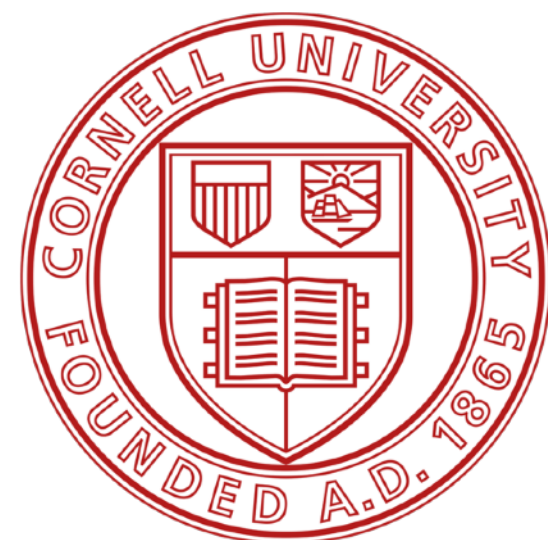
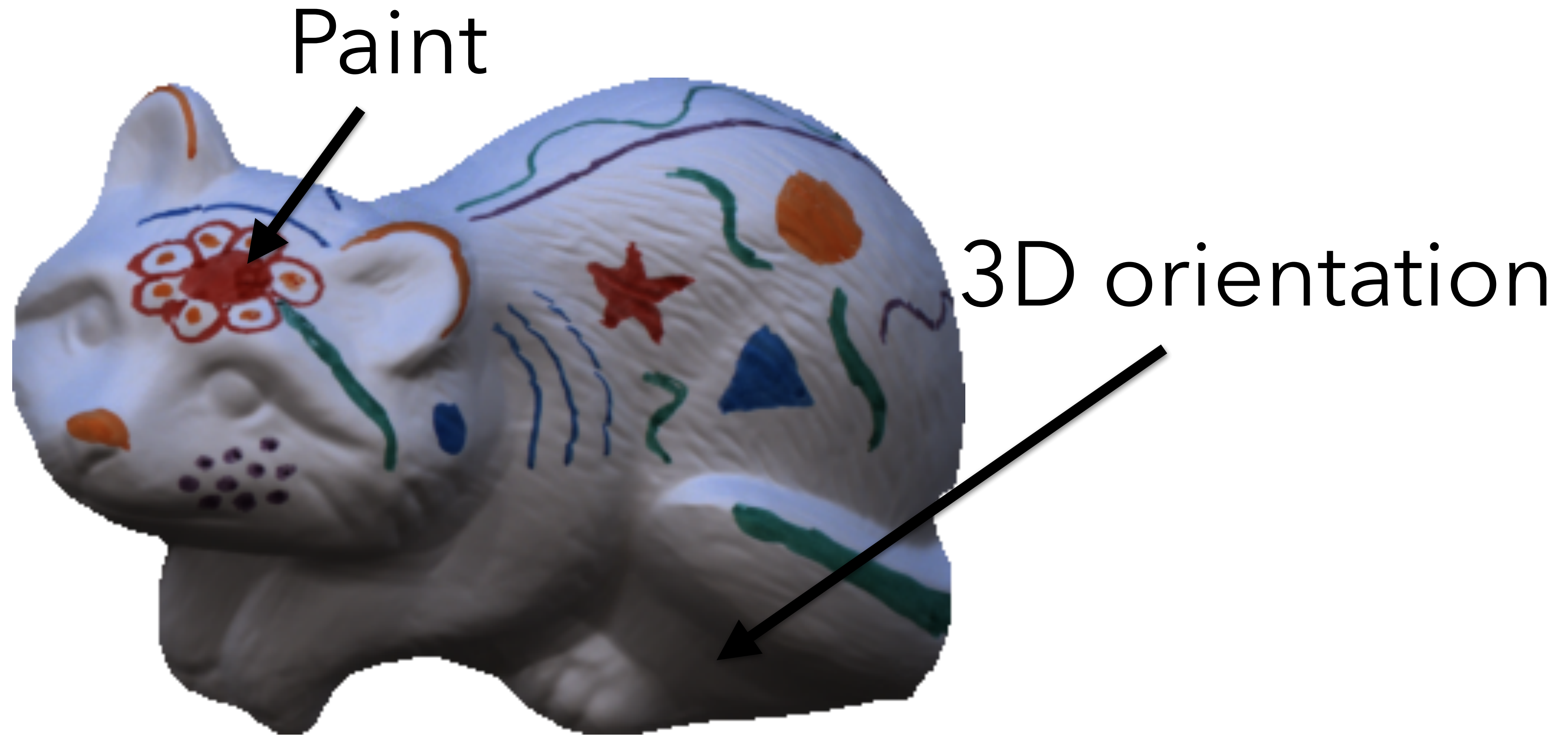


Lecture 23: Light, shading, and color

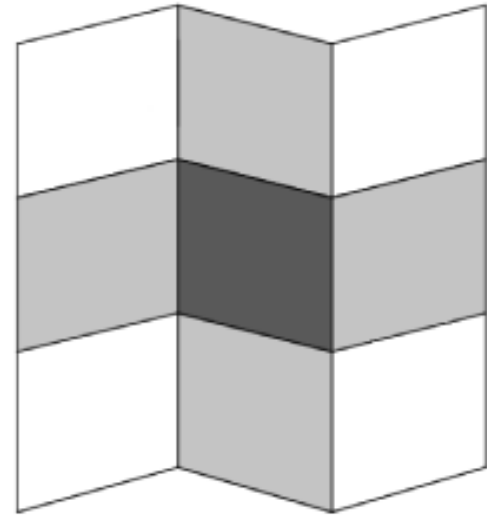
CS 5670: Introduction to Computer Vision



What can we infer from intensity changes?

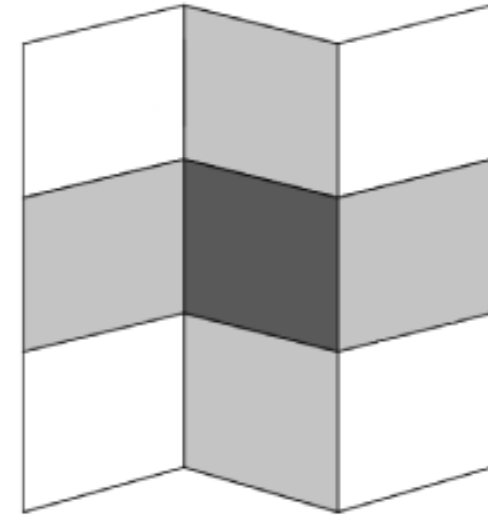


The Workshop Metaphor

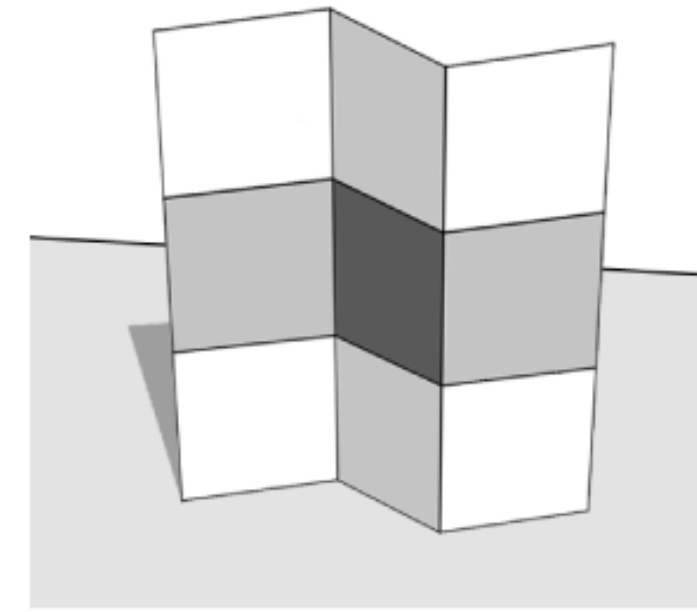


(a) an image

The Workshop Metaphor

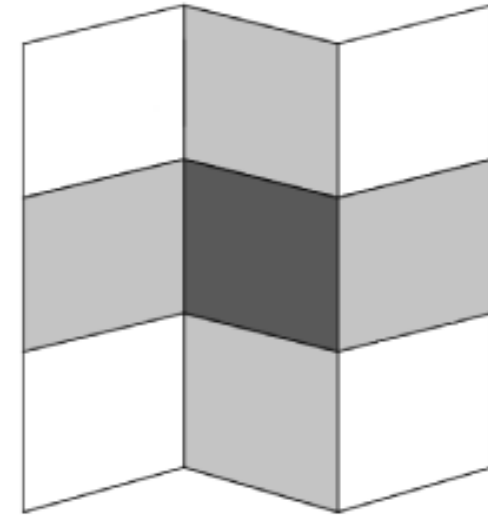


(a) an image

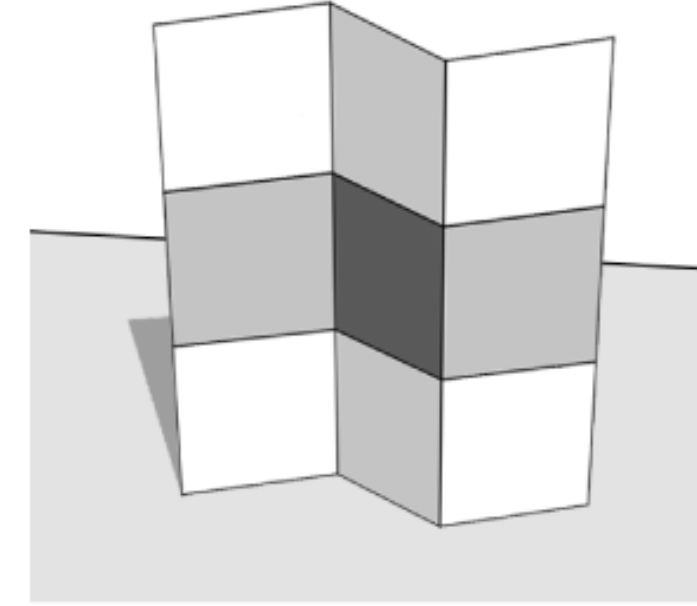


(b) a likely explanation

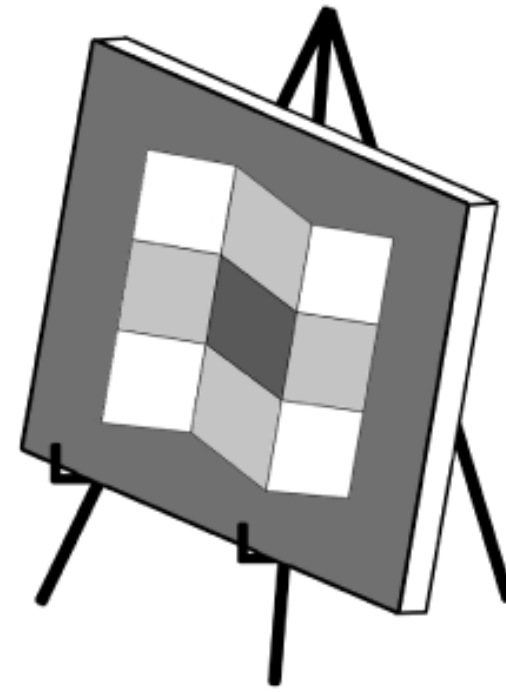
The Workshop Metaphor



(a) an image



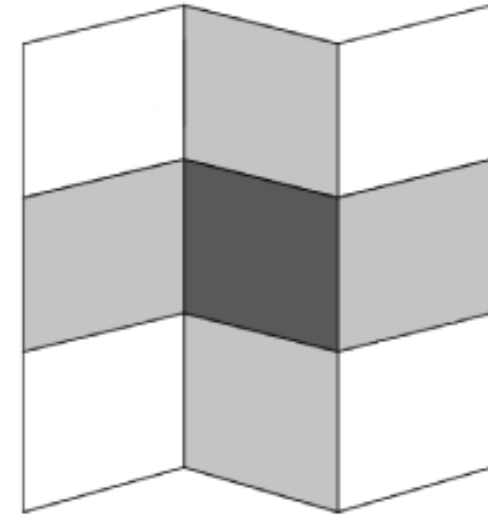
(b) a likely explanation



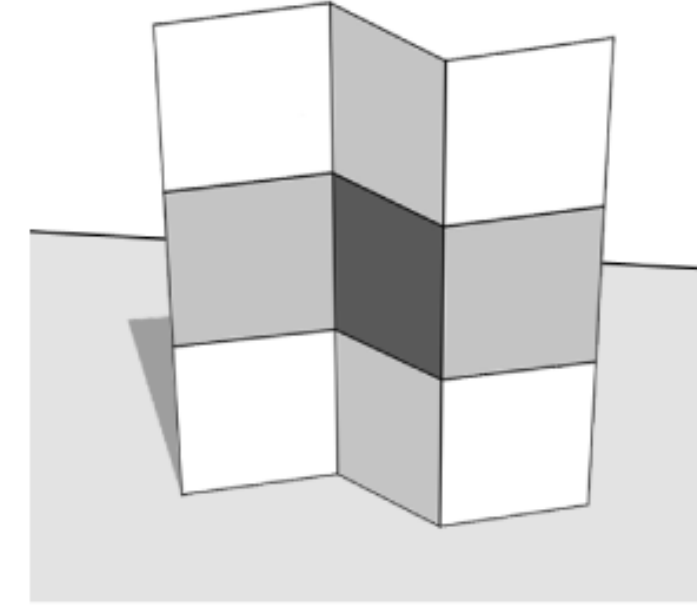
(c) painter's explanation

E. Adelson and A. Pentland, "The perception of shading and reflectance," *Perception as Bayesian inference*, 1996.

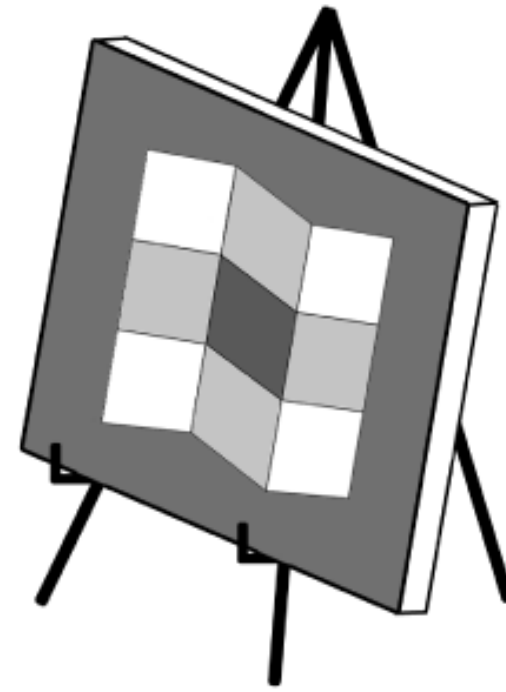
The Workshop Metaphor



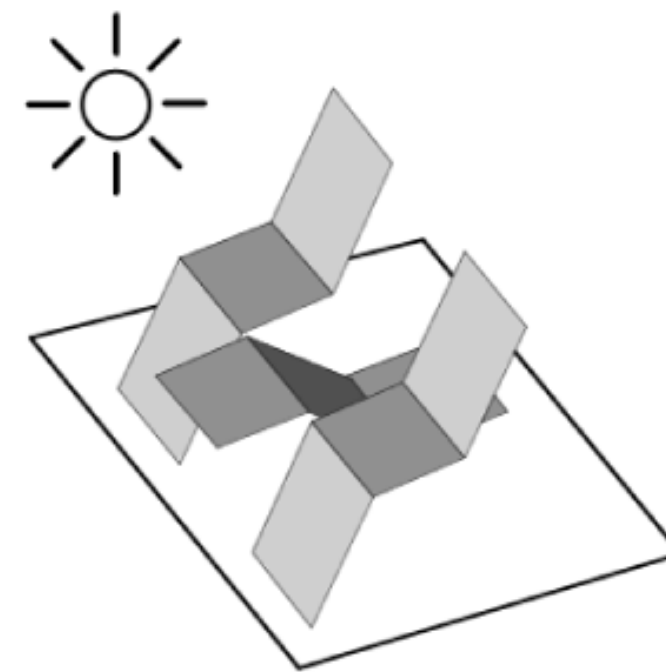
(a) an image



(b) a likely explanation



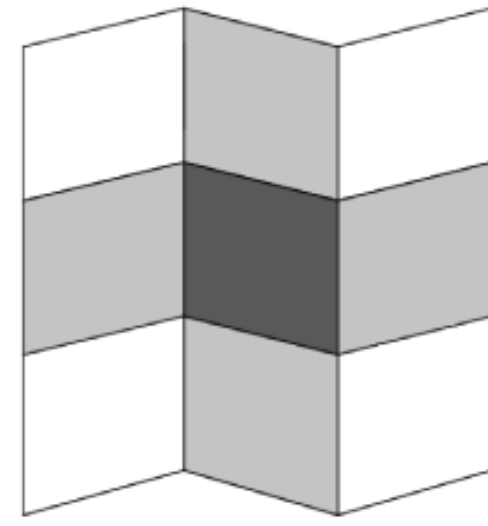
(c) painter's explanation



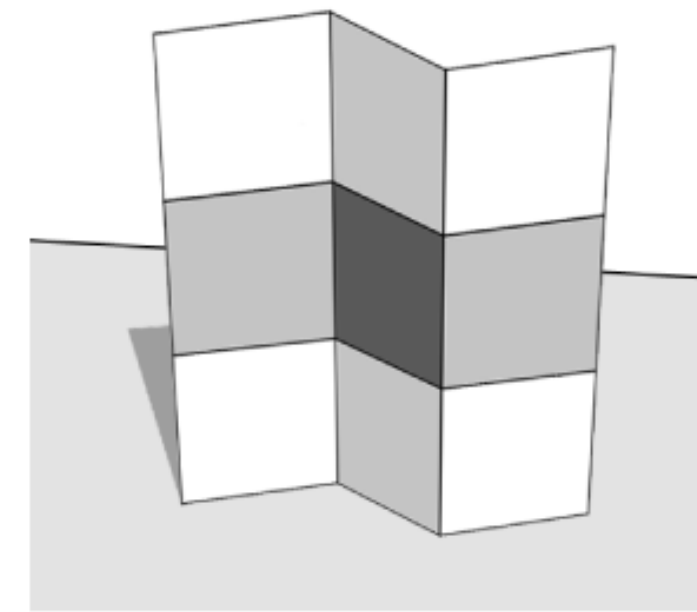
(d) sculptor's explanation

E. Adelson and A. Pentland, "The perception of shading and reflectance," *Perception as Bayesian inference*, 1996.

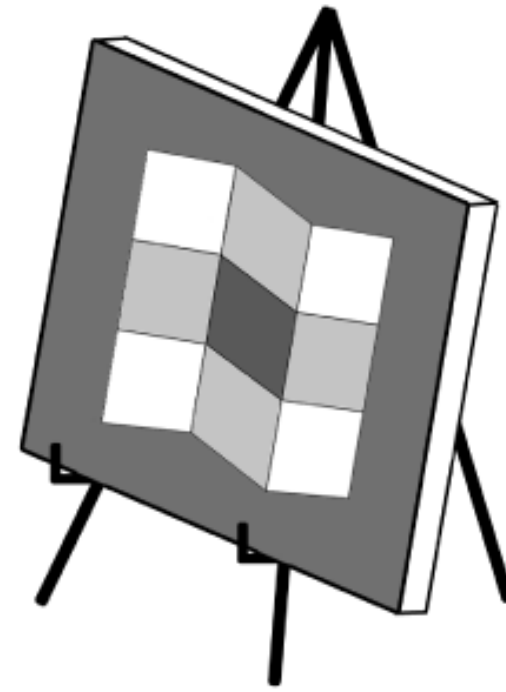
The Workshop Metaphor



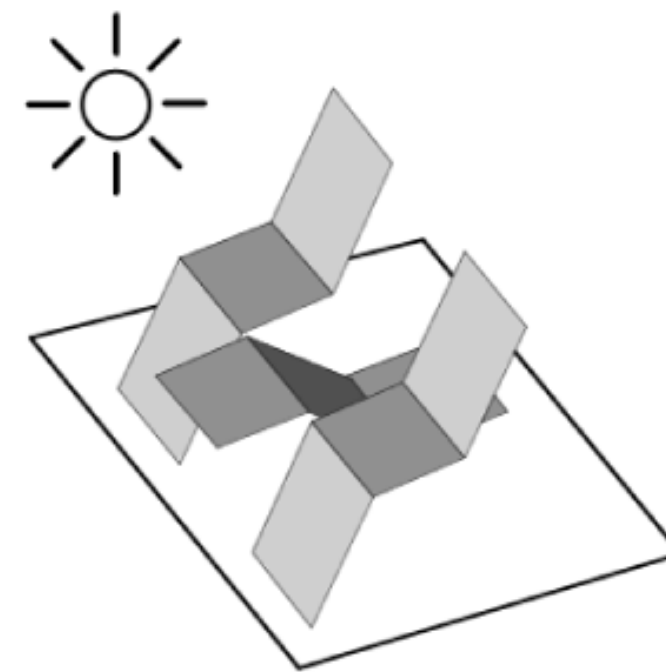
(a) an image



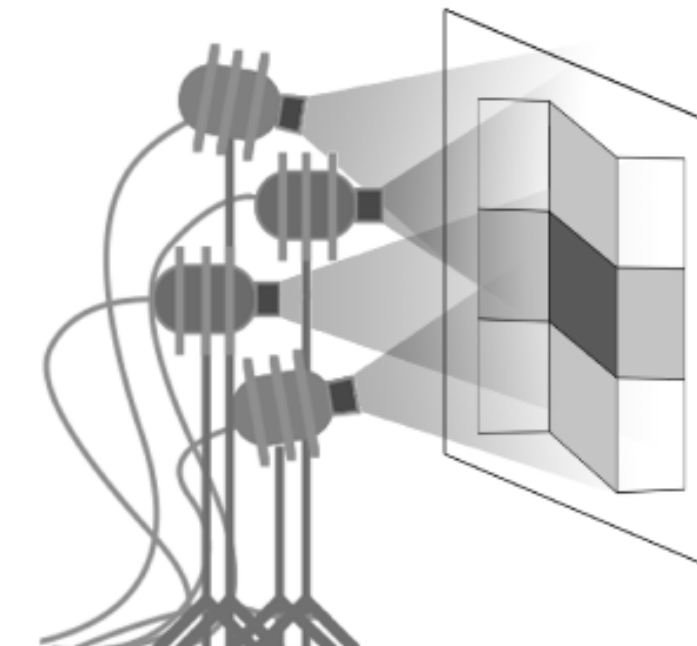
(b) a likely explanation



(c) painter's explanation



(d) sculptor's explanation



(e) gaffer's explanation

E. Adelson and A. Pentland, "The perception of shading and reflectance," *Perception as Bayesian inference*, 1996.

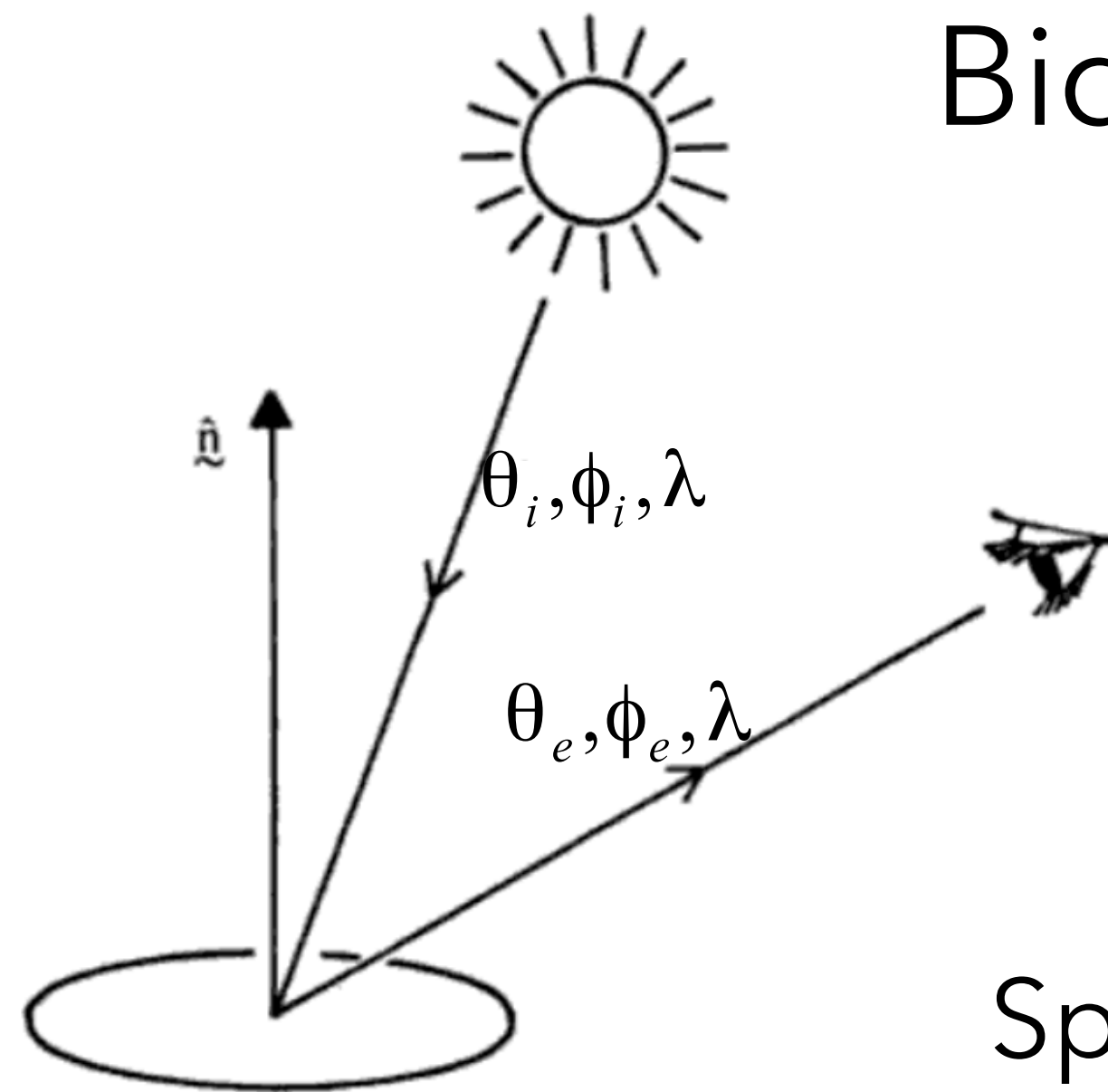
Today

- **Shape from shading**
- Intrinsic image decomposition
- Color perception

Shape perception



Interaction of light and surfaces



[Horn, 1986]

Bidirectional reflectance distribution function (BRDF)

$$BRDF = f(\theta_i, \phi_i, \theta_e, \phi_e, \lambda) = \frac{L(\theta_e, \phi_e, \lambda)}{E(\theta_i, \phi_i, \lambda)}$$

Spectral irradiance: incident power per unit area, per unit wavelength.

Effect of BRDF on sphere rendering



Diffuse reflection

For now, ignore specular reflection



And refraction...

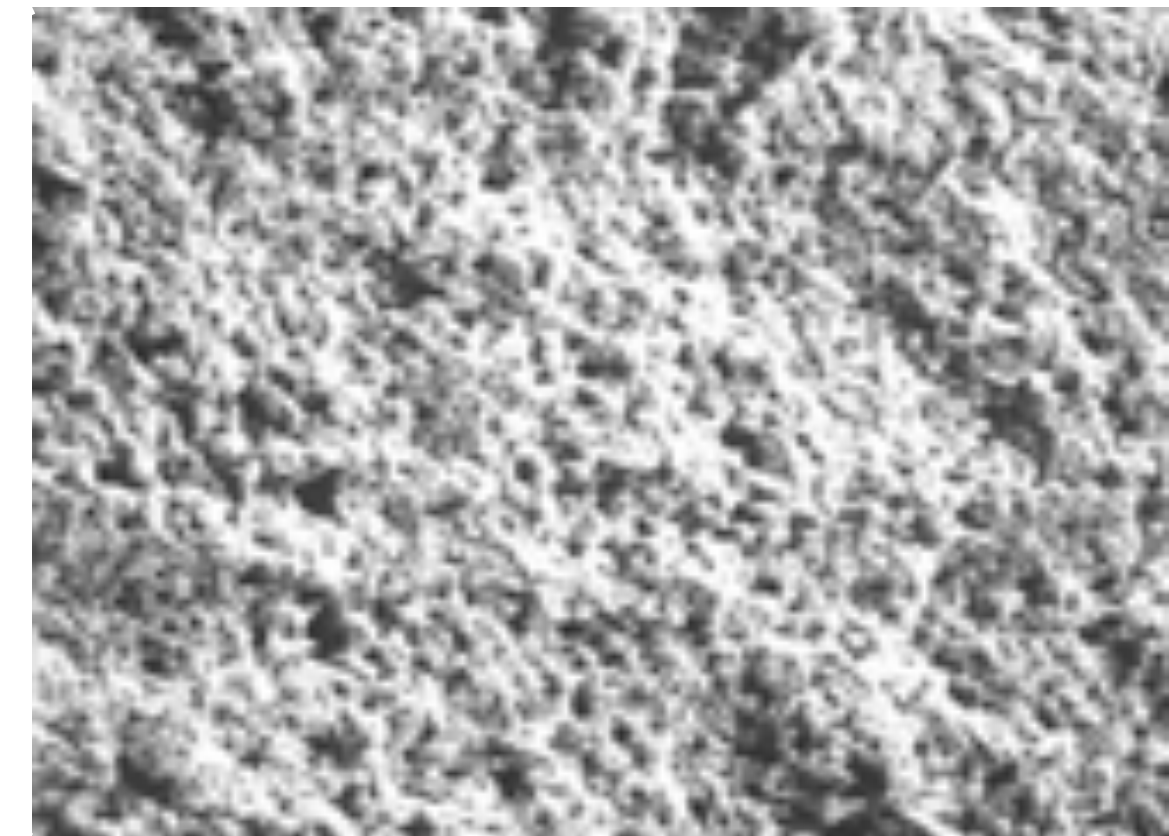
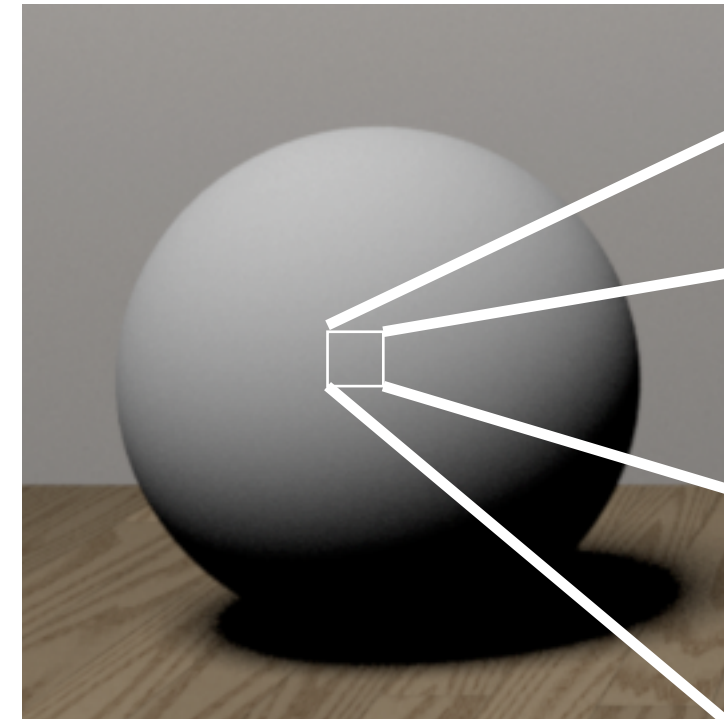
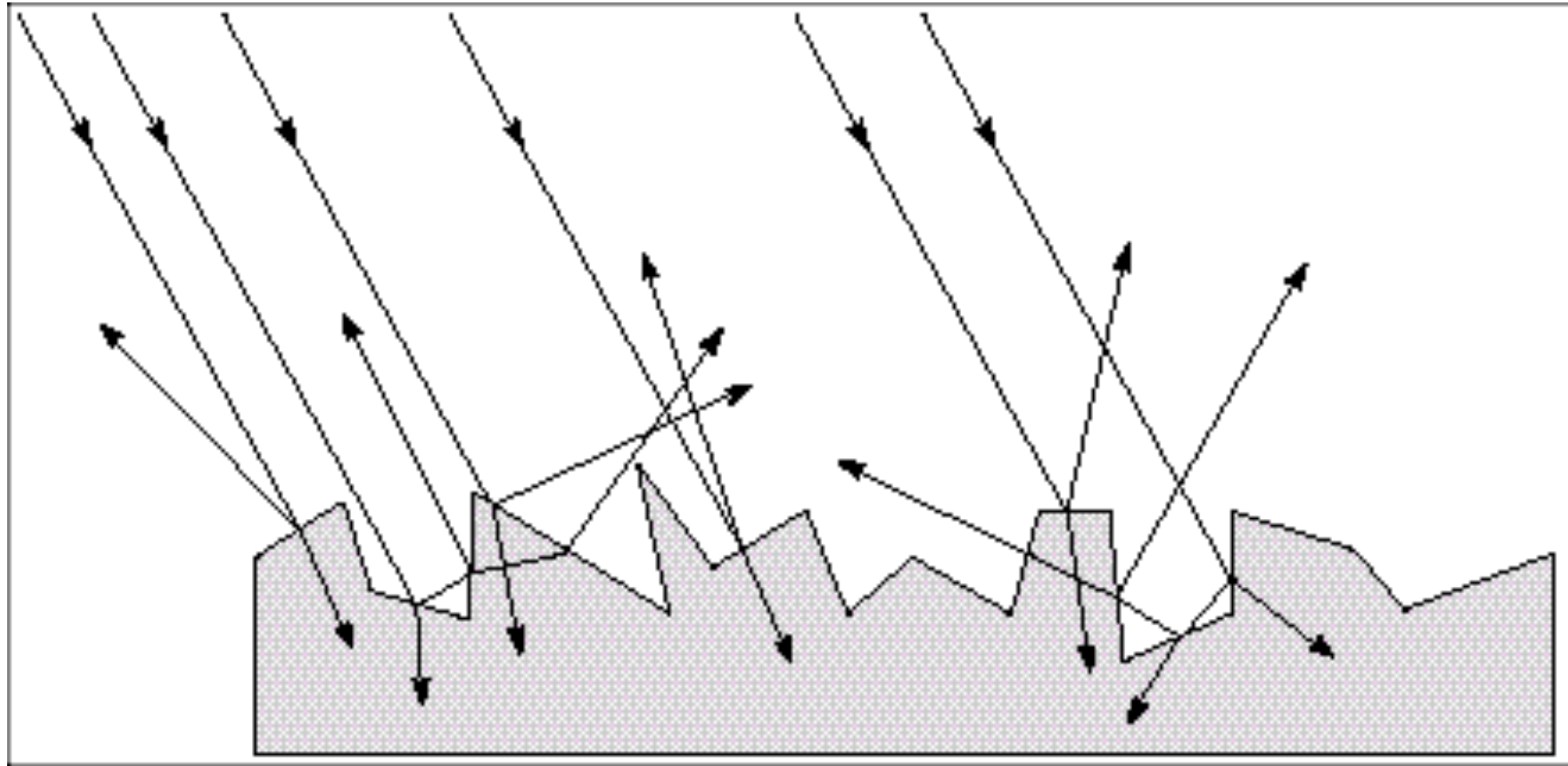


And interreflections...



