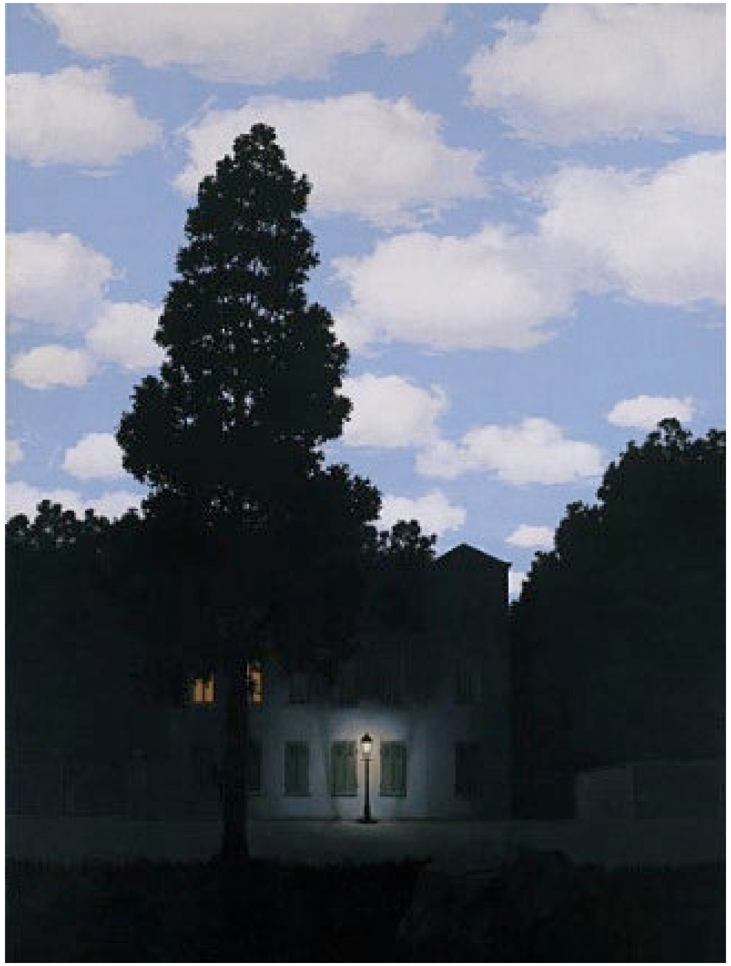
Light and Color



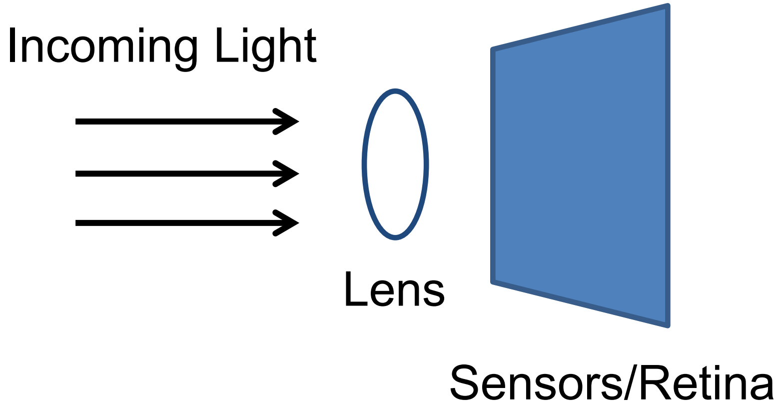
“Empire of Light”, Magritte

Computational Photography

Derek Hoiem, University of Illinois

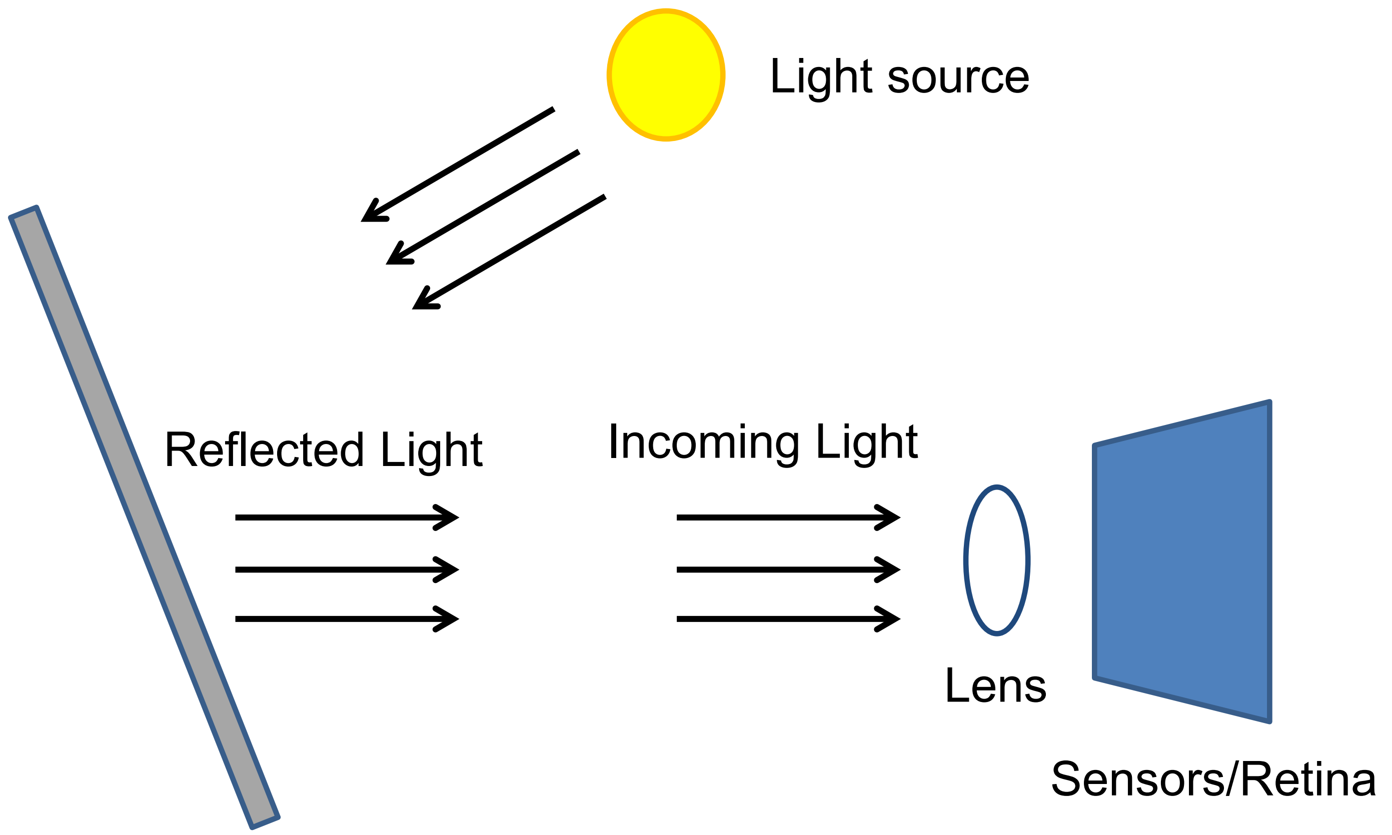
Today's class

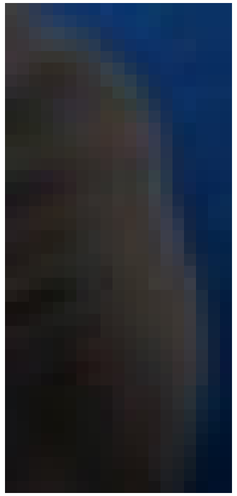
- How is incoming light measured by the eye or camera?



Today's class

- How is incoming light measured by the eye or camera?
- How is light reflected from a surface?





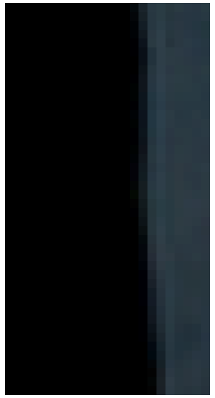
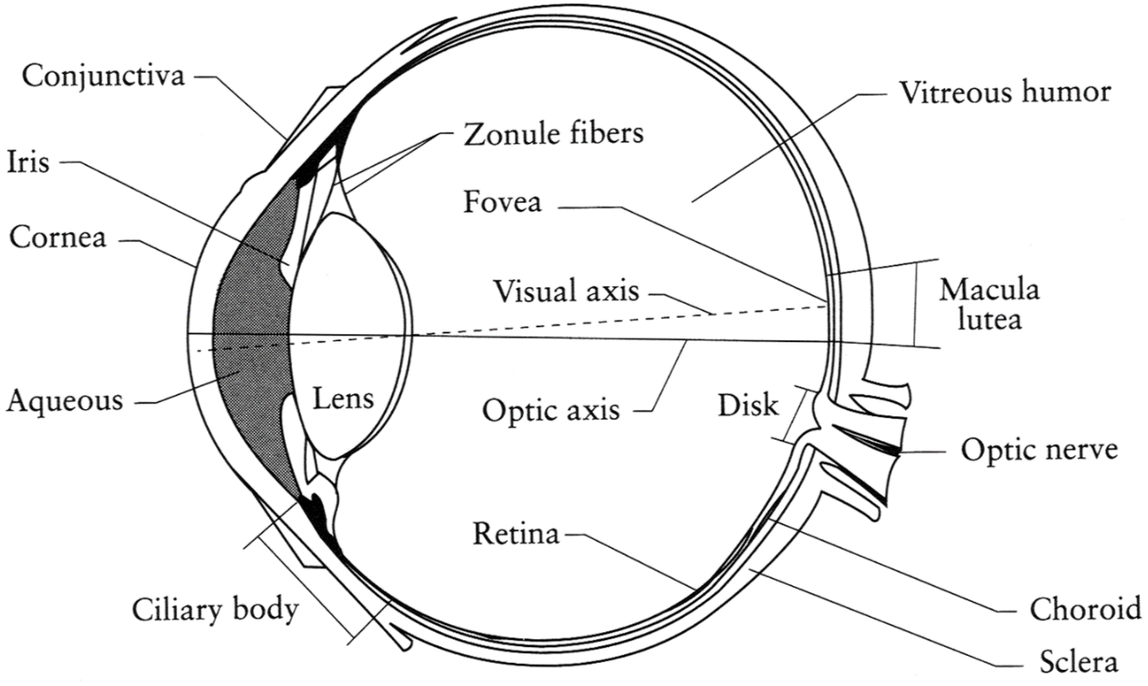


Photo by nickwheeleroz, Flickr

Slide: Forsyth

The Eye

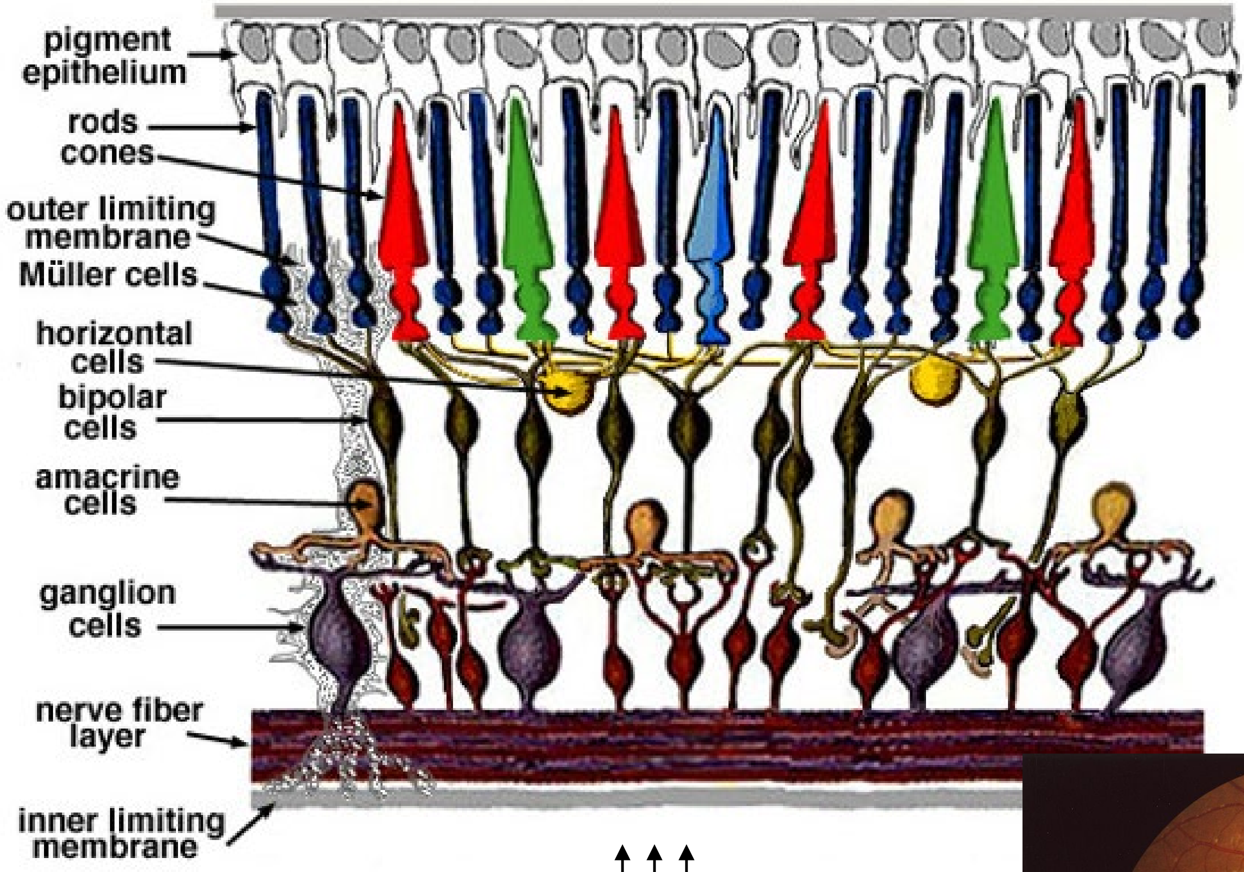


The human eye is a camera!

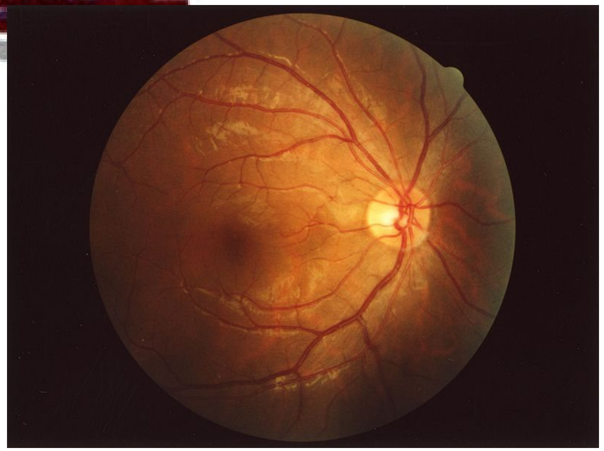
- **Iris** - colored annulus with radial muscles
- **Pupil** - the hole (aperture) whose size is controlled by the iris
- What's the "film"?
  - photoreceptor cells (rods and cones) in the **retina**

Image credit: Fig. 1.1, Principles of Digital Image Synthesis, Volume 1. Andrew Glassner

