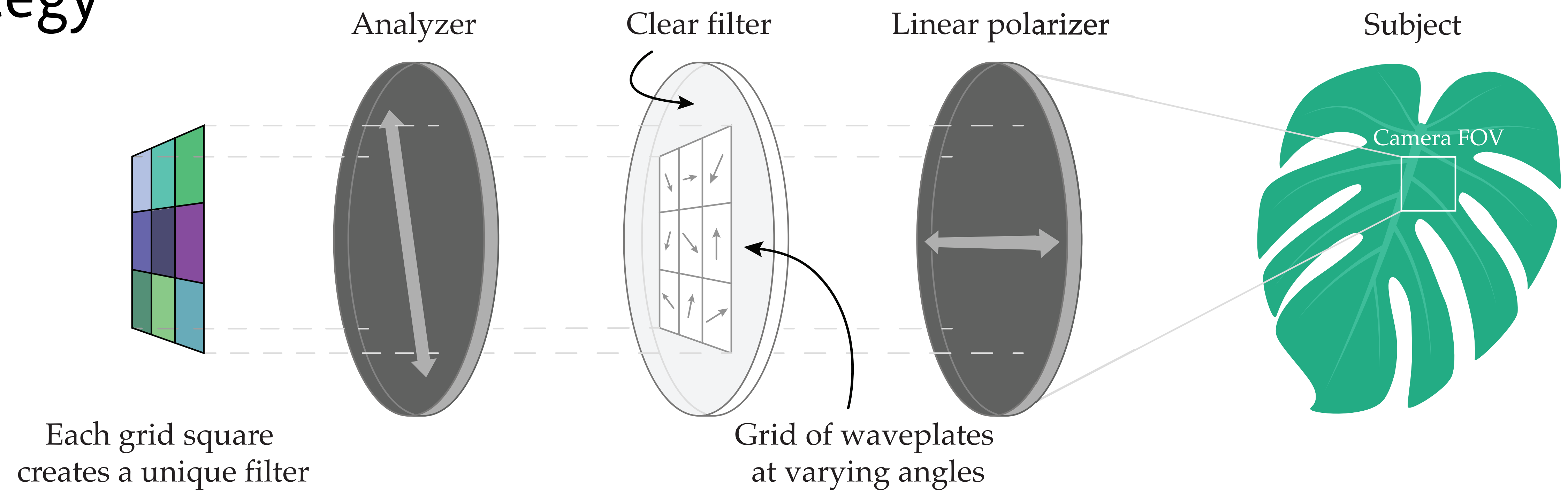
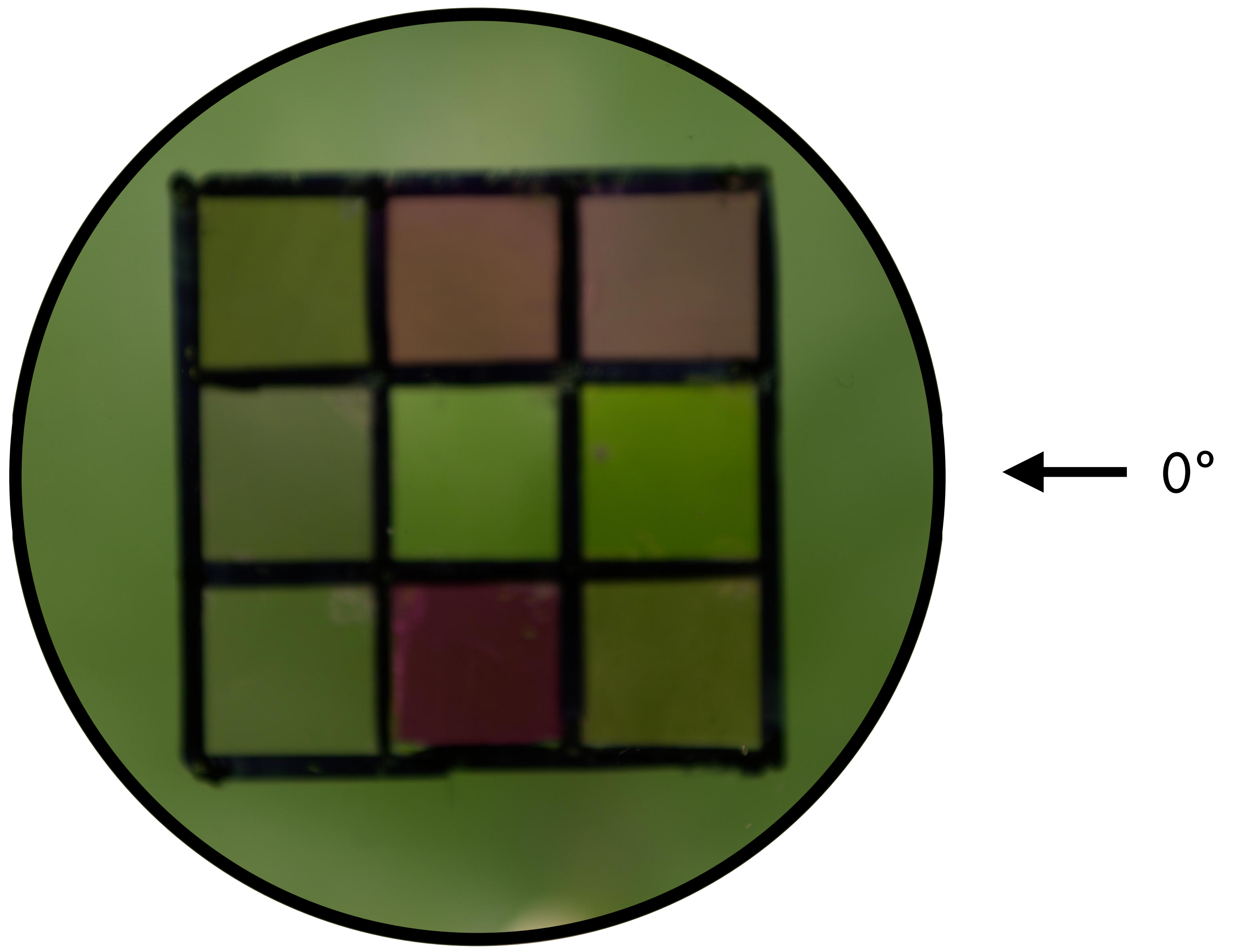


