Lecture 21:

Introduction to Color Science

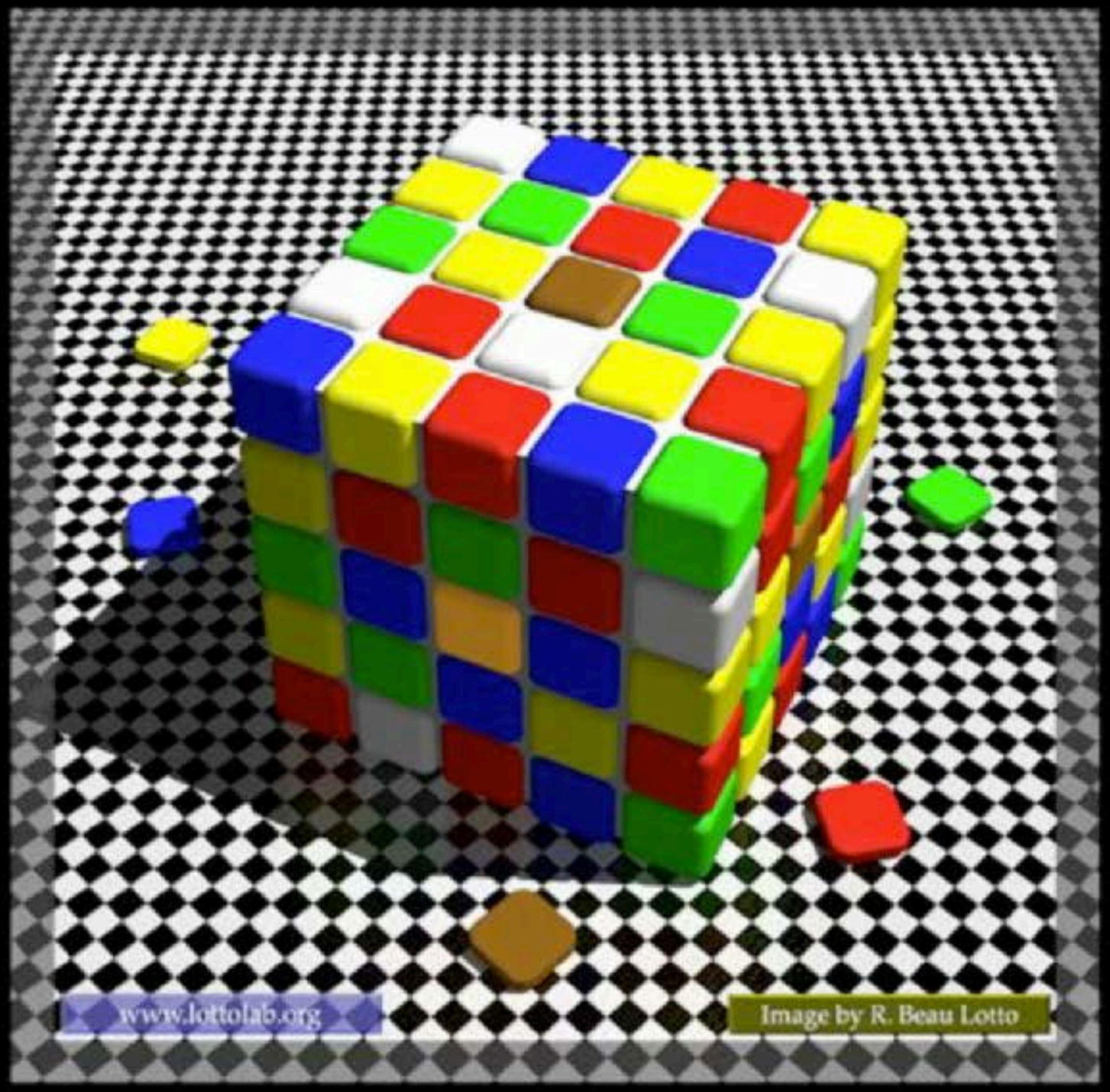
Computer Graphics and Imaging
UC Berkeley CS184/284A

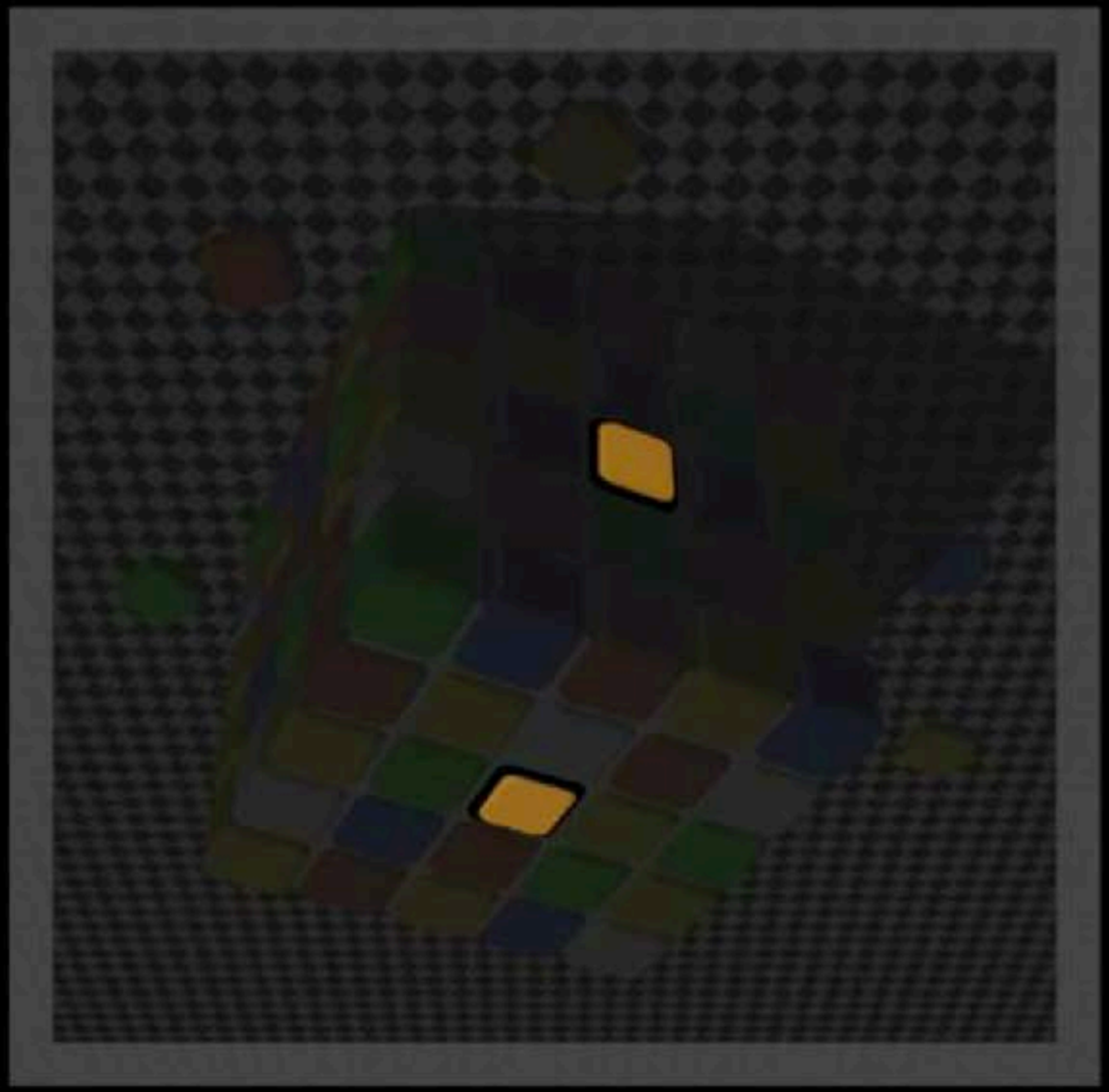

UMBRA GEBRANNT
BURNT UMBER
SIENNA
WINSOR & NEWTON
YELLOW

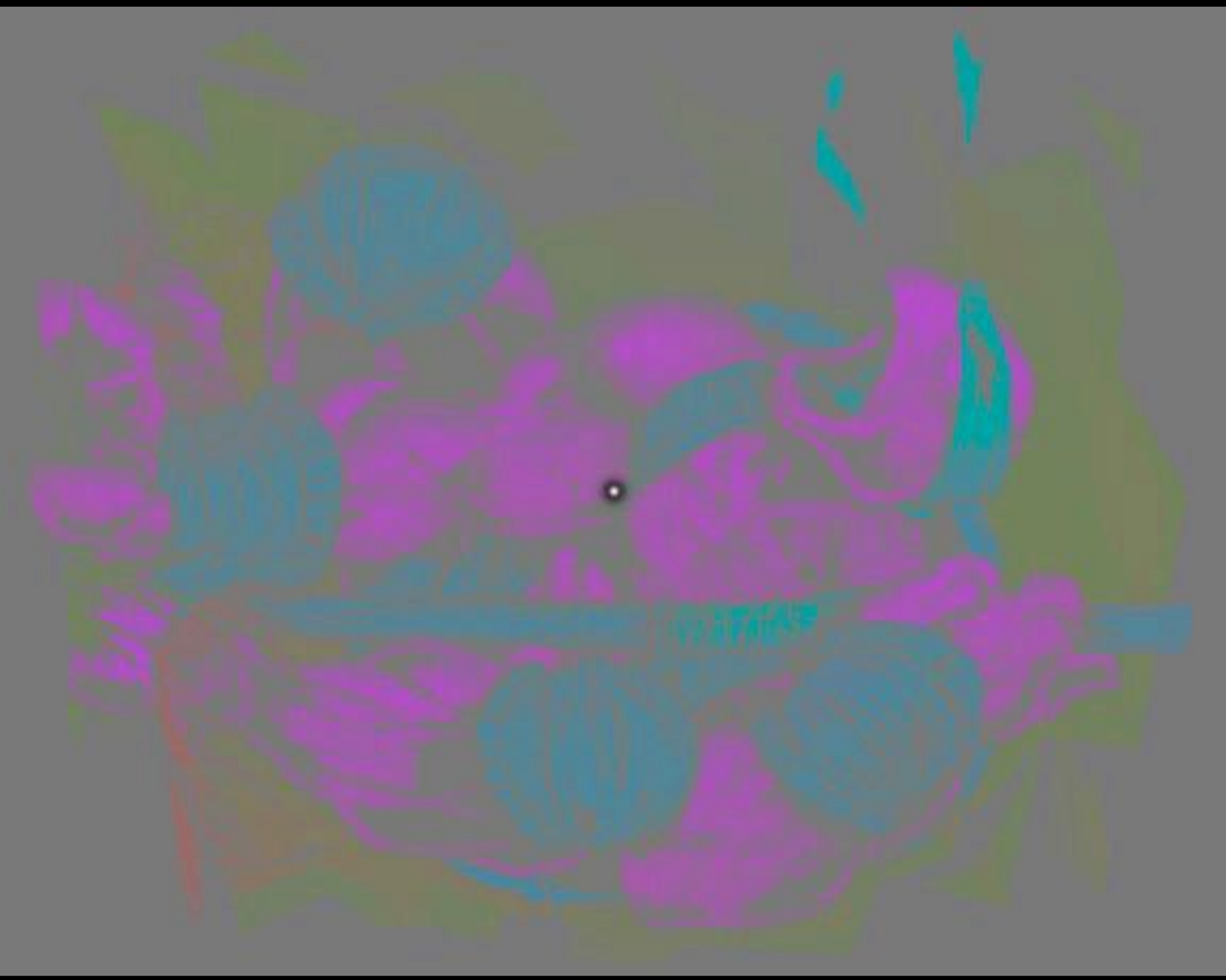
Wassily Kandinsky, Color Study. Squares with Concentric Circles, 1913
Munich, The Städtische Galerie im Lenbachhaus