Source: Photometric Methods for 3D Modeling, Matsushita, Wilburn, Ben-Ezra. Changes by N. Snavely

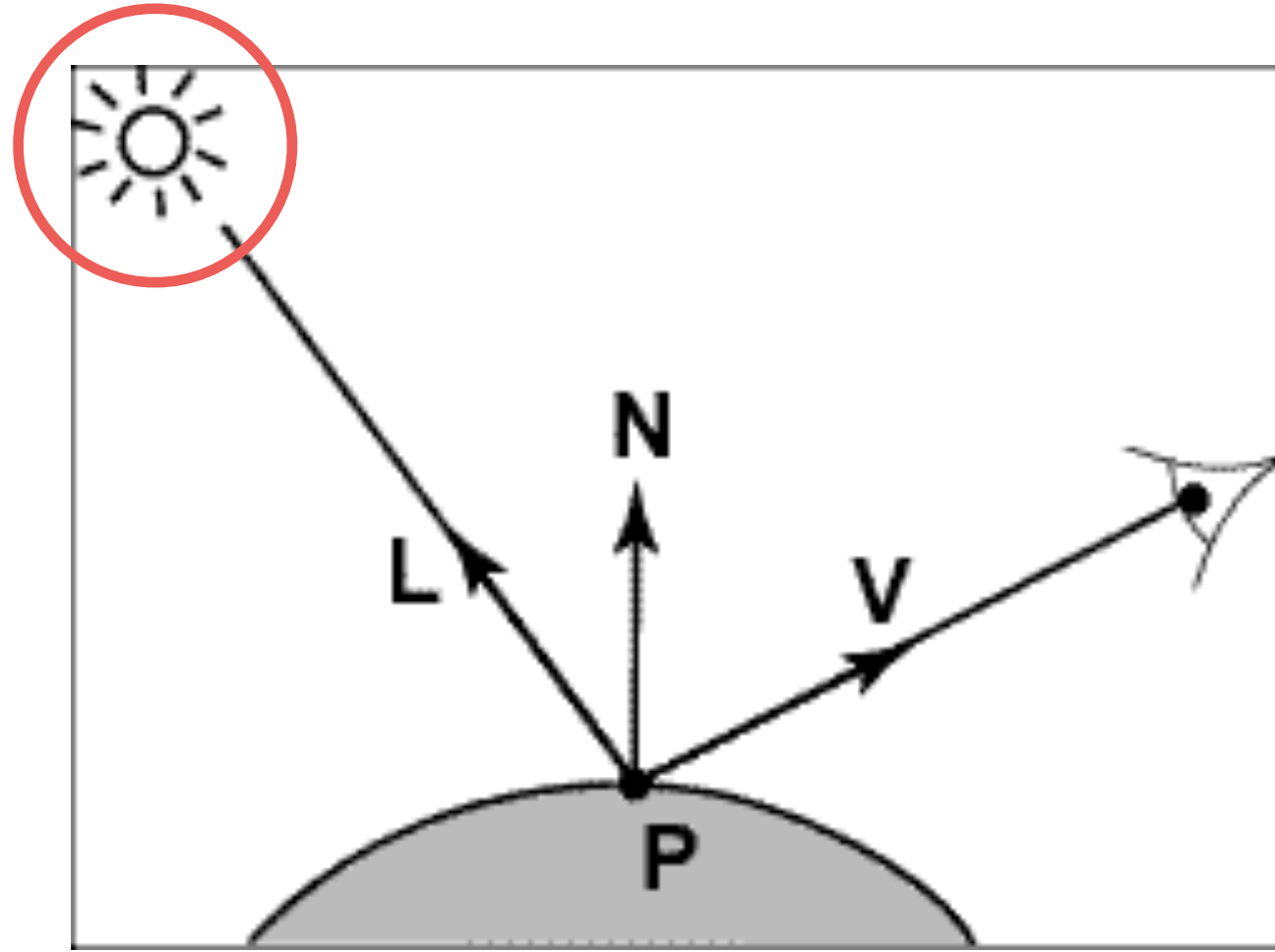
Diffuse reflection



Diffuse reflection

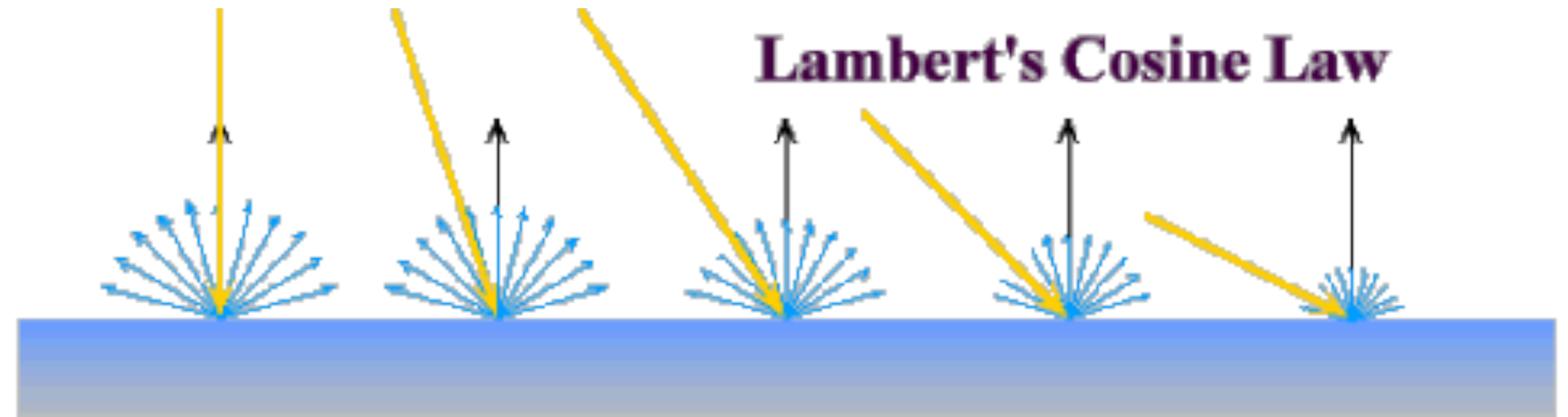
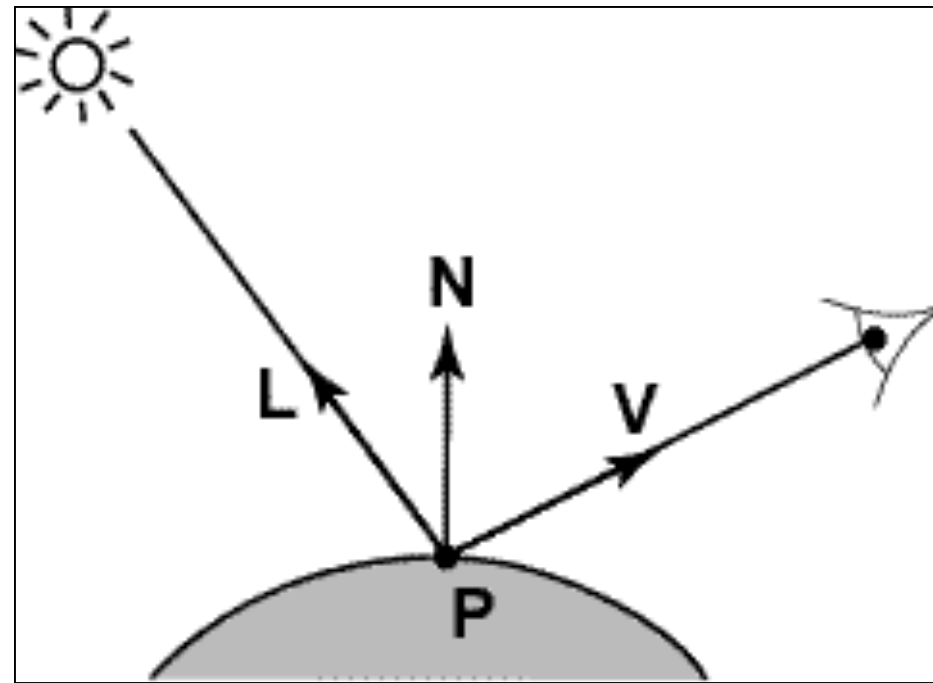
- Dull, matte surfaces like chalk or latex paint
- Microfacets scatter incoming light randomly
- Effect is that light is reflected equally in all directions

Directional lighting



- All rays are parallel
- Equivalent to an infinitely distant point source

Diffuse reflection

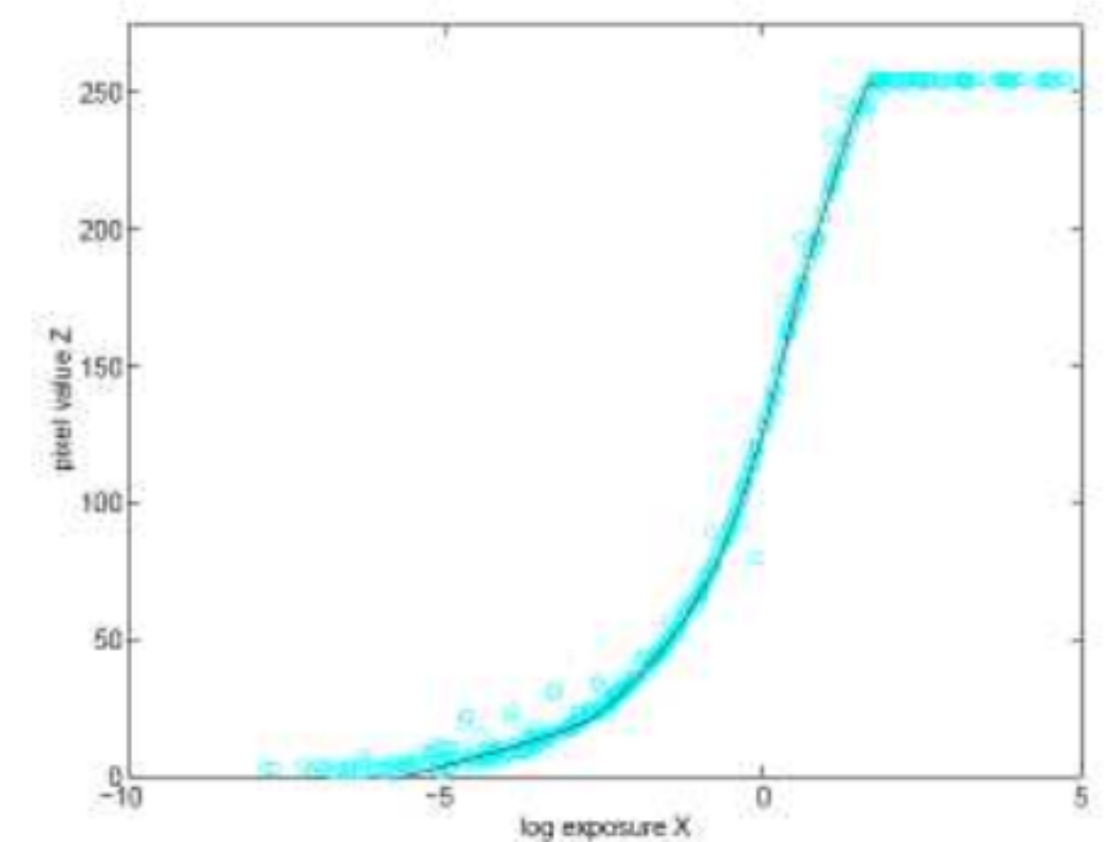


$$R_e = k_d \mathbf{N} \cdot \mathbf{L} R_i$$

image intensity of $\mathbf{P} \longrightarrow I = k_d \mathbf{N} \cdot \mathbf{L}$

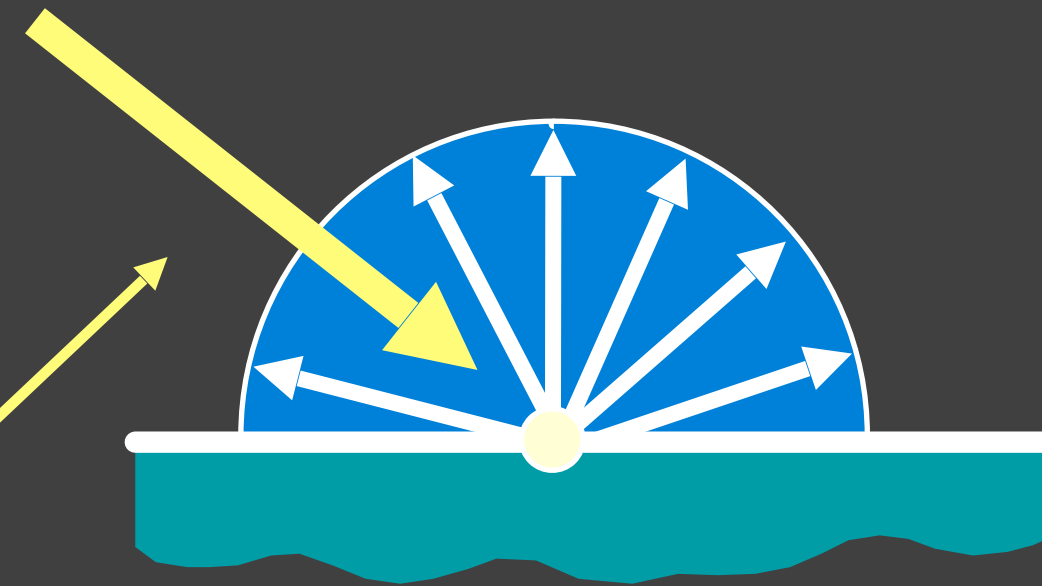
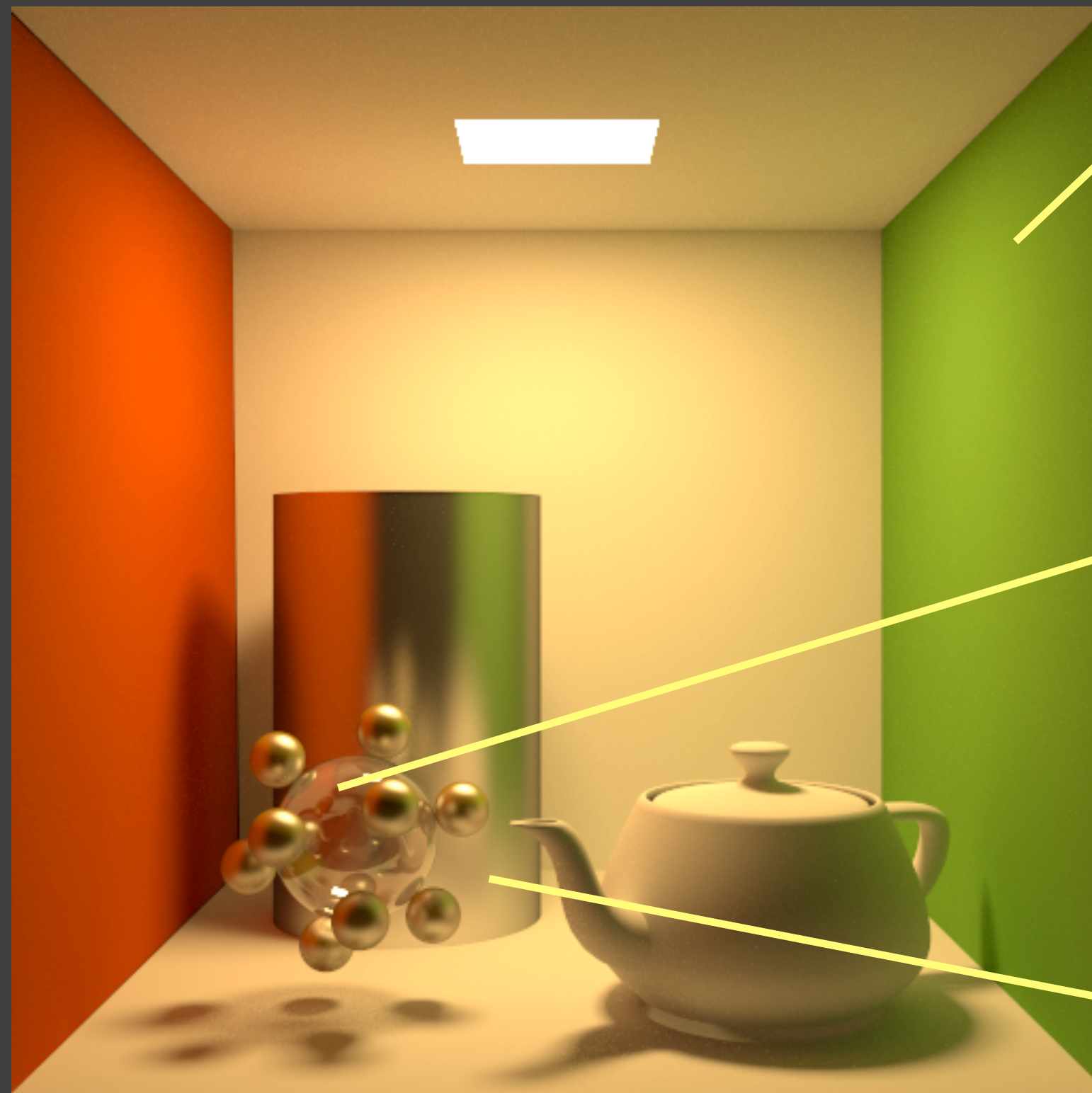
Simplifying assumptions we'll often make:

- $I = R_e$: "camera response function" is the identity
 - In actual cameras it is a nonlinear function
 - Can always achieve this in practice by inverting it
- $R_i = 1$: light source intensity is 1
 - Can achieve this by dividing each pixel in the image by R_i

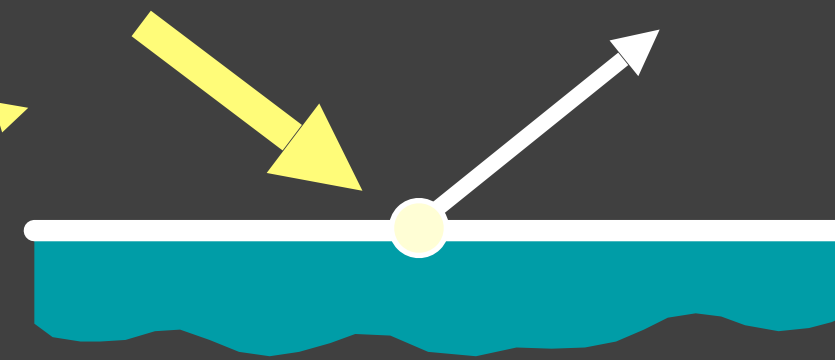


Source: [Debevec & Malik 1997]

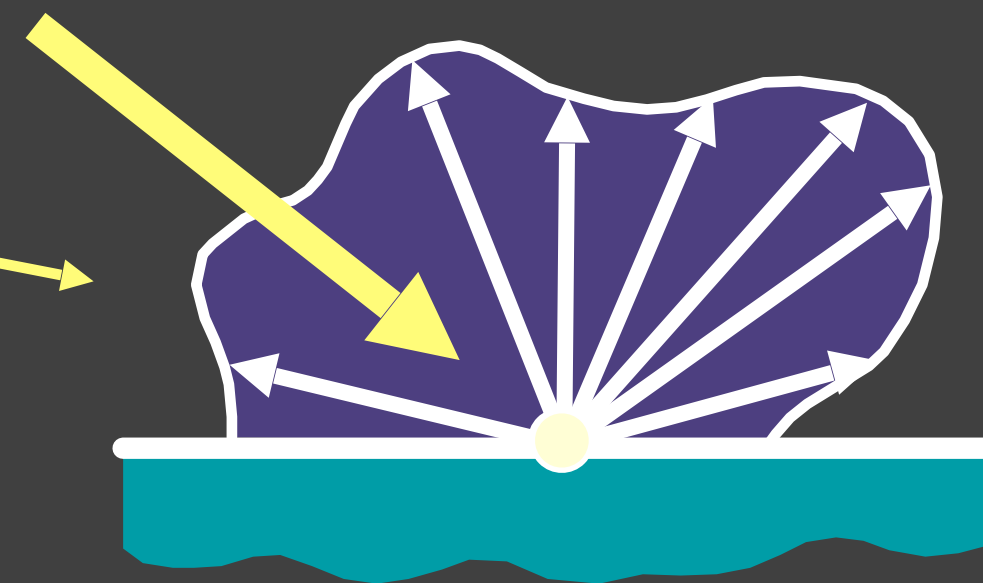
Other BRDFs



Ideal diffuse
(Lambertian)

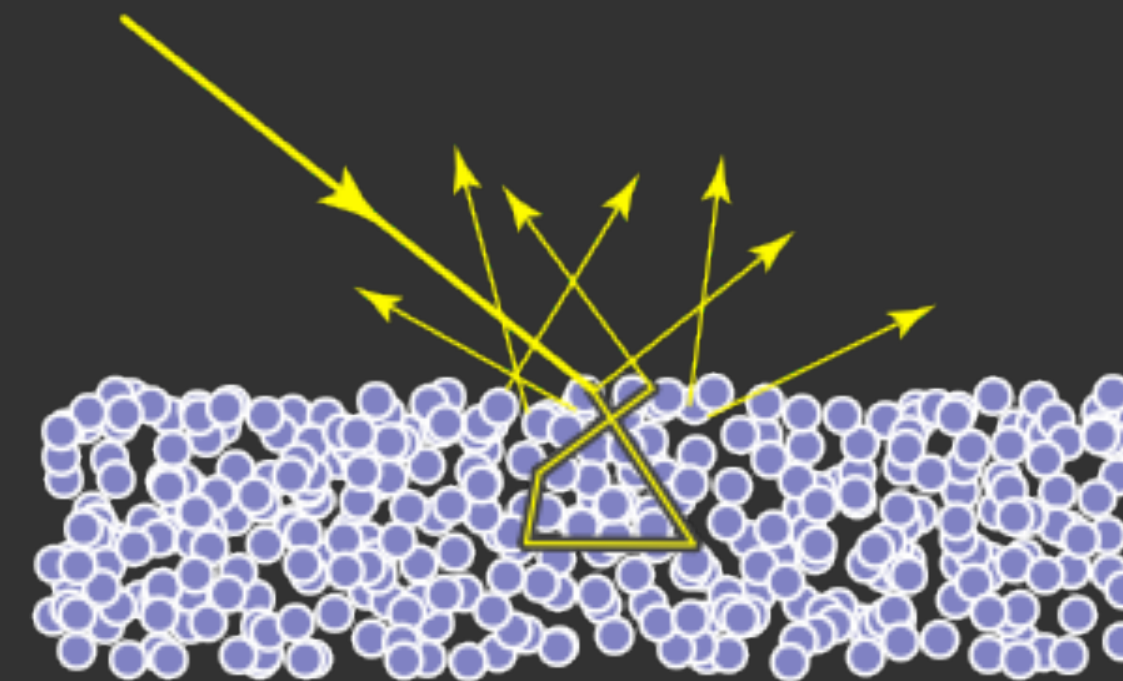
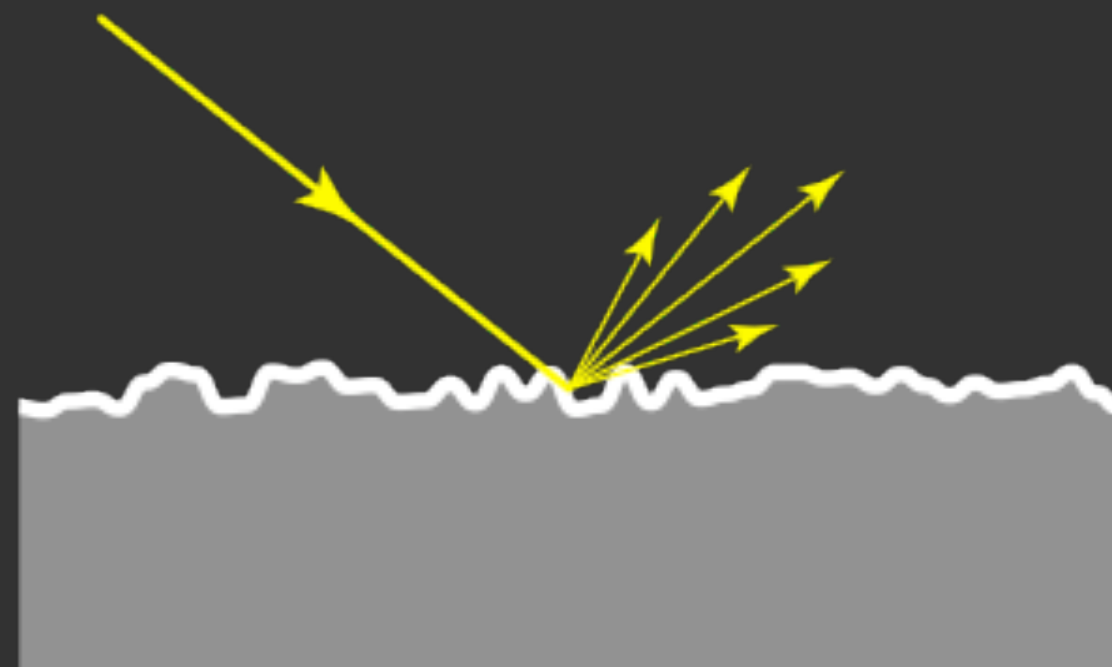


Ideal
specular



Directional
diffuse

Non-smooth-surfaced materials



Shape from shading



$$I = \kappa_d N \cdot L$$

Assume κ_d is 1 for now.

What can we measure from one image?

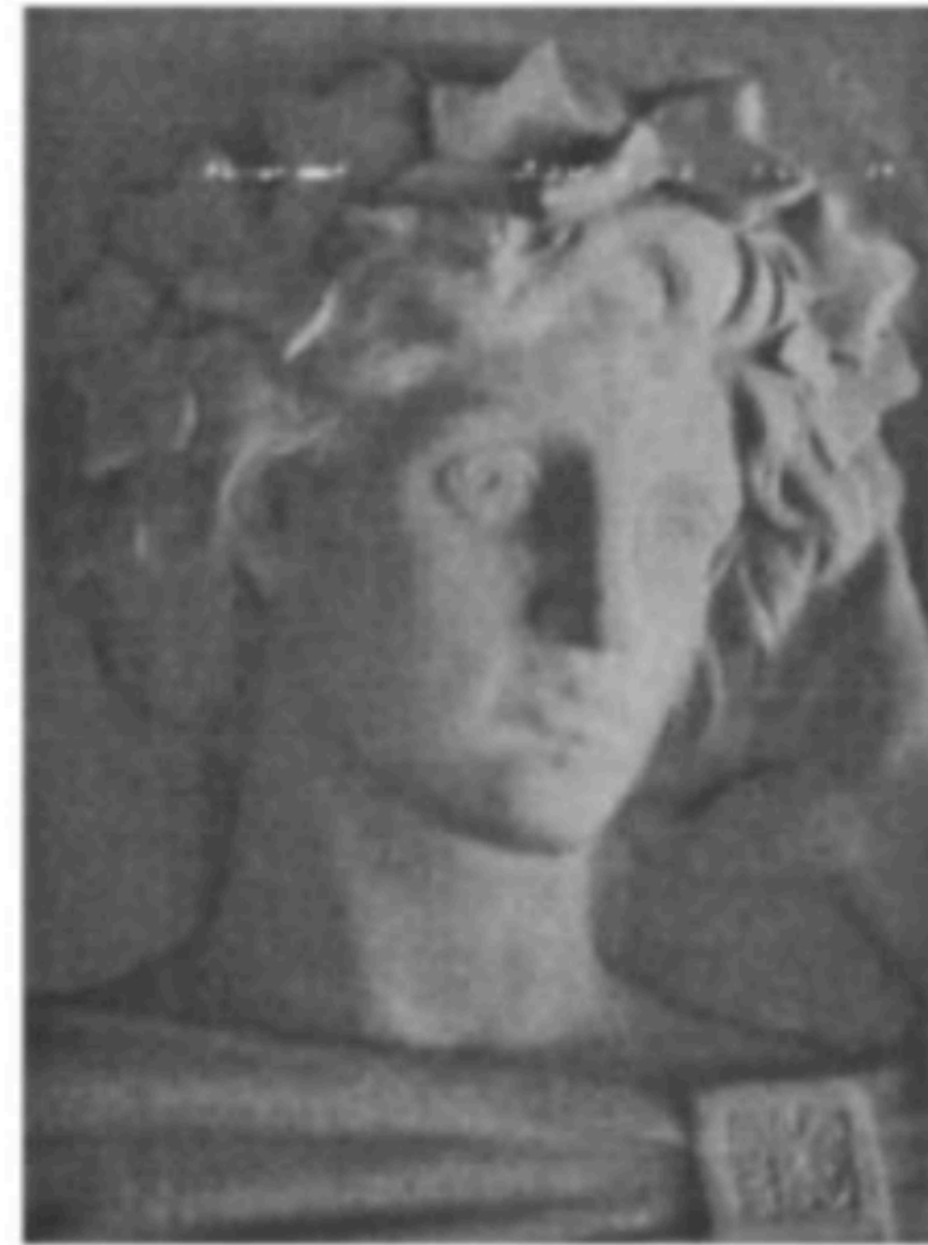
- $\cos^{-1}(I)$ is the angle between N and L

Add assumptions:

- Constant albedo
- A few known normals (e.g. silhouettes)
- Smoothness of normals

In practice, this doesn't work well: assumptions are too restrictive, too much ambiguity in nontrivial scenes.

