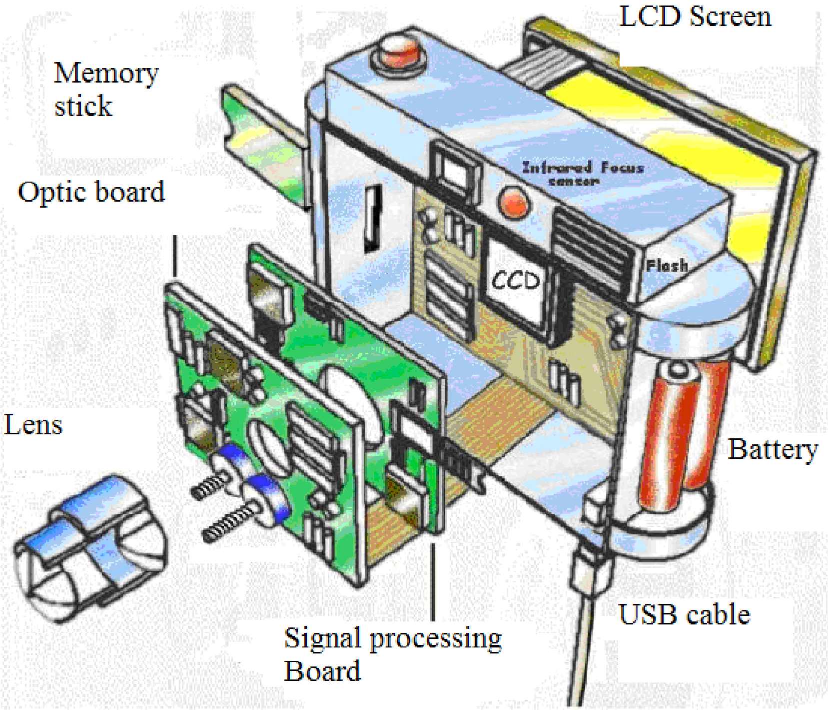
Digital Camera

How digital camera works

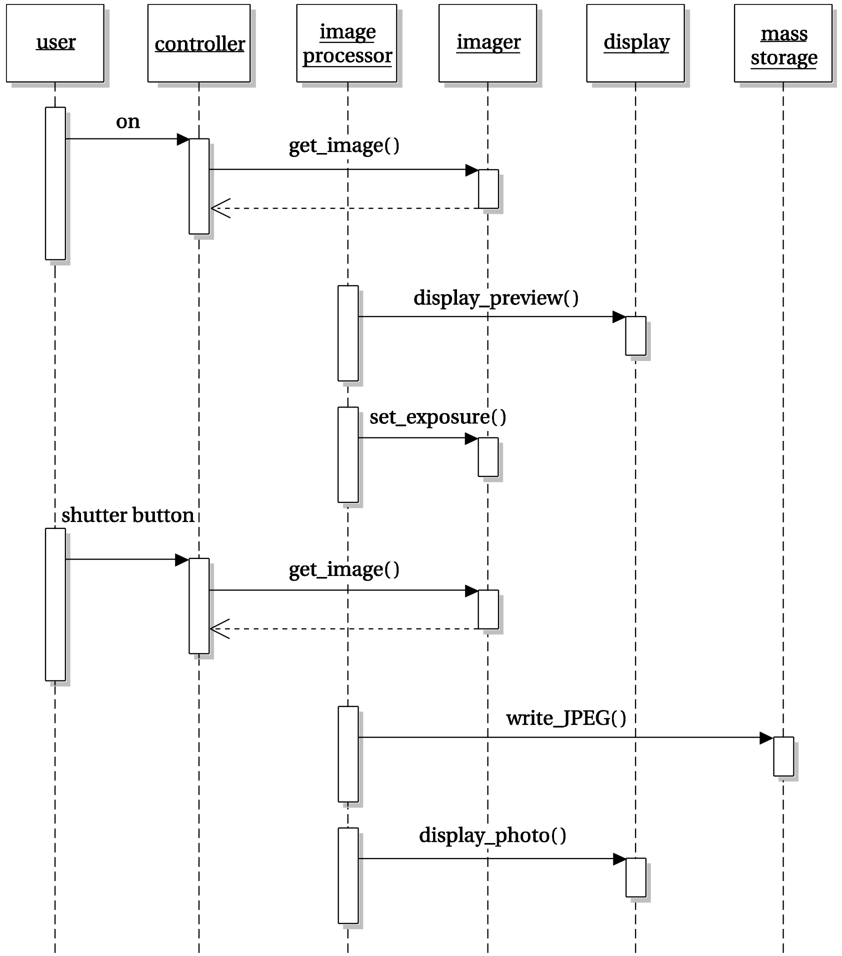
Introduction

- Digital cameras are very much like the still more familiar 35mm film cameras. Both contain a lens, an aperture, and a shutter. The lens brings light from the scene into focus inside the camera so it can expose an image. The aperture is a hole that can be made smaller or larger to control the amount of light entering the camera. The shutter is a device that can be opened or closed to control the length of time the light enters.



Digital still cameras

- DSC must determine exposure before taking picture.
- After taking picture:
  - Improve image quality.
  - Compress.
  - Save as file.



Digital still camera architecture

- DSC uses CPU for general-purpose processing, DSP for image processing.
- Internal memory buffers the passes on the image.
- Display is lower resolution than image sensor.
  - Image must be downsampled.