Mark Rothko
No. 61. Rust and Blue
1953,
Museum of Contemporary Art, Los Angeles

FIRE ENGINE

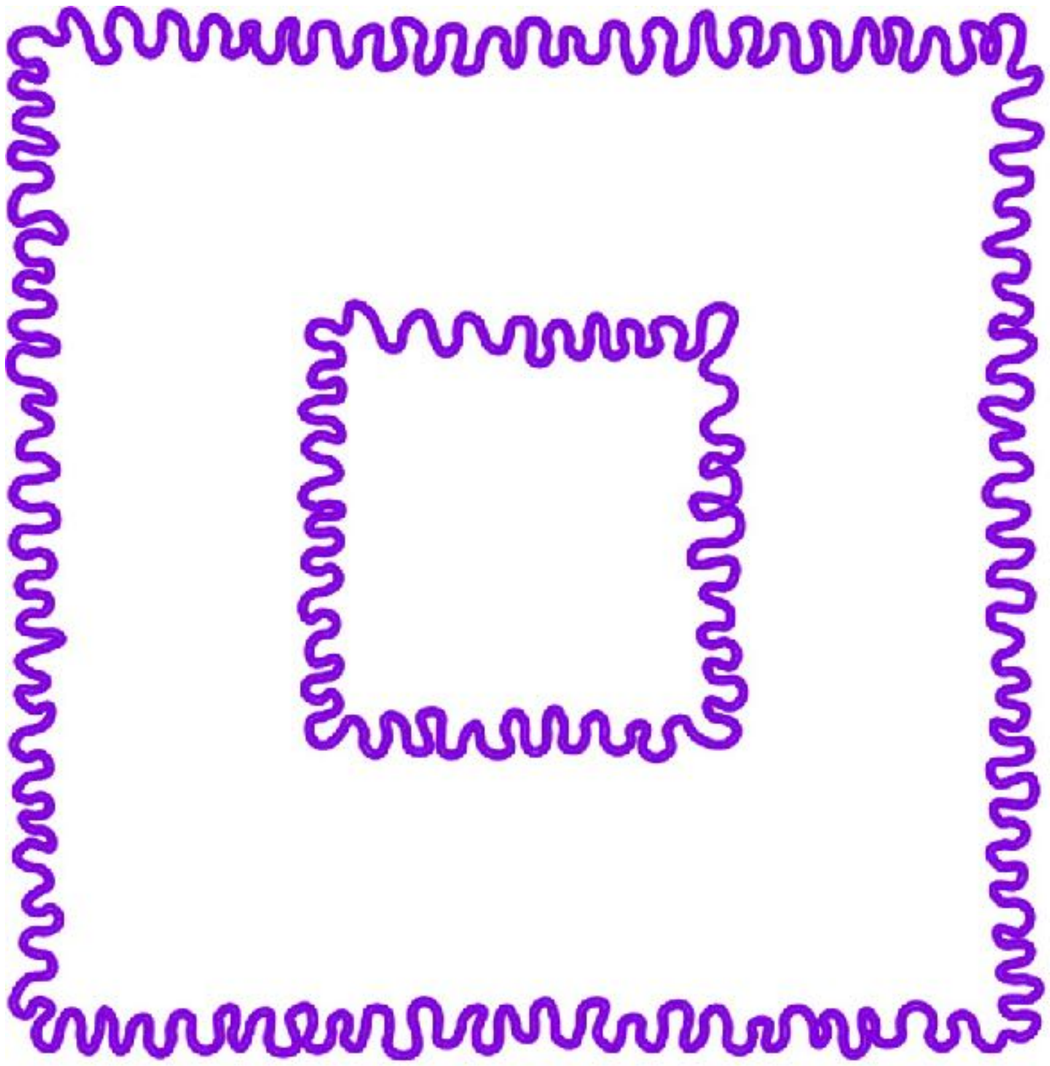

www.lottolab.org
Image by R. Beau Lotto





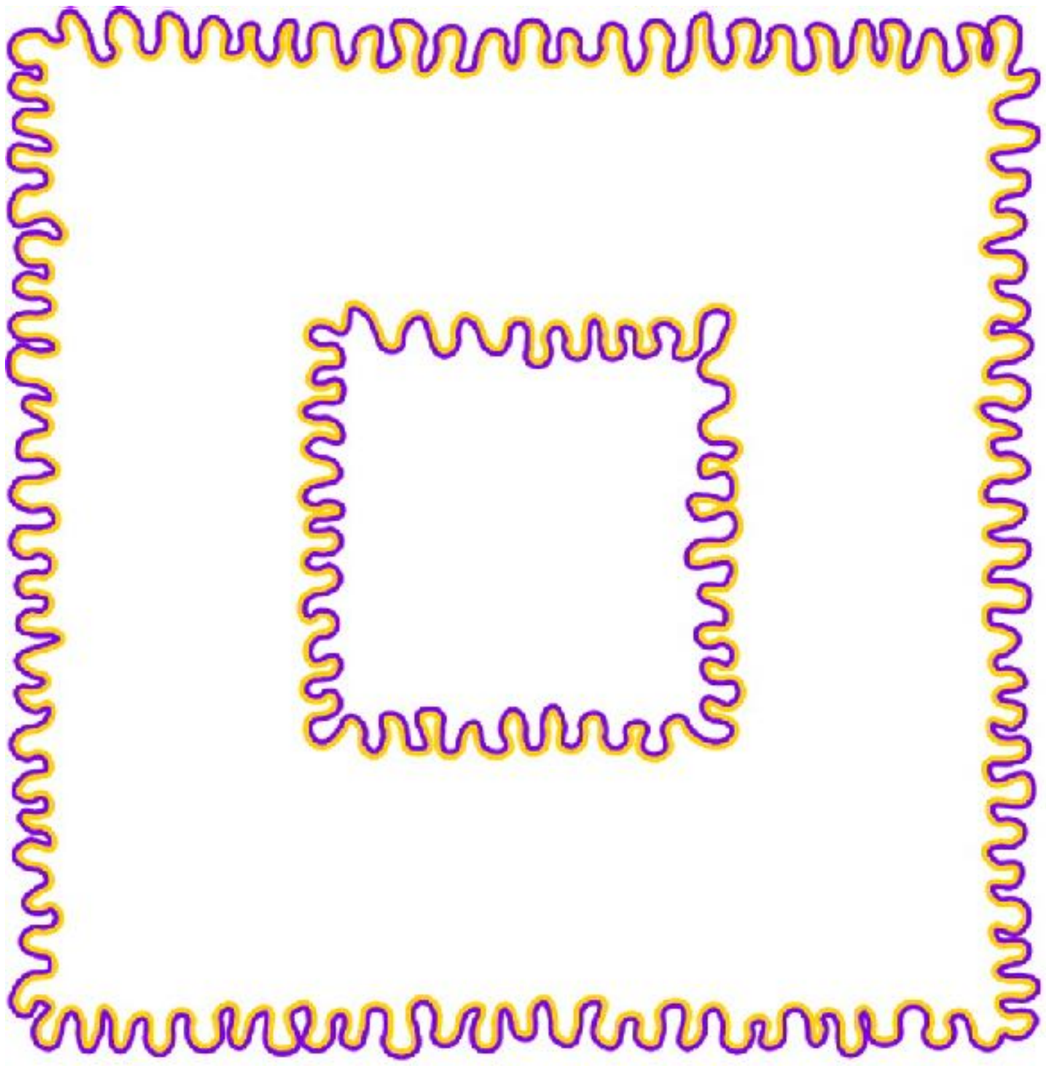

TOM 3

Watercolor Illusion



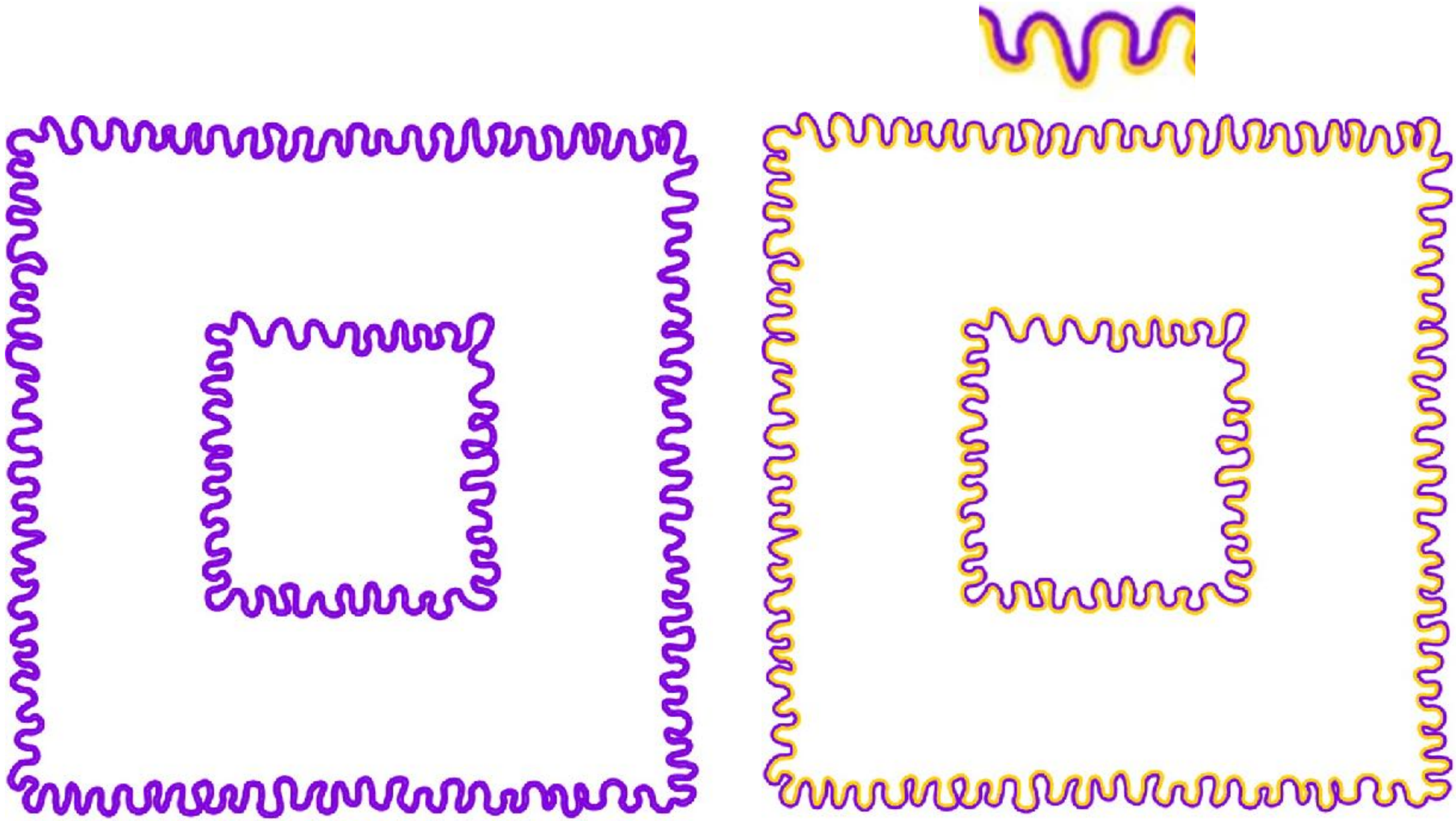
Pinna & Tanca, *JOV*, 2008

Watercolor Illusion

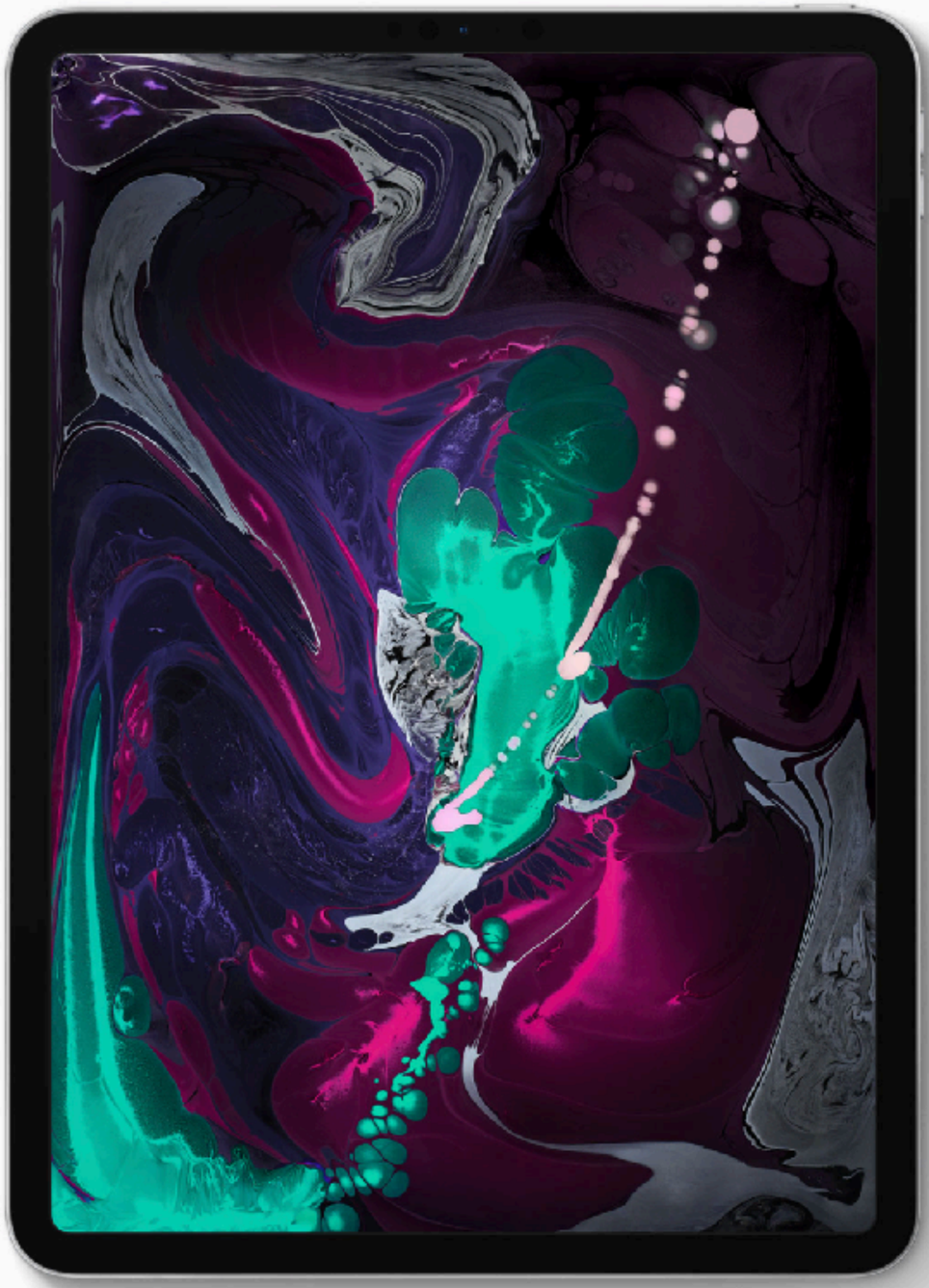


Pinna & Tanca, *JOV*, 2008

Watercolor Illusion

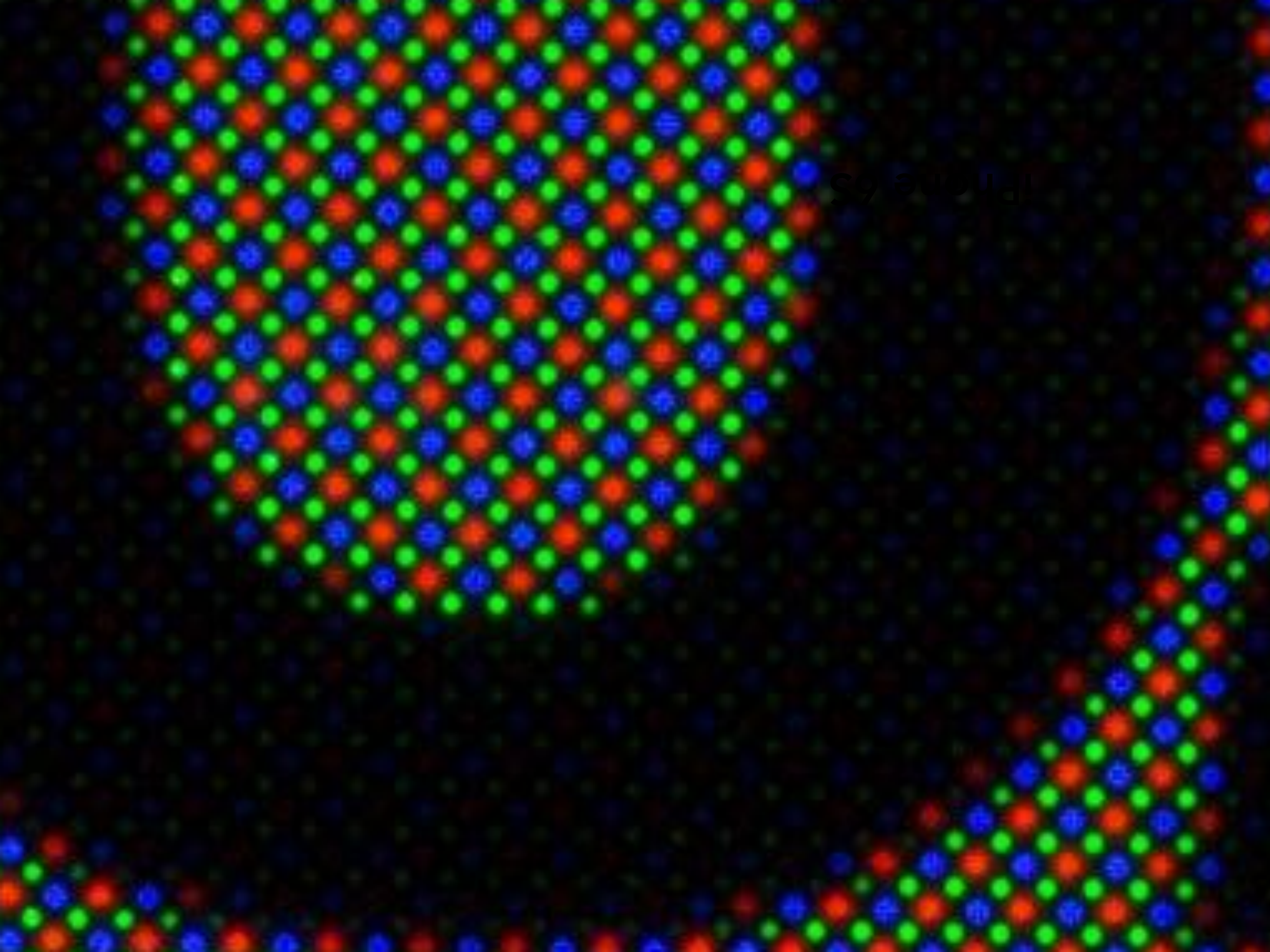


Pinna & Tanca, *JOV*, 2008



11″

12.9″



Discussion: Warm Ups (Breakout Rooms)

What is a fact you know about color?

What is something you want to learn about color?

- Mantis shrimp! A lot of photoreceptor classes. 16!
- Tetrachromacy — some women have 4 types of cone cells.
- Color is from different wavelengths
- Nothing inherently special to our visible spectrum, except H20 being transparent
- Synesthesia — hear music and see colors
- People couldn’t see or recognize blue until relatively modern times (?)
- Your language shapes your perception of color. E.g. lack of blue/green distinction in some languages