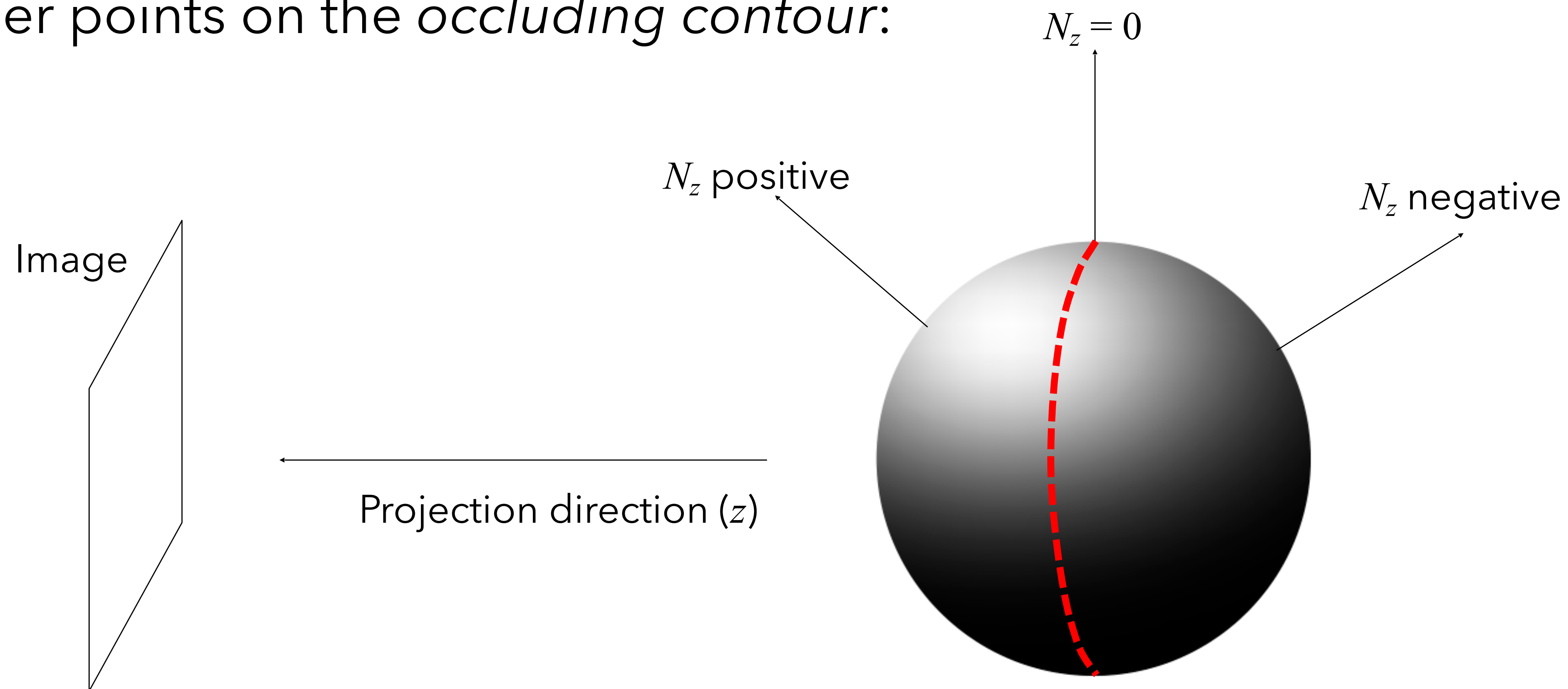
An ambiguity that artists exploit



[Belhumeur et al. "The Bas-Relief Ambiguity", 1999]

Contours provide extra shape information

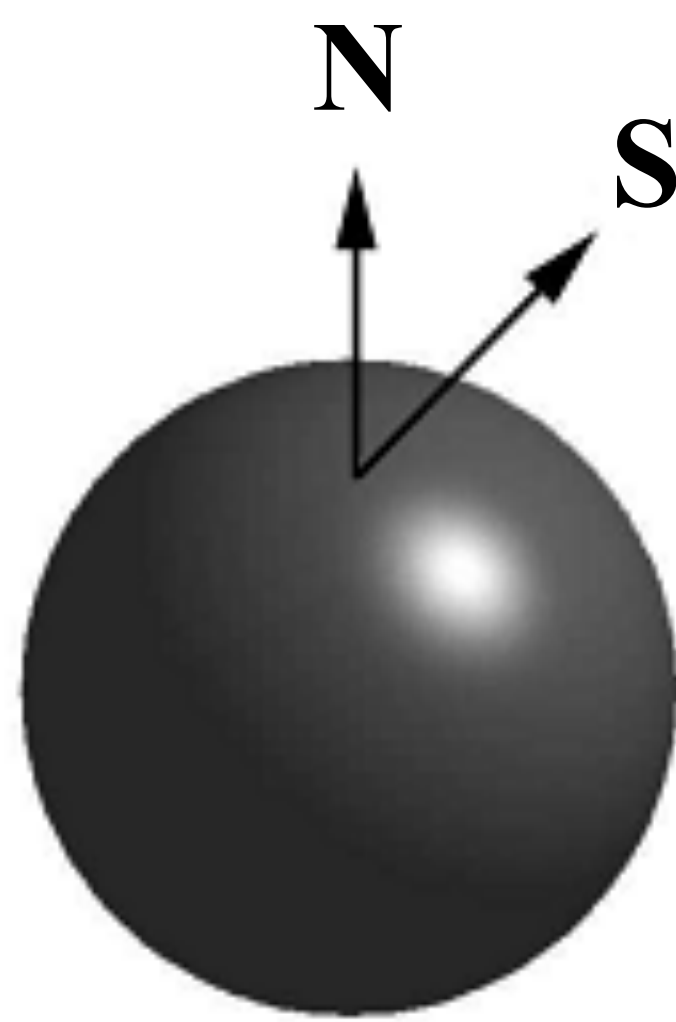
Consider points on the *occluding contour*:



Application: finding the direction of the light source

$$I(x,y) = \mathbf{N}(x,y) \cdot \mathbf{S}$$

Full 3D case:



$$\begin{pmatrix} N_x(x_1, y_1) & N_y(x_1, y_1) & N_z(x_1, y_1) \\ N_x(x_2, y_2) & N_y(x_2, y_2) & N_z(x_2, y_2) \\ \vdots & \vdots & \vdots \\ N_x(x_n, y_n) & N_y(x_n, y_n) & N_z(x_n, y_n) \end{pmatrix} \begin{pmatrix} S_x \\ S_y \\ S_z \end{pmatrix} = \begin{pmatrix} I(x_1, y_1) \\ I(x_2, y_2) \\ \vdots \\ I(x_n, y_n) \end{pmatrix}$$

For points on the occluding contour, $N_z = 0$:

$$\begin{pmatrix} N_x(x_1, y_1) & N_y(x_1, y_1) \\ N_x(x_2, y_2) & N_y(x_2, y_2) \\ \vdots & \vdots \\ N_x(x_n, y_n) & N_y(x_n, y_n) \end{pmatrix} \begin{pmatrix} S_x \\ S_y \end{pmatrix} = \begin{pmatrix} I(x_1, y_1) \\ I(x_2, y_2) \\ \vdots \\ I(x_n, y_n) \end{pmatrix}$$

Finding the direction of the light source



Application: detecting image splices

Real photo



Fake photo

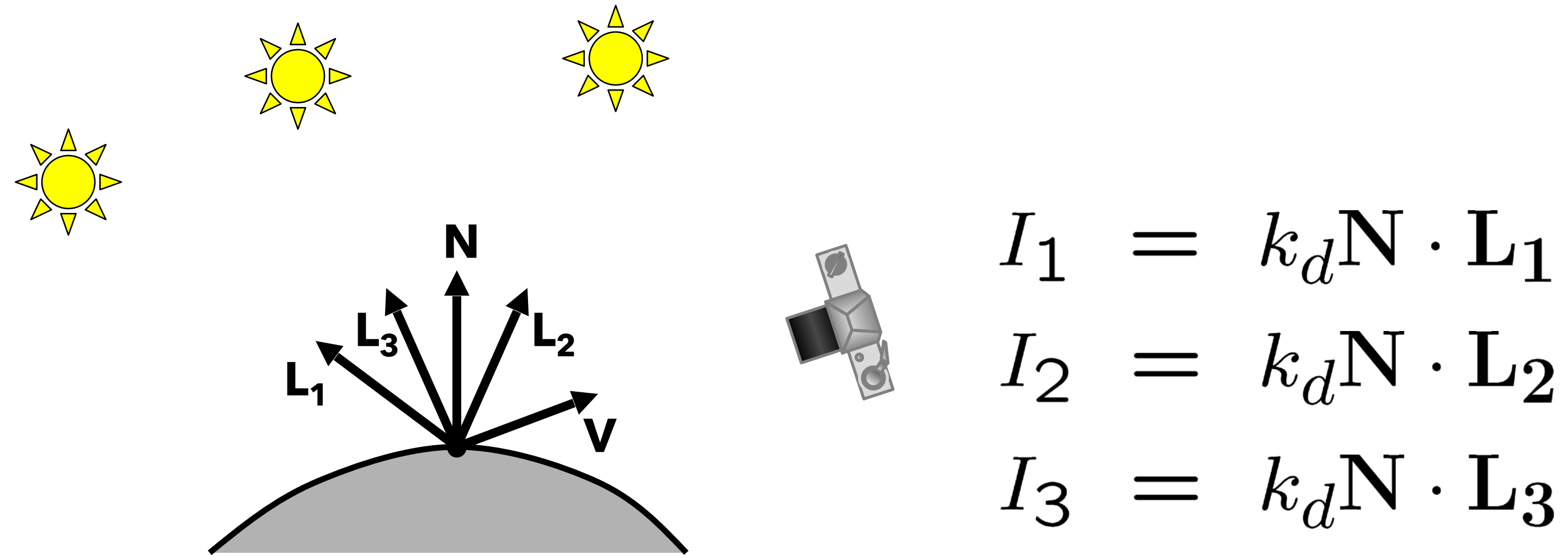


Can we make things easier?

Photometric stereo



Photometric stereo



Can write this as a linear system and solve:

$$\begin{bmatrix} I_1 \\ I_2 \\ I_3 \end{bmatrix} = k_d \begin{bmatrix} \mathbf{L}_1^T \\ \mathbf{L}_2^T \\ \mathbf{L}_3^T \end{bmatrix} \mathbf{N}$$

Photometric Stereo

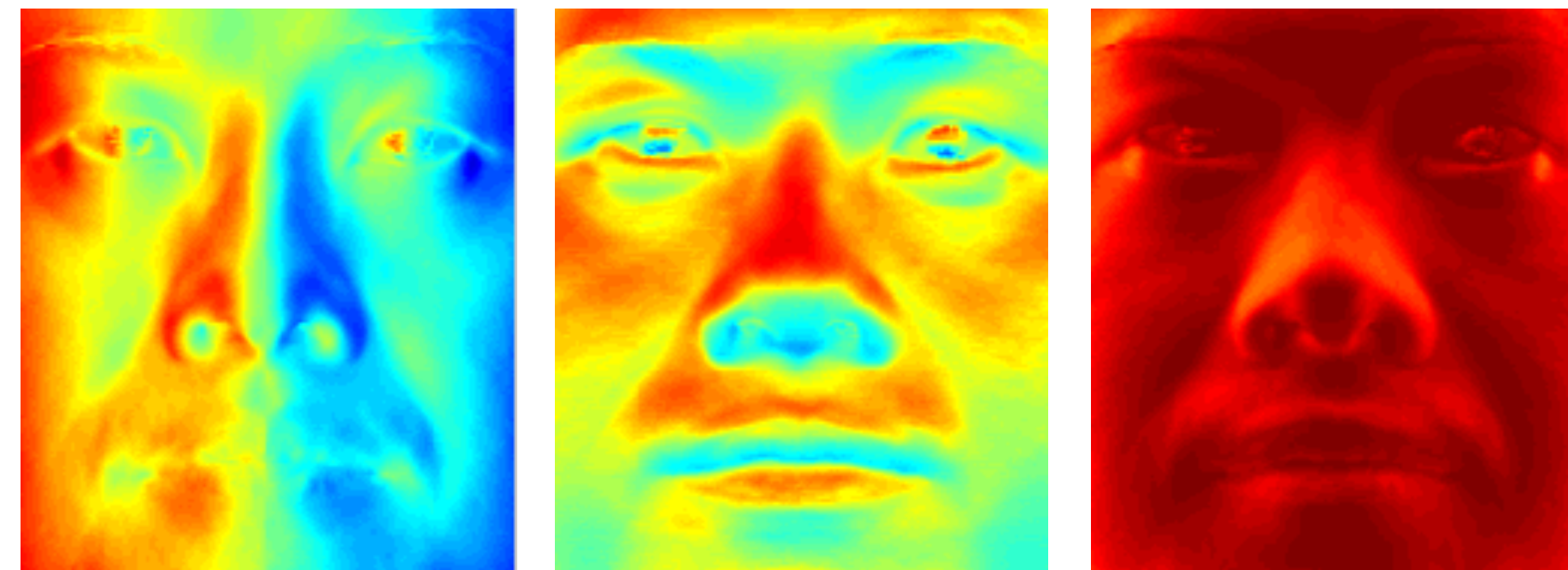
Input



Recovered
albedo



Recovered normal field

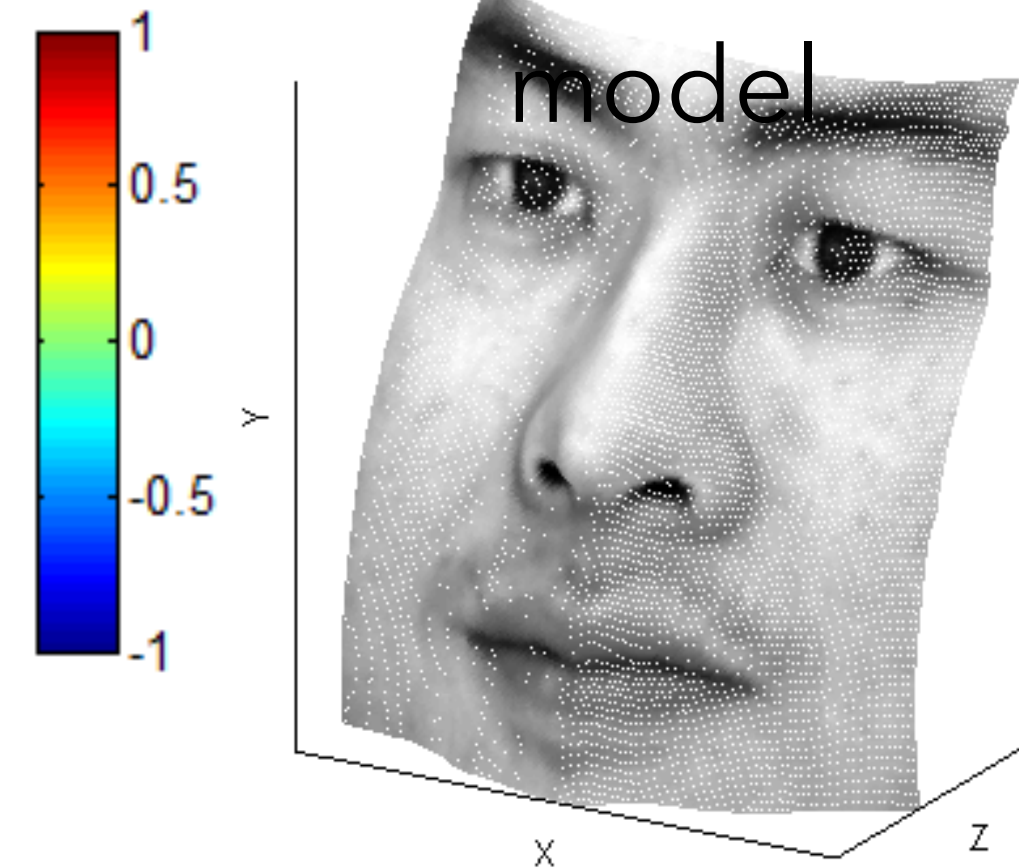


x

y

z

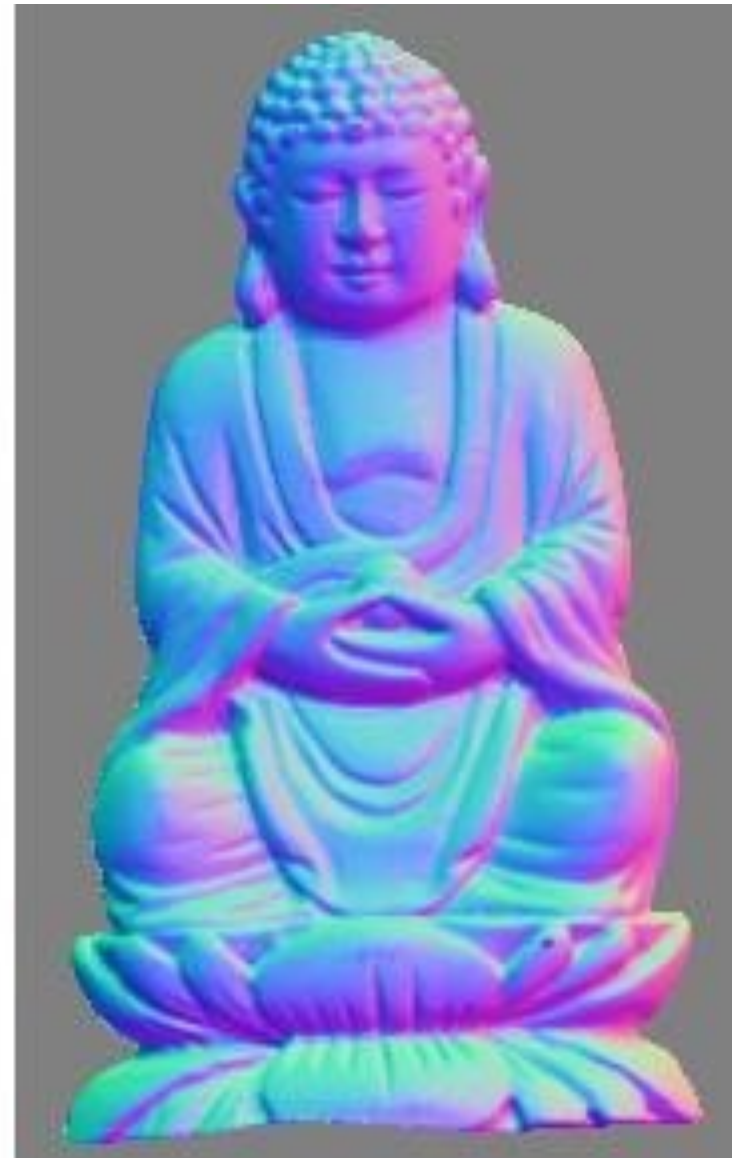
Recovered
surface
model



Photometric Stereo



Input
(1 of 12)



Normals (RGB
colormap)



Normals (vectors)



Shaded 3D
rendering



Textured 3D
rendering

Video photometric stereo

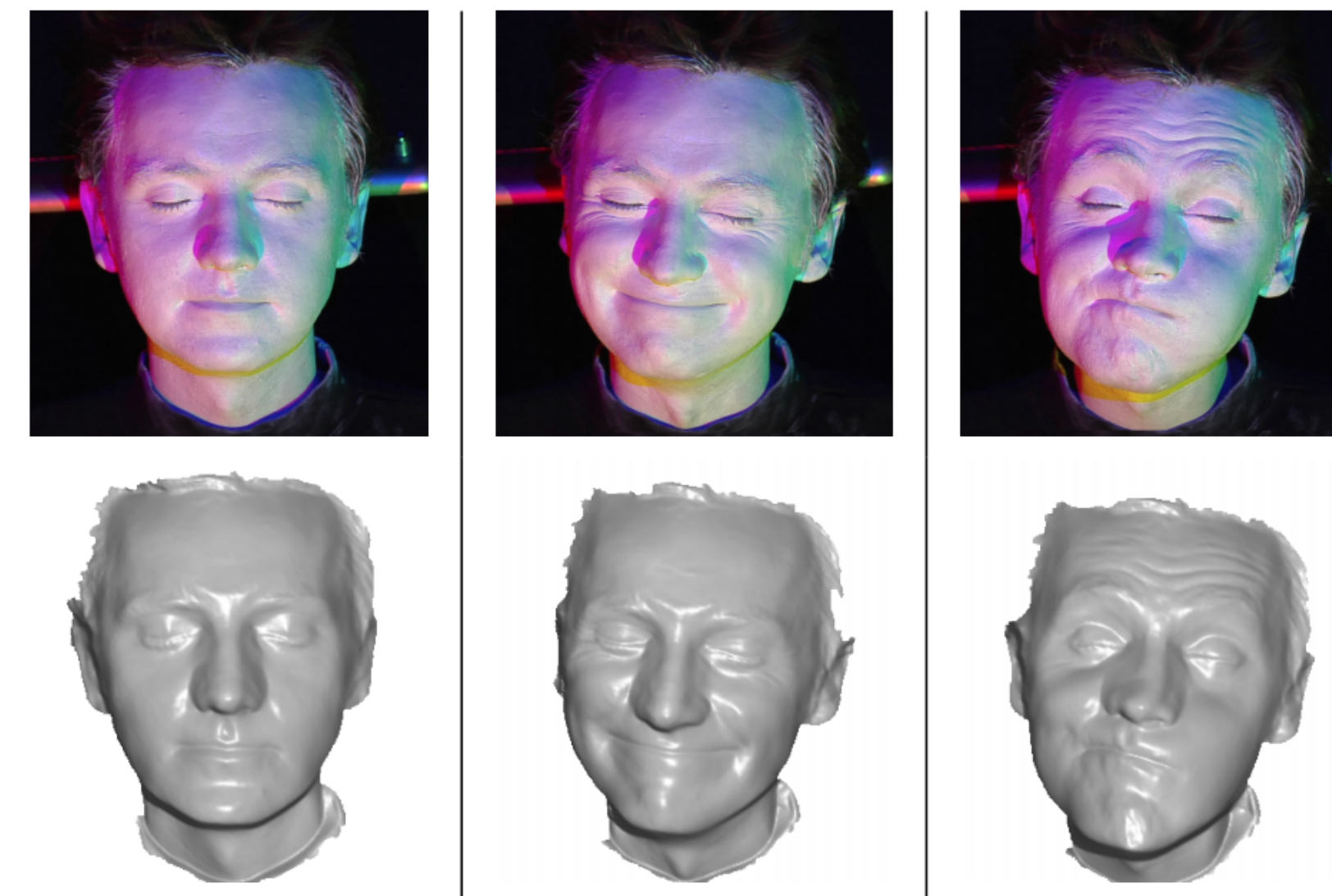
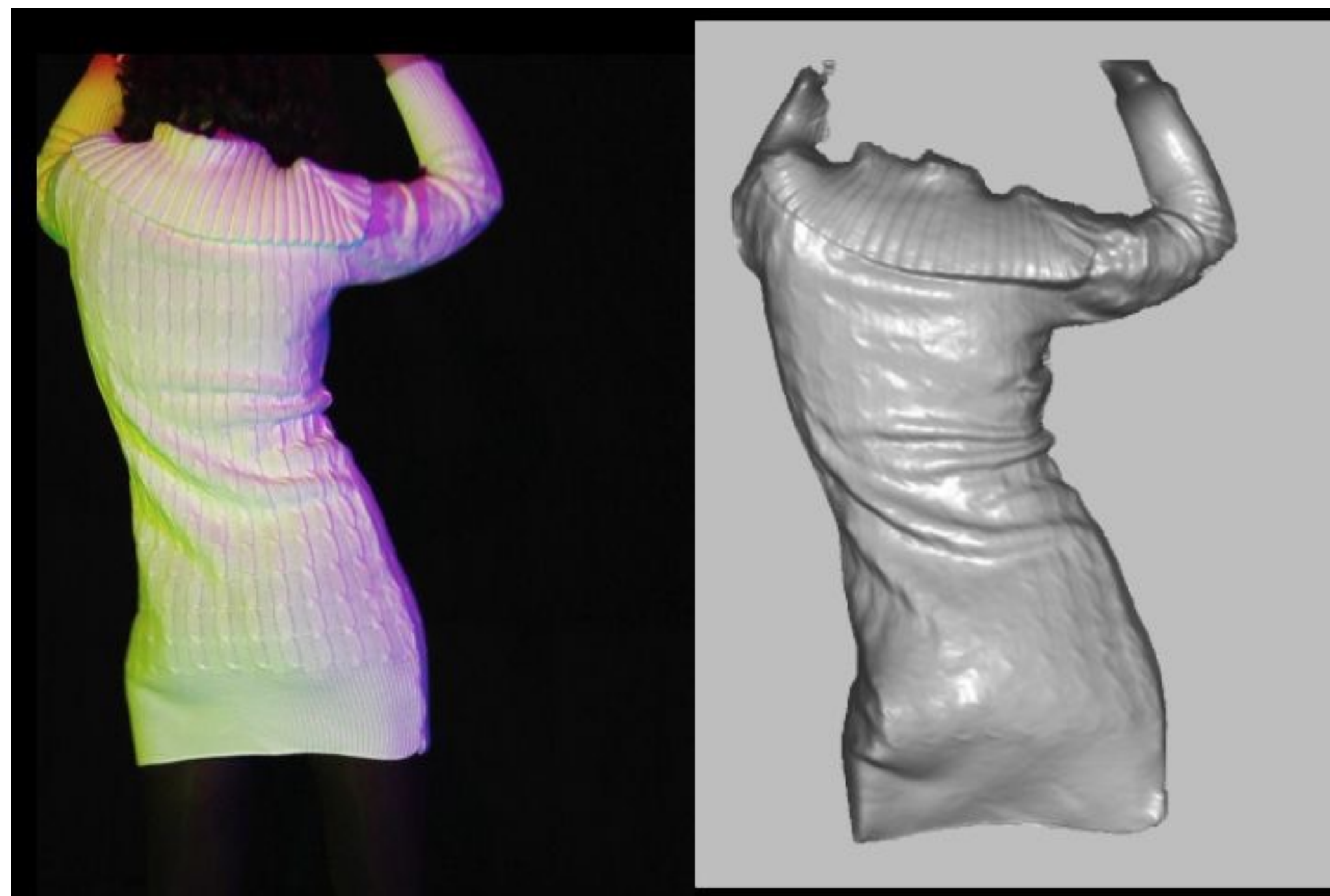
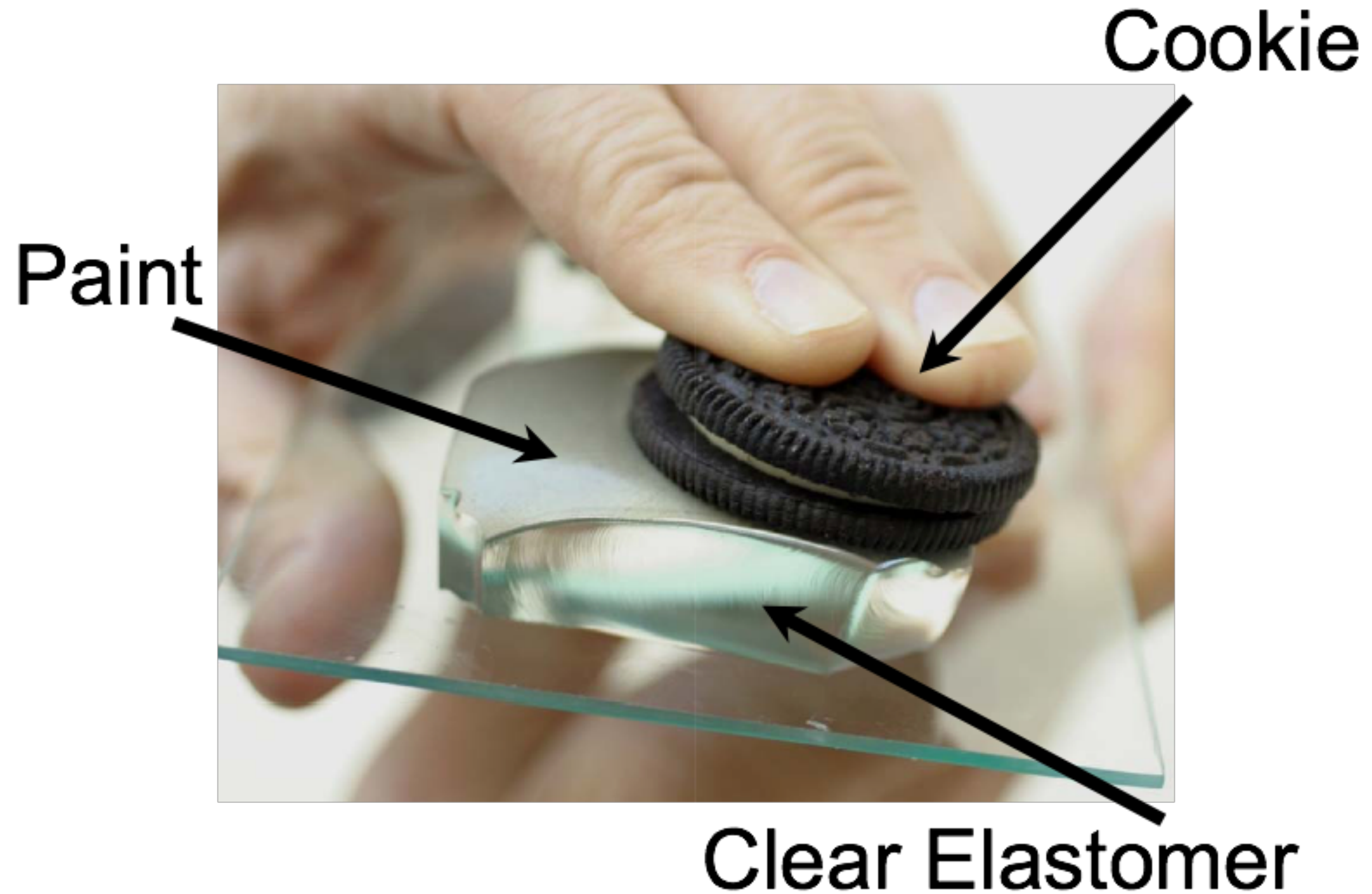


Fig. 2. Applying the original algorithm to a face with white makeup. Top: example input frames from video of an actor smiling and grimacing. Bottom: the resulting integrated surfaces.

What if we don't know the BRDF?



