Intelligent Multimedia Systems

Master AI, 2012, Lecture 2

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Image Formation

Projective Geometry and Camera Models

Light and Color Models

Reflection Models

Including slides from Derek Hoiem, Alexei Efros, Steve Seitz, and David Forsyth, James Hays

Projective Geometry and Camera Models

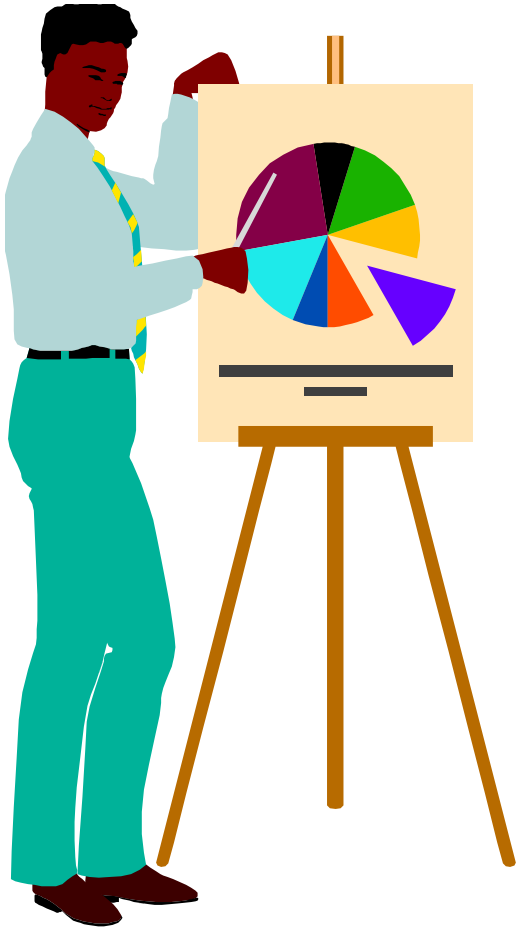
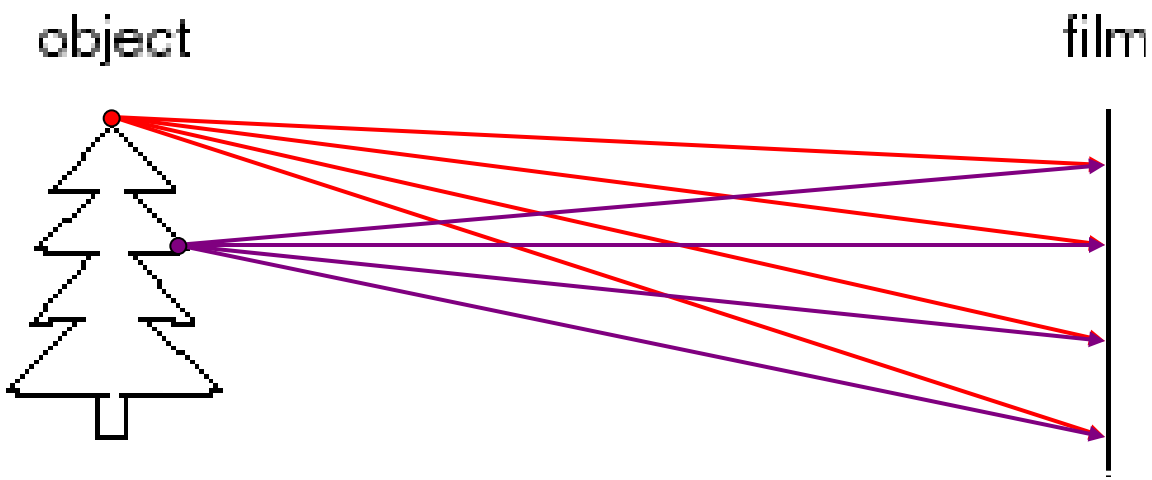


Image formation

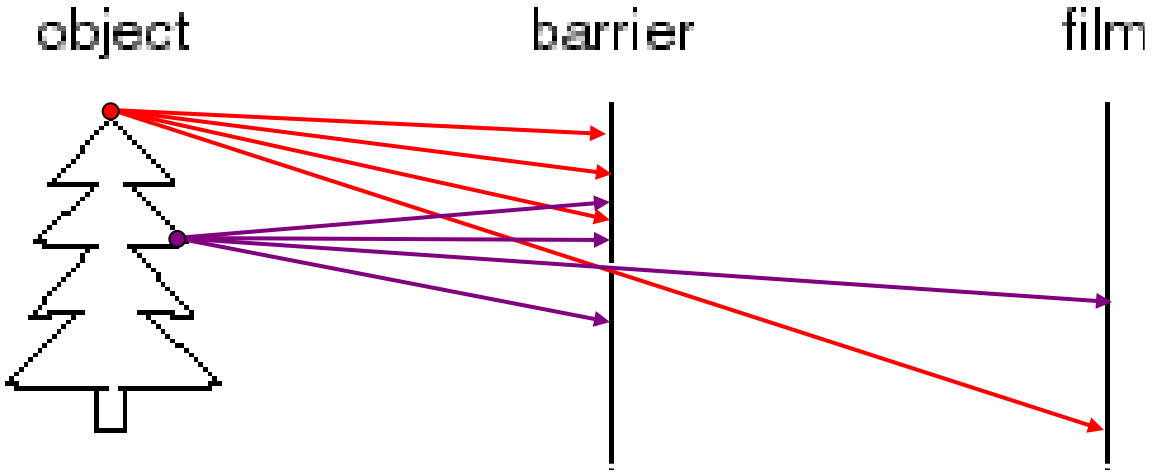


Let's design a camera

- Idea 1: put a piece of film in front of an object
- Do we get a reasonable image?

Slide source: Seitz

Pinhole camera

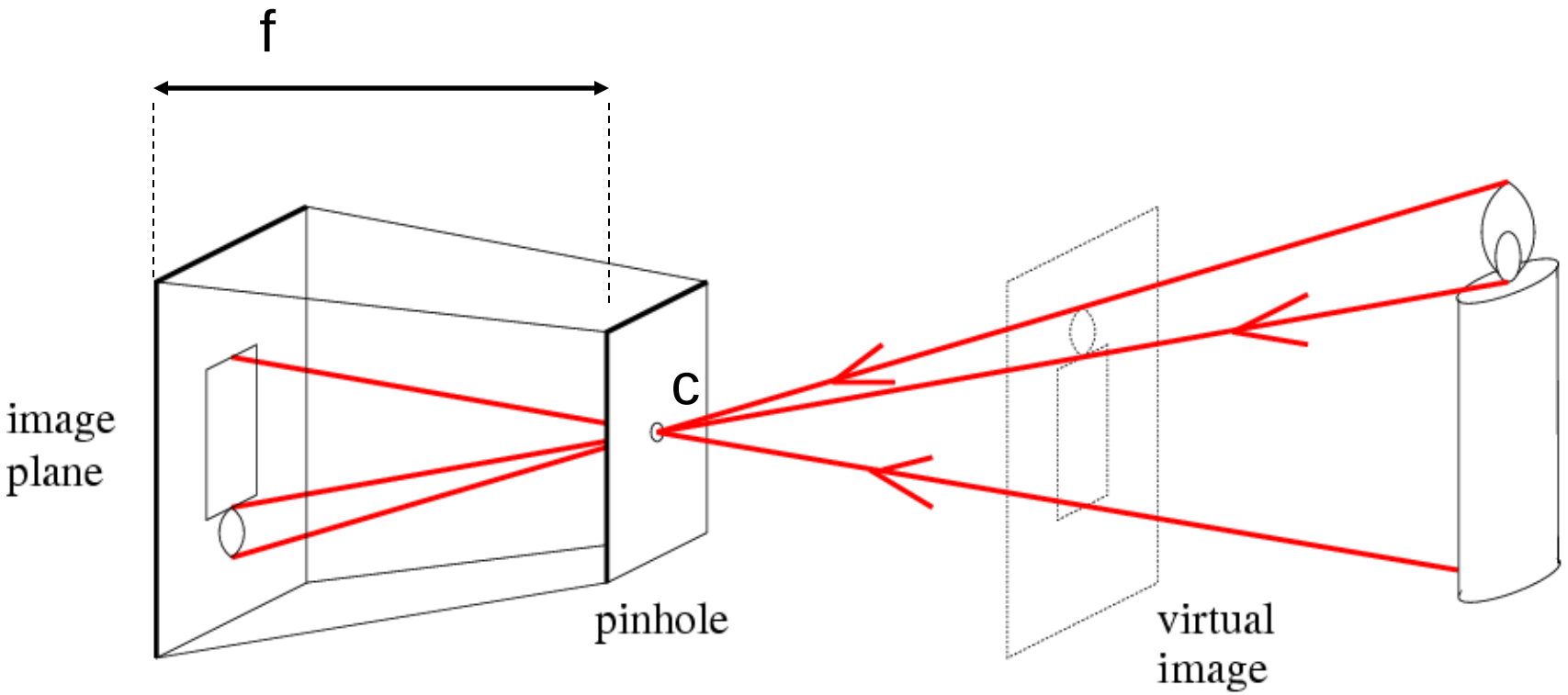


Idea 2: add a barrier to block off most of the rays

- This reduces blurring
- The opening known as the **aperture**

Slide source: Seitz

Pinhole camera



f = focal length
c = center of the camera

Figure from Forsyth

Camera Obscura

- Known during classical period in China and Greece (e.g. Mo-Ti, China, 470BC to 390BC)

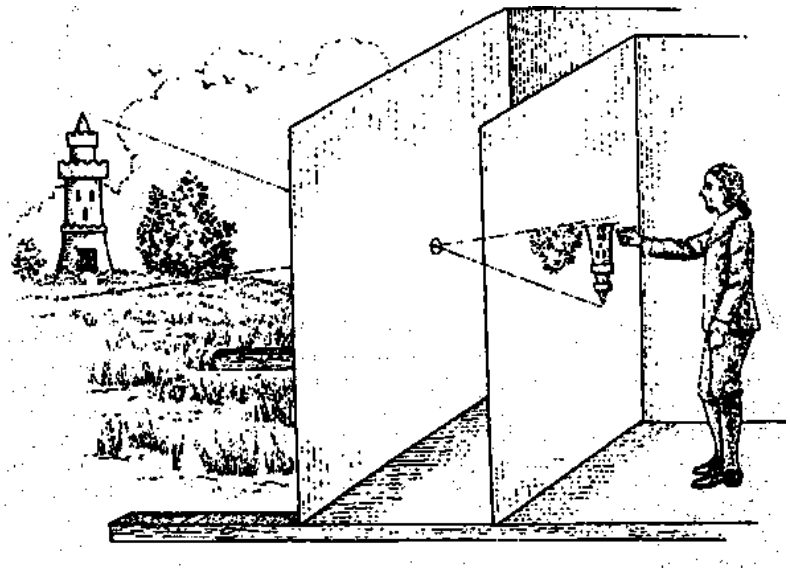
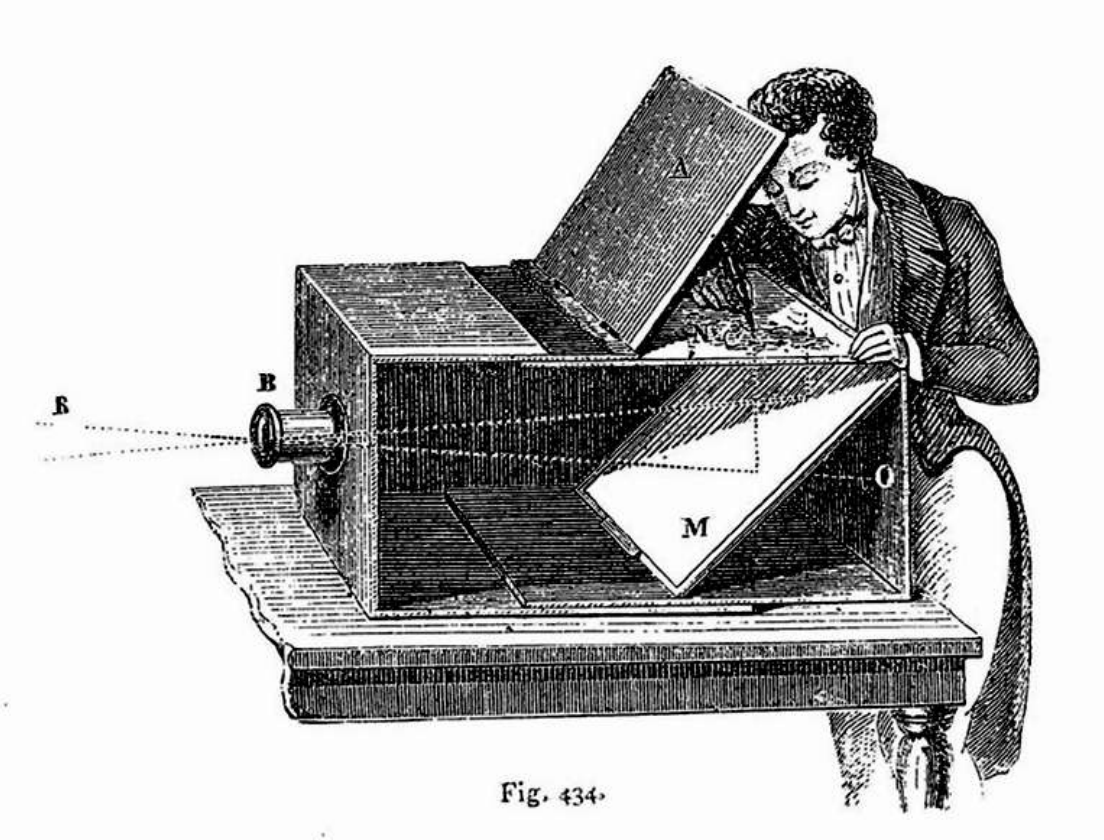


Illustration of Camera Obscura

Freestanding camera obscura at UNC Chapel Hill

Photo by Seth Ilys

Camera Obscura used for Tracing



Lens Based Camera Obscura, 1568

First Photograph

Oldest surviving photograph

- Took 8 hours on pewter plate

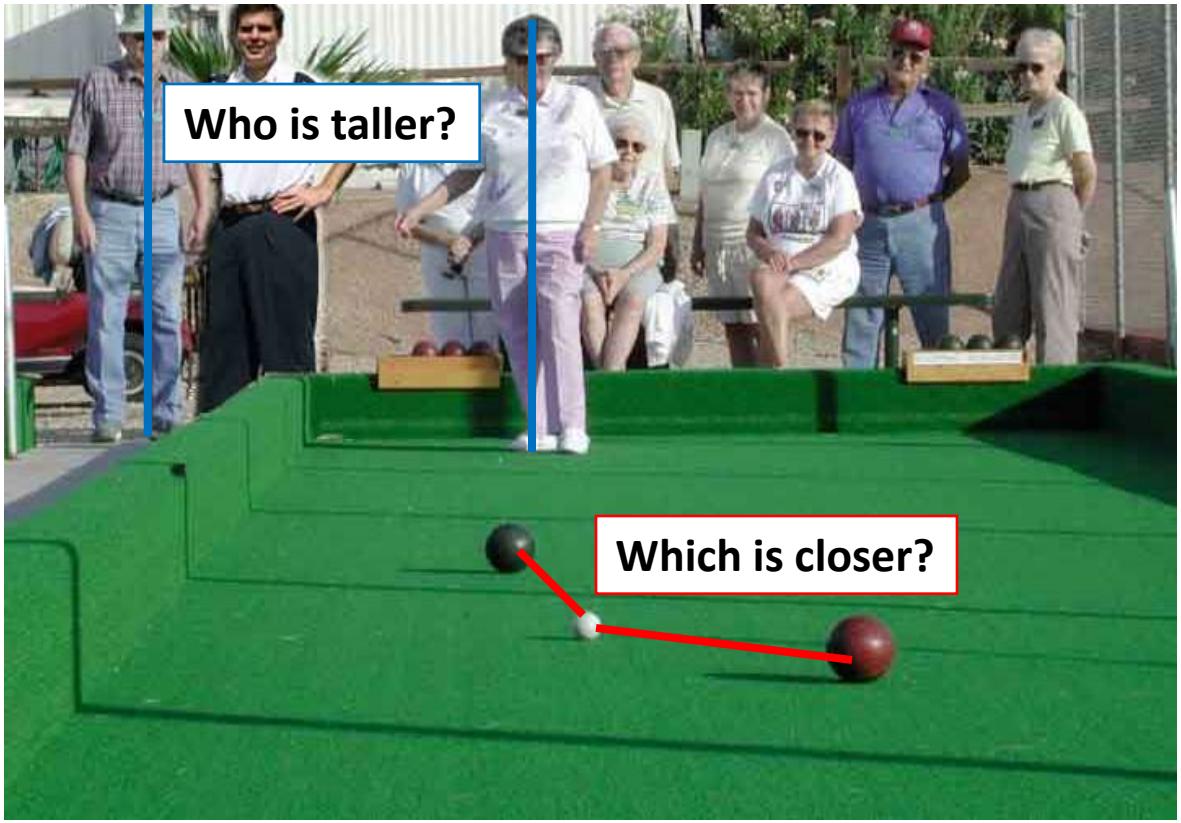
Joseph Niepce, 1826

Niepce later teamed up with Daguerre, who eventually created Daguerrotypes

Projective Geometry

What is lost?

- Length



Length is not preserved

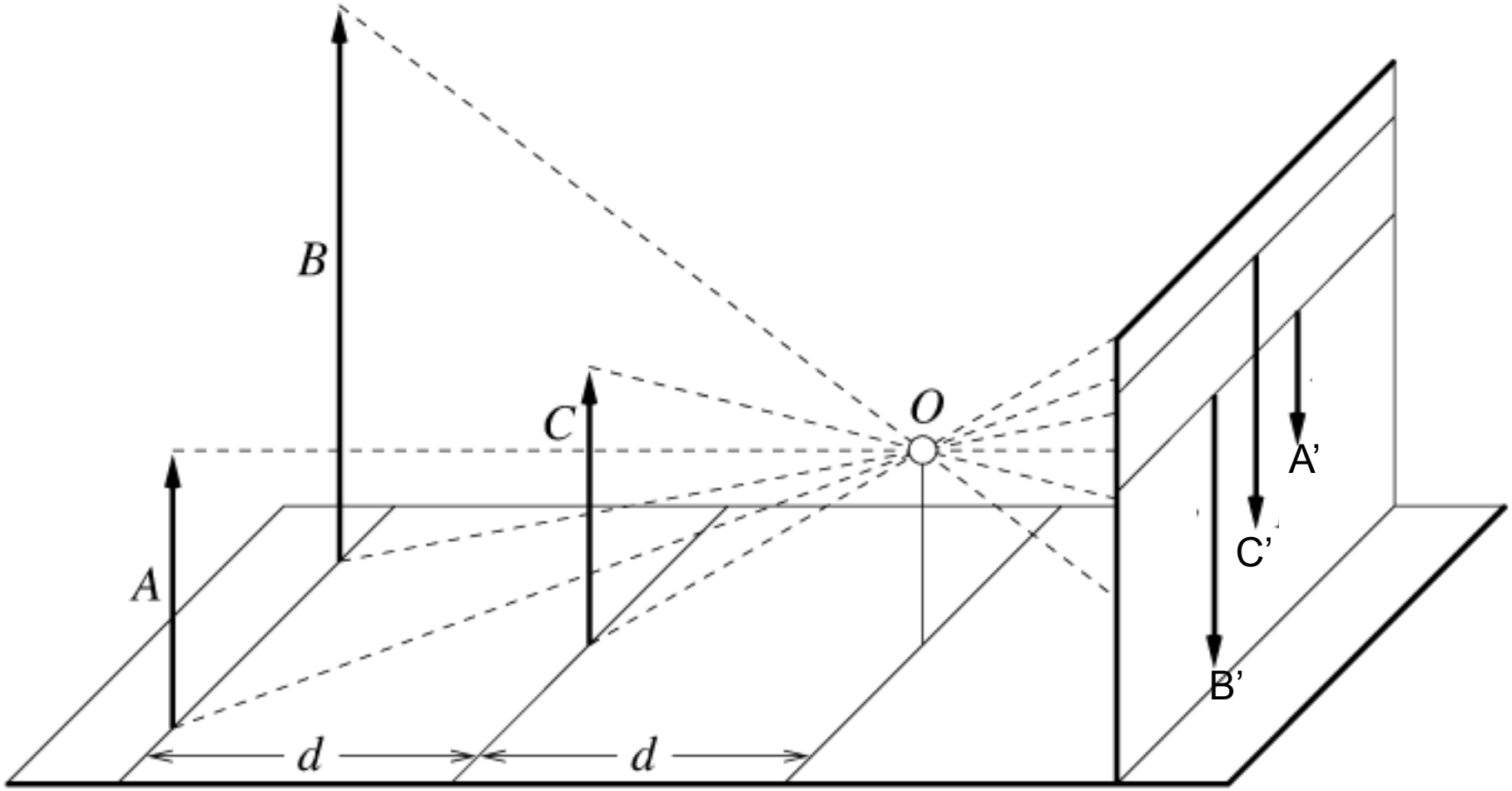
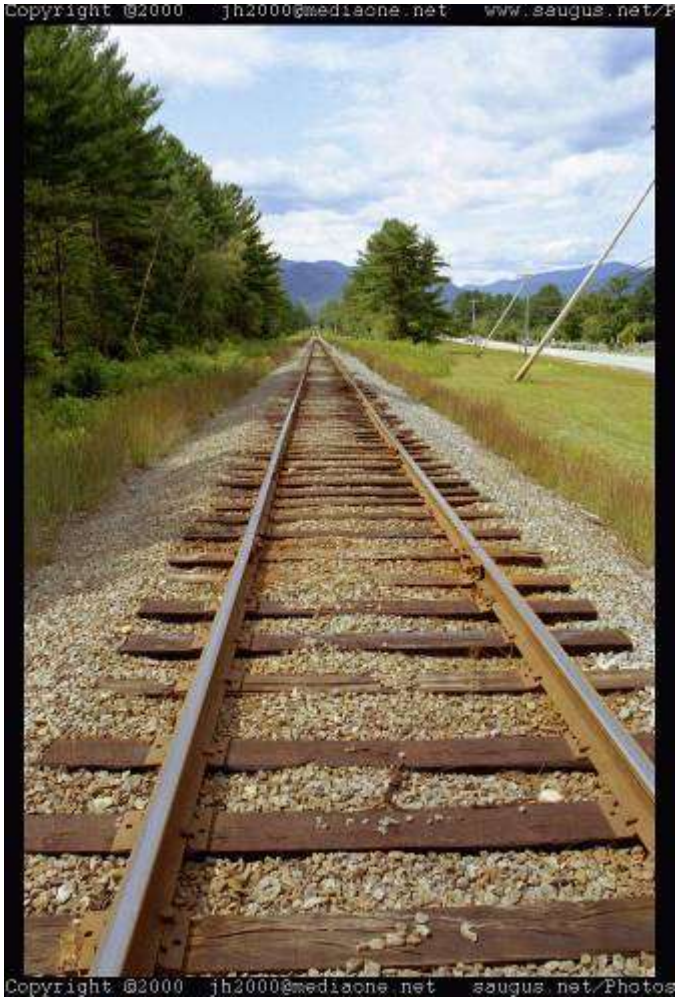