Retina up-close



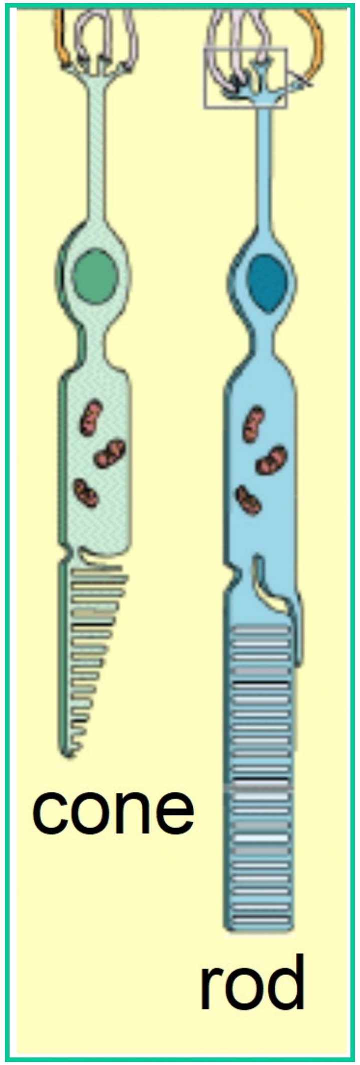
Light



Two types of light-sensitive receptors

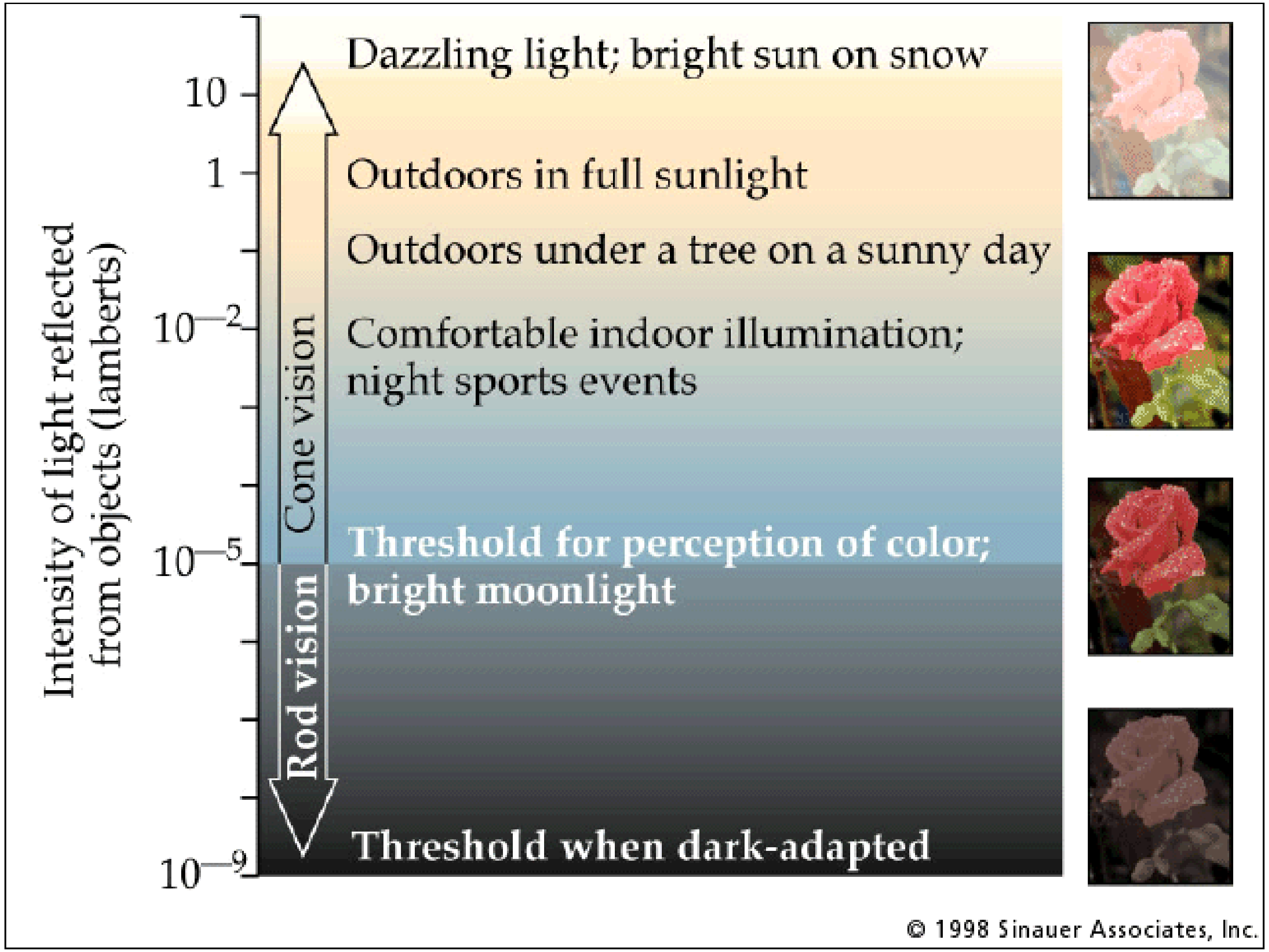
Cones
- cone-shaped
- less sensitive
- operate in high light
- color vision

Rods
- rod-shaped
- highly sensitive
- operate at night
- gray-scale vision
- slower to respond

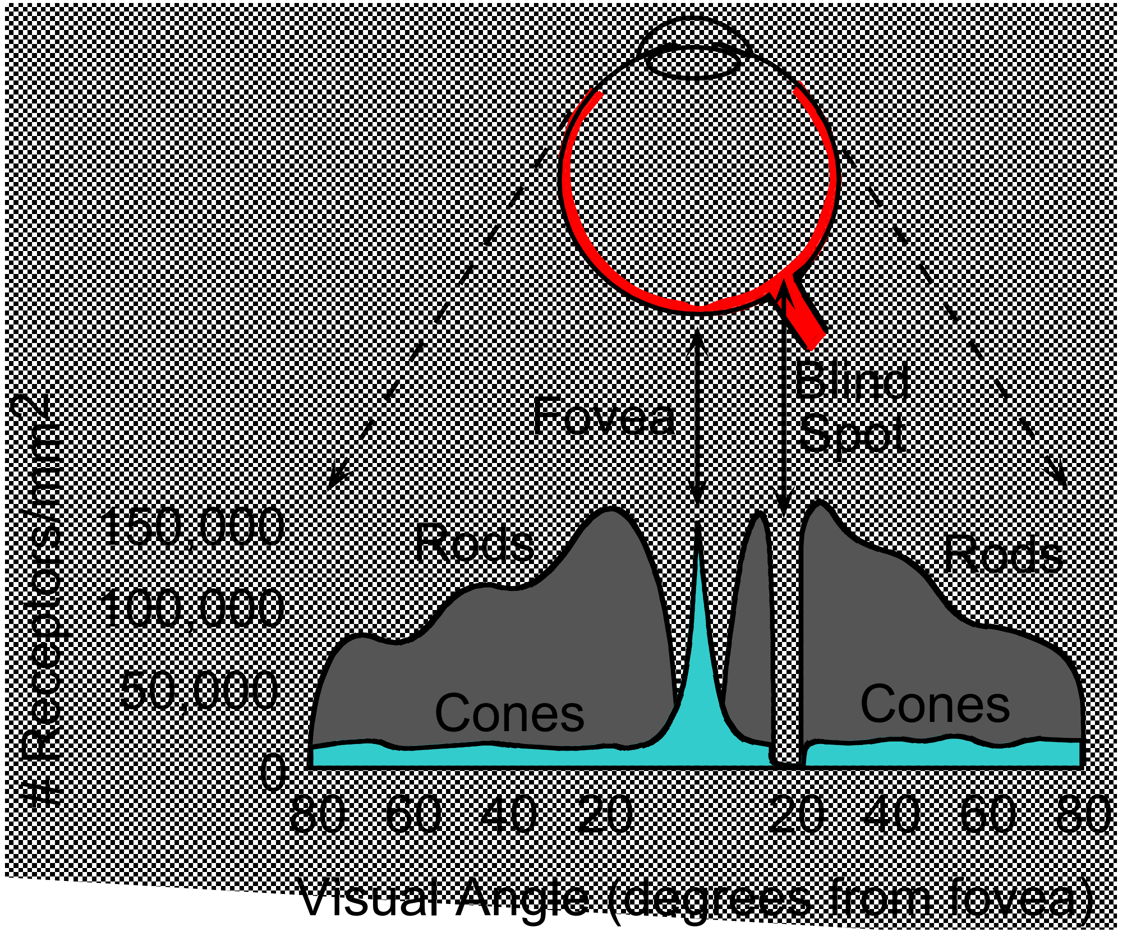


Slide Credit: Efros

Rod / Cone sensitivity



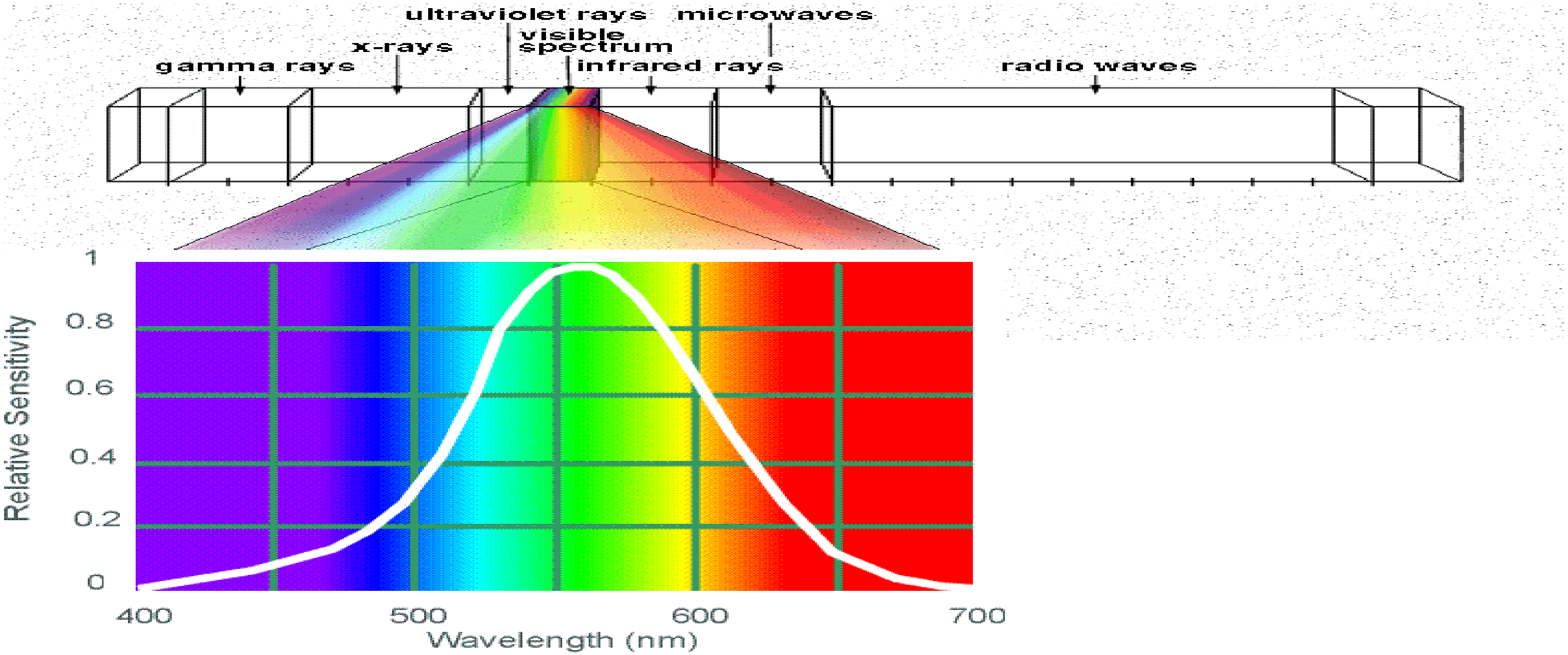
Distribution of Rods and Cones



Night Sky: why are there more stars off-center?

Slide Credit: Efros

Electromagnetic Spectrum

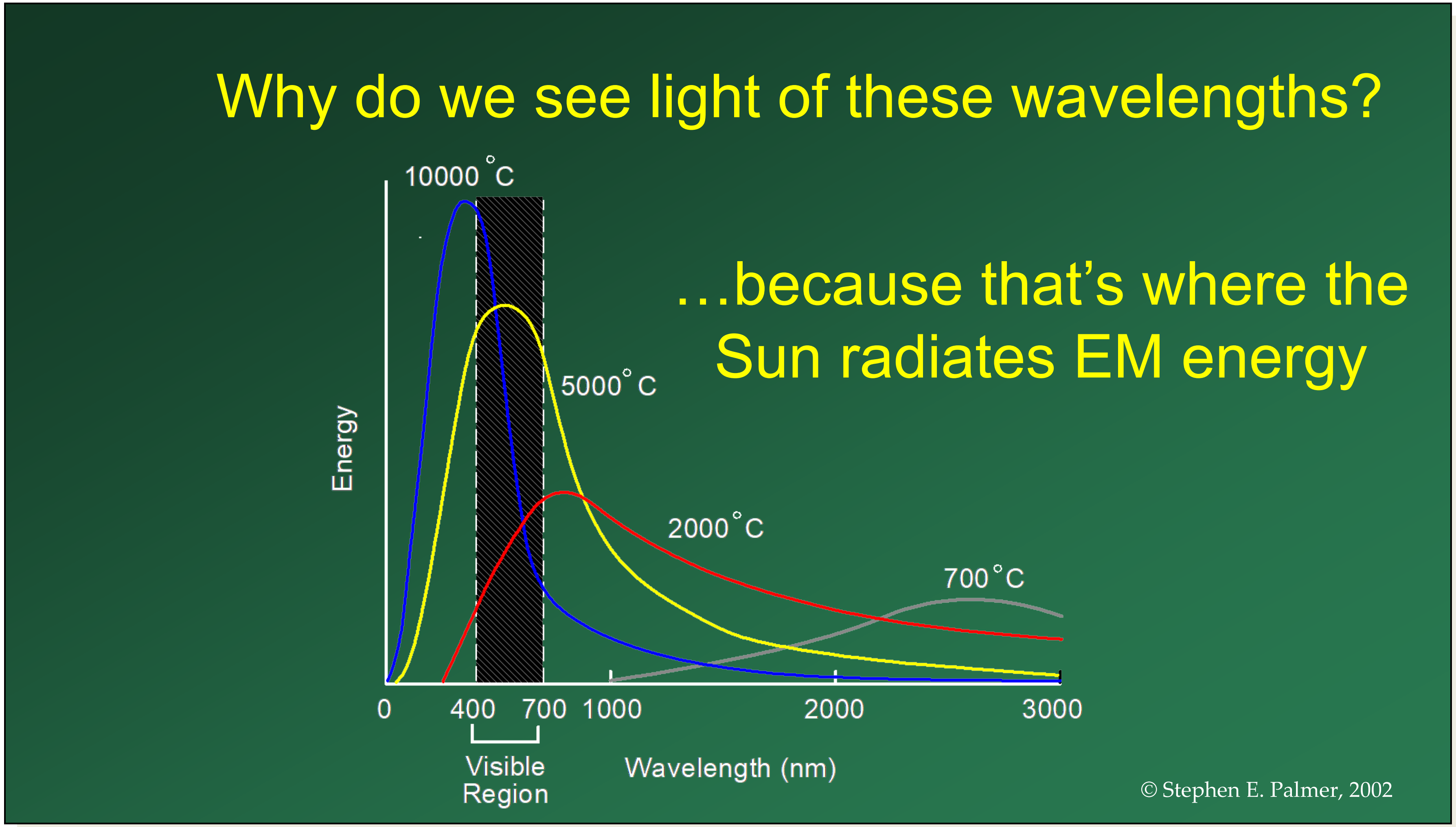


Human Luminance Sensitivity Function

http://www.yorku.ca/eye/photopik.htm

Slide Credit: Efros

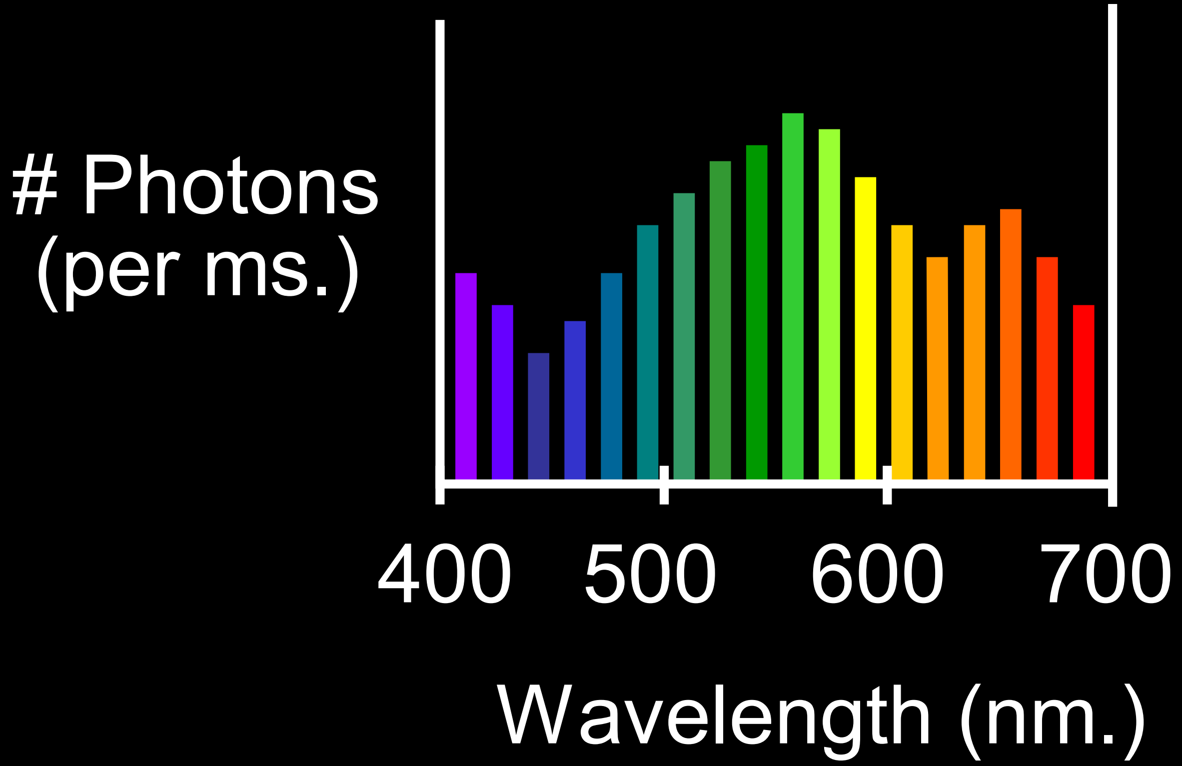
Visible Light



[Complete "Color Vision" by Palmer slides]

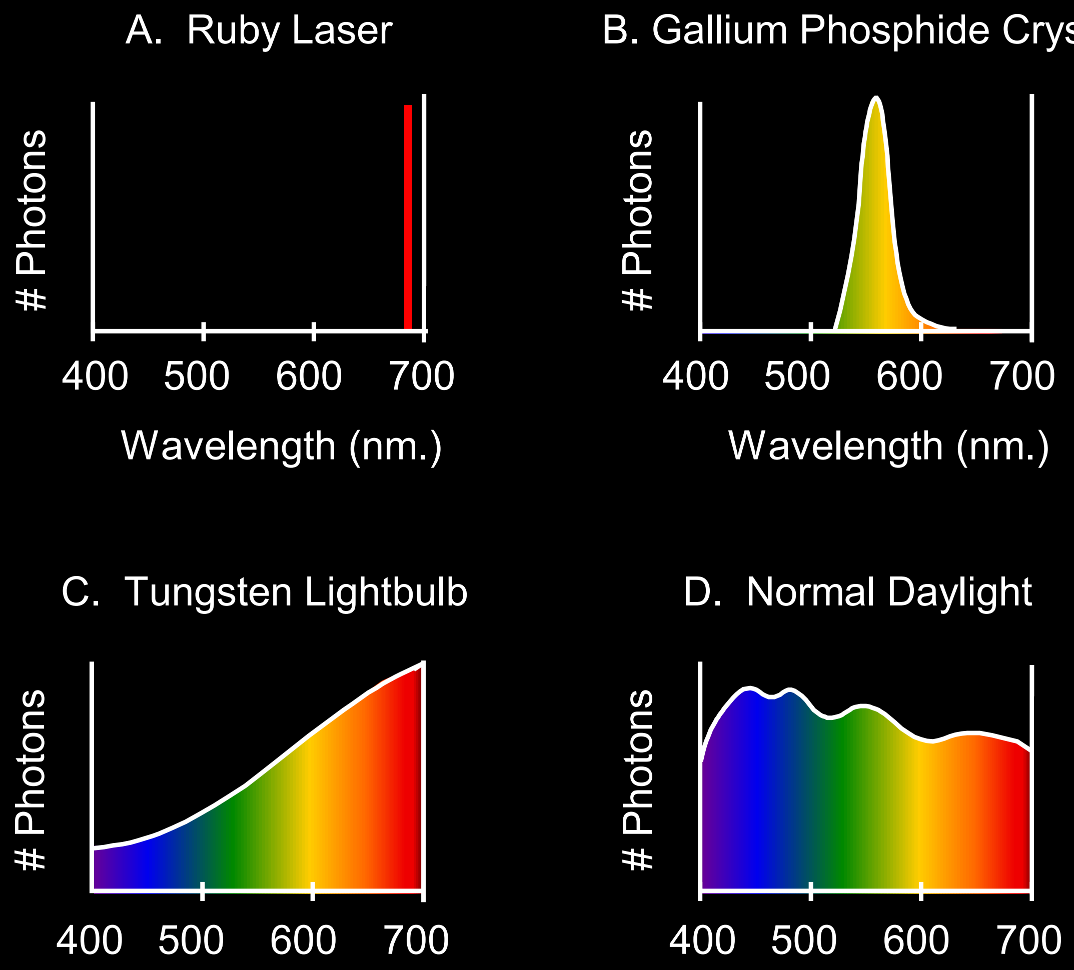
The Physics of Light

Any patch of light can be completely described physically by its spectrum: the number of photons (per time unit) at each wavelength 400 - 700 nm.