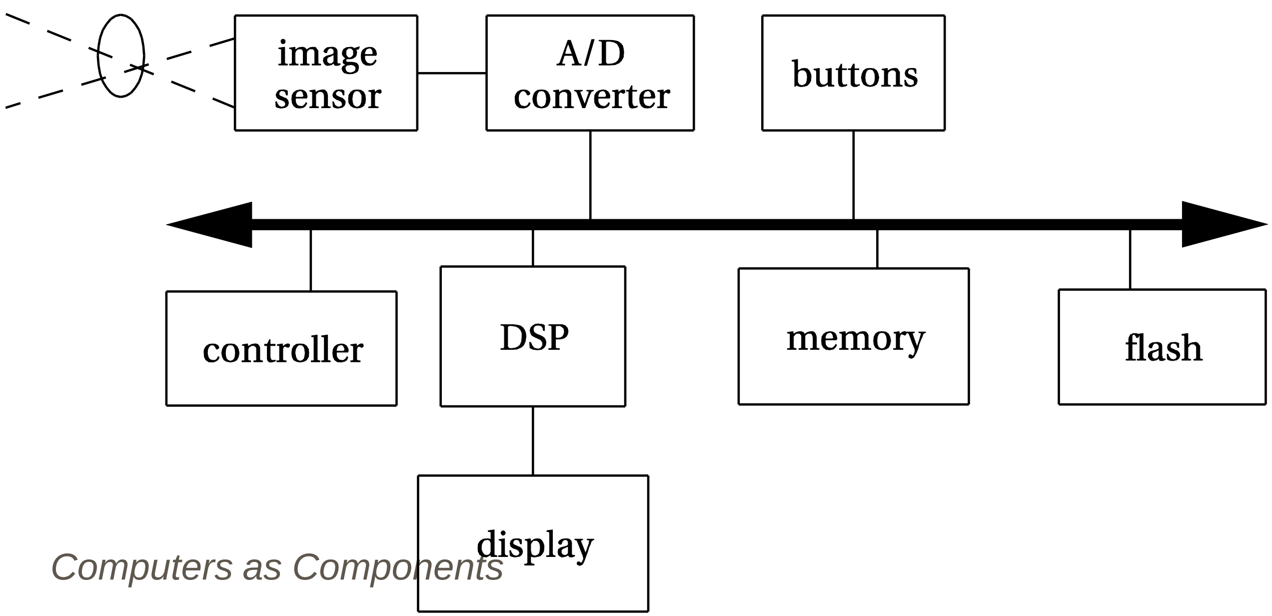


Image processing

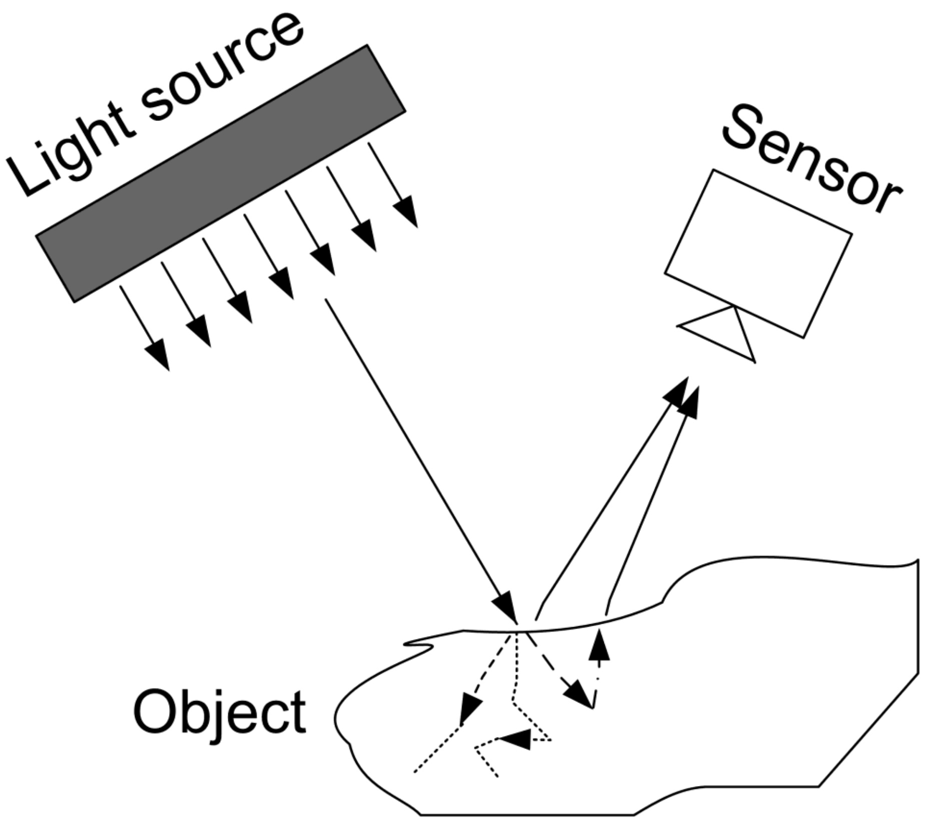
- Must perform basic processing to get usable picture:
  - Bayer->RGB interpolation.
- DSCs perform many functions formerly performed by photoprocessors for film:
  - Image sharpening.
  - Color balance.