- Our eyes are more sensitive to green — why our displays have more green pixels (?)
- Color does not always correspond to one wavelength
- Blue light disrupts sleep patterns — why we make our displays red at bedtime
- Red and yellow are most appetizing colors

Discussion: What is The Dimensionality of Color?

How do we know?

- 3D - 3 cone receptors in the human retina
- Some thought 3D, some thought wavelength (1D?)
- If function of frequency spectrum, then infinite dimensional
- Hidden dimensions of color — e.g. Ren's research on Oz Vision project
- Red green blue white black — 5D?
- CMYK printing — 4D?
- Position of the color may be important — e.g. the Lotto cube illusion
- HSV / RGB —
- Perception is 3D, but dimensionality of the ray of light itself perhaps infinite?

What is Color?

- Color is a phenomenon of human perception; it is not a universal property of light
- Colors are the perceptual sensations that arise from seeing light of different spectral power distributions
- Technically speaking, different wavelengths of light are not “colors”

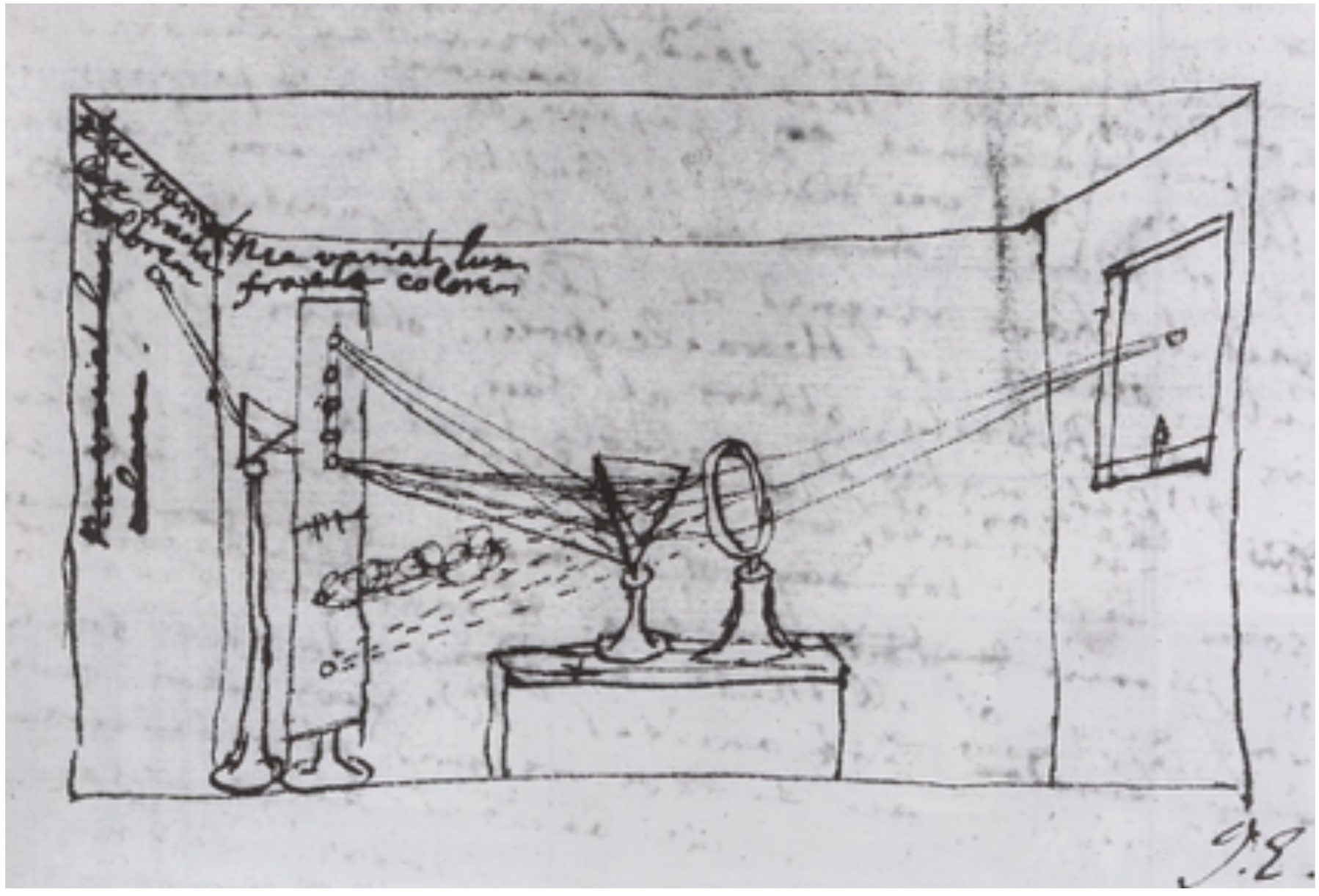
Physical Basis of Color

credit: Science Media Group.