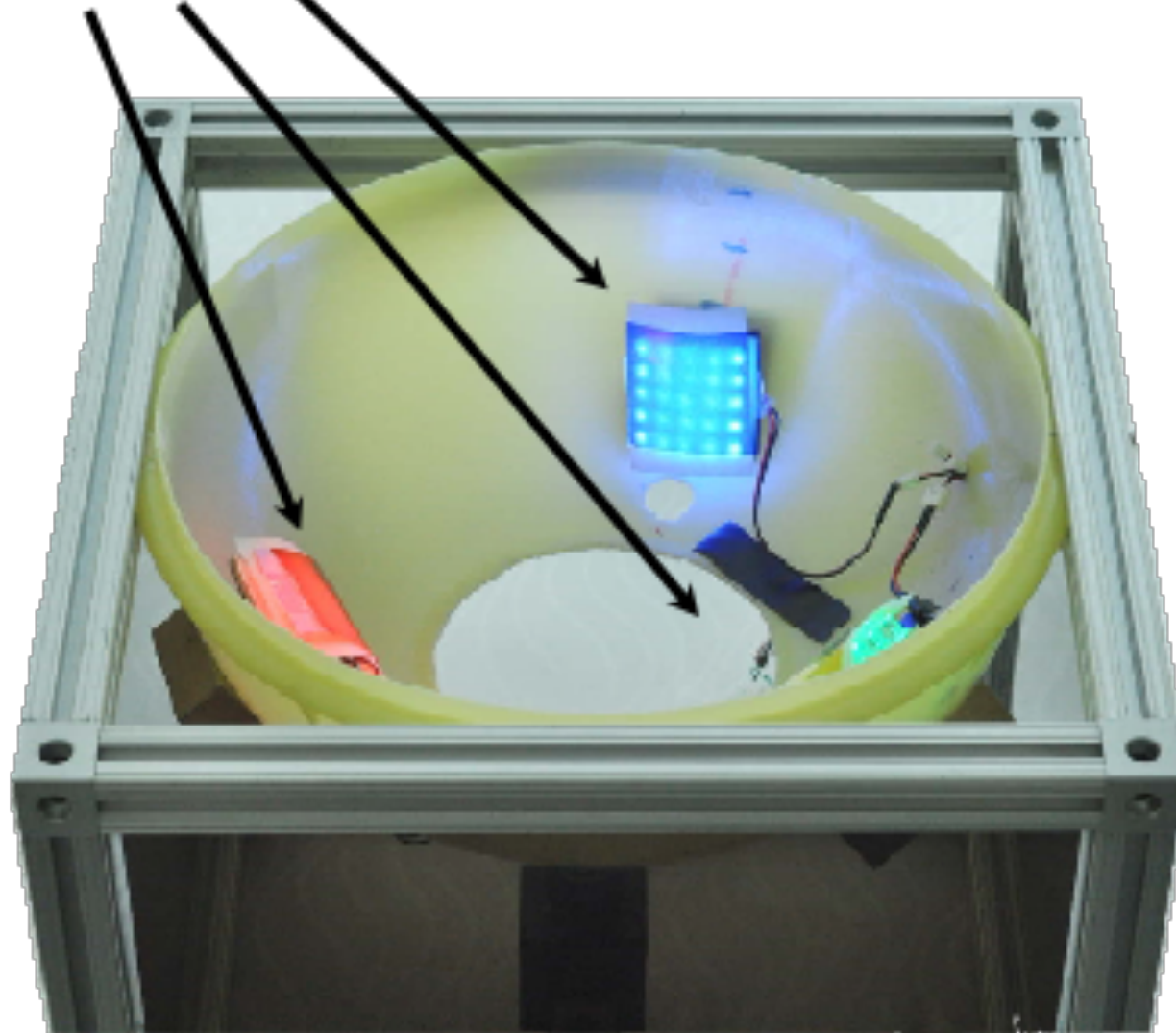
[Johnson and Adelson, 2009]



Sensor



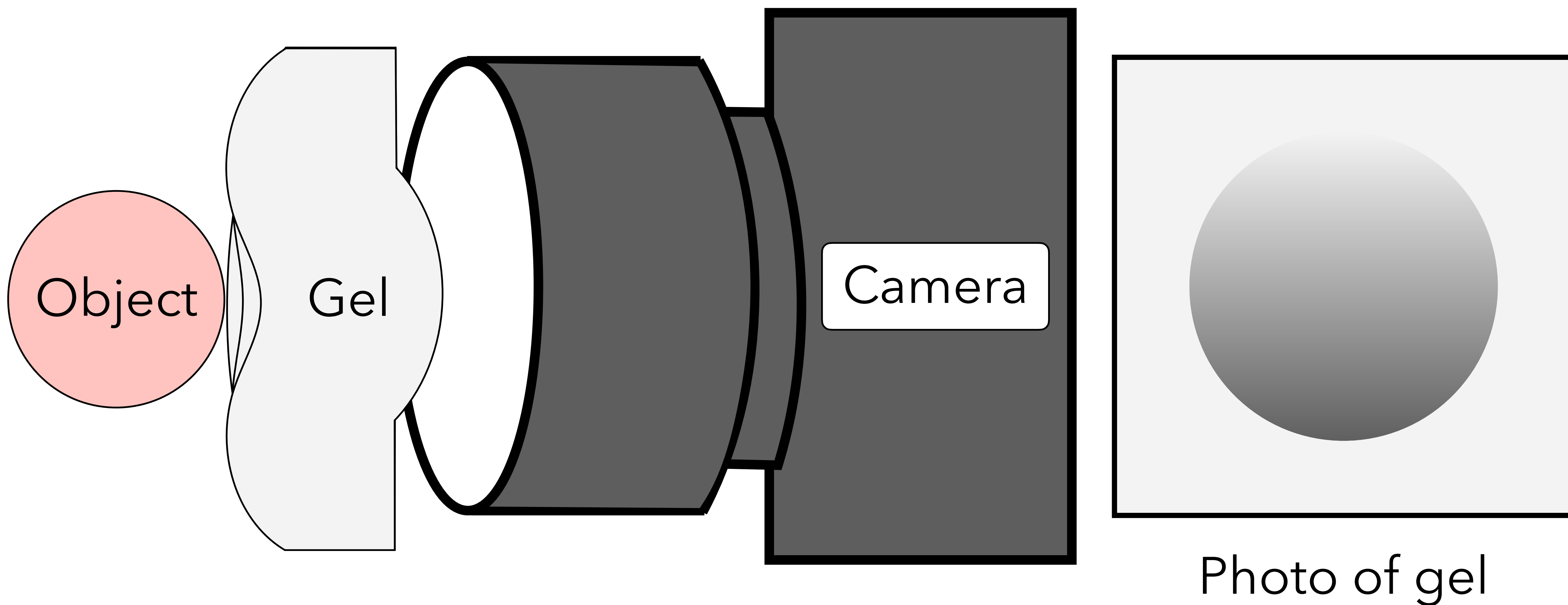
Lights



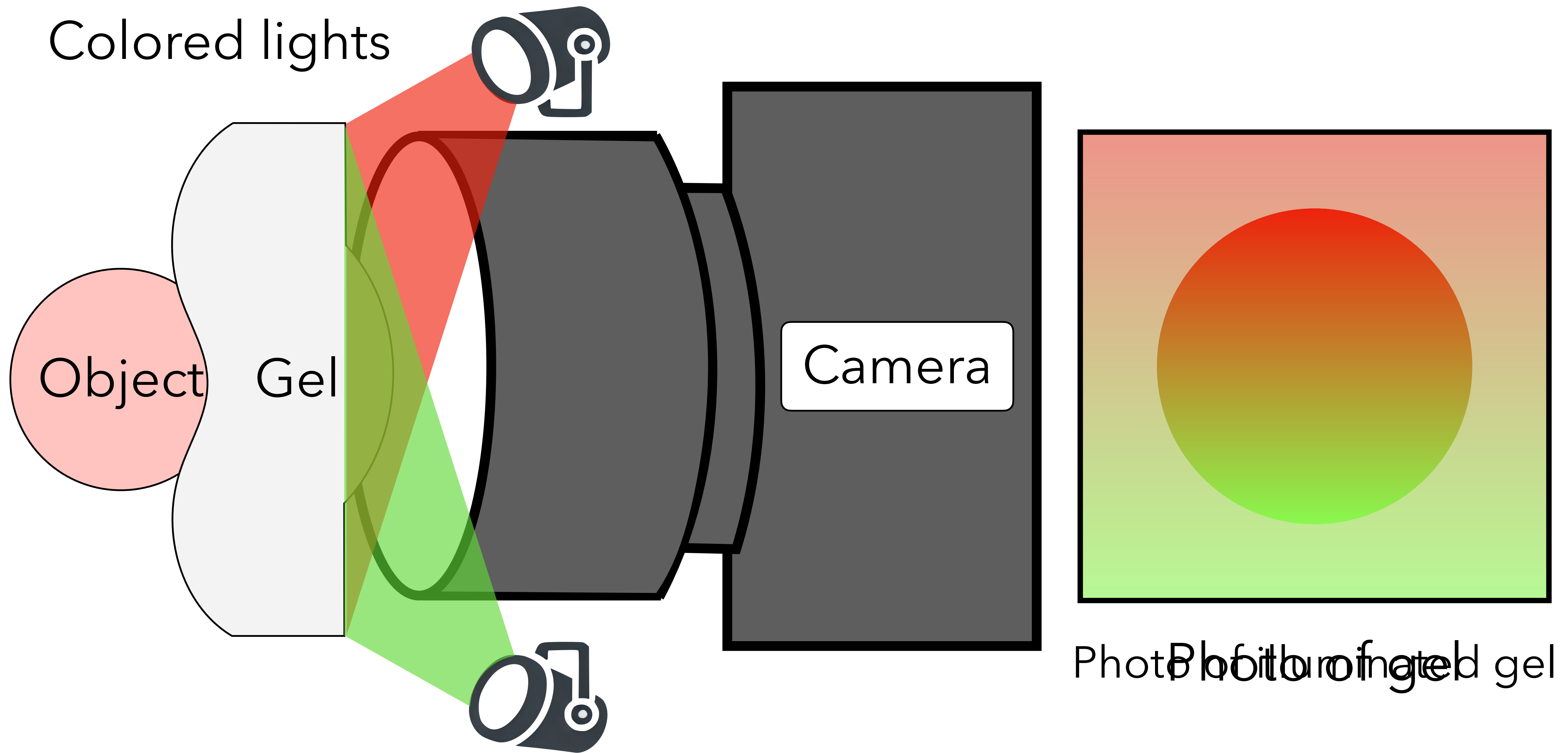
Camera



Photometric stereo reconstruction

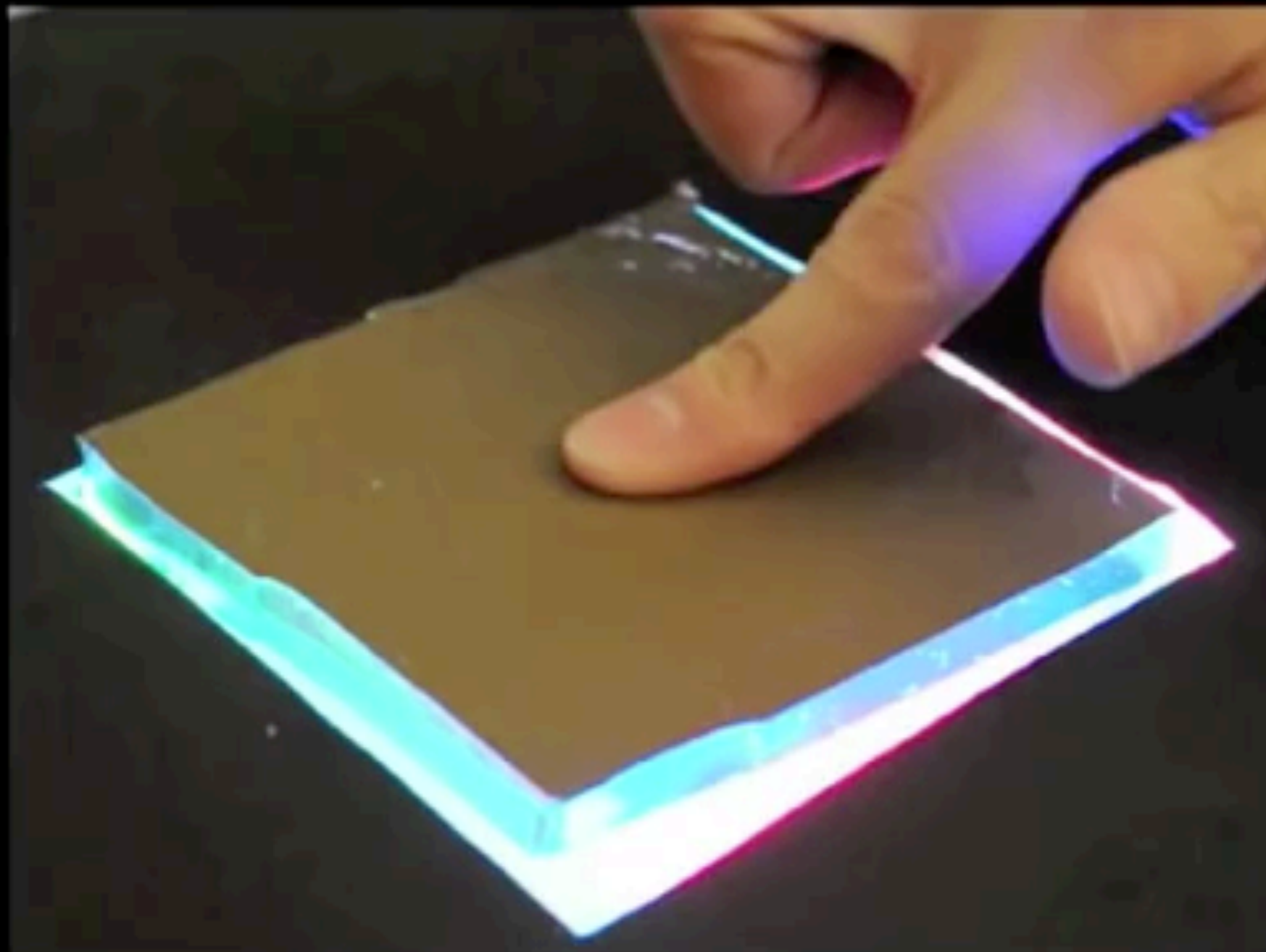


e.g., GelSight [Johnson and Adelson, 2009], [Yuan et al., 2017]

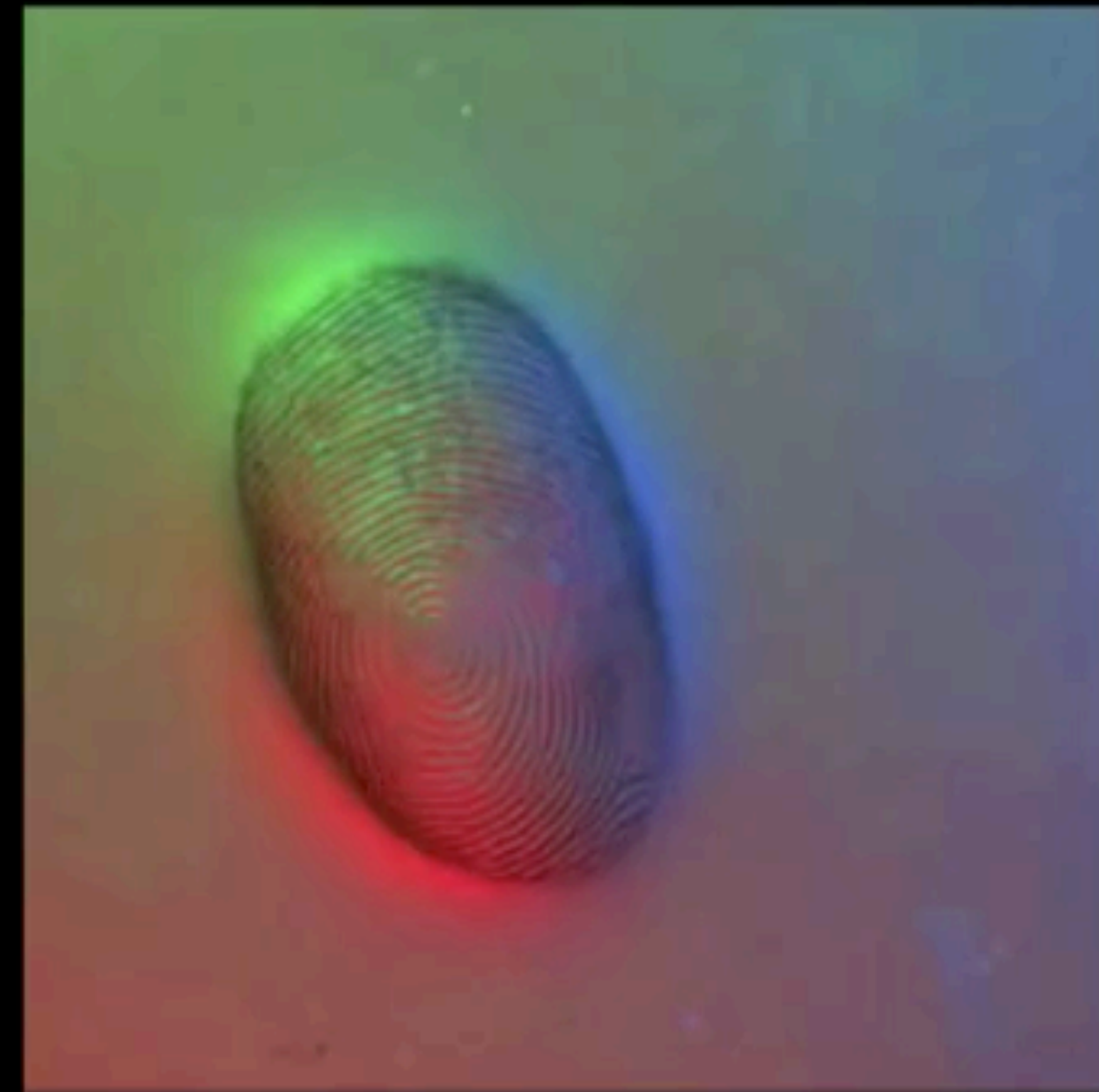


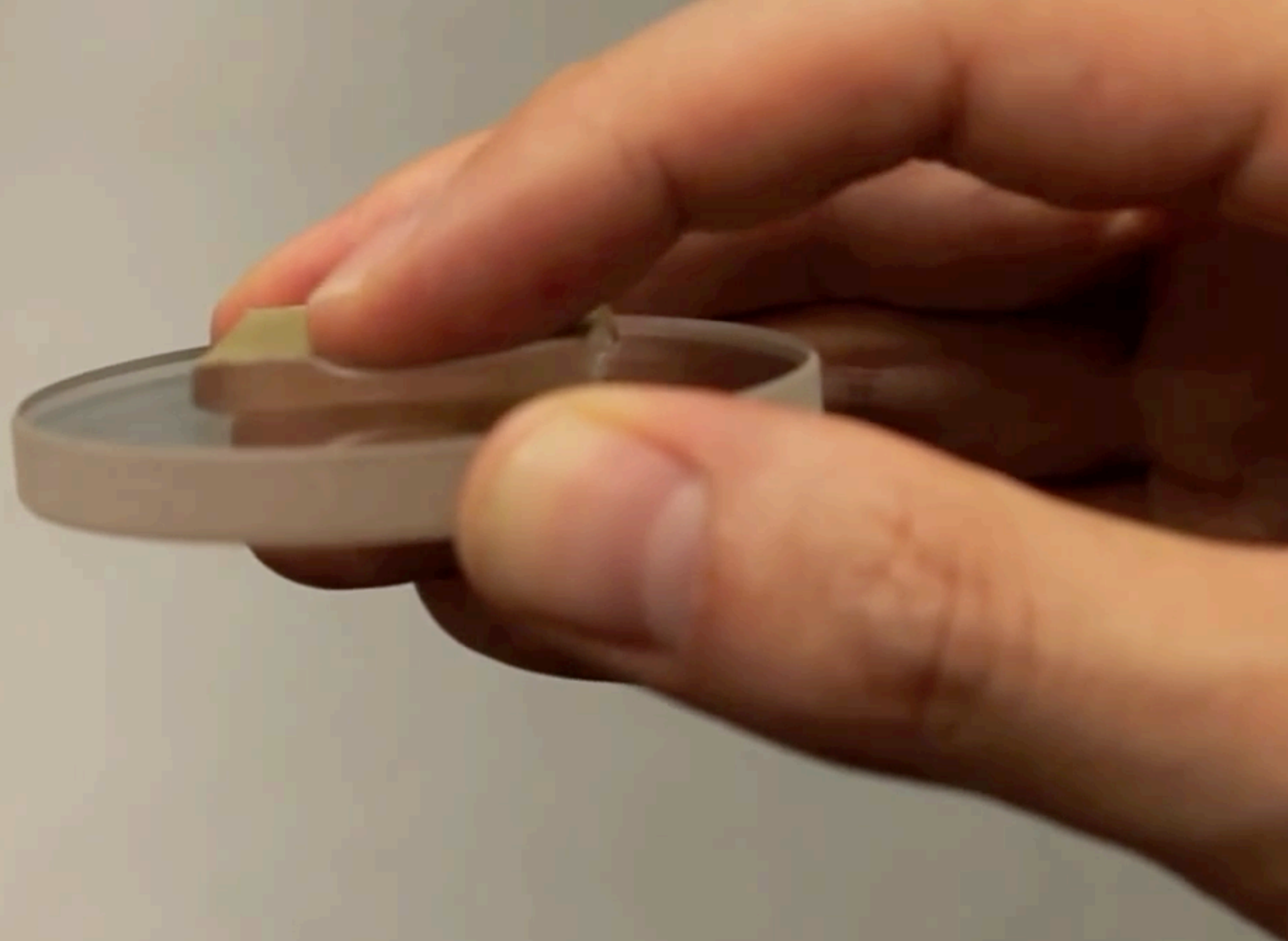
e.g., GelSight [Johnson and Adelson, 2009], [Yuan et al., 2017]

Sensor

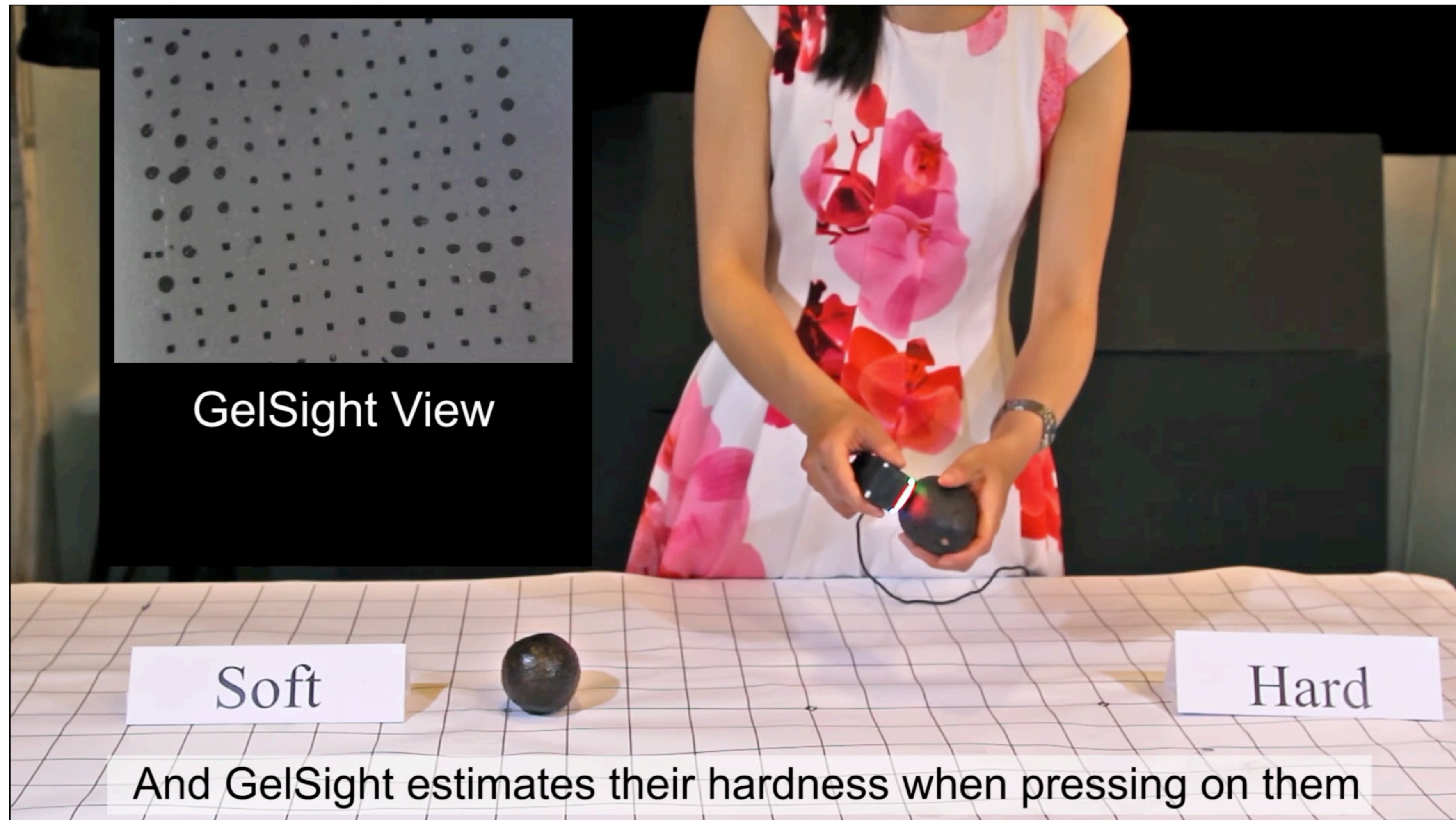


Camera View





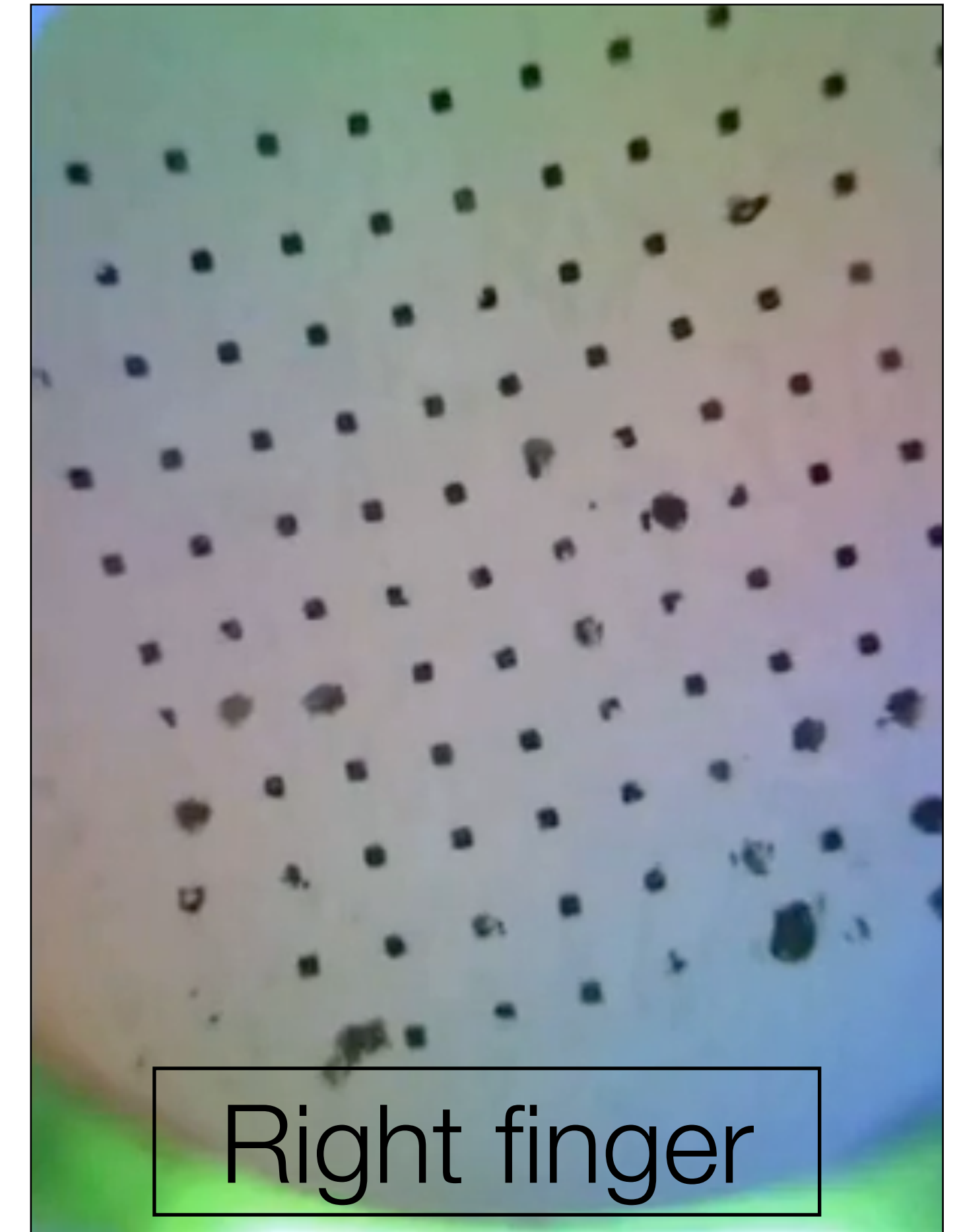
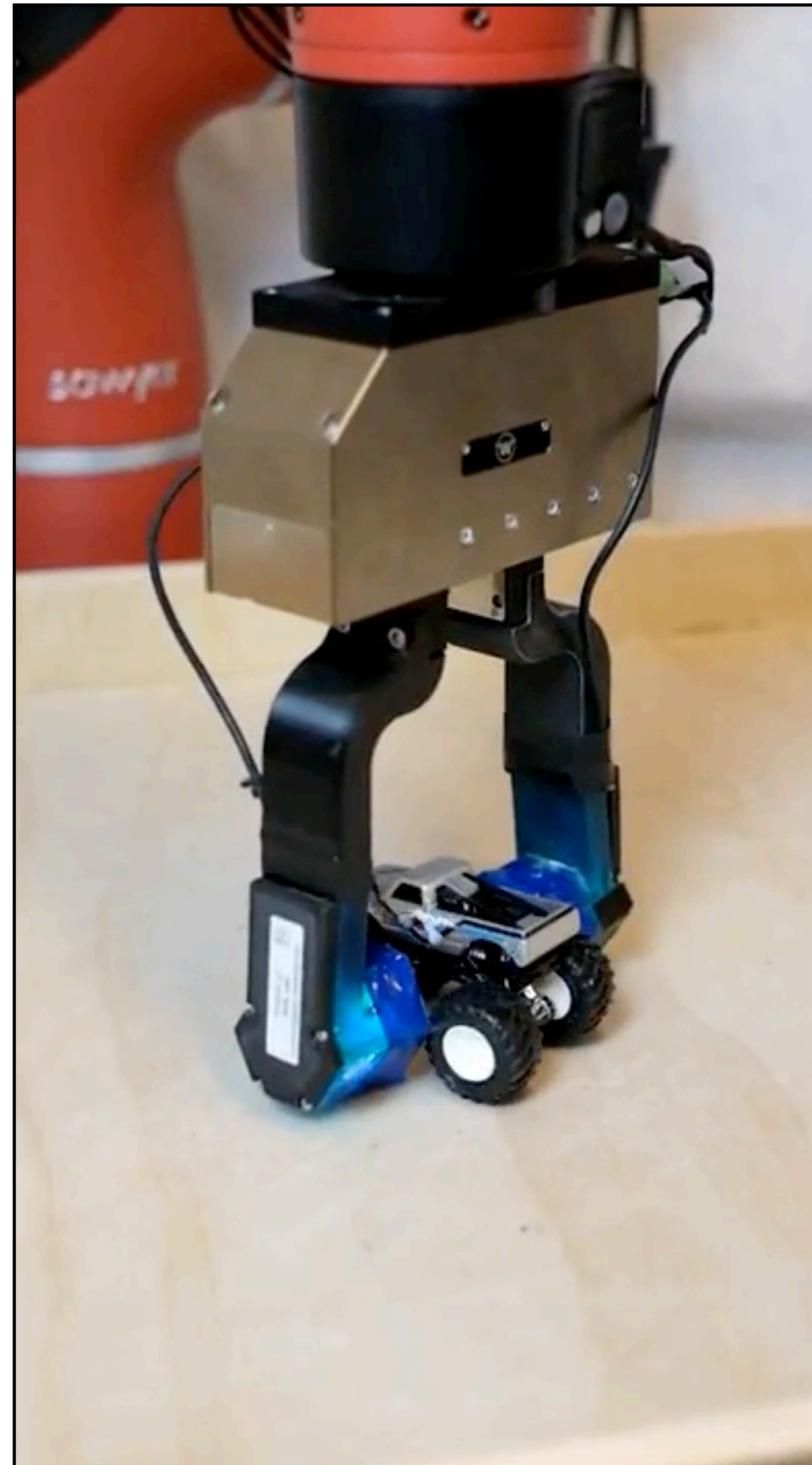
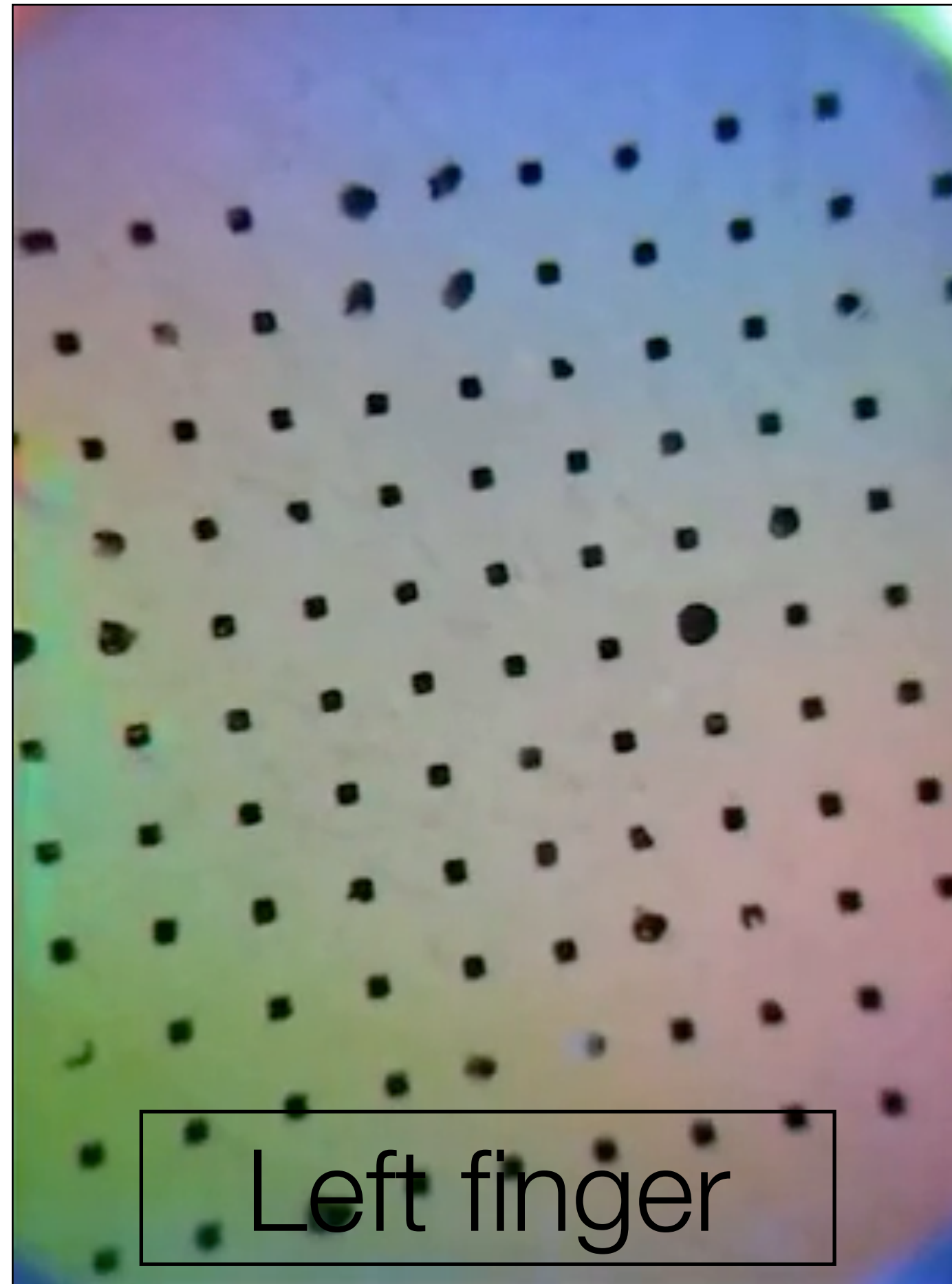
Vision-based touch sensing