Digital colors

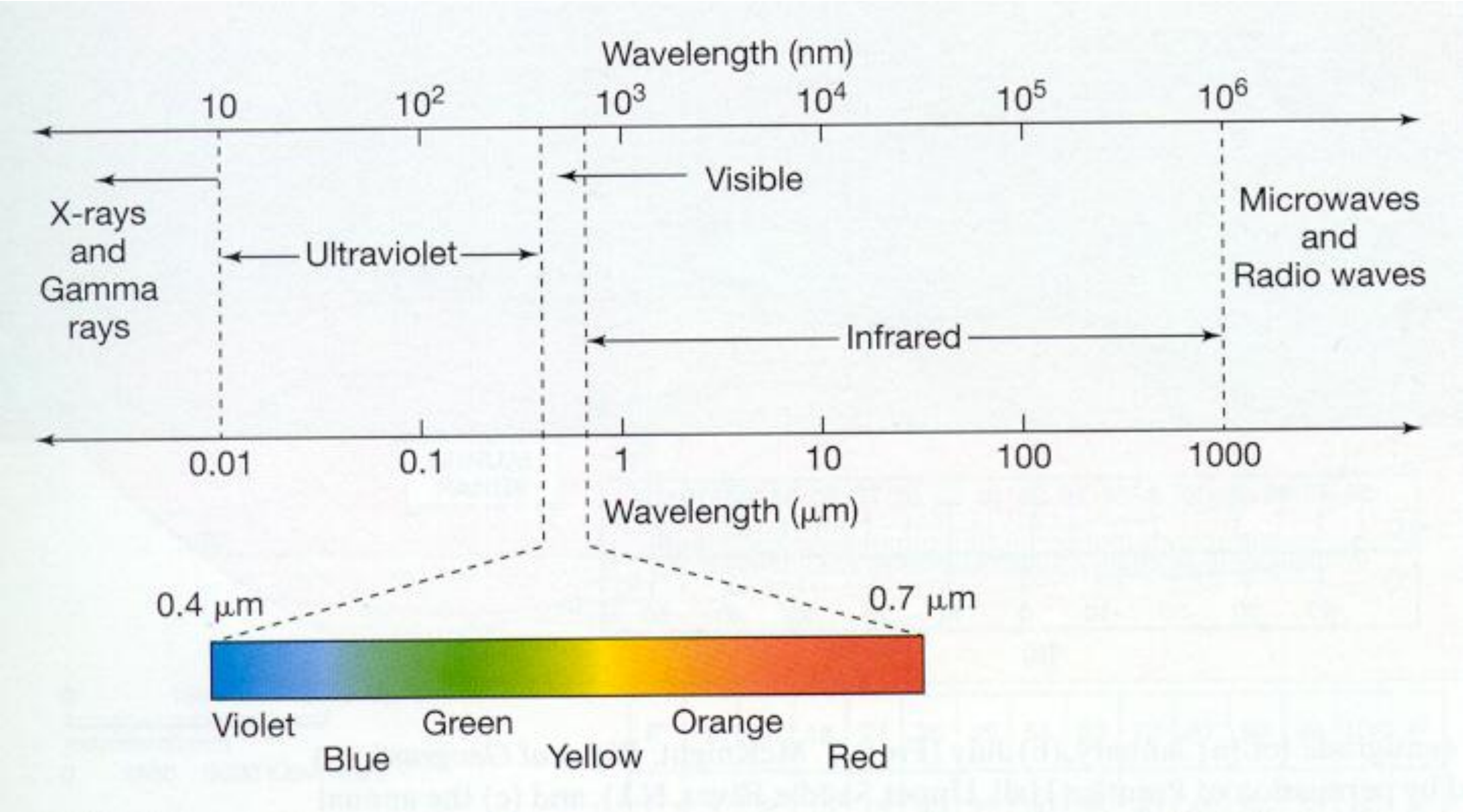
- What are digital colors ?
- What are color spaces ?
- Why do we have different color spaces?

What are Colors?

- The colors that humans and cameras perceive are determined by the nature of the light reflected from an object!
- Green objects reflect "green" light!



Spectrum



Wavelength (nm)
10
10^2