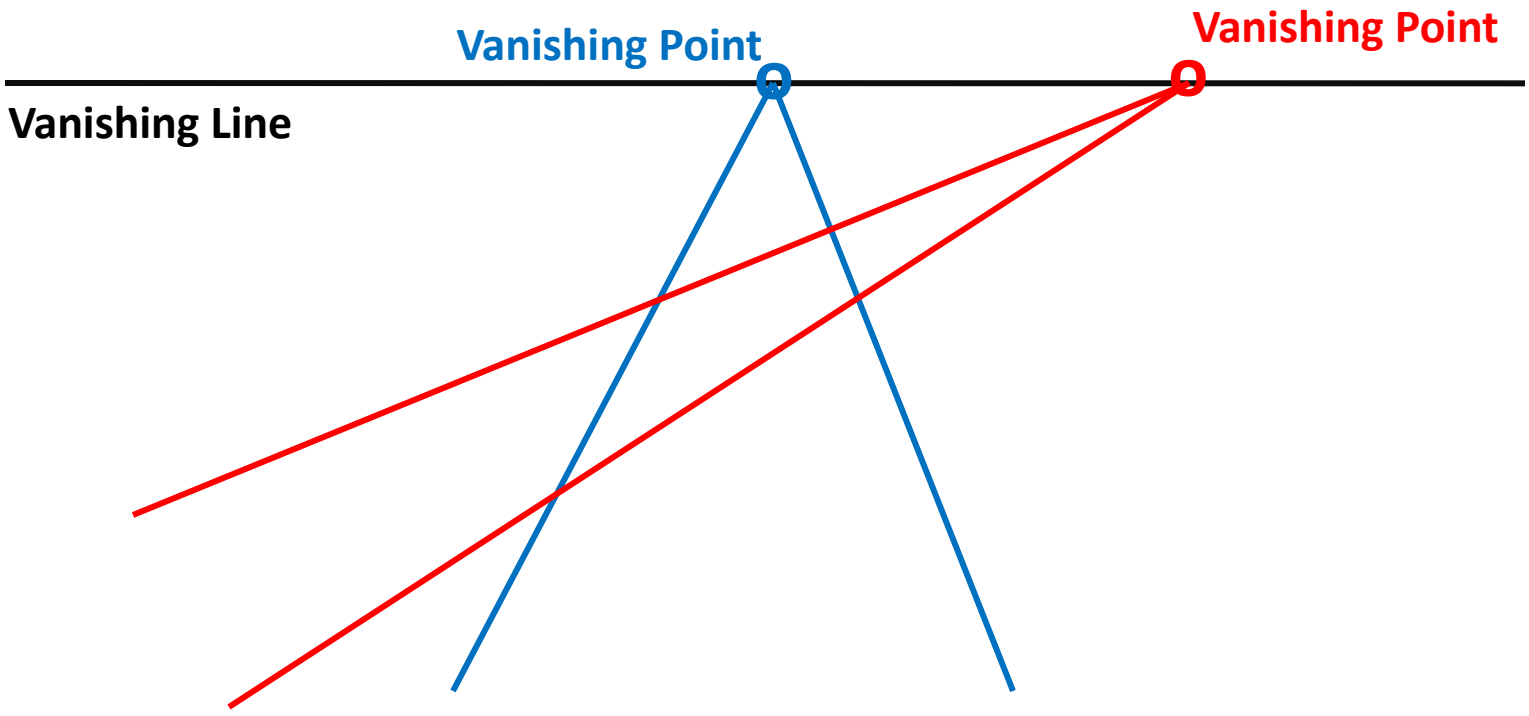
Figure by David Forsyth

Vanishing Points and Lines

Parallel lines in the world intersect in the image at a “vanishing point”

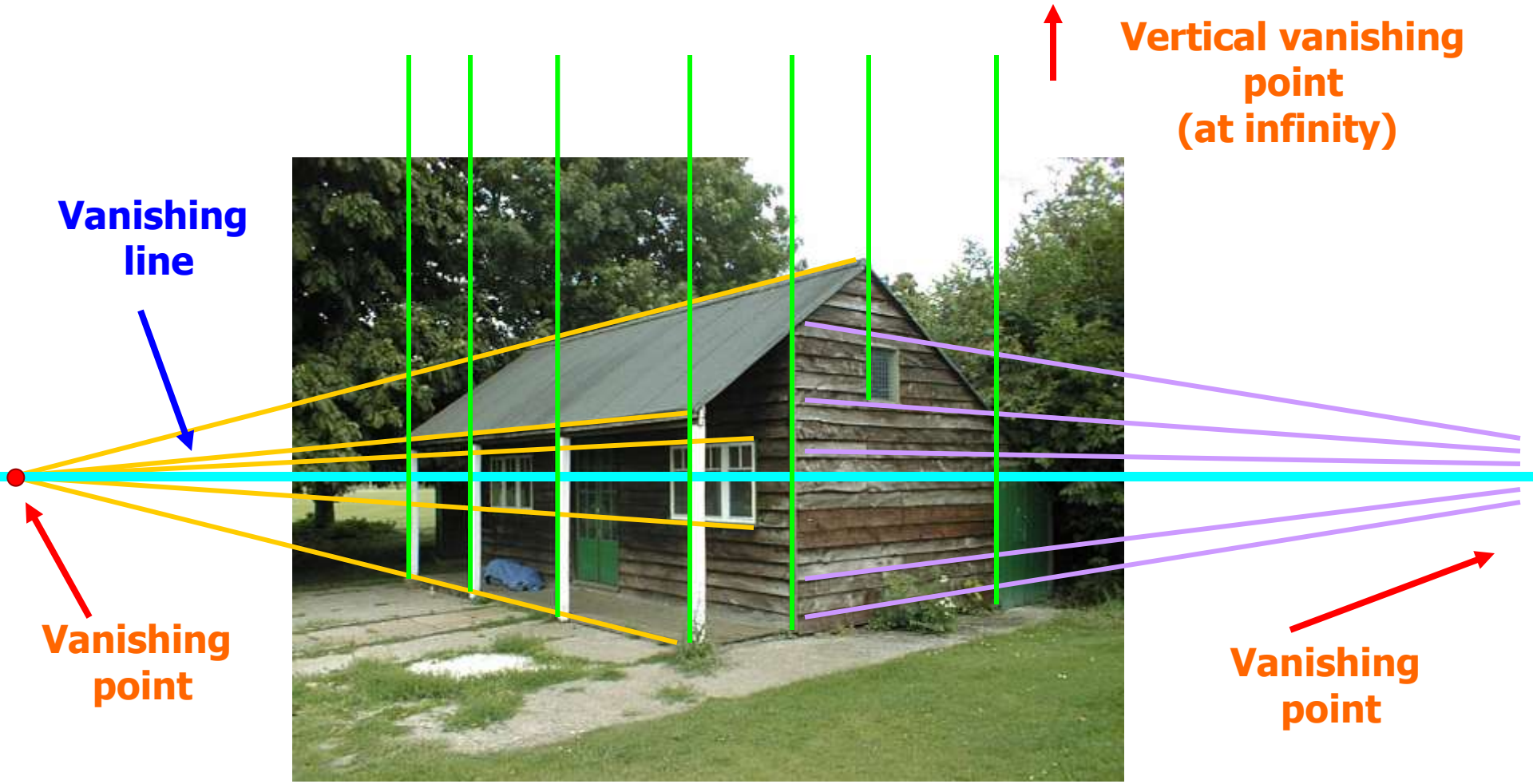


Vanishing points and lines



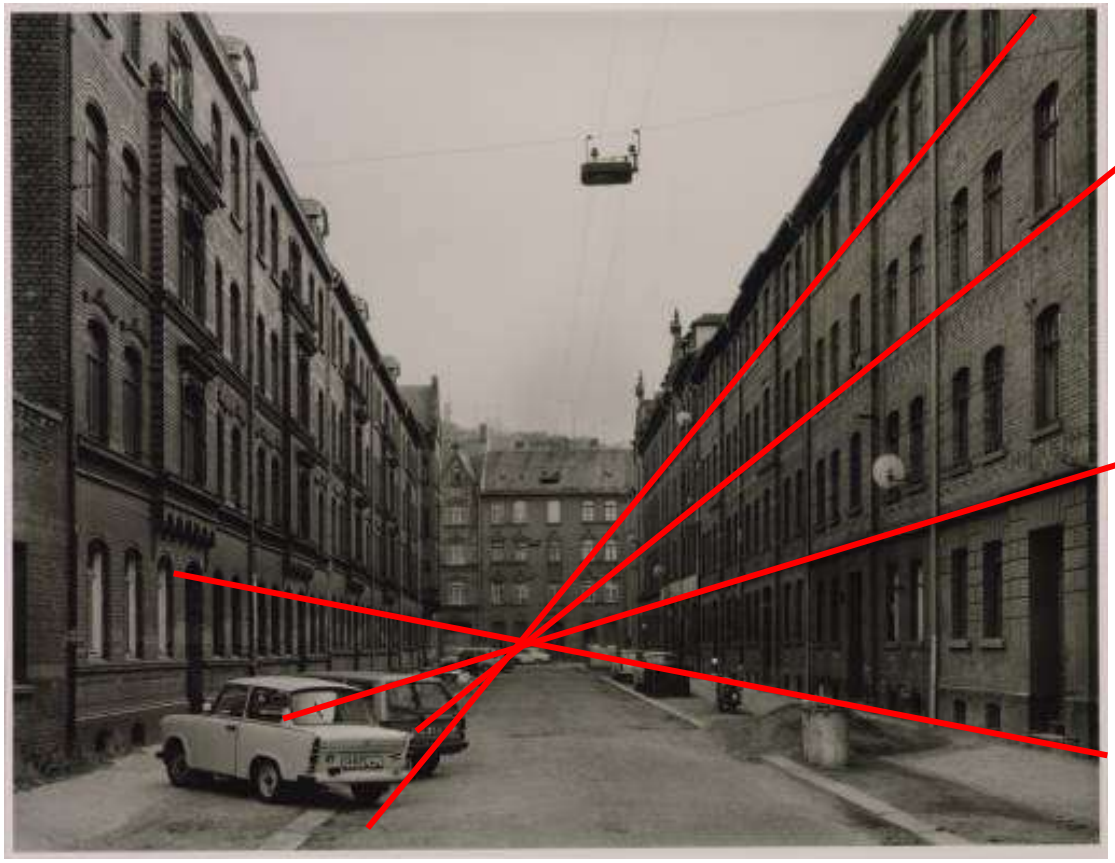
Slide source: James Hays

Vanishing Points and Lines

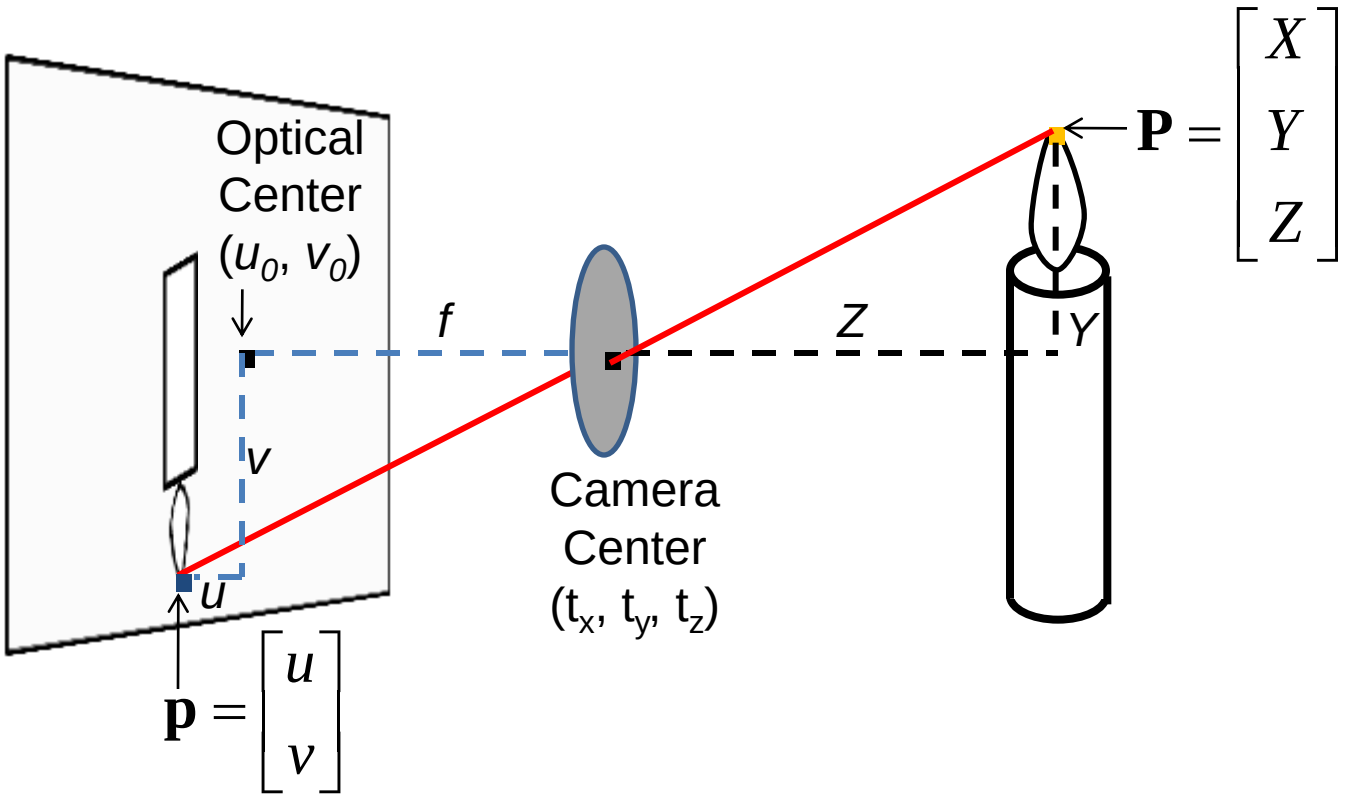


Slide from Efros, Photo from Criminisi

Vanishing Points



World Coordinates→Image Coordinates



Homogeneous coordinates

Conversion

Converting to *homogeneous* coordinates

$$(x, y) \Rightarrow \begin{bmatrix} x \\ y \\ 1 \end{bmatrix}$$

homogeneous image coordinates

$$(x, y, z) \Rightarrow \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix}$$

homogeneous scene coordinates

Converting *from* homogeneous coordinates

$$\begin{bmatrix} x \\ y \\ w \end{bmatrix} \Rightarrow (x/w, y/w)$$

$$\begin{bmatrix} x \\ y \\ z \\ w \end{bmatrix} \Rightarrow (x/w, y/w, z/w)$$

Homogeneous coordinates

Invariant to scaling

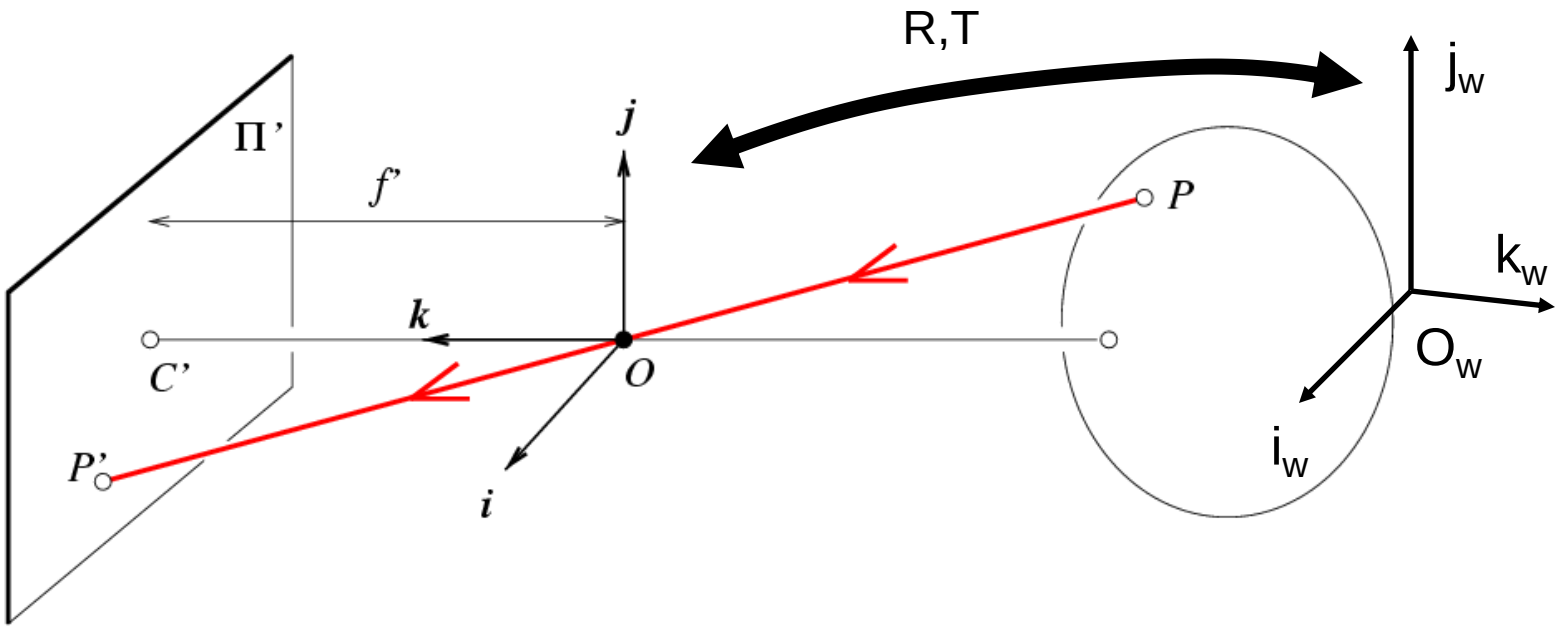
$$k\begin{bmatrix} x \\ y \\ w \end{bmatrix} = \begin{bmatrix} kx \\ ky \\ kw \end{bmatrix} \Rightarrow \begin{bmatrix} \frac{kx}{kw} \\ \frac{ky}{kw} \end{bmatrix} = \begin{bmatrix} \frac{x}{w} \\ \frac{y}{w} \end{bmatrix}$$

Homogeneous Coordinates

Cartesian Coordinates

Point in Cartesian is ray in Homogeneous

Projection matrix

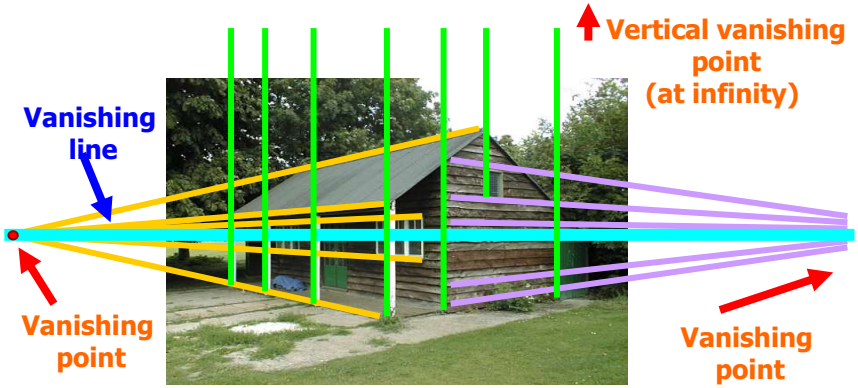


$$\mathbf{x} = \mathbf{K}\begin{bmatrix}\mathbf{R} & \mathbf{t}\end{bmatrix}\mathbf{X}$$

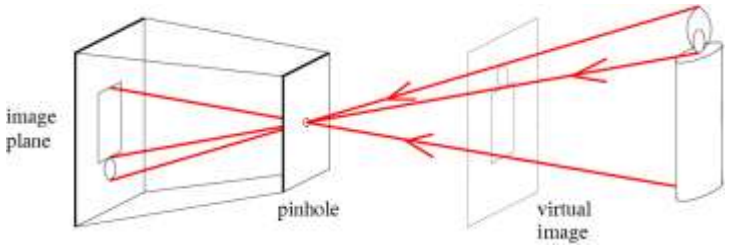
x: Image Coordinates: (u,v,1)
K: Intrinsic Matrix (3x3)
R: Rotation (3x3)
t: Translation (3x1)
X: World Coordinates: (X,Y,Z,1)

Things to remember

- Vanishing points and vanishing lines



- Pinhole camera model and camera projection matrix



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Reflection Models

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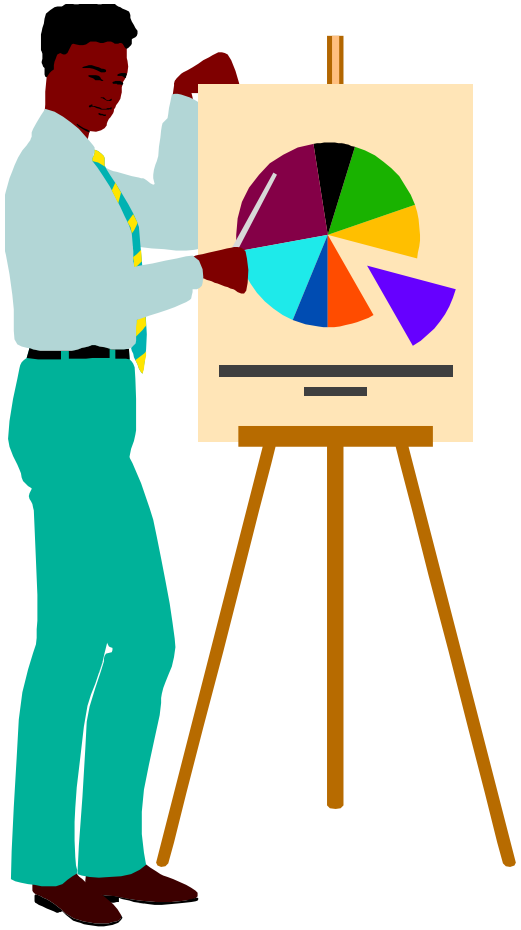
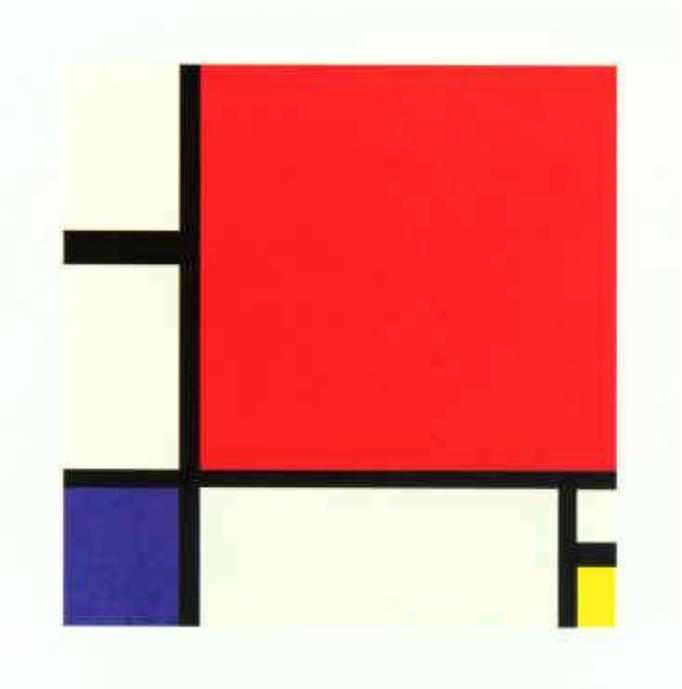