GelSight [Johnson and Adelson, 2009], [Yuan et al., 2017]

Example from [Yuan, Zhu, Owens, Srinivasan, Adelson, "Shape-independent Hardness Estimation...", ICRA 2017]

Robotic touch



Today

- Shape from shading
- **Intrinsic image decomposition**
- Color perception

What about paint?



$$I = k_d \mathbf{N} \cdot \mathbf{L}$$

k_d is **reflectance** or **albedo**

Intrinsic image decomposition

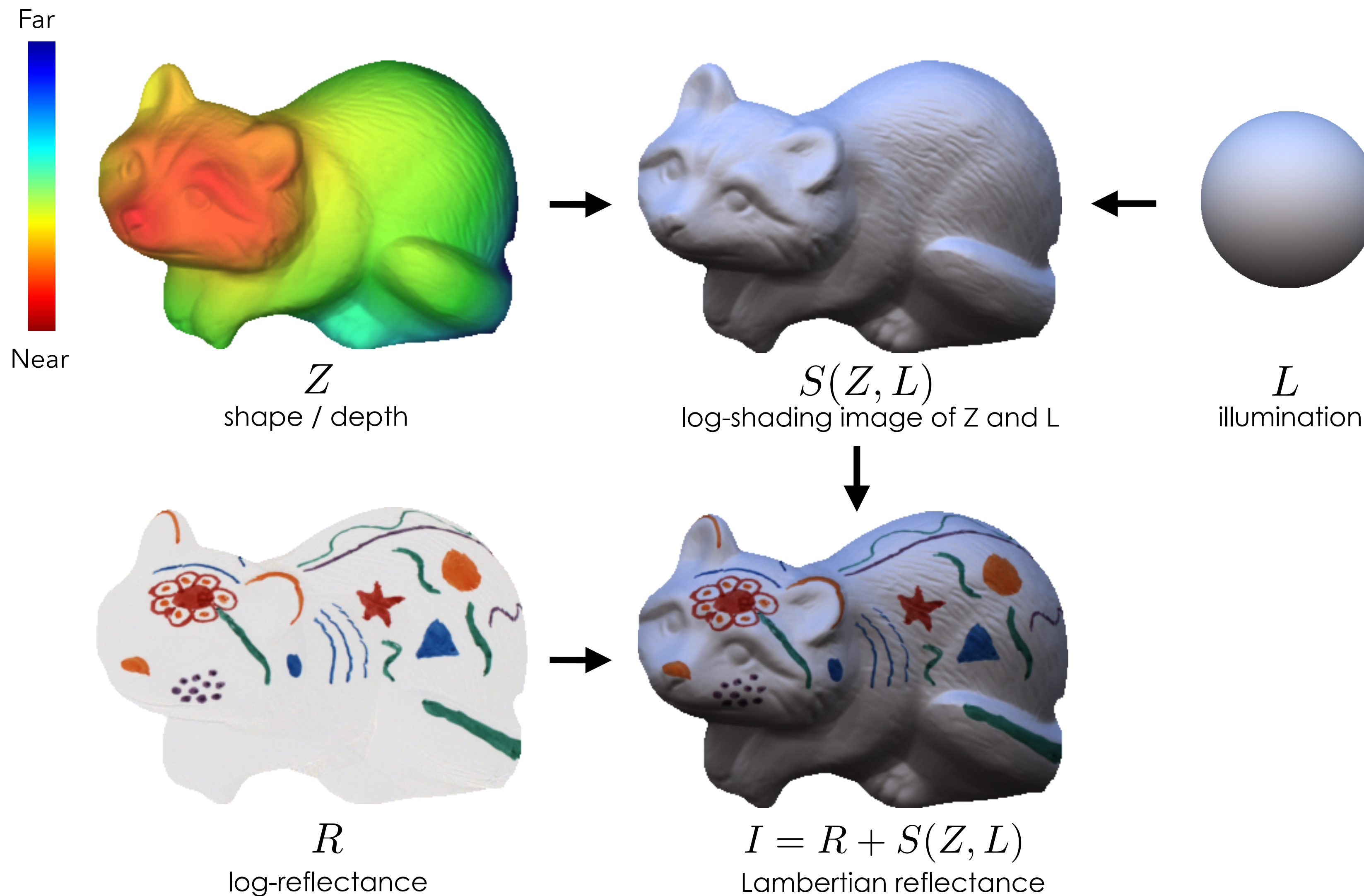


Reflectance

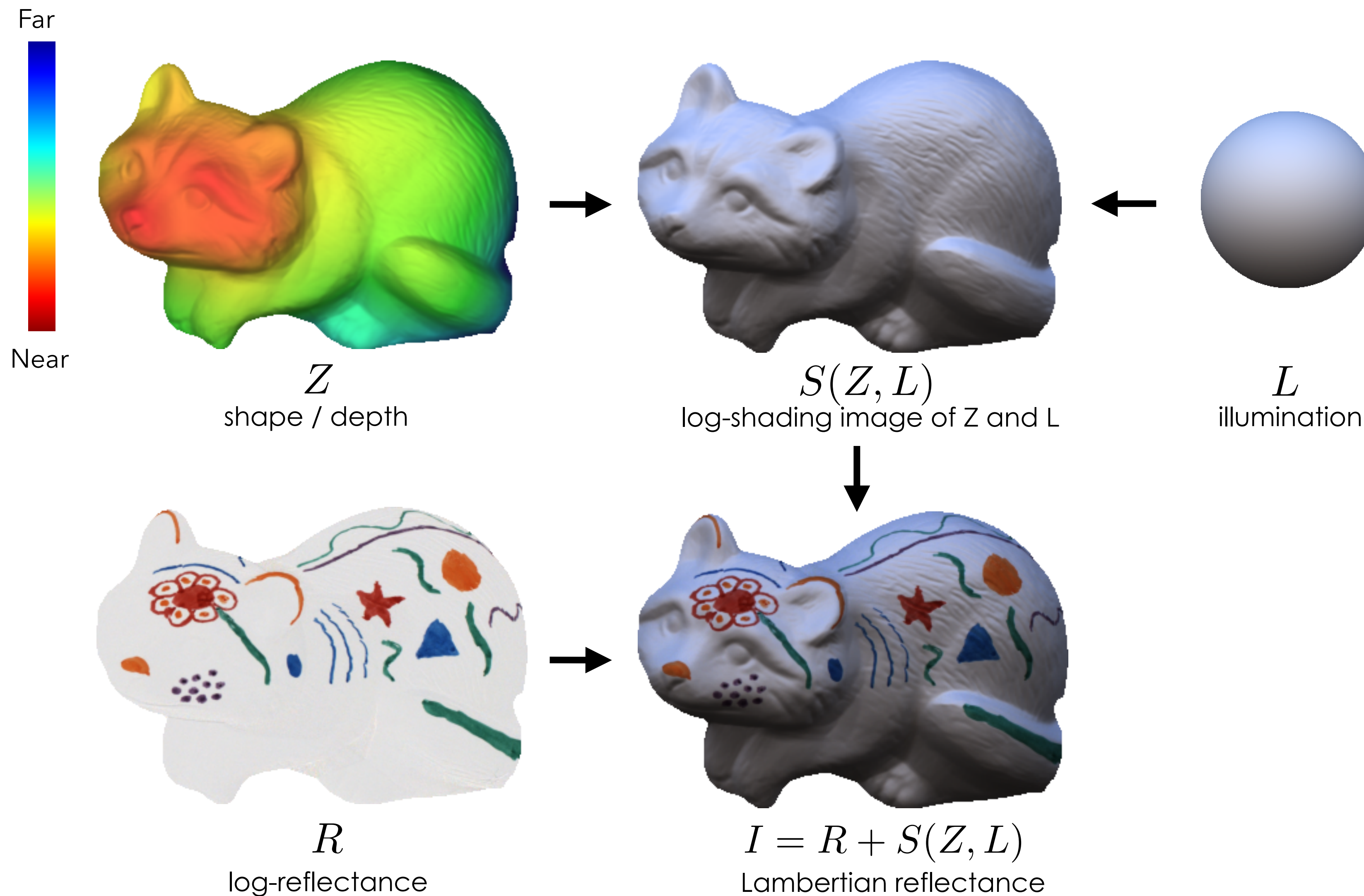


Shading

Intrinsic image decomposition



Intrinsic image decomposition



Retinex: keep only large magnitude edges



Input



Estimated reflectance

CNN-based reflectance estimation

Input



Reflectance



Shading



[Bell et al., "Intrinsic images in the wild", 2014]

Applications of intrinsic image decomposition

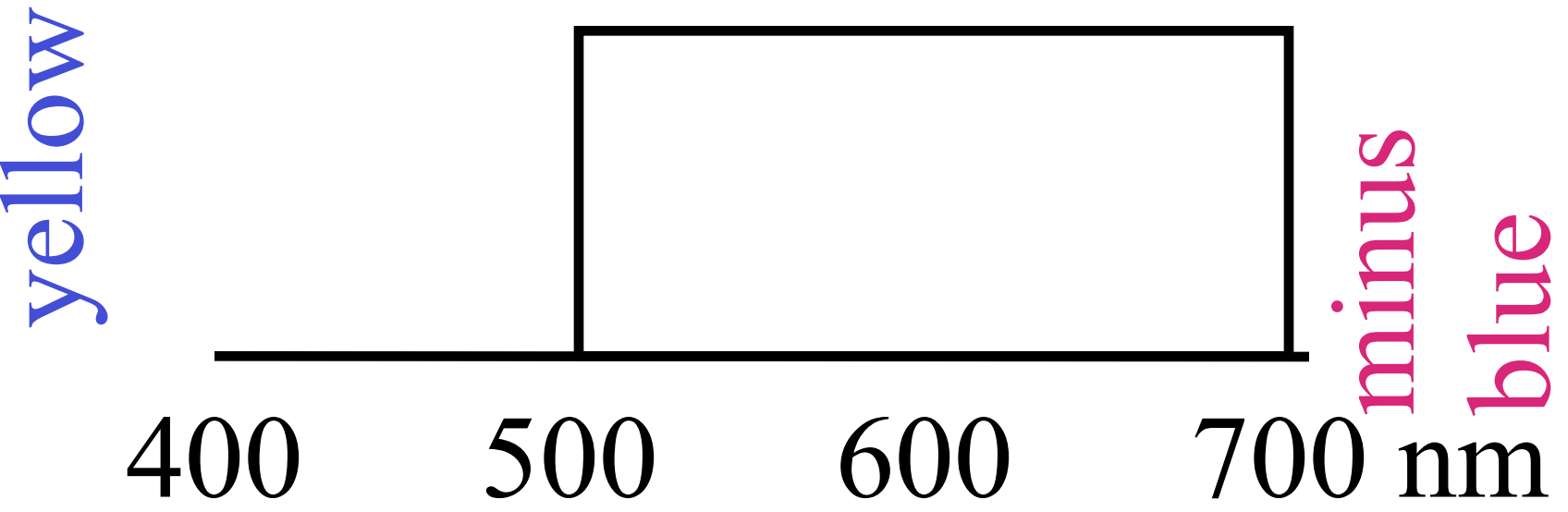
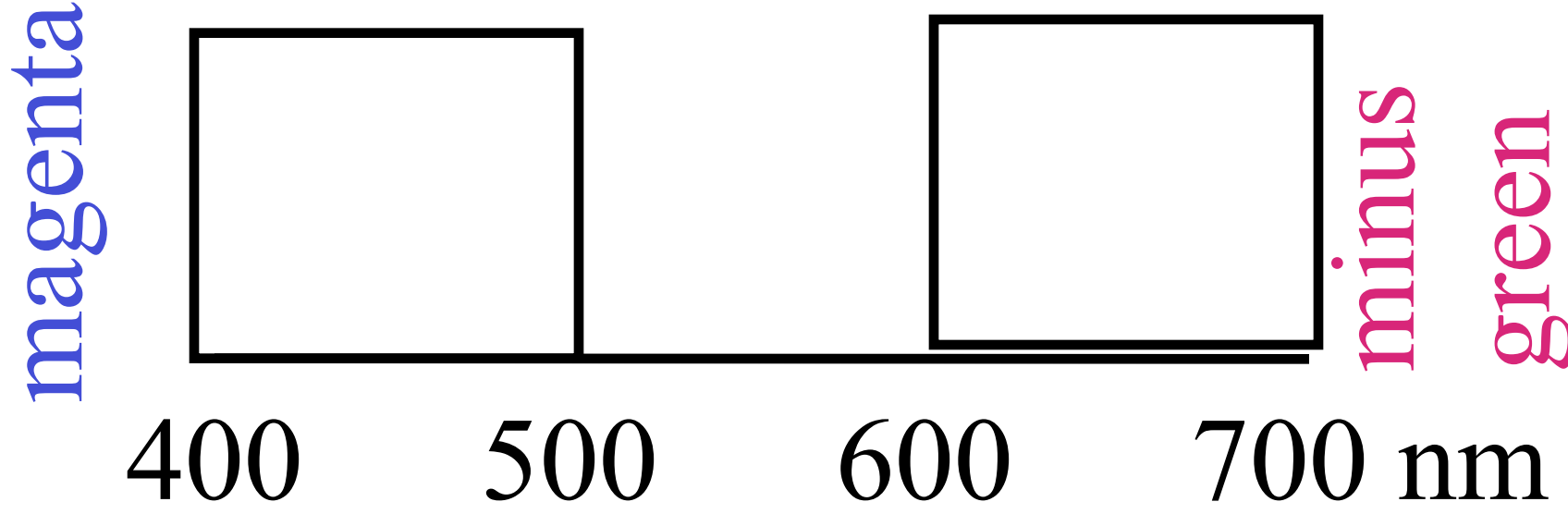
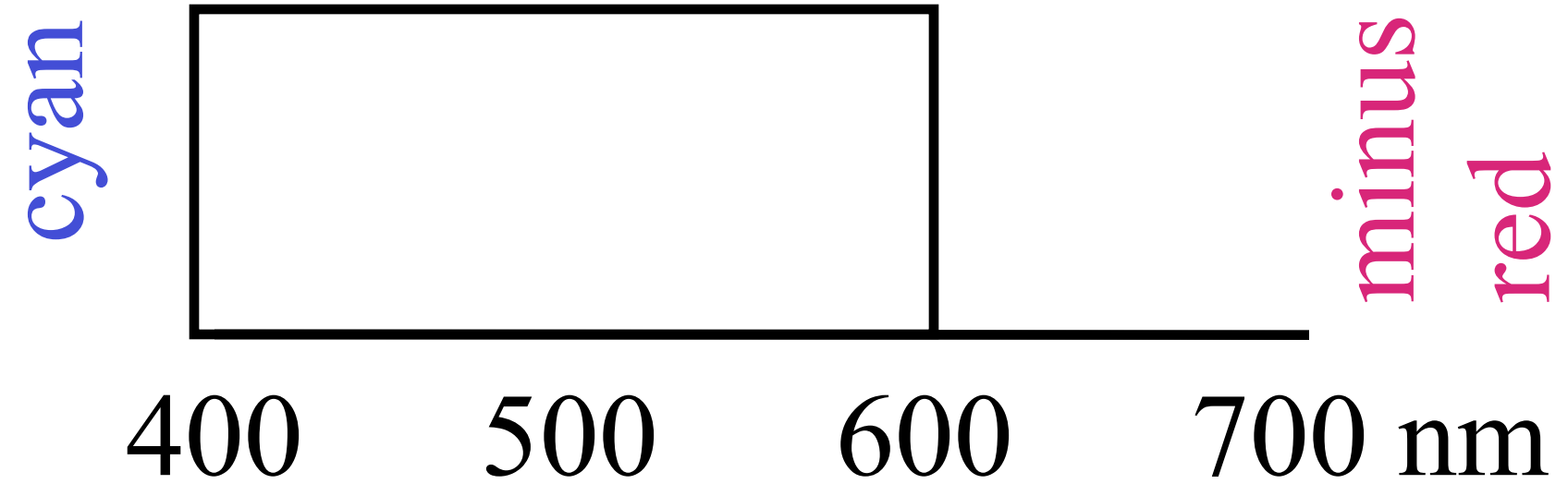
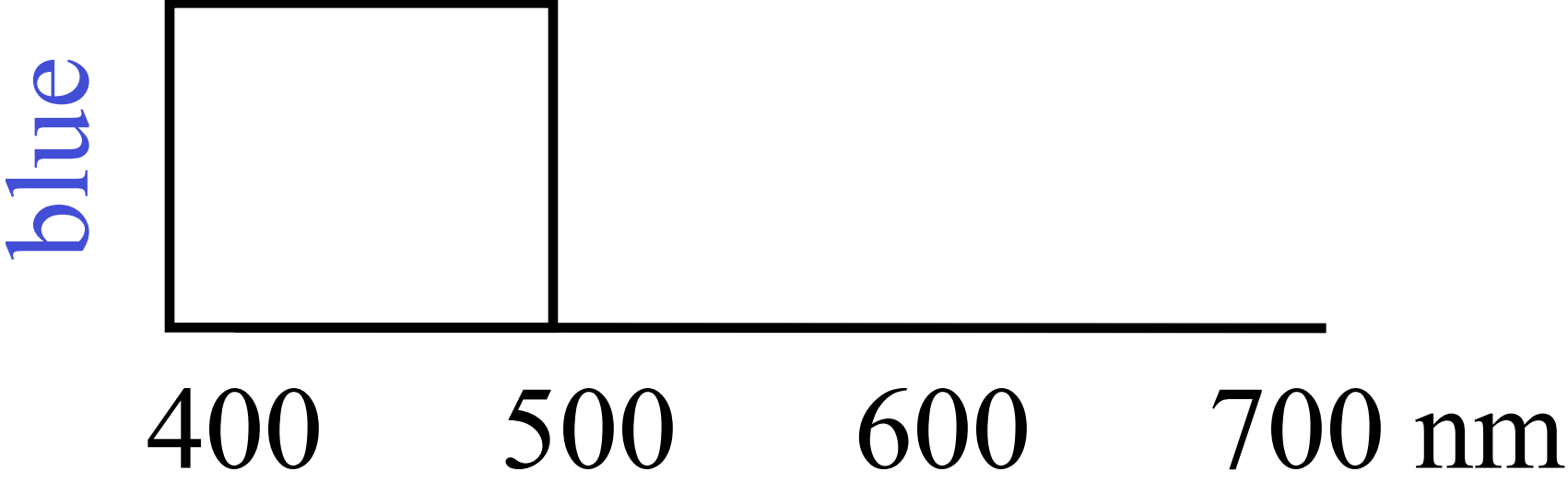
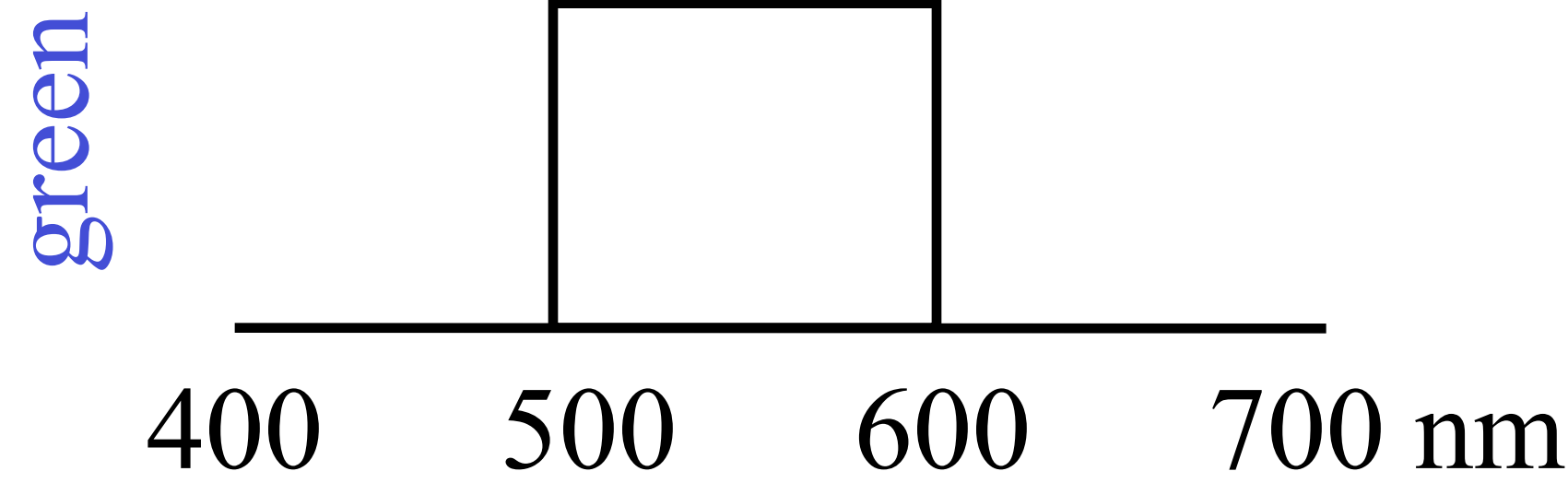
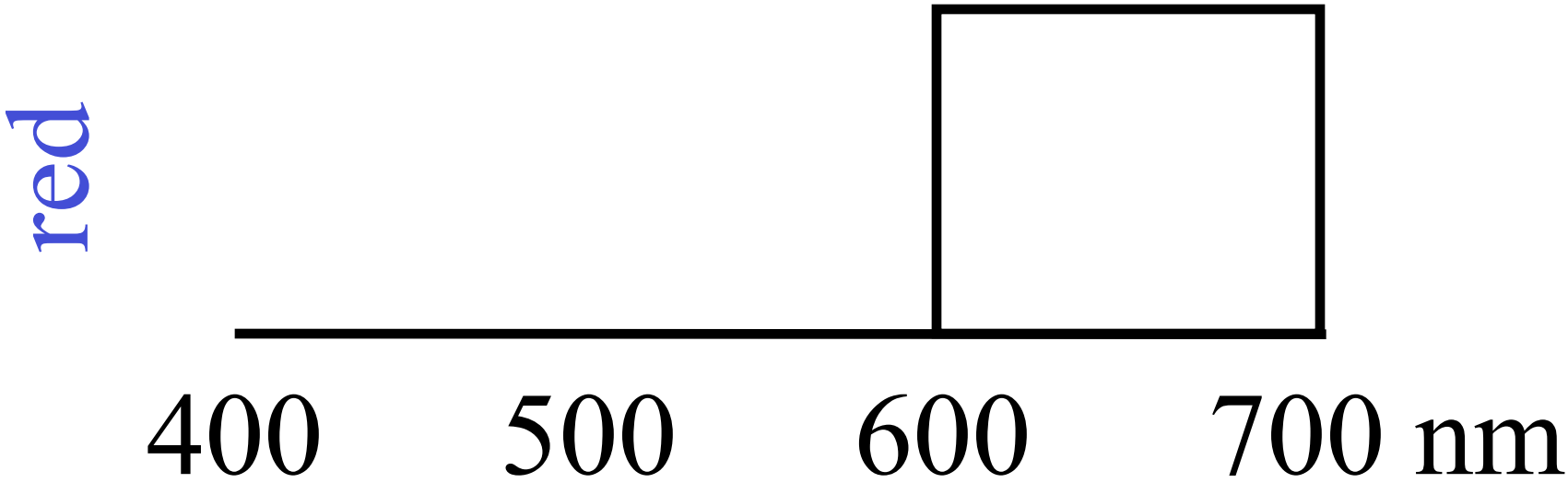
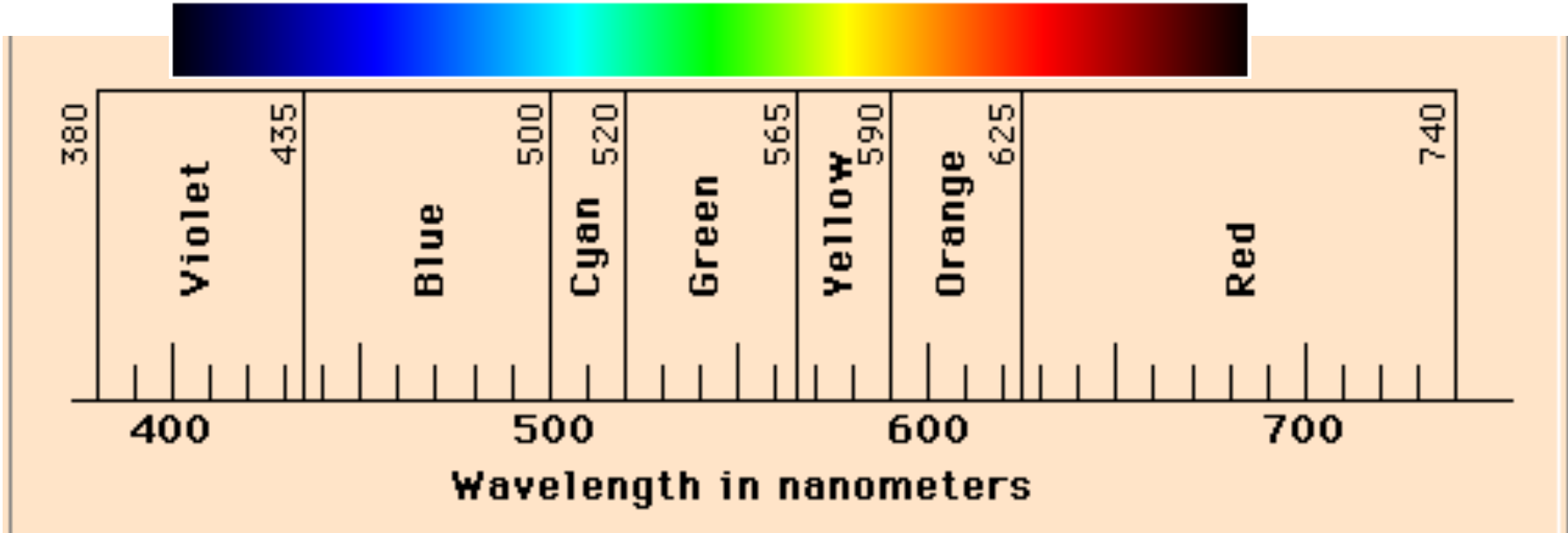


[Barron and Malik "SIRFS", 2012]