Isaac Newton's Experimentum Crucis

Isaac Newton performing his crucial prism experiment – the 'experimentum crucis' – in his Woolsthorpe Manor bedroom.
Acrylic painting by Sascha Grusche (17 Dec 2015)

The Fundamental Components of Light



- Newton showed sunlight can be subdivided into a rainbow with a prism
- Resulting light cannot be further subdivided with a second prism

The Visible Spectrum of Light

Electromagnetic radiation

- Oscillations of different frequencies (wavelengths)

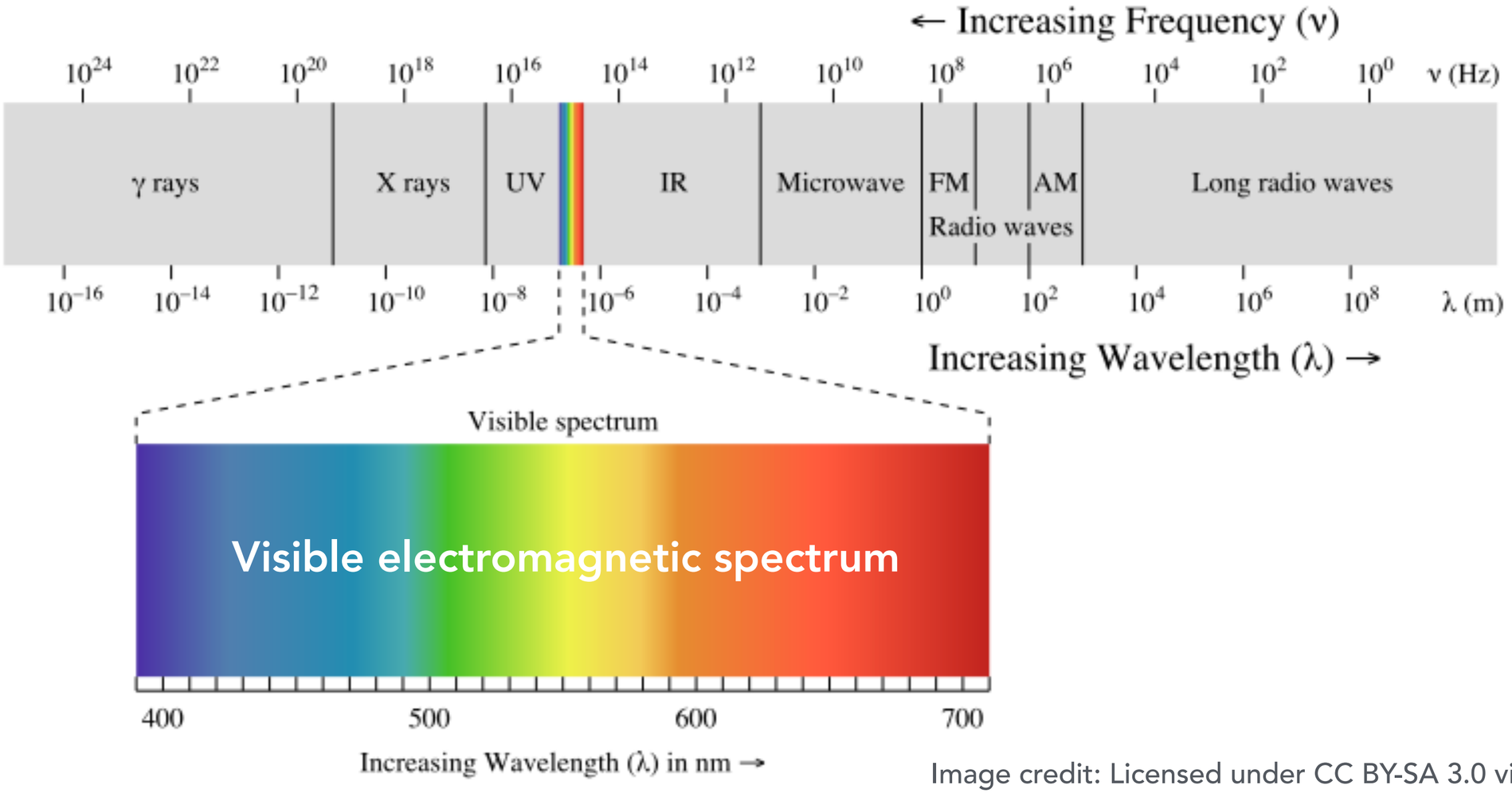
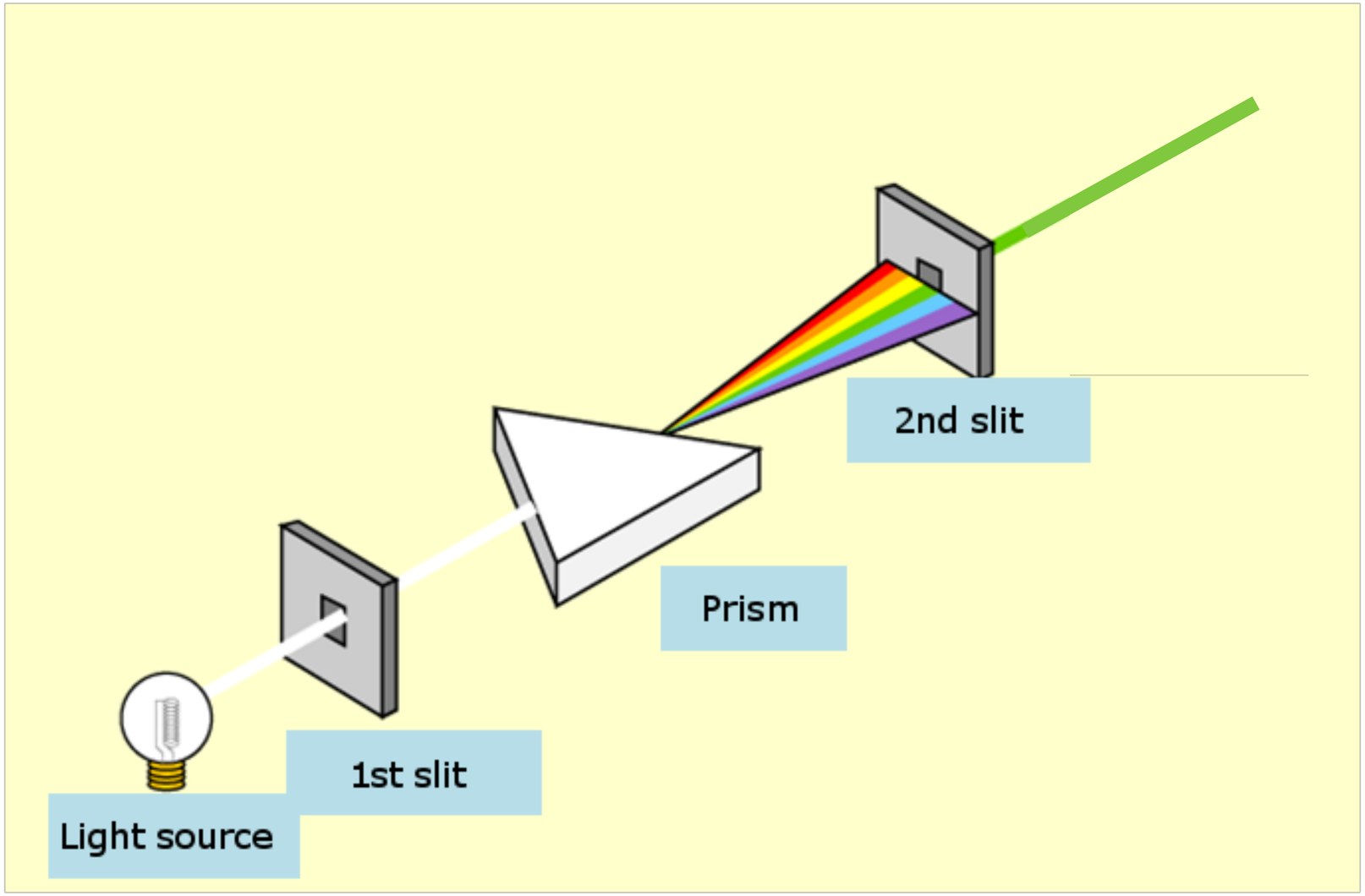


Image credit: Licensed under CC BY-SA 3.0 via Commons
https://commons.wikimedia.org/wiki/File:EM_spectrum.svg#/media/File:EM_spectrum.svg

Monochromator



A monochromator delivers light of a single wavelength from a light source with broad spectrum.
Control which wavelength by angle of prism.

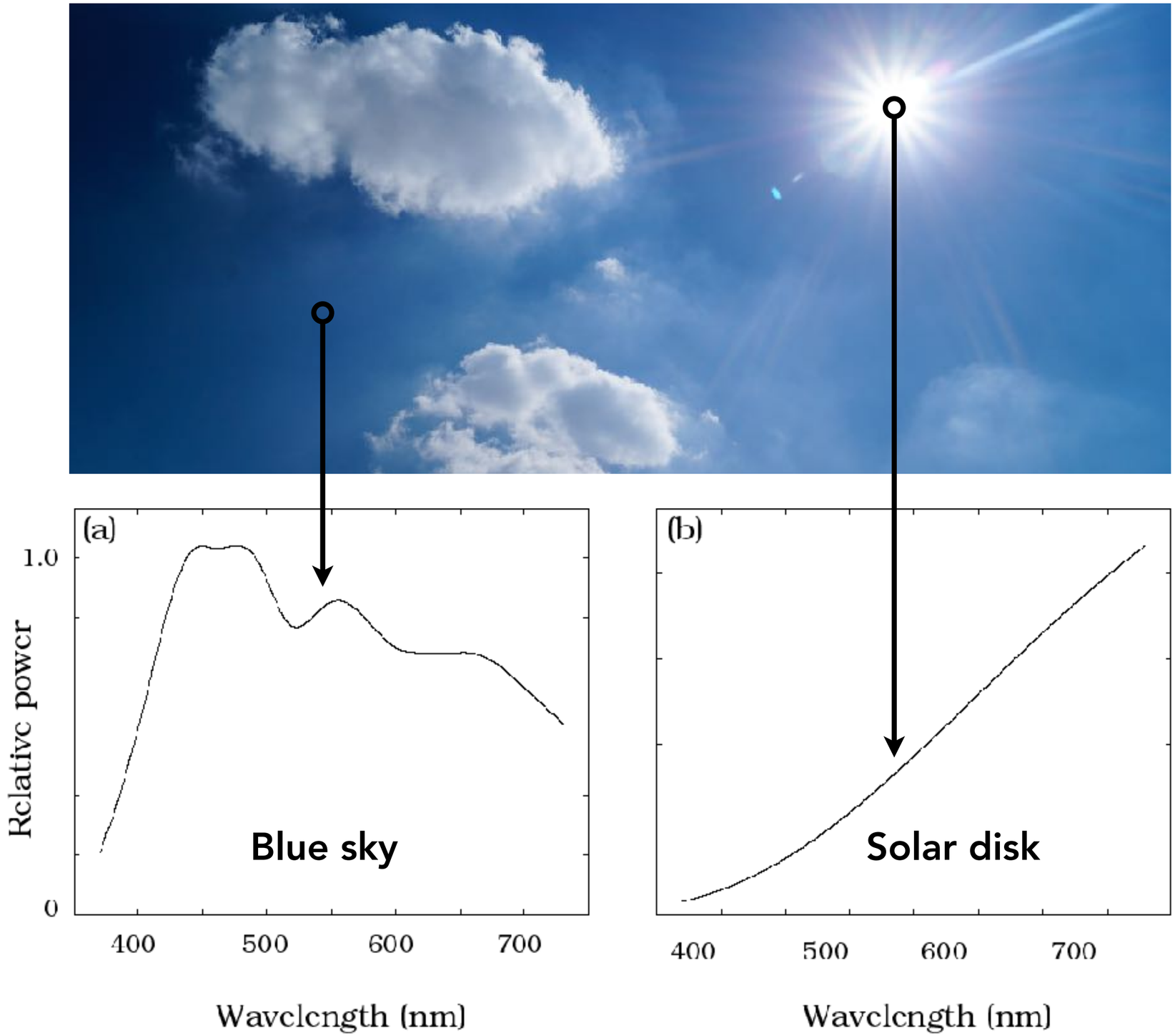
Hegyi et al. "Introduction to Practical Biochemistry" http://elte.prompt.hu/sites/default/files/tananyagok/IntroductionToPracticalBiochemistry/ch04s07.html

