Advanced Image Processing

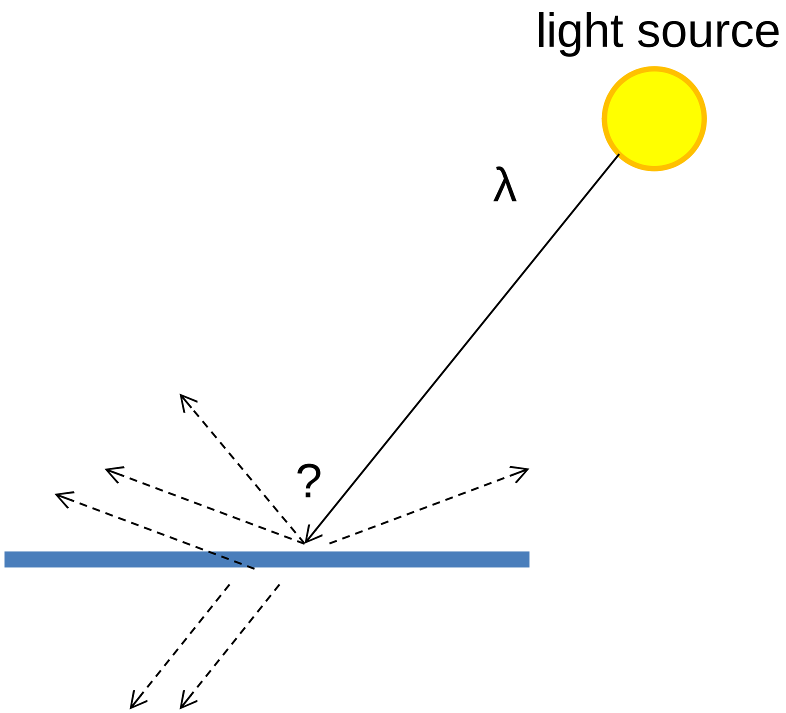
Cameras, Light and Color

SYDE 671

The Image formation process: Part 2 - Photometry

A photon's life choices

- Absorption
- Diffuse reflection
- Specular reflection
- Transparency
- Refraction
- Fluorescence
- Subsurface scattering
- Phosphorescence
- Interreflection



James Hays

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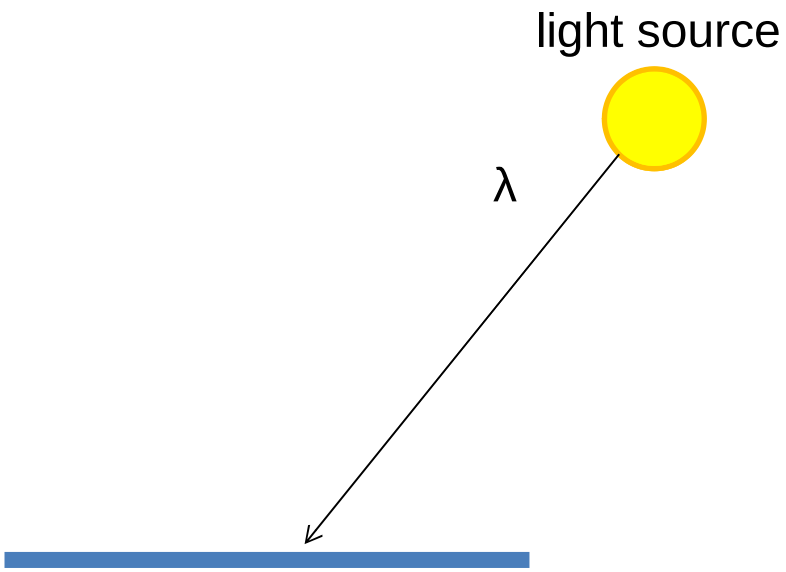

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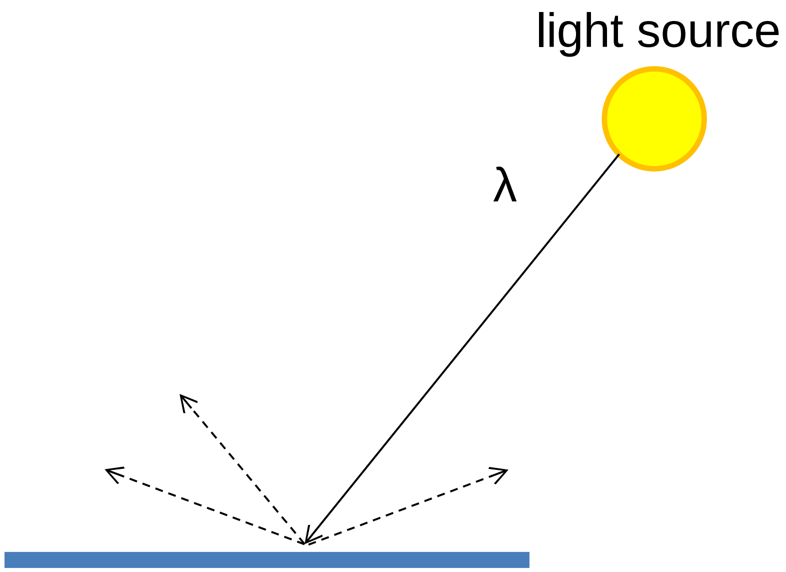

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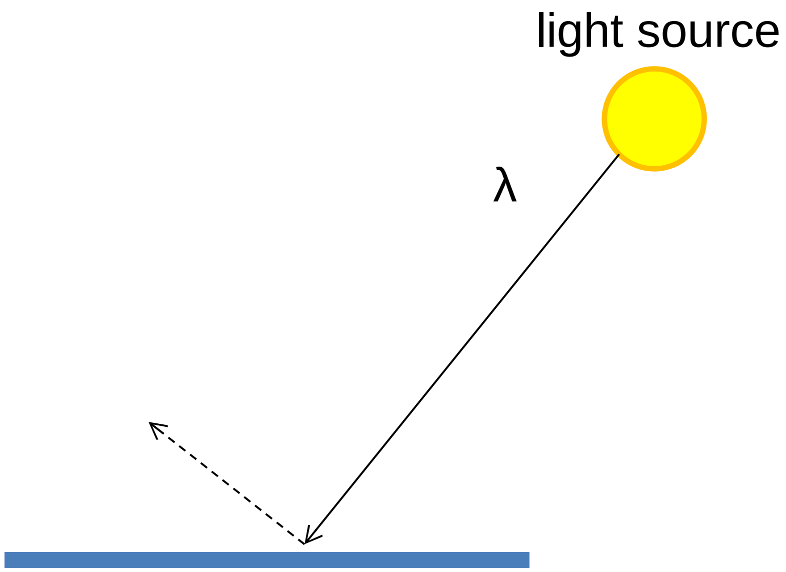

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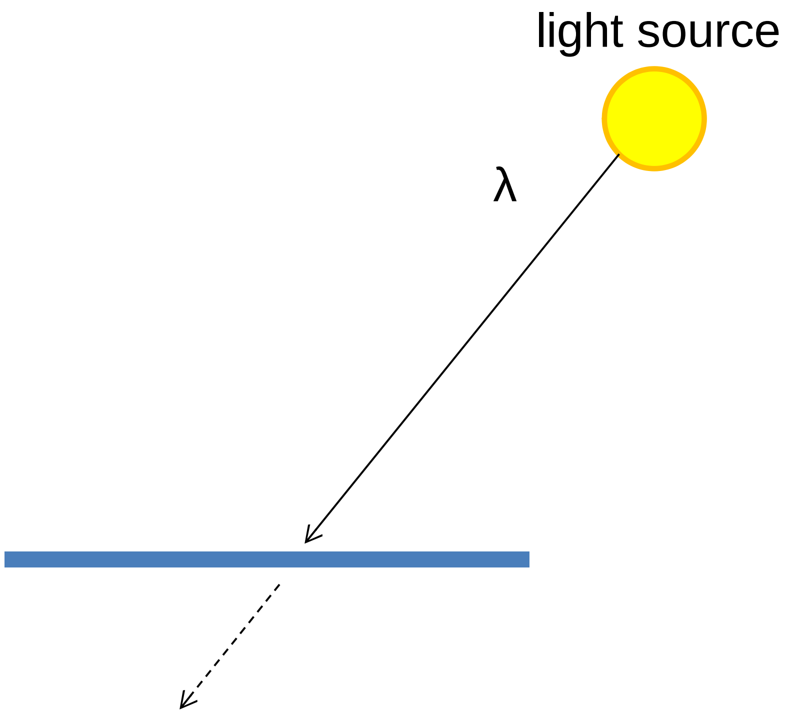

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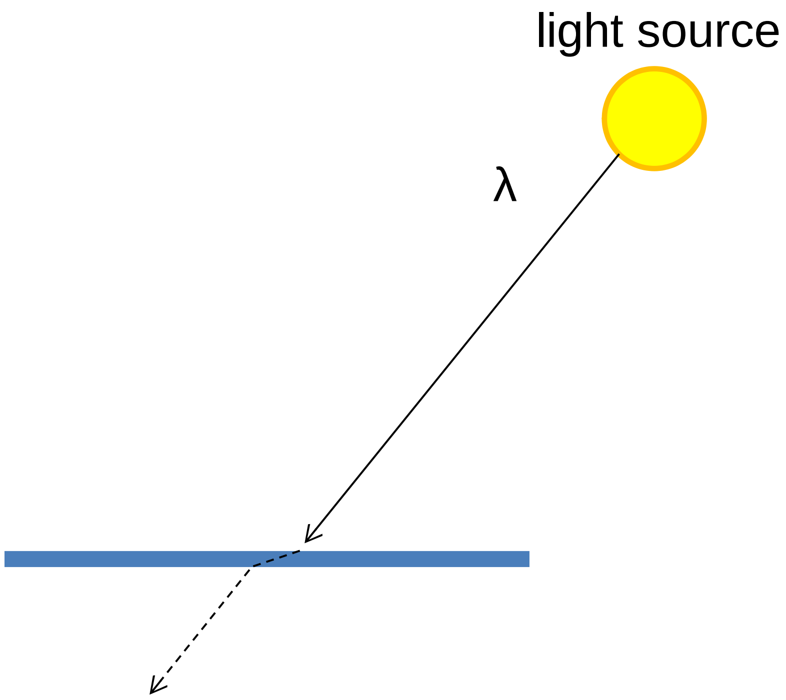

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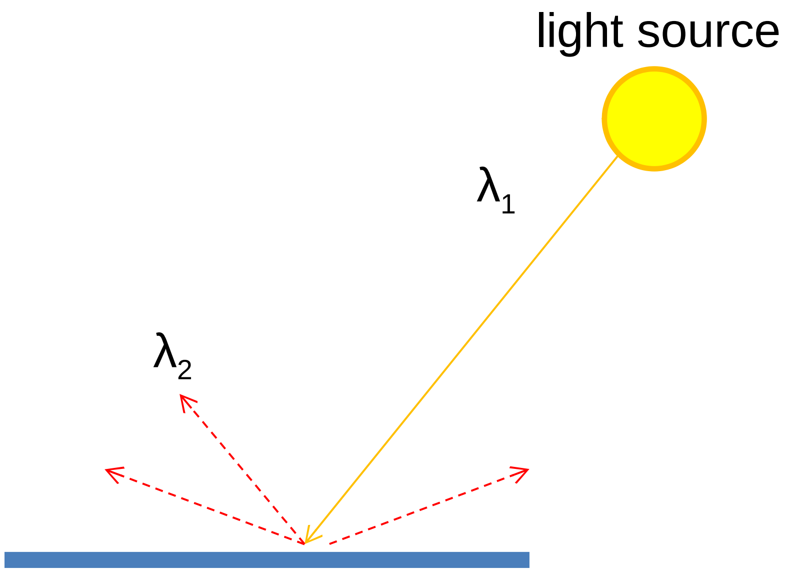

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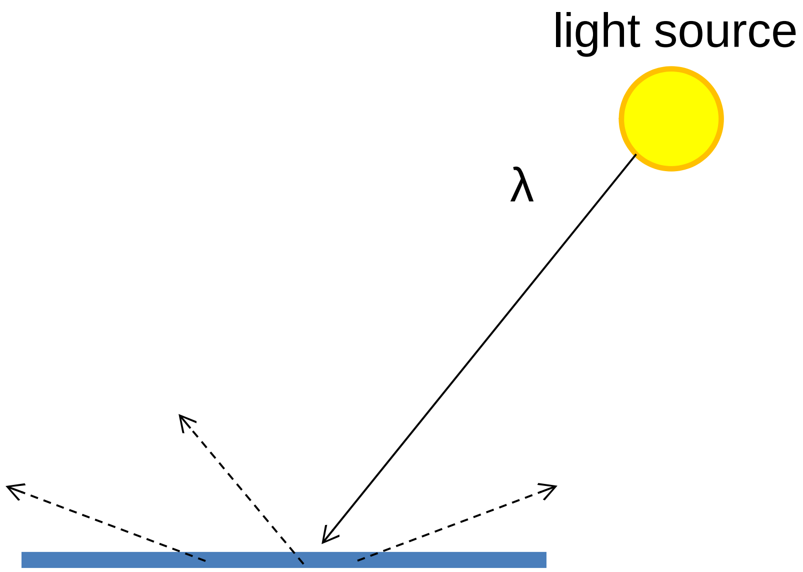

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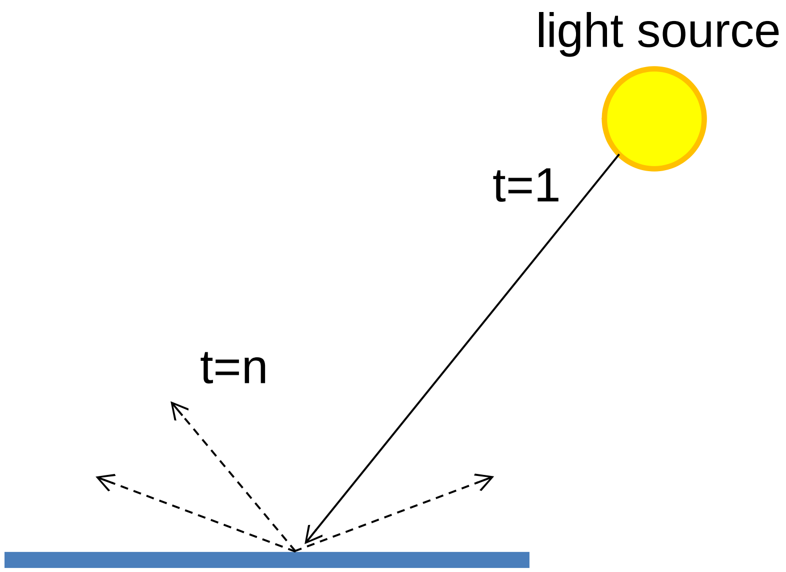

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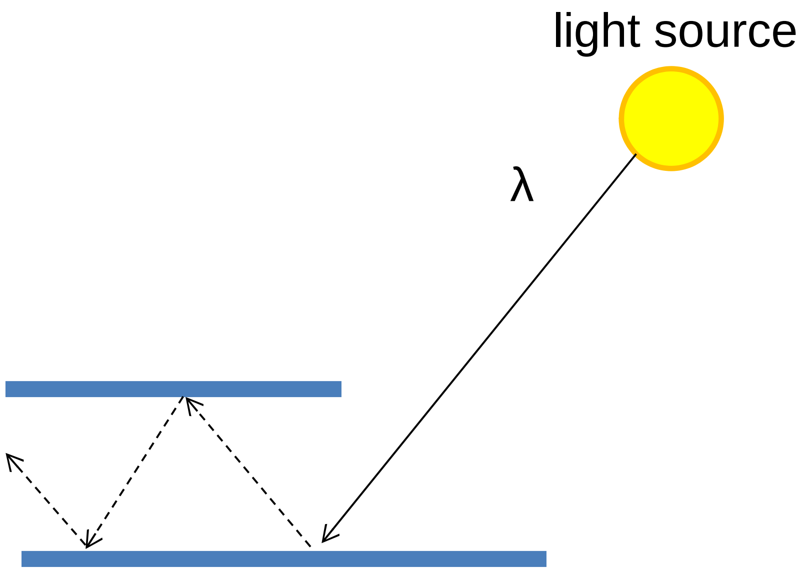

(Specular Interreflection)

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Lambertian Reflectance

- In computer vision, surfaces are often assumed to be ideal diffuse reflectors with no dependence on viewing direction.

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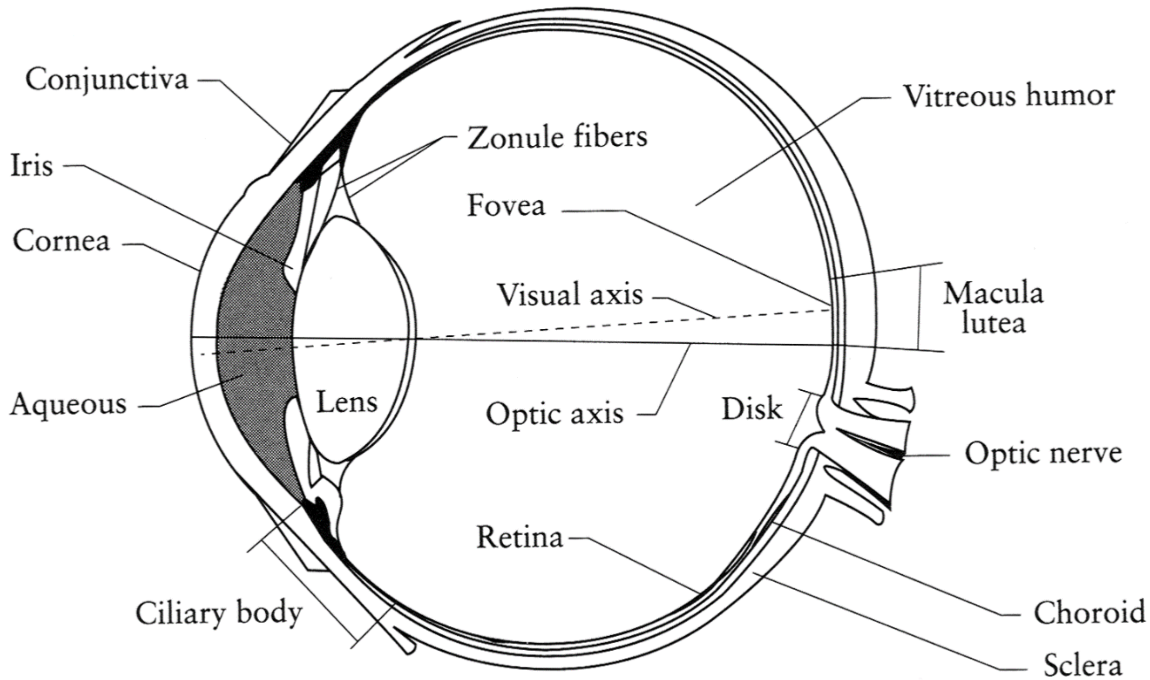
But what is color?

ANATOMY

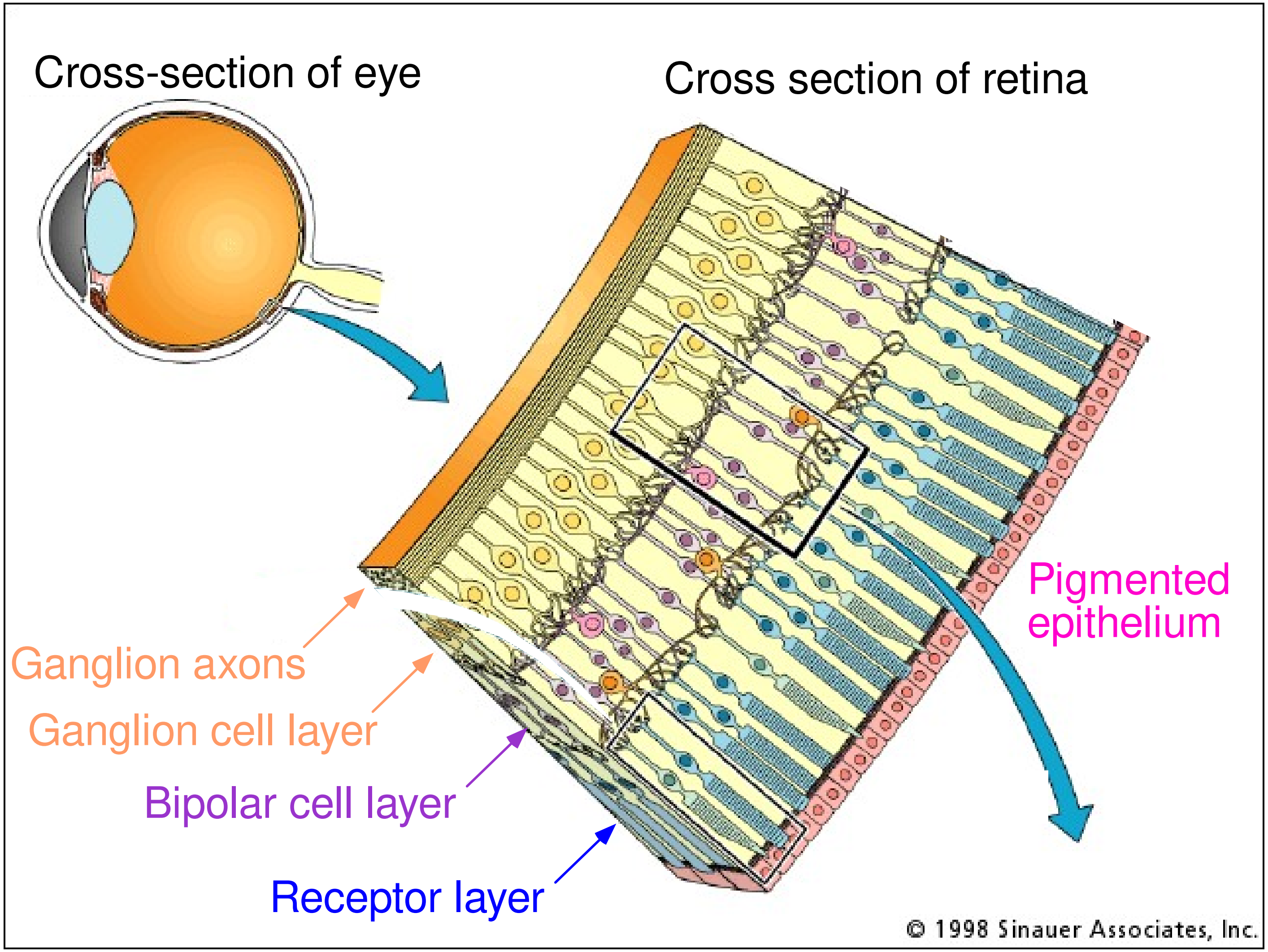
The Eye



- 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 sensor?
    - photoreceptor cells (rods and cones) in the **retina**

Slide by Steve Seitz

The Retina



Cross-section of eye
Cross section of retina
Pigmented epithelium
Ganglion axons
Ganglion cell layer
Bipolar cell layer
Receptor layer
© 1998 Sinauer Associates, Inc.