10^3
10^4
10^5
10^6
Visible
X-rays and Gamma rays
Ultraviolet
Microwaves and Radio waves
Infrared
0.01
0.1
1
10
100
1000
Wavelength (µm)
0.4 µm
0.7 µm
Violet
Blue
Green
Yellow
Orange
Red

Blackbody Radiation

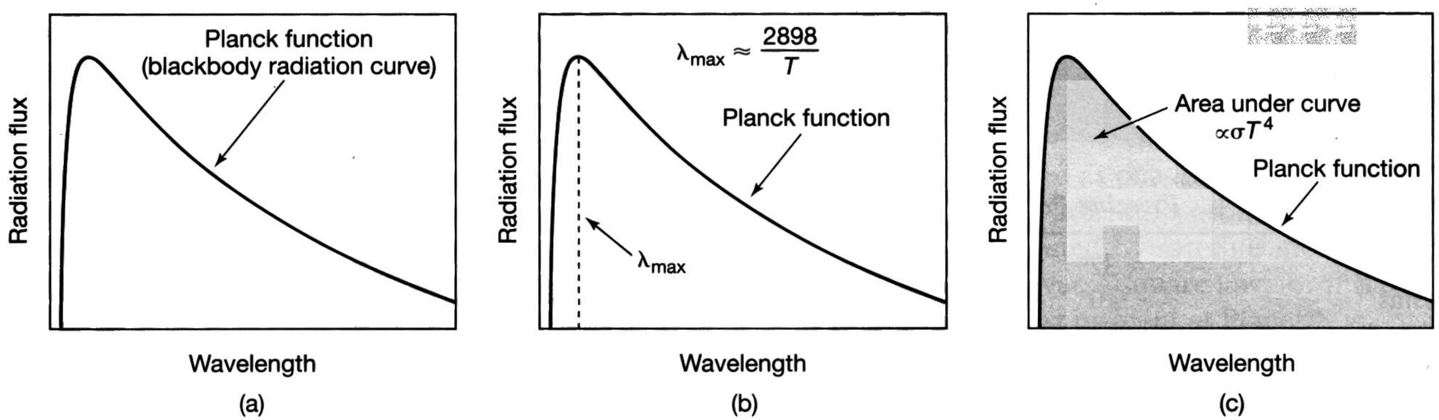


FIGURE 3-7
(a) The Planck function, or blackbody radiation curve; (b) Wien's law; (c) the Stefan–Boltzmann law.