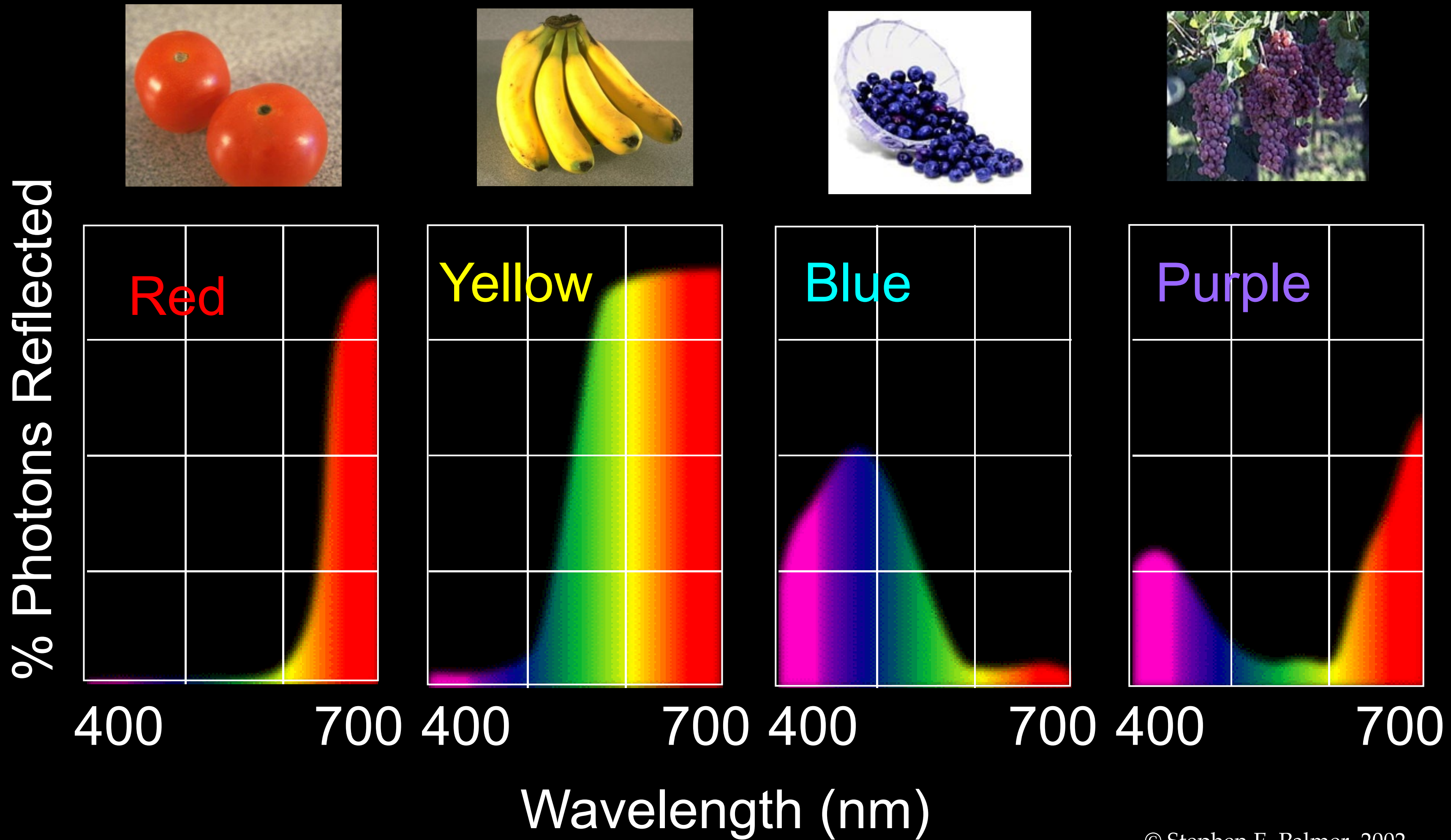
The Physics of Light

Some examples of the spectra of light sources

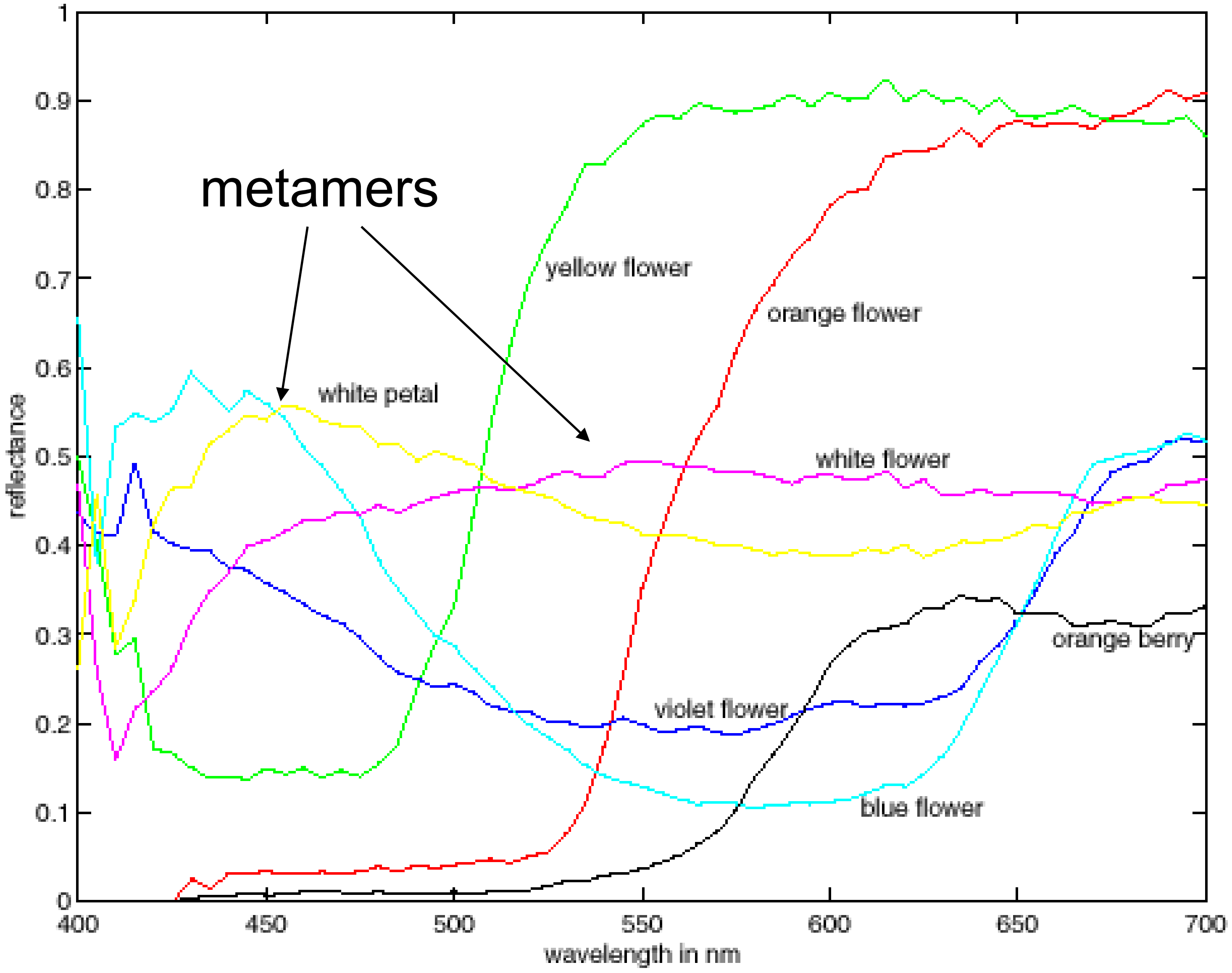


The Physics of Light

Some examples of the reflectance spectra of surfaces

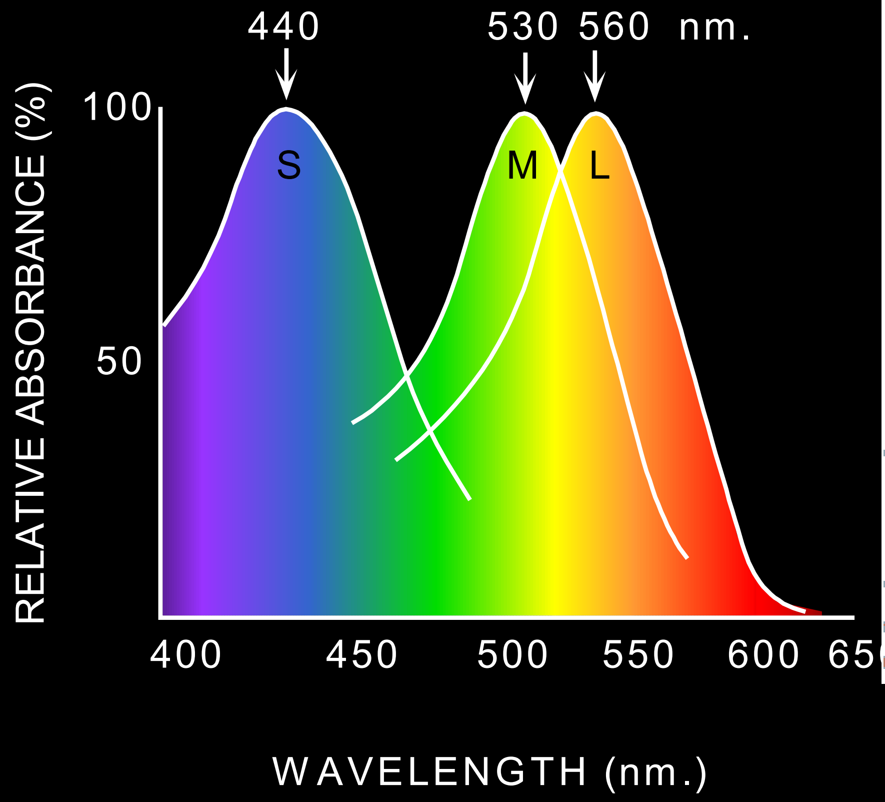


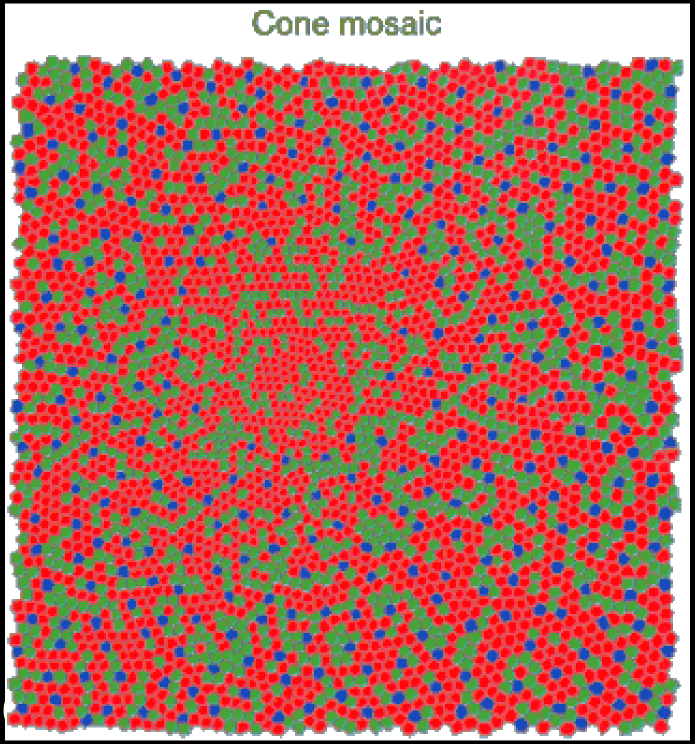
More Spectra



Physiology of Color Vision

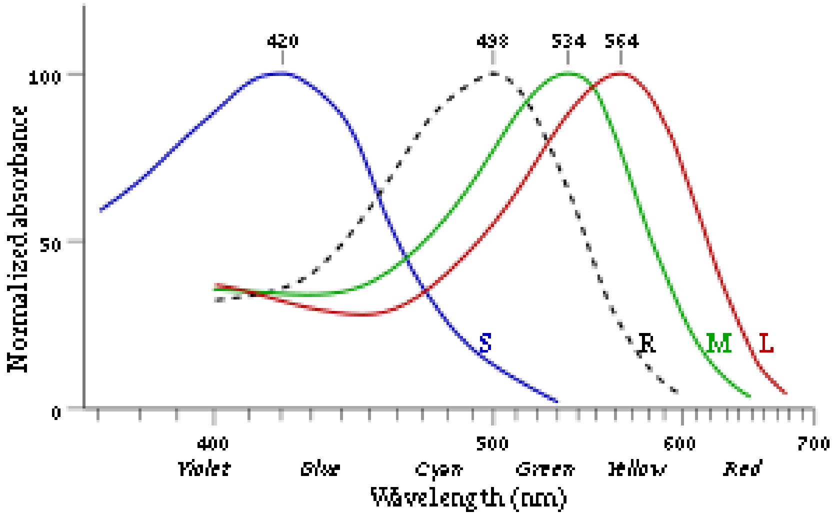
Three kinds of cones:





- Why are M and L cones so close?
- Why are there 3?