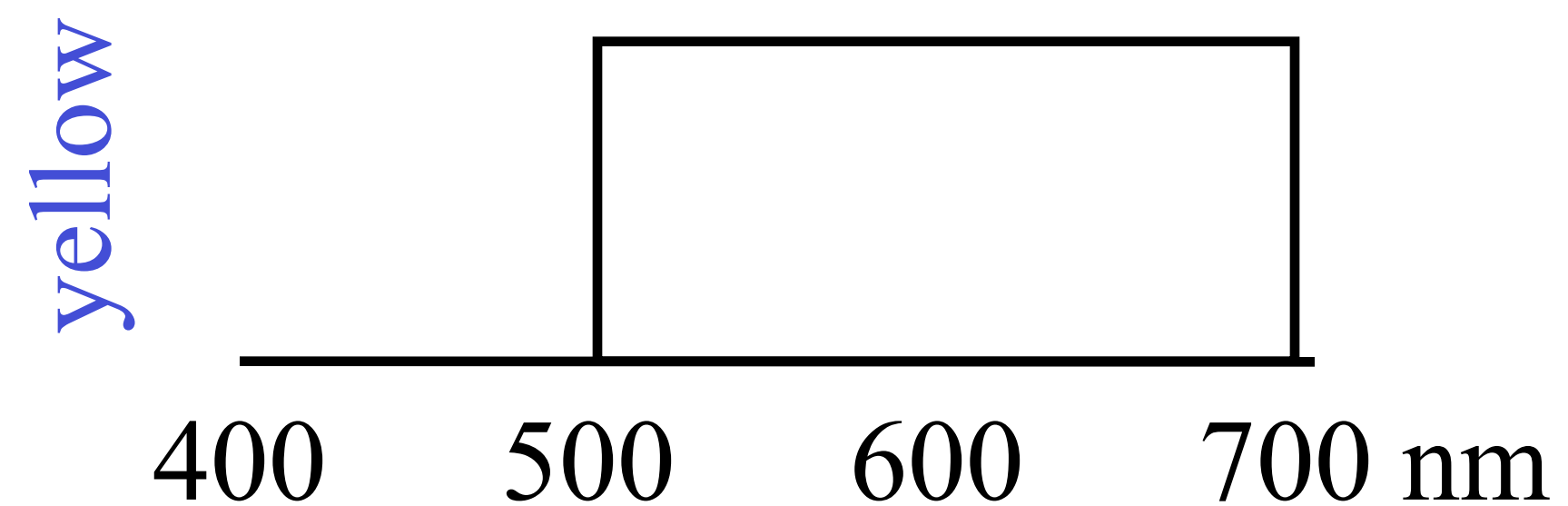
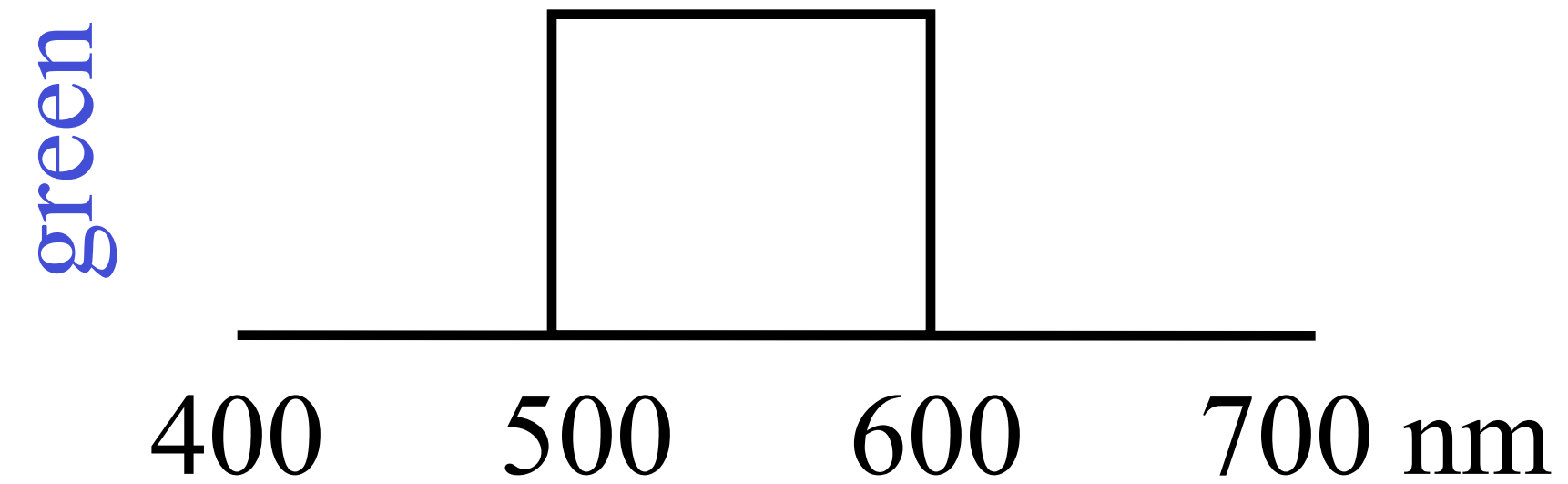
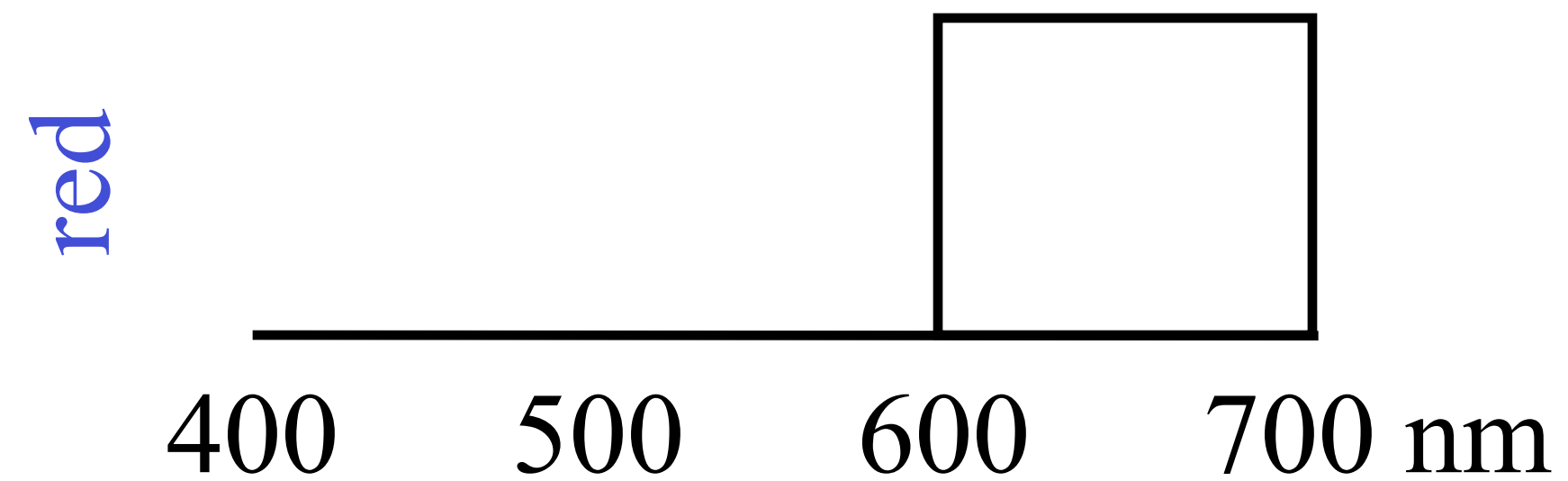
Today

- Shape from shading
- Intrinsic image decomposition
- **Color perception**

Color names for cartoon spectra



Additive color mixing



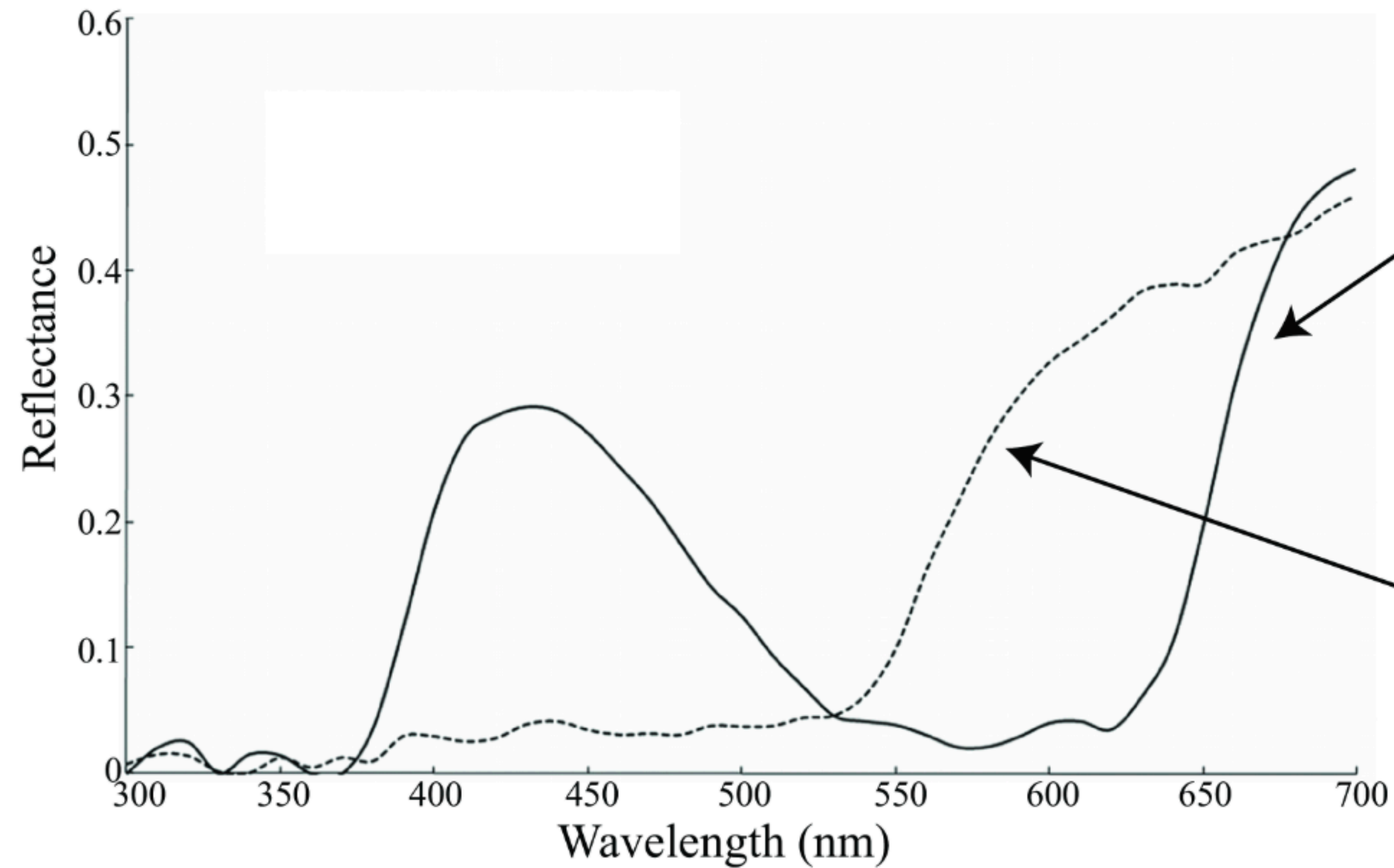
When colors combine by *adding* the color spectra.

Example color displays that follow this mixing rule: CRT phosphors, multiple projectors aimed at a screen.

Red and green make...

Yellow!

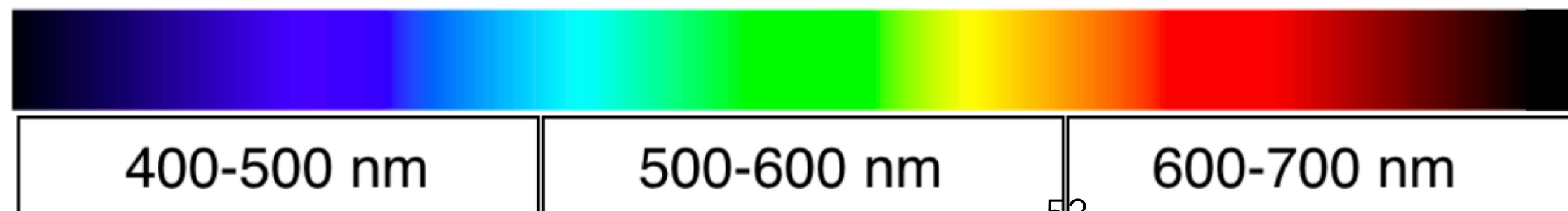
Real-world spectra



Hepatica nobilis



Pyrostegia venusta



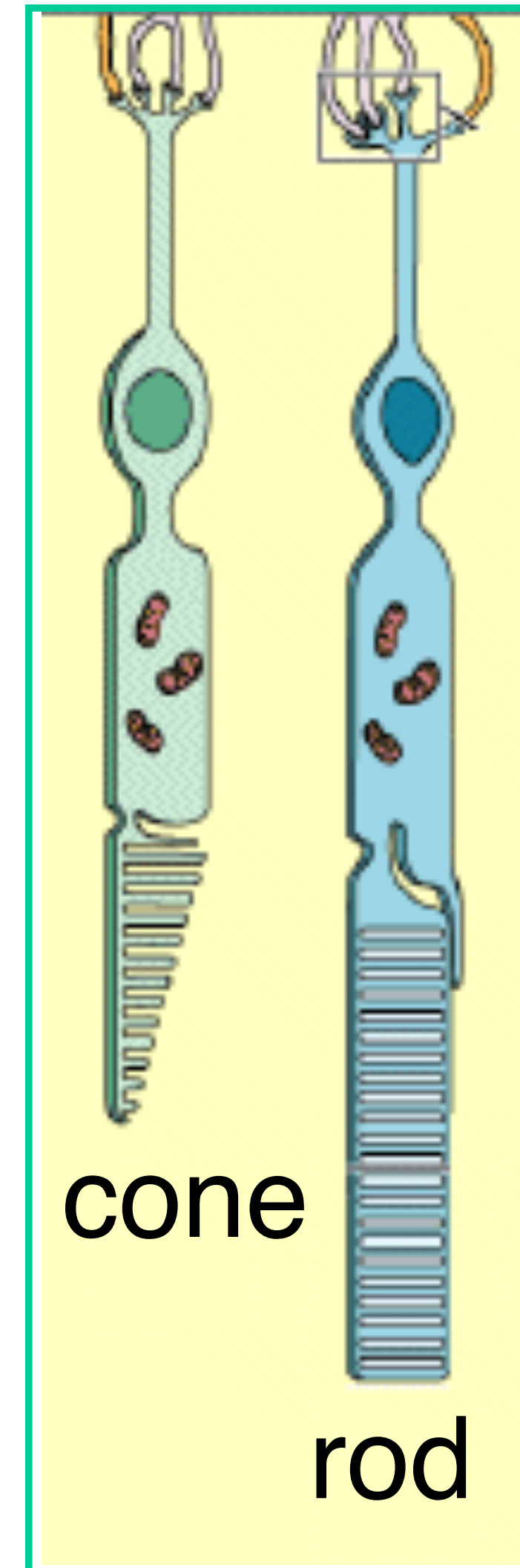
How is color perceived in the eye?

Cones

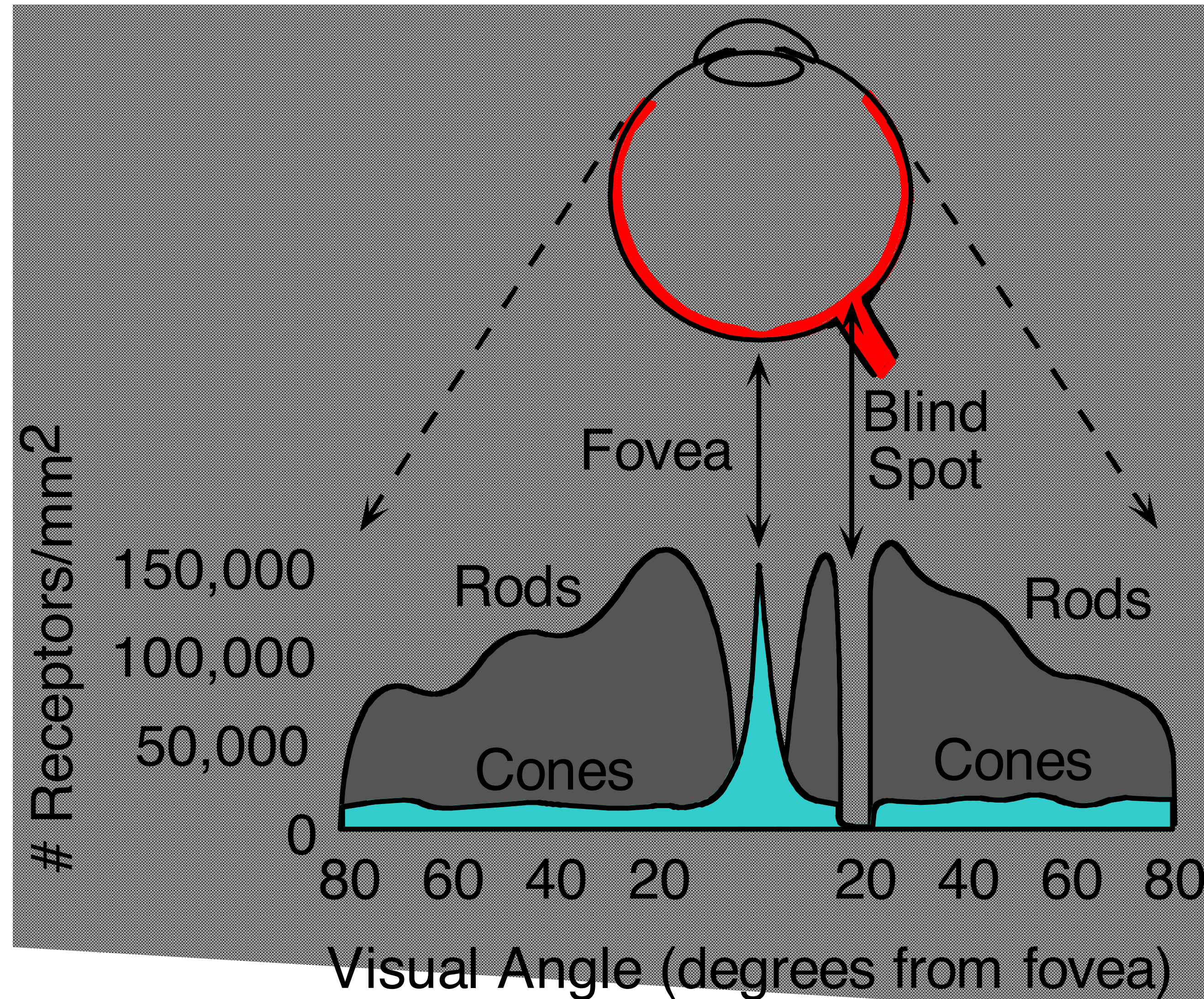
cone-shaped
less sensitive
operate in high light
color vision

Rods

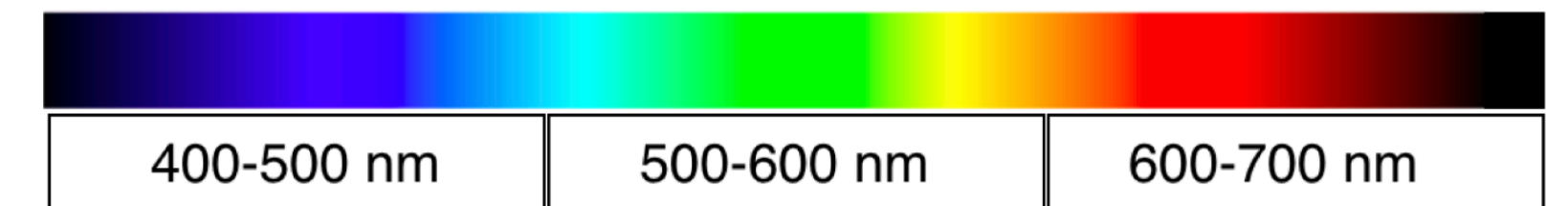
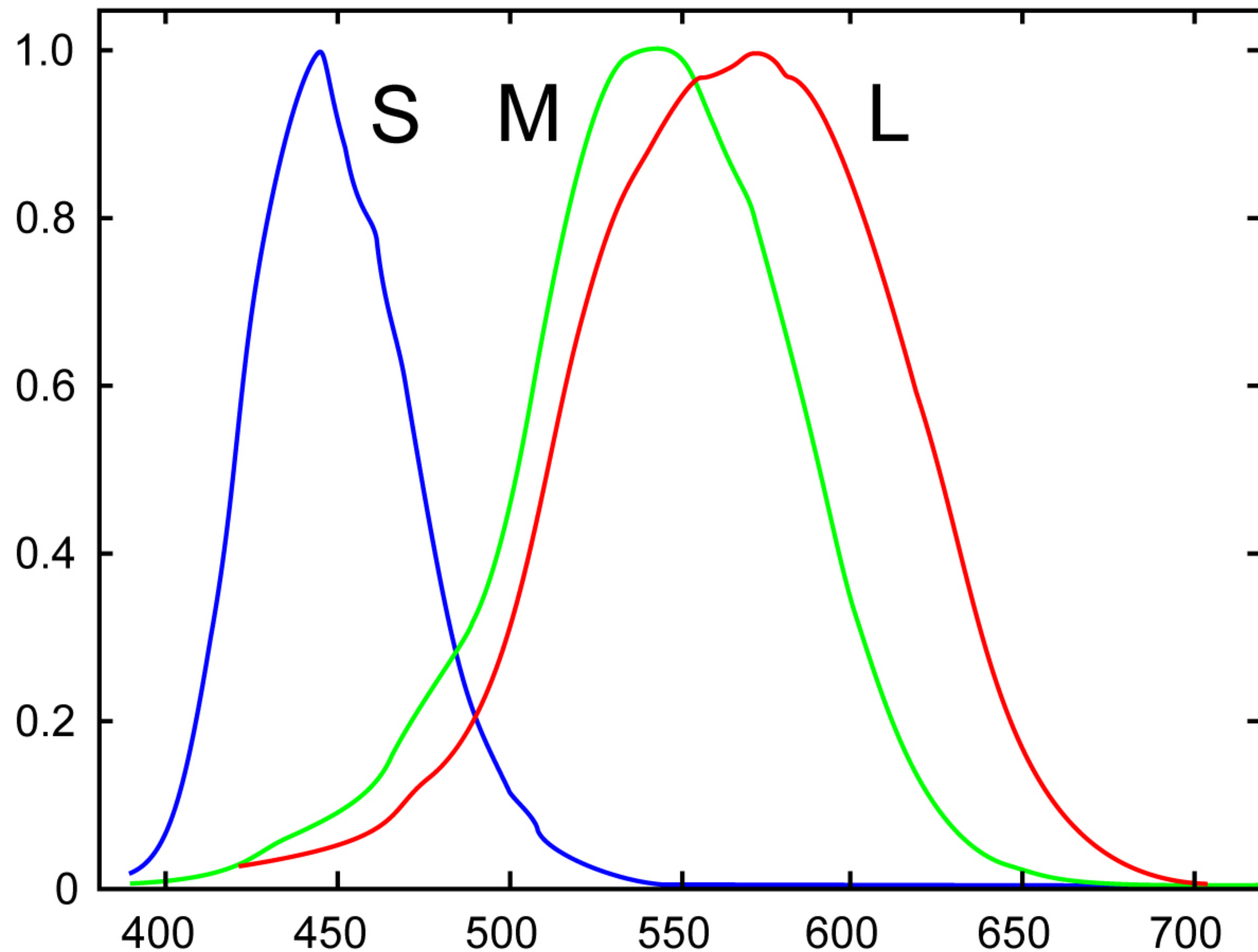
rod-shaped
highly sensitive
operate at night
gray-scale vision



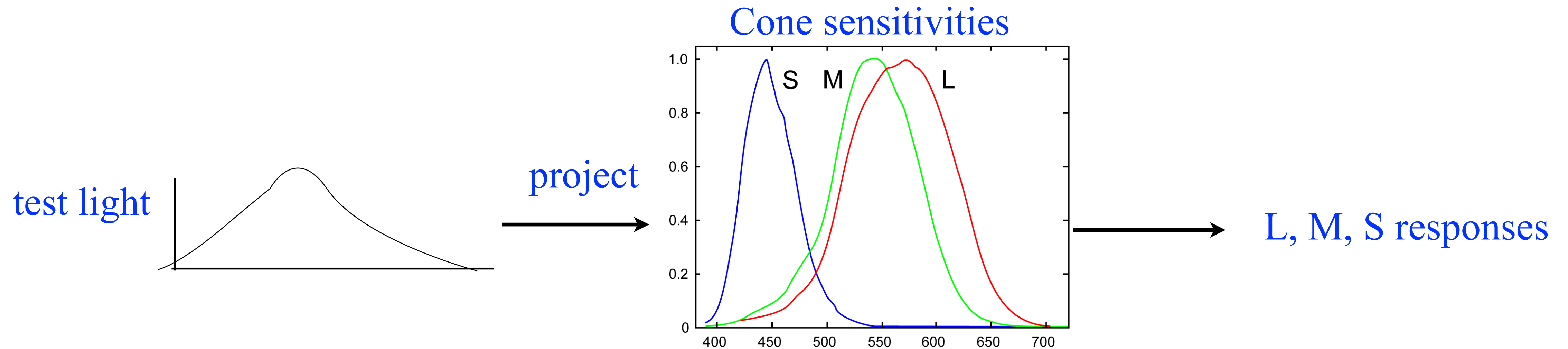
Distribution of Rods and Cones



Human eye photoreceptor spectral sensitivities



How we sense light spectra



Biophysics: integrate the response over all wavelengths, weighted by the photosensor's sensitivity at each wavelength.

Mathematically: take dot product of input spectrum with the cone sensitivity basis vectors. Project the high-dimensional test light into a 3D space.

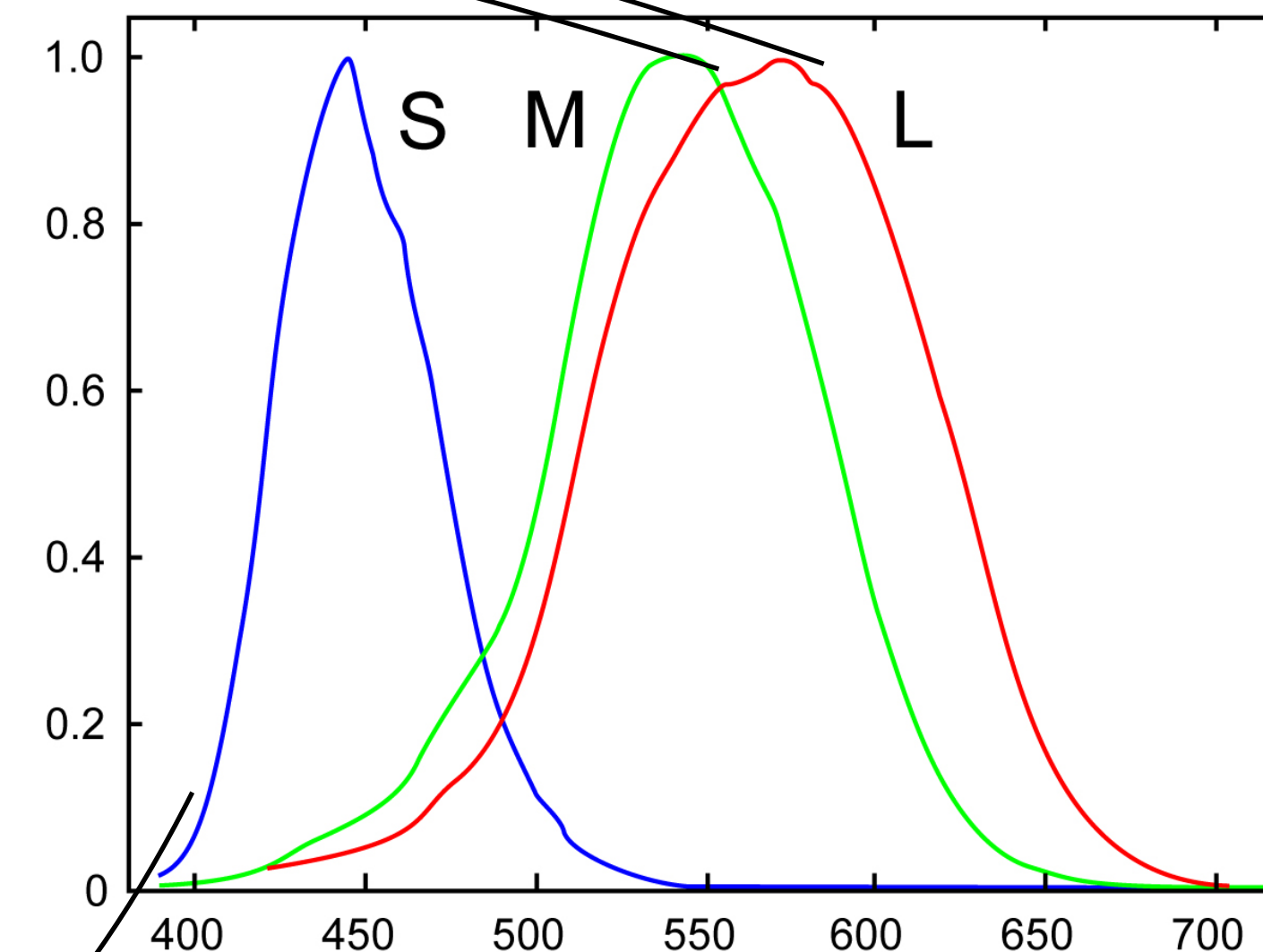
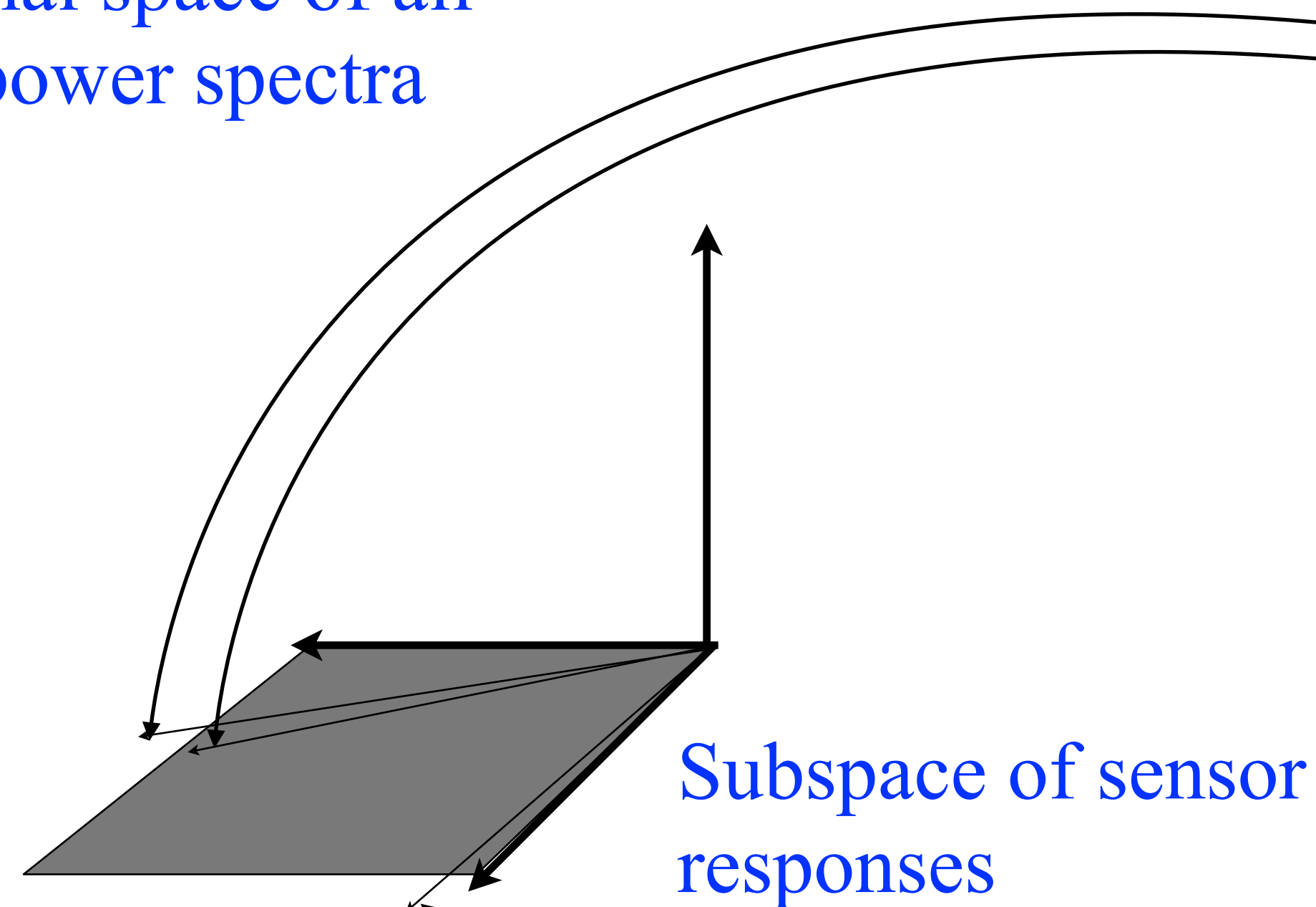
$$R = C t$$