Blackbody radiation—radiation emitted by a body that emits (or absorbs) equally well at all wavelengths

Basic laws of Radiation

- Wien's Law

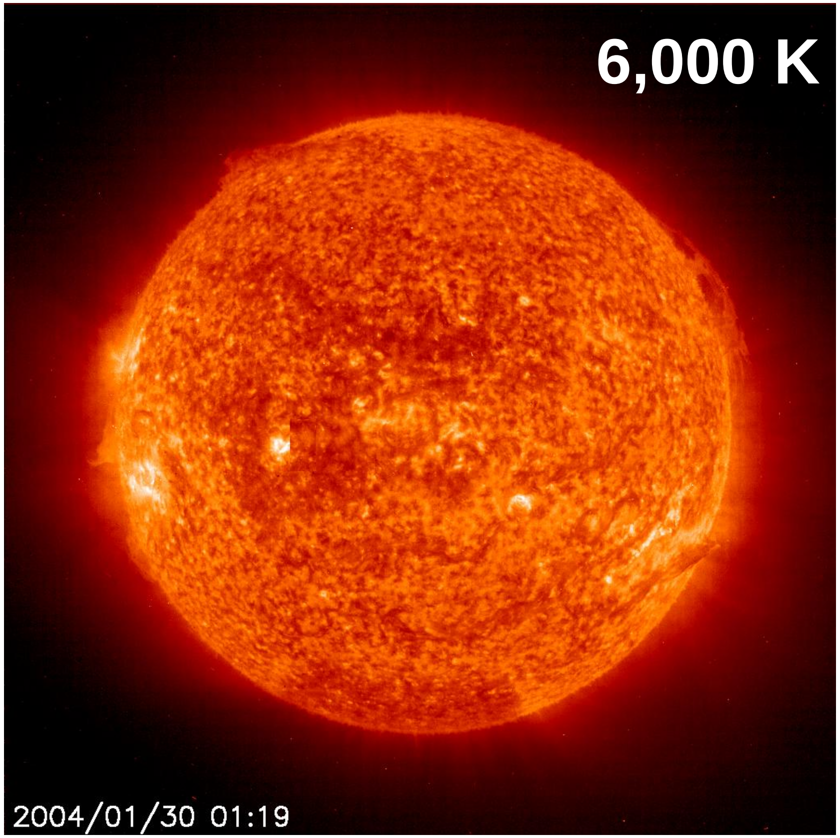
$$\lambda_{max} \cong \frac{3000\ \mu m}{T(K)}$$