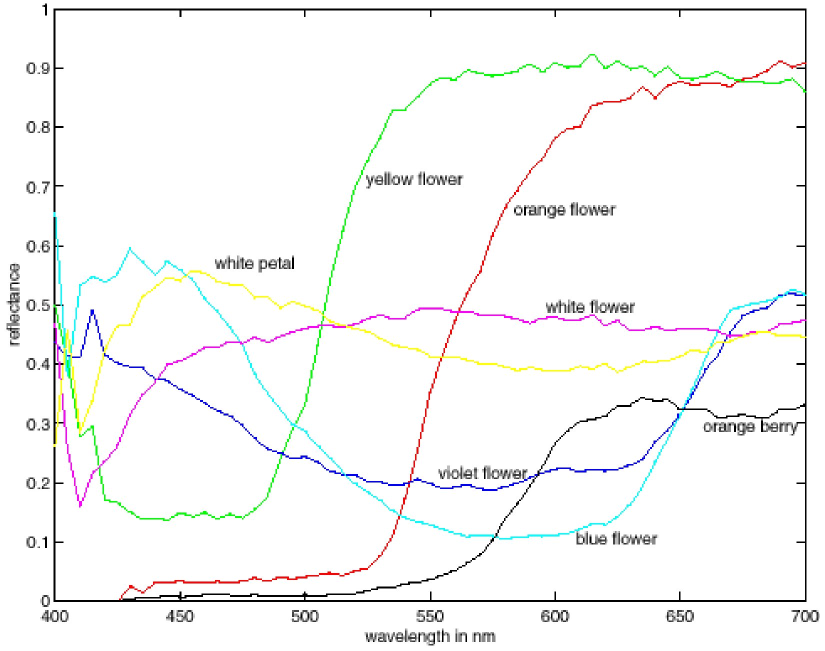
3 is better than 2…



- “M” and “L” on the X-chromosome
  - Why men are more likely to be color blind
- “L” has high variation, so some women are tetrachromatic
- Some animals have 1 (night animals), 2 (e.g., dogs), 4 (fish, birds), 5 (pigeons, some reptiles/amphibians), or even 12 (mantis shrimp) types of color receptors

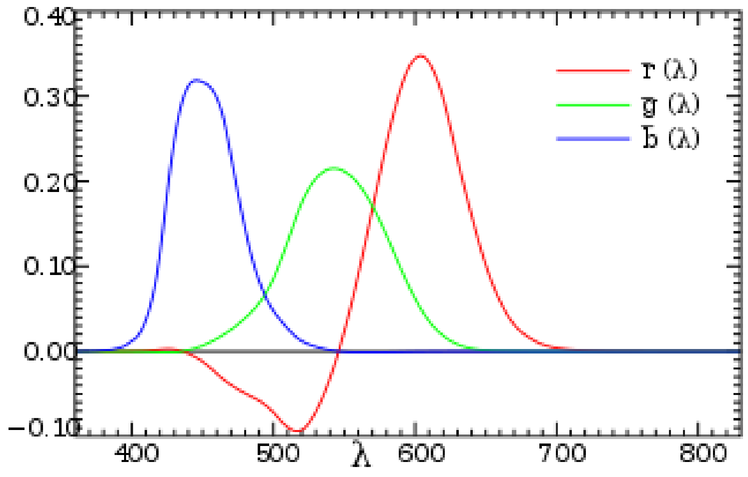
http://en.wikipedia.org/wiki/Color_vision

We don’t perceive a spectrum (or even RGB)

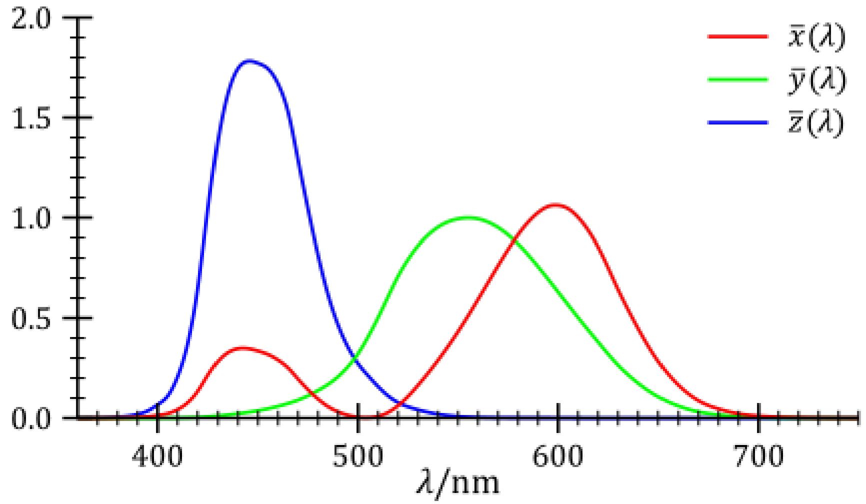


- We perceive
  - Hue: mean wavelength, color
  - Saturation: variance, vividness
  - Intensity: total amount of light
- Same perceived color can be recreated with combinations of three primary colors (“trichromacy”)

Trichromacy and CIE-XYZ



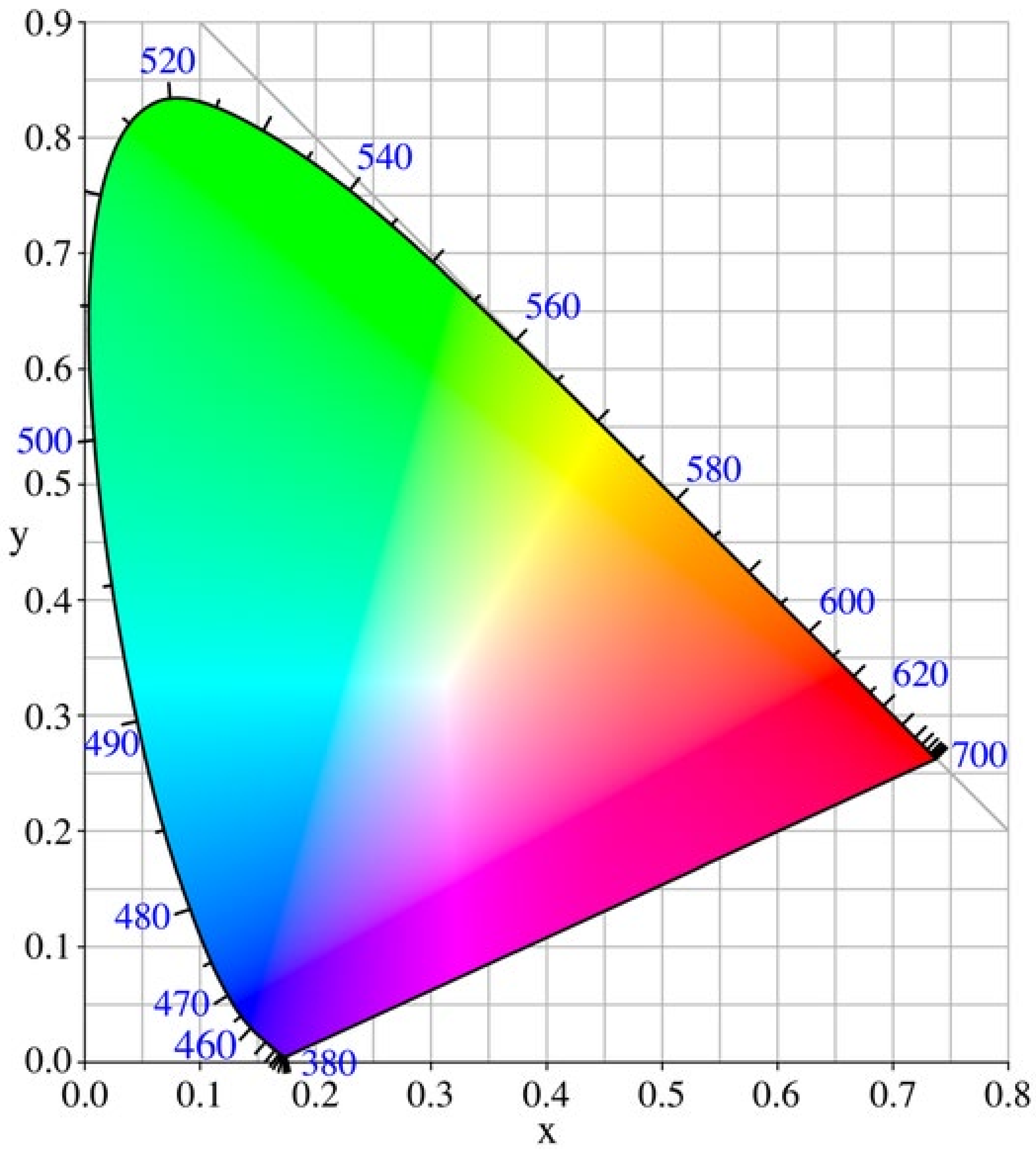
Perceptual equivalents with RGB



Perceptual equivalents with CIE-XYZ

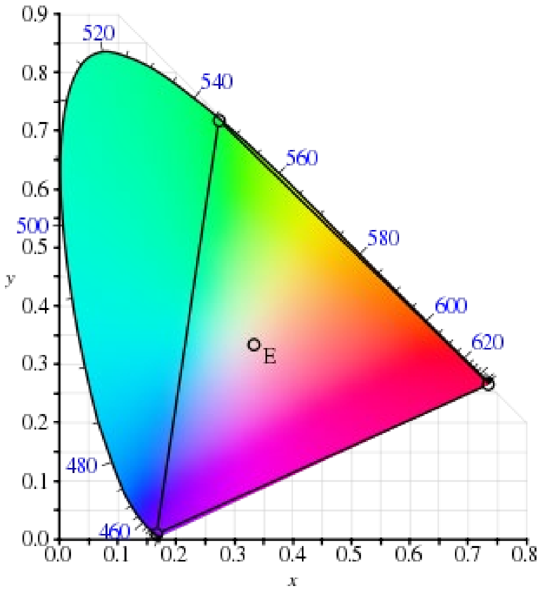
$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \frac{1}{0.17697} \begin{bmatrix} 0.49 & 0.31 & 0.20 \\ 0.17697 & 0.81240 & 0.01063 \\ 0.00 & 0.01 & 0.99 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

CIE-XYZ



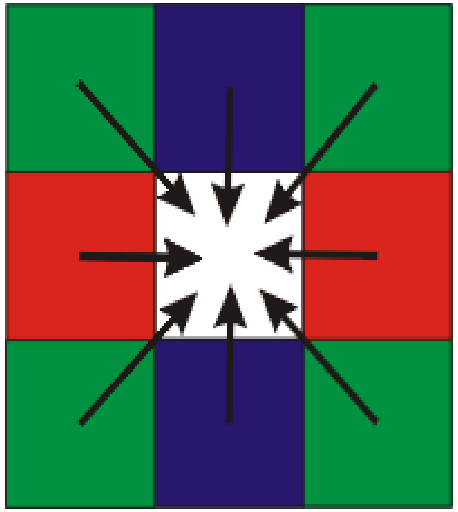
$$x = \frac{X}{X + Y + Z}$$

$$y = \frac{Y}{X + Y + Z}$$

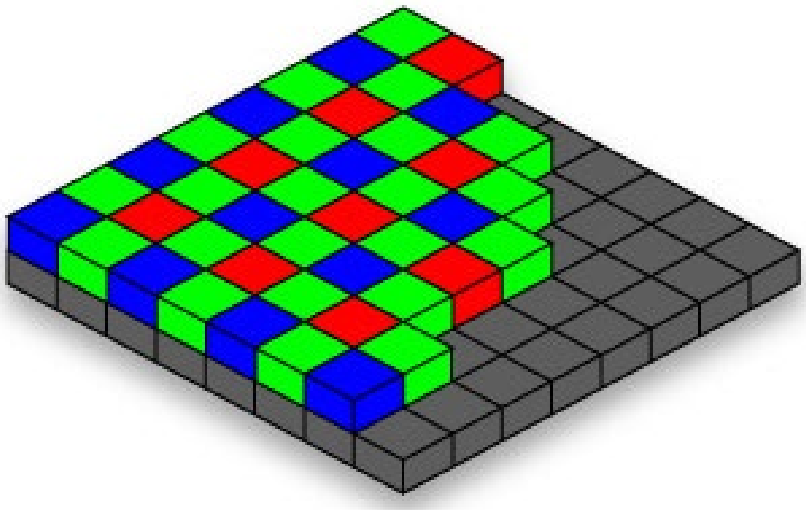


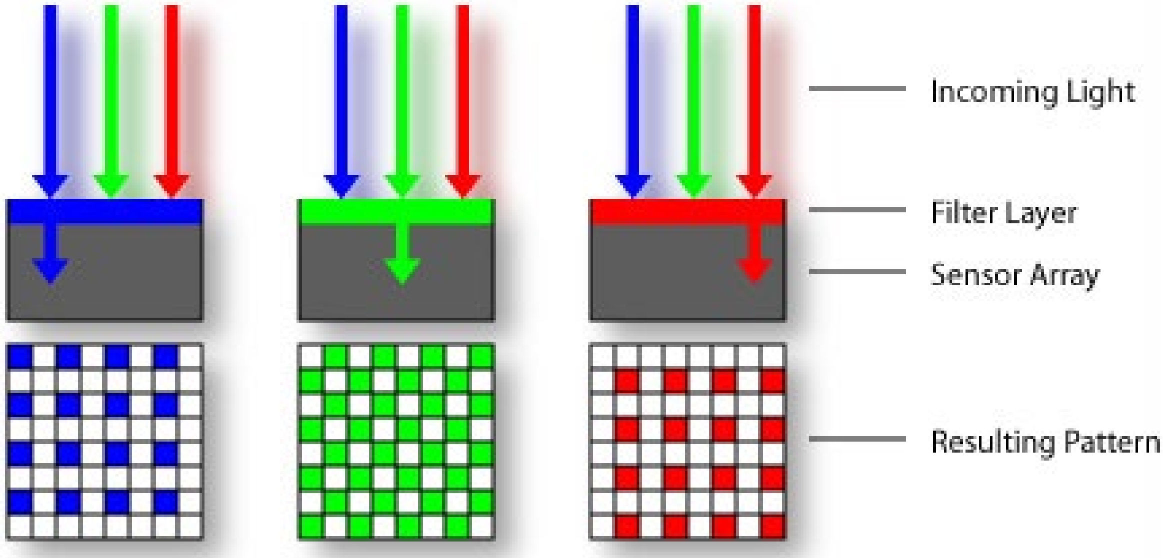
RGB portion is in triangle

Color Sensing: Bayer Grid



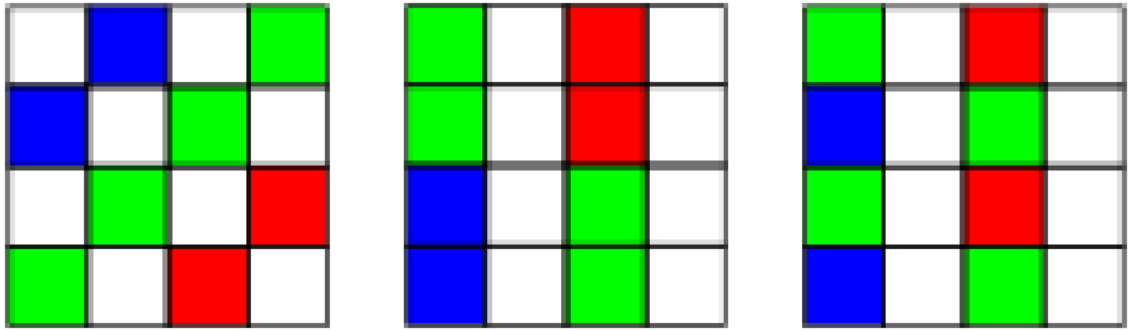
Estimate RGB at each cell
from neighboring values





http://en.wikipedia.org/wiki/Bayer_filter

Alternative to Bayer: RGB+W

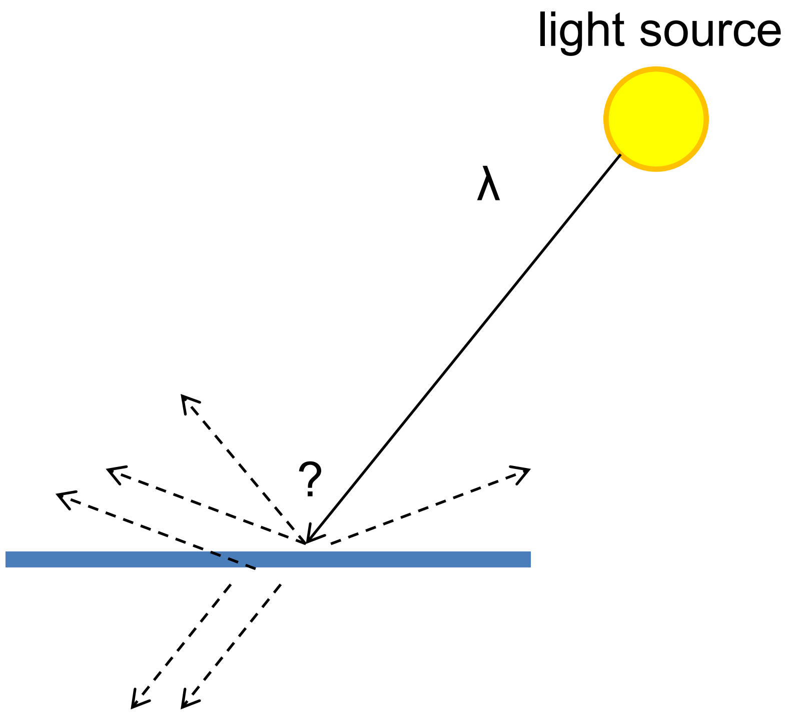


Kodak 2007

How is light reflected from a surface?

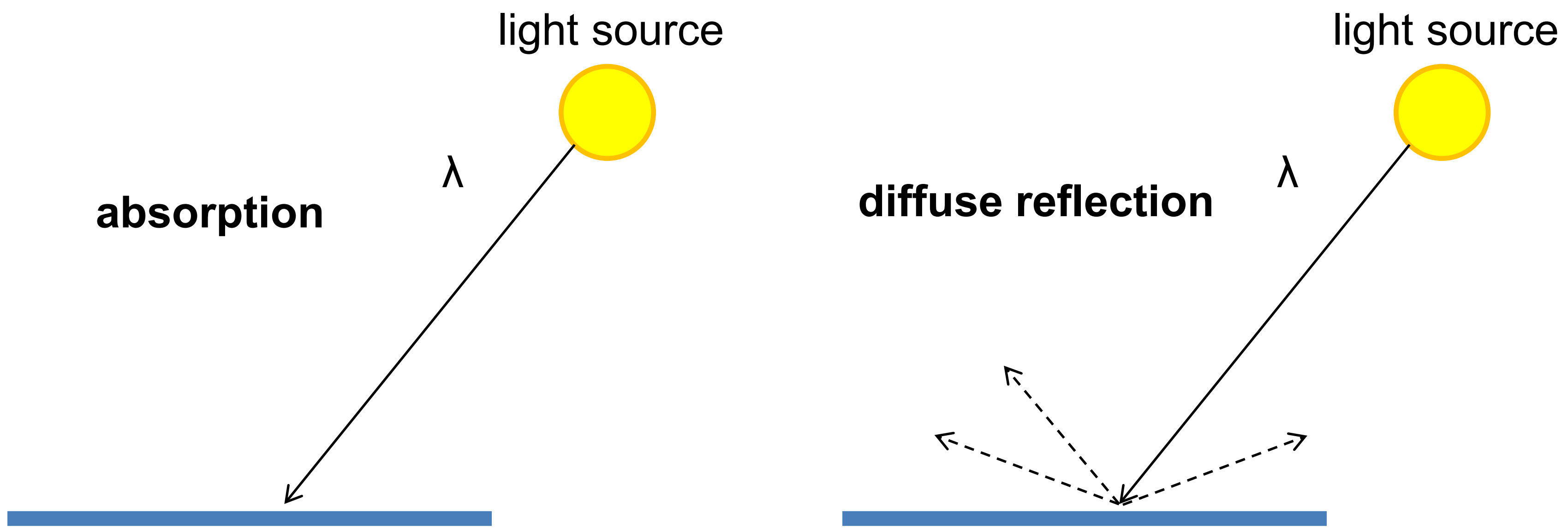
Depends on

- Illumination properties: wavelength, orientation, intensity
- Surface properties: material, surface orientation, roughness, etc.