The science of Light and Colour

Fundamentals of colour science

Hall of fame



Mondrian

Pythagoras: undulation theory

Aristoteles: curpus theory

Newton 1665 "Opticks"

Planck, Einstein and Bohr "Quantum mechanics"

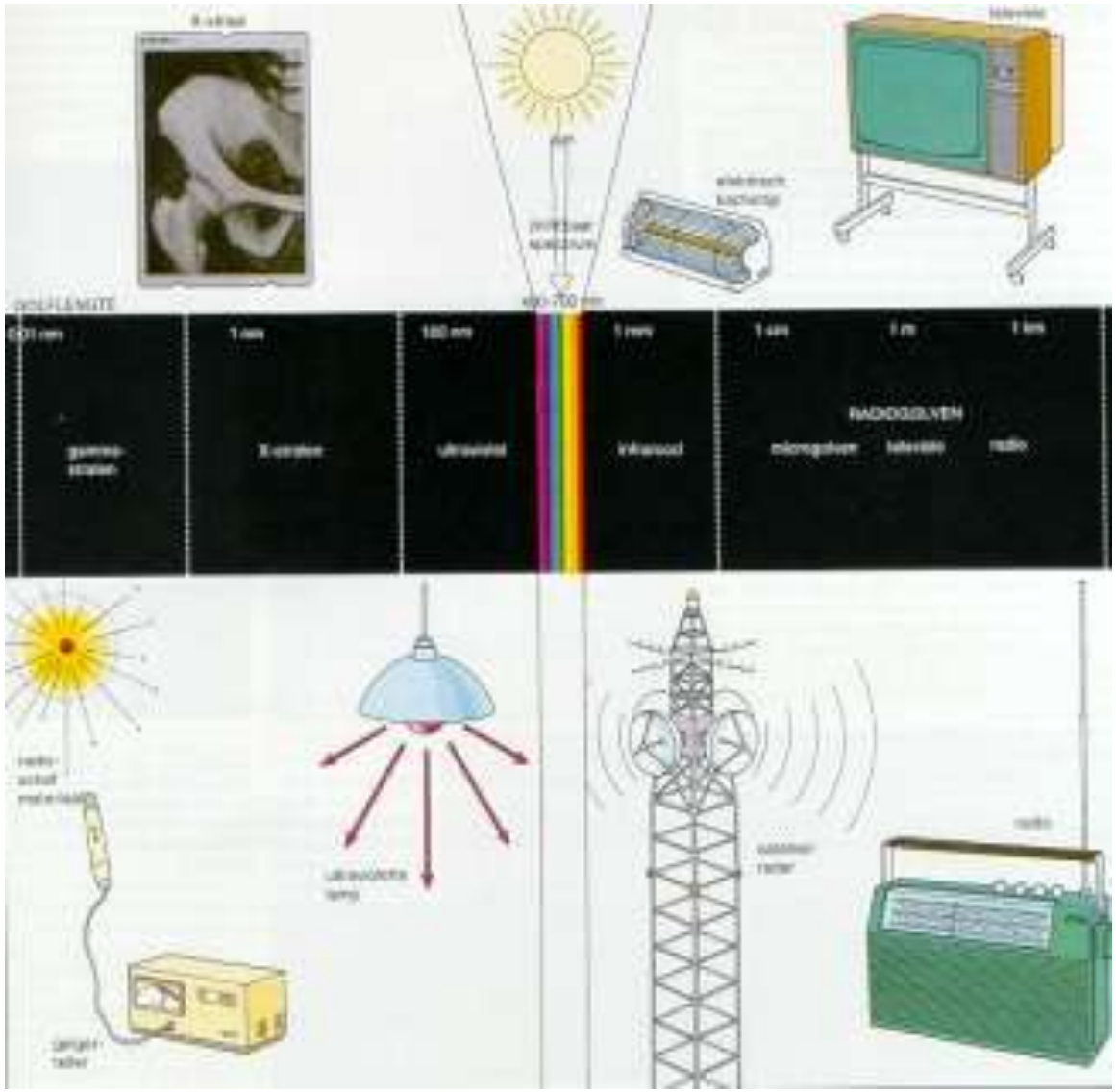
Goethe 1840 "Farbenlehre"

Munsell 1905 "A Colour Notation"

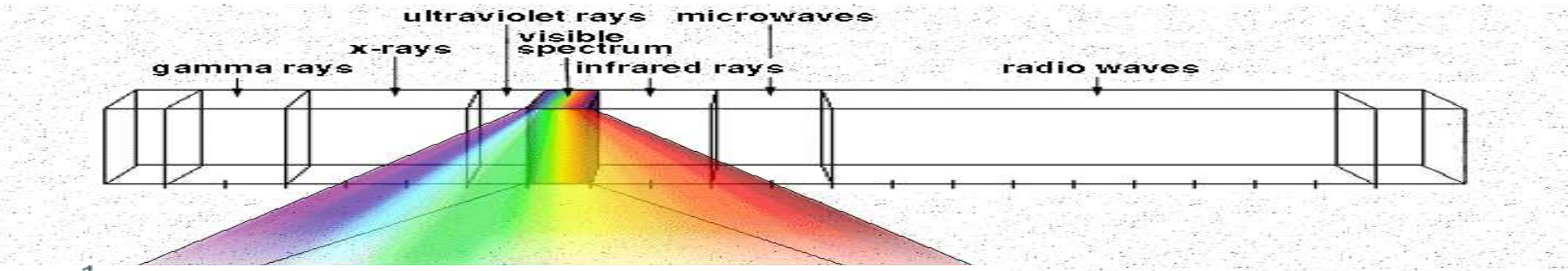
Descartes, Schopenhauer,

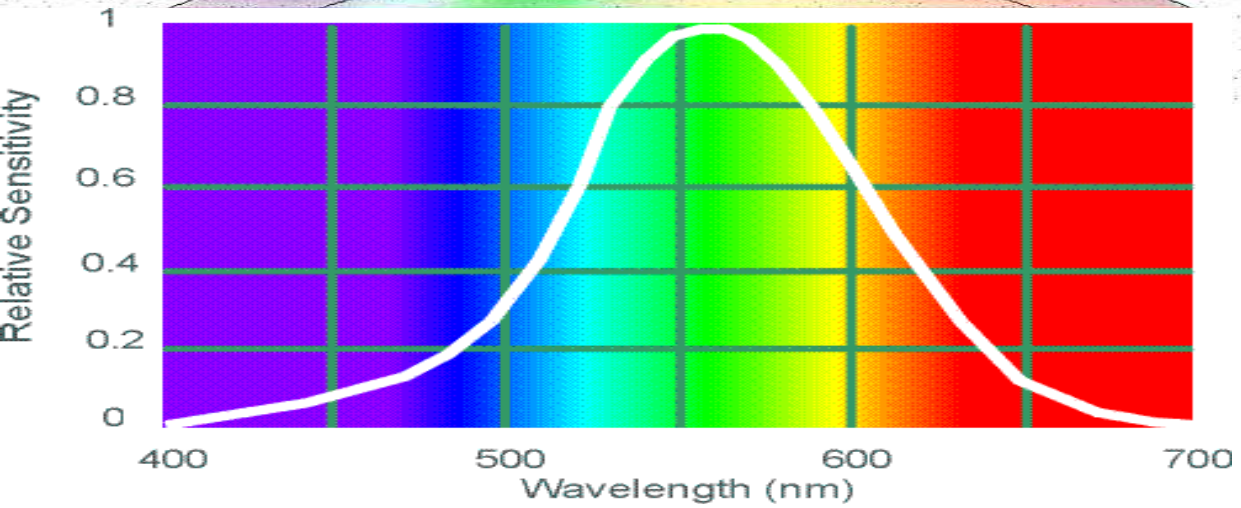
Hegel, Wittgenstein…and many others

Fundamentals Electromagnetic Spectrum



Electromagnetic Spectrum

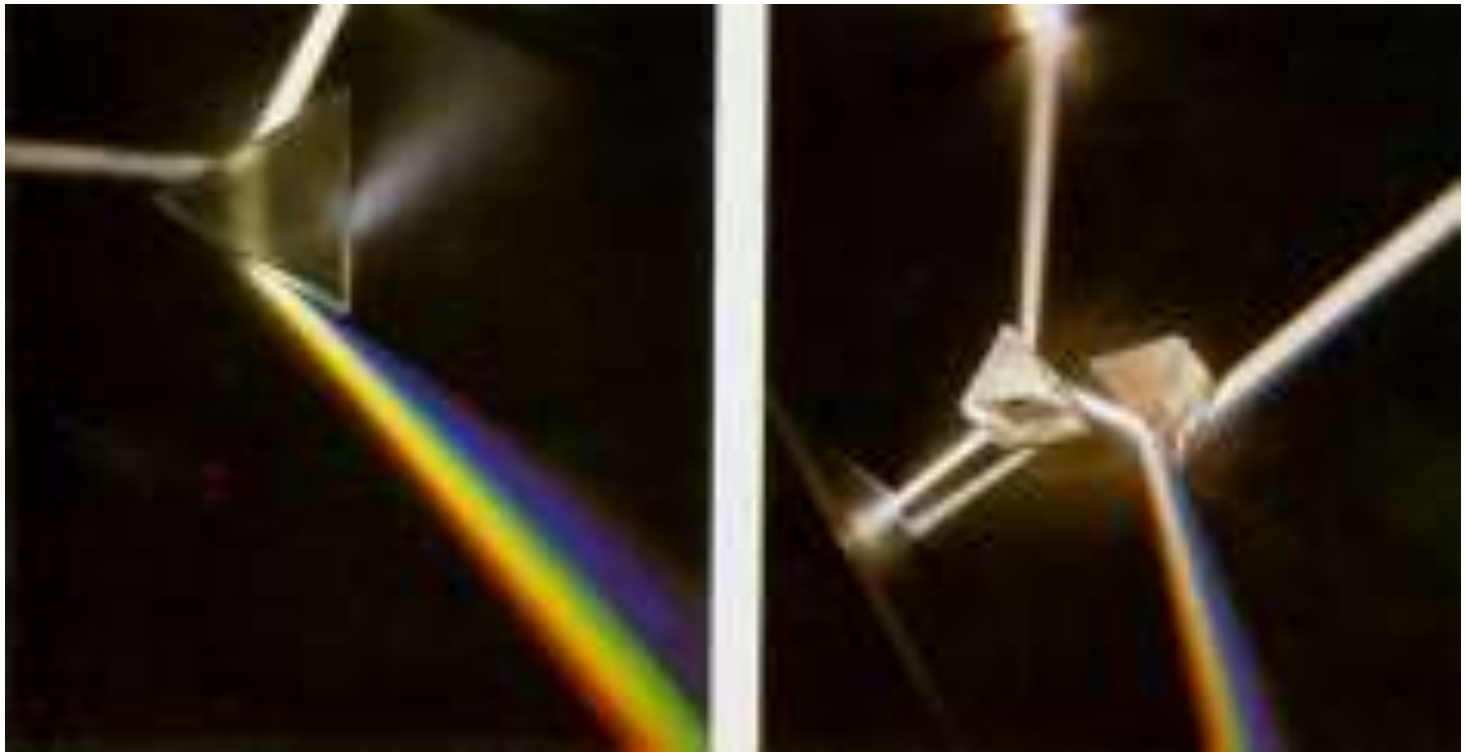




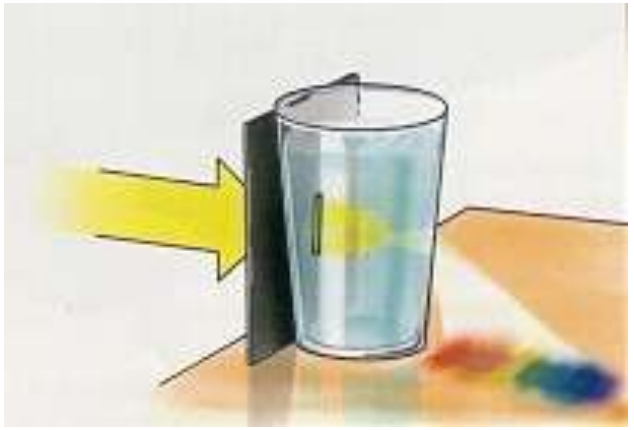
Human Luminance Sensitivity Function

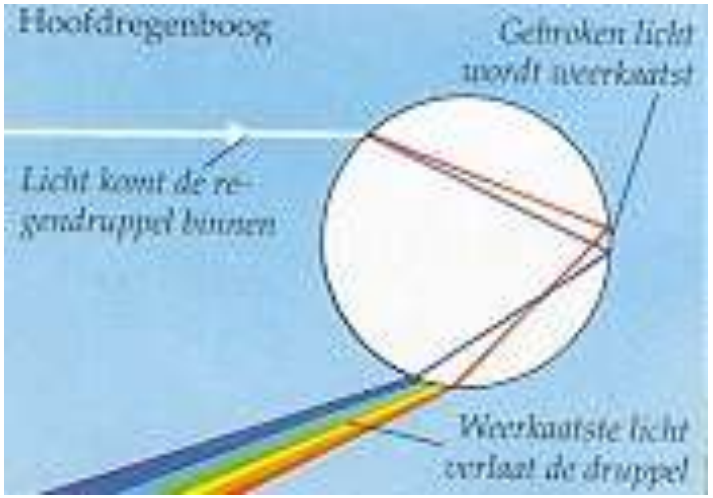
http://www.yorku.ca/eye/photopik.htm

Electromagnetic Spectrum



Electromagnetic Spectrum



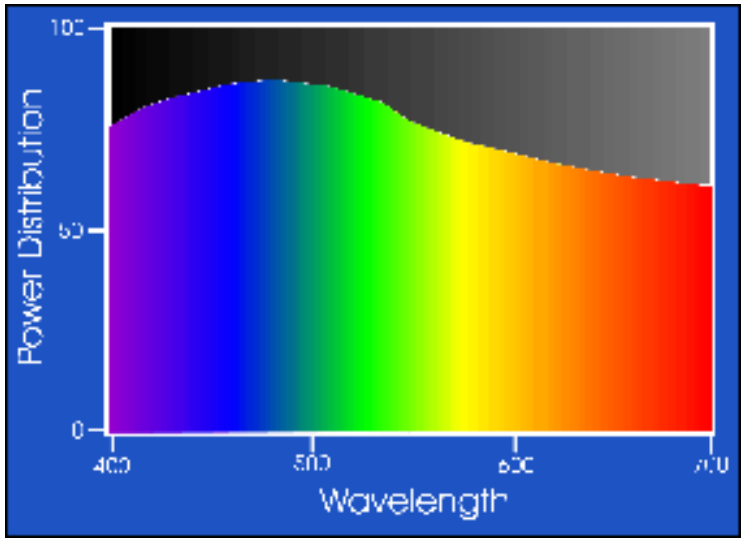


Spectral Power Distribution

Hue: dominant wavelength of the SPD: EH

Saturation: purity of the colour: EH-EW

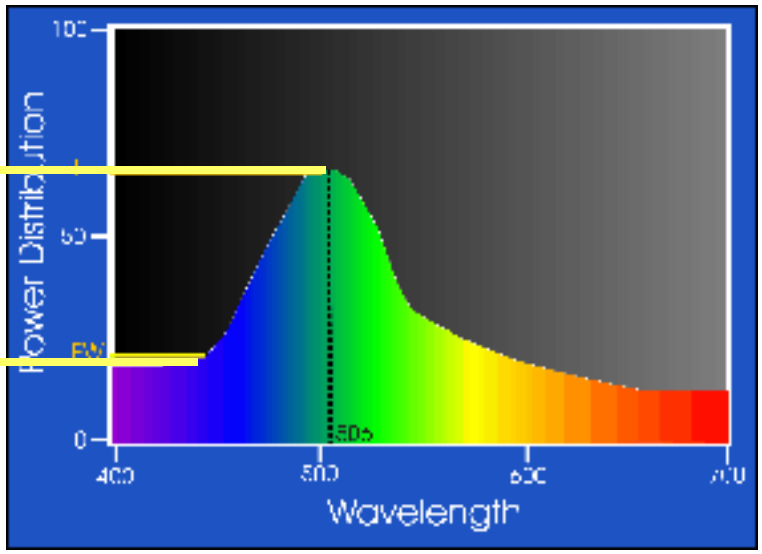
Intensity: brightness of the colour: EW



White light

EH

EW



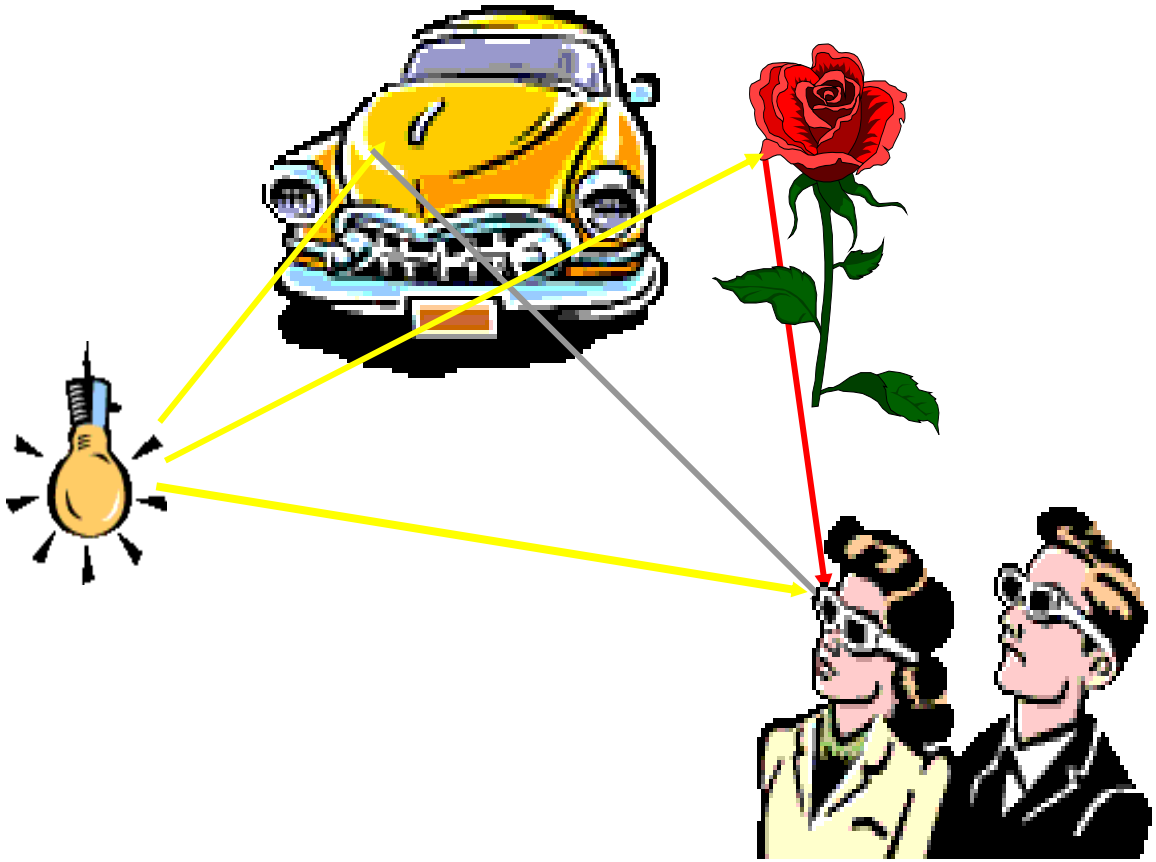
Green light

What makes an image?
the triplet light-objects-observer

Light source

Object(s)

Sensor



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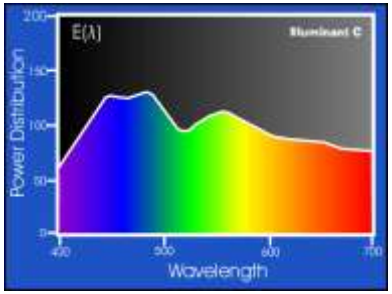
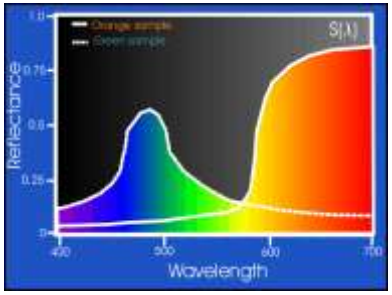