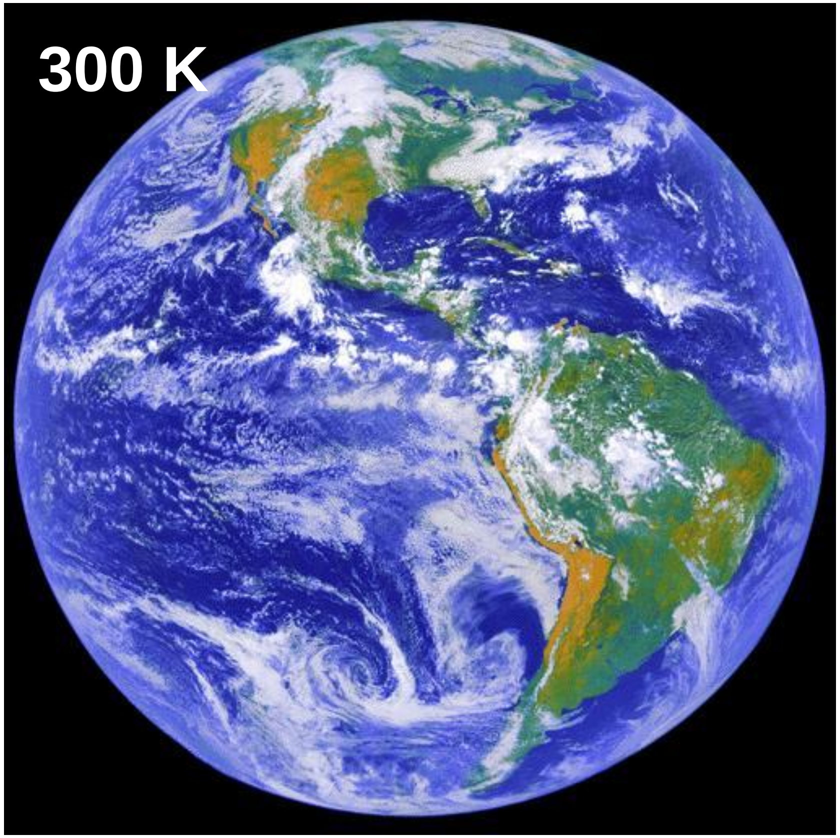
- Stefan Boltzman Law.

$$F = \sigma T^4$$

F = flux of energy (W/m^2)
T = temperature (K)
$\sigma = 5.67 \times 10^{-8}\ W/m^2K^4$ (a constant)

Sun and Earth



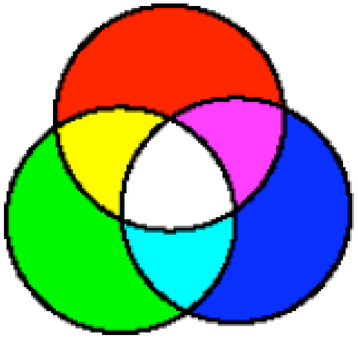


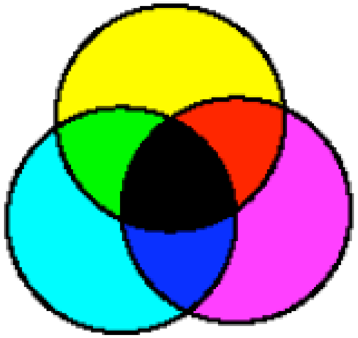
Sun and Earth

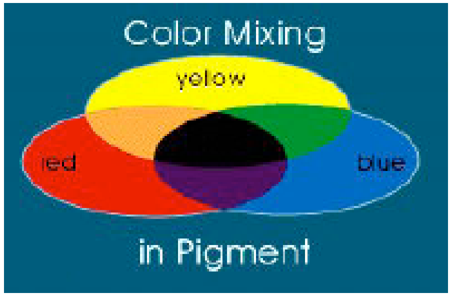
	T (K)	λ_{max} (μm)	region in spectrum	F (W/m^2)
Sun	6000	0.5	Visible (green)	7×10^7
Earth	300	10	infrared	460

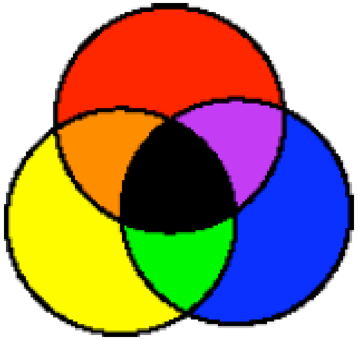
- Blue light from the Sun is removed from the beam by Rayleigh scattering, so the Sun appears yellow when viewed from Earth's surface even though its radiation peaks in the green

FOUR PRIMARY COLOR GROUPS









Additive colors are created with light. You project a red light through a red screen or on a monitor or television. The additive primaries are red, green and blue **(RGB).** If you combine red, green and blue light you get white.

Subtractive colors apply to print and pigment. In this case color exists because the pigment absorbs some light rays and reflects others. If we use red paint the pigment absorbs or subtracts all light rays other than red, which it reflects back to the eye. The subtractive primaries are magenta, yellow, cyan and black **(CMYK).** If you combine M, Y & C you get black.