Lambertian surface

- Some light is absorbed (function of albedo)
- Remaining light is reflected in all directions (diffuse reflection)
- Examples: soft cloth, concrete, matte paints



Diffuse reflection

Intensity *does* depend on illumination angle because less light comes in at oblique angles.

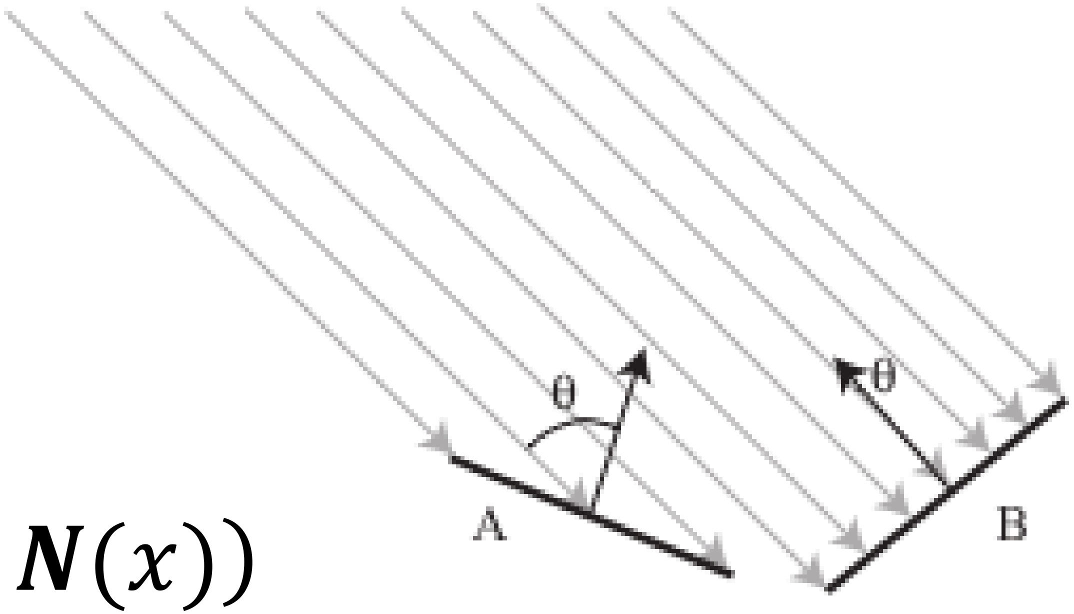
$\rho =$ albedo

$\boldsymbol{S} =$ directional source

$\boldsymbol{N} =$ surface normal

$\mathrm{I} =$ image intensity

$$I(x) = \rho(x)(\boldsymbol{S} \cdot \boldsymbol{N}(x))$$



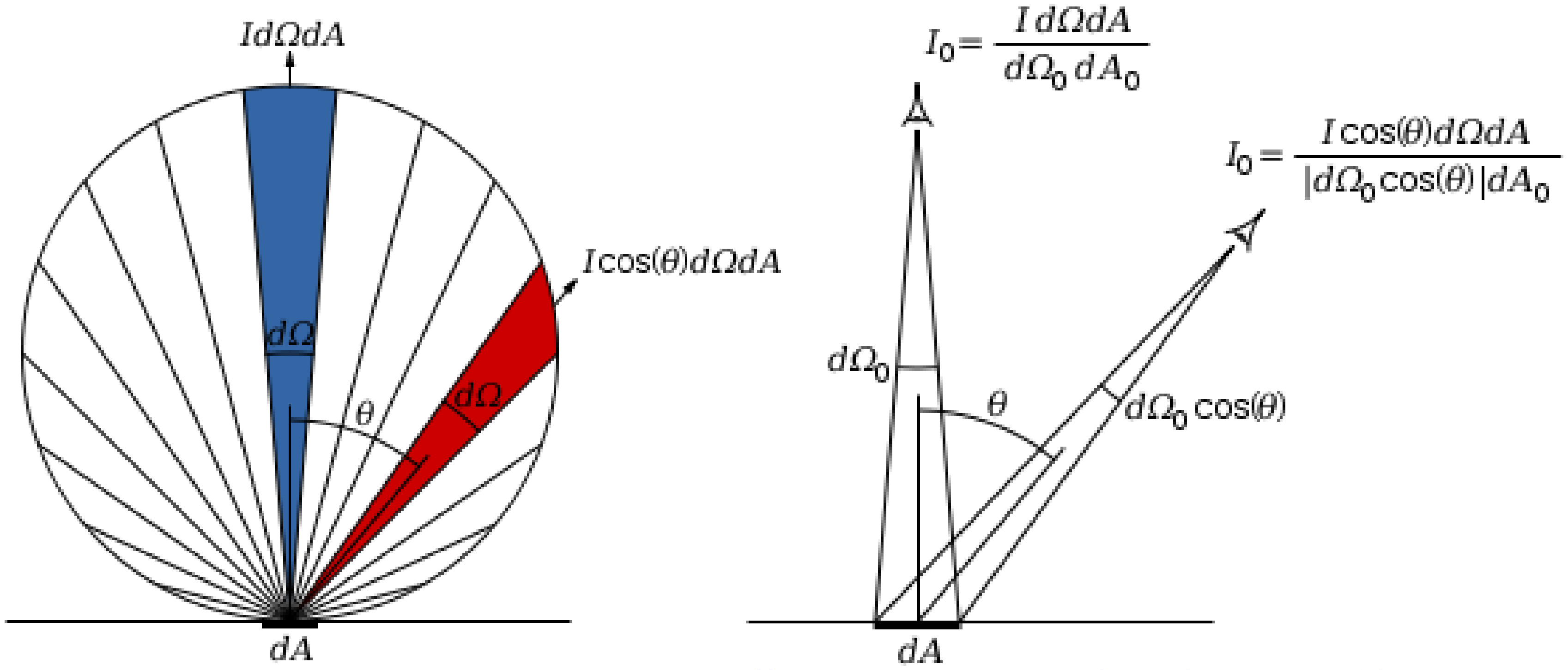
Slide: Forsyth


1
2

Diffuse reflection

Perceived intensity does *not* depend on viewer angle.

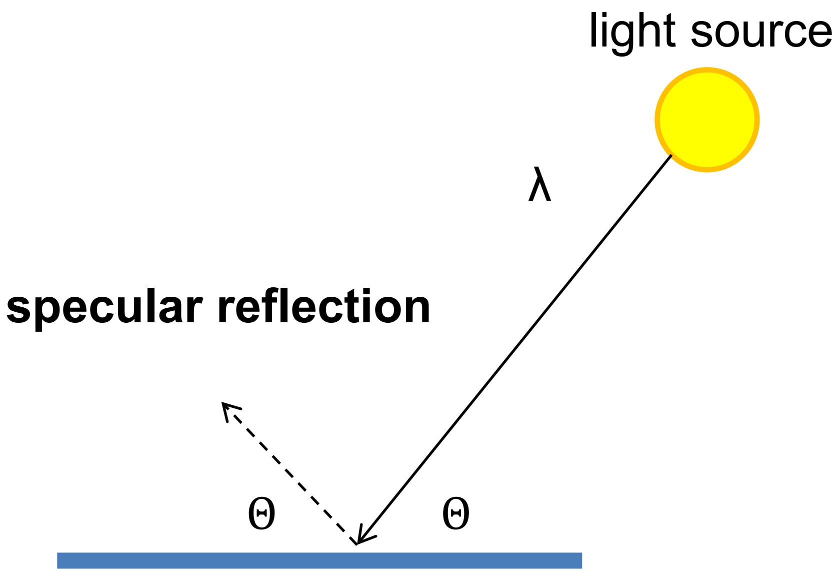
- Amount of reflected light proportional to cos(theta)
- Visible solid angle also proportional to cos(theta)



http://en.wikipedia.org/wiki/Lambert%27s_cosine_law

Specular Reflection

- Reflected direction depends on light orientation and surface normal
- E.g., mirrors are fully specular



by Richard

by Jeff Petersen

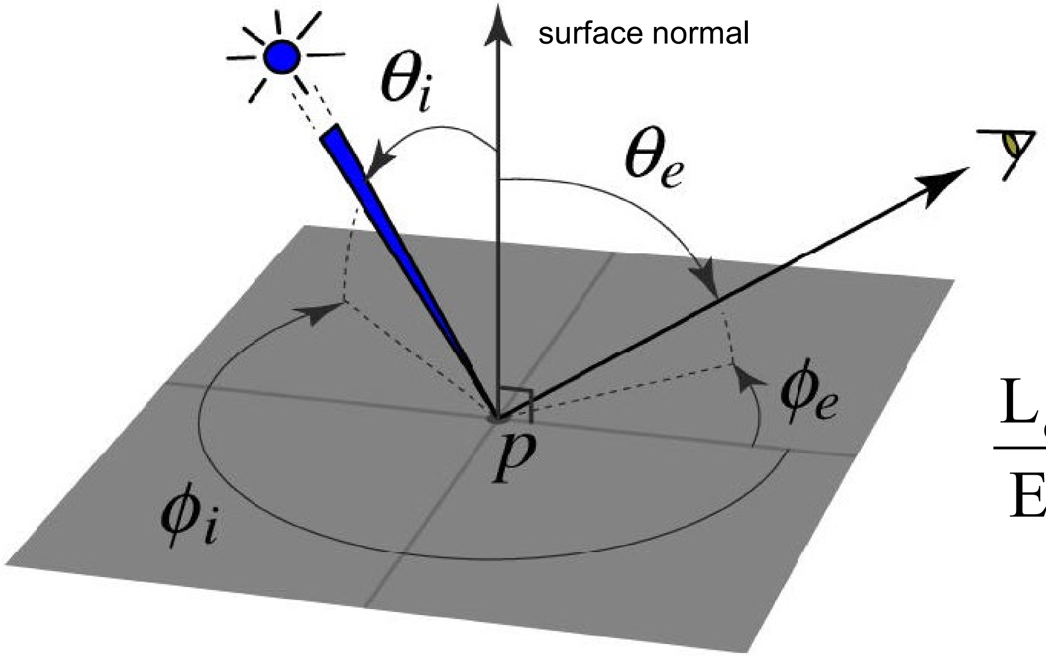
Many surfaces have both specular and diffuse components

Specularity = spot where specular reflection dominates (typically reflects light source)

Photo: northcountryhardwoodfloors.com

BRDF: Bidirectional Reflectance Distribution Function

Model of local reflection that tells how bright a surface appears when viewed from one direction when light falls on it from another

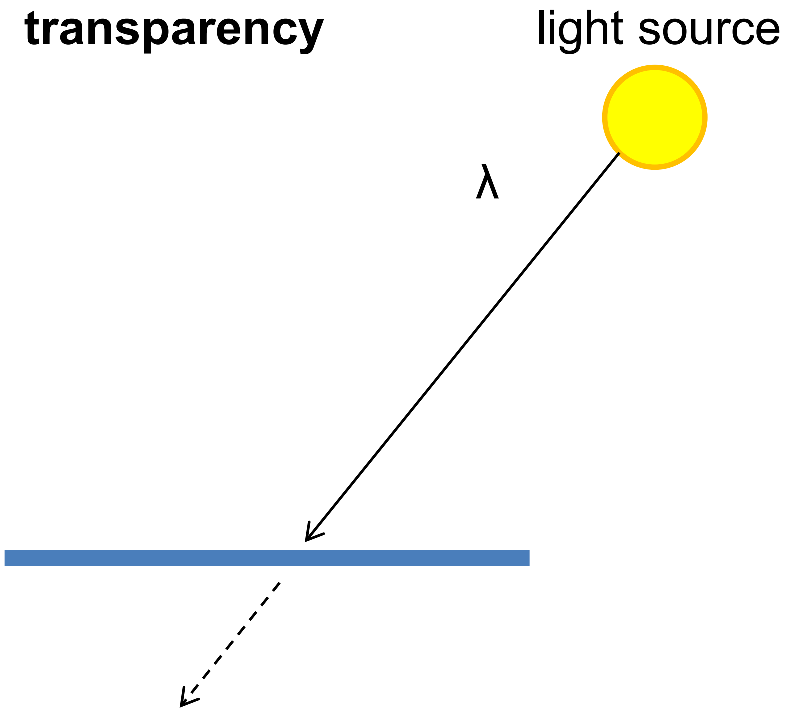


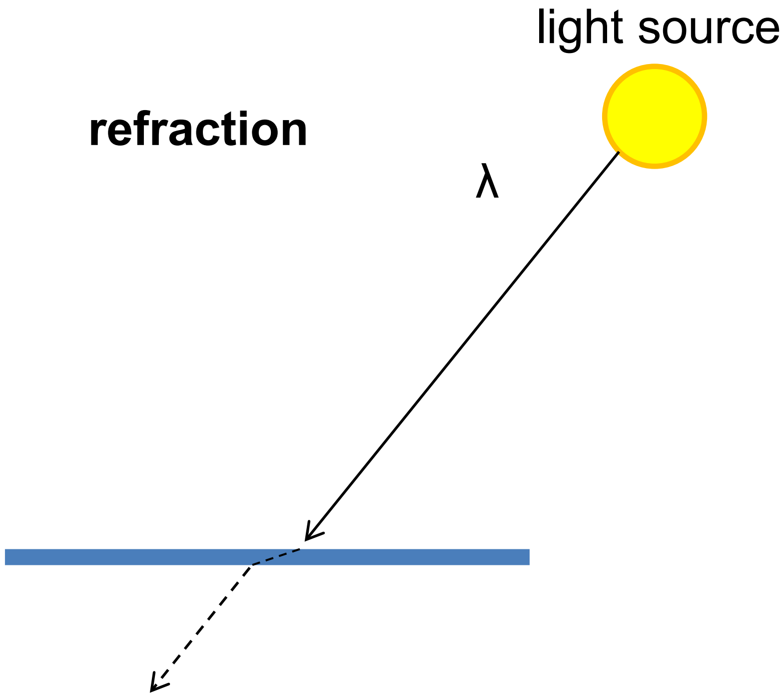
$$\rho(\theta_i, \phi_i, \theta_e, \phi_e; \lambda) =$$

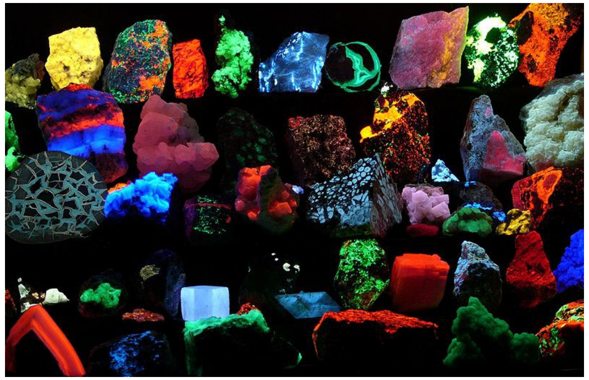
$$\frac{L_e(\boldsymbol{\theta}_e, \boldsymbol{\phi}_e)}{E_i(\boldsymbol{\theta}_i, \boldsymbol{\phi}_i)} = \frac{L_e(\boldsymbol{\theta}_e, \boldsymbol{\phi}_e)}{L_i(\boldsymbol{\theta}_i, \boldsymbol{\phi}_i) \cos \boldsymbol{\theta}_i d\boldsymbol{\omega}}$$