Spectral Power Distribution (SPD)

Salient property in measuring light

- The amount of light present at each wavelength
- Units:
  - radiometric units / nanometer (e.g. watts / nm)
    - Can also be unit-less
- Often use “relative units” scaled to maximum wavelength for comparison across wavelengths when absolute units are not important

Daylight Spectral Power Distributions Vary



[Brian Wandell]

Spectral Power Distribution of Light Sources

Describes distribution of energy by wavelength

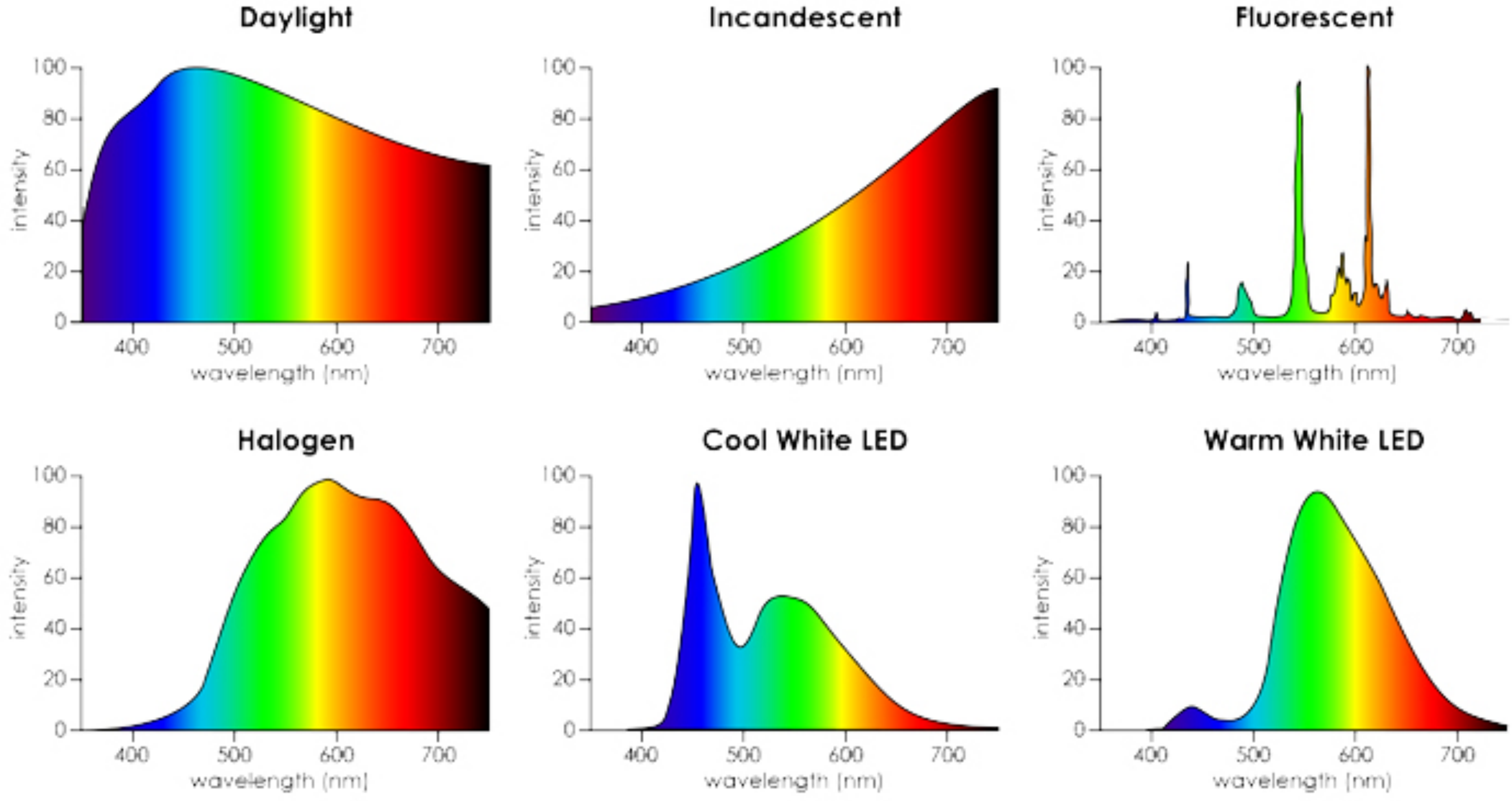
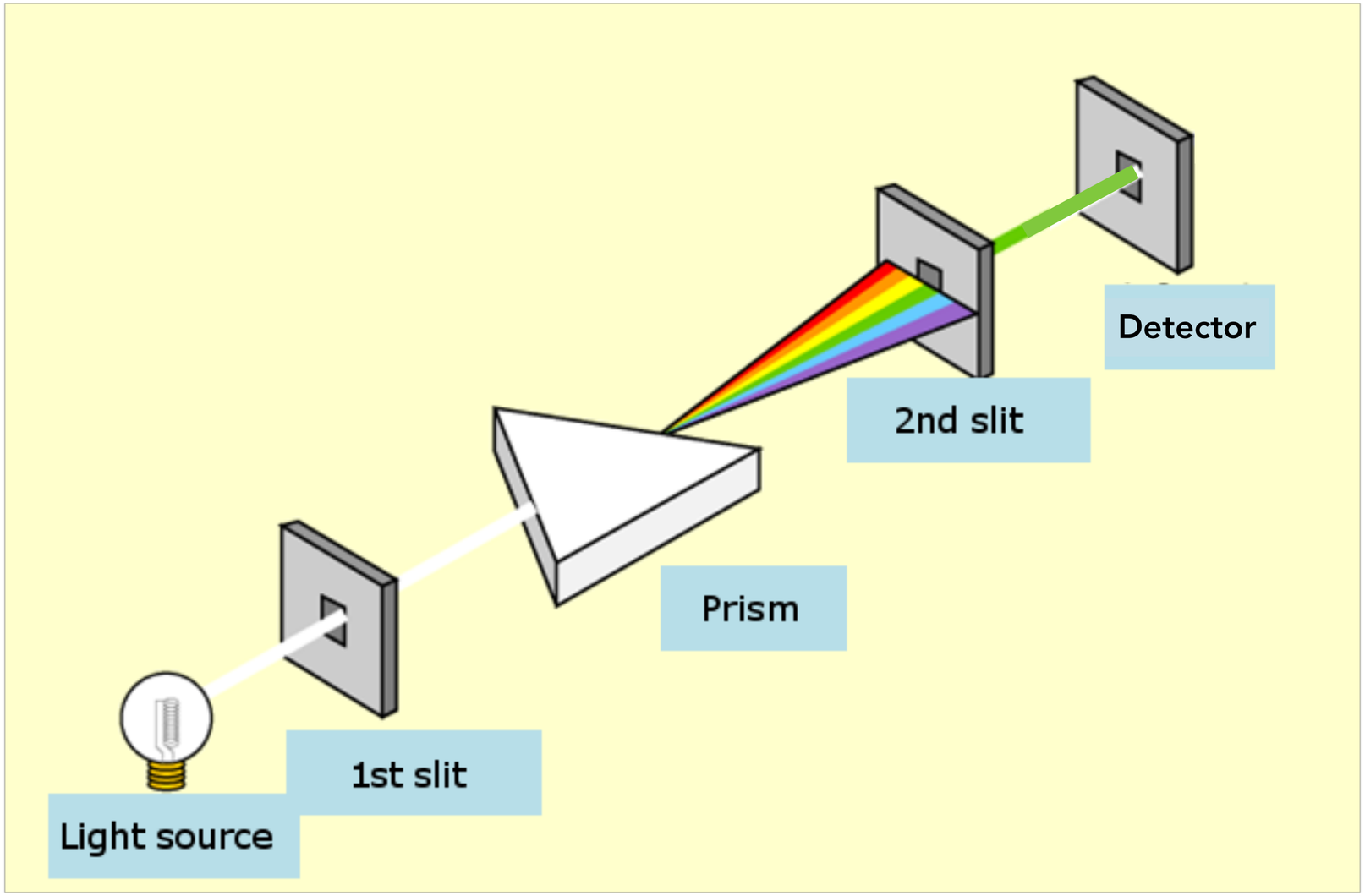