$\begin{bmatrix} R \end{bmatrix} = \begin{bmatrix} C \end{bmatrix} * \begin{bmatrix} t \end{bmatrix}$

 cone responses = cone sensitivities * input spectrum

Cone response curves as basis vectors in a 3D subspace of light power spectra

3D depiction of the high-dimensional space of all possible power spectra



Spectral sensitivities of L, M, and S cones

UNITED STATES DEPARTMENT OF AGRICULTURE

COLOR STANDARDS

for

FROZEN

FRENCH FRIED POTATOES

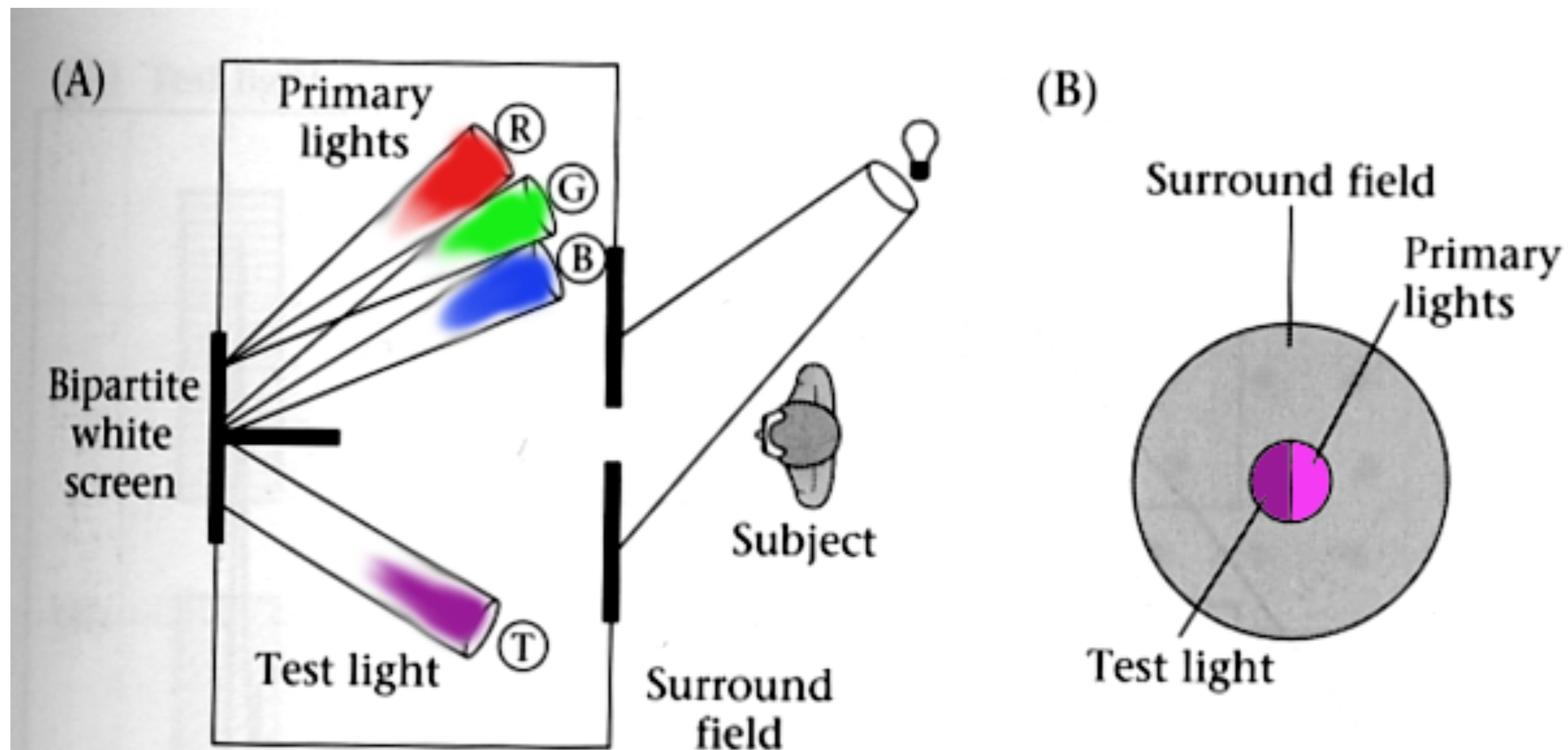


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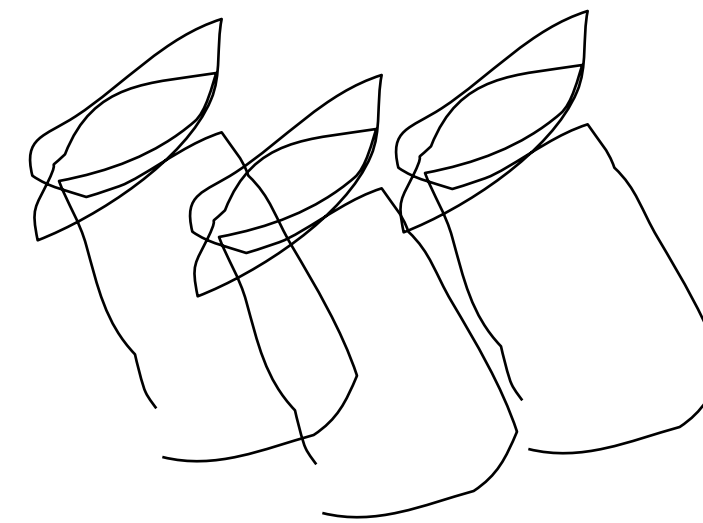
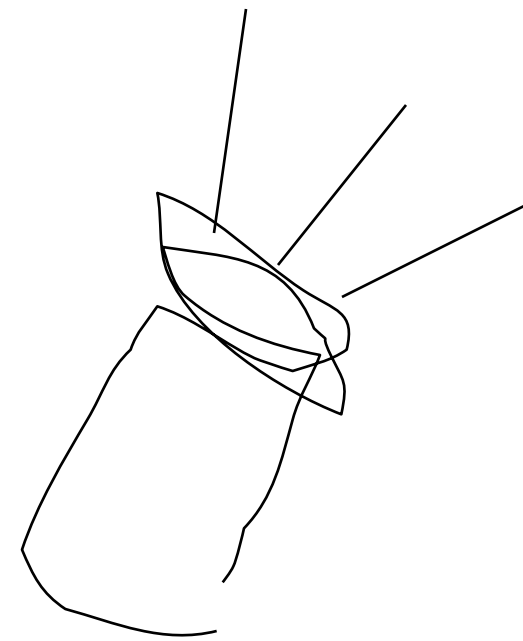
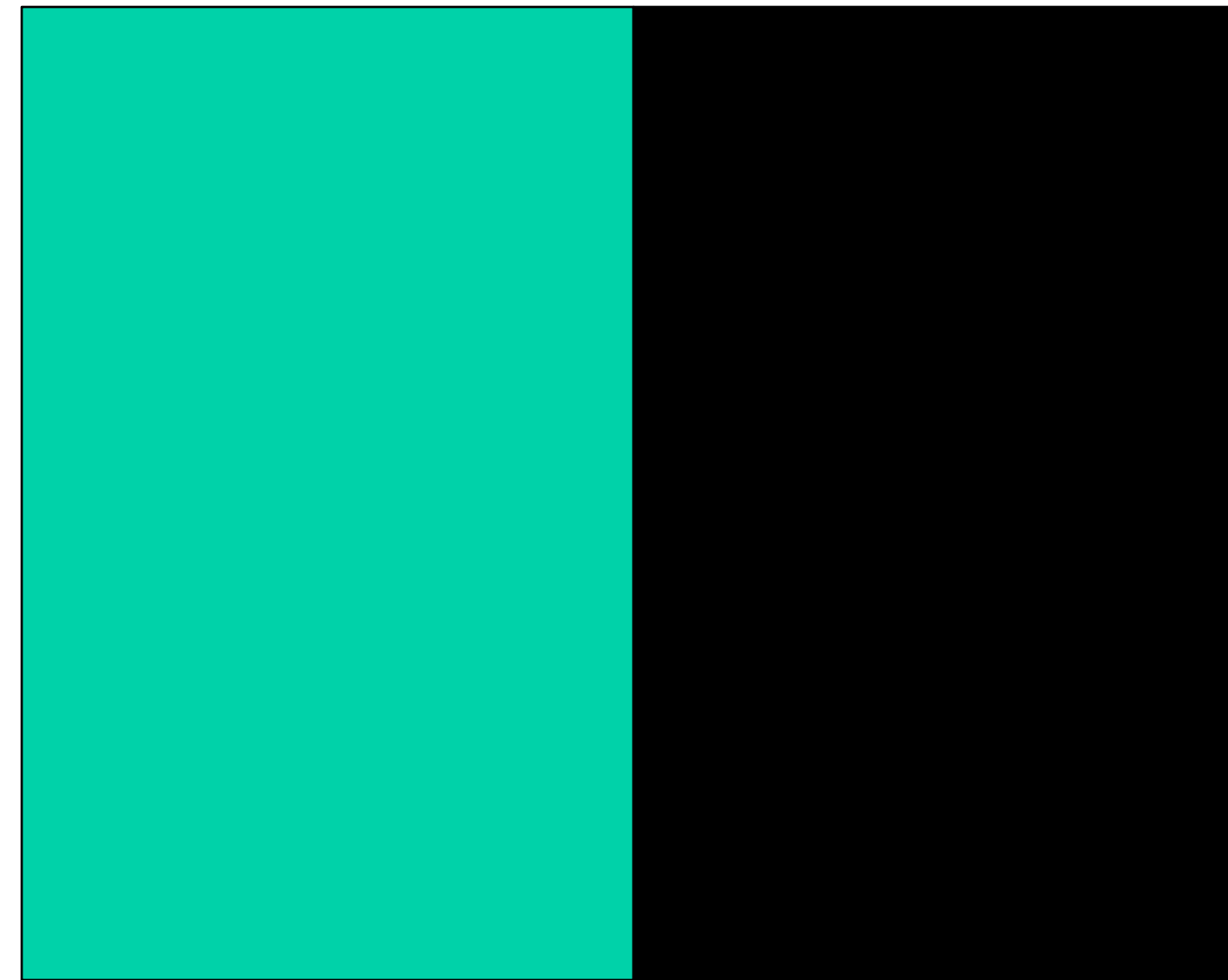


Color matching experiment

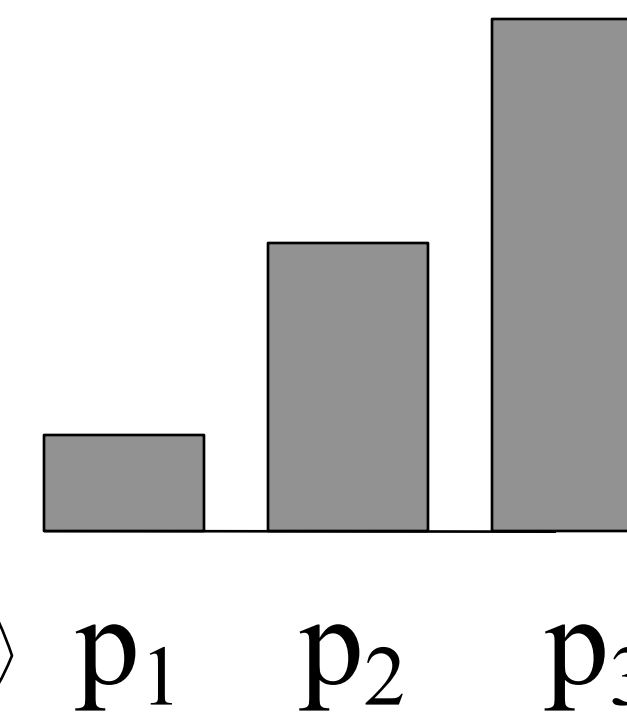
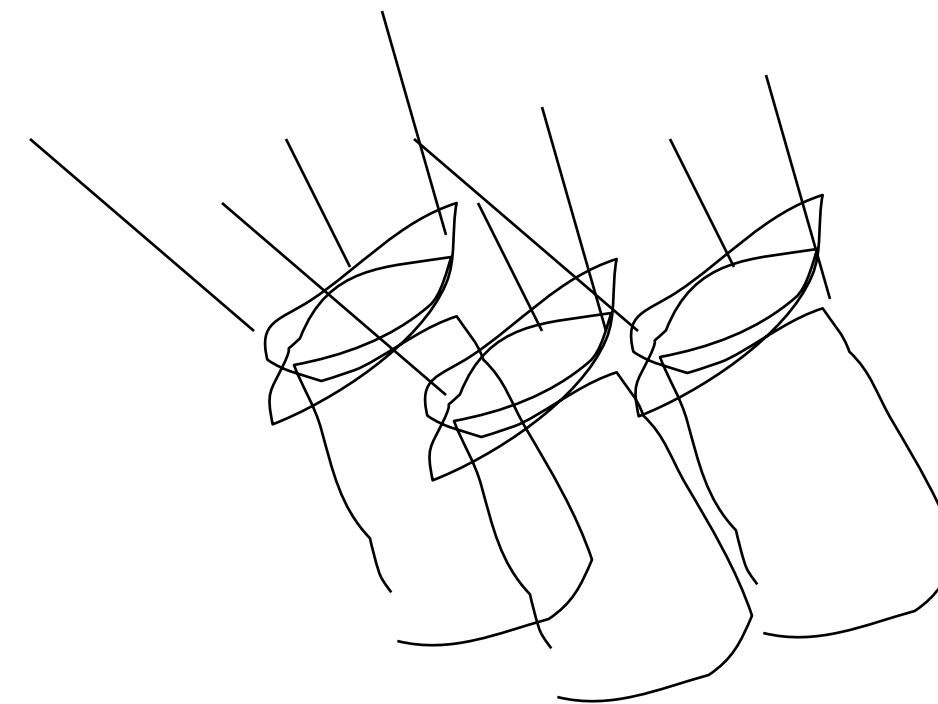
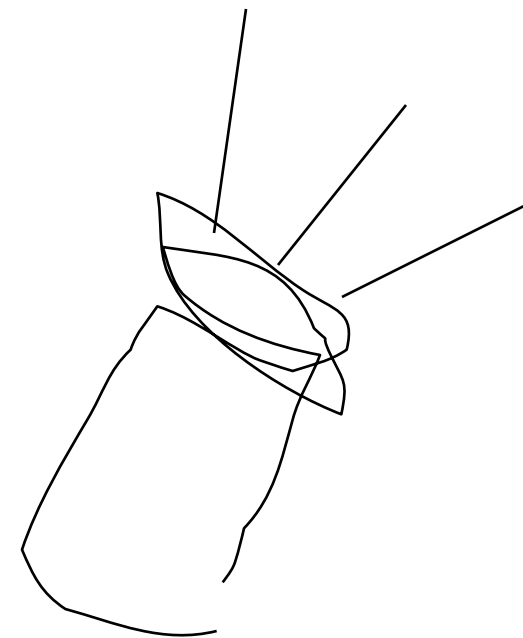
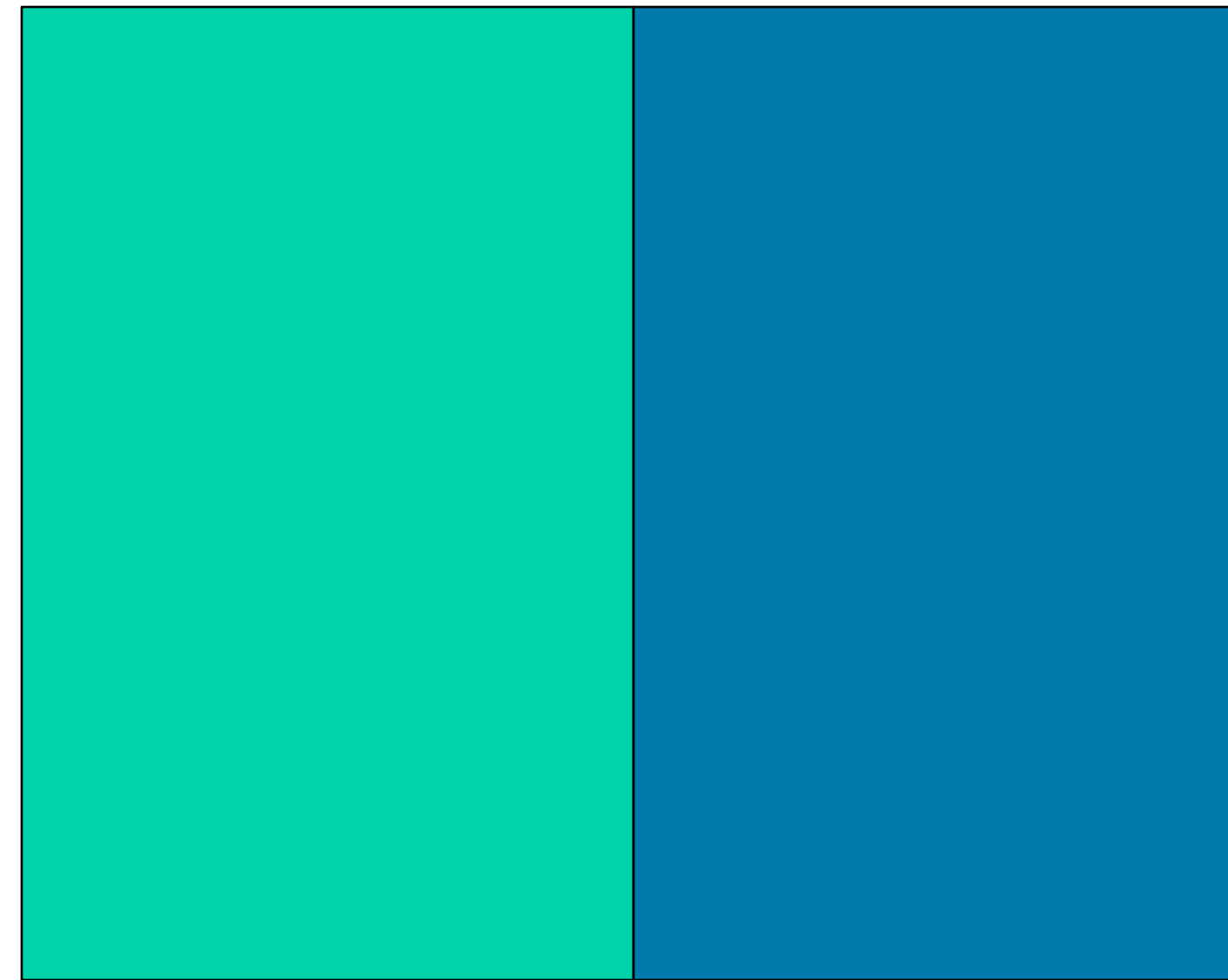


4.10 THE COLOR-MATCHING EXPERIMENT. The observer views a bipartite field and adjusts the intensities of the three primary lights to match the appearance of the test light. (A) A top view of the experimental apparatus. (B) The appearance of the stimuli to the observer. After Judd and Wyszecki, 1975.

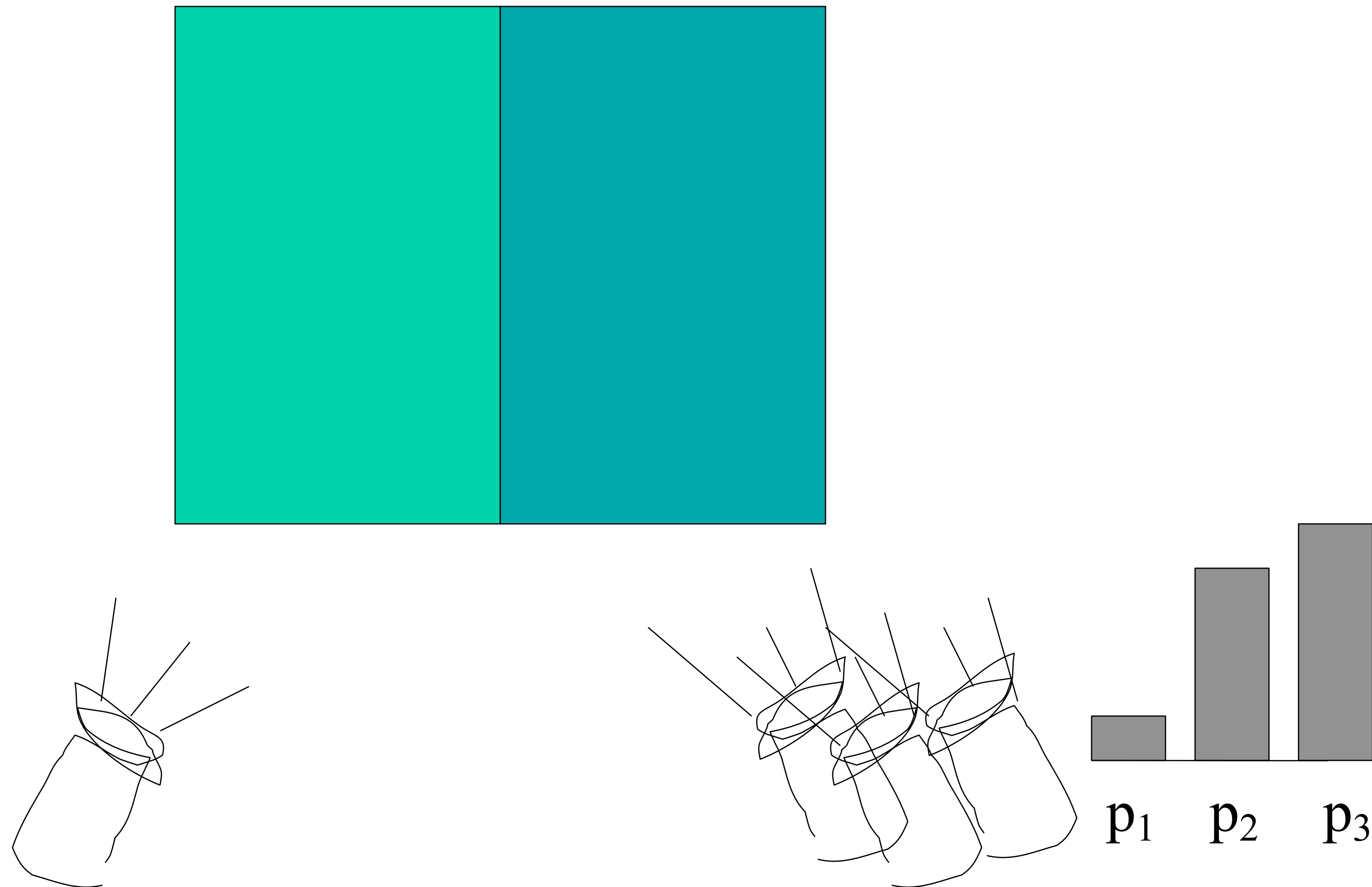
Color matching experiment



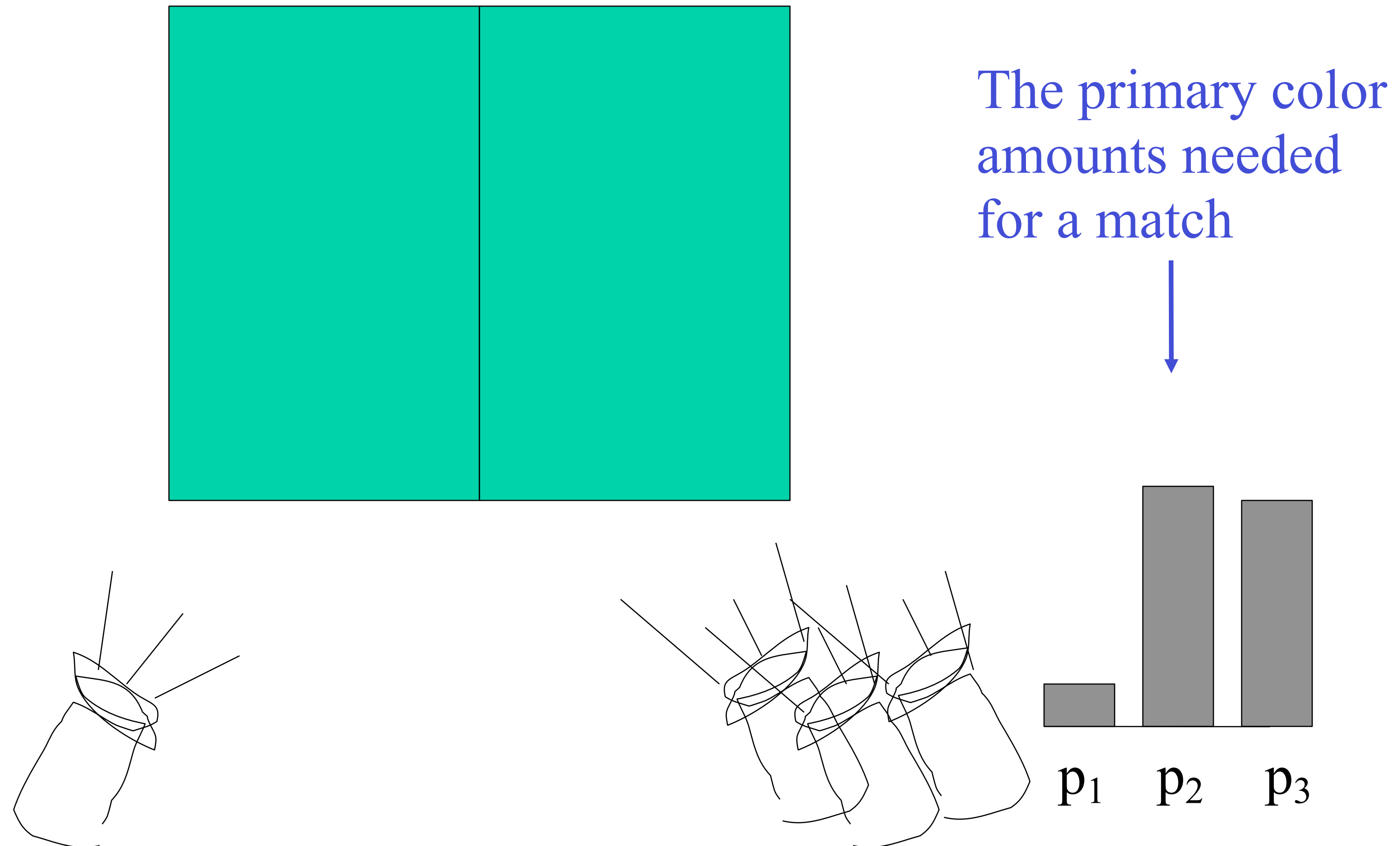
Color matching experiment



Color matching experiment

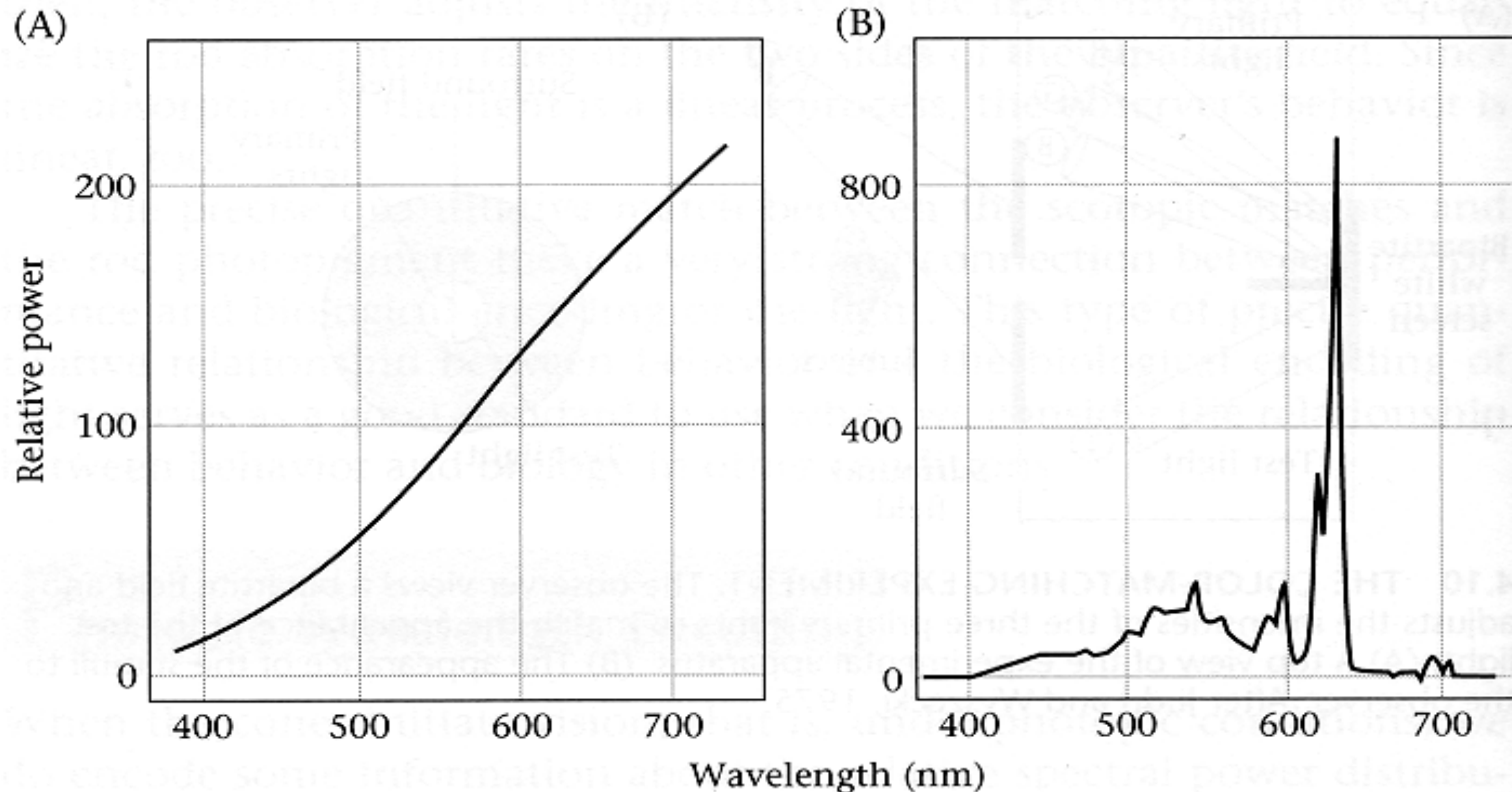


Color matching experiment



Metameric lights

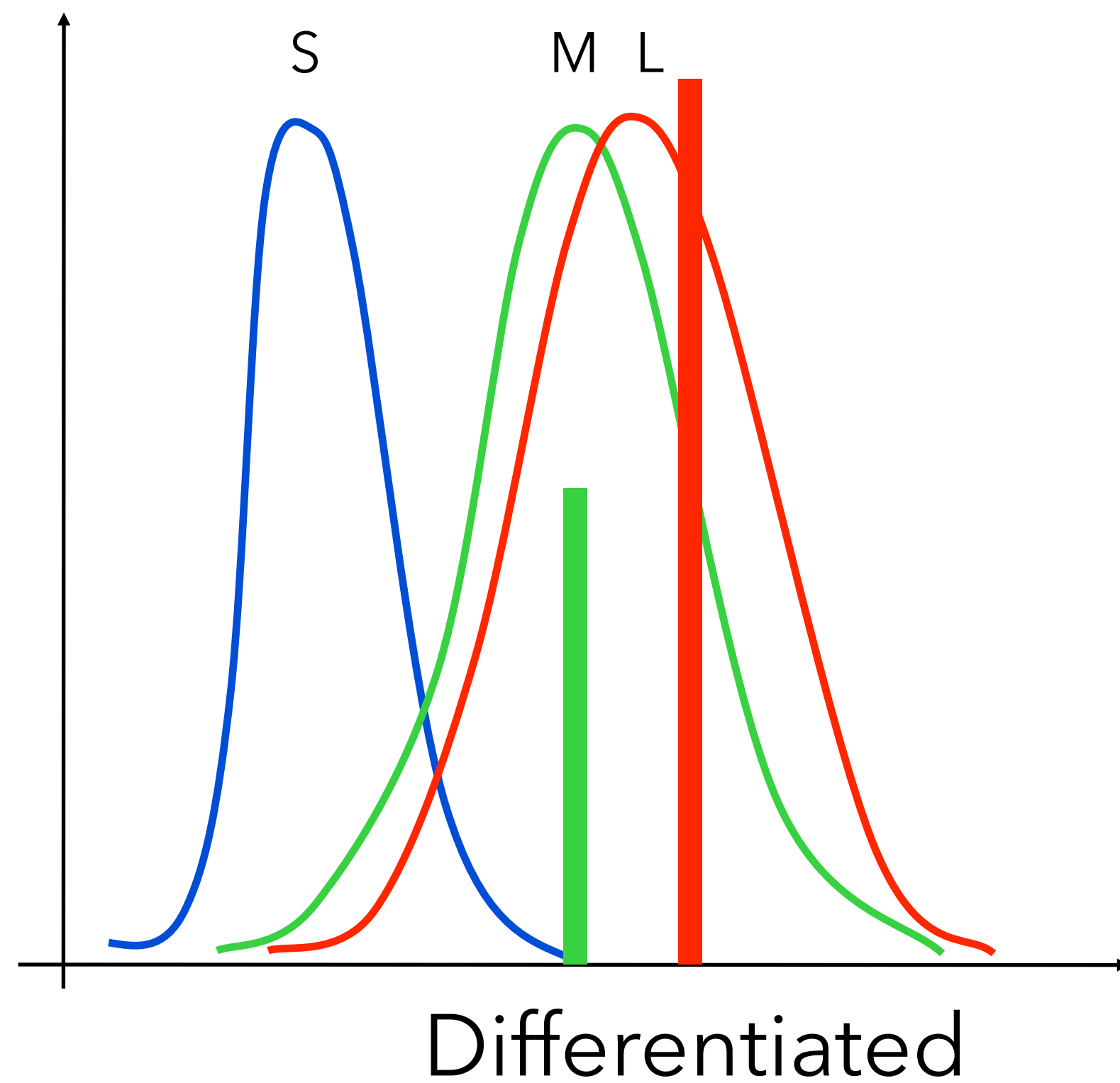
Foundations of Vision, by Brian Wandell, Sinauer Assoc., 1995



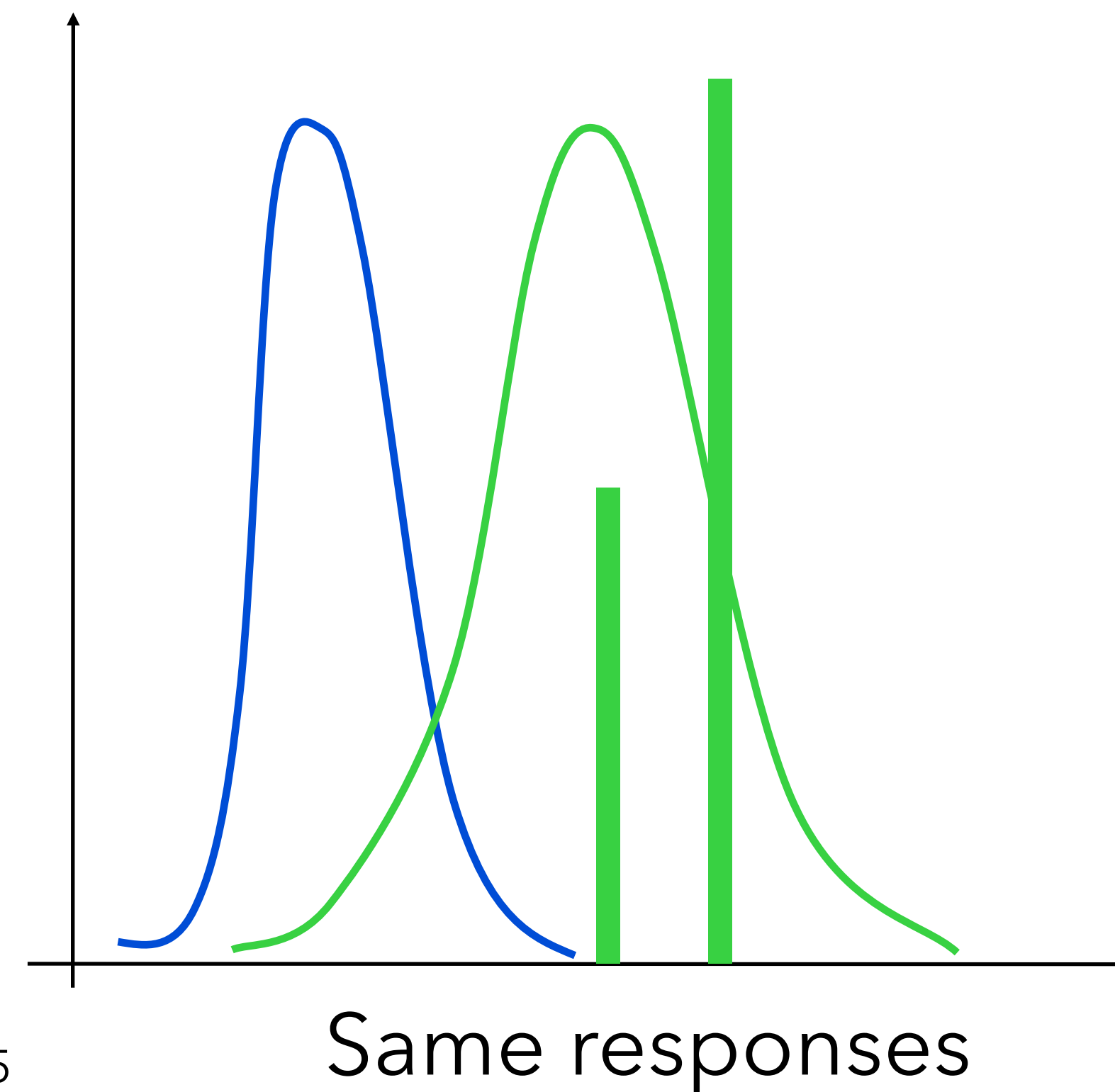
4.11 METAMERIC LIGHTS. Two lights with these spectral power distributions appear identical to most observers and are called metamers. (A) An approximation to the spectral power distribution of a tungsten bulb. (B) The spectral power distribution of light emitted from a conventional television monitor whose three phosphor intensities were set to match the light in panel A in appearance.