Slide credit: S. Savarese

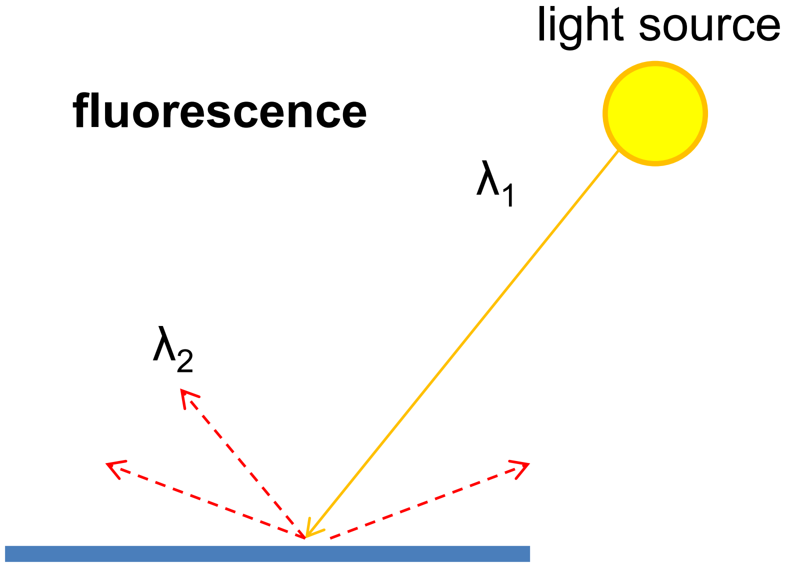
More complicated effects



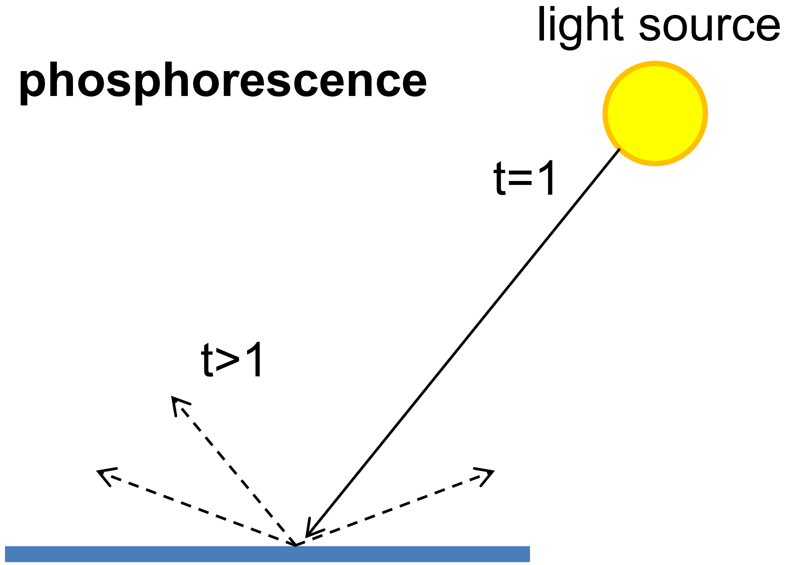


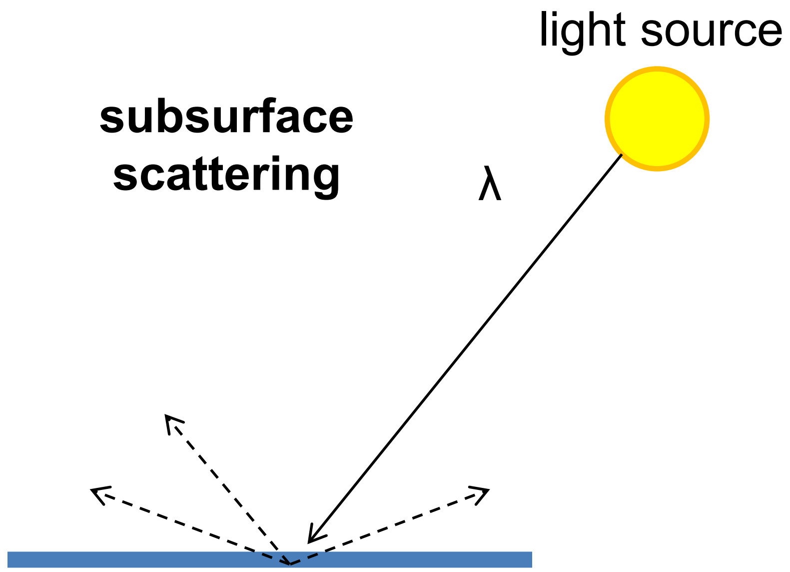


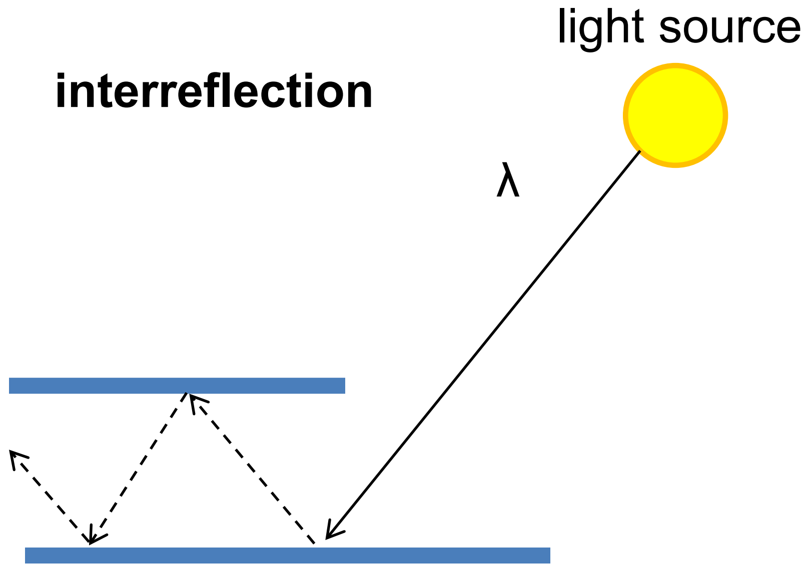
fluorescence



phosphorescence

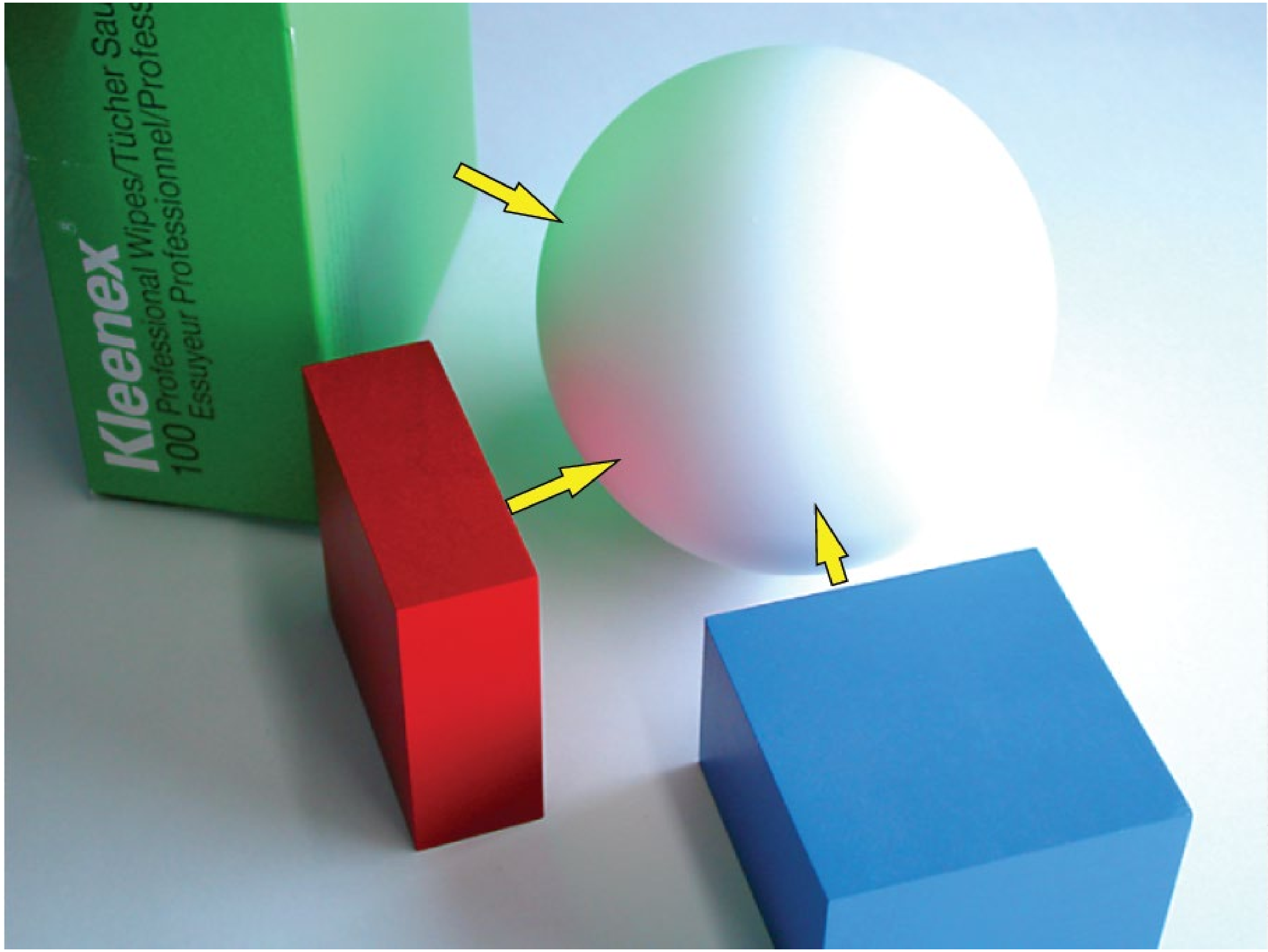



subsurface
scattering
light source
λ


interreflection
light source
λ

Inter-reflection is a major source of light

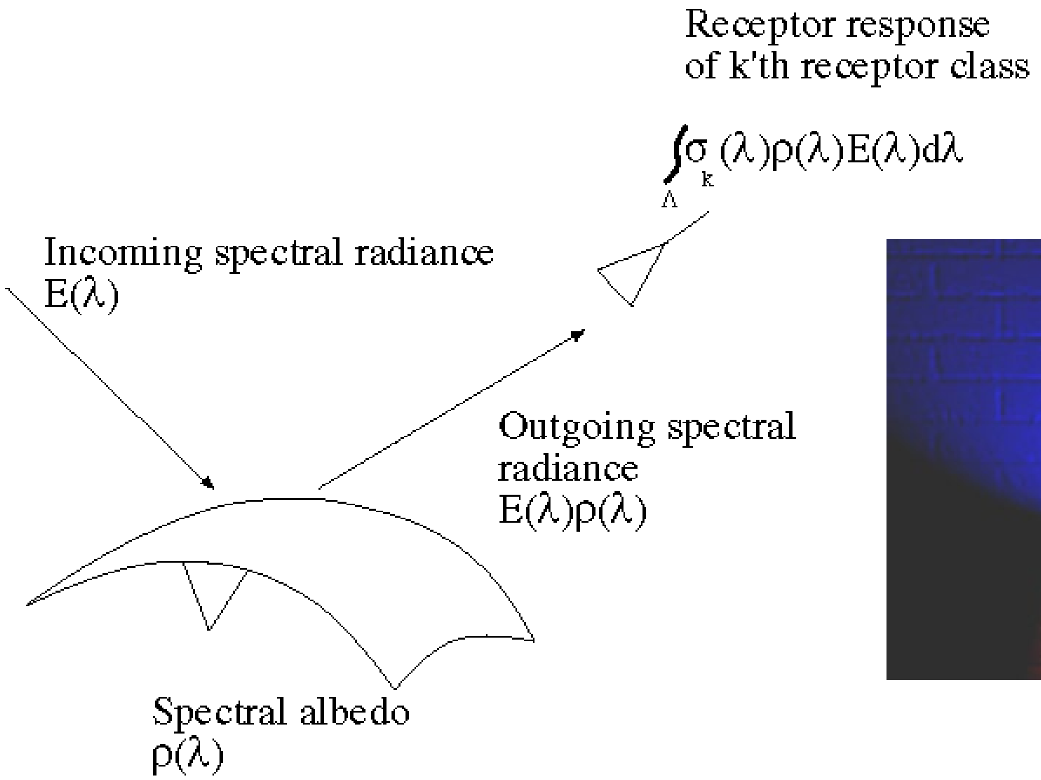
Inter-reflection affects the apparent color of objects

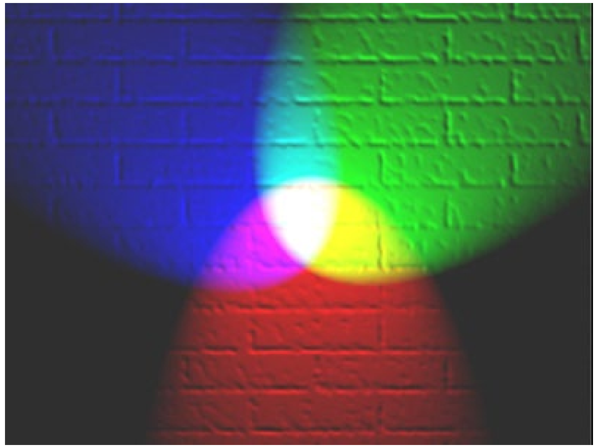


From Koenderink slides on image texture and the flow of light

The color of objects

- Colored light arriving at the camera involves two effects
  - The color of the light source (illumination + inter-reflections)
  - The color of the surface

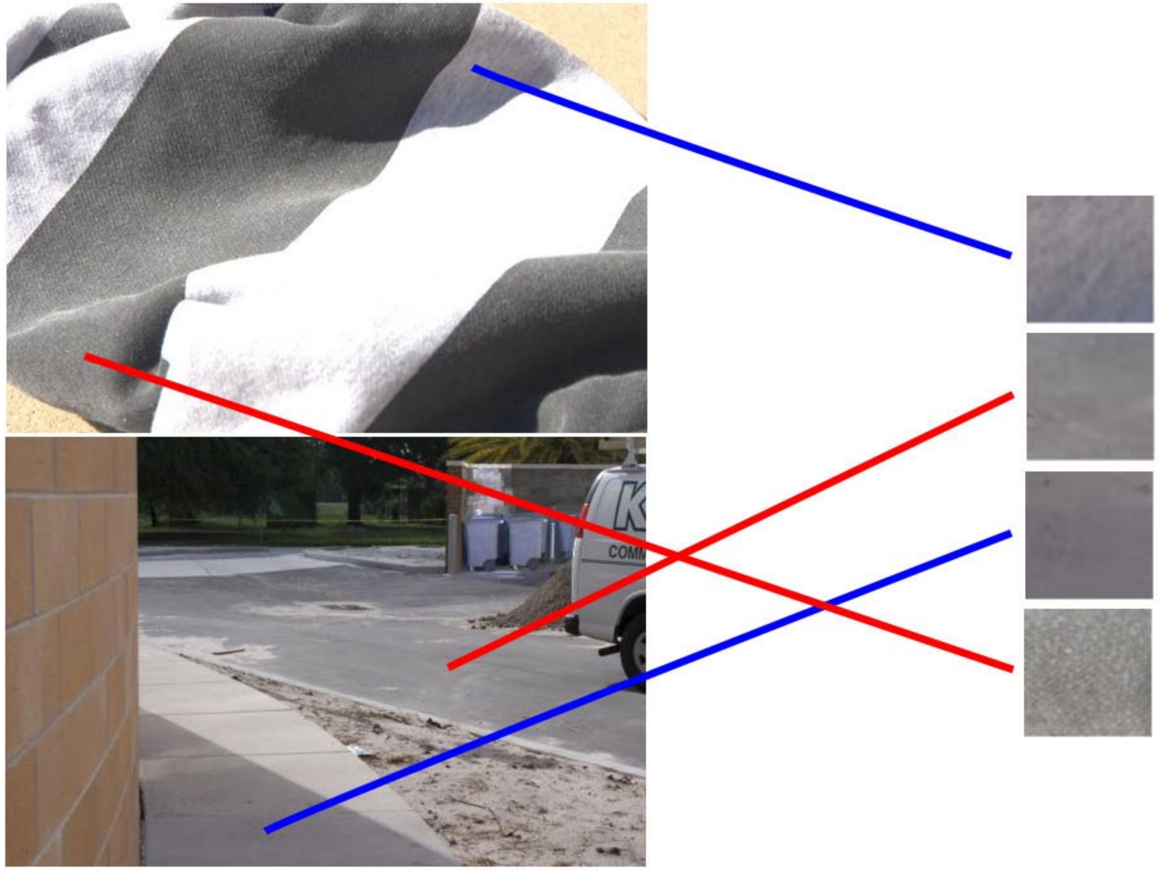




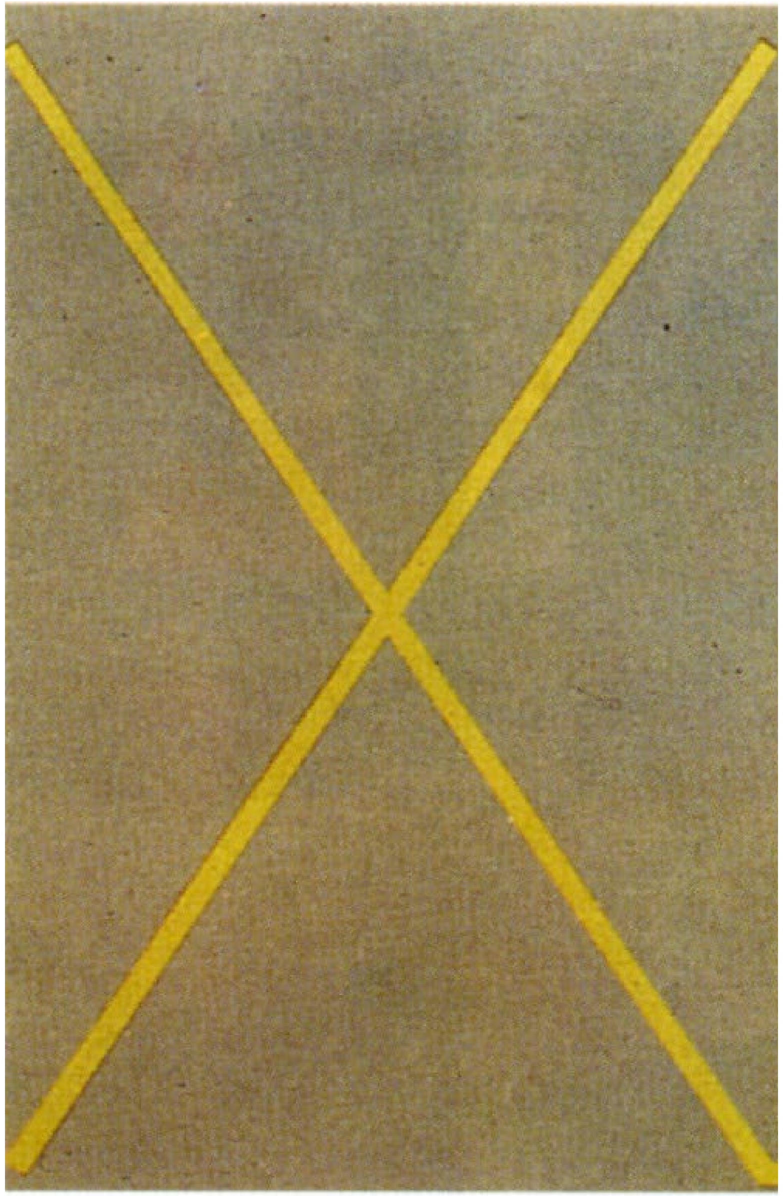
Slide: Forsyth

Color constancy

- Interpret surface in terms of albedo or “true color”, rather than observed intensity
  - Humans are good at it
  - Computers are not nearly as good