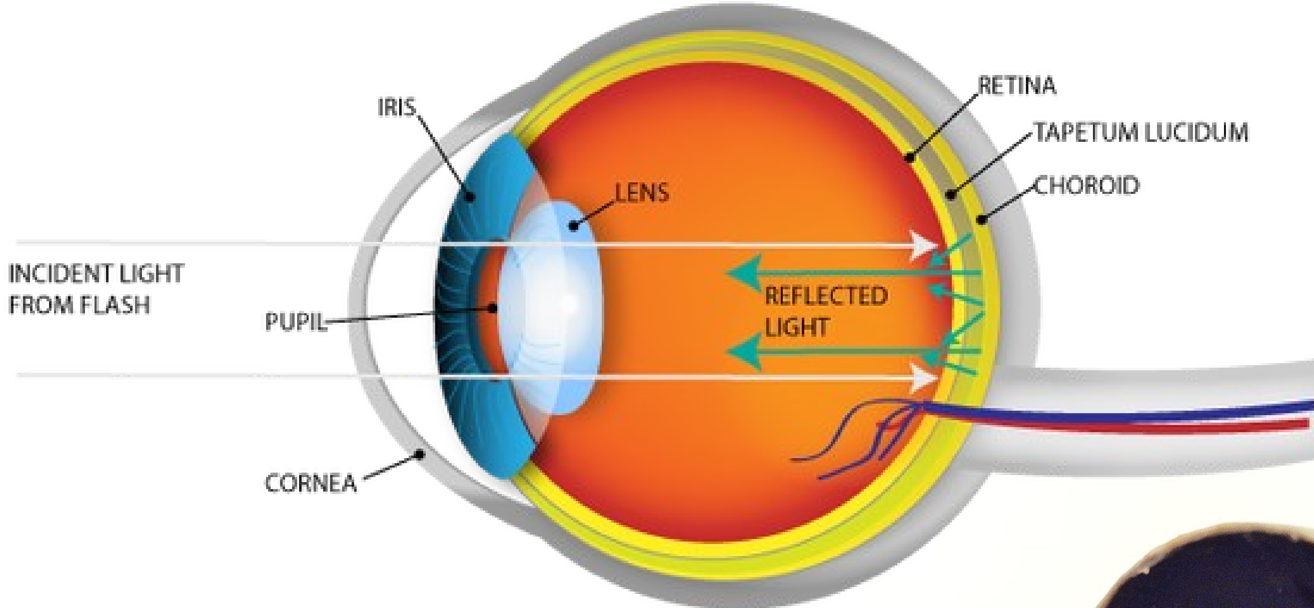
Wait, the blood vessels are in front of the photoreceptors??

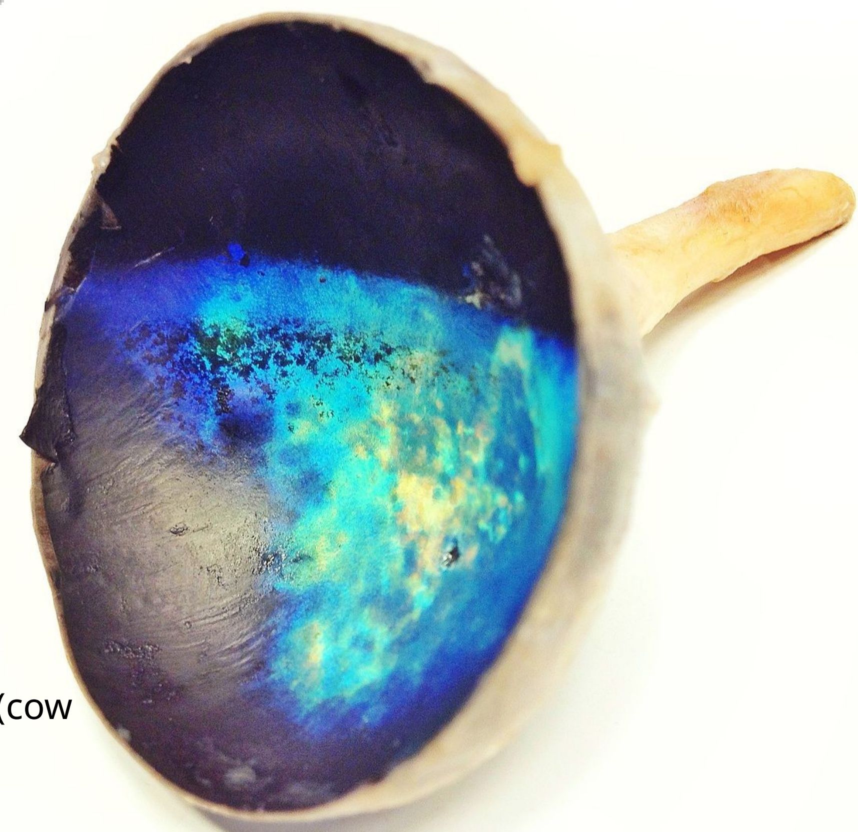
https://www.youtube.com/watch?v=L_W-IXqoxHA

Must watch

What humans don’t have: tapetum lucidum

Human eyes can reflect a tiny bit and blood in the retina makes this reflection red.





Tapetum lucidum exposed (cow eye)

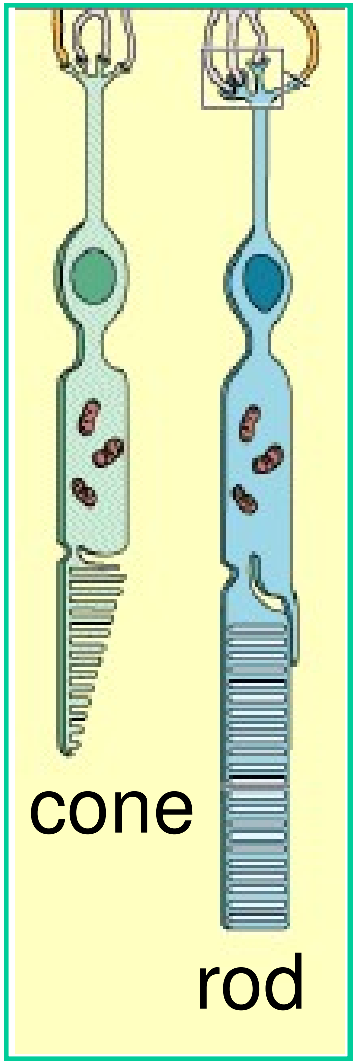
Two types of light-sensitive receptors

Cones

cone-shaped
less sensitive
operate in high light
color vision

Rods

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



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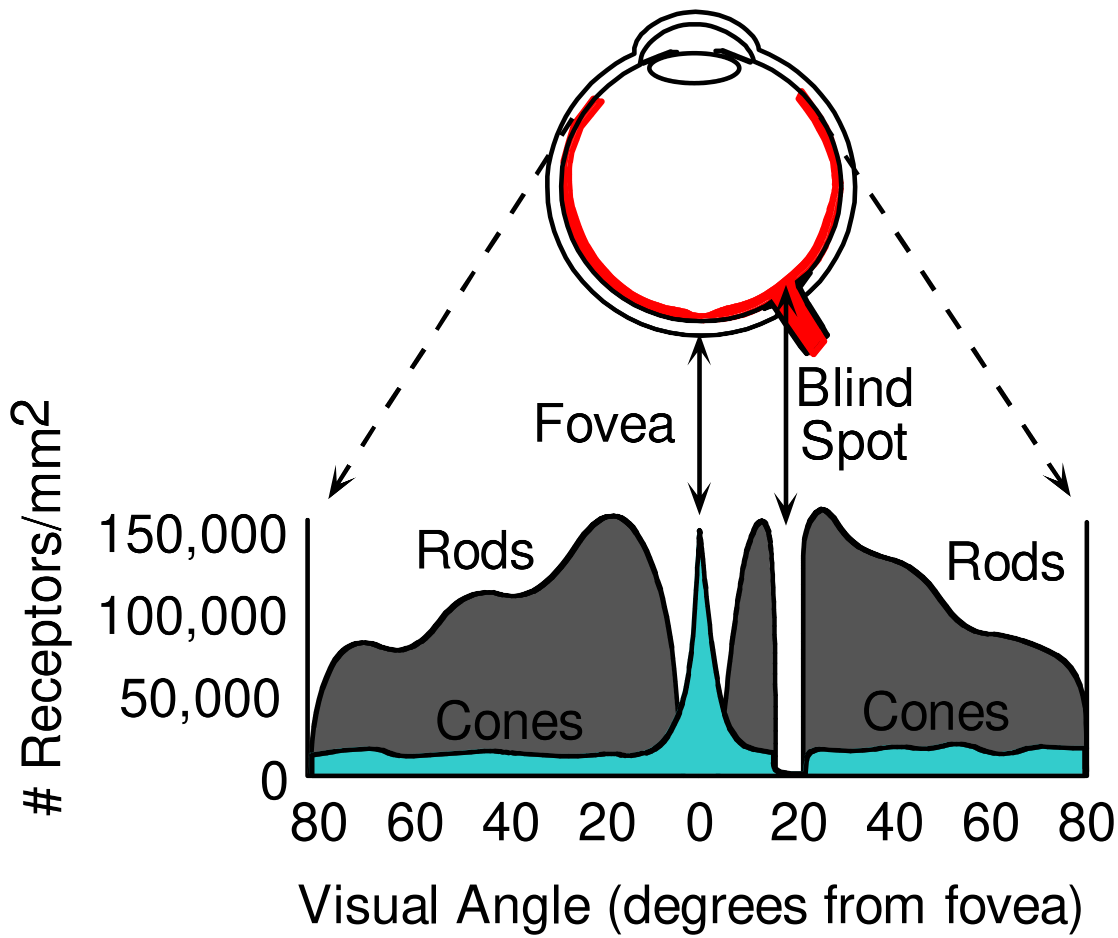
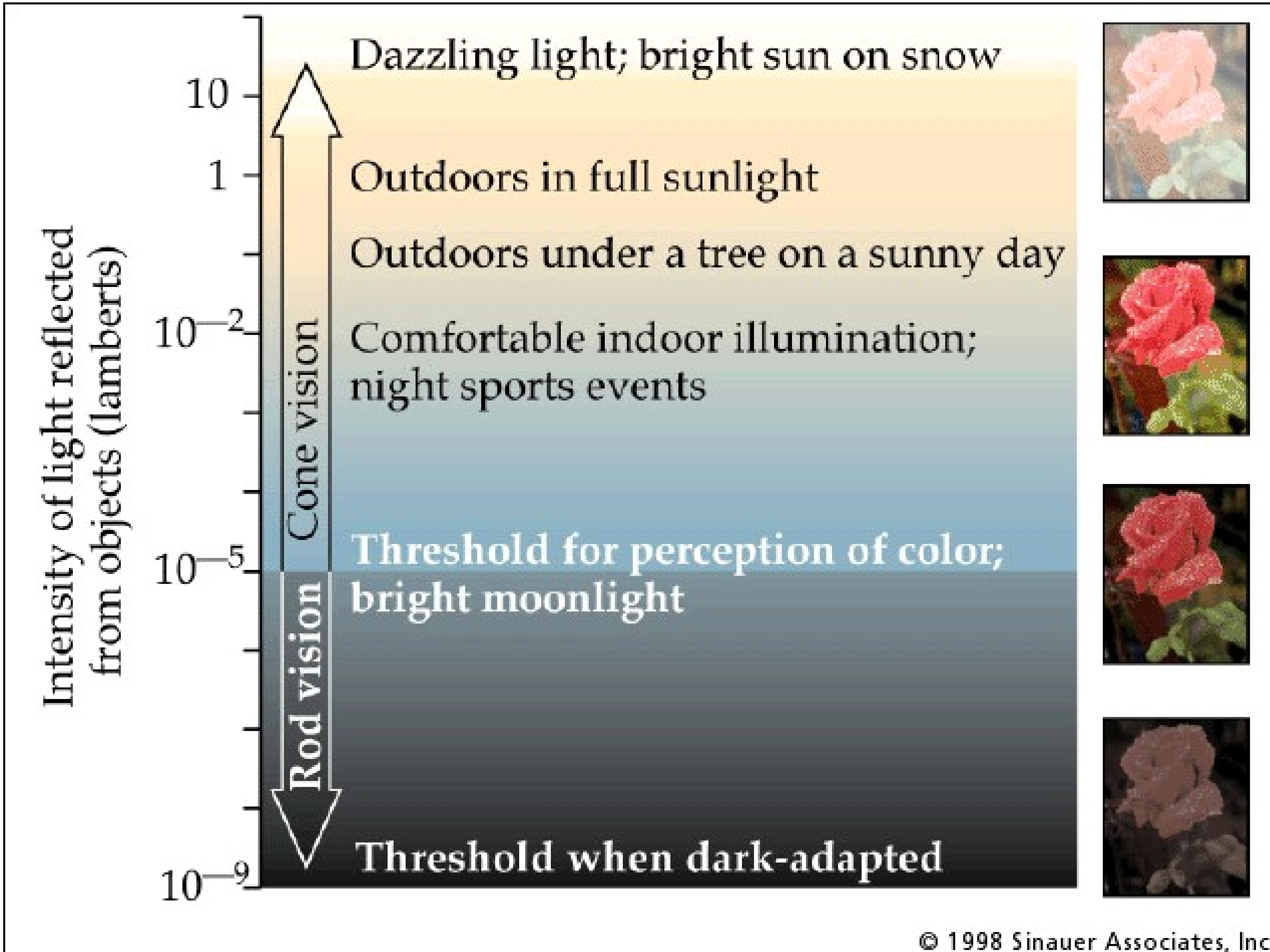
Distribution of Rods and Cones



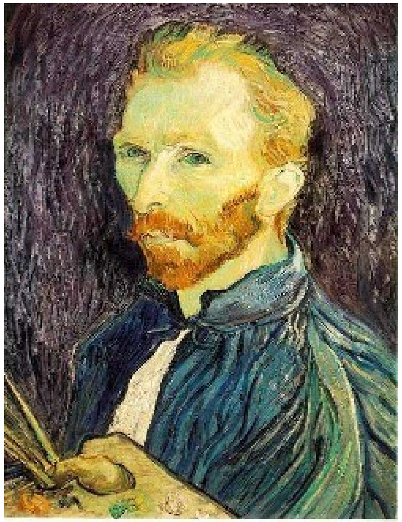
Night Sky: why are there more stars off-center?

Averted vision: http://en.wikipedia.org/wiki/Averted_vision

Rod / Cone sensitivity



Does the eye alias?



4x downsample
nearest neighbor

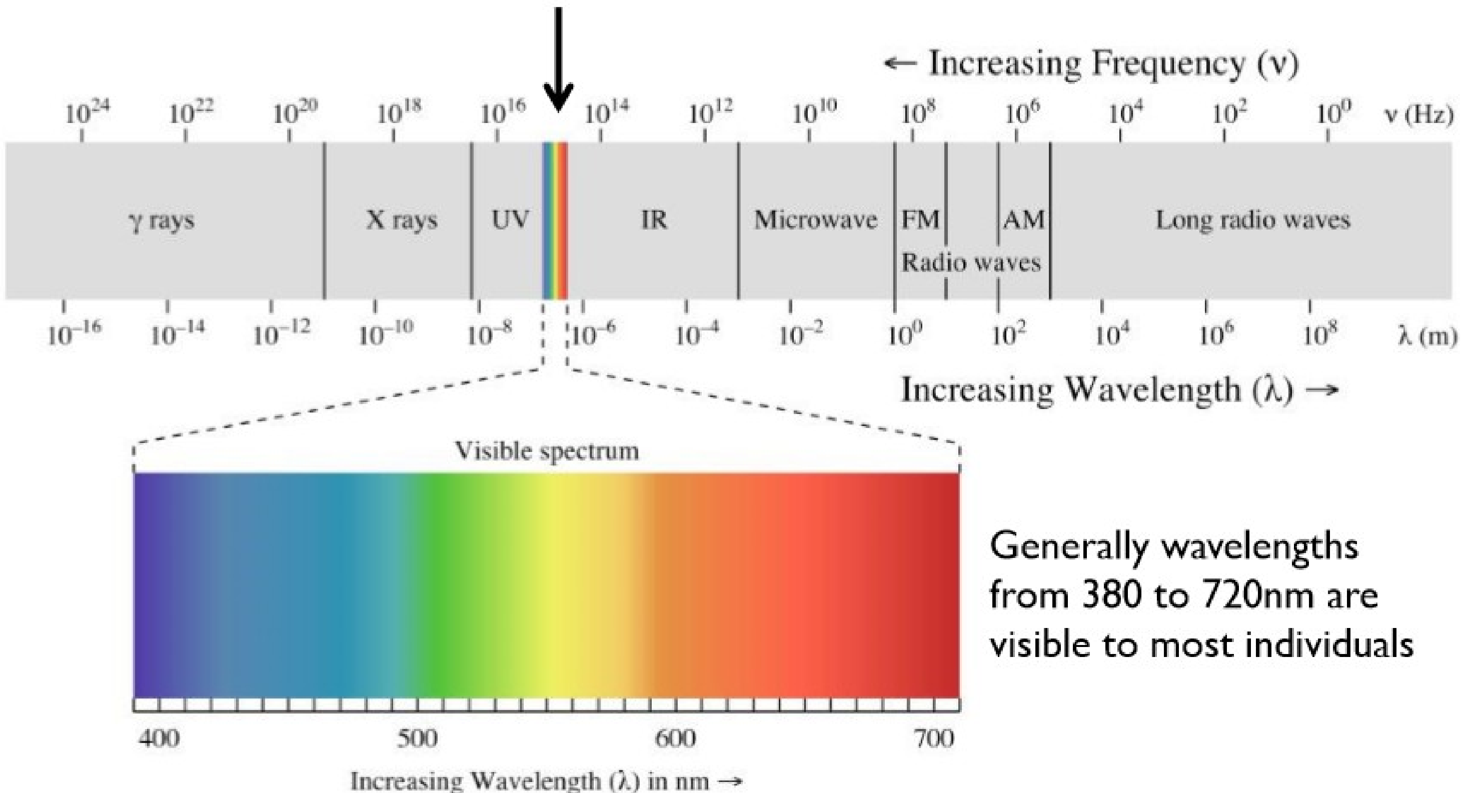
Spatially, apparently not: Eye Resolution ≈ 576 MP.

The retina (sensor) has high resolution, but the optics (lens) of the eye cannot meet that resolution.