Figure credit: admesy ADVANCED MEASUREMENT SYSTEMS

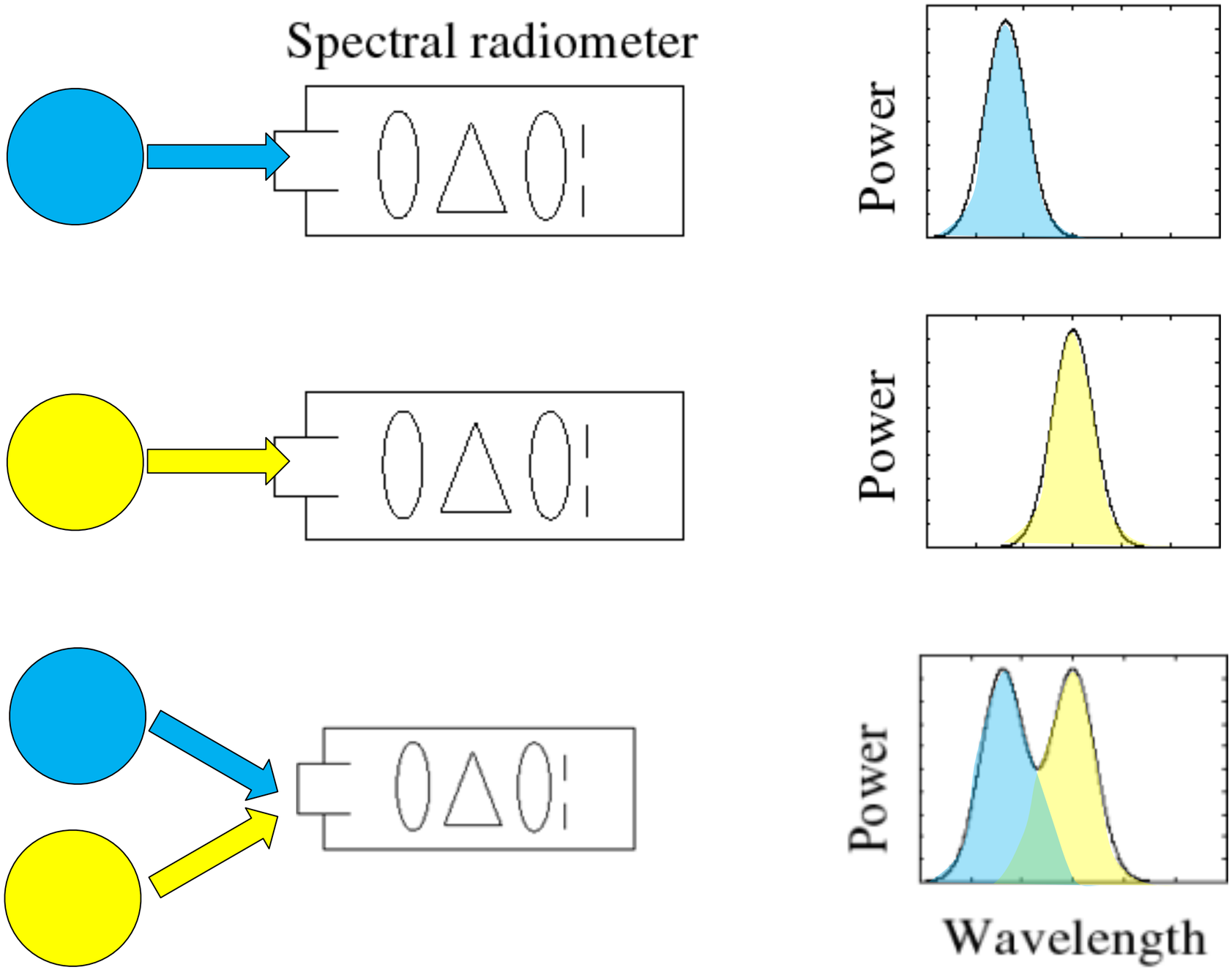
Spectrometer



For unknown light source, use a monochromator to isolate each wavelength of light for measurement

http://elte.prompt.hu/sites/default/files/tananyagok/IntroductionToPracticalBiochemistry/ch04s07.html Hegyi et al. "Introduction to Practical Biochemistry"

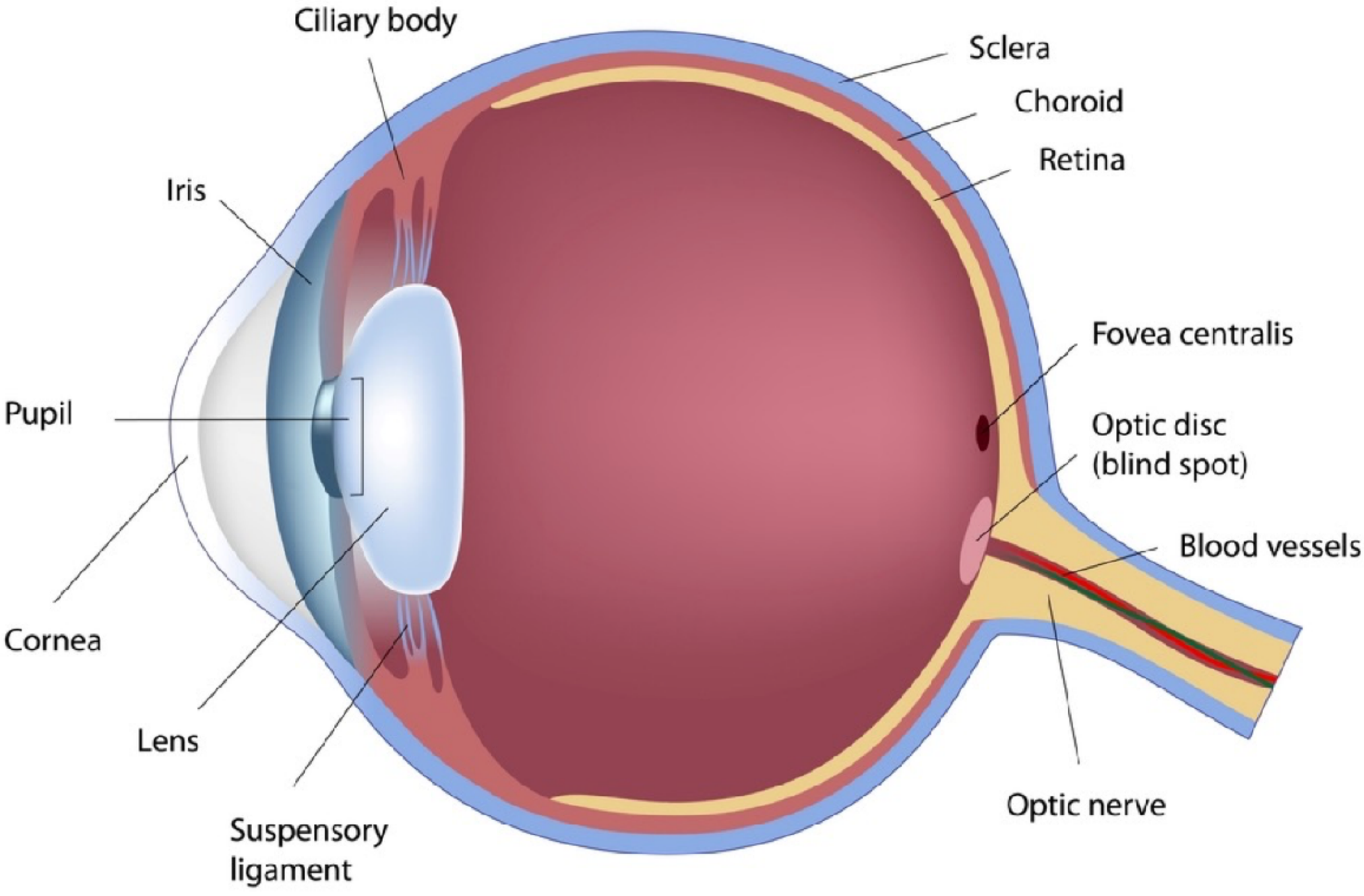
Superposition (Linearity) of Spectral Power Distributions



[Brian Wandell]

Biological Basis of Color

Anatomy of The Human Eye



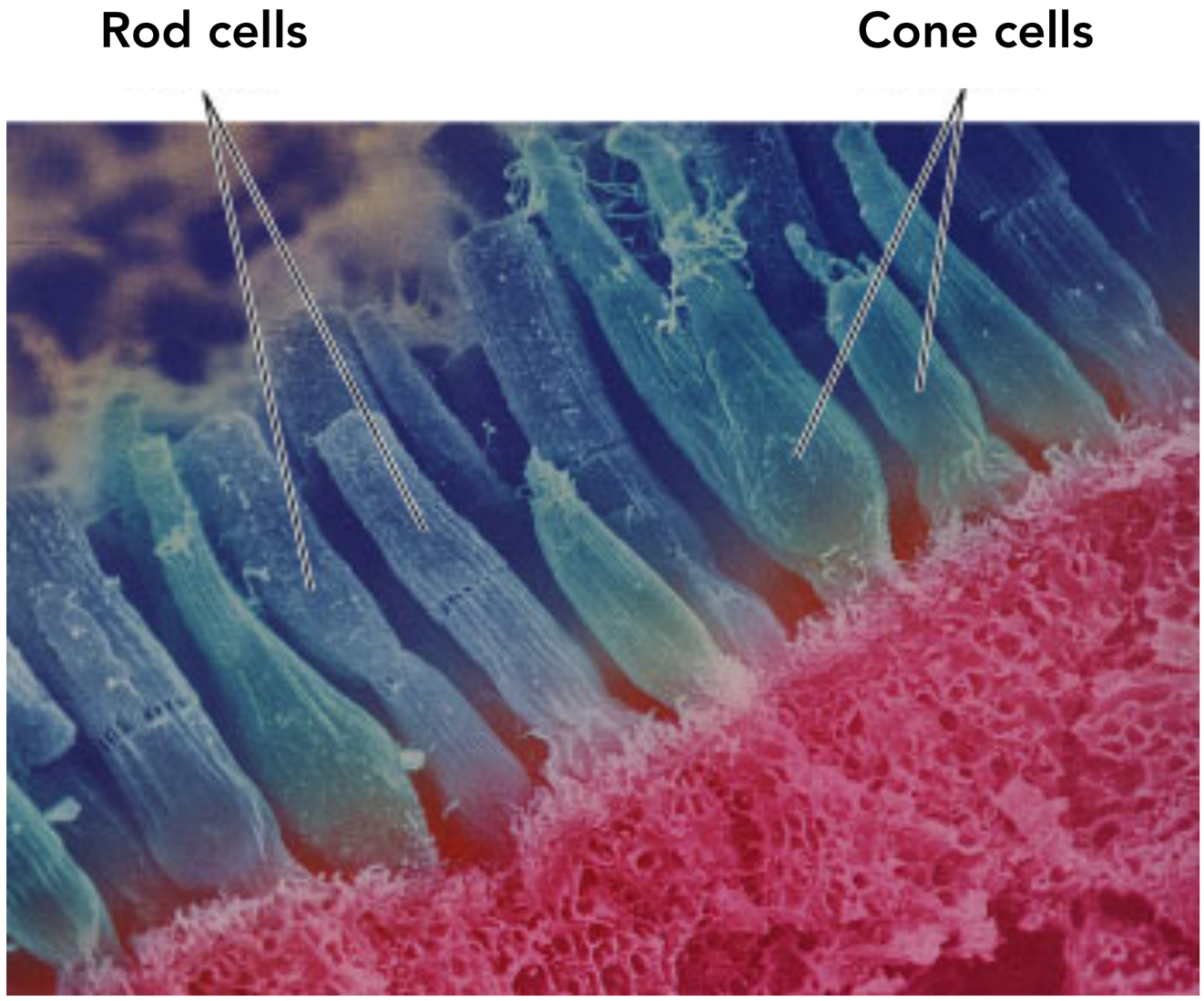
Retinal Photoreceptor Cells: Rods and Cones

Rods are primary receptors in very low light ("scotopic" conditions), e.g. dim moonlight

- ~120 million rods in eye
- Perceive only shades of gray, no color

Cones are primary receptors in typical light levels ("photopic")