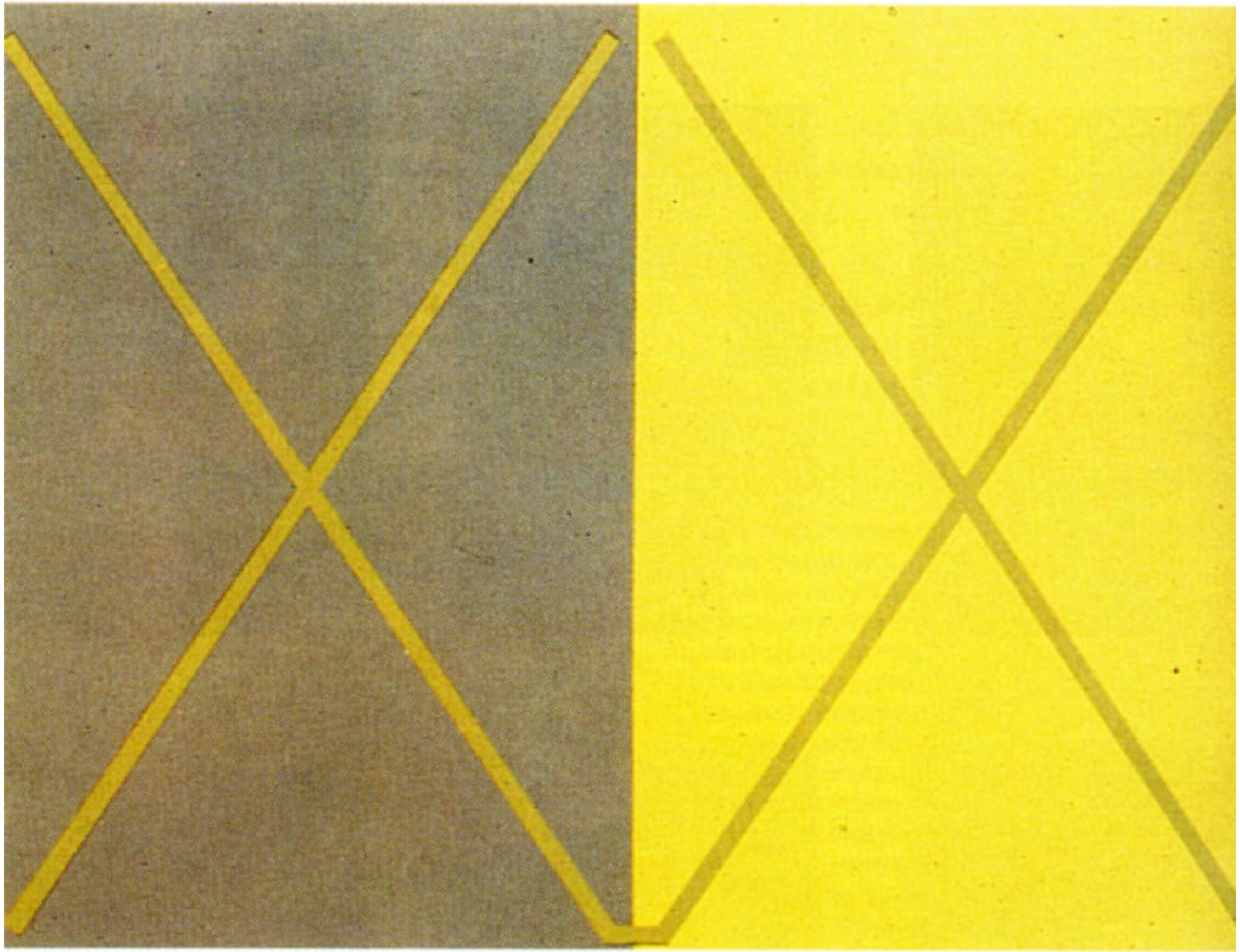


Color illusions

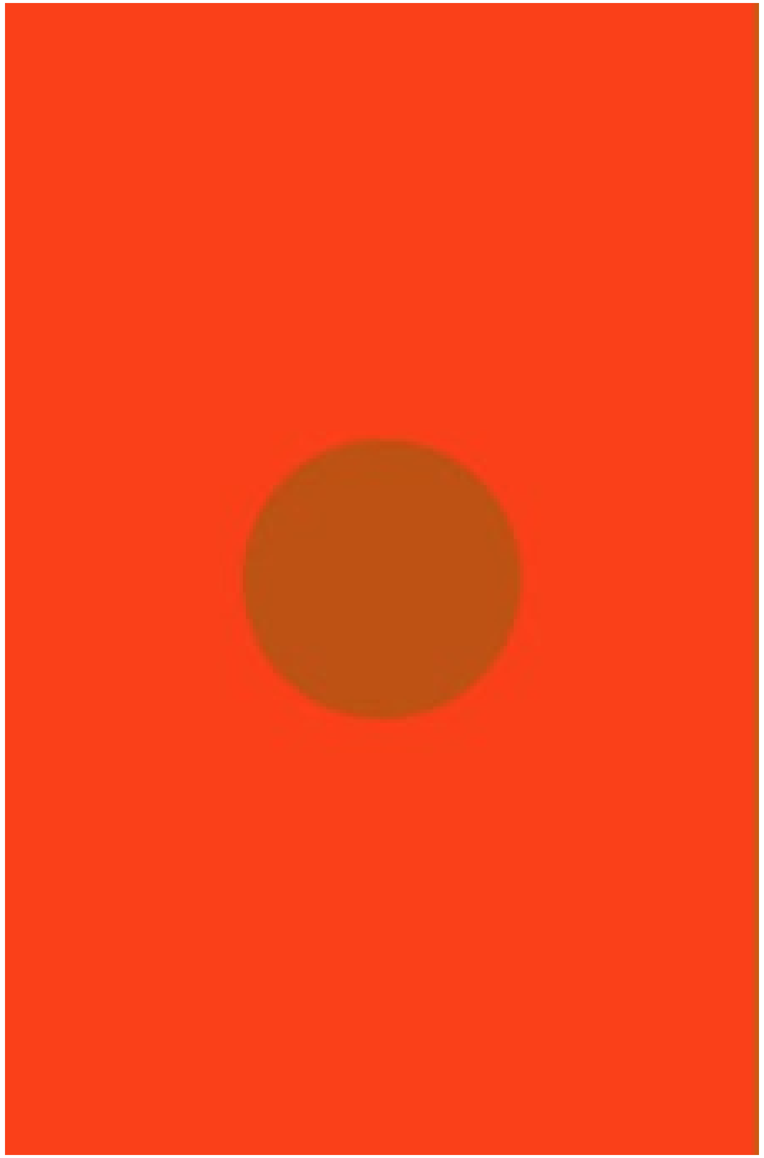


Color illusions

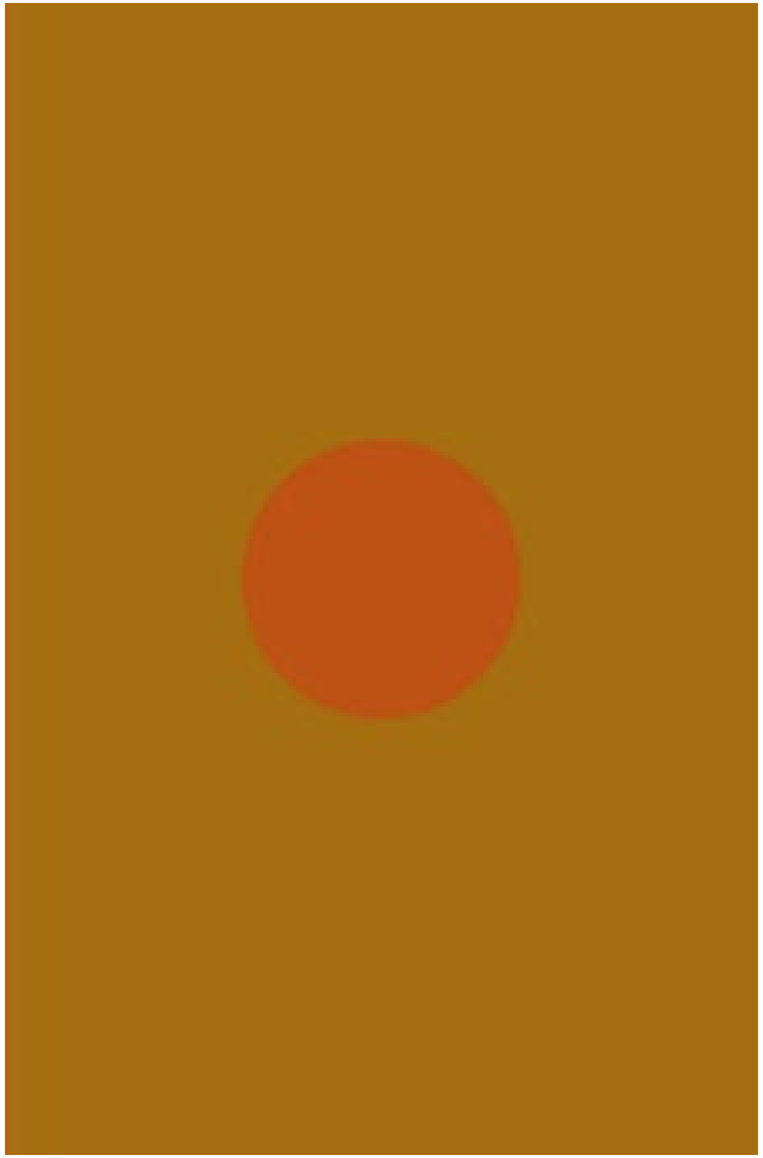
Color illusions



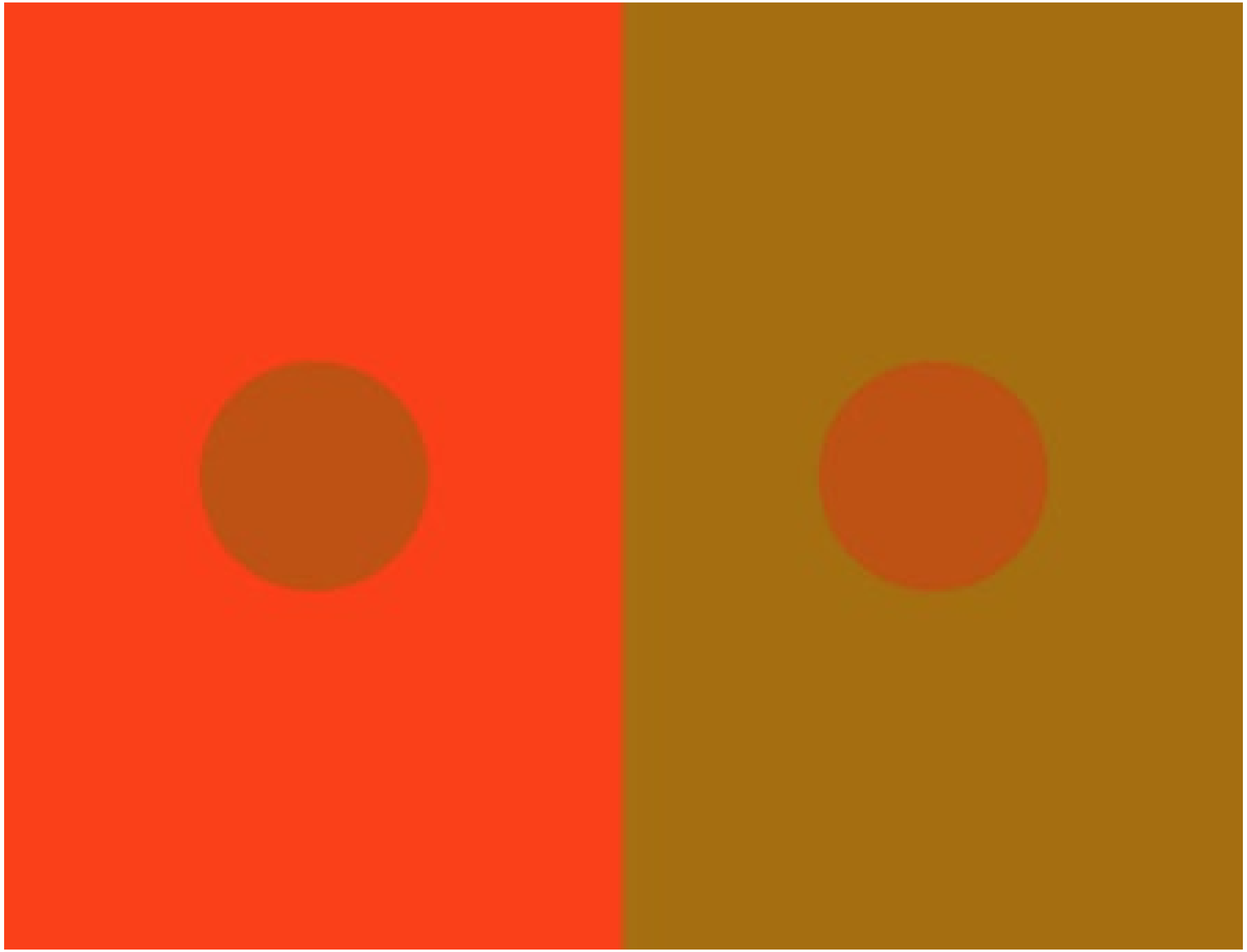
Color illusions



Color illusions



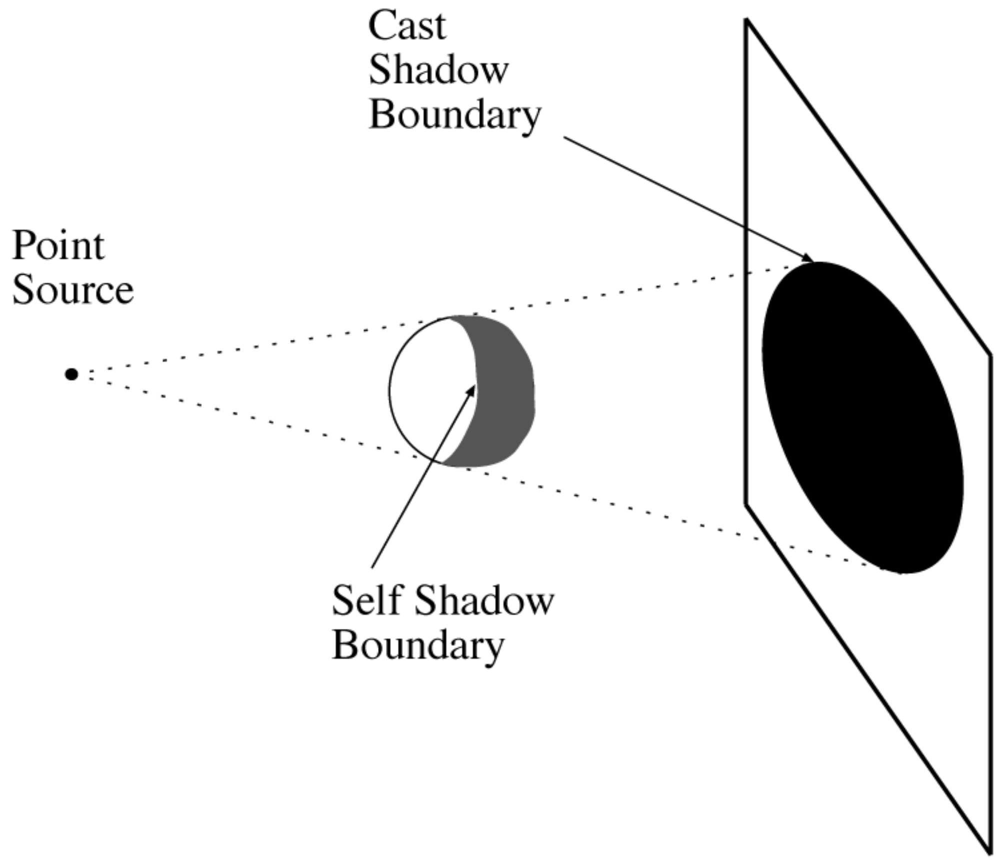
Color illusions



http://www.echalk.co.uk/amusements/OpticalIllusions/colourPerception/colourPerception.html

Shadows cast by a point source

- A point that can't see the source is in shadow
- For point sources, the geometry is simple