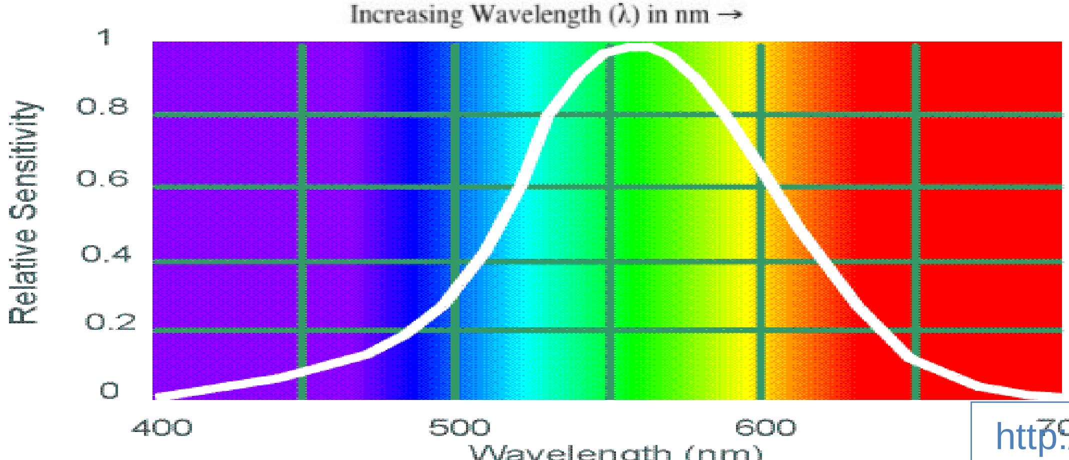
[Thanks to Leslie Bresnahan]

Electromagnetic Spectrum

A *very* small range of electromagnetic radiation



Generally wavelengths from 380 to 720nm are visible to most individuals

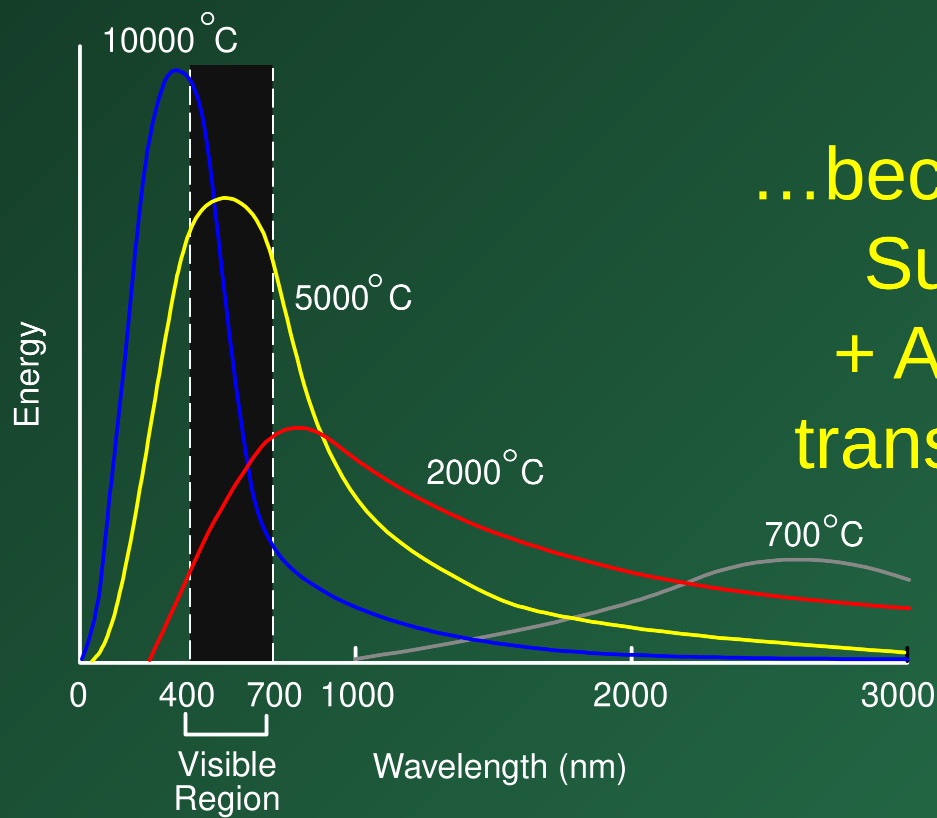


Human Luminance Sensitivity Function

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

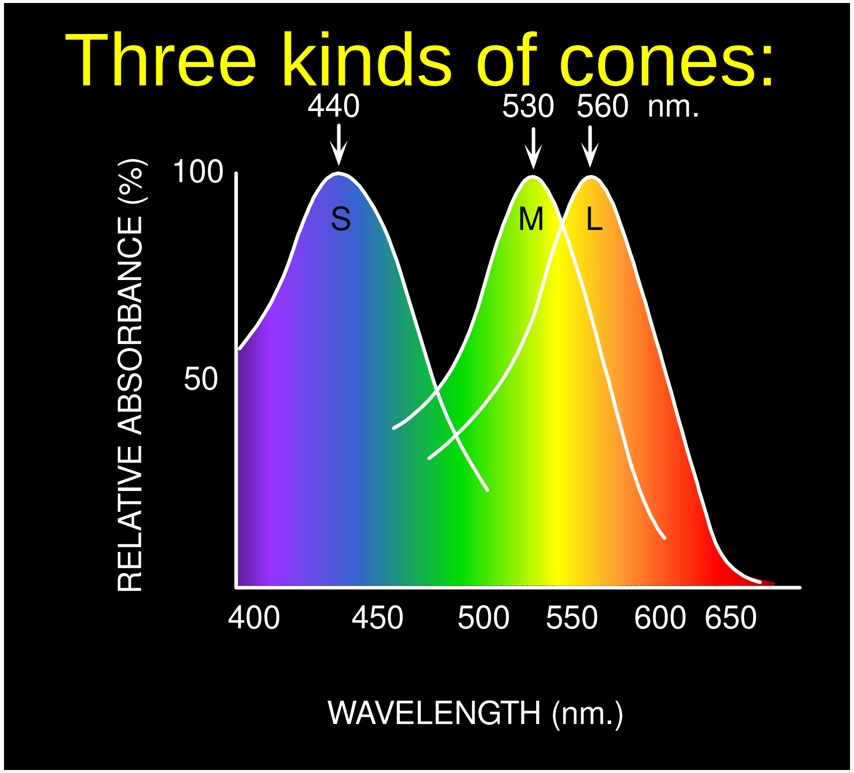
Visible Light

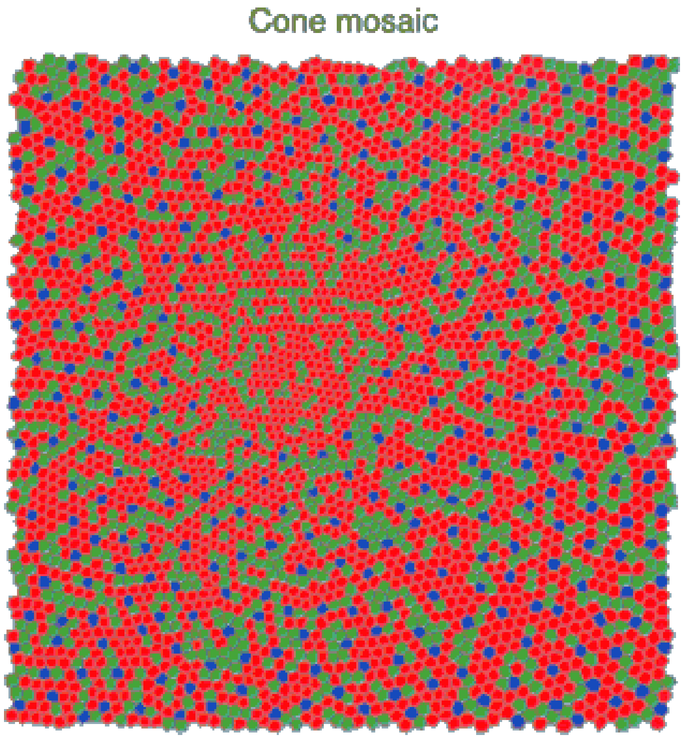
Why do we see light of these wavelengths?



…because that's where the Sun's peak radiation + Atmosphere is fairly transparent in that range

Physiology of human Color Vision

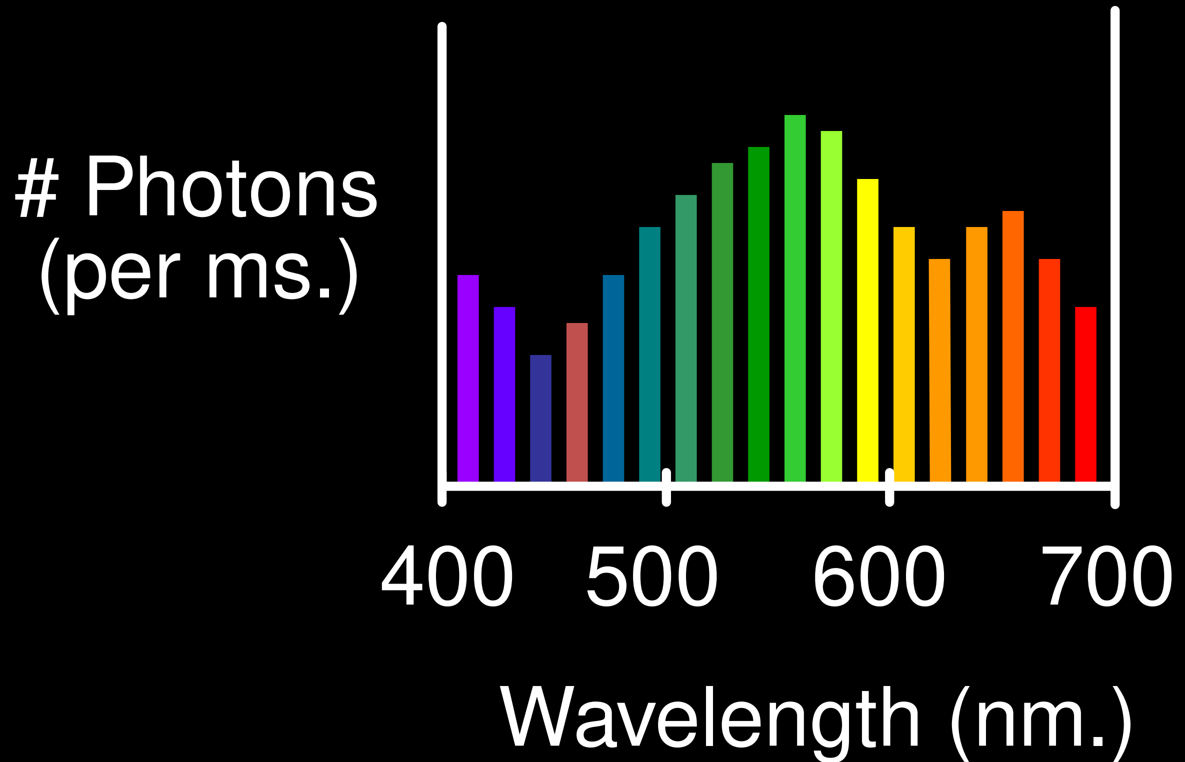




- Humans have 3 types of photopsin proteins found in the cone cells: Trichromatic view.
- Most animals are dichromatic.
- Our early ancestors (90 mil years ago) are believed to have been dichromatic and were capable of seeing some range of UV light. This was lost as they transitioned from a nocturnal lifestyle to diurnal lifestyle.

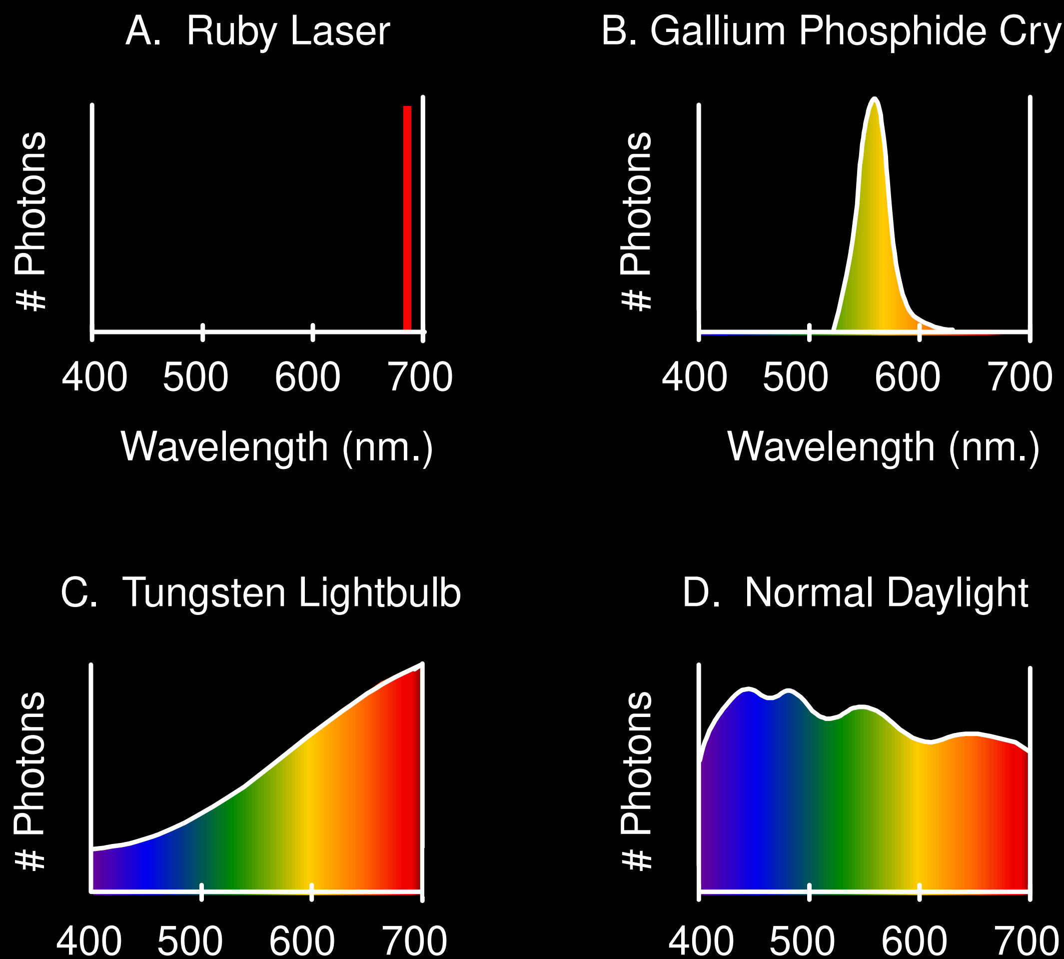
The Physics of Light

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.



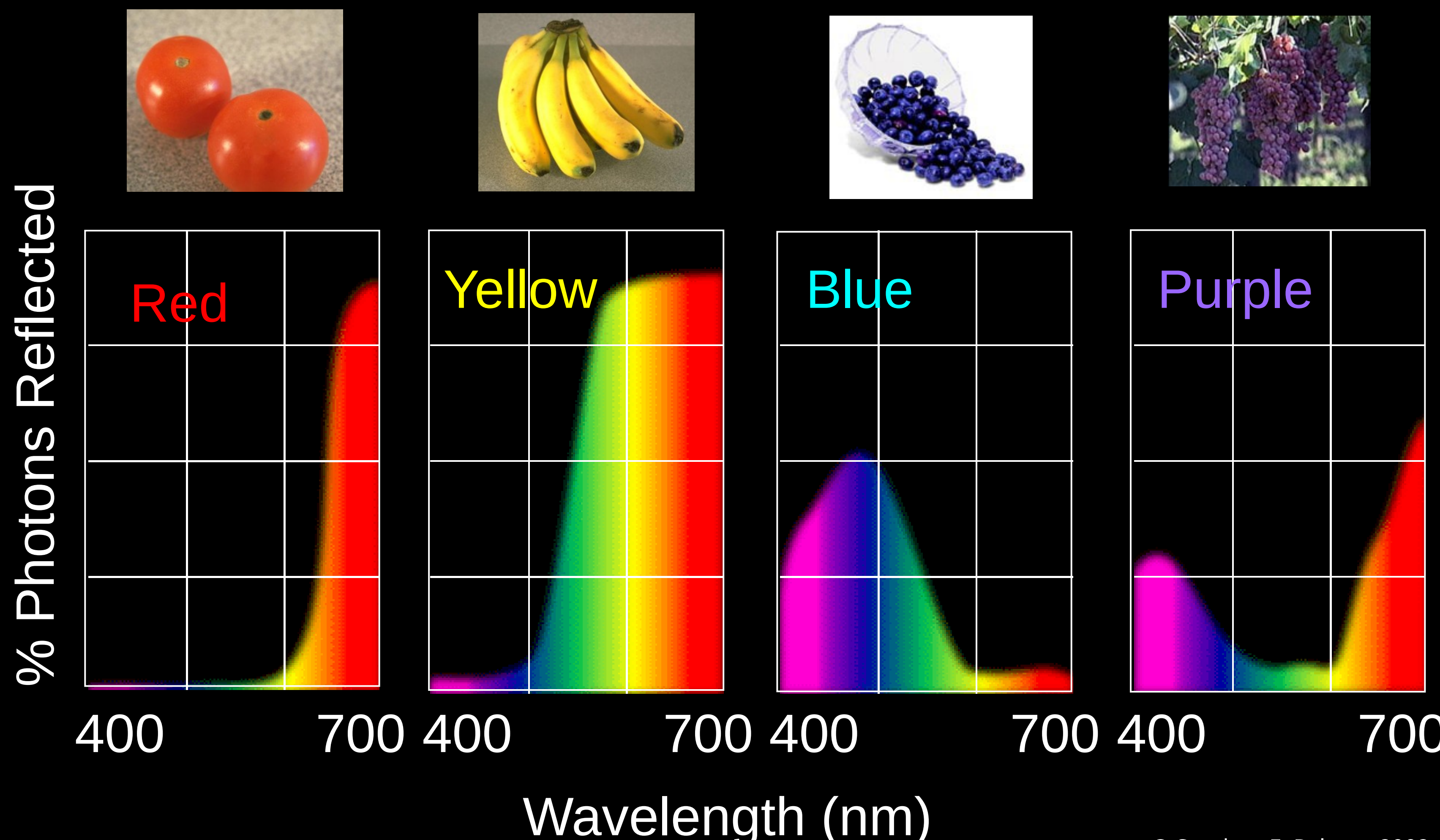
The Physics of Light

Some examples of the spectra of light sources



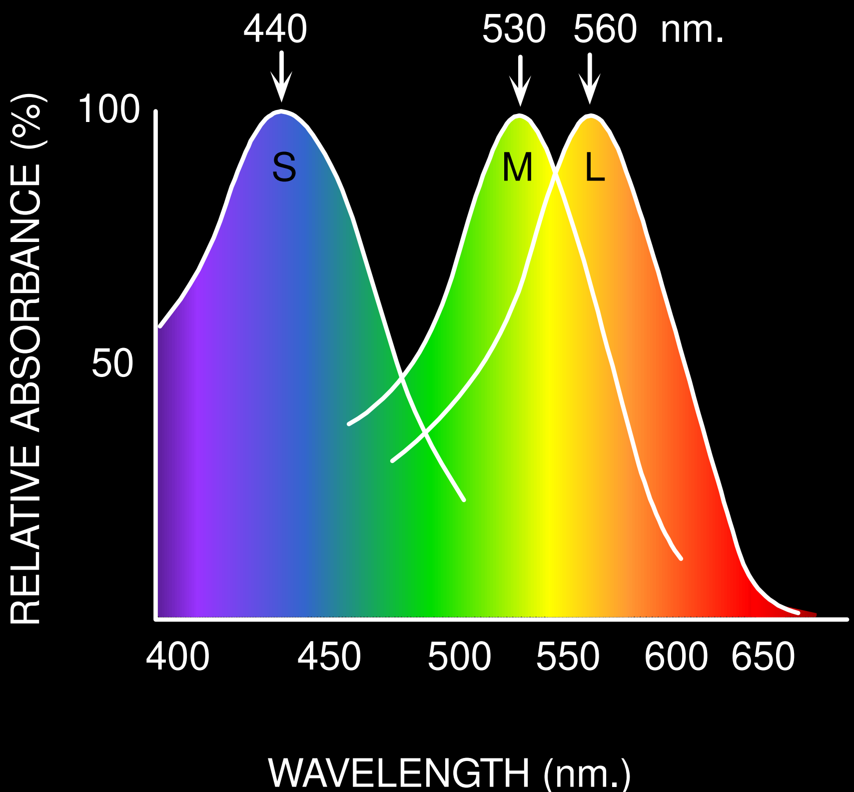
The Physics of Light

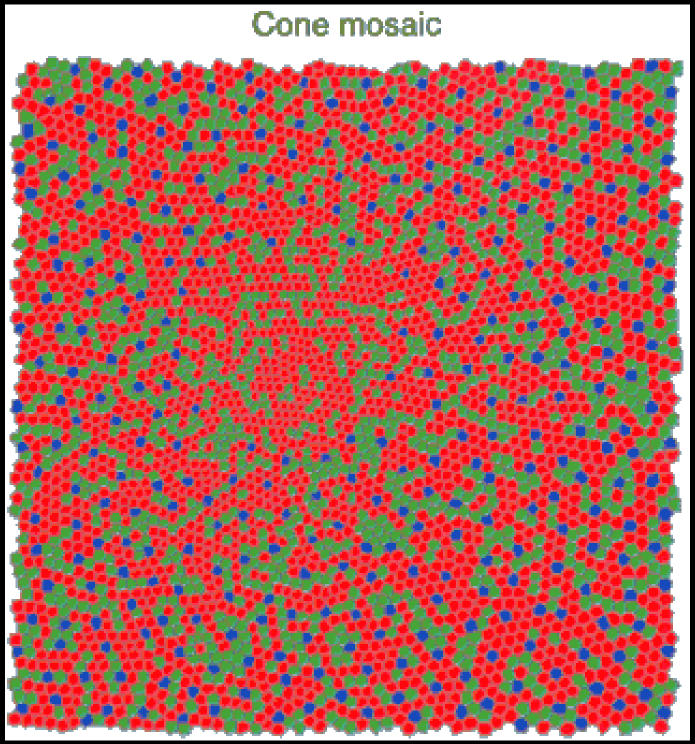
Some examples of the reflectance spectra of surfaces



Physiology of Color Vision

Three kinds of cones:





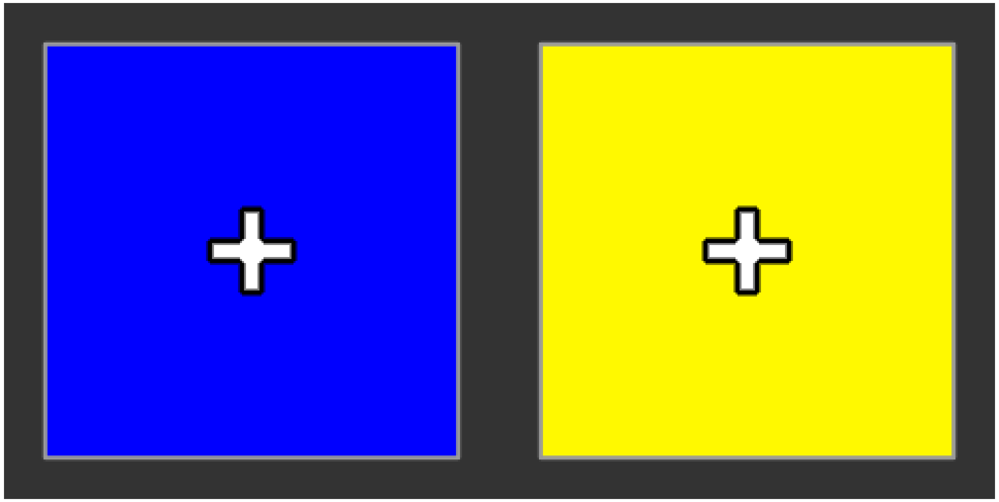
Why are M and L cones so close?

Why are there 3?

Impossible Colors

Can you make the cones respond in ways that typical light spectra never would?