Analyzer rotating from 0° to 180°



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Results

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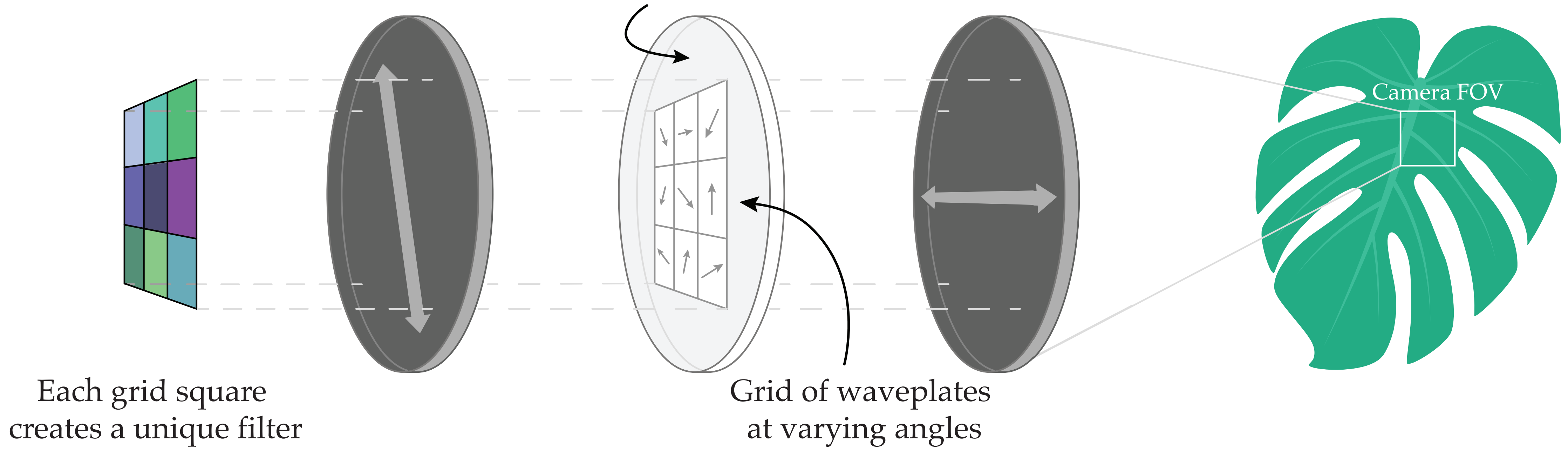