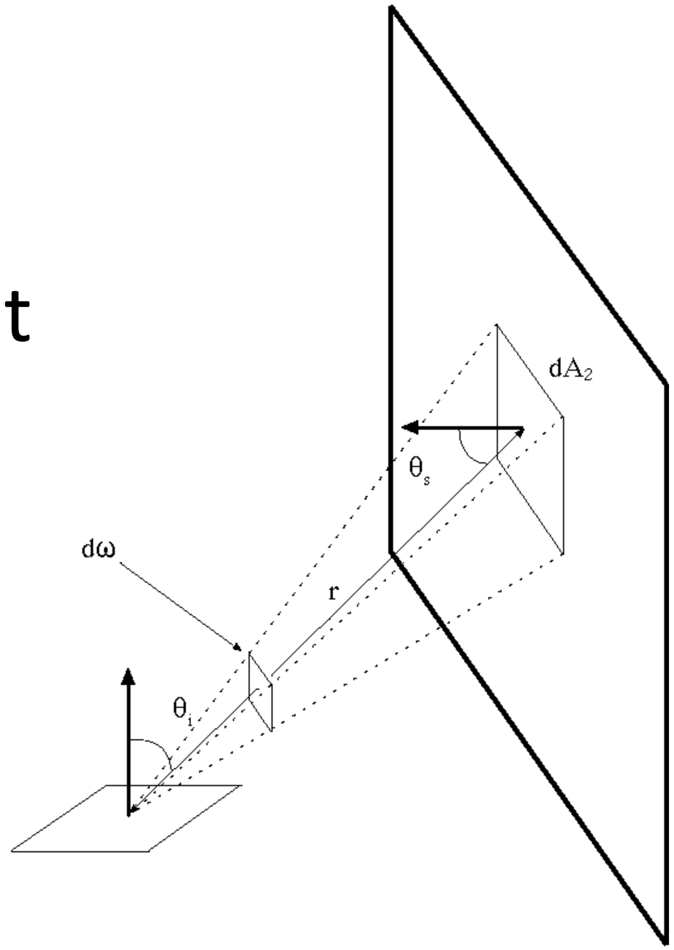


Slide: Forsyth

Area sources

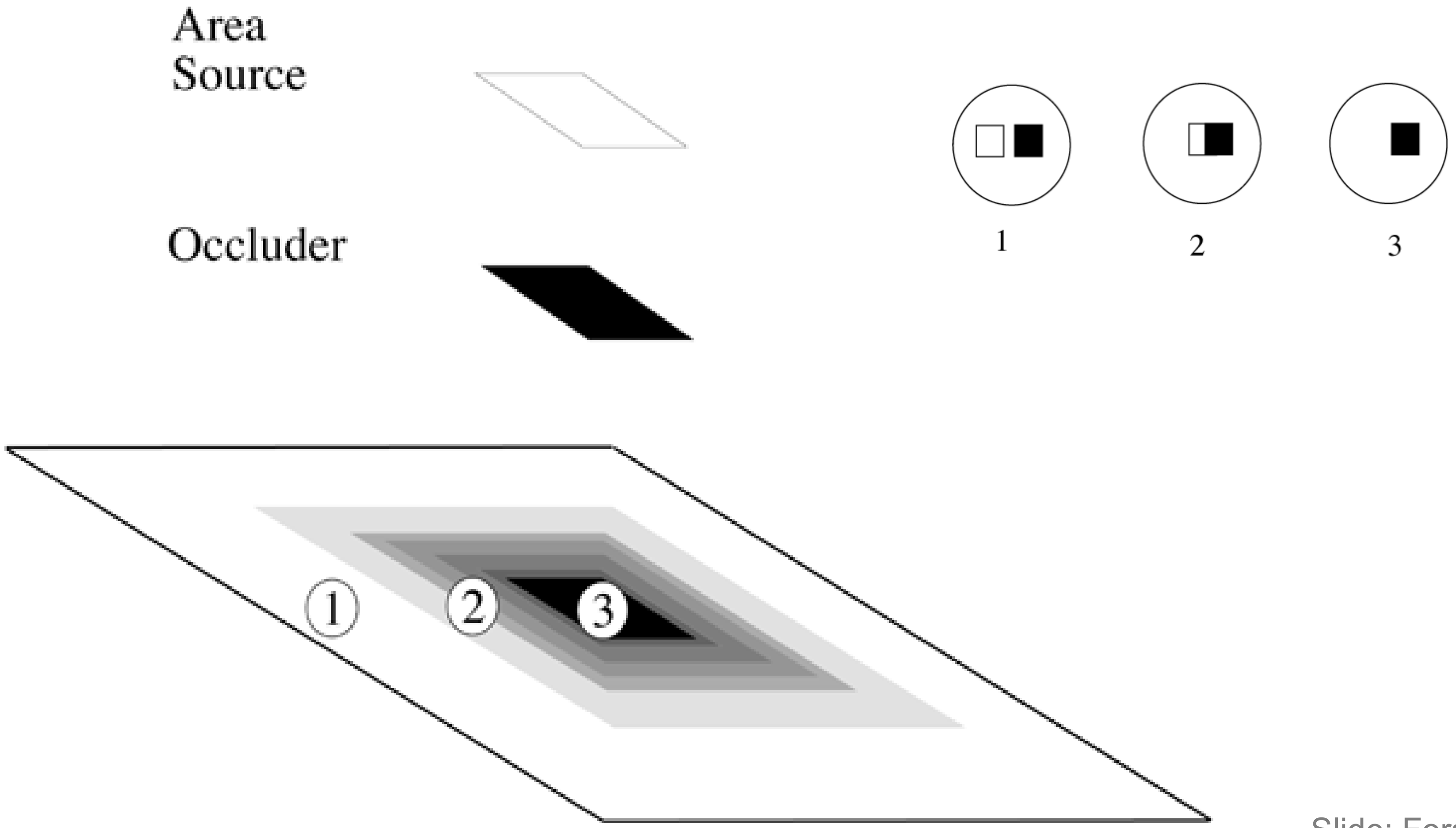
- Examples: diffuser boxes, white walls

- The energy received at a point due to an area source is obtained by adding up the contribution of small elements over the whole source



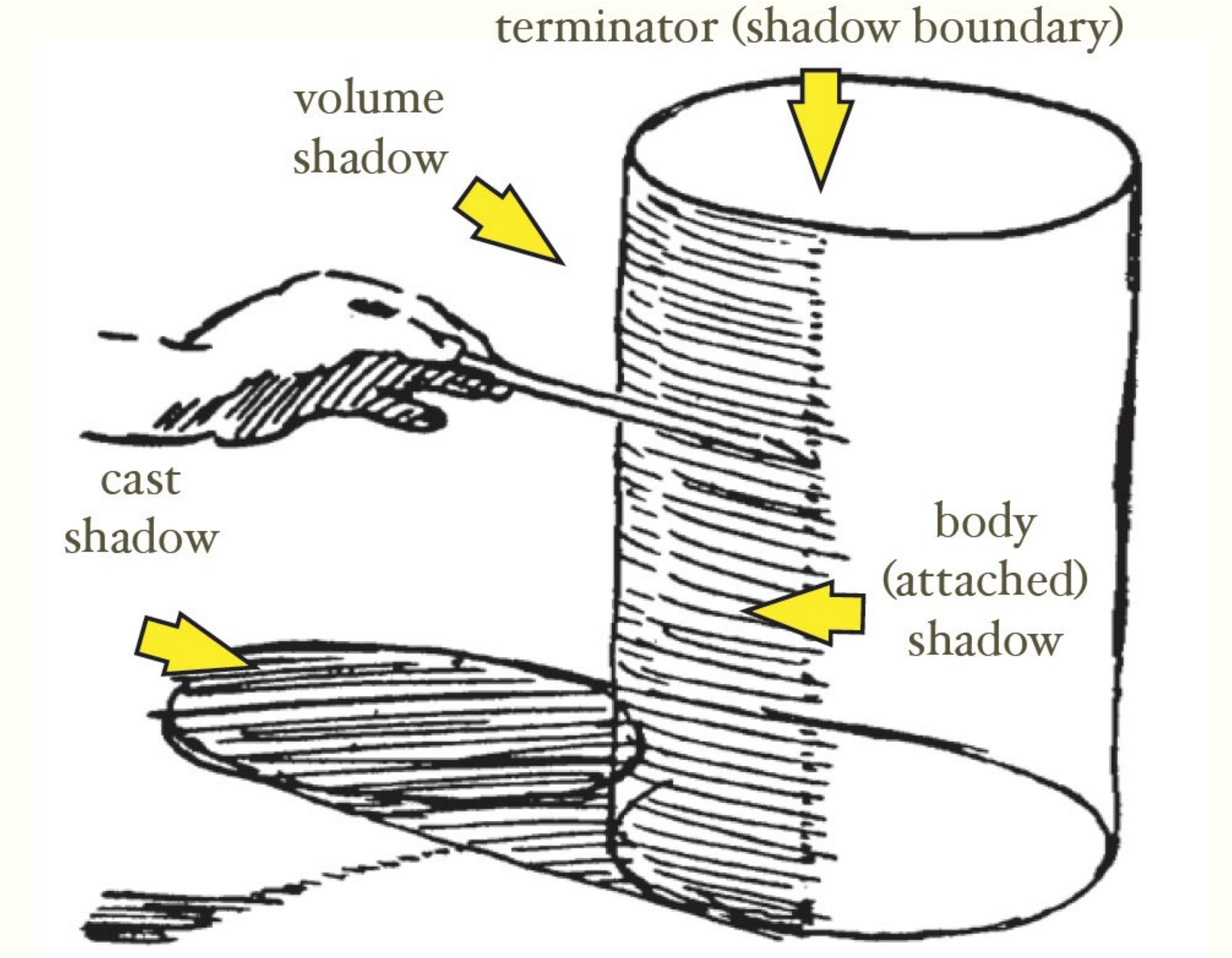
Slide: Forsyth

Area Source Shadows



Slide: Forsyth

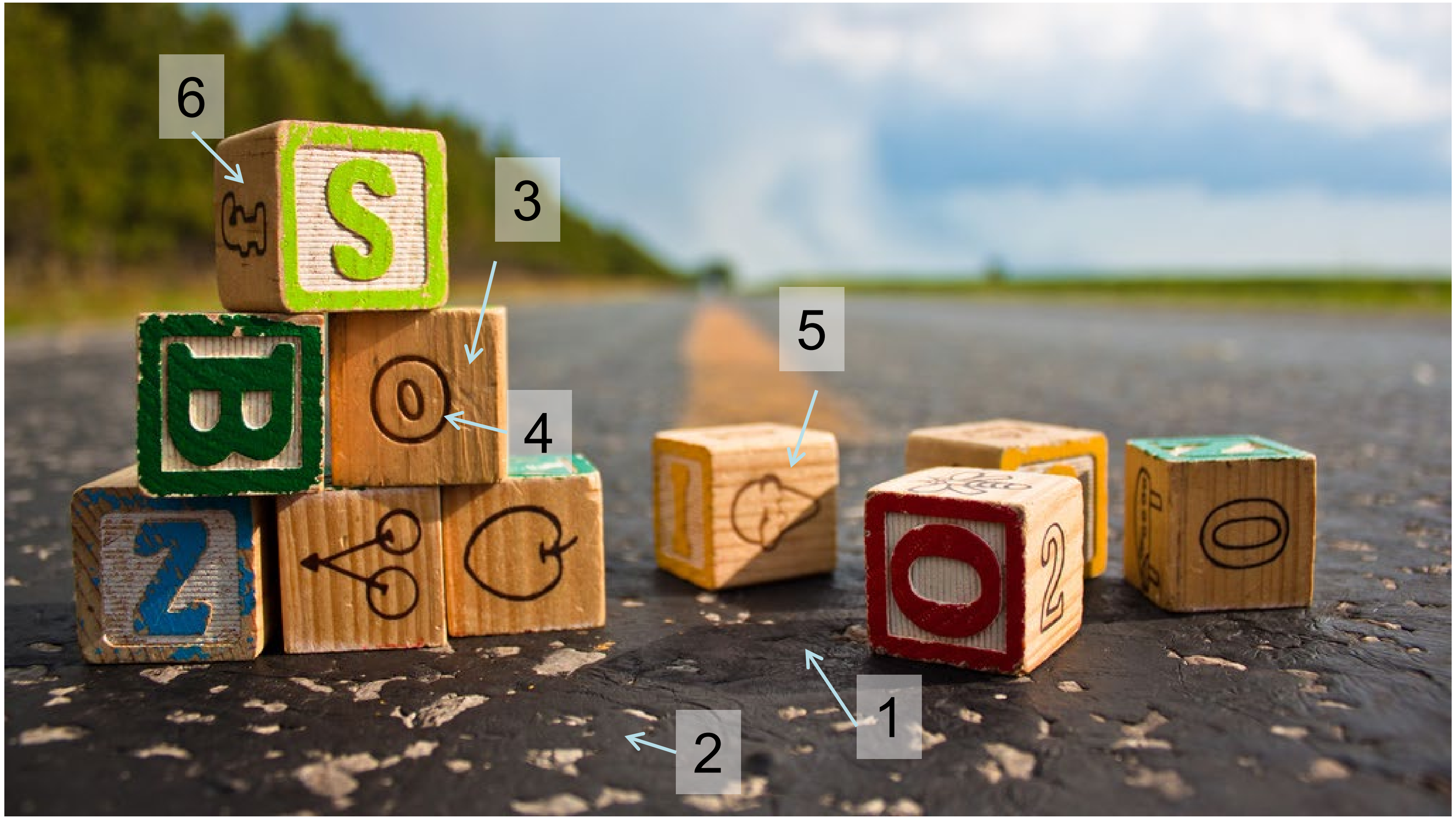
Shading and shadows are major cues to shape and position



From Koenderink slides on image texture and the flow of light

Slide: Forsyth

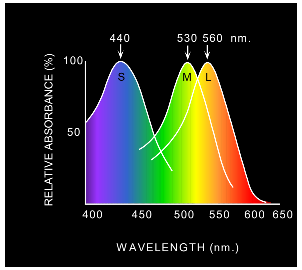
Recap



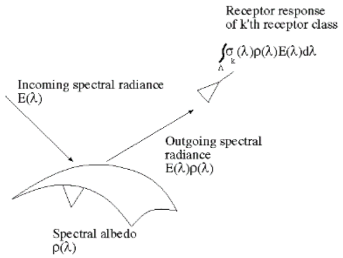
1. Why is (2) brighter than (1)? Each points to the asphalt.
2. Why is (4) darker than (3)? 4 points to the marking.
3. Why is (5) brighter than (3)? Each points to the side of the wooden block.
4. Why isn't (6) black, given that there is no direct path from it to the sun?

Things to remember

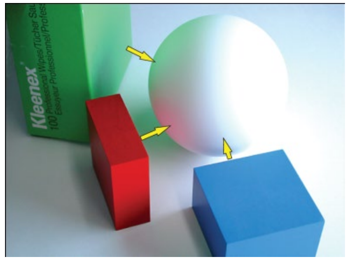
- Light has a spectrum of wavelengths
  - Humans (and RGB cameras) have color sensors sensitive to three ranges



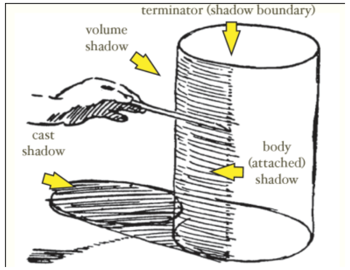
- Observed light depends on: illumination intensities, surface orientation, material (albedo, specular component, diffuse component), etc.



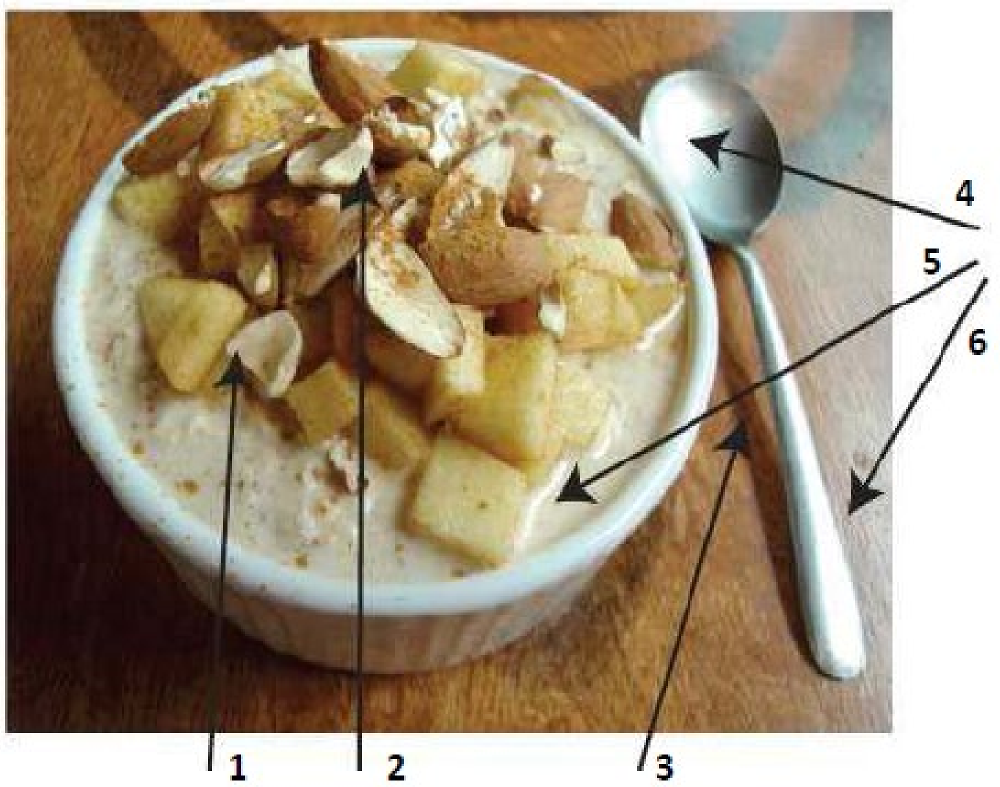
- Every object is an indirect light source for every other



- Shading and shadows are informative about shape and position



Take-home questions



A. For each of the arrows in the above image, name the reasons the pixel near the end of the arrow has its brightness value and explain very briefly. The arrow pointing to milk is pointing to the thin bright line at the edge of the piece of apple; the arrow pointing to the spoon handle is pointing to the bright area on the handle.

Possible factors: albedo, shadows, texture, specularities, curvature, lighting direction