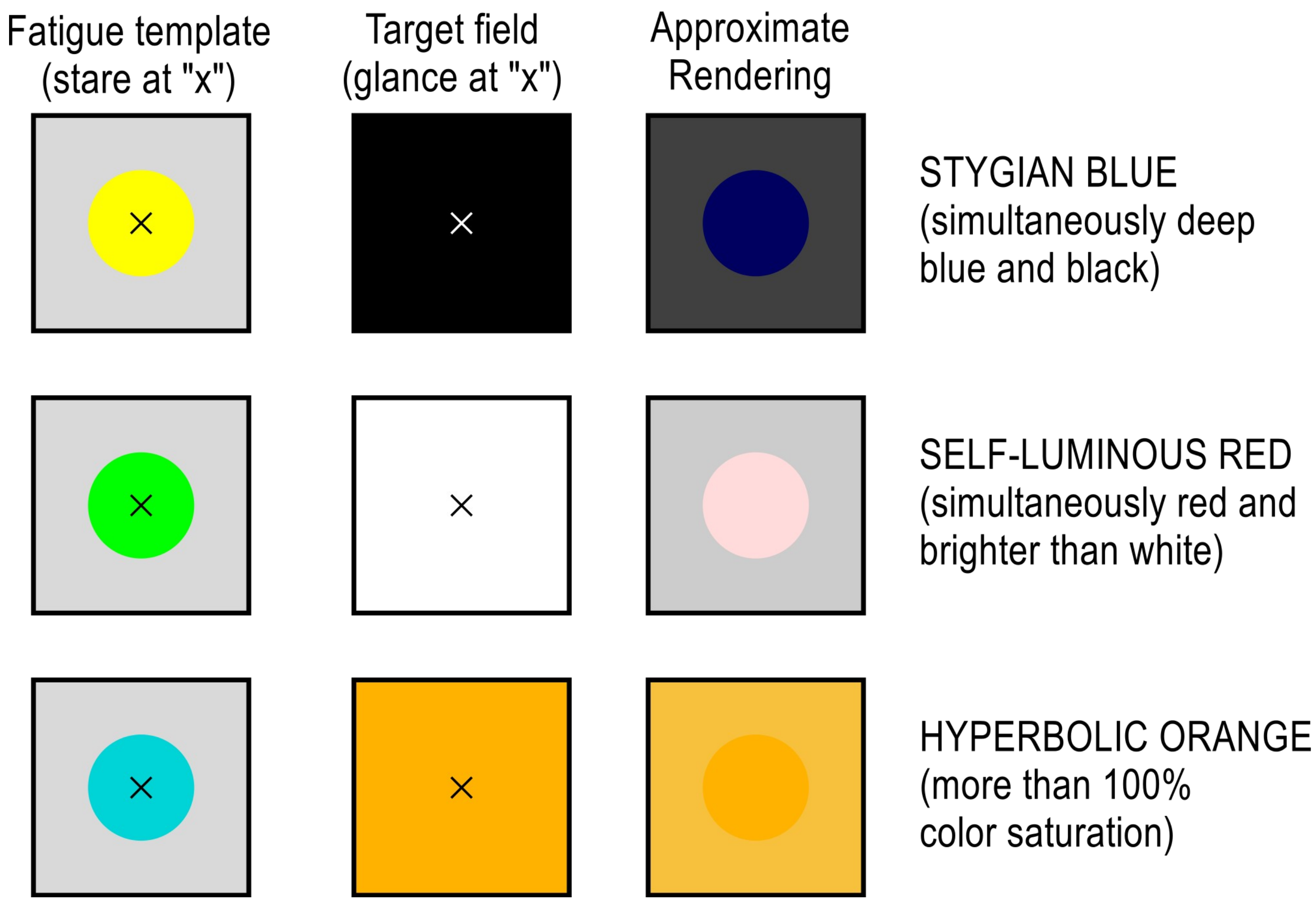
http://en.wikipedia.org/wiki/Impossible_colors



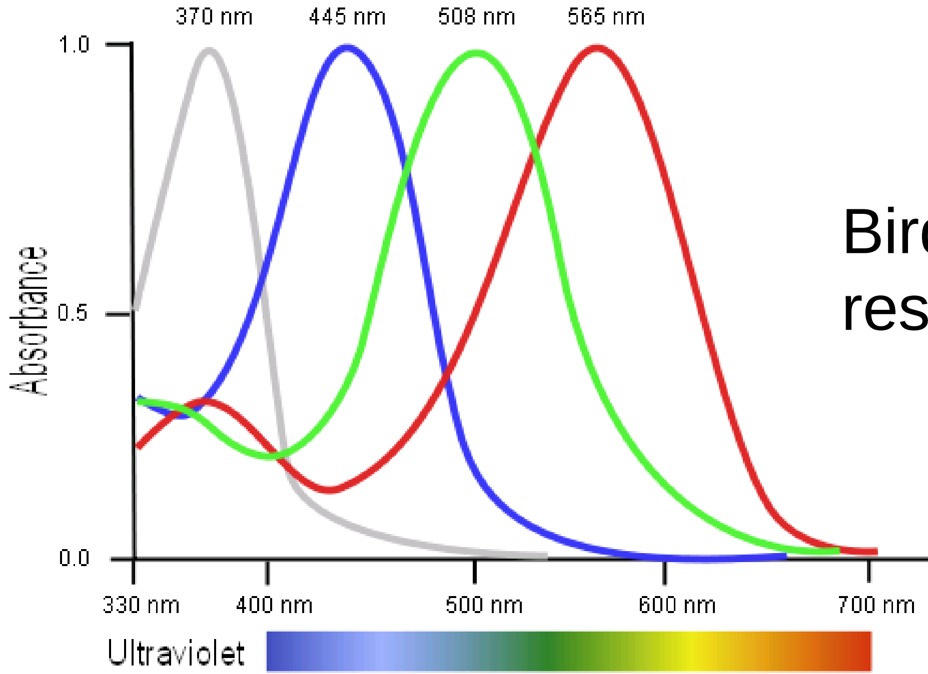
Cross your eyes so that the + sign in both is on top of each other.
Some people will be able to see an impossible color: Blue-Yellow

James Hays

CHIMERICAL COLOR DEMO TEMPLATES



Tetrachromatism



Bird cone responses

- Most birds, and many other animals, have cones for ultraviolet light.
- Some humans seem to have four cones (12% of females).
- True tetrachromatism is _rare_;

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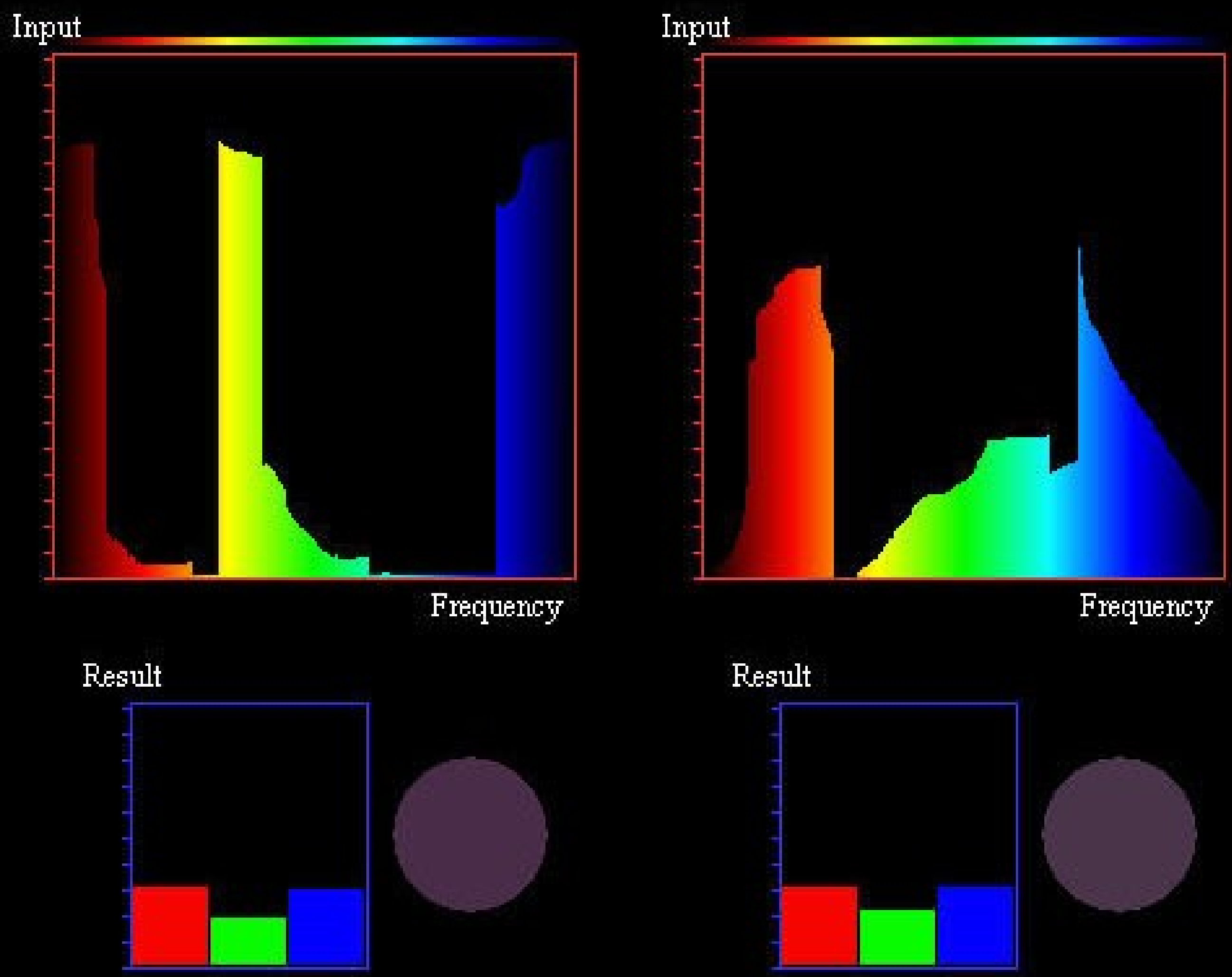
Bee vision

Metamers



by Jeff Beall, Adam Doppelt and John F. Hughes

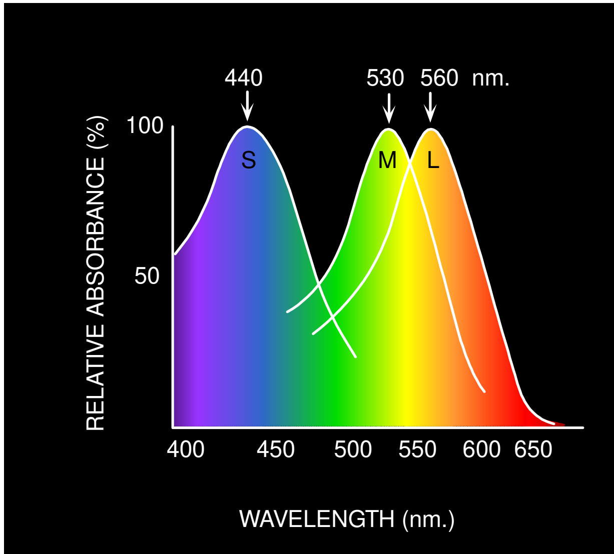
‘Color’ != position on EM spectrum

Our cells induce color perception
by interpreting spectra.

Most mammals are dichromats:

- Lack ‘L’ cone; cannot distinguish green-red
- 1% of men (protanopia color blindness)

Trichromaticity *evolved.*
No implicit reason for effect of



Thanks to Cam Allen-Lloyd

What is color?

Why do we even care about human vision in this class?

Why do we care about human vision?

- We don’t, necessarily.

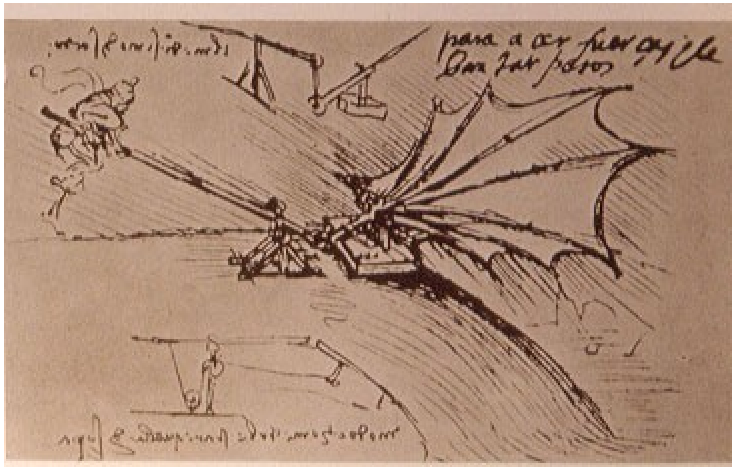
- But biological vision shows that it is possible to make important judgements from images.

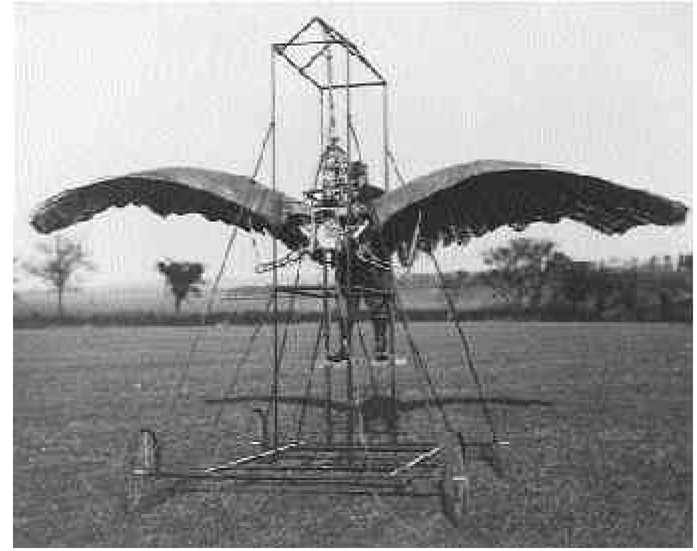
Why do we care about human vision?

- We don’t, necessarily.

- But biological vision shows that it is possible to make important judgements from images.

- It’s a human world -> cameras imitate the frequency response of the human eye to try to see as we see.





"Can machines fly like a bird?"
No, because airplanes don’t flap.

"Can machines fly?"
Yes, but airplanes use a different mechanism.

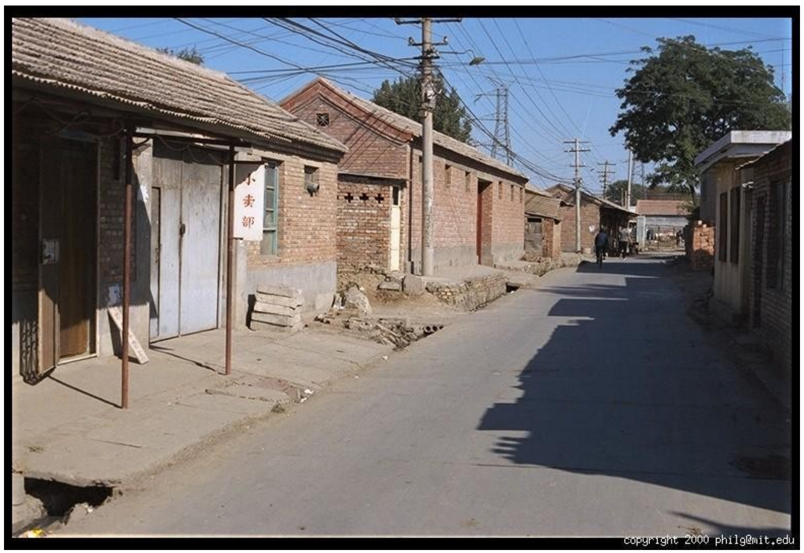
"Can machines perceive?"
Is this question like the first, or like the second?

James Hays

Grayscale intensity

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



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Images in Python Numpy

N x M RGB image "im"

- im[0,0,0] = top-left pixel value in R-channel
- Im[x, y, b] = x pixels to right, y pixels down in the b^th channel
- Im[N-1, M-1, 3] = bottom-right pixel in B-channel

Column →

Row ↓

R

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

G

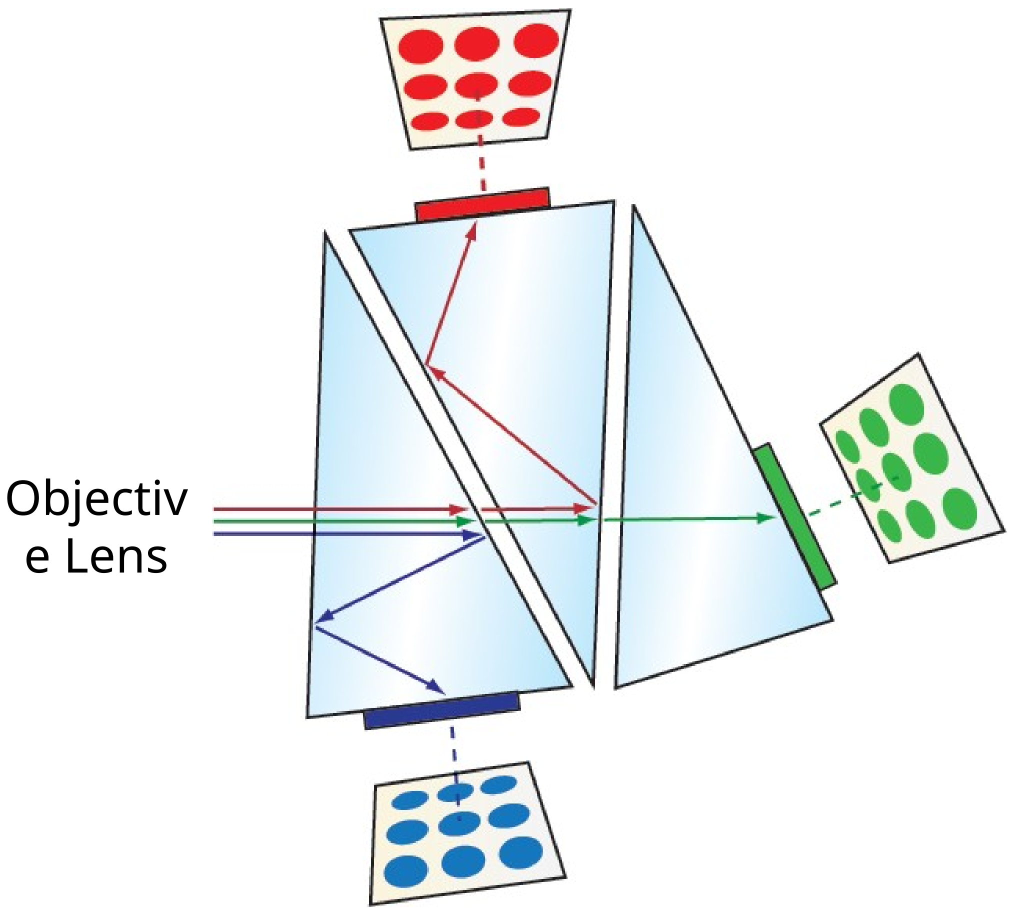
									0.92	0.99
									0.95	0.91
									0.91	0.92
									0.97	0.95
									0.79	0.85
									0.45	0.33
									0.49	0.74
									0.82	0.93
									0.90	0.99
0.79	0.73	0.90	0.67	0.33	0.61	0.69	0.79	0.73	0.93	0.97
0.91	0.94	0.89	0.49	0.41	0.78	0.78	0.77	0.89	0.99	0.93

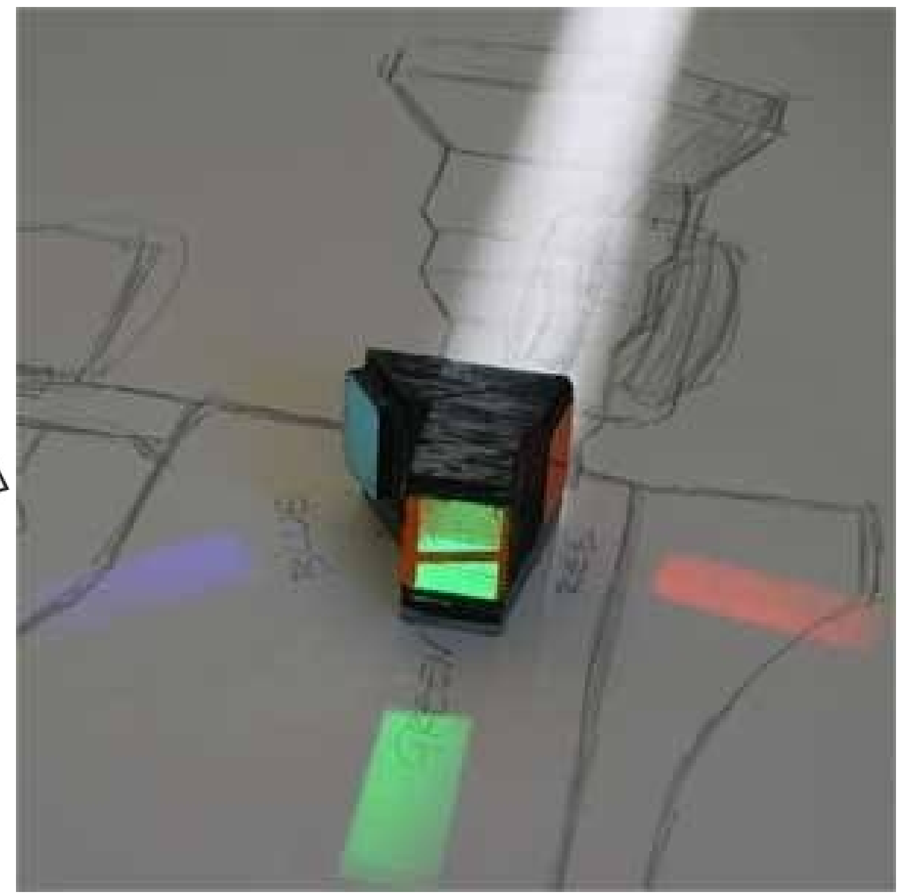
B

									0.92	0.99
									0.95	0.91
									0.91	0.92
									0.97	0.95
									0.79	0.85
									0.45	0.33
									0.49	0.74
									0.82	0.93
									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

James Hays

Cameras with Three Sensors

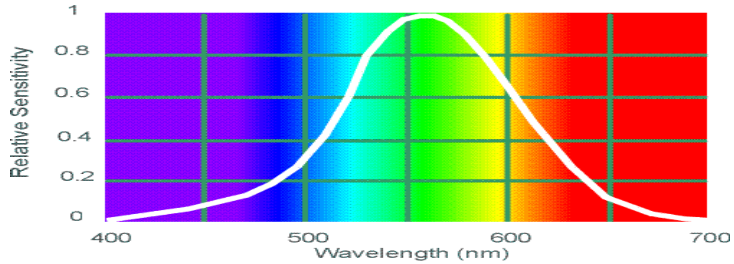


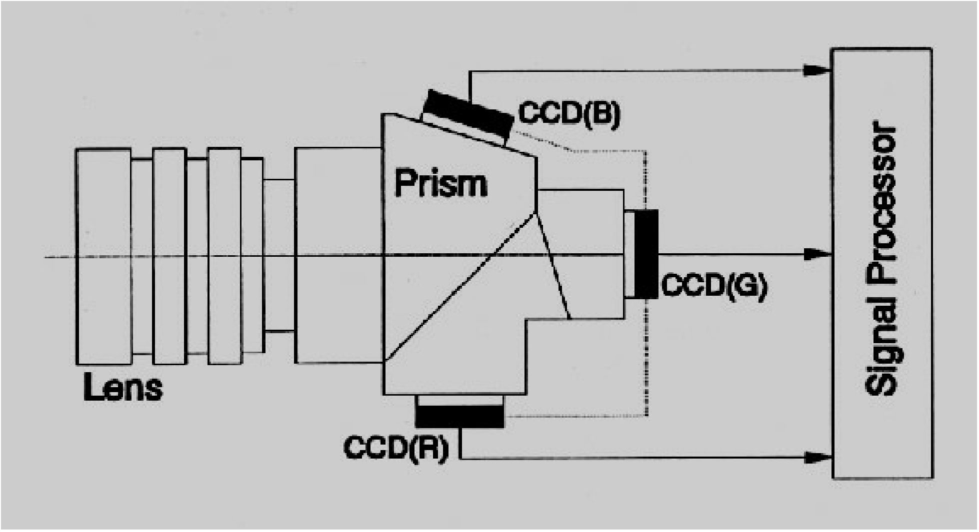


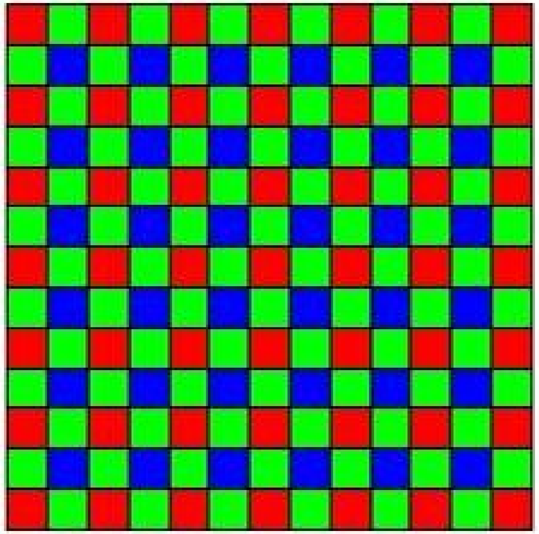
[Edmund Optics; Adam
Wilt]

Color Sensing in Camera (RGB)

- 3-chip vs. 1-chip: quality vs. cost
- Why more green?