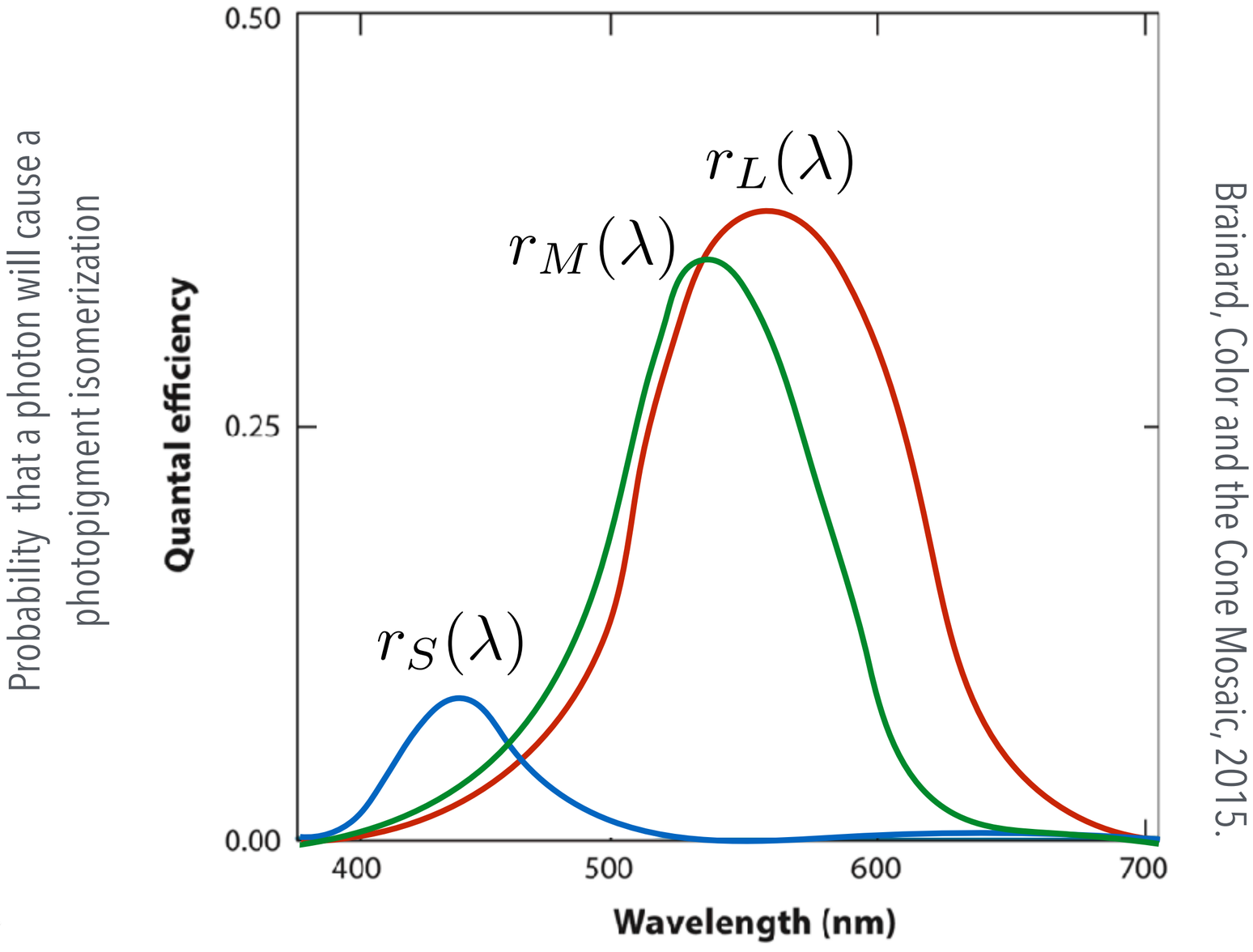
- ~6-7 million cones in eye
- Three types of cones, each with different spectral sensitivity
- Provide sensation of color



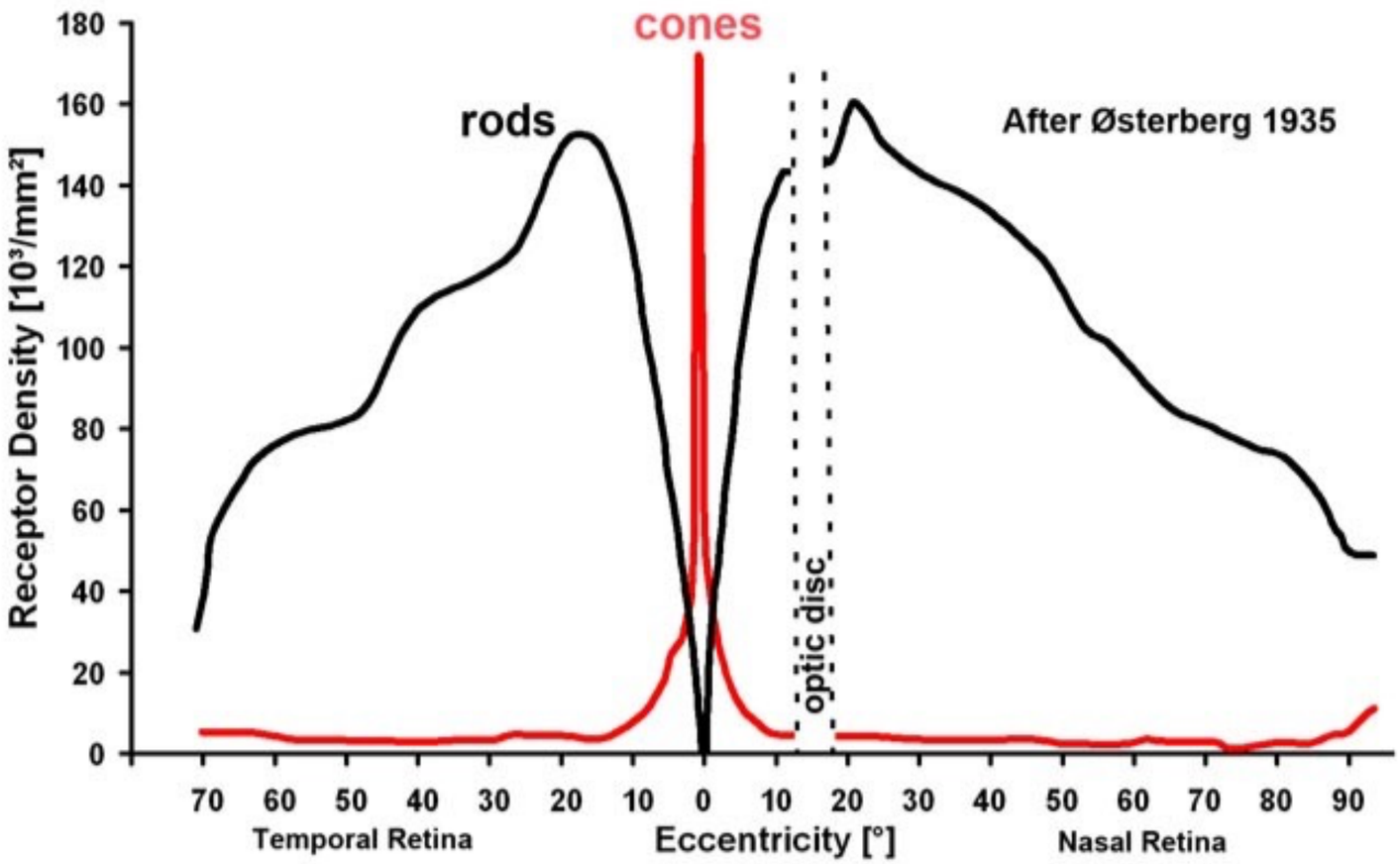
http://ebooks.bfwpub.com/life.php Figure 45.18

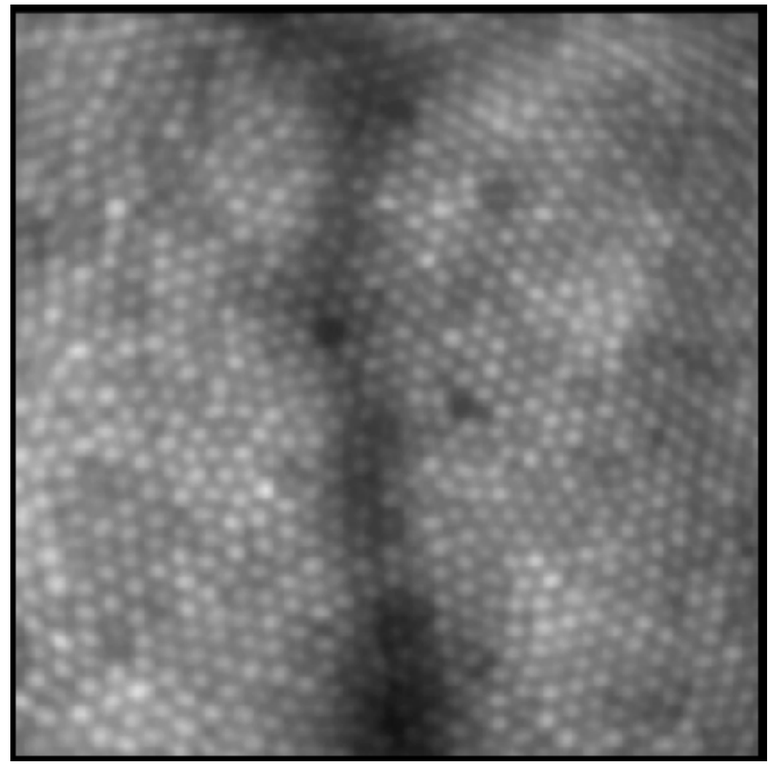
Human Retinal Cone Cell Response Functions (L, M, S Types)

Three types of cone cells: S, M, and L (corresponding to peak response at short, medium, and long wavelengths)



An Aside: Spatial Resolution of Rods and Cones in the Retina

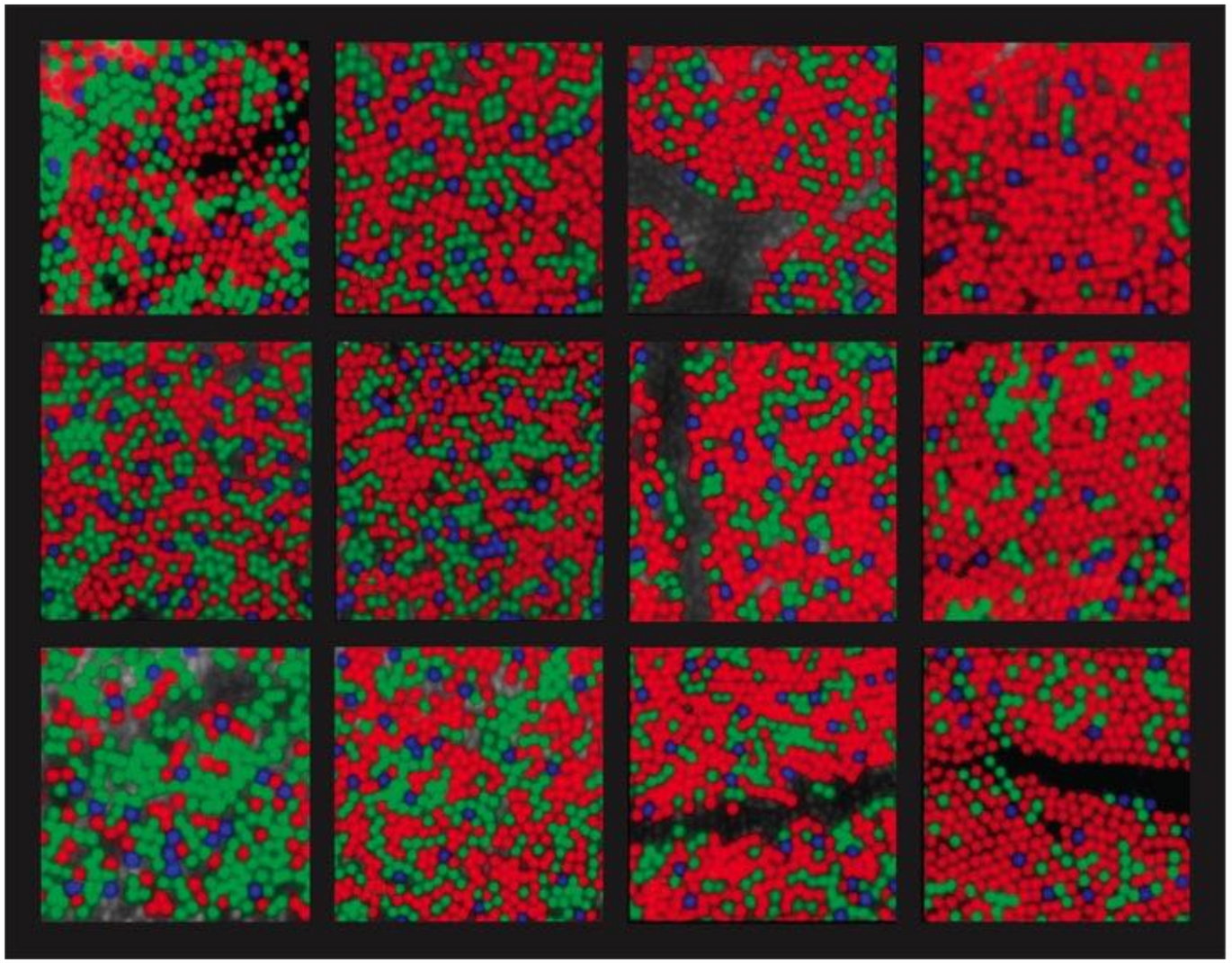




[Roorda 1999]