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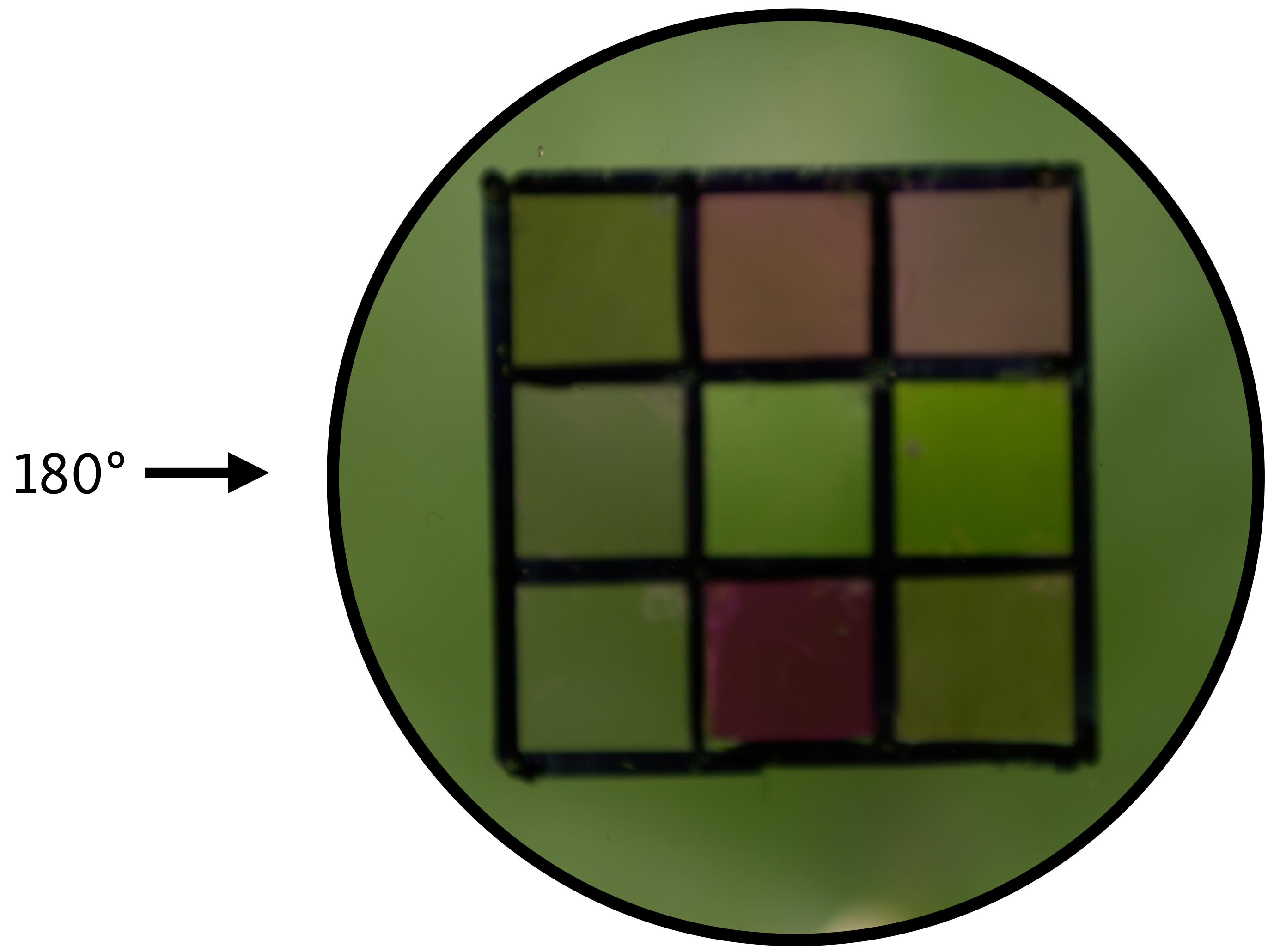