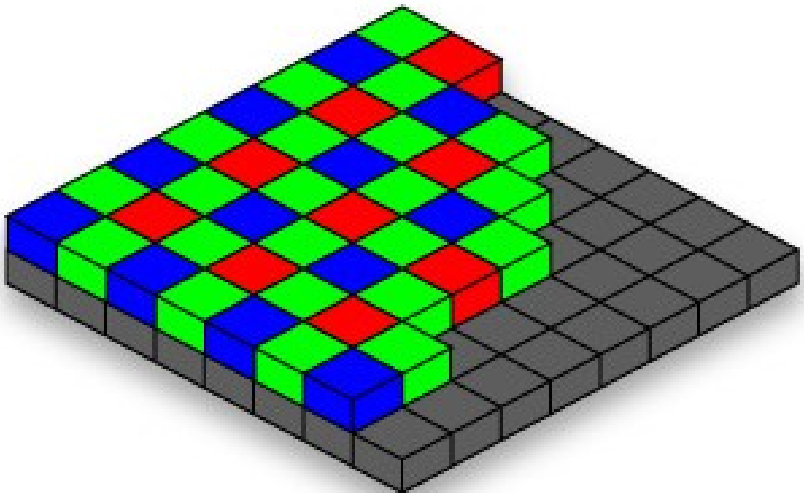
Bayer filter

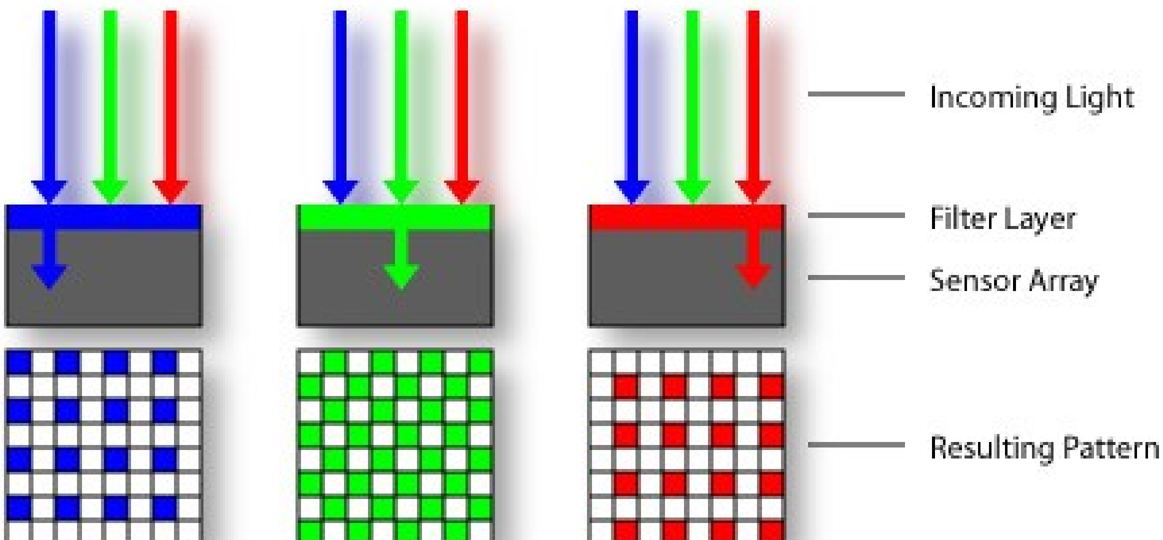
Why 3 colors?

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

Slide by Steve Seitz

Cheaper/More Compact Color Sensing: Bayer Grid

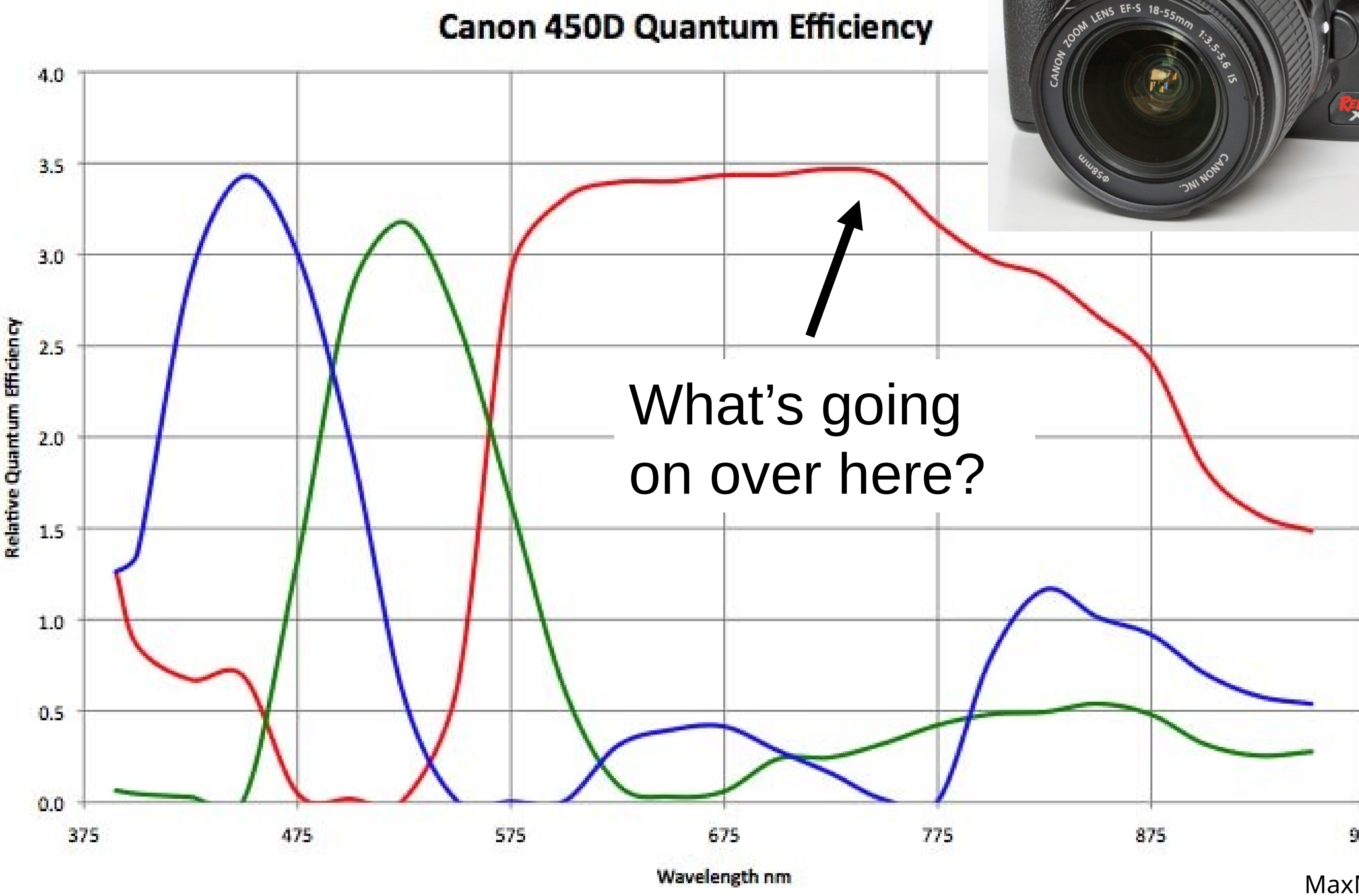




Estimate RGB

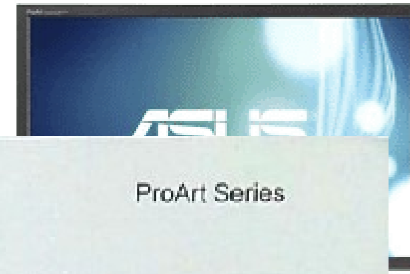
Slide by Steve Seitz

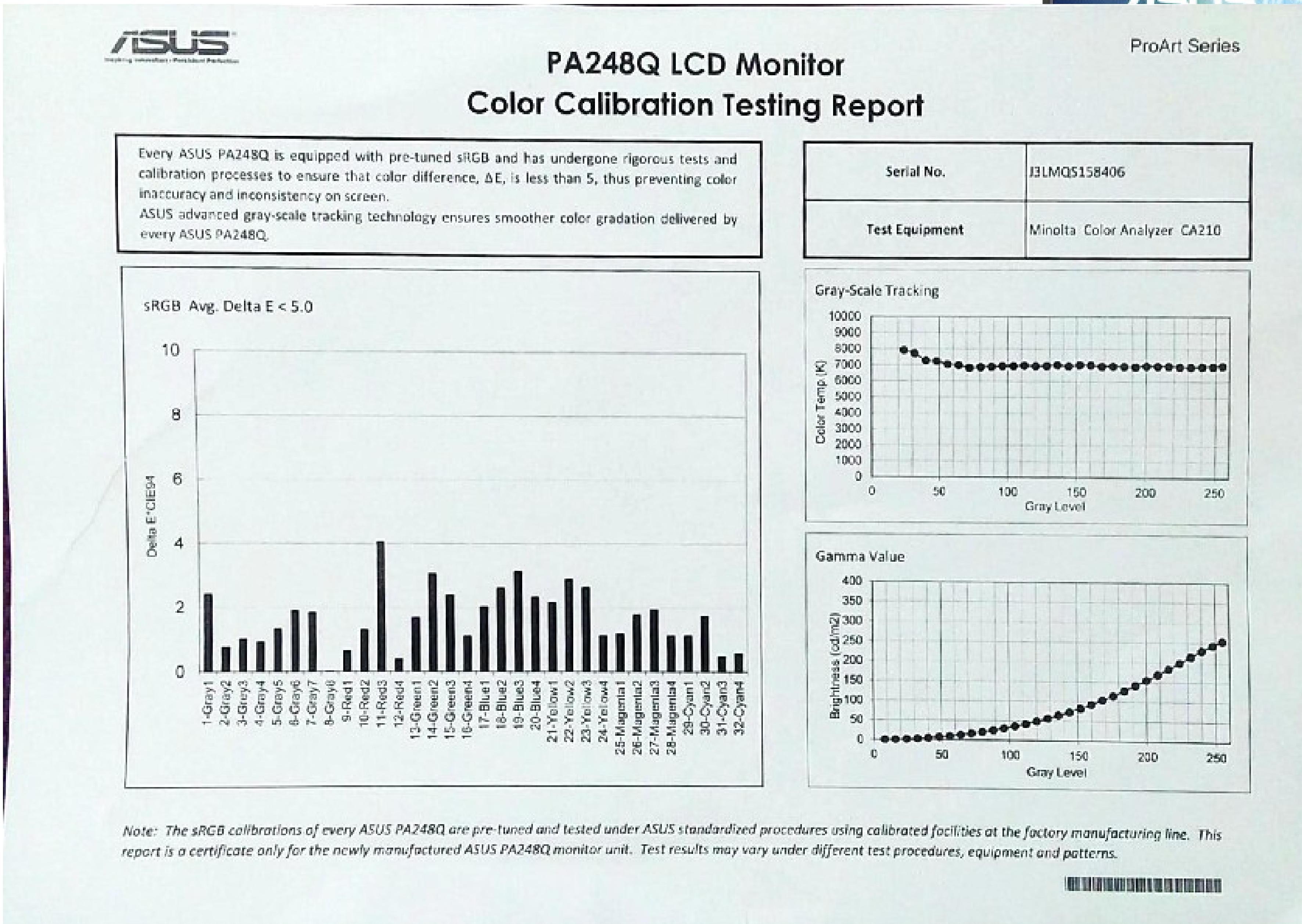
RGB Camera Color Respon



MaxMax.com

Display Color Response





ProArt Series

PA248Q LCD Monitor
Color Calibration Testing Report

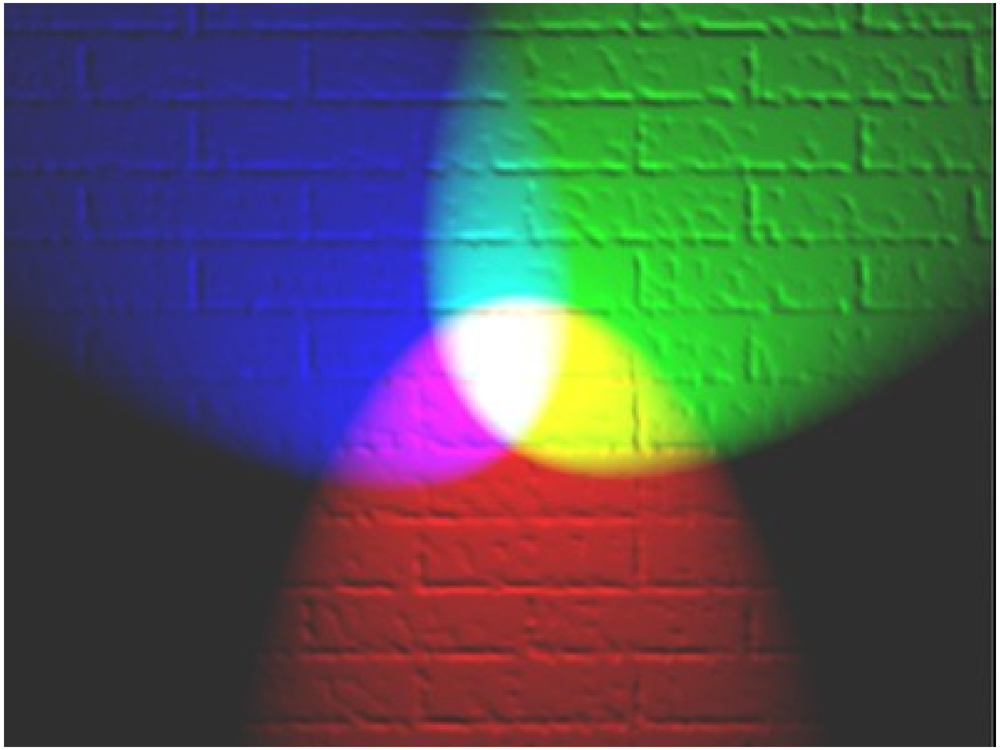
Every ASUS PA248Q is equipped with pre-tuned sRGB and has undergone rigorous tests and calibration processes to ensure that color difference, ΔE, is less than 5, thus preventing color inaccuracy and inconsistency on screen.
ASUS advanced gray-scale tracking technology ensures smoother color gradation delivered by every ASUS PA248Q.

Serial No.	J3LMQS158406
Test Equipment	Minolta Color Analyzer CA210

Note: The sRGB calibrations of every ASUS PA248Q are pre-tuned and tested under ASUS standardized procedures using calibrated facilities at the factory manufacturing line. This report is a certificate only for the newly manufactured ASUS PA248Q monitor unit. Test results may vary under different test procedures, equipment and patterns.

Color spaces

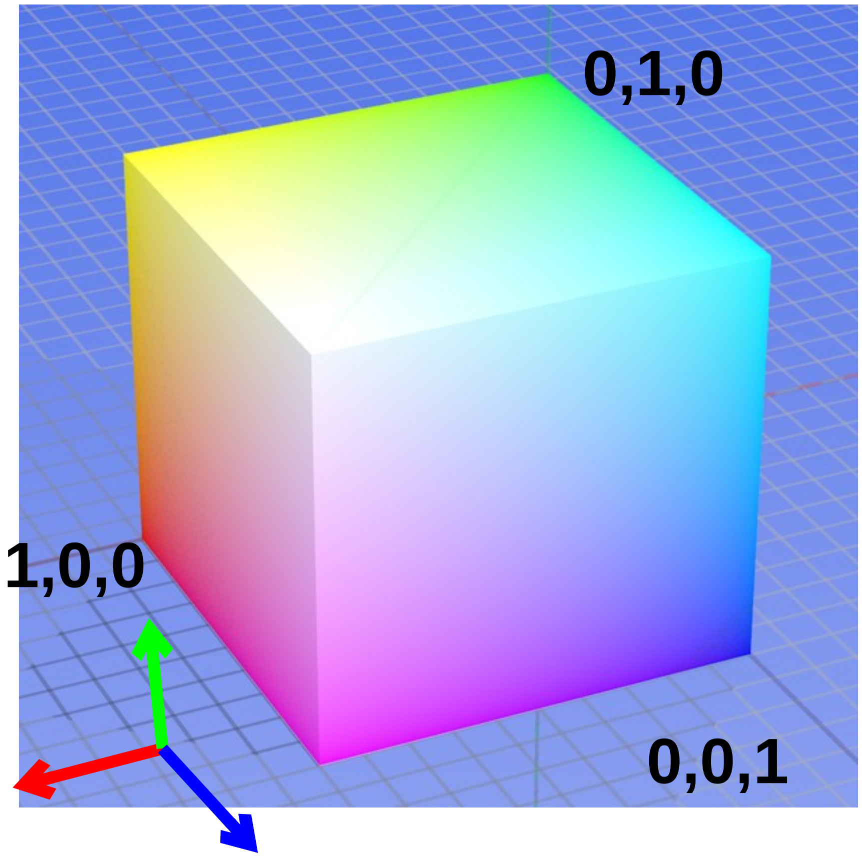
How can we represent color?



http://en.wikipedia.org/wiki/File:RGB_illumination.jpg

Color spaces: RGB

Default color space



R = 1
(G=0,B=0)

G = 1
(R=0,B=0)

B = 1
(R=0,G=0)

Any color = r*R + g*G + b*B
- Strongly correlated channels
- Non-perceptual

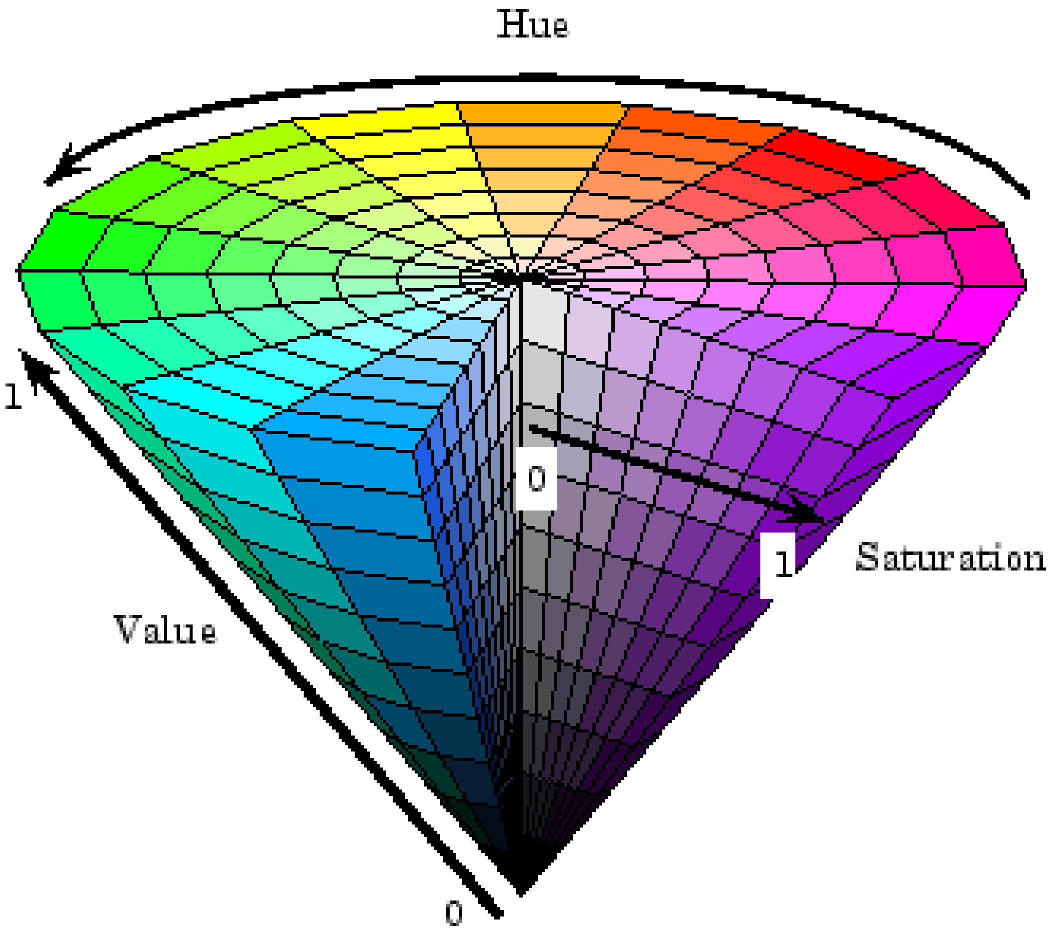
Image from: http://en.wikipedia.org/wiki/File:RGB_color_solid_cube.png

Got it.   C = r*R + g*G + b*B

IS COLOR A VECTOR SPACE?