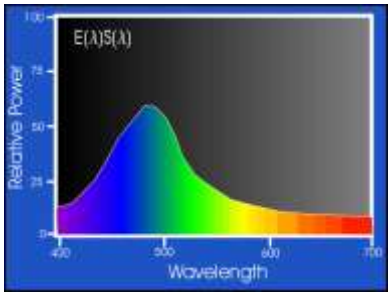
$e(\lambda)$

Object



$\rho(\lambda)$

Sensor



$e(\lambda)\rho(\lambda)$

Light sources and illuminants

Light sources:

sun, candle,

fluorescent lamp,

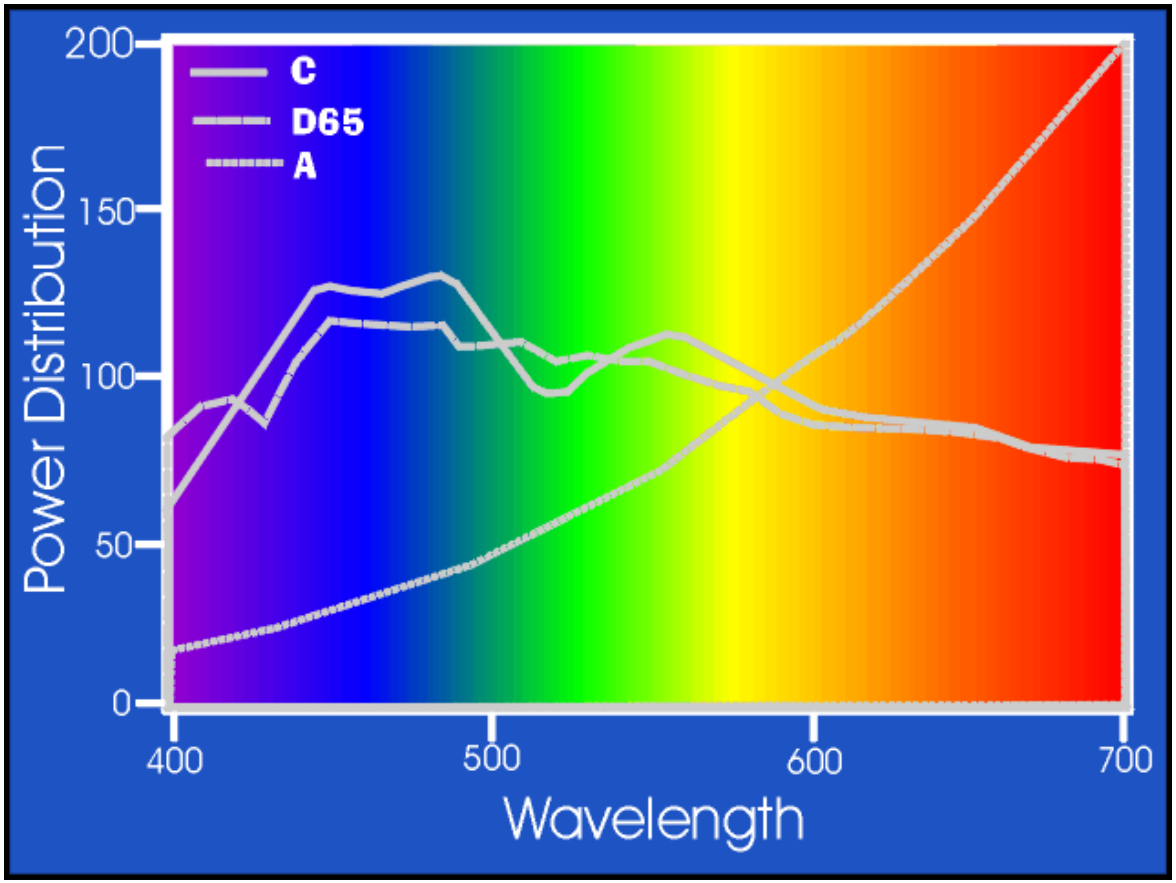
incandescent lamp

Illuminants:

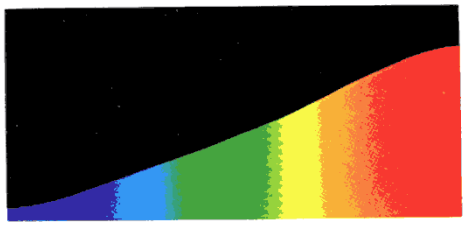
illuminant A

illuminant D65

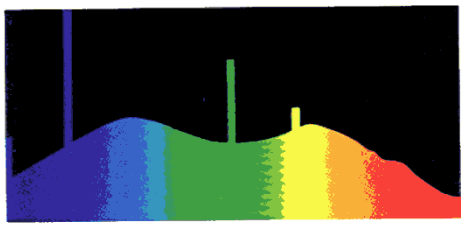
illuminant C



Light sources and illuminants



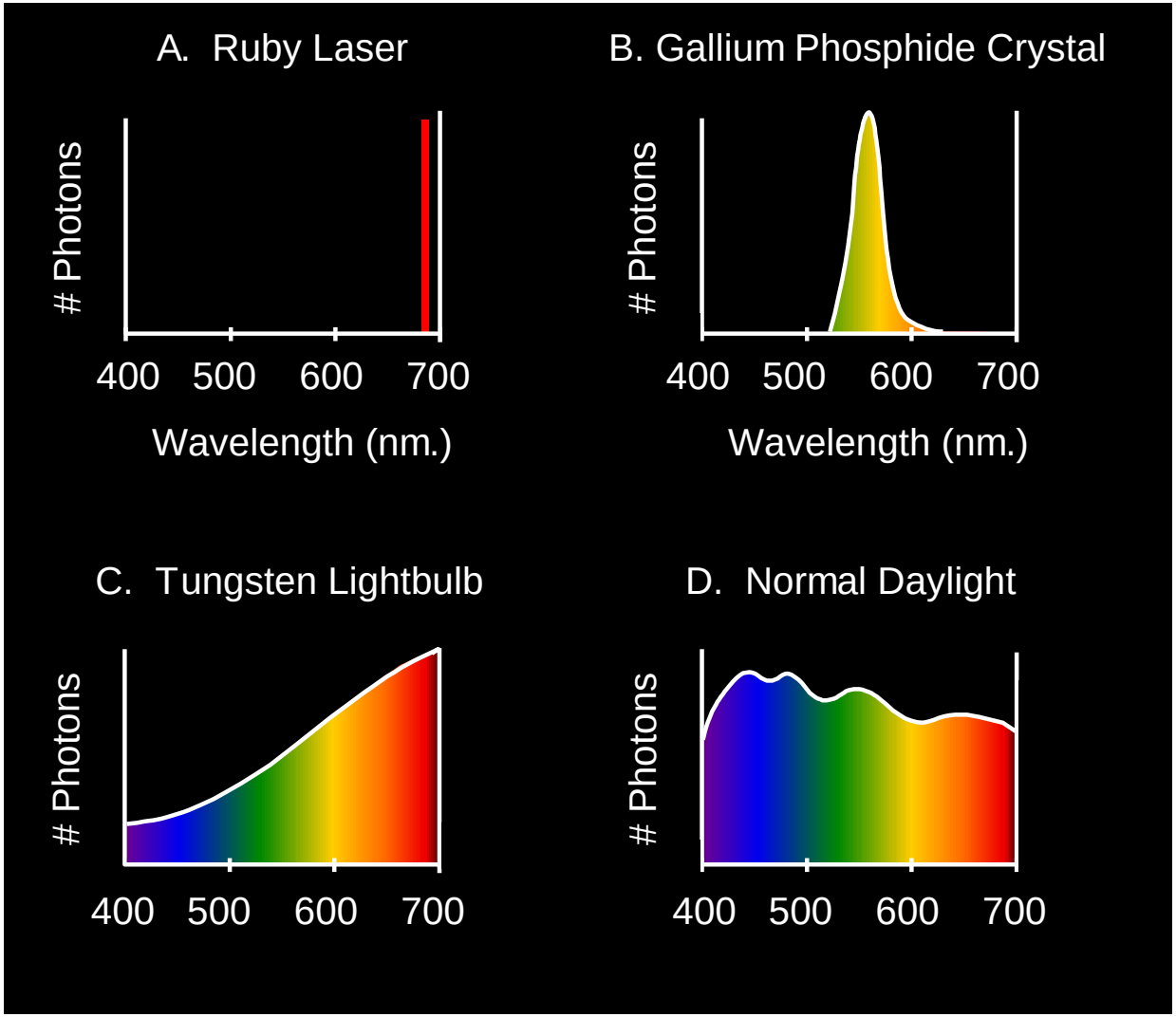
Incandescent lamp



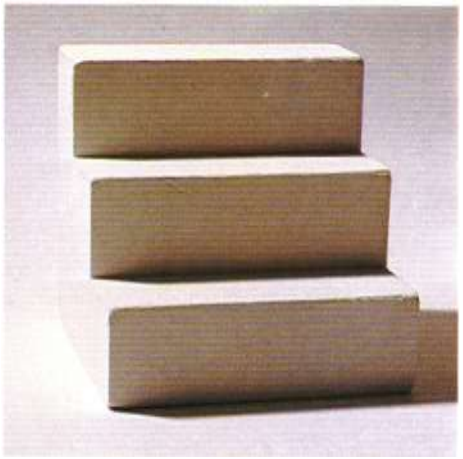
Fluorescent lamp

The Physics of Light

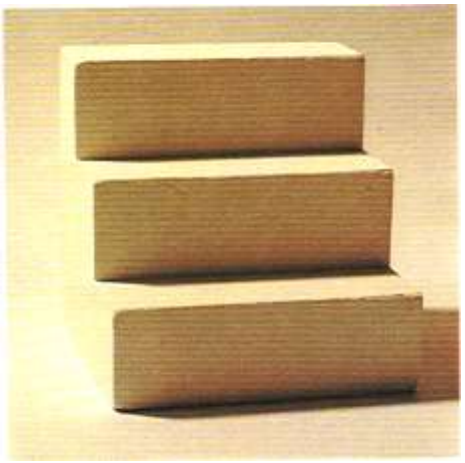
Some examples of the spectra of light sources



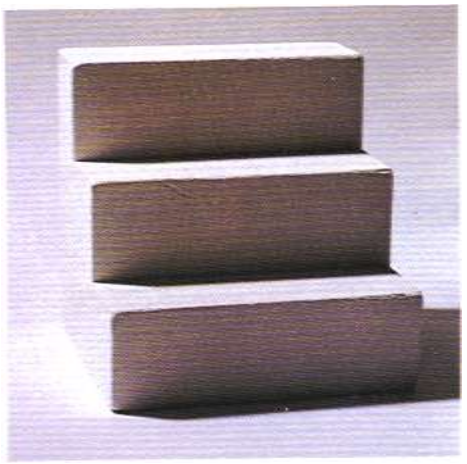
Influence of Light Sources



Average daylight



Incandescent lamp



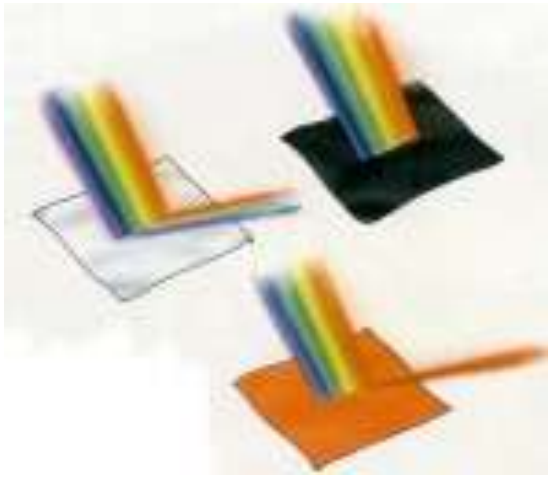
Fluorescent lamp

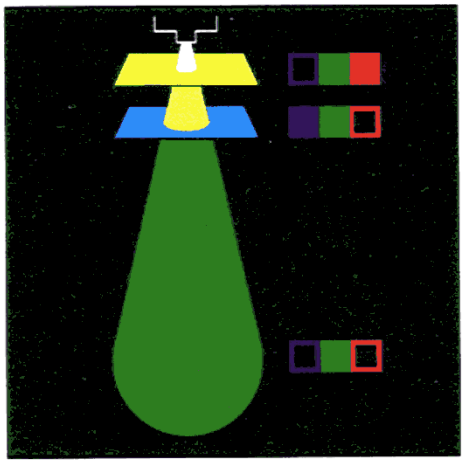
Object Colours

Materials:

- Transparent
- Opaque

Spectral Reflectance $\rho(\lambda)$



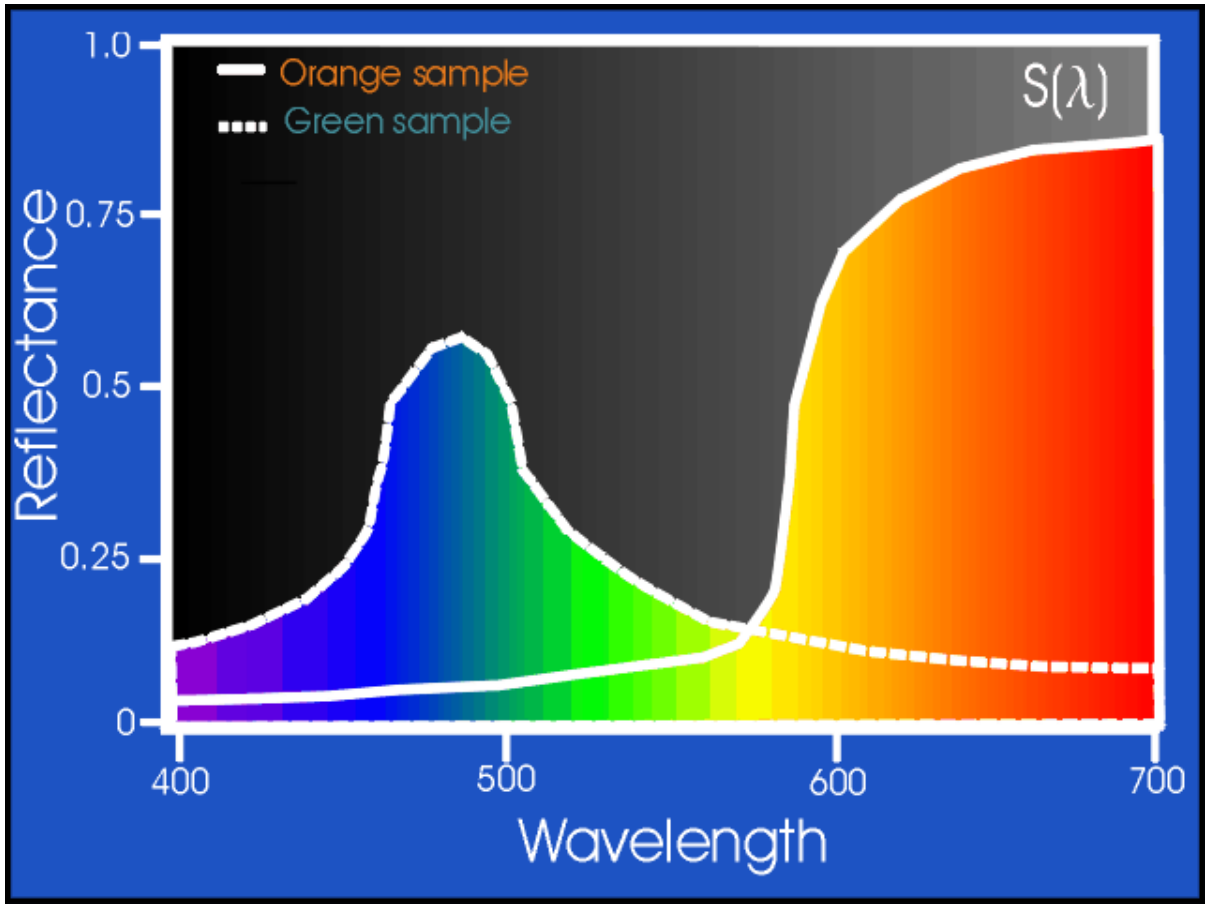


Object Colours

Material

spectrophotometer

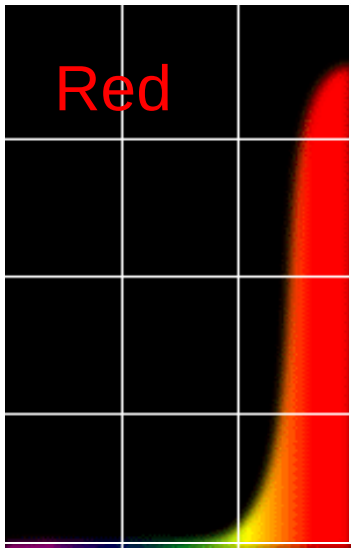
Reflectance curve

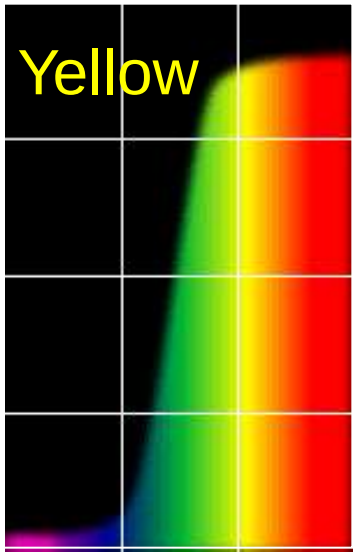


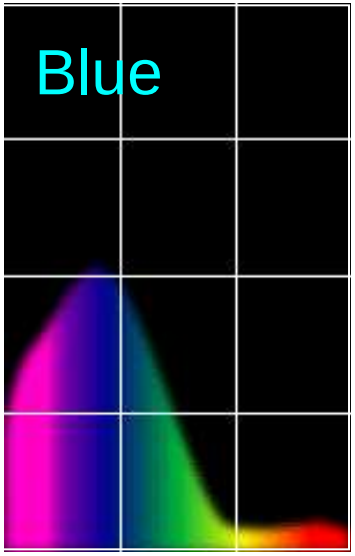
Object Colours

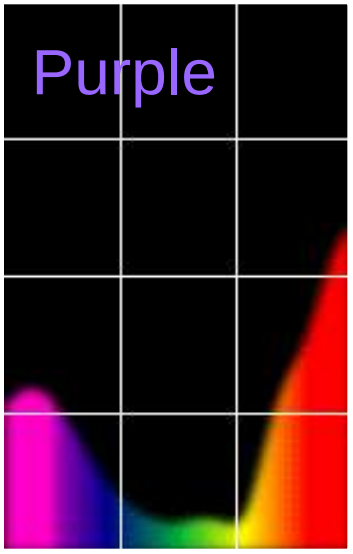
Some examples of the reflectance spectra of surfaces



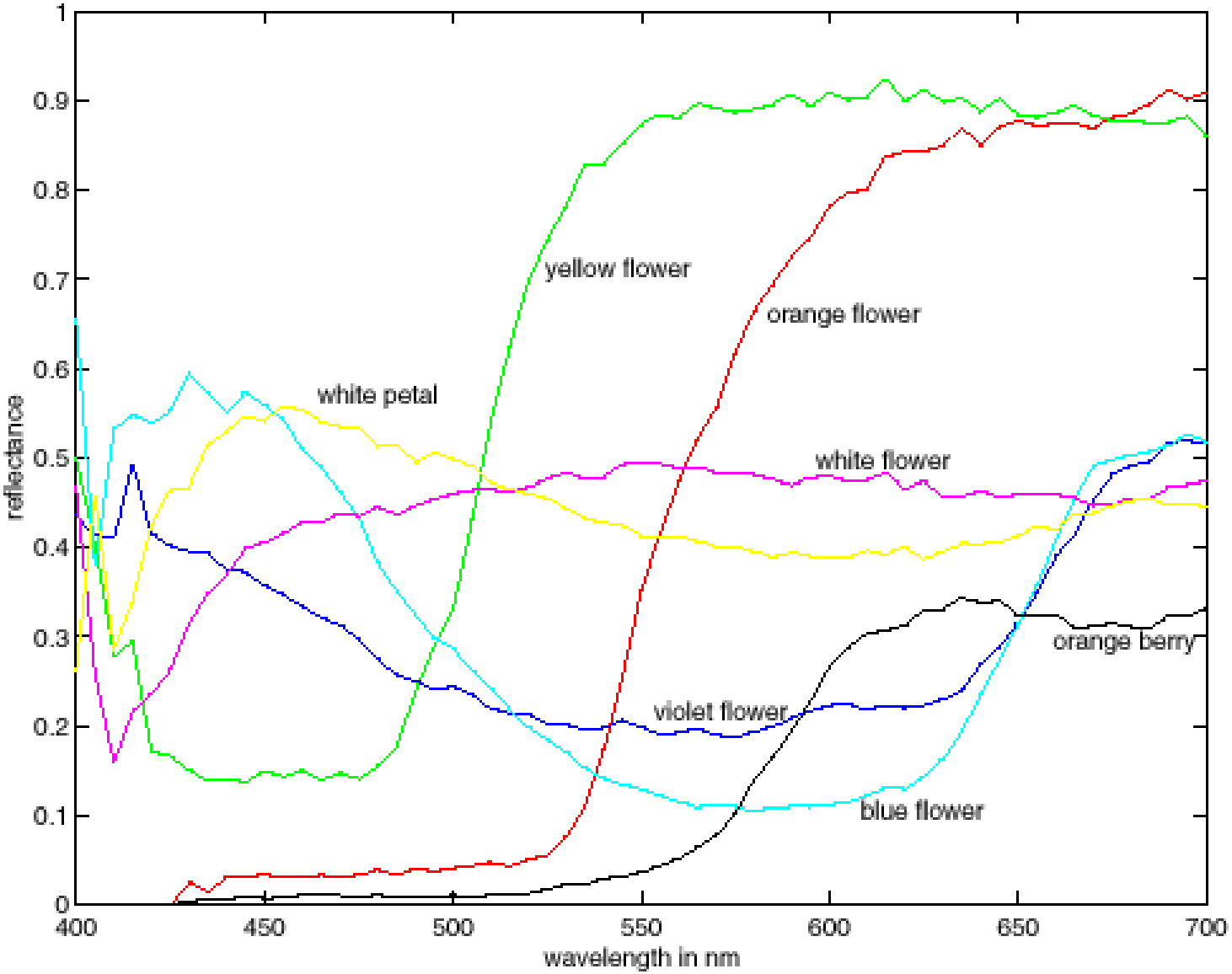






Wavelength (nm)

More Spectra

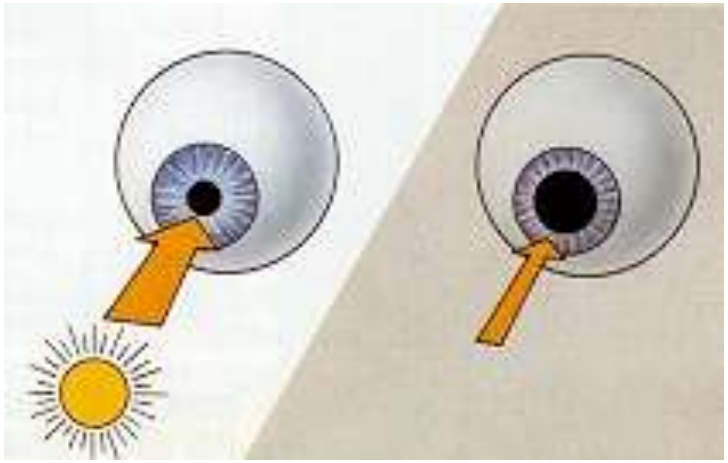


Observer

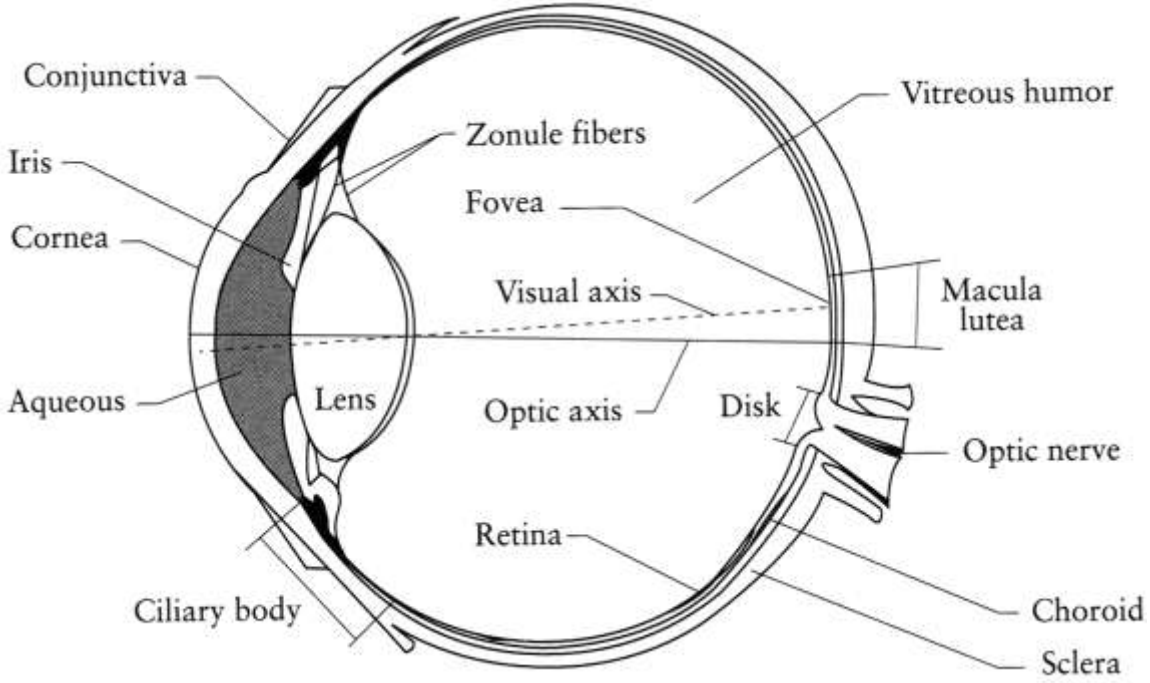
Eyes: rods and cones

Theories:

- Trichromaticity theory
- Opponent theory
- Retinex theory



Observer: The Eye

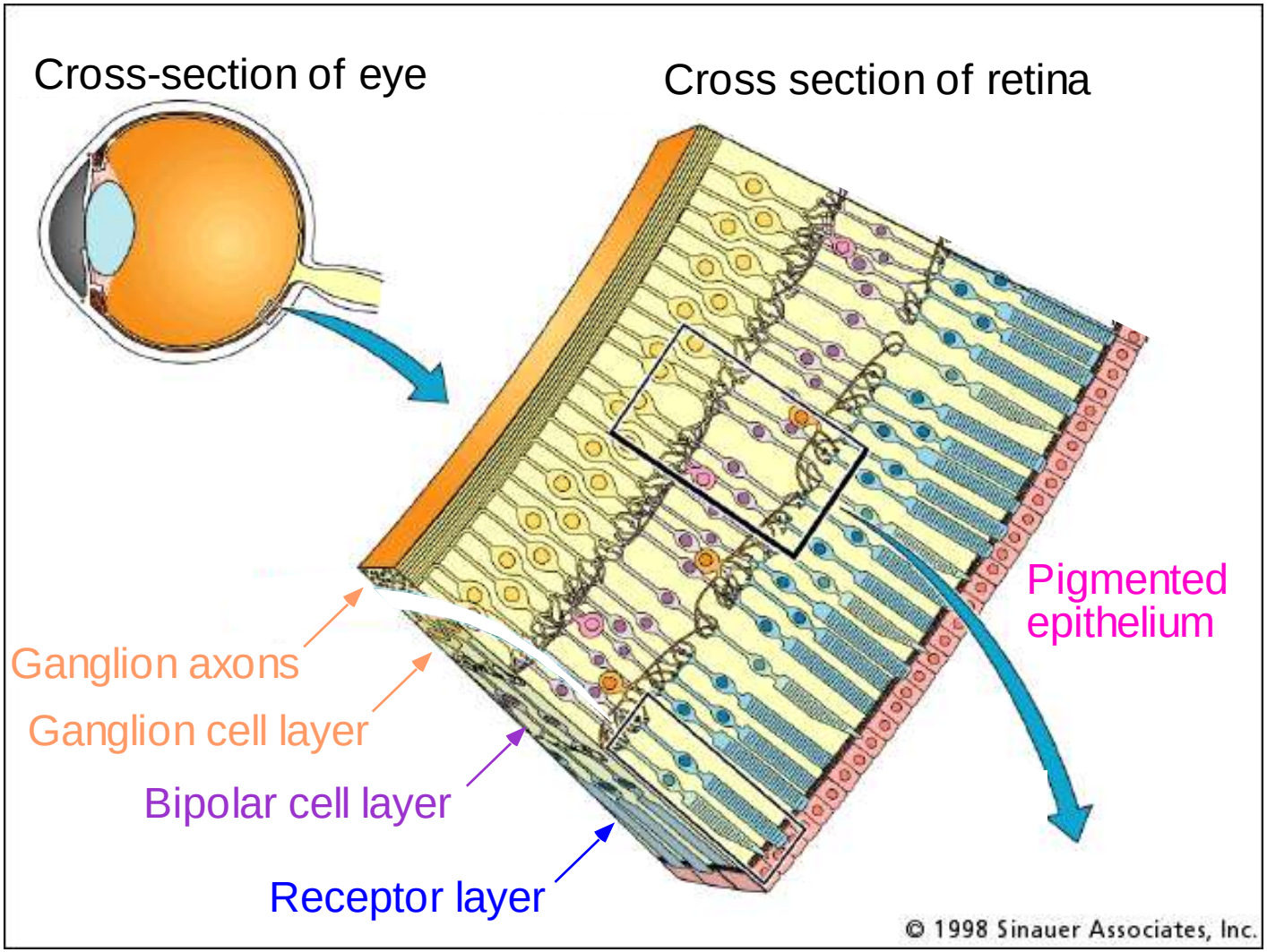


The human eye is a camera!

- **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**

Slide by Steve Seitz

Observer: The Retina



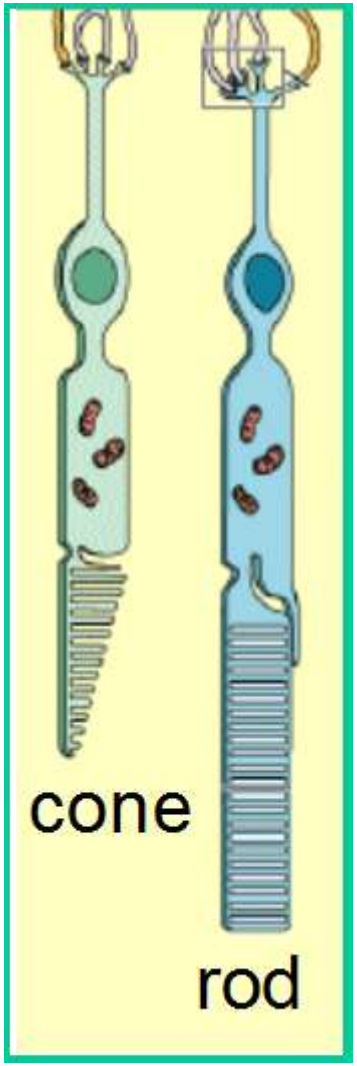
Two Types of Light-Sensitive Receptors

Cones

cone-shaped
less sensitive
operate in high light
color vision

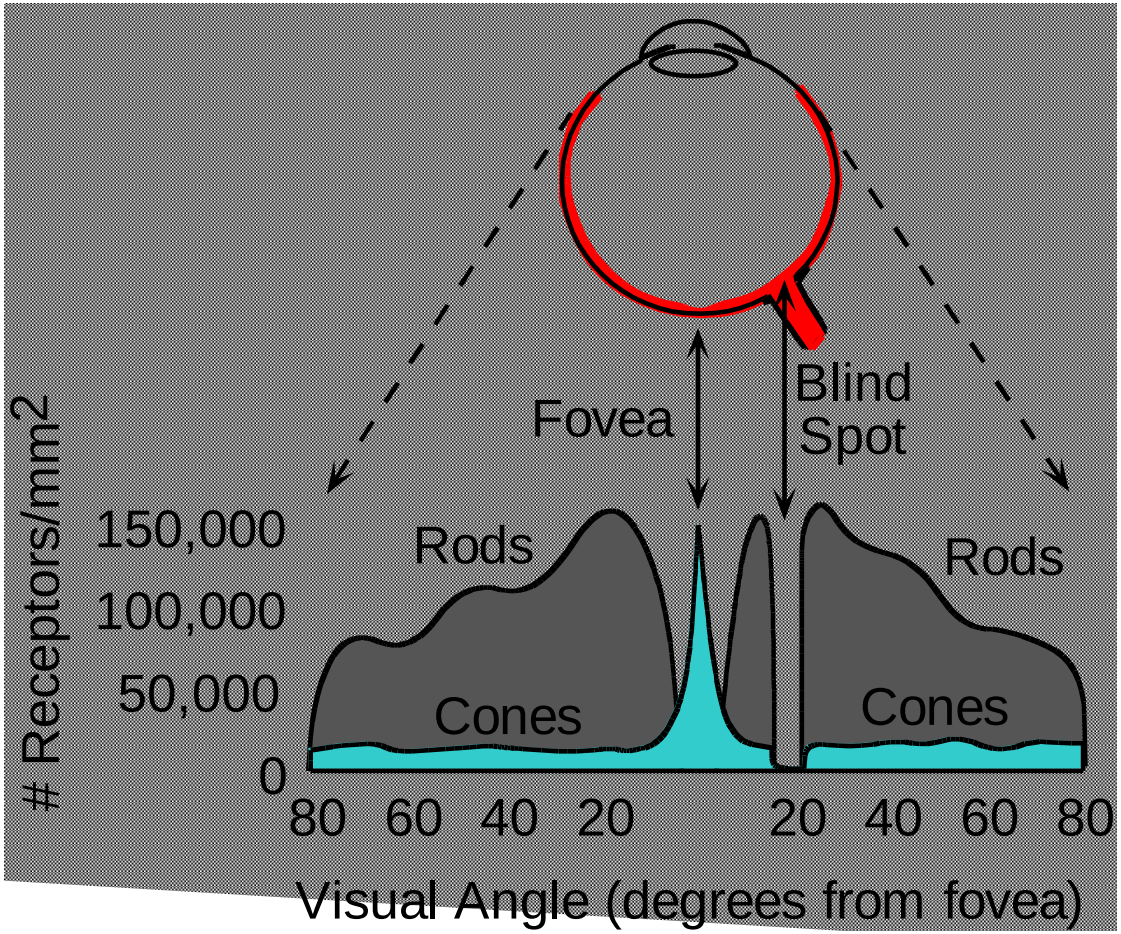
Rods

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



Slide source: James Hays

Distribution of Rods and Cones

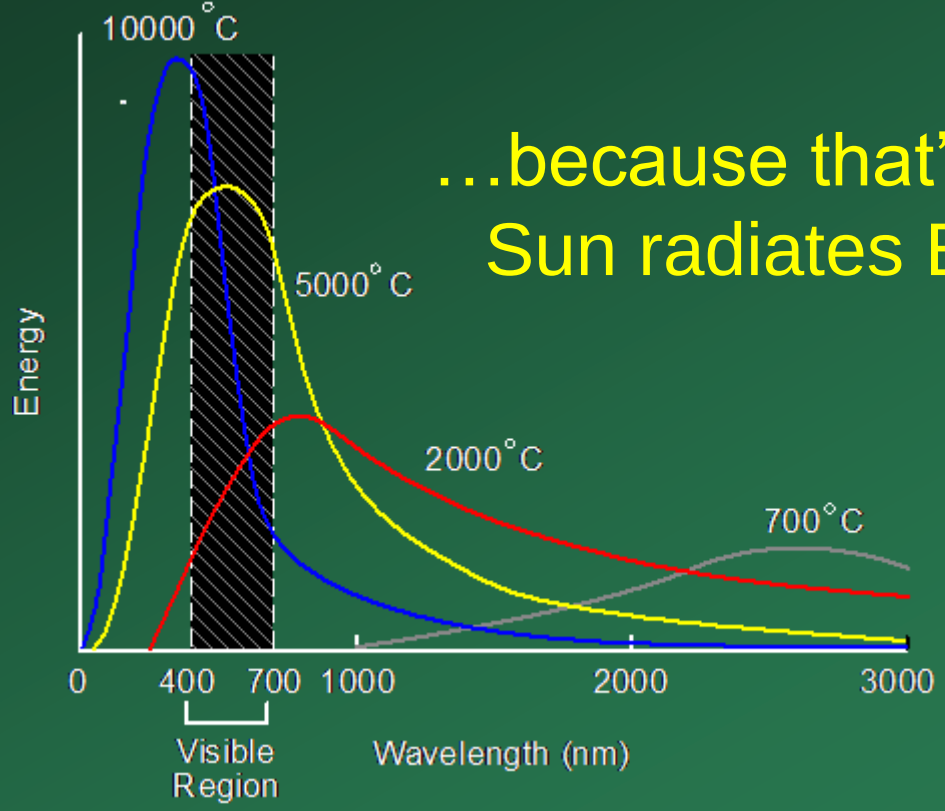


Night Sky: why are there more stars off-center?
Averted vision: http://en.wikipedia.org/wiki/Averted_vision

Slide source: James Hays

Visible Light

Why do we see light of these wavelengths?



…because that's where the Sun radiates EM energy

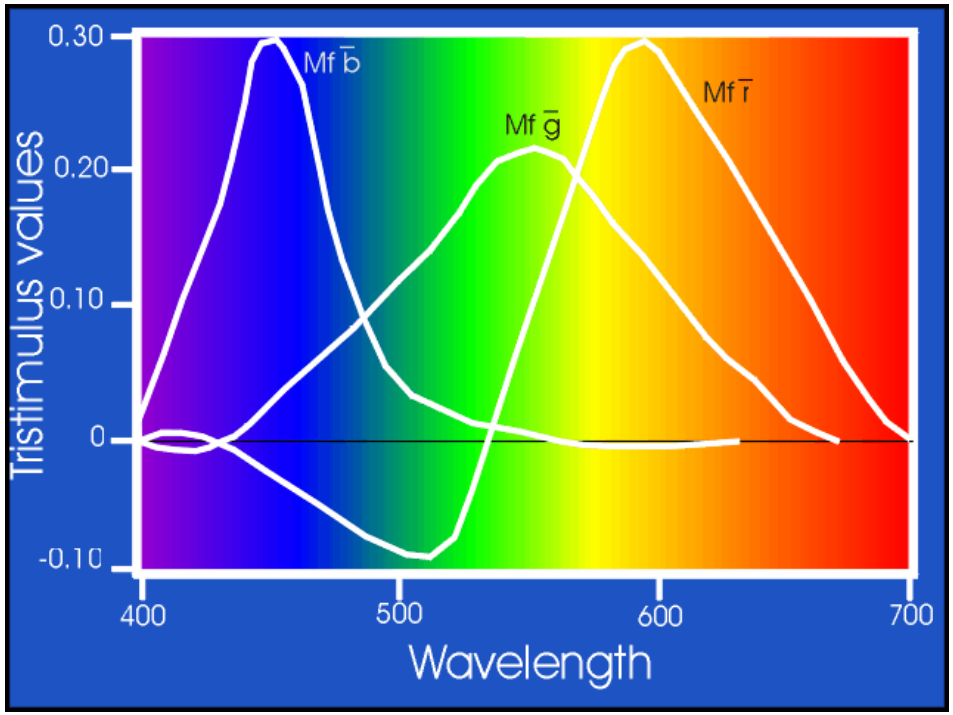
Observer: Trichromacy

Young-Helmholtz approach

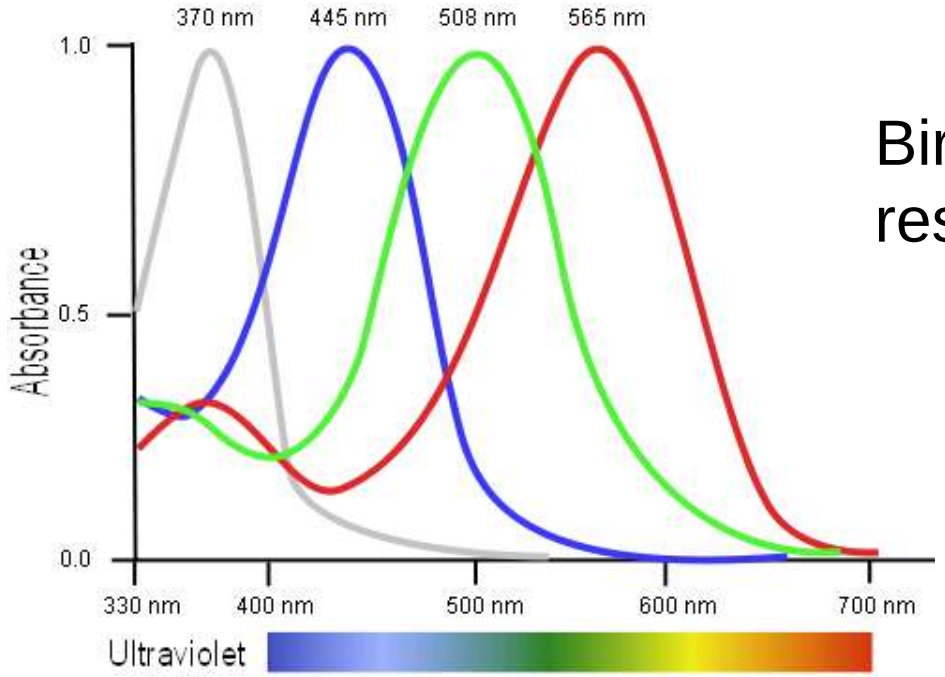
Tristimulus values R, G, and B

Wright (7) Guild (10)

Stiles and Burch (50)



Other Species

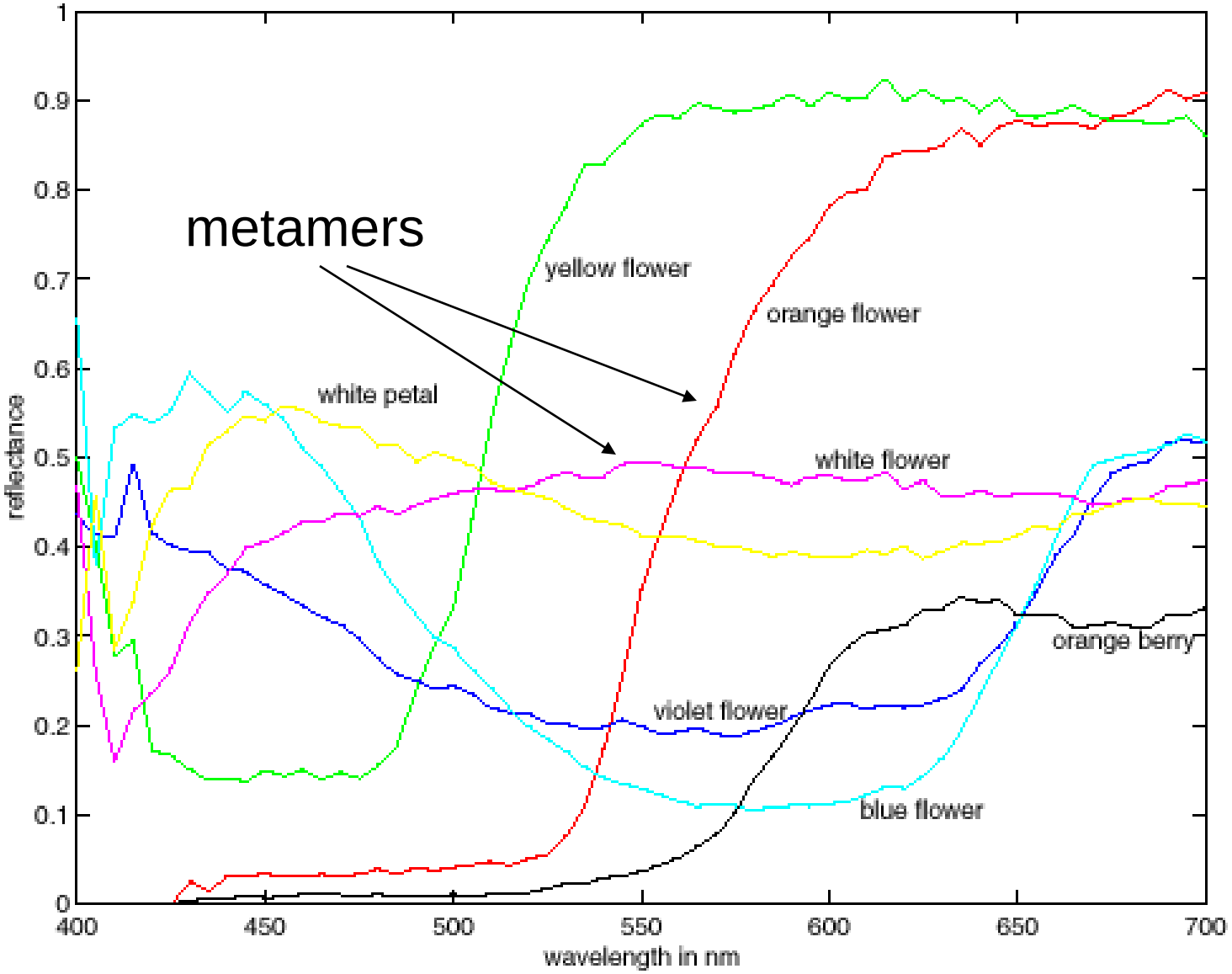


Bird cone responses

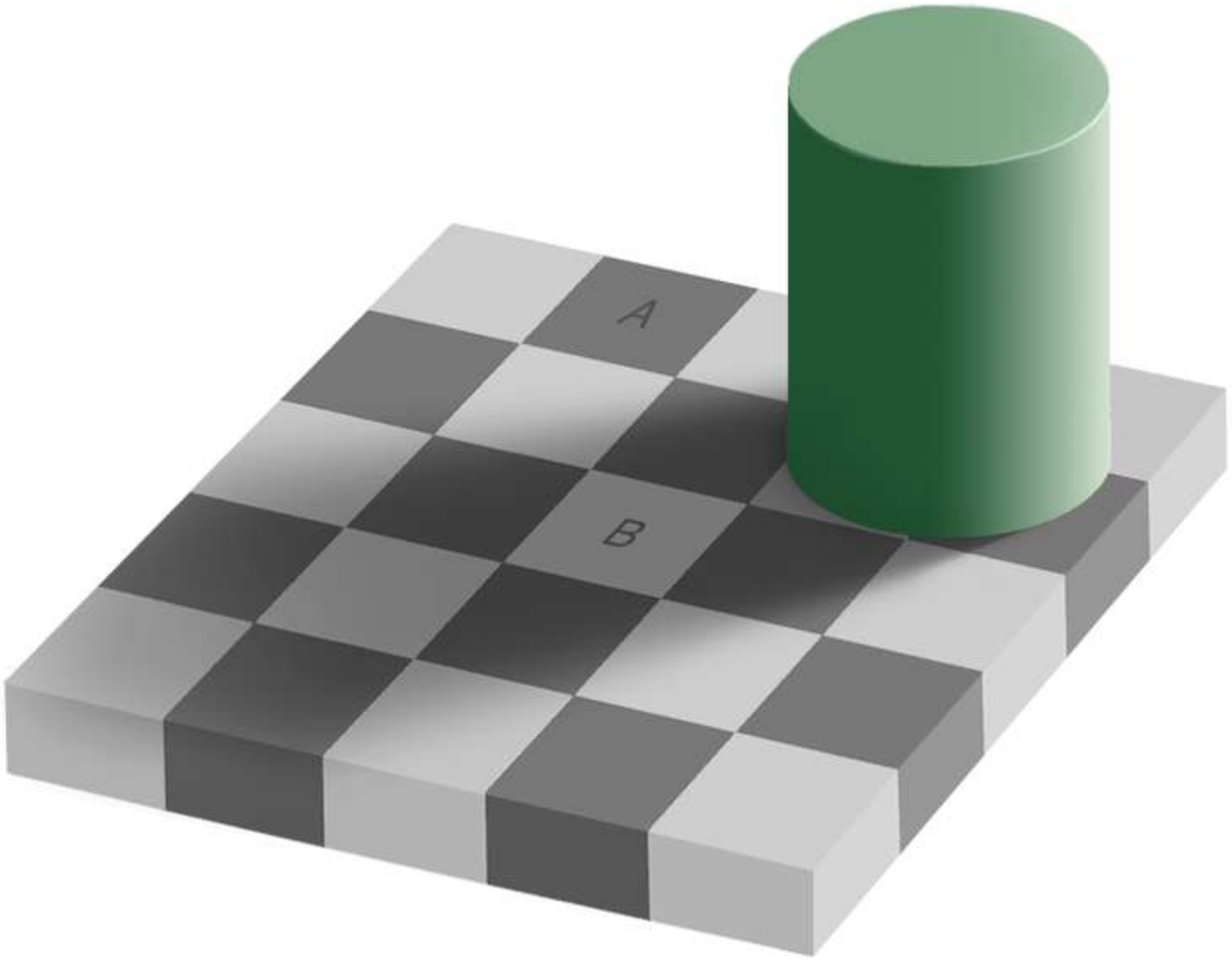
Most birds, and many other animals, have cones for ultraviolet light.