Artist's primaries consist of red, yellow, and blue. From these primary colors the secondary colors **orange, green and purple** can be mixed from combinations of two primaries. The result when all three primaries are mixed is **black**

Psychological colors consist of red, yellow, blue, green and the achromatic pair, black and white. This is the group we were taught as children. All colors can be described verbally as a mixture o: these four psychological primaries.

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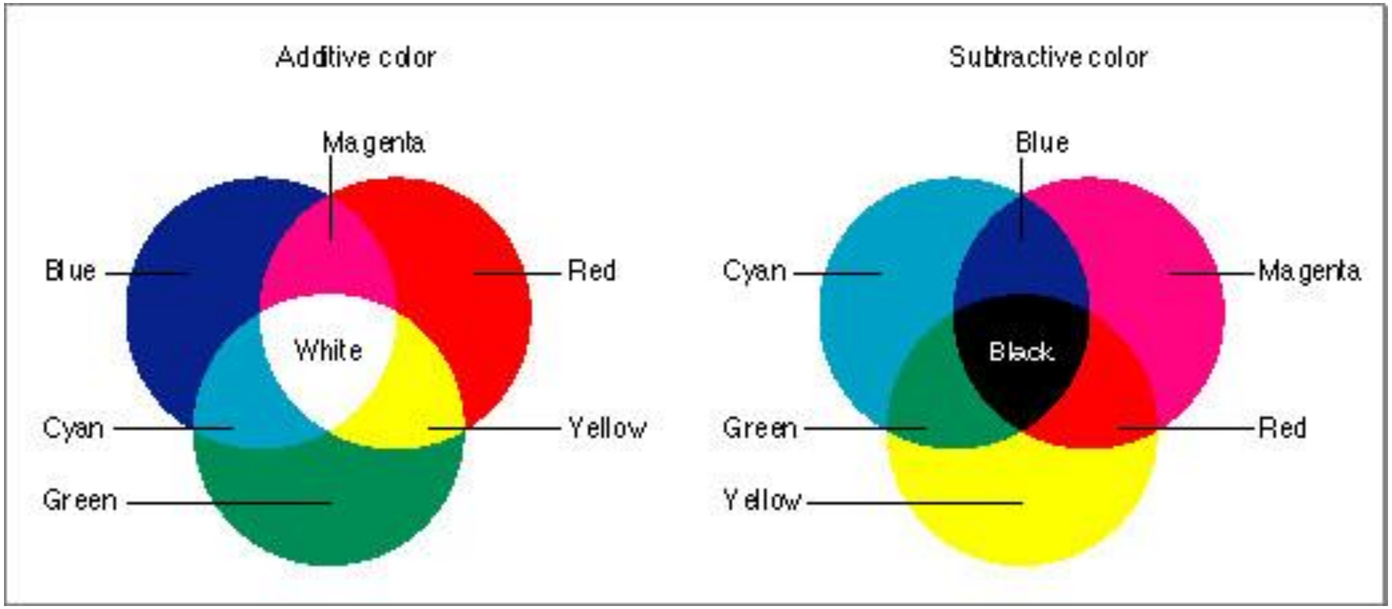
Additive/Subtractive Color

- **Additive Color (RGB)**: Sum of light of different wave lengths. That light reaches our eye directly.
  - Examples: TV, Multimedia Projector
- **Subtractive Color (CMY)**: White Color is emitted by the sun and is only partly reflected from an object!
  - Red paint absorbs red, but reflects others
  - Yellow paint absorbs blue, but reflects red and green
  - Examples: Paint

R+G+B=White? Black?

- So why don't we get white, when we use paint? *Subtractive Color!*
- But why does it work for the TV?