Color spaces: HSV

Intuitive color space



If you had to choose, would you rather go without:
- intensity (‘value’), or
- hue + saturation (‘chroma’)?

James Hays

Most information in intensity

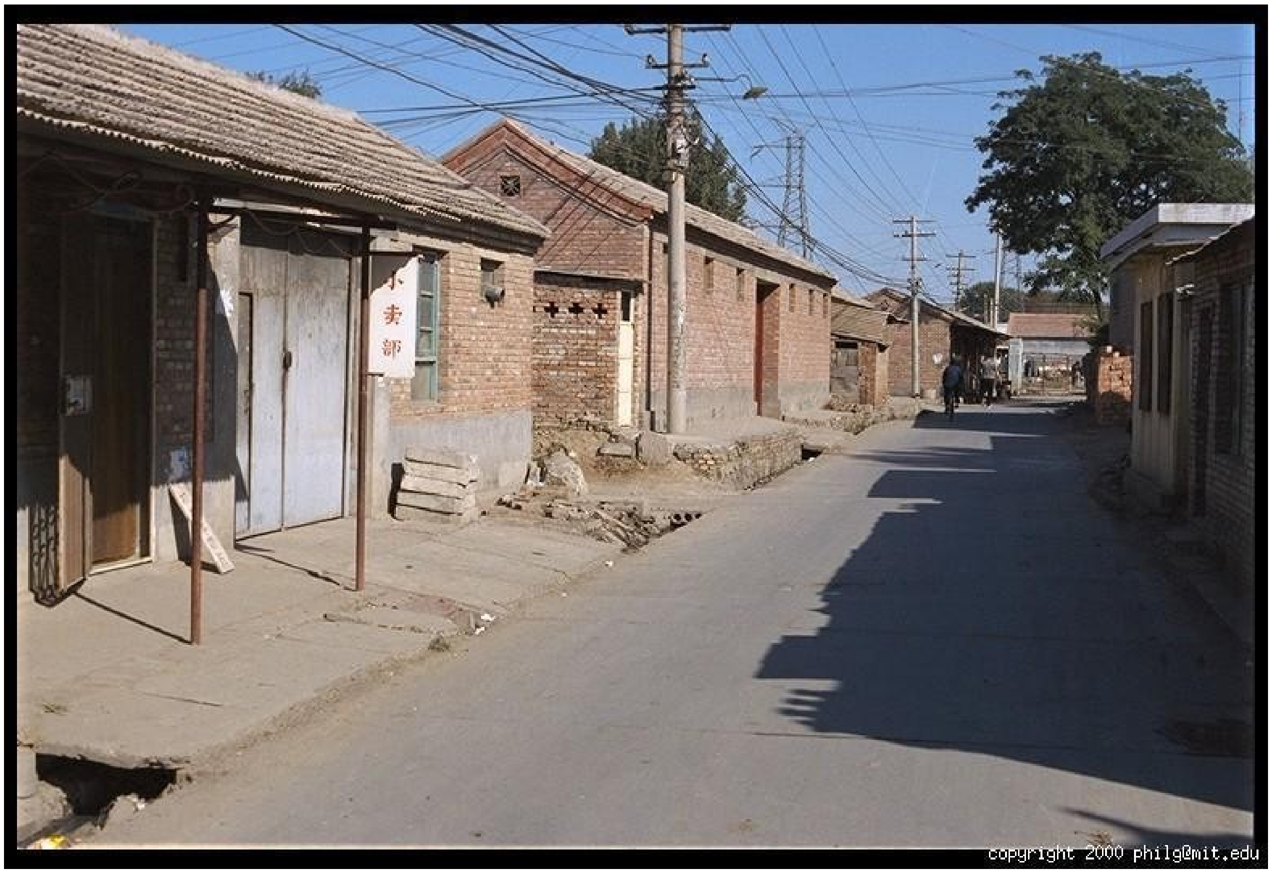
Only color shown – constant intensity

James Hays

Most information in intensity

Only intensity shown – constant color

Most information in intensity

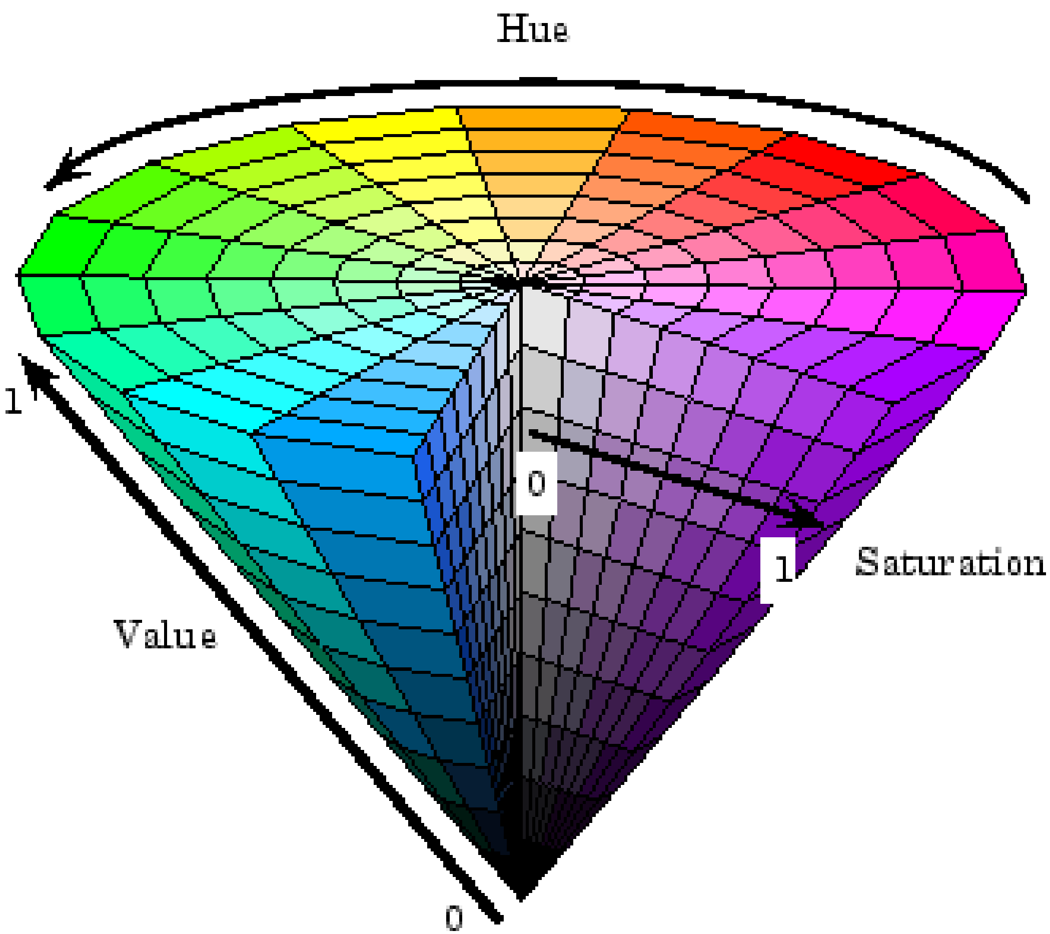


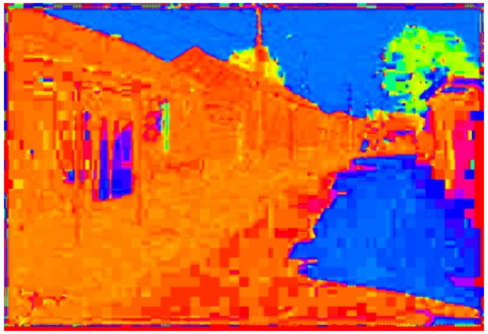
Original image

James Hays

Color spaces: HSV

Intuitive color space





H
(S=1,V=1)

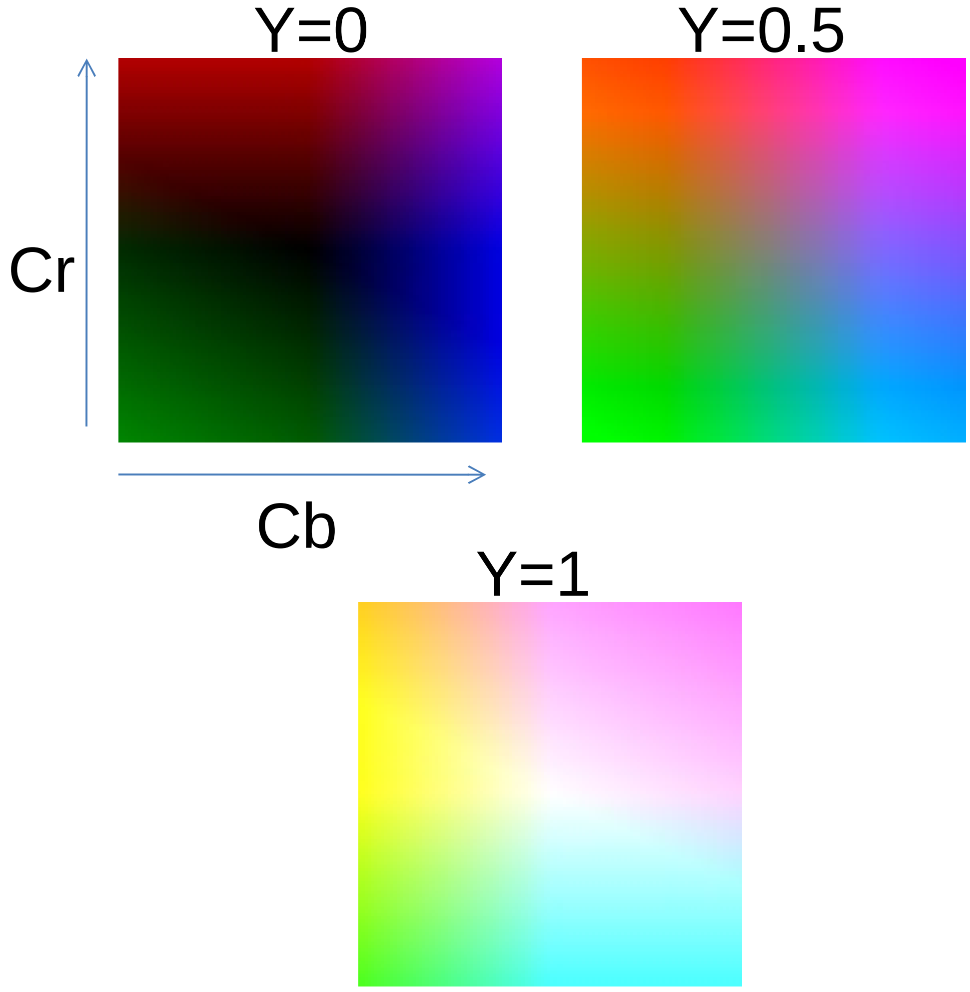
S
(H=1,V=1)

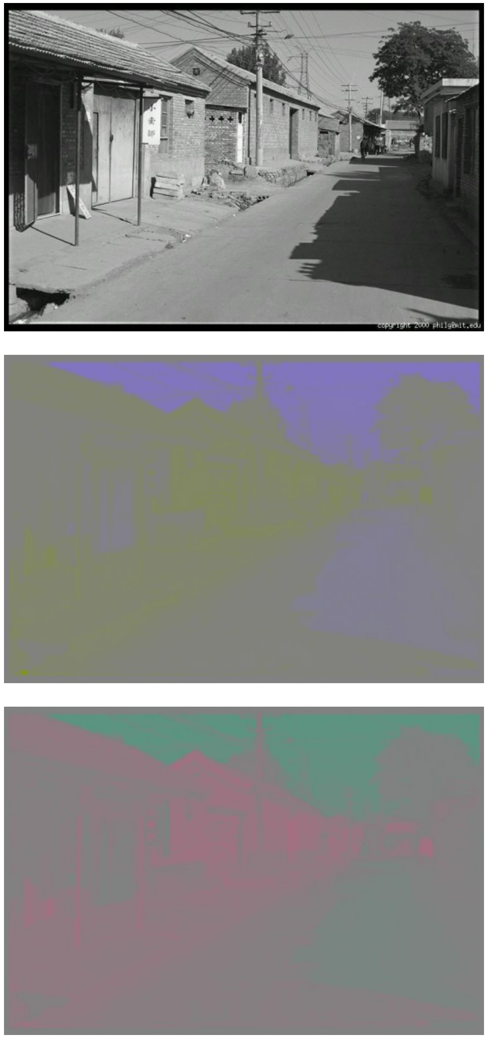
V
(H=1,S=0)

James Hays

Color spaces: YCbCr

Fast to compute, good for compression, used by TV





Y
(Cb=0.5,Cr=0.5)

Cb
(Y=0.5,Cr=0.5)

Cr
(Y=0.5,Cb=05)

James Hays

Most JPEG images & videos subsample chroma

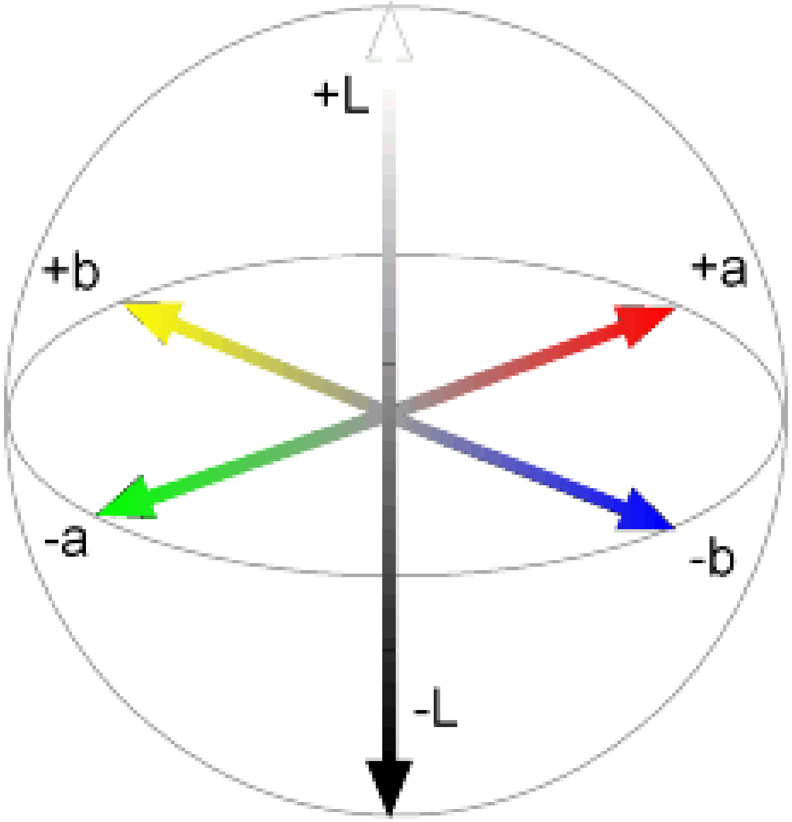
PSP Comp 3
2x2 Chroma subsampling
285K

Original
1,261K lossless
968K PNG

IS COLOR PERCEPTION A VECTOR SPACE?

Color spaces: L*a*b*

"Perceptually uniform"* color space



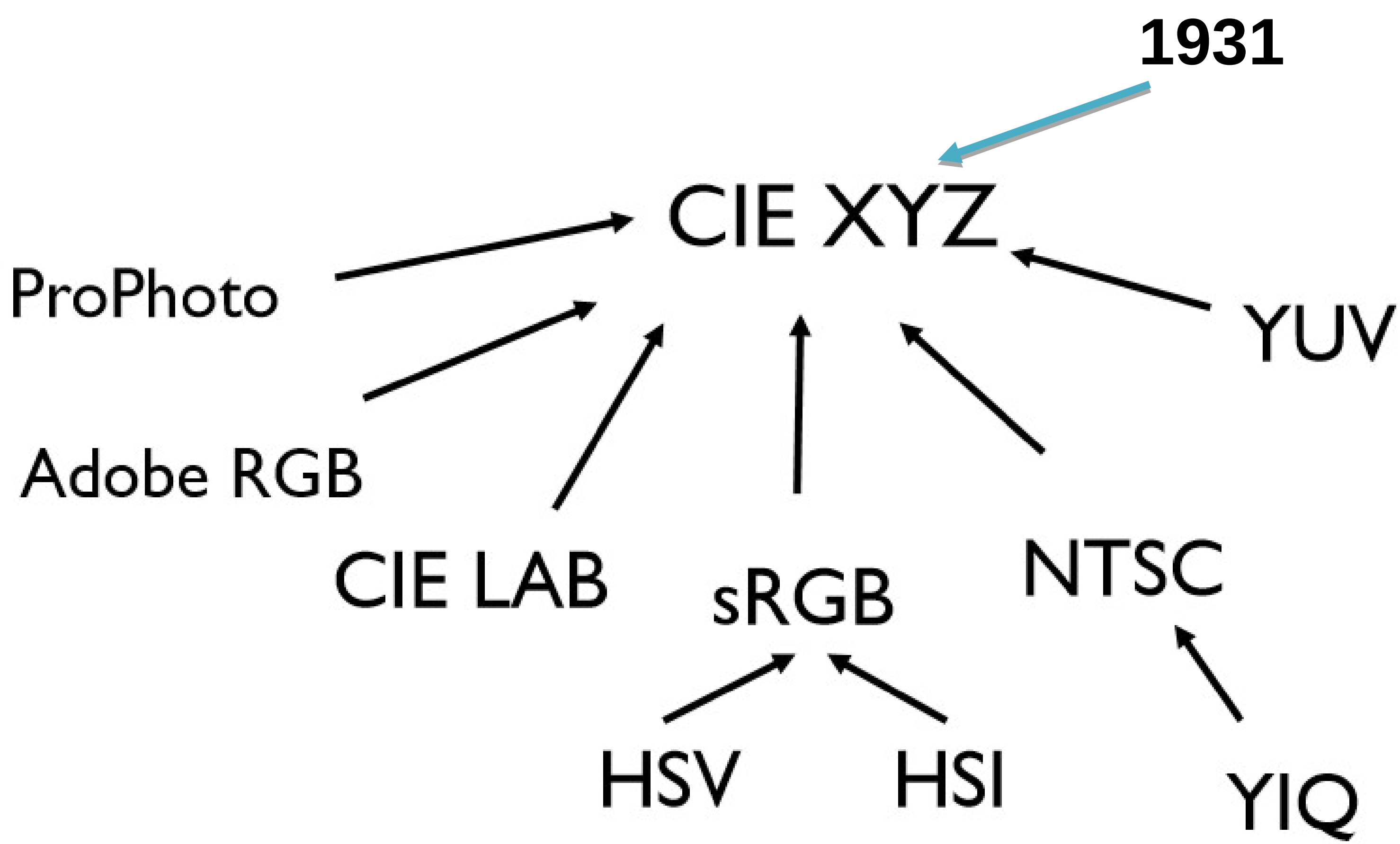
L
(a=0,b=0)

a
(L=65,b=0)

b
(L=65,a=0)

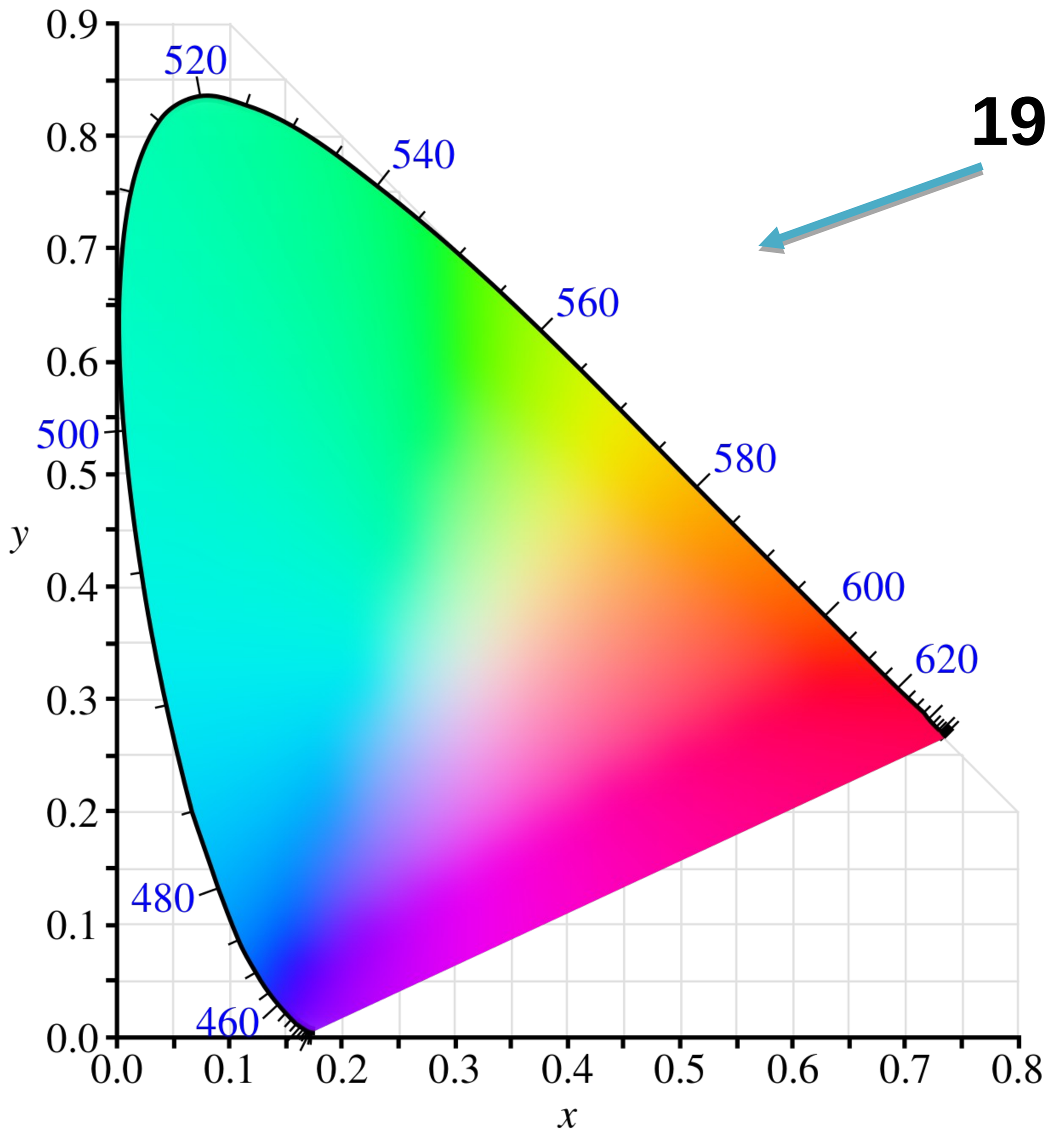
James Hays

Are we done with colors?