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Results

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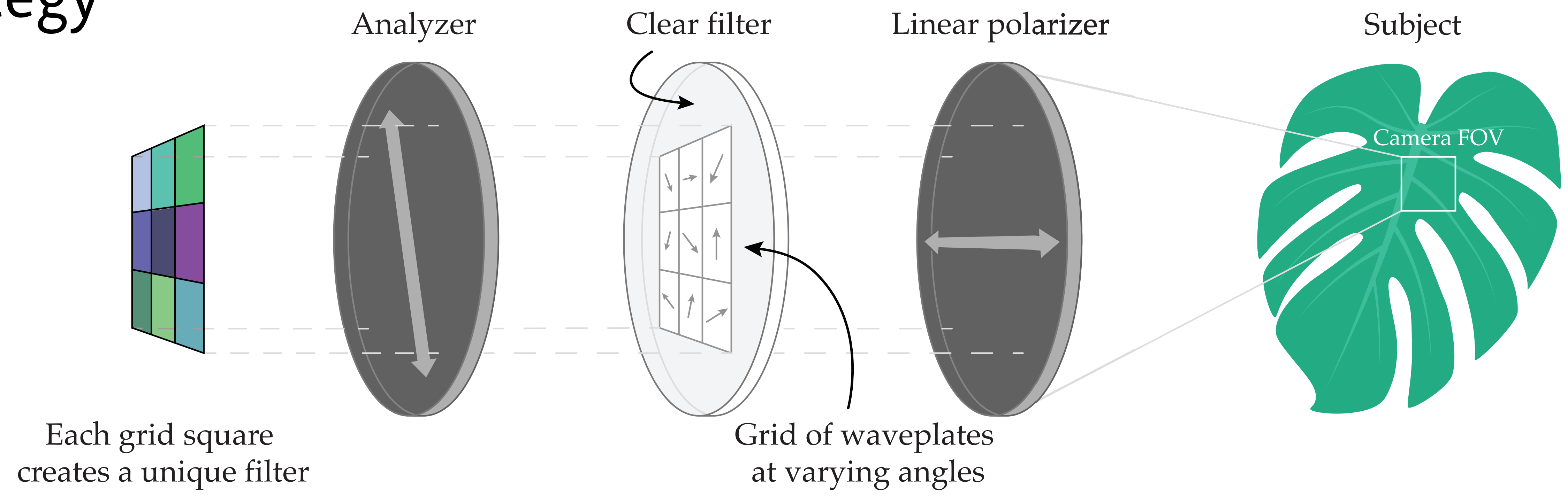