- Highest density of cones is in fovea (and no rods there)
- "Blind spot" at the optic disc, where optic nerve exits eye

Fraction of Three Cone Cell Types Varies Widely



Distribution of cone cells at edge of fovea in 12 different humans with normal color vision. Note high variability of percentage of different cone cell types. (false color image)

Measuring Light

A Simple Model of a Light Detector

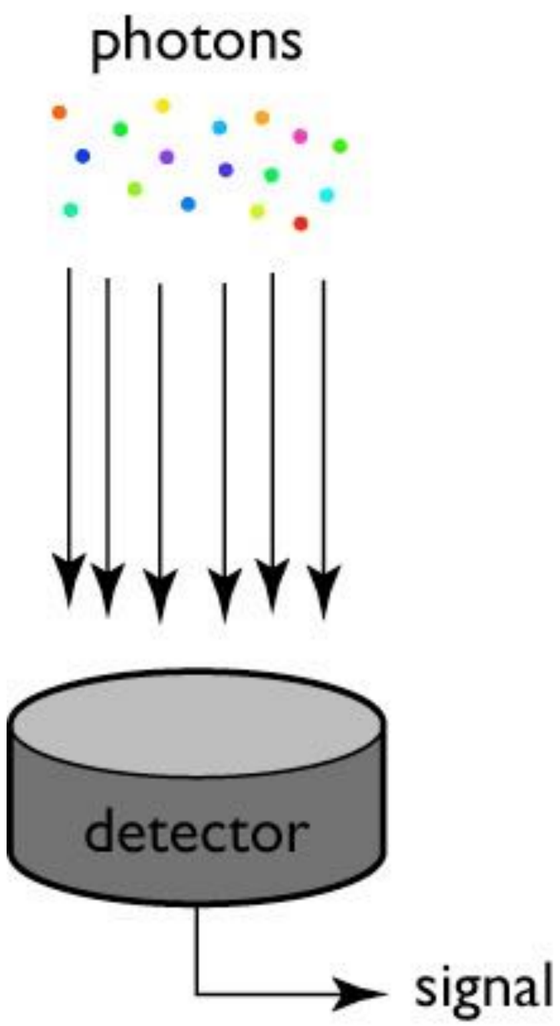
Produces a scalar value (a number) when photons land on it

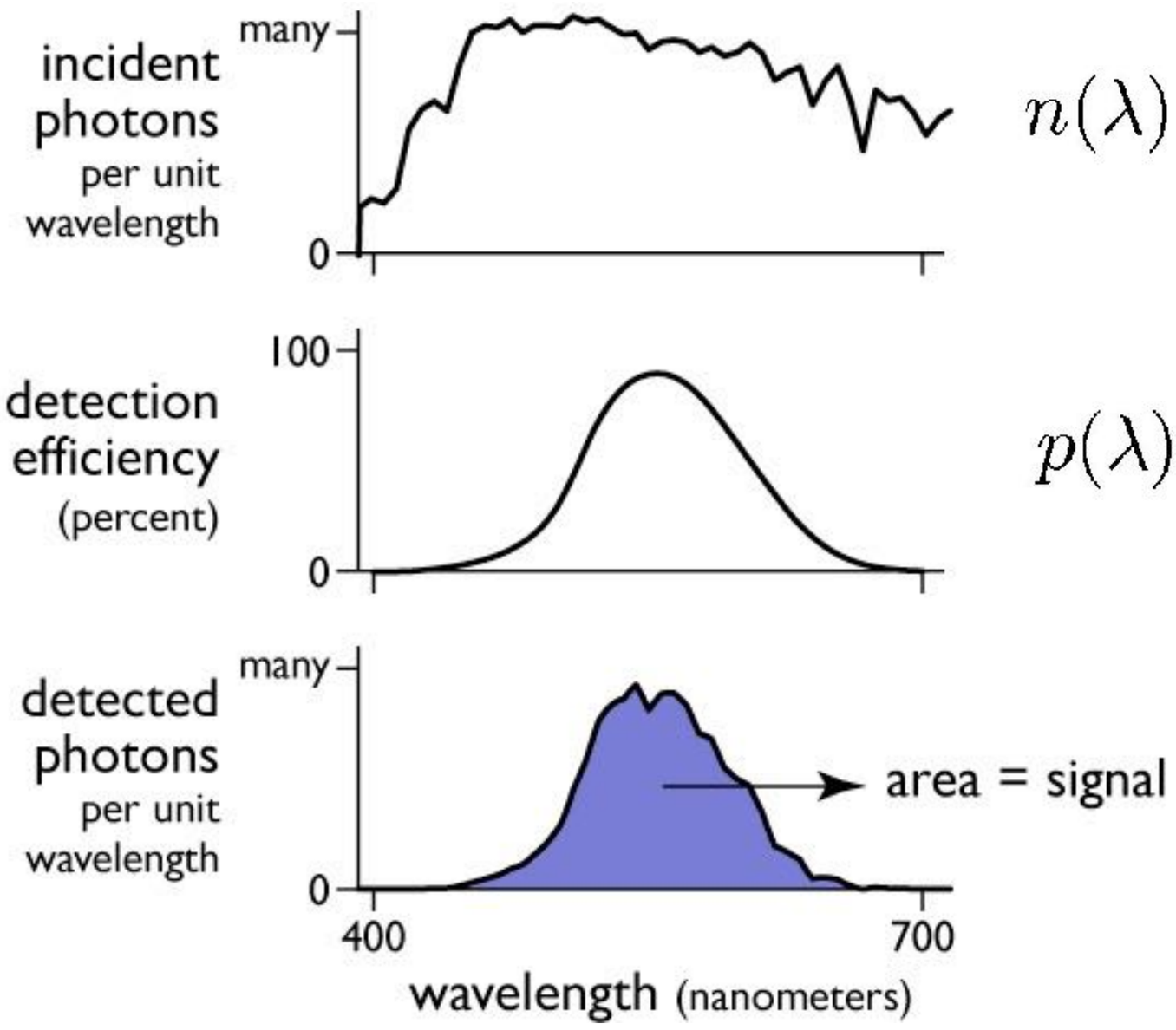
- Value depends only on the number of photons detected
- Each photon has a probability of being detected that depends on the wavelength
- No way to distinguish between signals caused by light of different wavelengths: there is just a number

This model works for many detectors:

- based on semiconductors (such as in a digital camera)
- based on visual photopigments (such as in human eyes)

A Simple Model of a Light Detector





Credit: Marschner

$$X = \int n(\lambda)p(\lambda)\,d\lambda$$

Mathematics of Light Detection

Same math carries over to spectral power distributions

- Light entering the detector has its spectral power distribution, s(λ)
- Detector has its spectral sensitivity or spectral response, r(λ)

$$X = \int s(\lambda) r(\lambda)\, d\lambda$$

measured signal

input spectrum

detector's sensitivity

Mathematics of Light Detection

If we think of s and r as discrete, sampled representations (vectors) rather than continuous functions, this integral operation is a dot product:

$$X = s \cdot r$$

We can also write this in matrix form:

$$X = \begin{bmatrix} — & s & — \end{bmatrix} \begin{bmatrix} | \\ r \\ | \end{bmatrix}$$

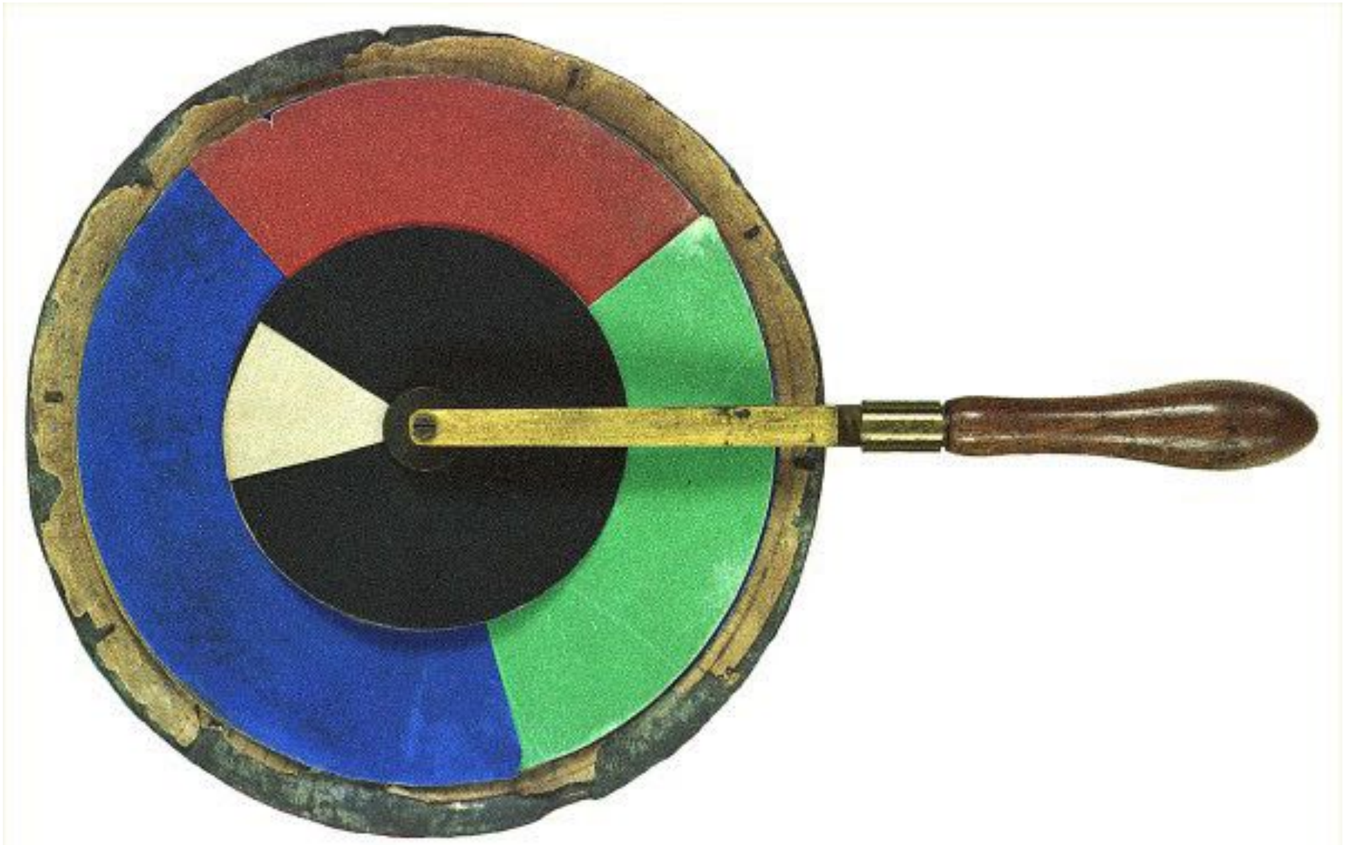
Dimensionality Reduction From ∞ to 1

At the detector:

- SPD is a function of wavelength (∞ - dimensional signal)
- Detector result is a scalar value (1 - dimensional signal)

Tristimulus Theory of Color

Maxwell's Crucial Color Matching Experiment



http://designblog.rietveldacademie.nl/?p=68422

Portrait: http://rsta.royalsocietypublishing.org/content/366/1871/1685

To Be Continued