M. Brown

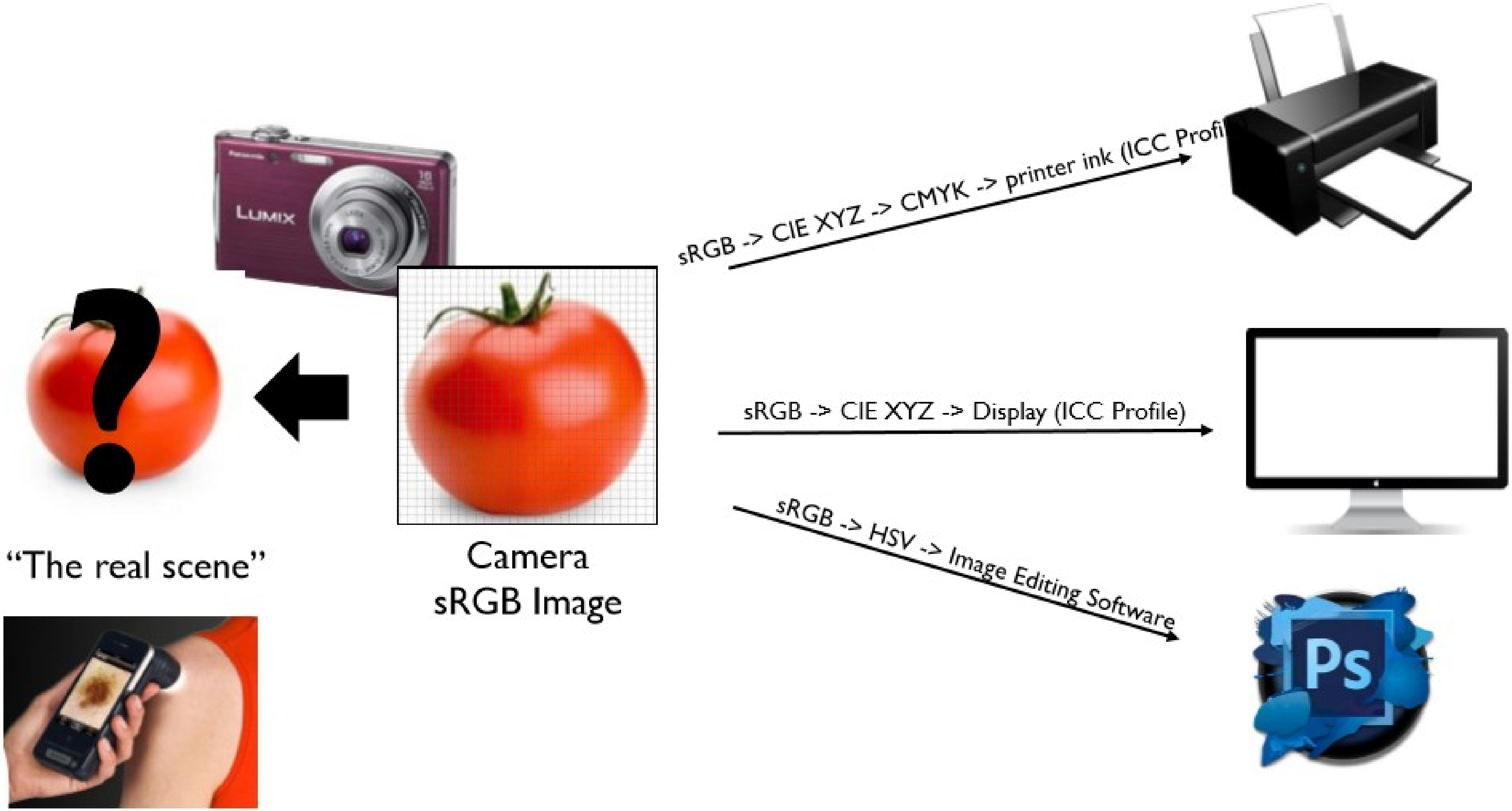
Are we done with colors?



1931

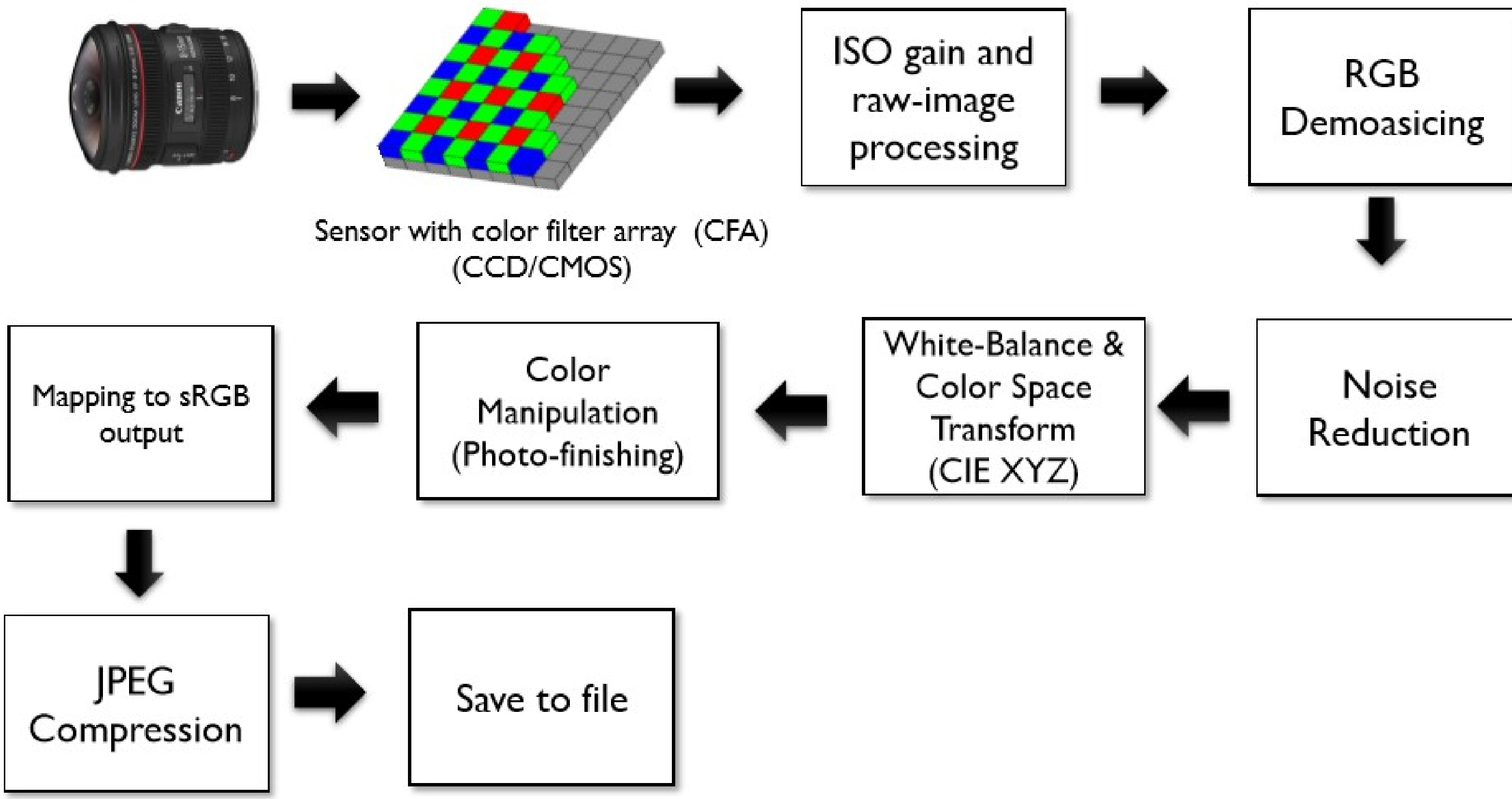
Wikipedia – CIE 1931

Are we done with colors?



M. Brown

The full Image formation process: Photometry



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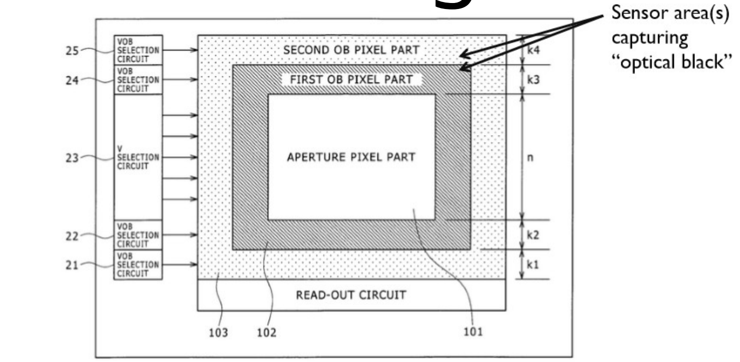
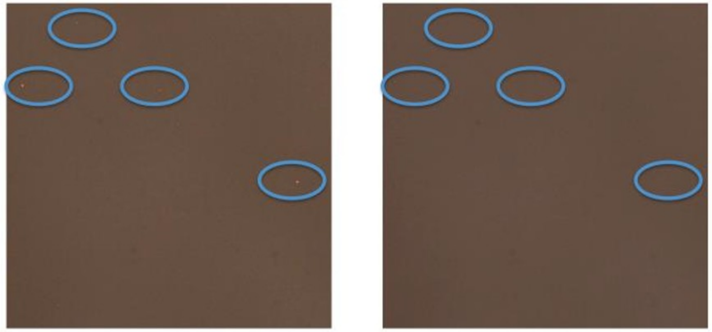
ISO gain and raw Image Processesing:

- Black level subtraction



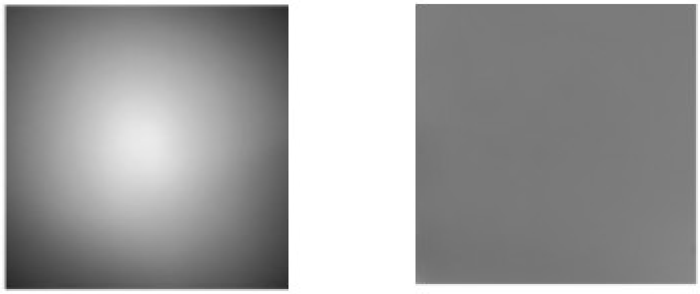
Black light capturing areas (likely exaggerated) from Sony US Patent US8227734B2 (Filed 2008) .

- Defective/Dead pixels



Identifying "dead pixels"   After interpolation

- Flat field correction (e.g. Vignetting)



Before   After

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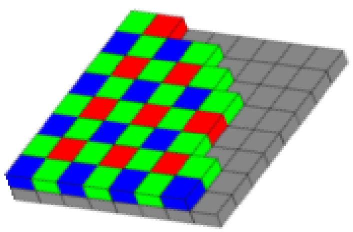
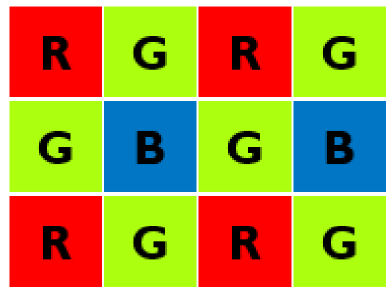
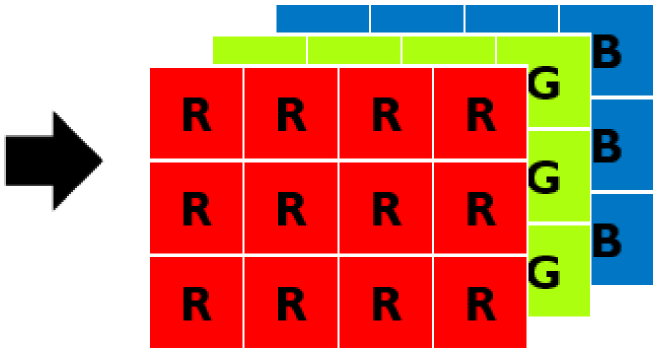
RGB demosaicing :



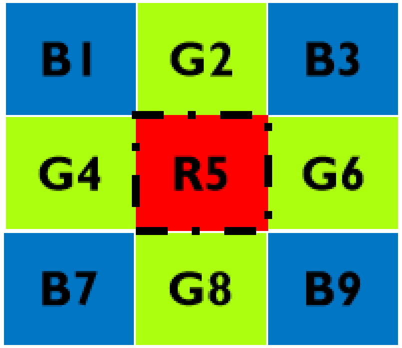
Sensor with color filter array
(CMOS)

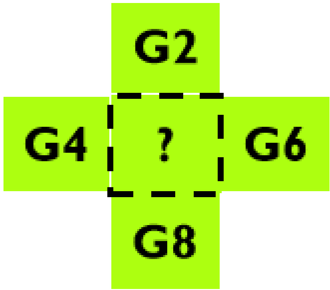


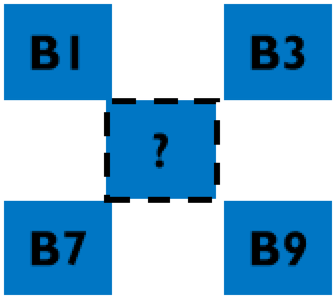
Sensor RGB layout



Desired output with RGB per pixel.







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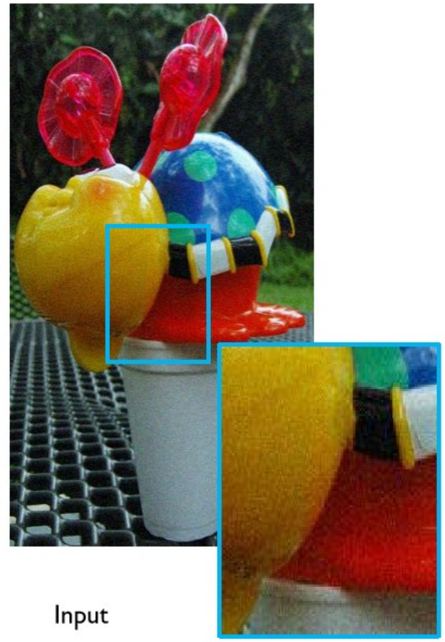
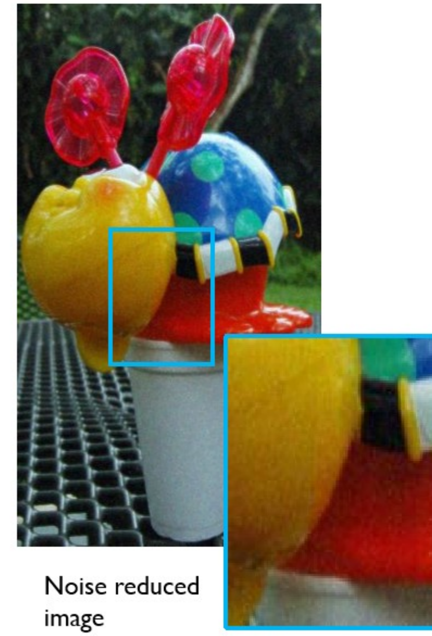
Noise Reduction

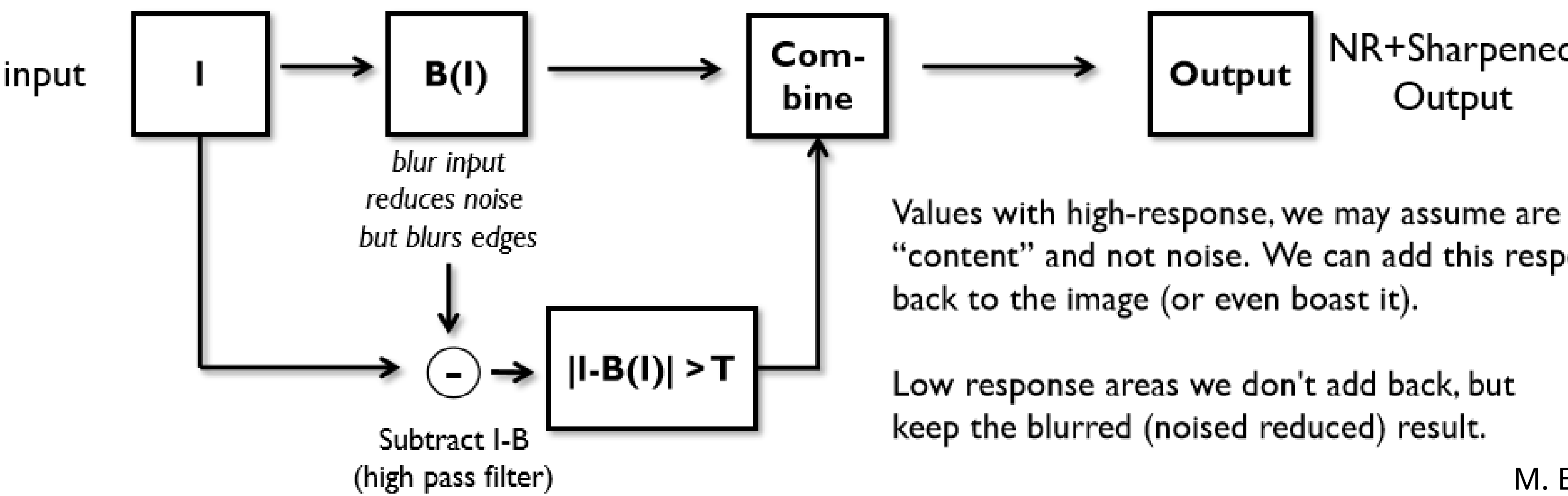


Input



Noise reduced image

Sketch of the procedure here



Values with high-response, we may assume are image "content" and not noise. We can add this response back to the image (or even boast it).

Low response areas we don't add back, but keep the blurred (noised reduced) result.

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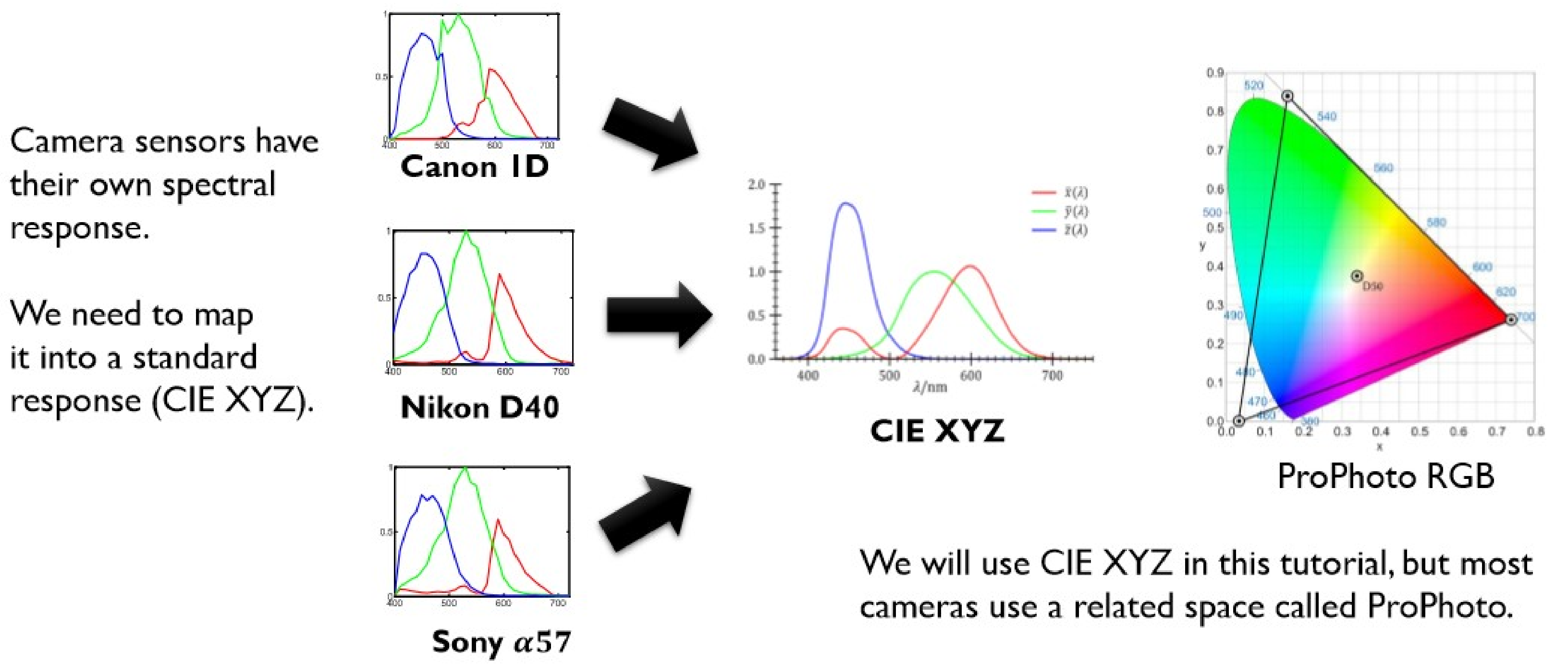
Color transform and White Balancing



- The challenging part for white-balance is determining the proper white-balance setting!
- Users can manually set the white balance by choosing camera specific white-balance matrices

- auto white balance (AWB) can be used.
- In computer vision, we often refer to AWB as "illumination estimation"

M. Brown

Color transform and White Balancing

WB SETTINGS	COLOR TEMPERATURE	LIGHT SOURCES
	10000 - 15000 K	Clear Blue Sky
	6500 - 8000 K	Cloudy Sky / Shade
	6000 - 7000 K	Noon Sunlight
	5500 - 6500 K	Average Daylight
	5000 - 5500 K	Electronic Flash
	4000 - 5000 K	Fluorescent Light
	3000 - 4000 K	Early AM / Late PM
	2500 - 3000 K	Domestic Lightning
	1000 - 2000 K	Candle Flame

Cameras can pre-calibrate their sensor's response for common illuminations.
Typical mapping of WB icons to related color temperate.