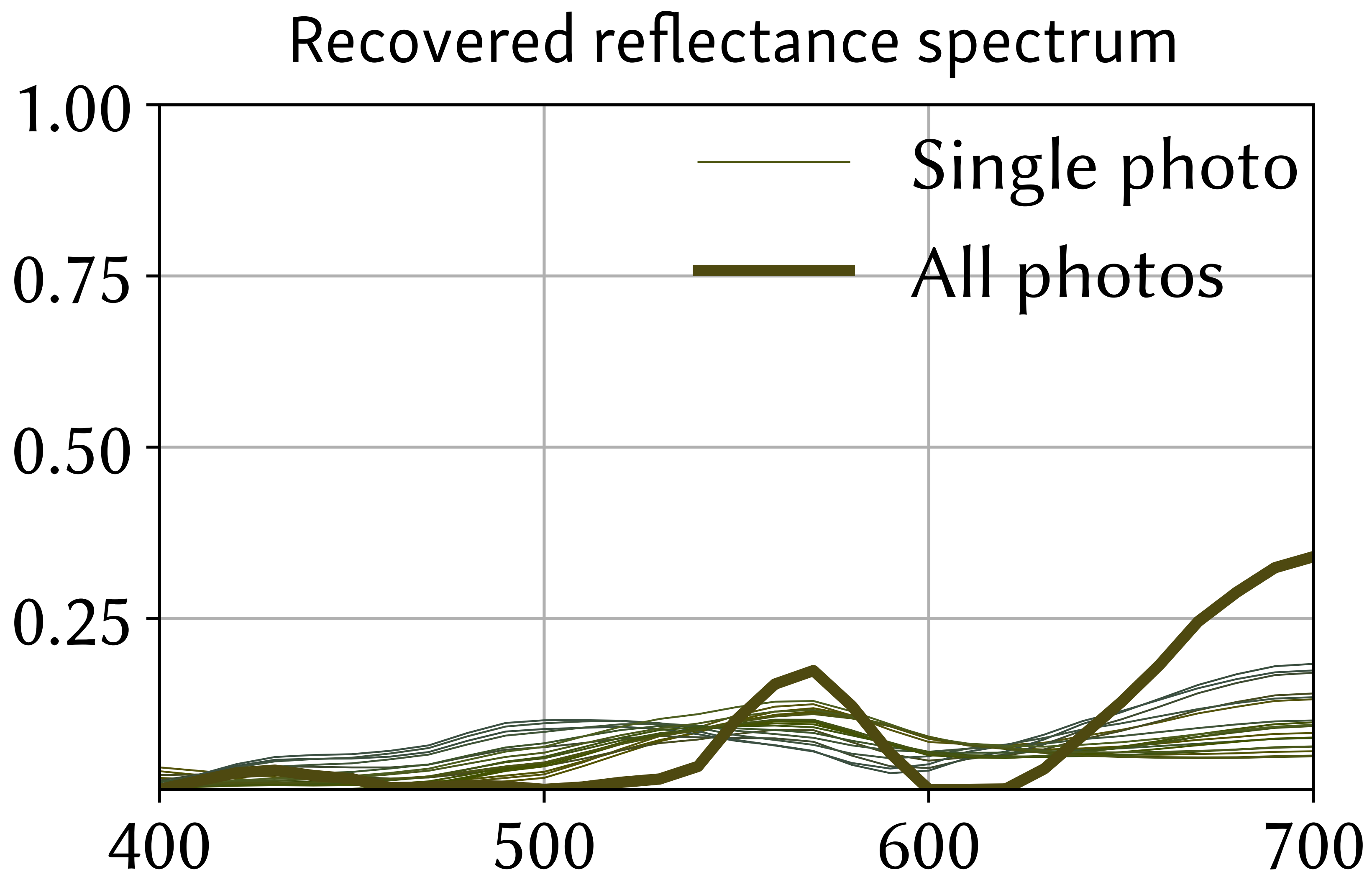

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Recap

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Recap

1. We create broadband spectral filters with a **continuous spectral gamut** using **polarization** and **birefringence**.