Some humans, mostly female, seem to have slight tetrachromatism.

Metamers

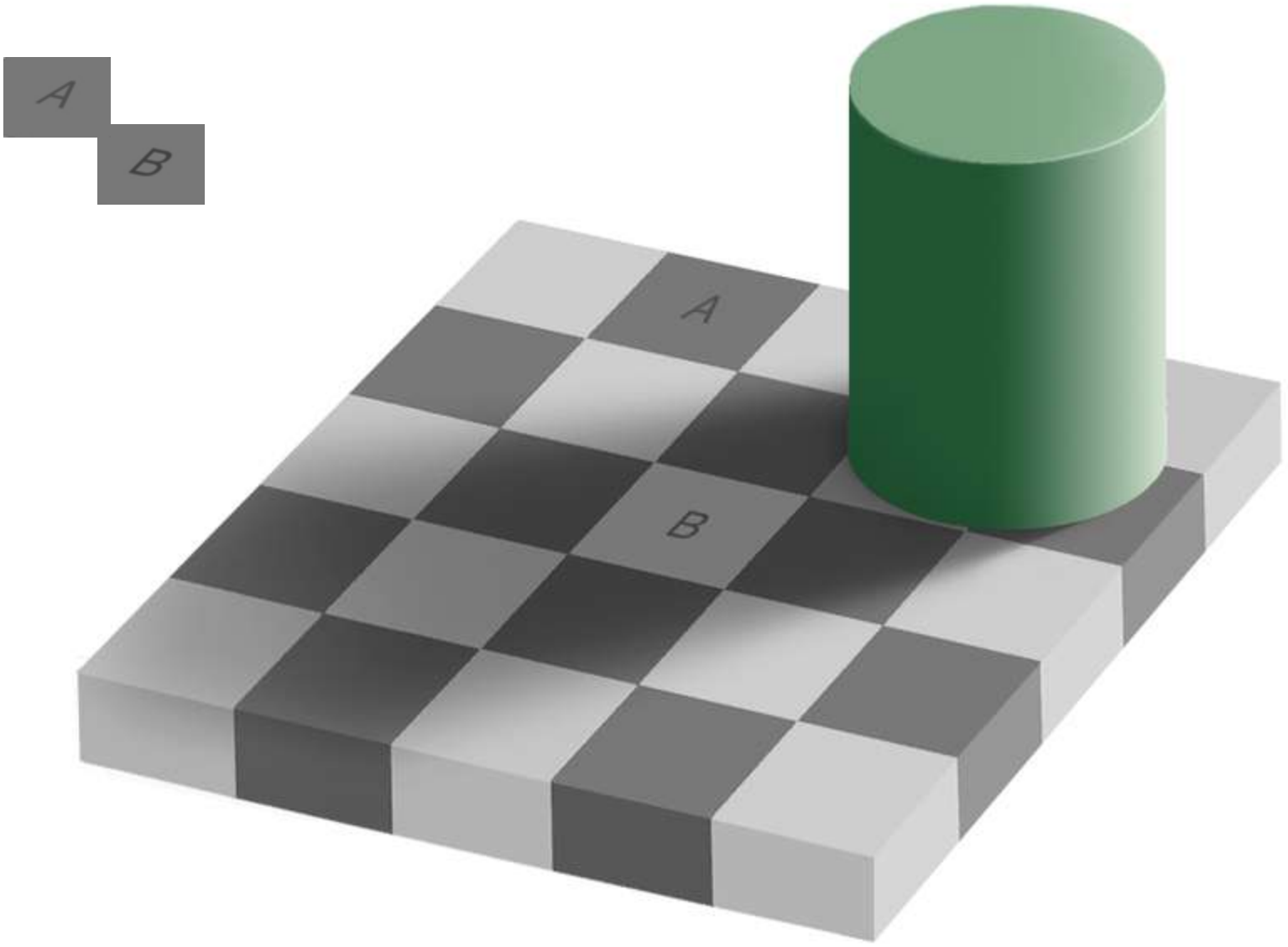

metamers
yellow flower
orange flower
white petal
white flower
orange berry
violet flower
blue flower
reflectance
wavelength in nm
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
400
450
500
550
600
650
700

Perception of Intensity



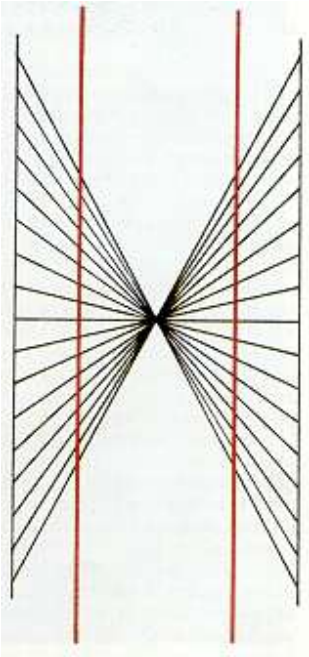
from Ted Adelson

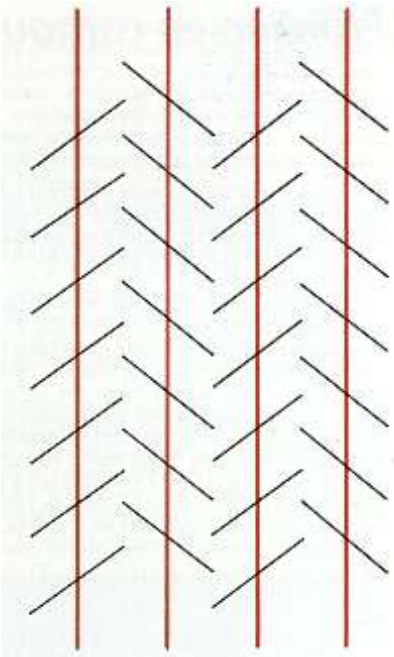
Perception of Intensity

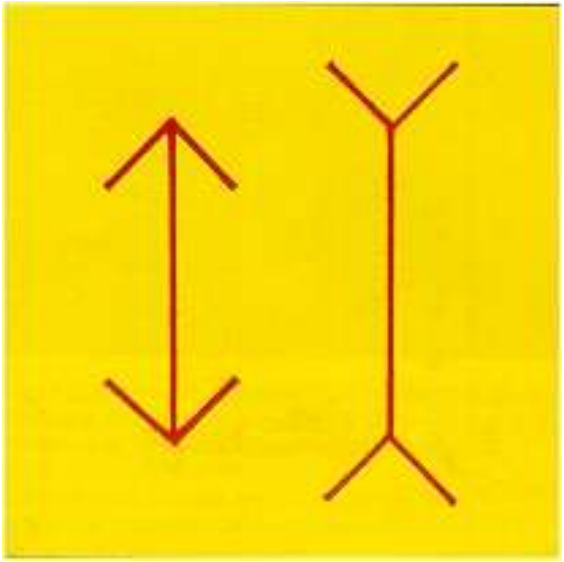


from Ted Adelson

Illusions







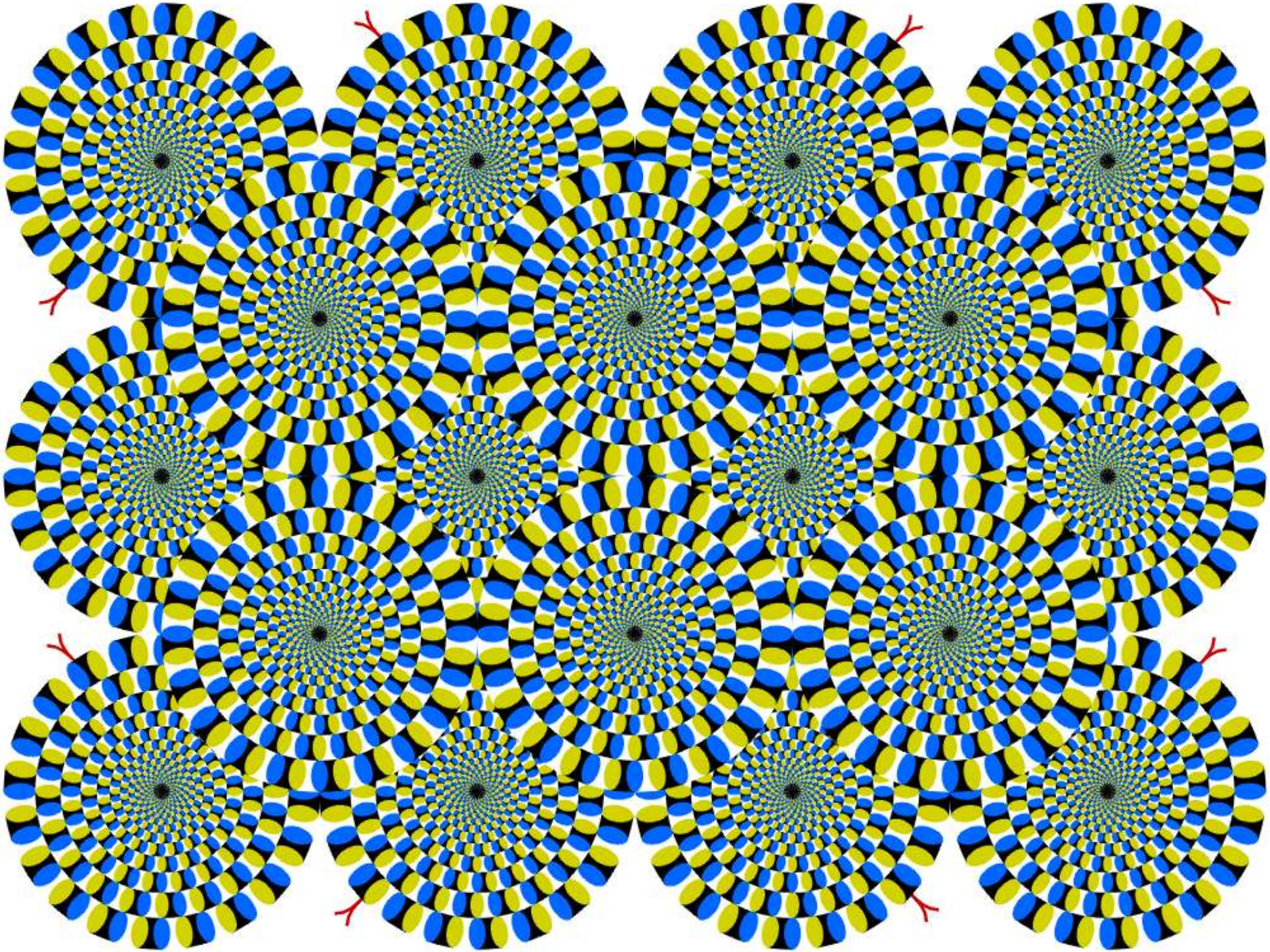


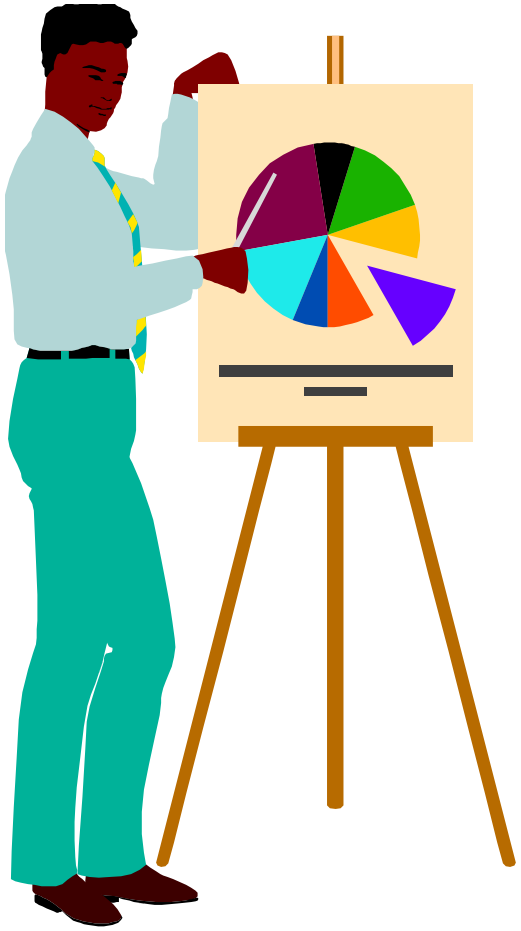
Image Formation

Projective Geometry and Camera Models

Light and Color Models

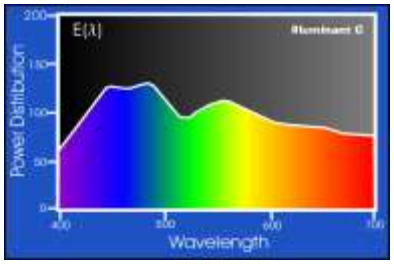
Reflection Models

Reflection Models



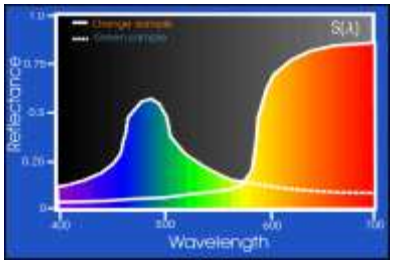
What makes an image?
the triplet light-objects-observer

Light source



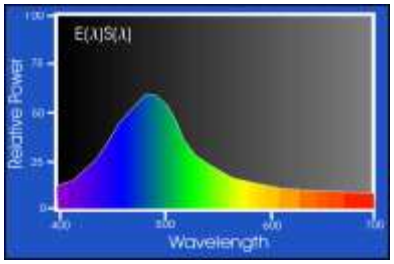
$e(\lambda)$

Object



$\rho(\lambda)$

Sensor



$e(\lambda)\rho(\lambda)$

$$R = \int_{\lambda} e(\lambda)\rho(\lambda) f_R(\lambda) d\lambda, \quad G = \int_{\lambda} e(\lambda)\rho(\lambda) f_G(\lambda) d\lambda, \quad B = \int_{\lambda} e(\lambda)\rho(\lambda) f_B(\lambda) d\lambda$$

Imaging

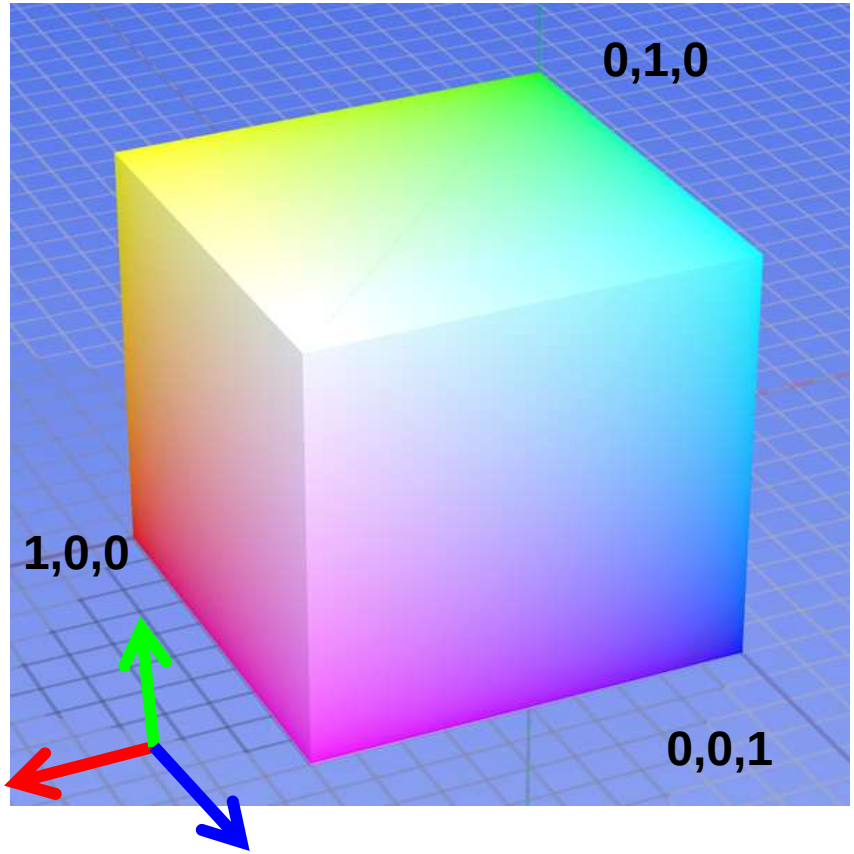
A color imaging system obtains N measurements at each location p given by:

$$q_k = \int_{\lambda} e(\lambda)^p \, \rho(\lambda)^p \, f_k(\lambda) d\lambda$$

where $e(\lambda)$ is the illumination spectrum, $\rho(\lambda)^p$ is the surface reflectance (surface albedo) at the point p, and $f_k(\lambda)$ and q_k for $1 \leq k \leq N$ are the spectral response and the camera outputs, respectively. For the ease of illustration, we consider $1 \leq k \leq 3$ corresponding to R, G, B.

Color spaces: RGB

Default color space



R
(G=0,B=0)

G
(R=0,B=0)

B
(R=0,G=0)

Some drawbacks

- Strongly correlated channels
- Non-perceptual

Slide: James Hays

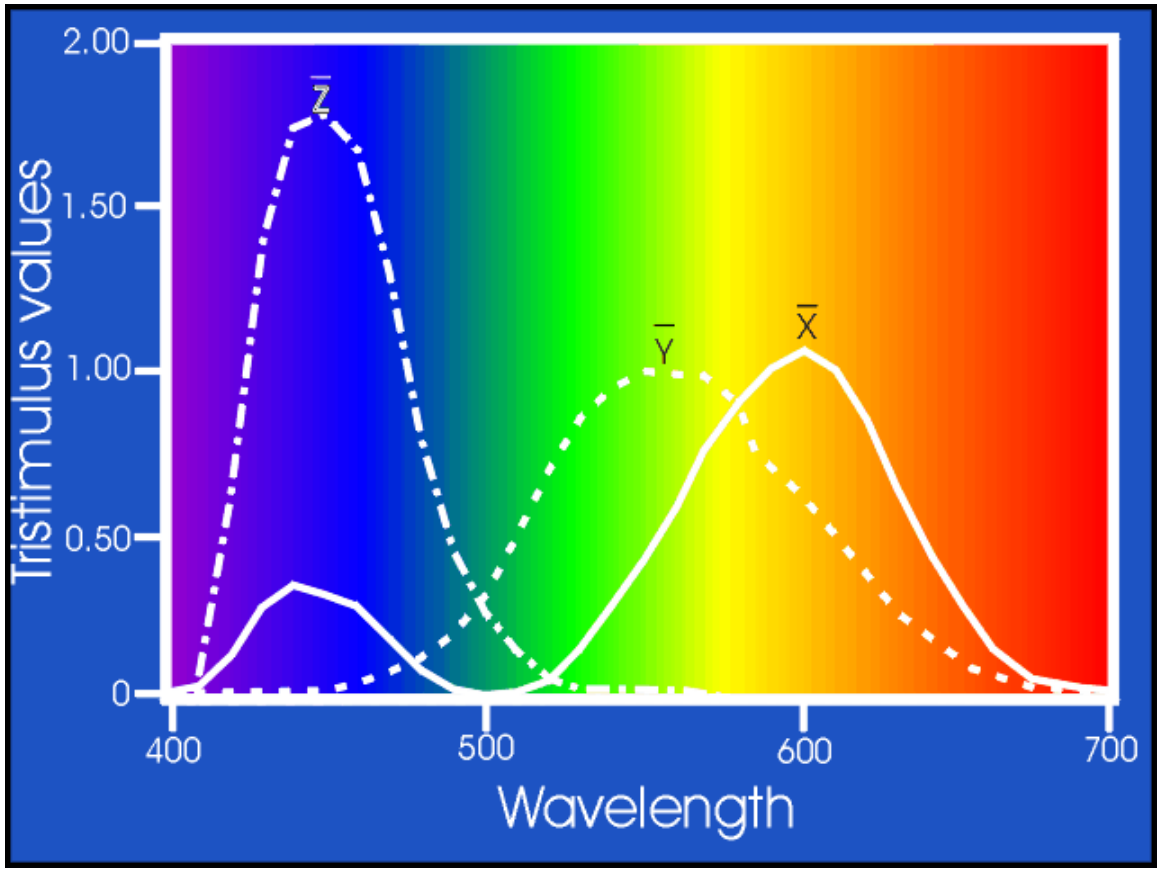
Image from: http://en.wikipedia.org/wiki/File:RGB_color_solid_cube.png