Input

Gray World

White Patch

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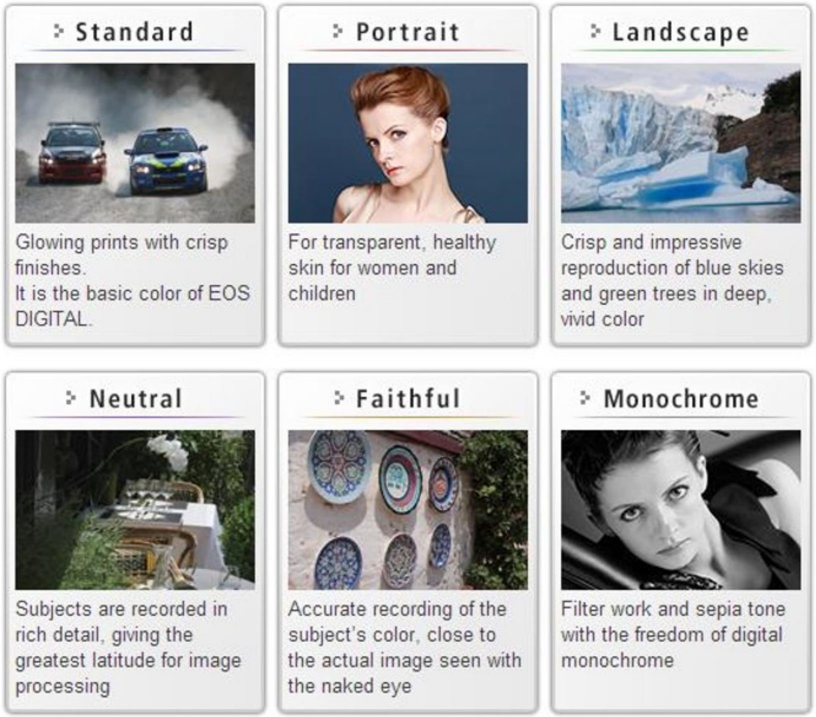
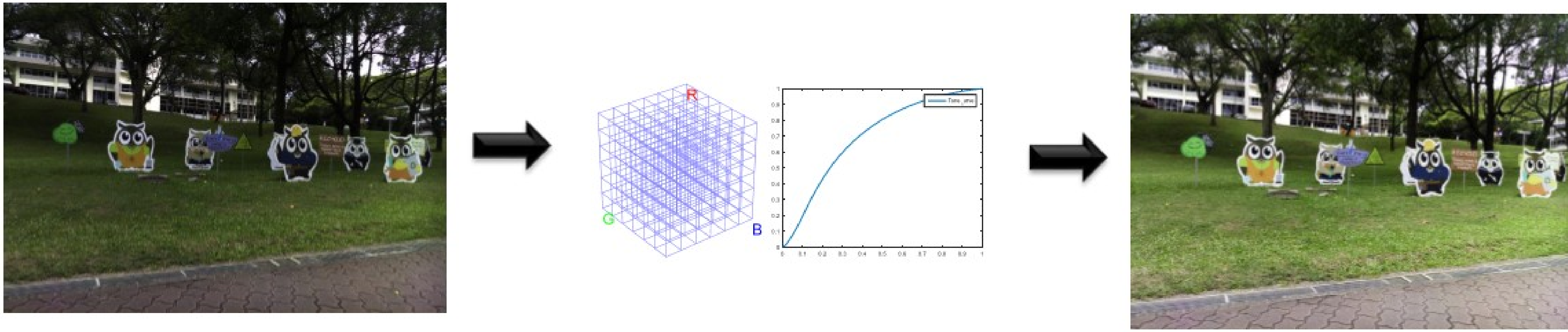
Color Manipulation: Photo finishing



From Canon's user manual

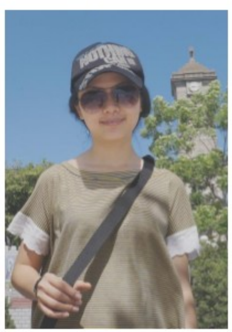
Example of four different picture styles from Nikon
This image is the **same** raw-RGB image processed in four different ways.

Color Manipulation: Nonlinear Tone Curves

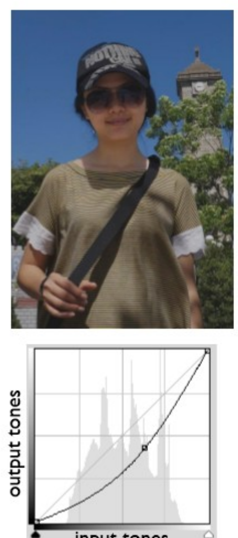


3D Look up table (LUT)

1D Tone Curve

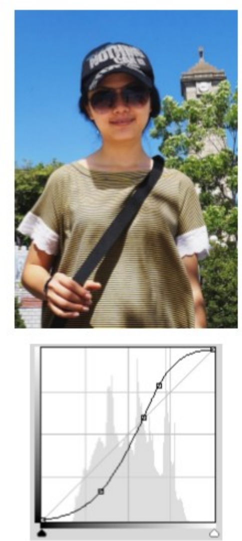


Input



Darkening the image

Brightening the image



Enhancing contrast (called an S-curve)

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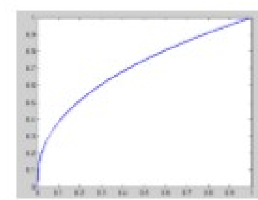
Map from XYZ to sRGB

Photo-finished CIE XYZ

Covert to linear sRGB

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} 3.2404542 & -1.5371385 & 0.4985314 \\ -0.9692660 & 1.8760108 & 0.0415560 \\ 0.0556434 & -0.2040259 & 1.0572252 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}$$

Apply sRGB gamma



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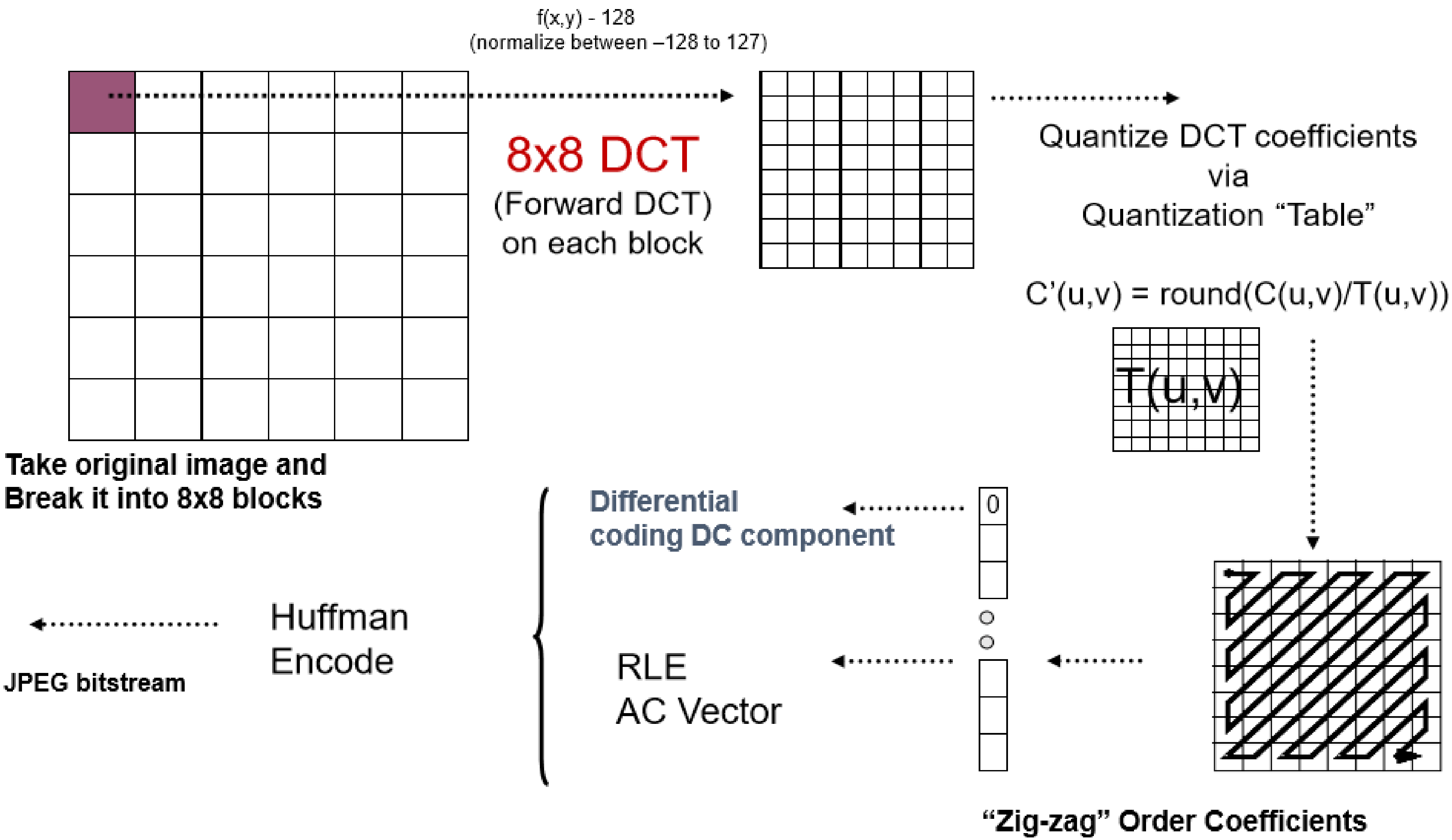
JPEG compression to store in a file



JPEG applies almost every compression trick known.
1) Transform coding, 2) psychovisual (loss), 3) Run-length-encoding (RLE), 4) Difference coding, and Huffman.

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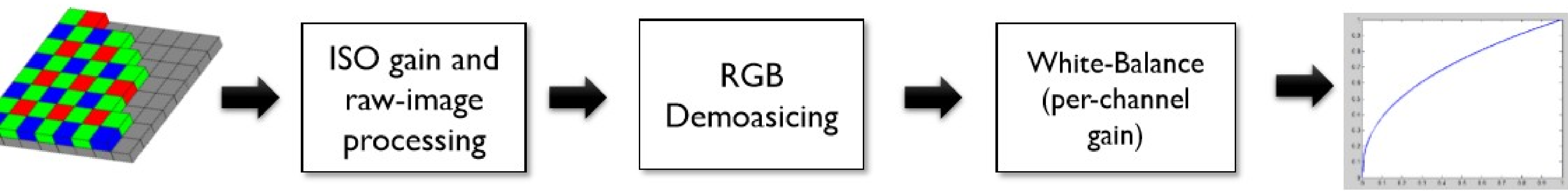
Typical Computer vision camera (non-consumer design)



Typical machine vision pipeline

Point grey grasshopper camera.

Advantages of Raw RGB image:

- It is linear with respect to the scene's physical light. This means the pixel values are related to the scene.

- Certain CV problems make this assumption e.g.
  1. Shape from shading
  2. Intrinsic image decomposition
  3. Image deblurring
- However, many times these problems are attempted in the sRGB space!

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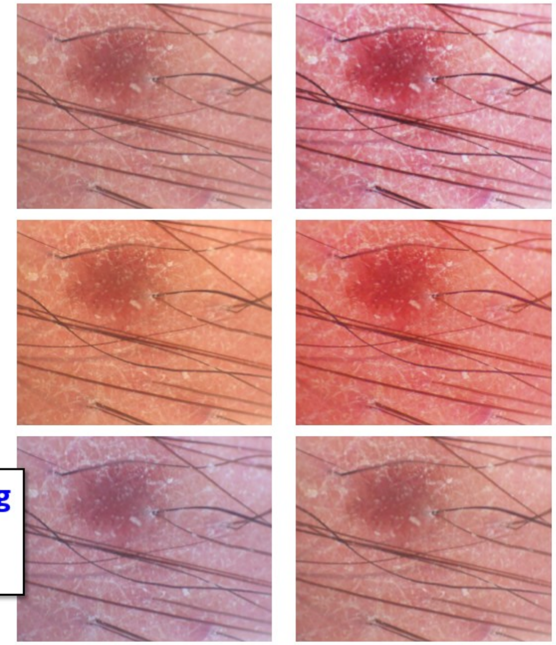
Addressing some misconceptions

- The colors you see in the image are the colors of the photograph NOT the colors of the scene!!

This assumption can led to serious mistakes in a computer vision application.



This type of processing is not suitable for scientific applications!

Which one is correct?

- Intensity Image: rgb2gray(Img) $Y = 0.299R + 0.587G + 0.114B$.

Some papers claim that applying this is recovering the scene luminance! It's not. You need to account for the photometric process.

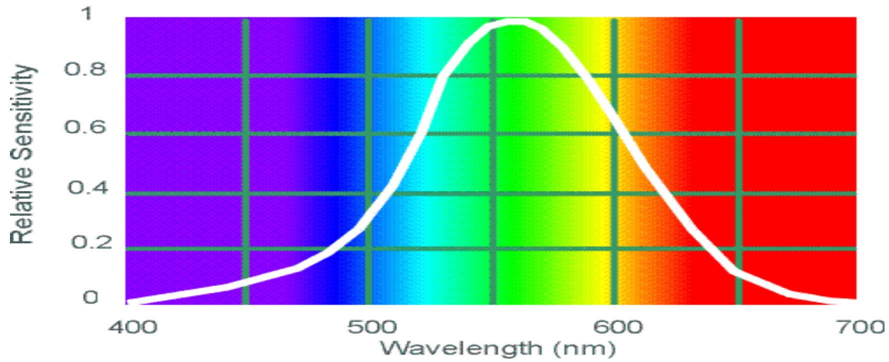
M. Brown

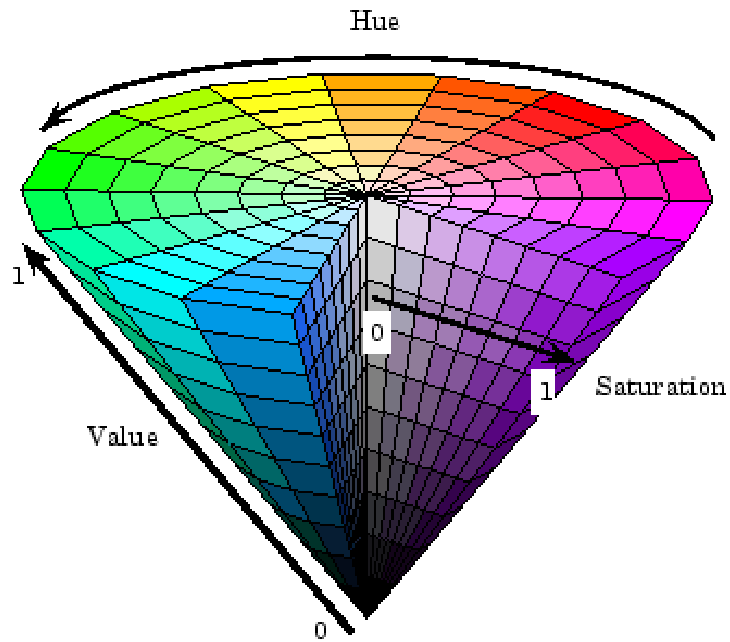
More references

- https://www.colorsystem.com/

- A description of many different color systems developed through history.
- Navigate from the right-hand links.

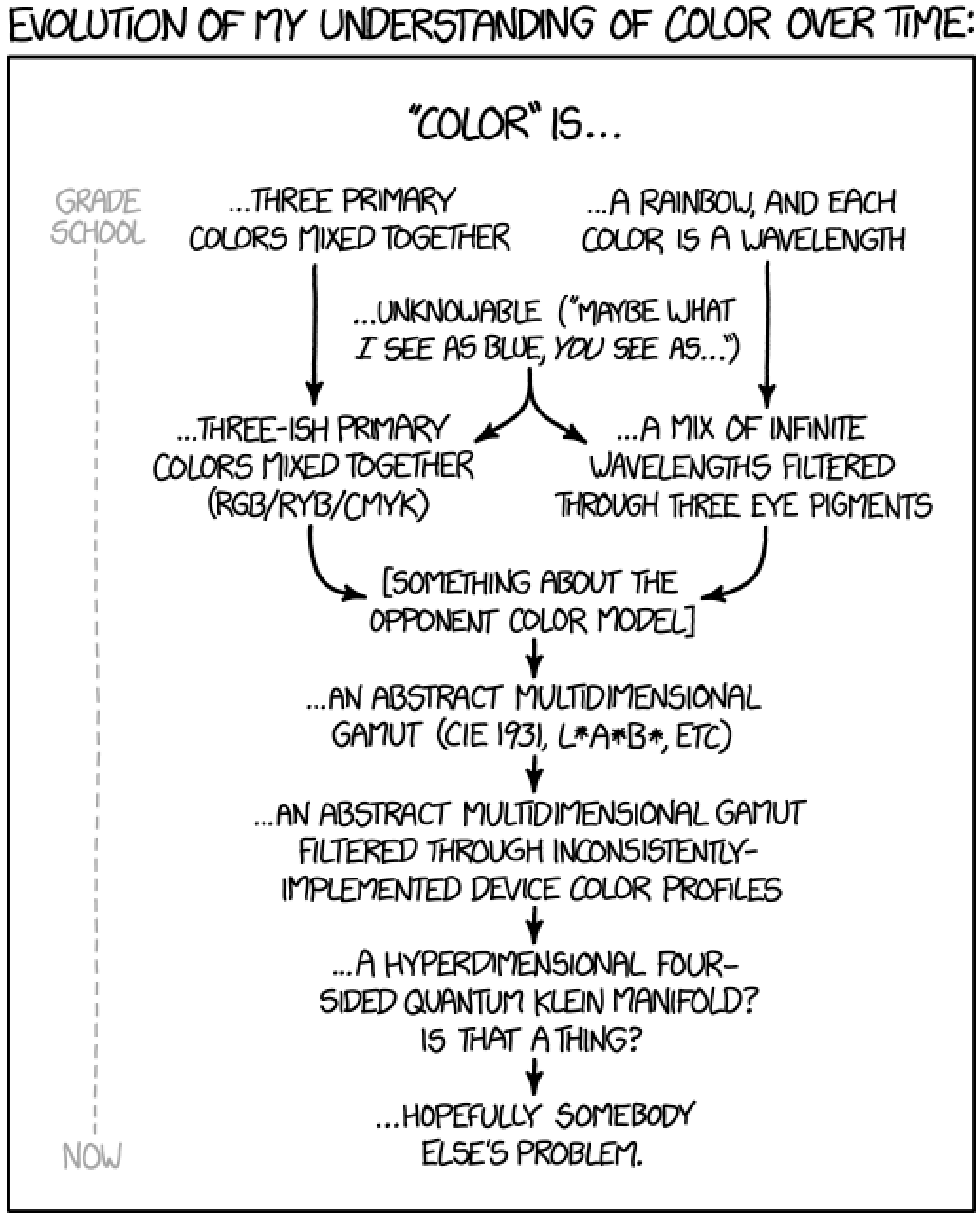
“Intuitive” color space?





Wait a minute...

WHY DOES COLOR LOOK LIKE IT MAPS SMOOTHLY TO A CIRCLE?


EVOLUTION OF MY UNDERSTANDING OF COLOR OVER TIME:
"COLOR" IS...
GRADE SCHOOL
...THREE PRIMARY COLORS MIXED TOGETHER
...A RAINBOW, AND EACH COLOR IS A WAVELENGTH
...UNKNOWABLE ("MAYBE WHAT I SEE AS BLUE, YOU SEE AS...")
...THREE-ISH PRIMARY COLORS MIXED TOGETHER (RGB/RYB/CMYK)
...A MIX OF INFINITE WAVELENGTHS FILTERED THROUGH THREE EYE PIGMENTS
[SOMETHING ABOUT THE OPPONENT COLOR MODEL]
...AN ABSTRACT MULTIDIMENSIONAL GAMUT (CIE 1931, L*A*B*, ETC)
...AN ABSTRACT MULTIDIMENSIONAL GAMUT FILTERED THROUGH INCONSISTENTLY-IMPLEMENTED DEVICE COLOR PROFILES
...A HYPERDIMENSIONAL FOUR-SIDED QUANTUM KLEIN MANIFOLD? IS THAT A THING?
...HOPEFULLY SOMEBODY ELSE'S PROBLEM.
NOW

XKCD