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Recap

DARTMOUTH VISUAL COMPUTING LAB

1. We create broadband spectral filters with a **continuous spectral gamut** using **polarization** and **birefringence**.
2. We take measurements of an unknown spectrum using these spectral filters.

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Recap

1. We create broadband spectral filters with a **continuous spectral gamut** using **polarization** and **birefringence**.
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3. We solve for the unknown spectrum by **solving a linear system** given the known camera responses and filter transmissions.

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Recap

1. We create broadband spectral filters with a **continuous spectral gamut** using **polarization** and **birefringence**.
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This procedure could be used with materials of any price/quality.

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Recap

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1. We create broadband spectral filters with a **continuous spectral gamut** using **polarization** and **birefringence**.
2. We take measurements of an unknown spectrum using these spectral filters.
3. We solve for the unknown spectrum by **solving a linear system** given the known camera responses and filter transmissions.
4. We construct a low-cost prototype of this design using an ordinary **digital camera**, **linearly polarized filters** meant for casual photography, and **clear packing tape** as a birefringent material.

This procedure could be used with materials of any price/quality.

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Future Work

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- Smarter choice of filter set from continuous space
- Remove assumptions with more complex physically based rendering
  - e.g. incident light is unpolarized, incident light enters normal to filter plane
- Realize theoretical system design with higher cost/quality materials or even liquid crystals
  - Liquid crystals have variable birefringence controlled by electric currents — could be dynamically driven
  - e.g. concurrent work [Sankaranarayanan et al. 2021]

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Visit: dartgo.org/hyperspectral

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

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References

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- Slide 2 screenshot: https://www.exploratorium.edu/snacks/polarized-light-mosaic
- Slide 3 images:
  - https://www.nikonsmallworld.com/galleries/2008-photomicrography-competition/pleurosigma-marine-diatoms
  - https://www.nikonsmallworld.com/galleries/1988-photomicrography-competition/antibiotic-crystals
  - https://en.wikipedia.org/wiki/Photoelasticity
  - https://cosmosmagazine.com/physics/dancing-liquid-crystals/
- H. Du, X. Tong, X. Cao, and S. Lin, “A prism-based system for multispectral video acquisition,” in Proc. ICCV. New York, NY, USA: IEEE, 2009.
- S.-H. Baek, I. Kim, D. Gutierrez, and M. H. Kim, “Compact single-shot hyperspectral imaging using a prism,” Proc. SIGGRAPH Asia, vol. 36, no. 6, Nov. 2017.
- R. Habel, M. Kudenov, and M. Wimmer, “Practical spectral photography,” CGF, vol. 31, 2012.
- D. S. Jeon, S.-H. Baek, S. Yi, Q. Fu, X. Dun, W. Heidrich, and M. H. Kim, “Compact snapshot hyperspectral imaging with diffracted rotation,” Proc. SIGGRAPH, vol. 38, no. 4, Jul. 2019.
- A. C. Sankaranarayanan, V. Saragadam, V. Rengarajan, R. Tadano, T. Zhuang, H. Oyaizu, and J. Murayama, “Programmable spectral filter arrays for hyperspectral imaging,” 2021. [Online]. Available: https://arxiv.org/abs/2109.14450
- A. Belendez, E. Fernandez, J. Frances, and C. Neipp, “Birefringence of cellotape: Jones representation and experimental analysis,” European Journal of Physics, vol. 31, no. 3, mar 2010.
- S. W. Oh, M. S. Brown, M. Pollefeys, and S. J. Kim, “Do it yourself hyperspectral imaging with everyday digital cameras,” in Proc. IEEE CVPR. New York, NY, USA: IEEE, 2016.
- P. Indyk, S. Mahabadi, M. Mahdian, and V. S. Mirrokni, “Composable core-sets for diversity and coverage maximization,” in Proceedings of the Symposium on Principles of Database Systems, ser. PODS ’14. New York, NY, USA: ACM Press, 2014.

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