Colorimetry: CIE XYZ-system

$$X = \int_{\lambda} e(\lambda)\rho(\lambda)\bar{x}(\lambda)d\lambda$$

$$Y = \int_{\lambda} e(\lambda)\rho(\lambda)\bar{y}(\lambda)d\lambda$$

$$Z = \int_{\lambda} e(\lambda)\rho(\lambda)\bar{z}(\lambda)d\lambda$$



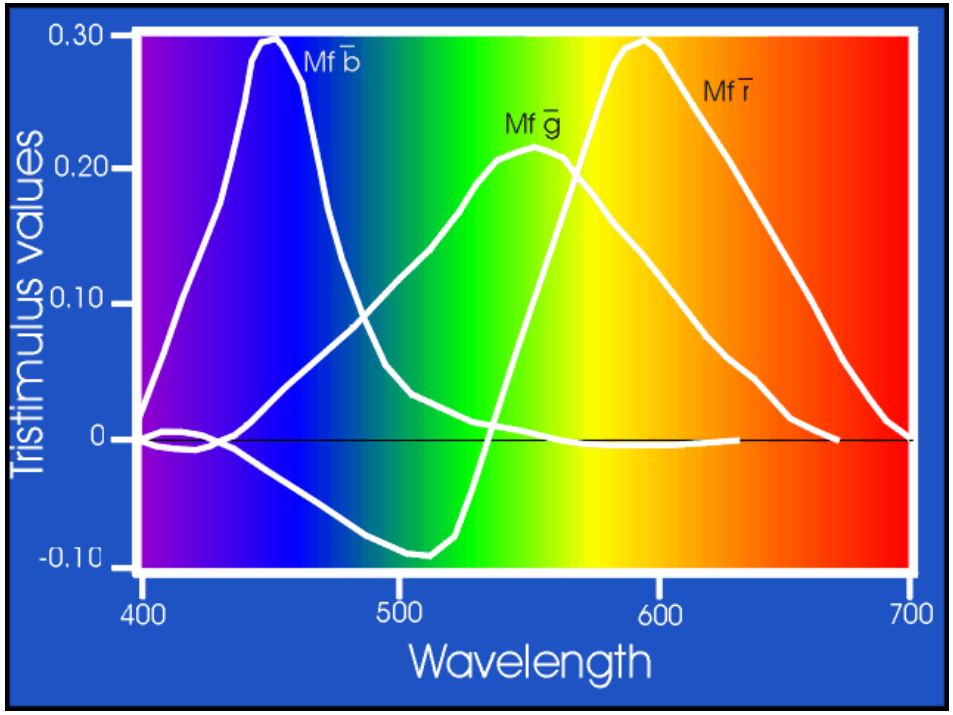
The Eye

Young-Helmholtz approach

Tristimulus values R, G, and B

Wright (7) Guild (10)

Stiles and Burch (50)

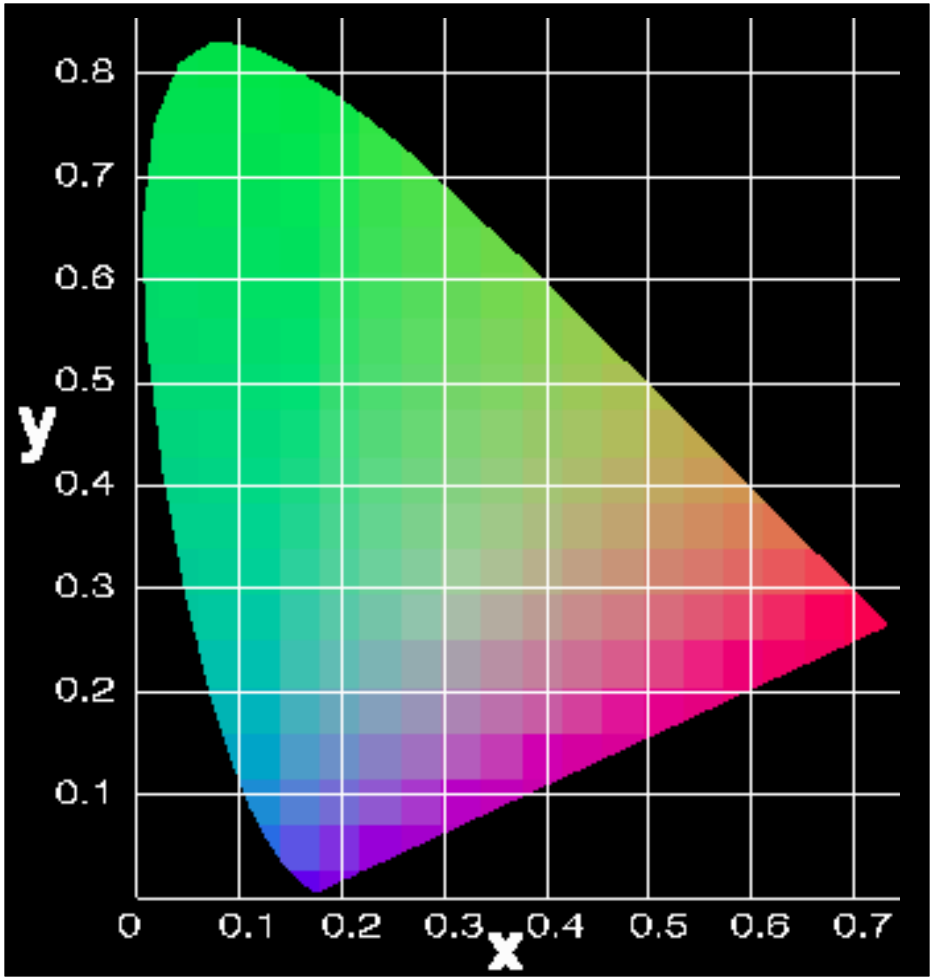


Colorimetry: CIE xy-system

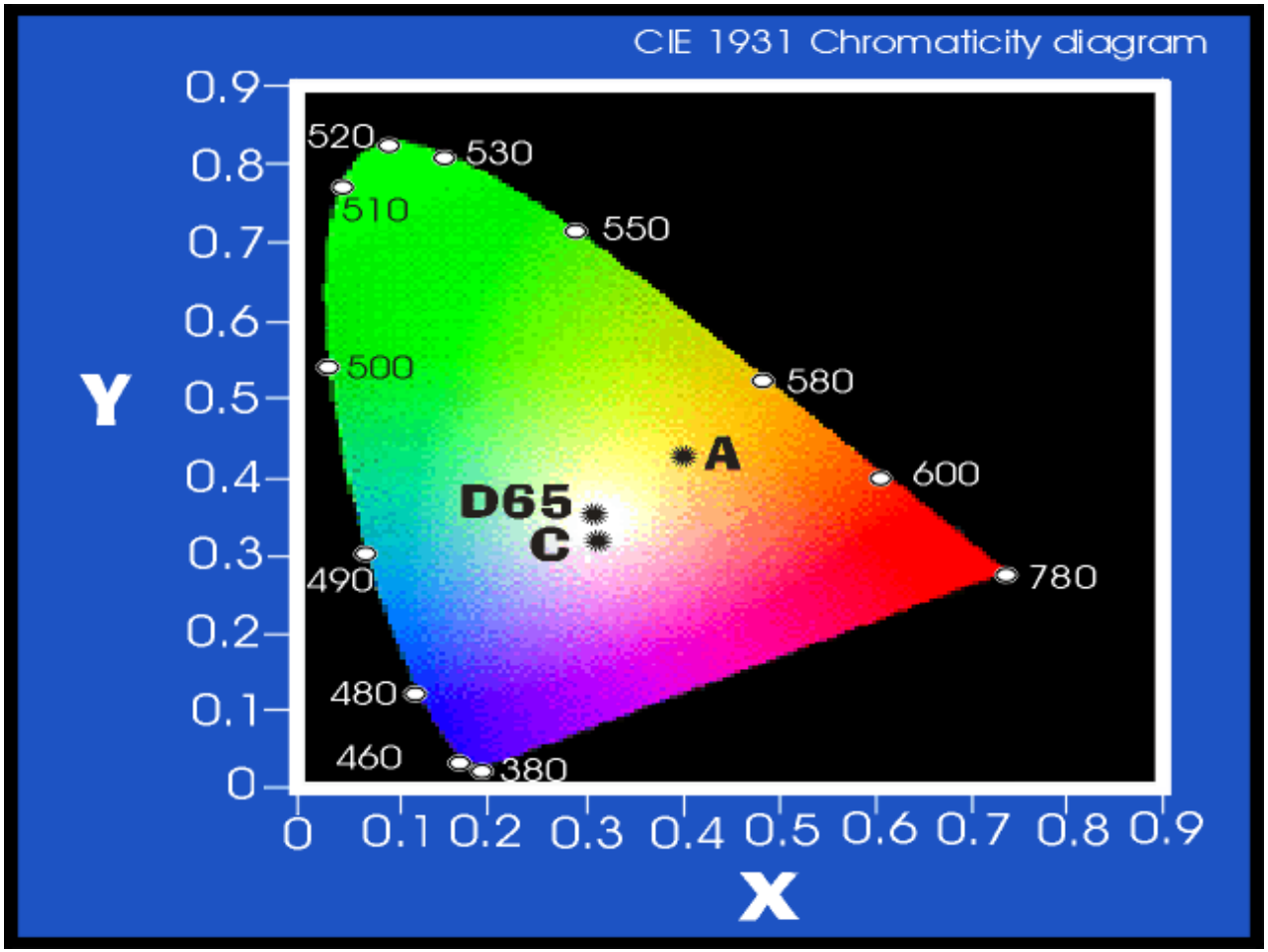
$$x = \frac{X}{X + Y + Z}$$

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

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



Colorimetry: Illuminants in the xy-plane



Light Sources and Illuminants

Light sources:

sun, candle,

fluorescent lamp,

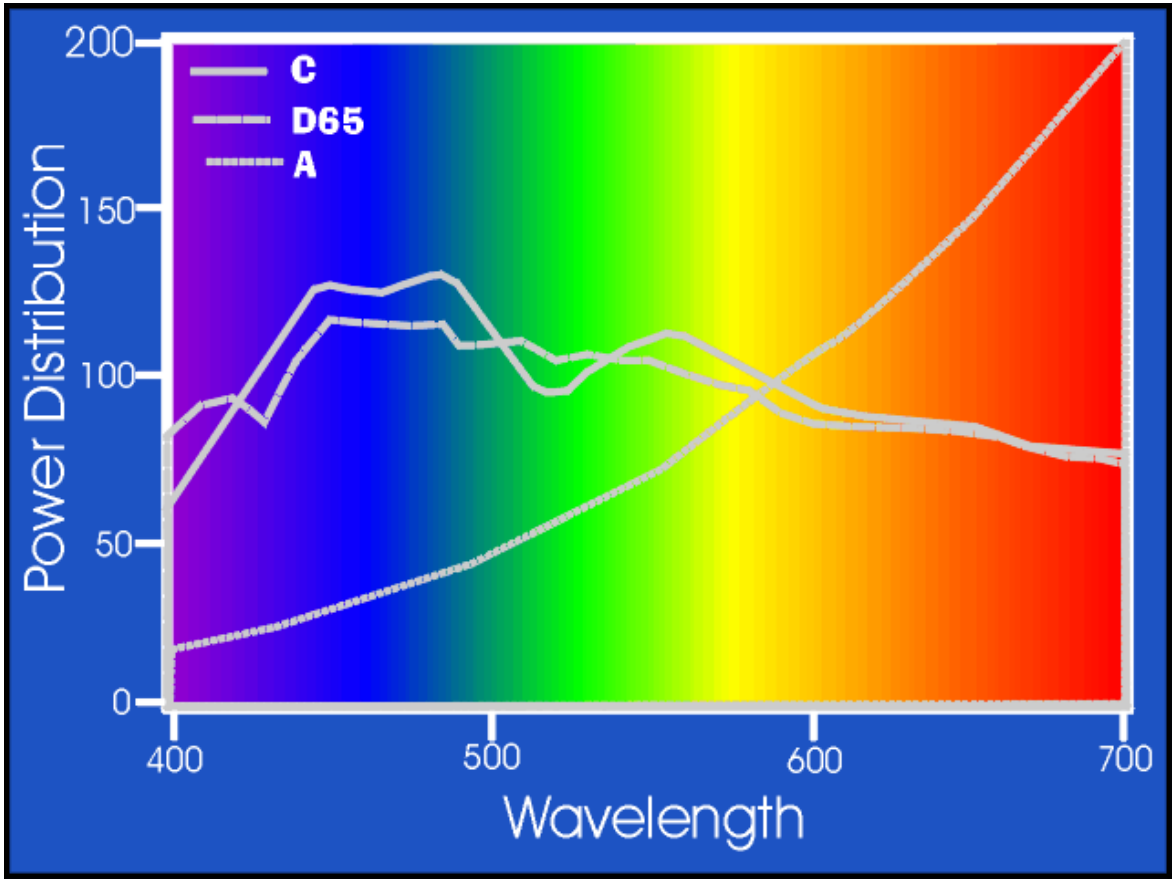
incandescent lamp

Illuminants:

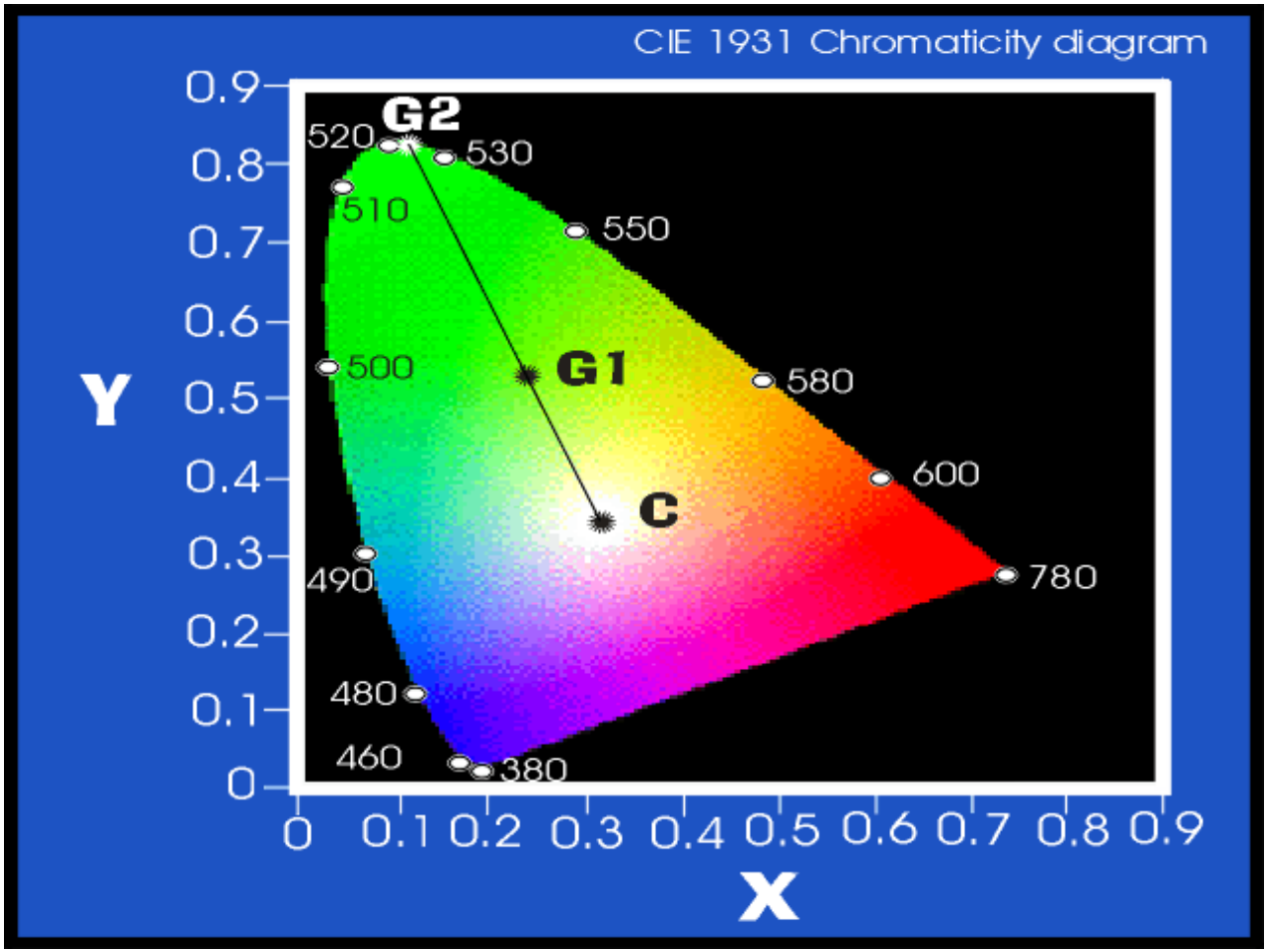
illuminant A

illuminant D65

illuminant C



Colorimetry: HSI in the xy-plane

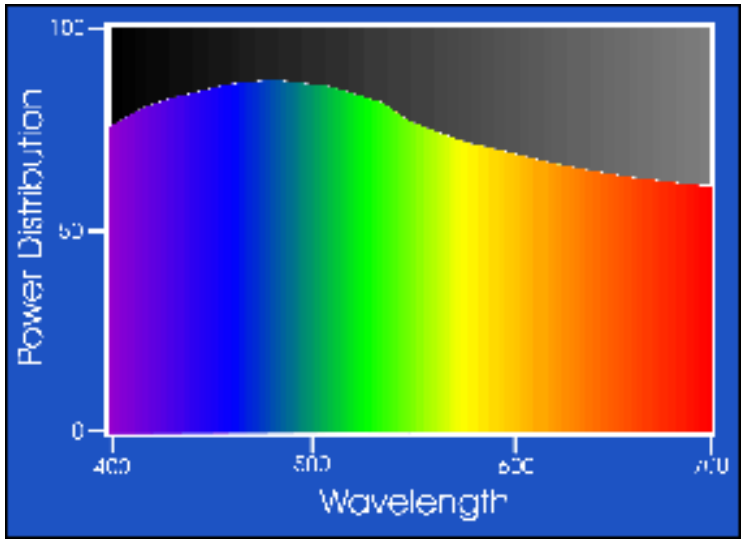


Spectral power distribution

Hue: dominant wavelength of the SPD: EH

Saturation: purity of the colour: EH-EW

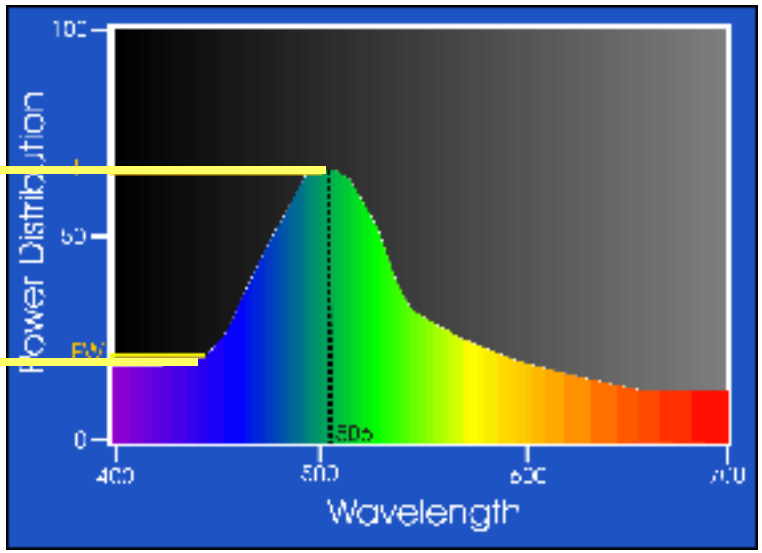
Intensity: brightness of the colour: EW



White light

EH

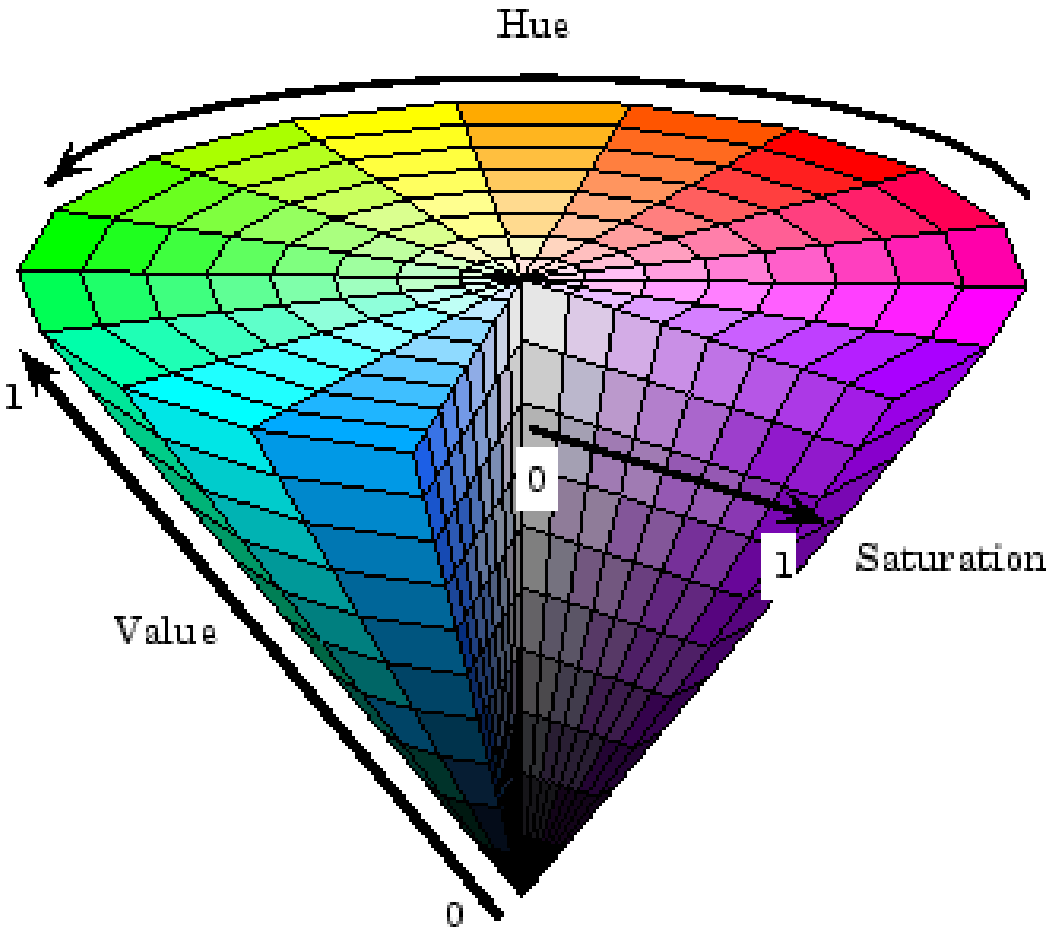
EW

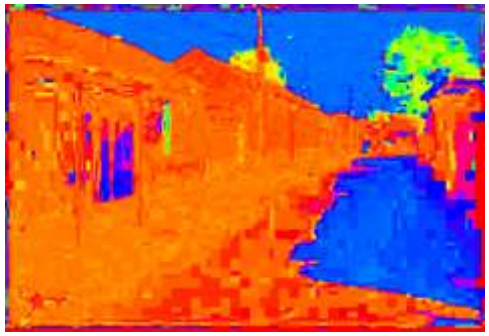


Green light

Color Spaces: HSV

Intuitive color space





H
(S=1,V=1)

S
(H=1,V=1)

V
(H=1,S=0)