Color blindness

- Classical case: 1 type of cone is missing (e.g. red)
- Makes it impossible to distinguish some spectra.
- There are also tetrachromats, who have 4 cones.

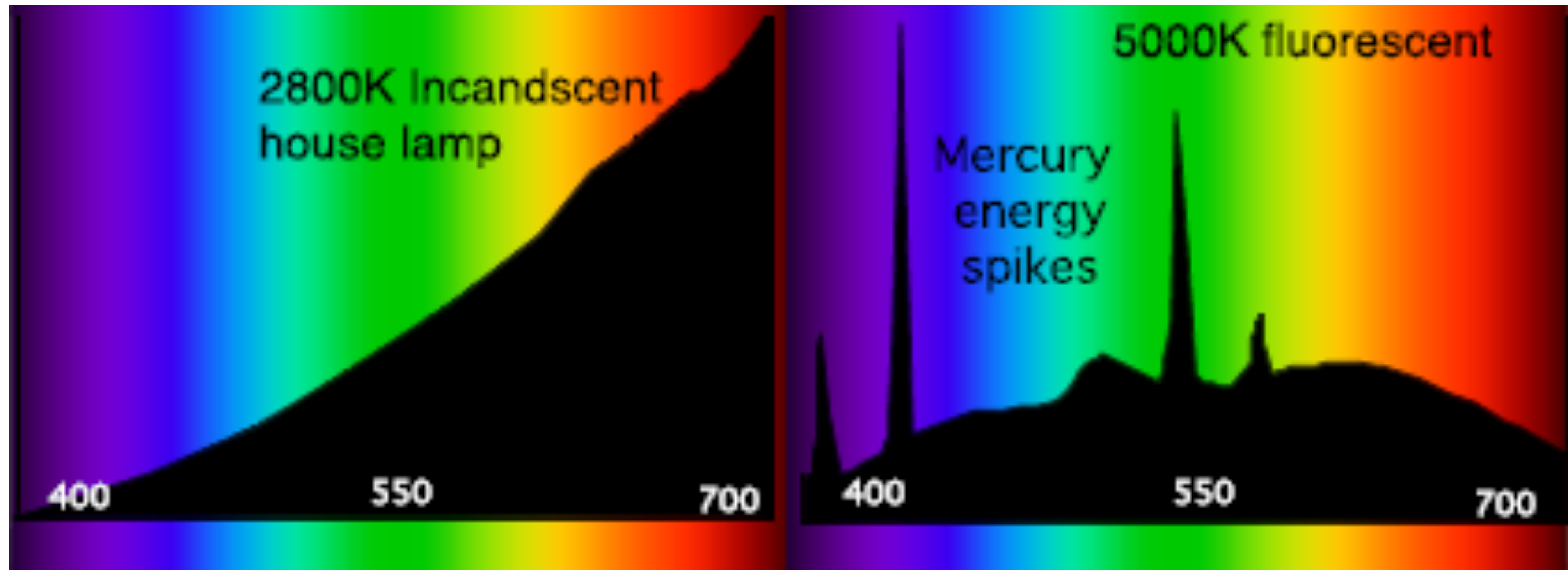


65



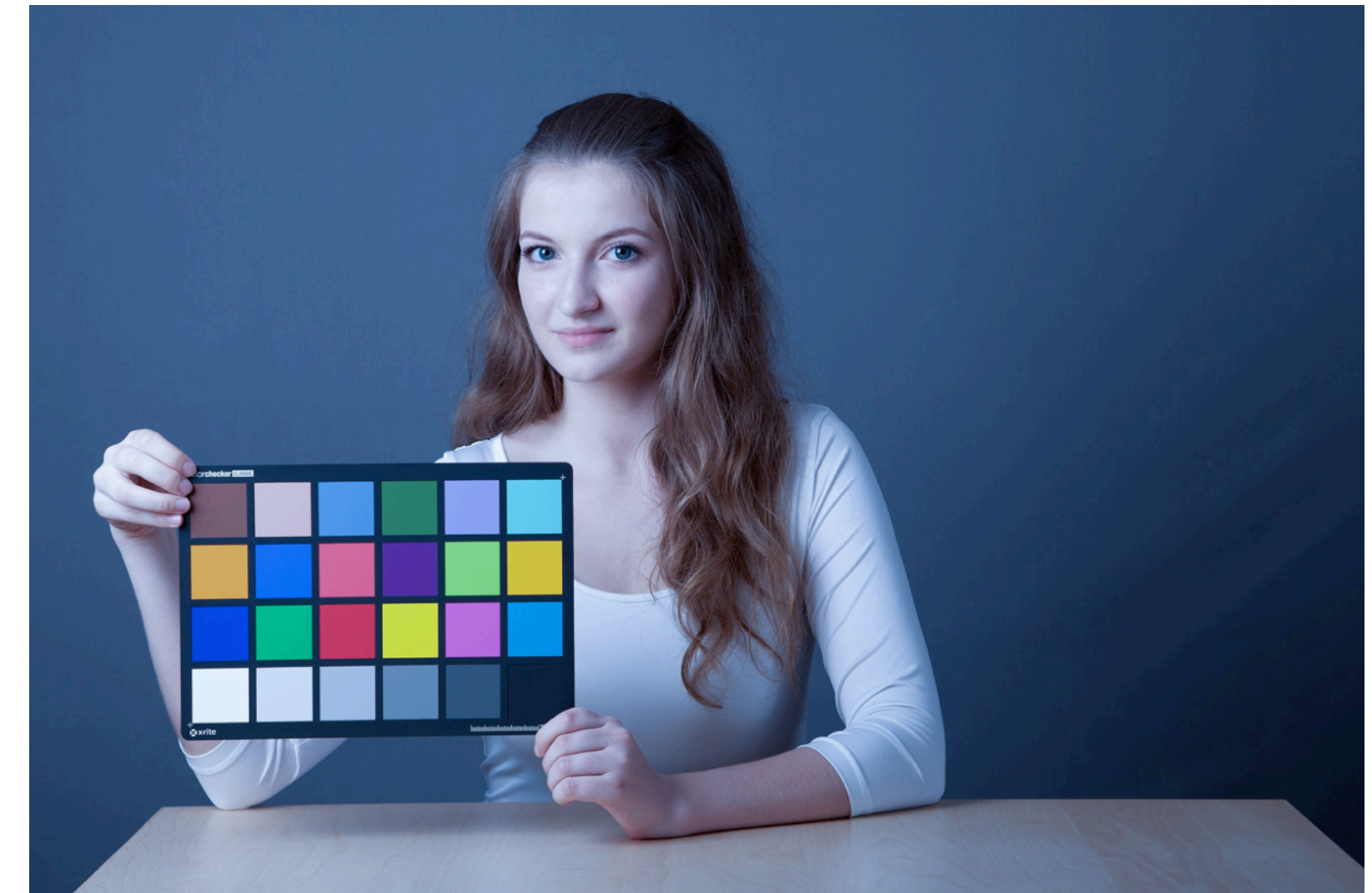
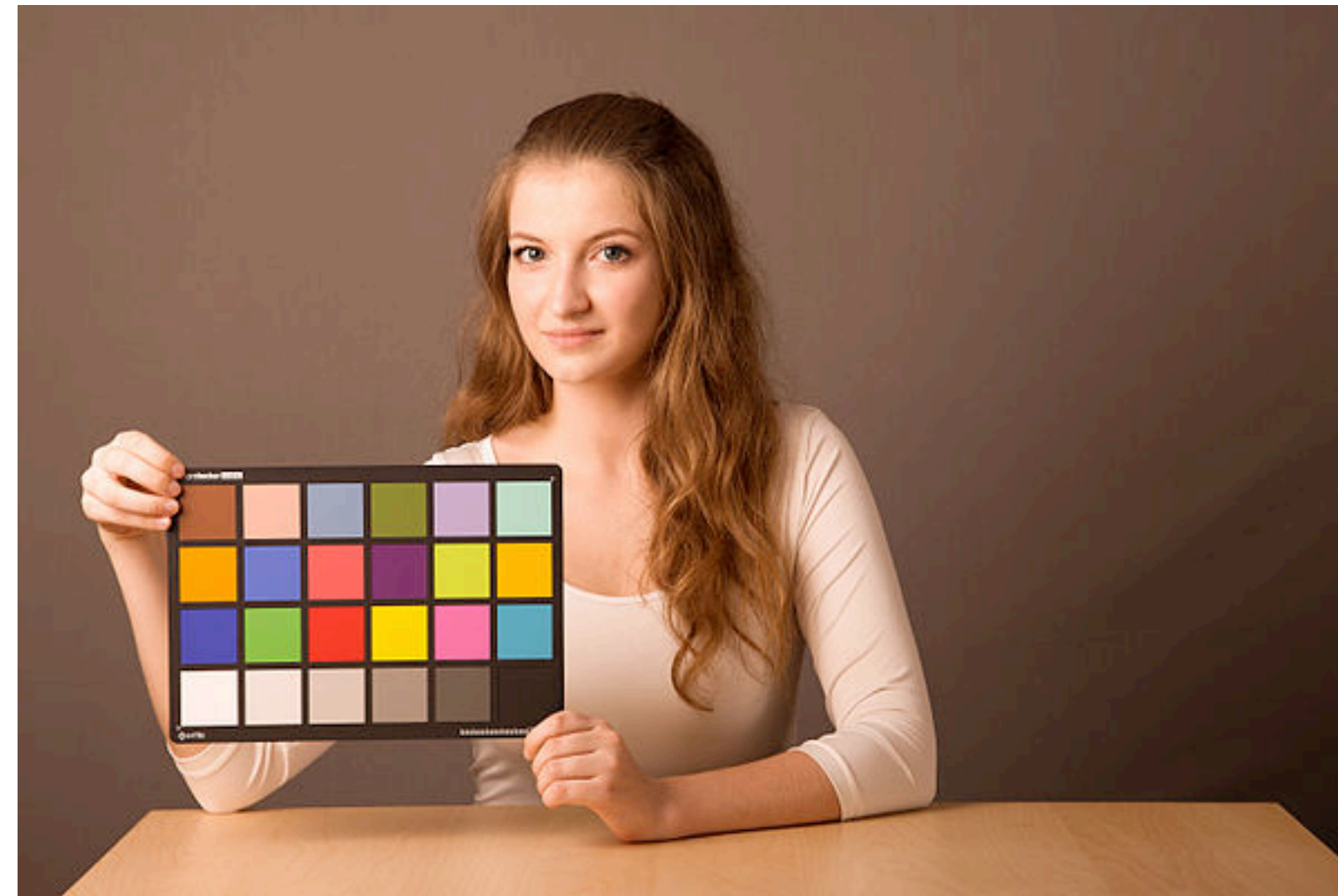
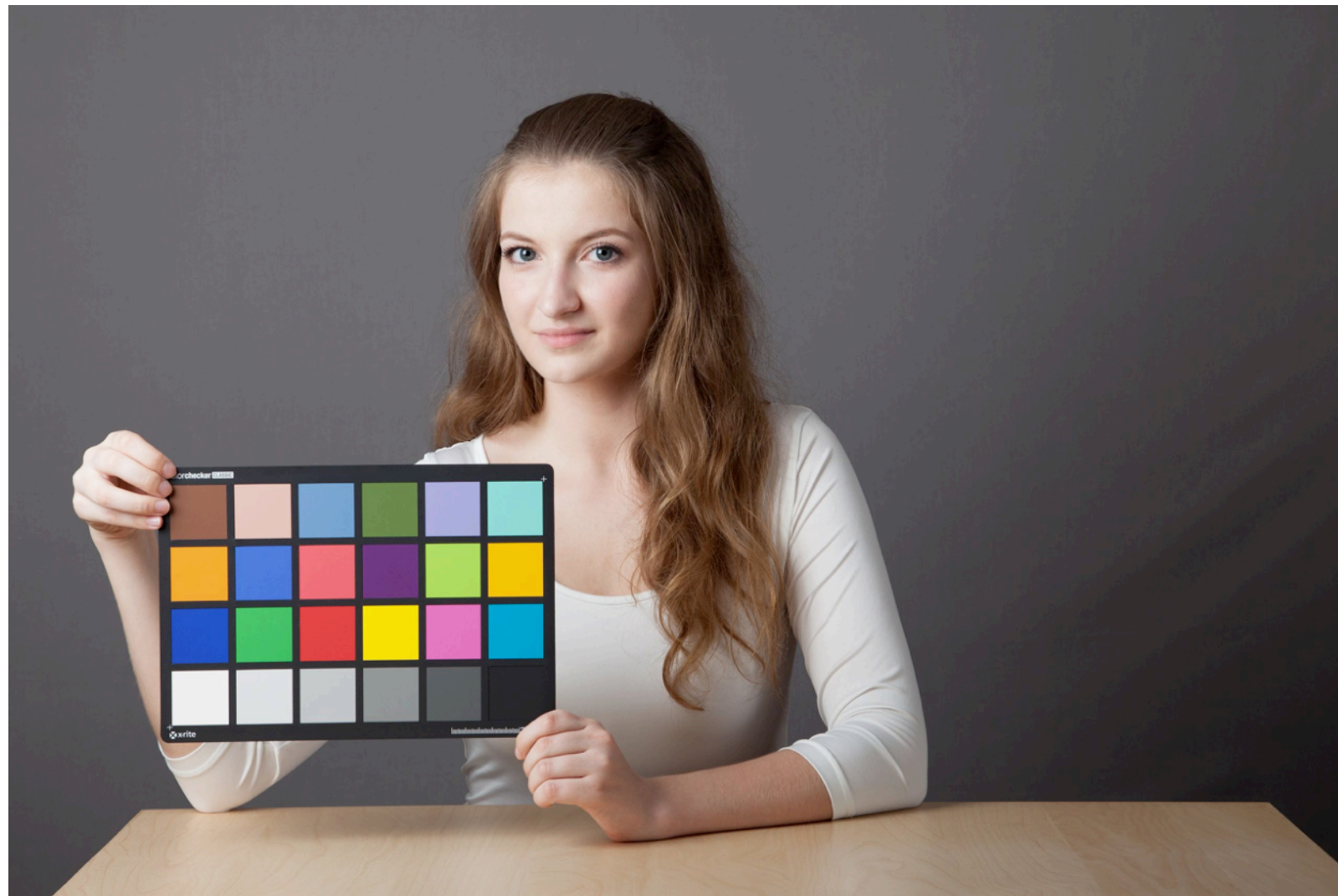
Source: F. Durand

Light sources



https://en.wikipedia.org/wiki/Color_temperature

Same scene under different illuminations



https://en.wikipedia.org/wiki/Color_balance

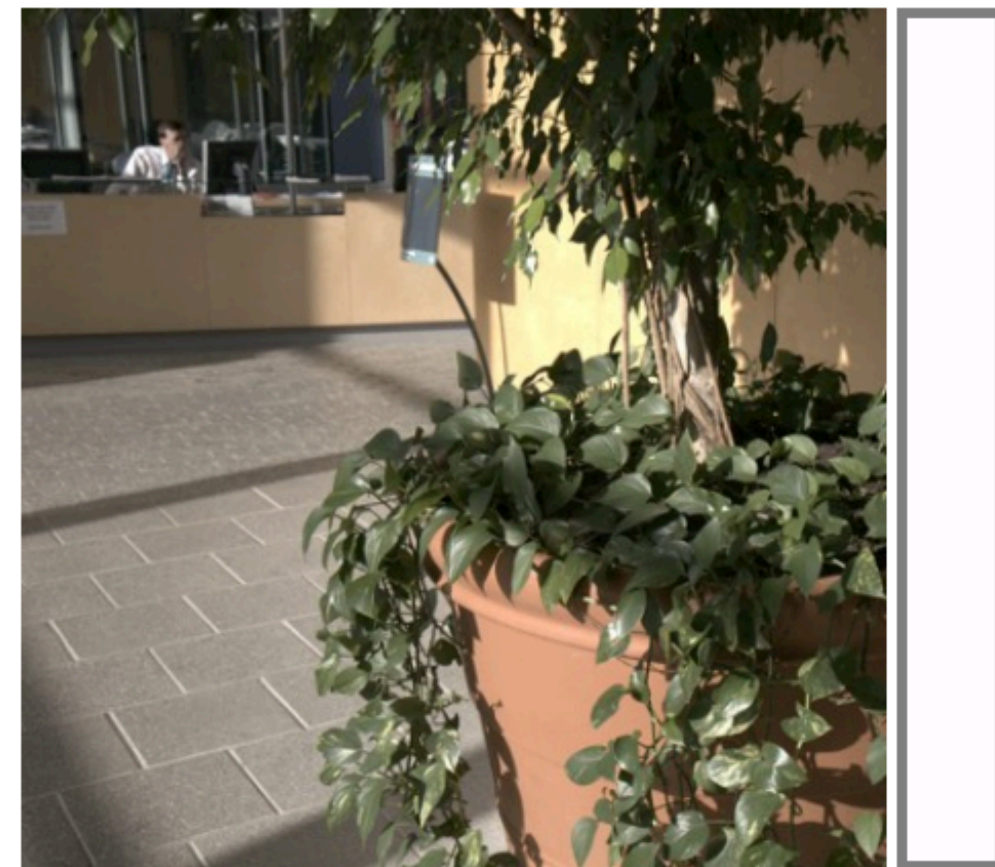
White balancing



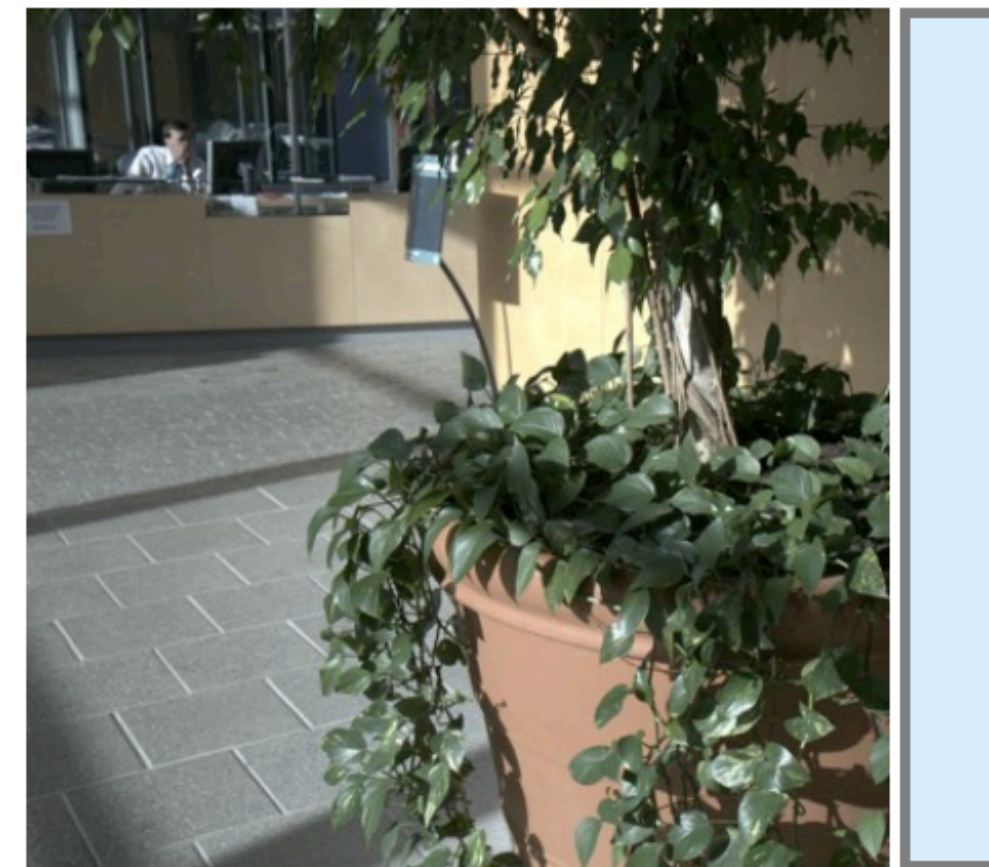
Is this a green light and a white object, or a green object and a white light?

White balancing


$$I = W \times L$$



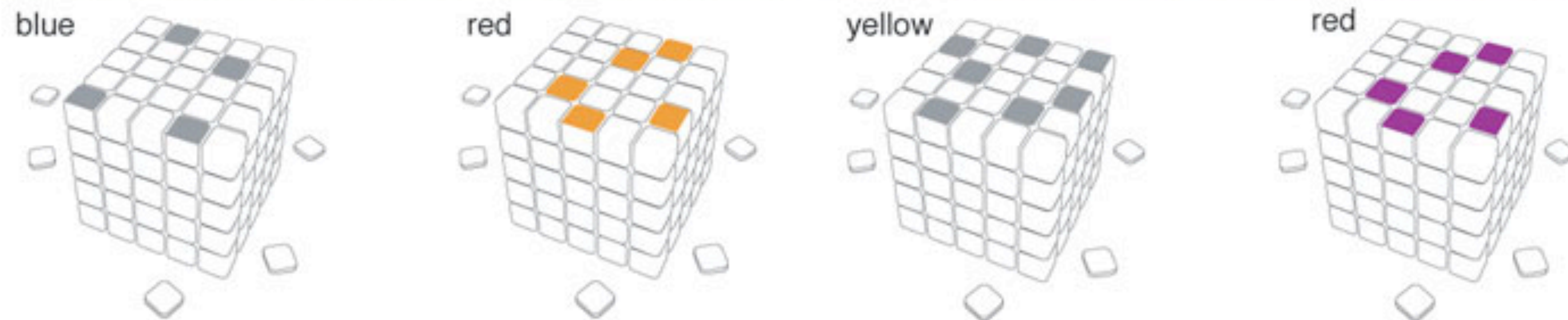
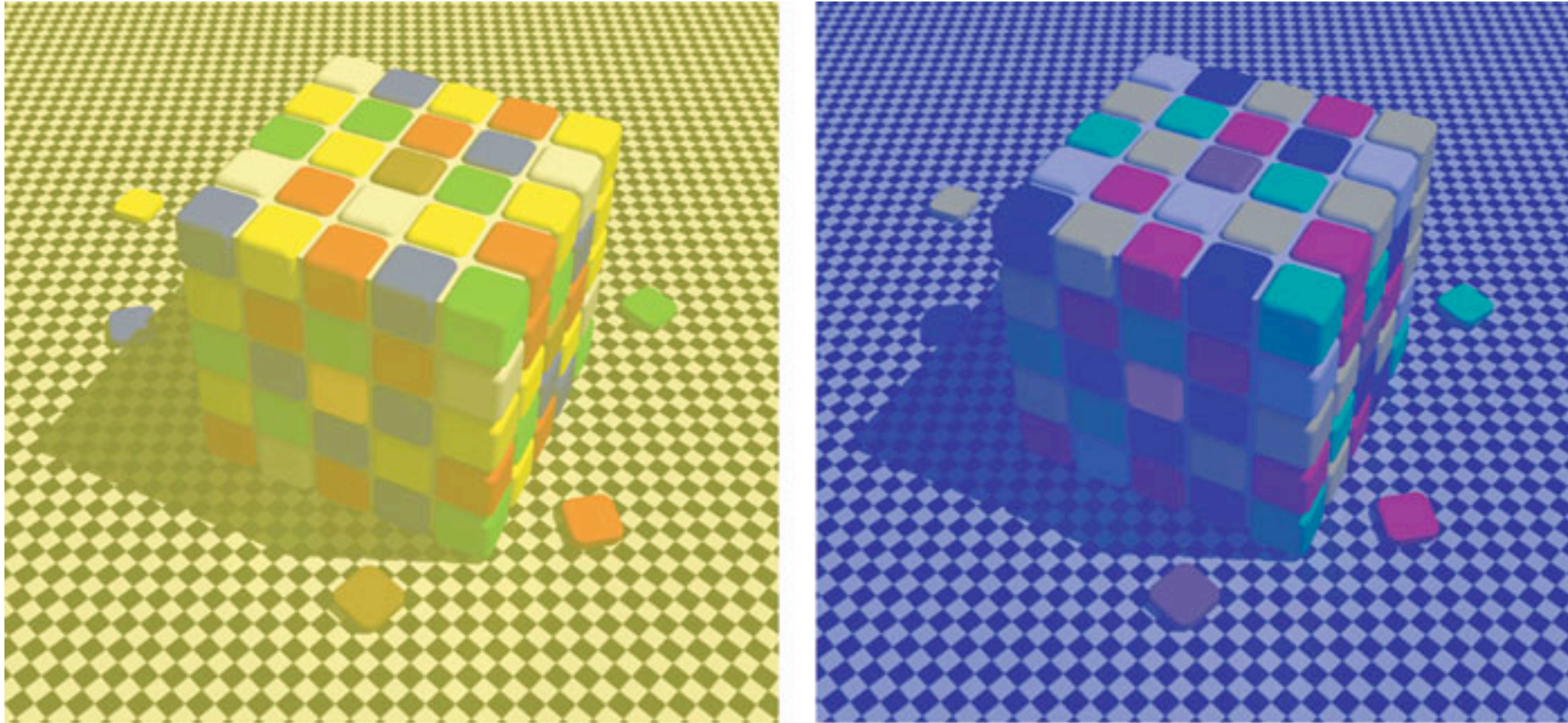
our $\hat{W}$, $\hat{L}$, err = 0.13°



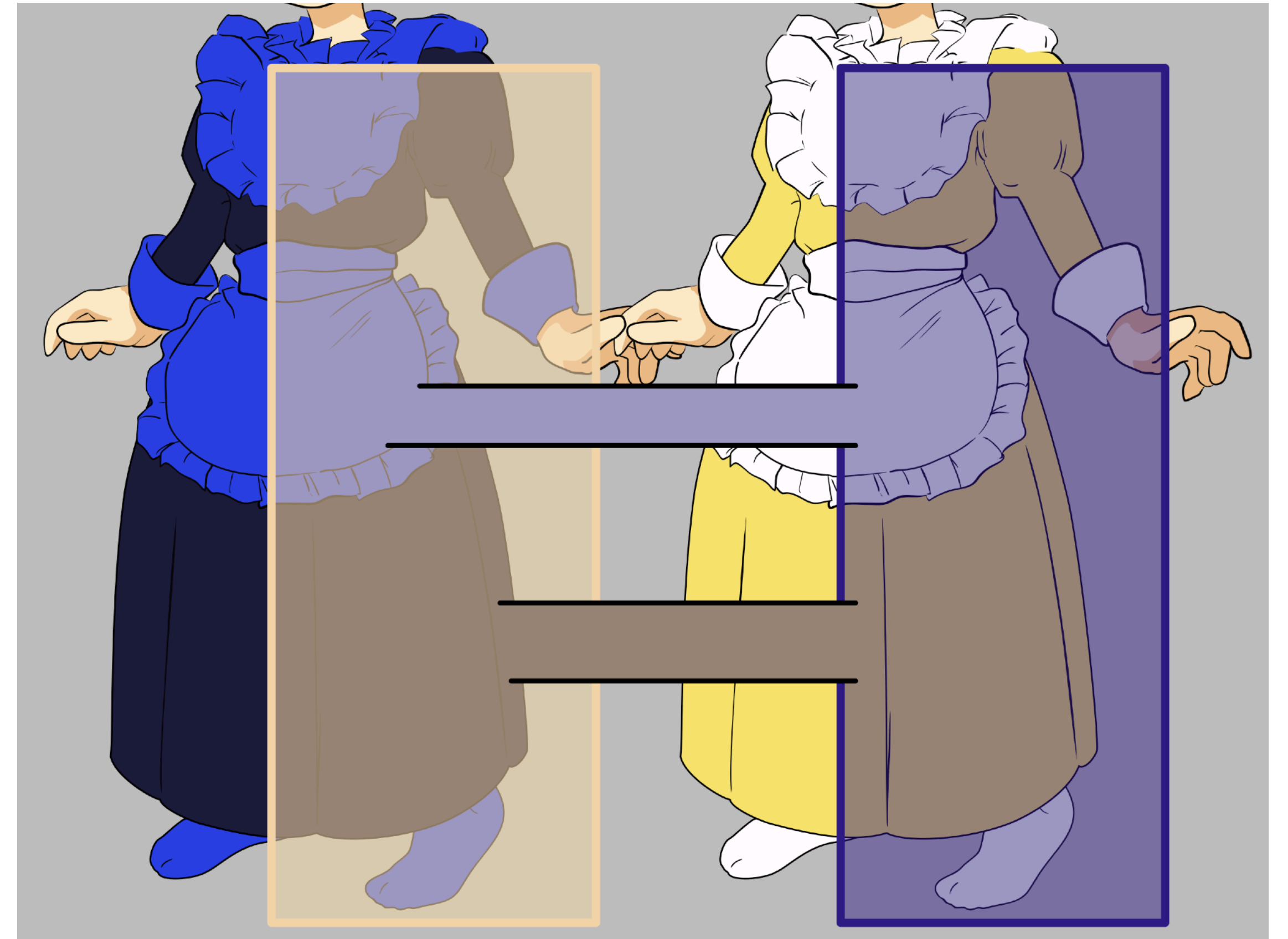
baseline $\hat{W}$, $\hat{L}$, err = 5.34°

[Barron, "Convolutional Color Constancy", 2015]

Color constancy



The dress



Two interpretations

Next classes: advanced topics