Colour Gamuts in the xy-plane

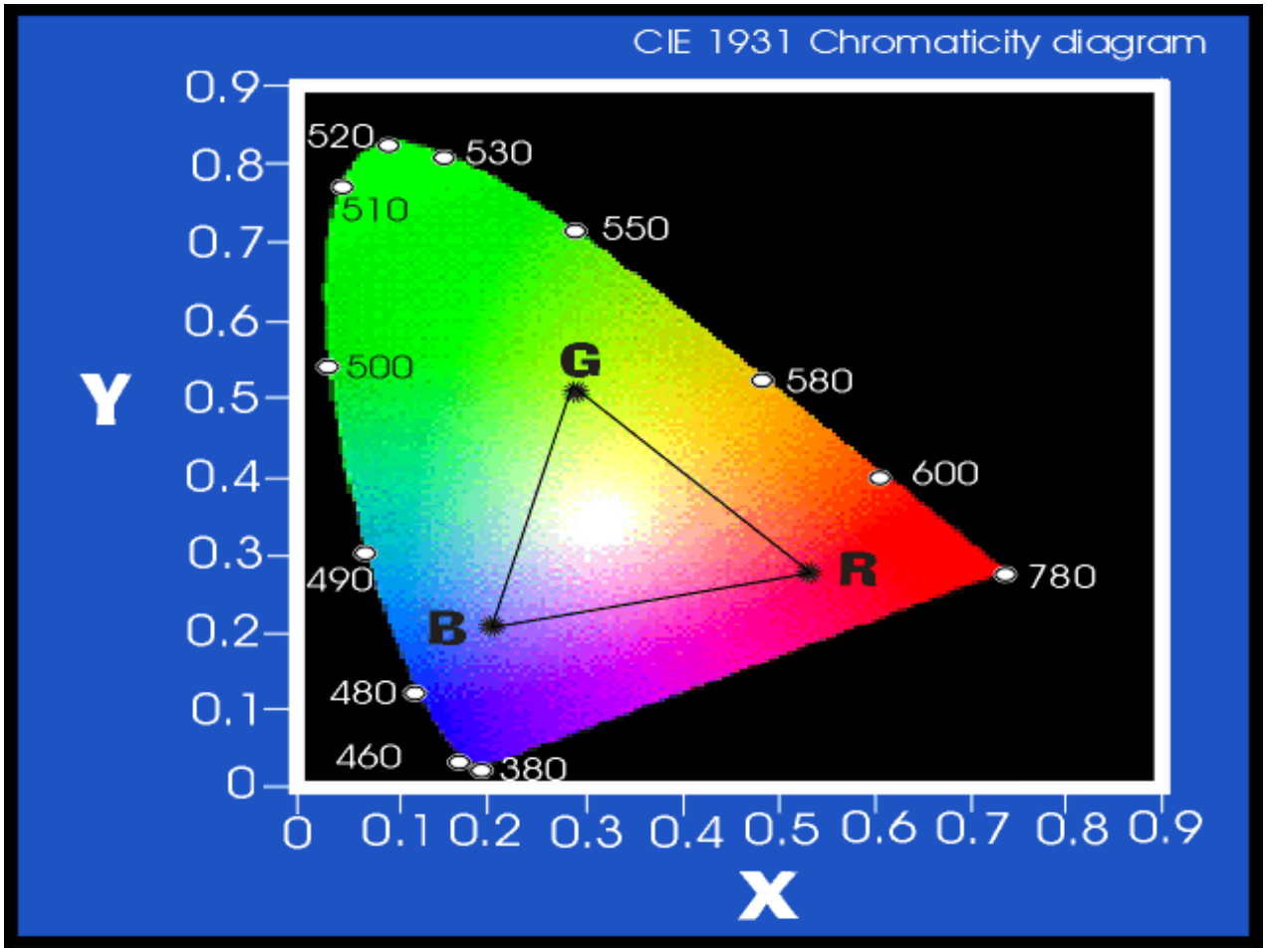
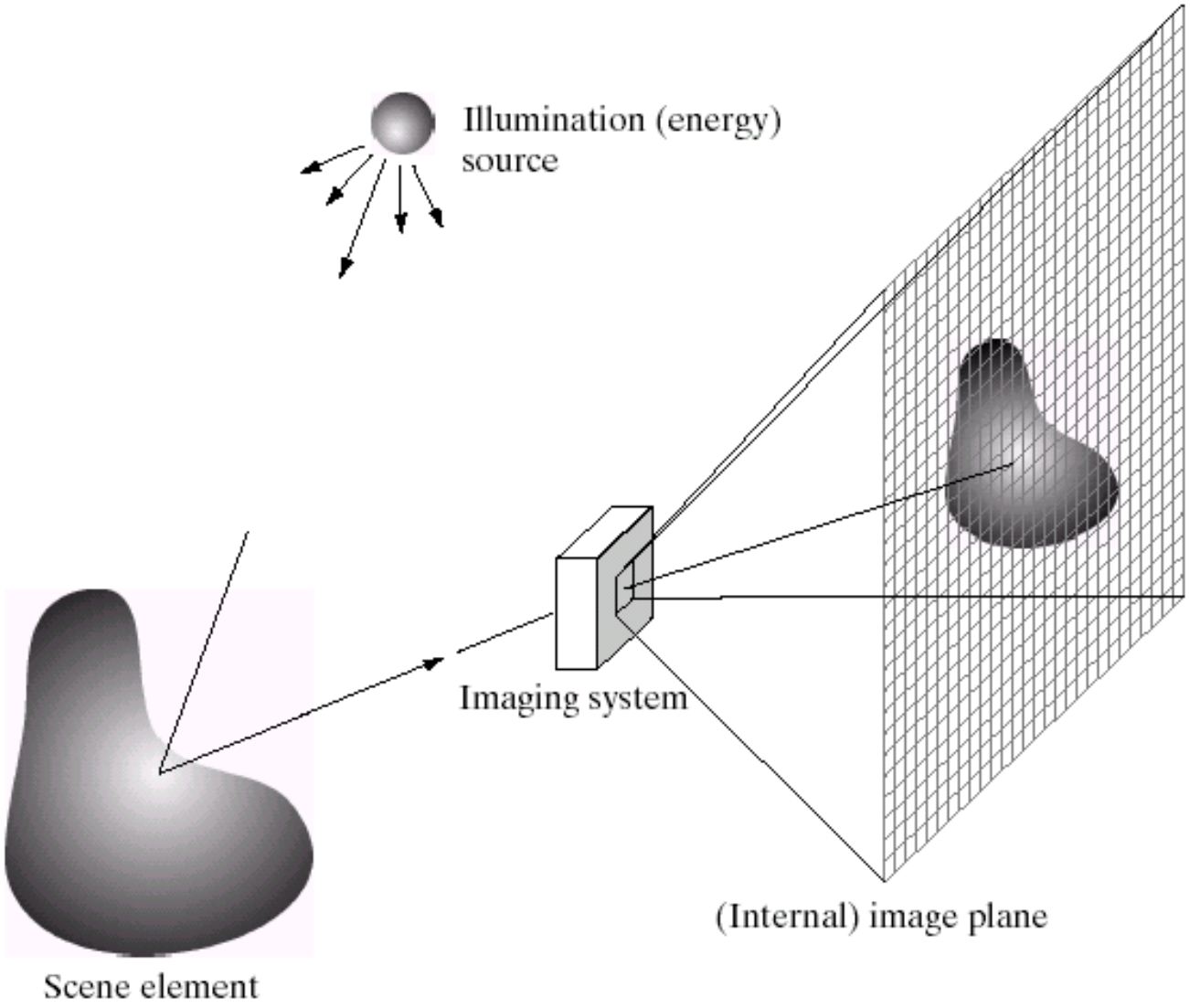


Image Formation



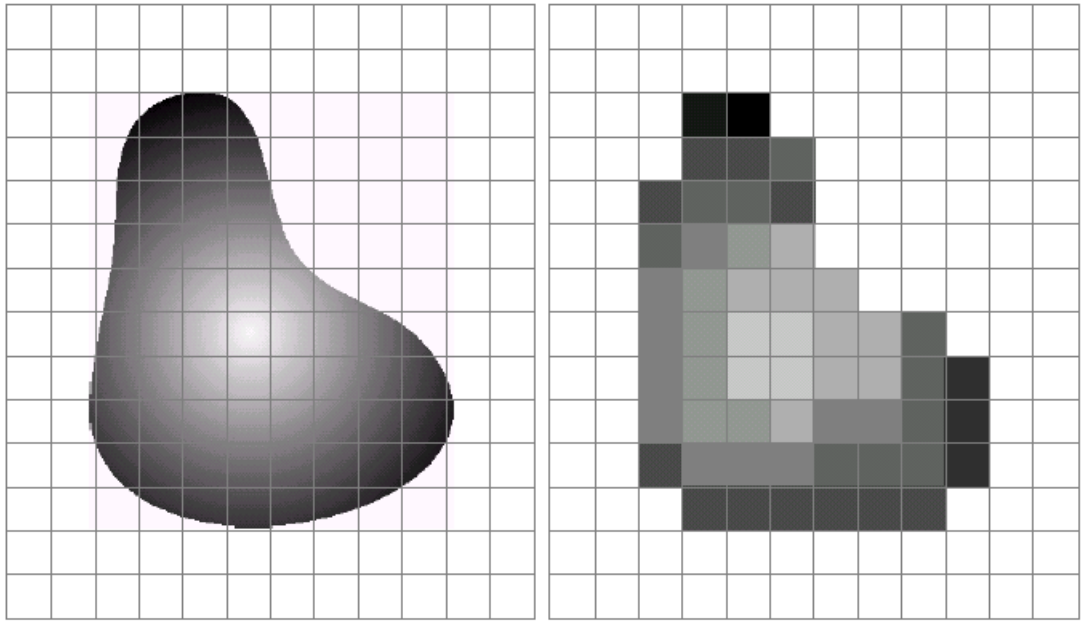
Digital camera

A digital camera replaces film with a sensor array

- Each cell in the array is light-sensitive diode that converts photons to electrons
- Two common types: Charge Coupled Device (CCD) and CMOS
- http://electronics.howstuffworks.com/digital-camera.htm

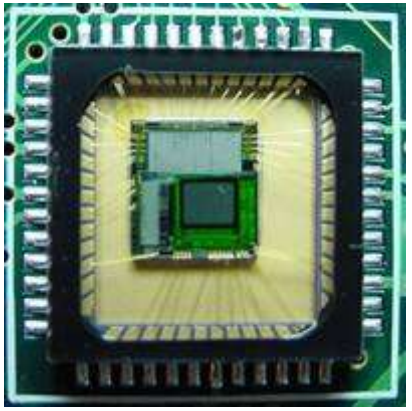
Slide by Steve Seitz

Sensor Array



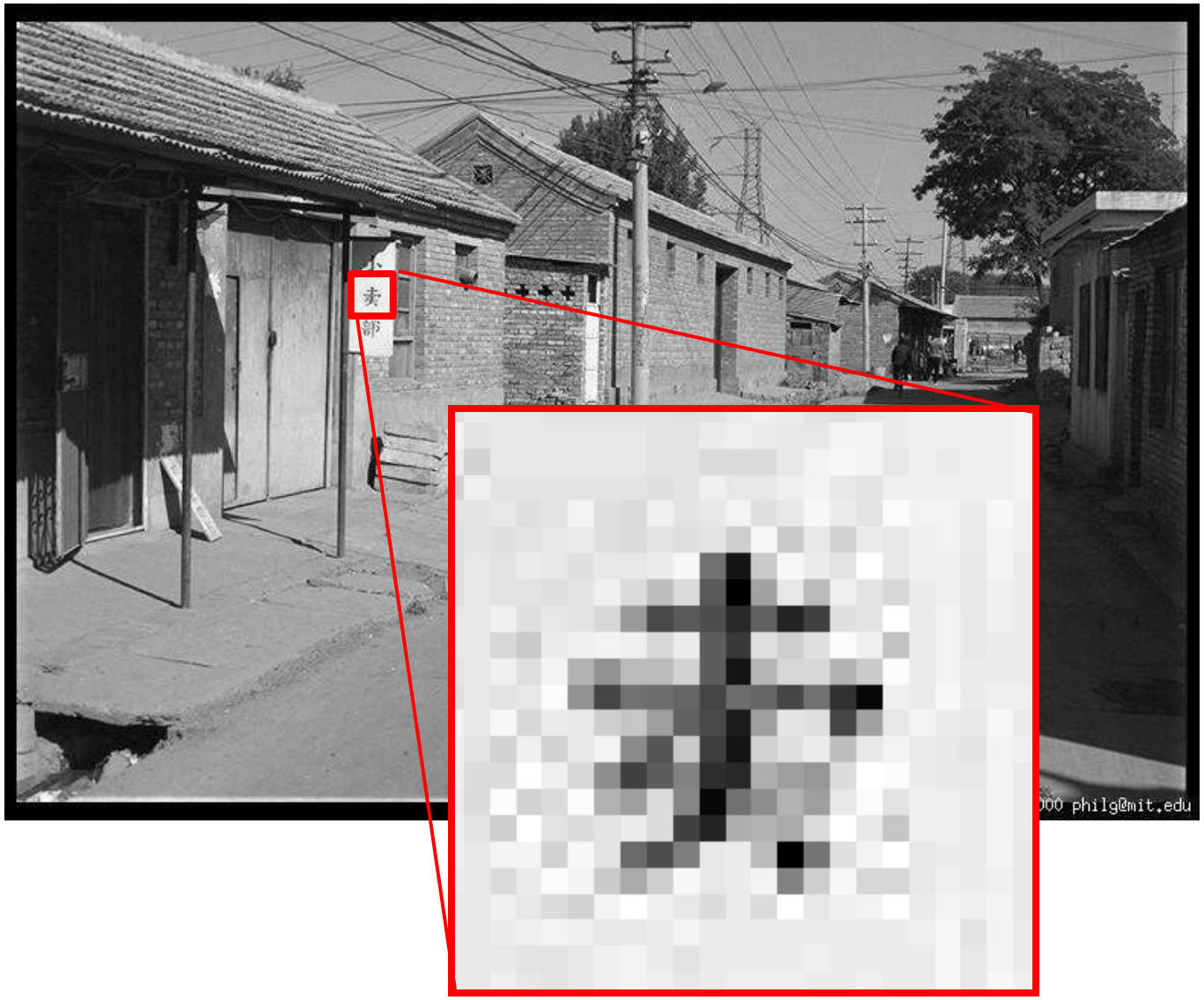
a b

FIGURE 2.17 (a) Continuos image projected onto a sensor array. (b) Result of image sampling and quantization.



CMOS sensor

The Raster Image (Pixel Matrix)

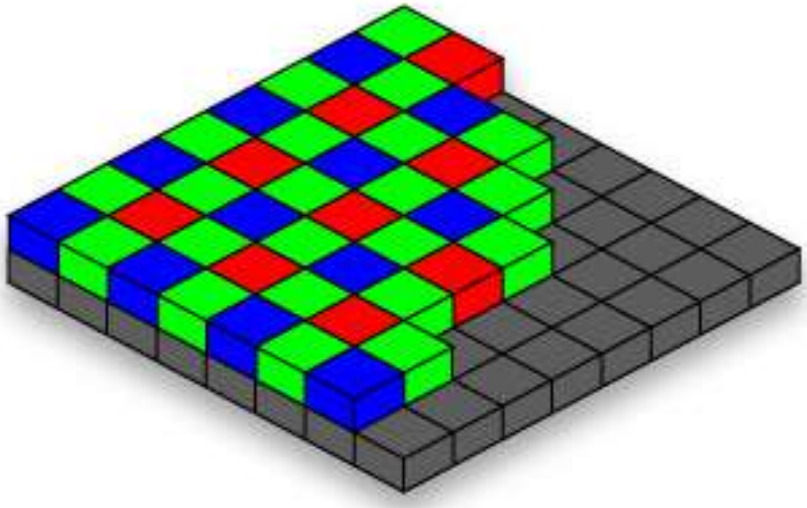


Slide: James Hays

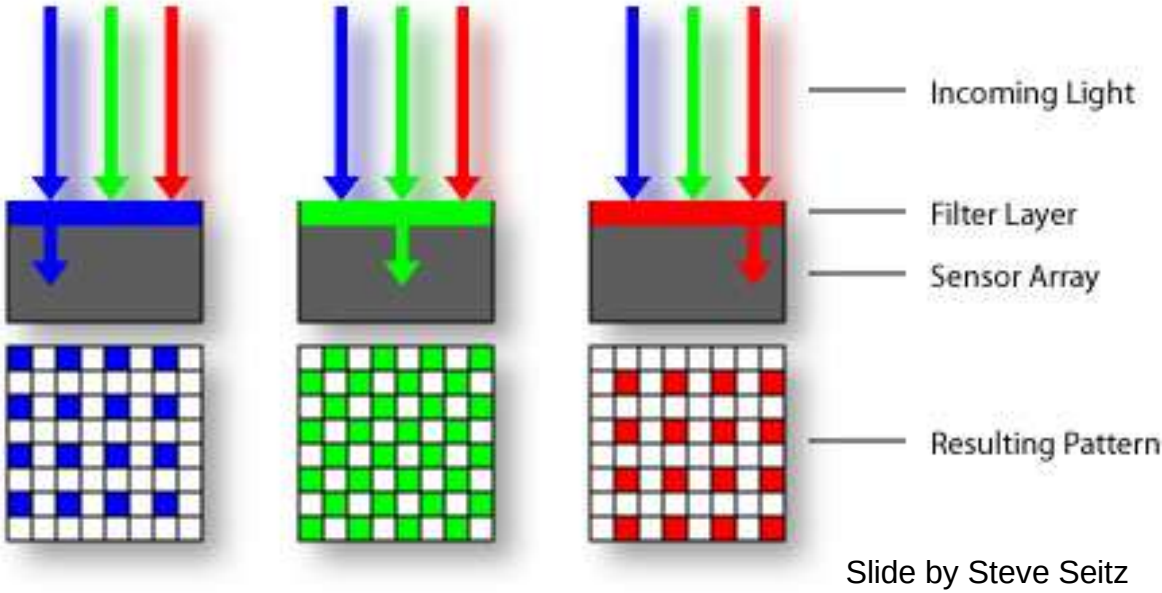
The Raster Image (Pixel Matrix)

0.92	0.93	0.94	0.97	0.62	0.37	0.85	0.97	0.93	0.92	0.99
0.95	0.89	0.82	0.89	0.56	0.31	0.75	0.92	0.81	0.95	0.91
0.89	0.72	0.51	0.55	0.51	0.42	0.57	0.41	0.49	0.91	0.92
0.96	0.95	0.88	0.94	0.56	0.46	0.91	0.87	0.90	0.97	0.95
0.71	0.81	0.81	0.87	0.57	0.37	0.80	0.88	0.89	0.79	0.85
0.49	0.62	0.60	0.58	0.50	0.60	0.58	0.50	0.61	0.45	0.33
0.86	0.84	0.74	0.58	0.51	0.39	0.73	0.92	0.91	0.49	0.74
0.96	0.67	0.54	0.85	0.48	0.37	0.88	0.90	0.94	0.82	0.93
0.69	0.49	0.56	0.66	0.43	0.42	0.77	0.73	0.71	0.90	0.99
0.79	0.73	0.90	0.67	0.33	0.61	0.69	0.79	0.73	0.93	0.97
0.91	0.94	0.89	0.49	0.41	0.78	0.78	0.77	0.89	0.99	0.93

Color Images: Bayer Grid



Estimate RGB at ‘G’ cells from neighboring values



http://www.cooldictionary.com/words/Bayer-filter.wikipedia

Slide by Steve Seitz

Color Image

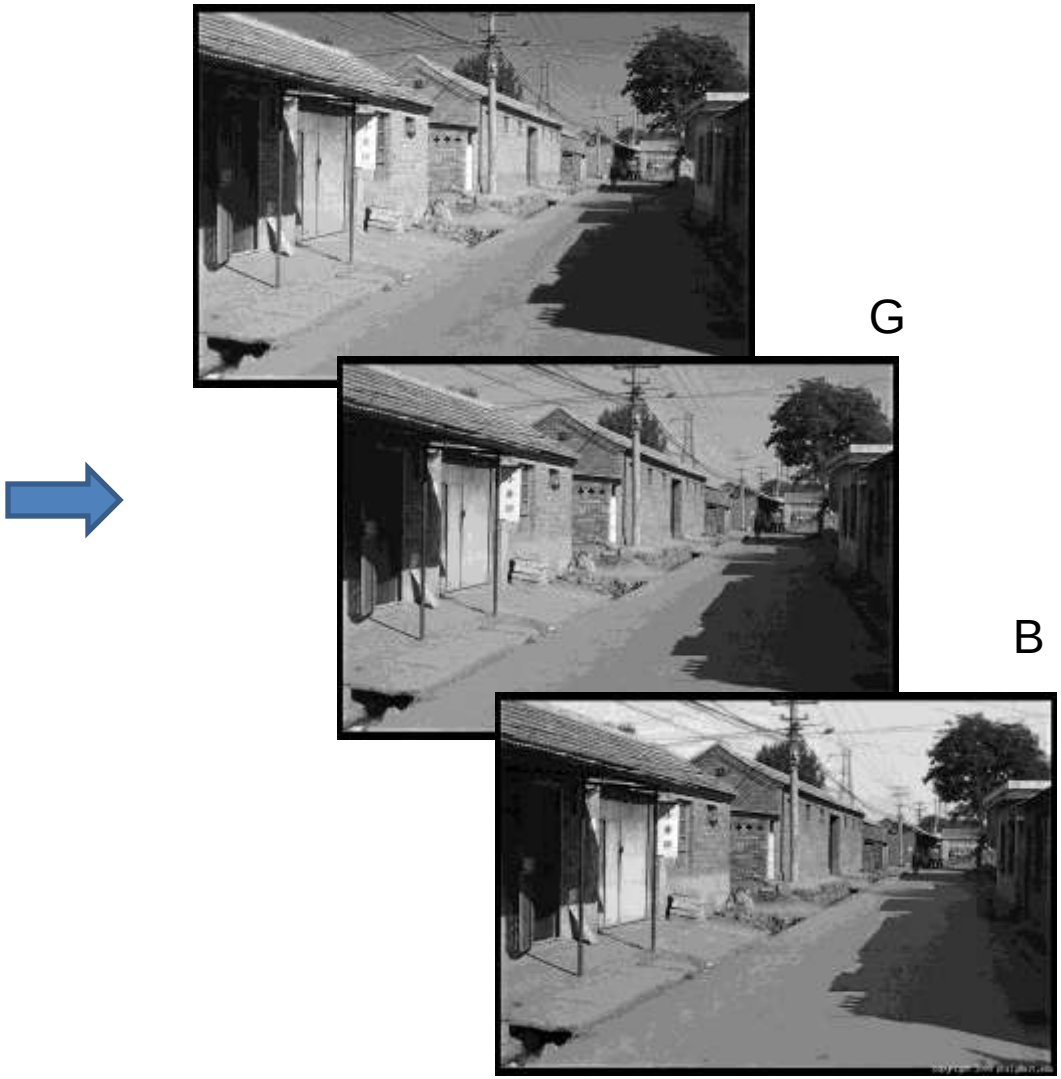


Image Formation

Projective Geometry and Camera Models

Light and Color Models

Reflection Models