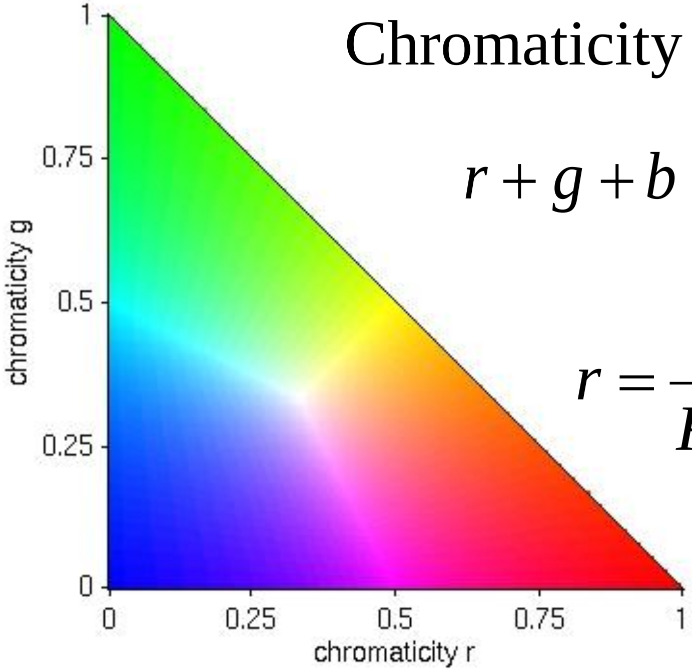
  Additive Color!



Red, Green, Blue

- R,G,B are called **Primary Colors**
- R,G,B where chosen due to the structure of the human eye
- R,G,B are used in cameras

Color and Intensity are mixed RGB to Chromaticities



Chromaticity Plane

$$r + g + b = 1$$

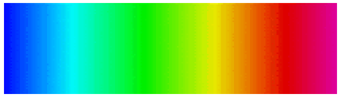
$$r = \frac{R}{R+G+B} \quad g = \frac{G}{R+G+B} \quad b = \frac{B}{R+G+B}$$

- Used in Computer Vision: normalised RGB

Another way of separating color and intensity: HSI

- H=Hue S=Saturation I=intensity

- H and S may characterize a color: **Chromaticities**
- **Hue**: associated with the dominant wavelength in the mixture of light waves, as perceived by an observer.



  – Hue is color attribute that describes a pure color
- **Saturation**: relative purity; inverse of the amount of white light mixed with hue

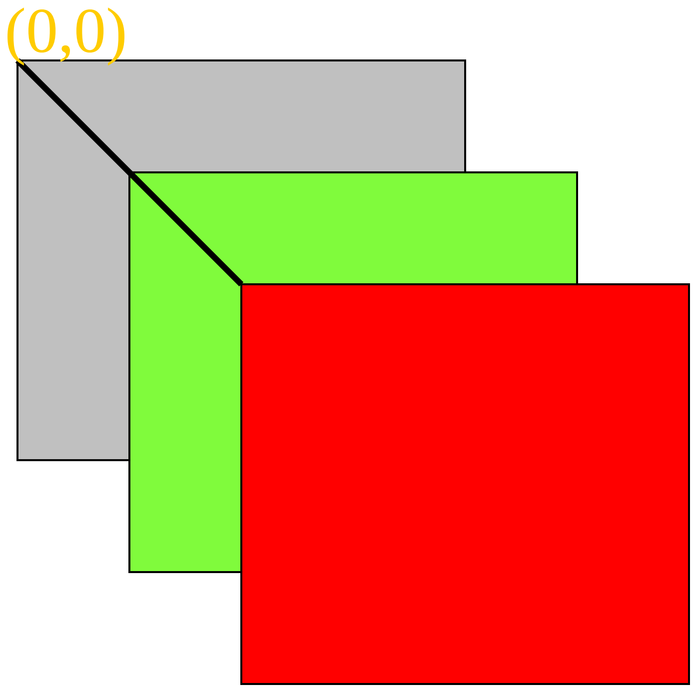
  – **Example:** Pure colors are fully saturated. Not saturated are for example pink (red+white)

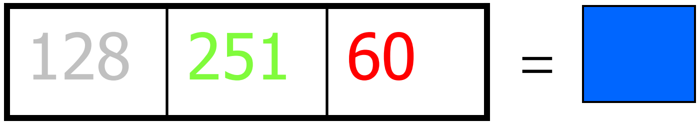
YUV Color Space

- YUV: used in commercial color TV broadcasting and video signals
- We need a format that decouples grayscale and color: HSI
- “Poor-man’s” HSI
  - Much easier to compute from RGB, than HSI

YUV Color Space

A single pixel consists of three components.
Each pixel is a **Vector**





Pixel-Vector in the computer memory

Final pixel in the image

Same Caution as before applies here!

Example YUV

Original Image

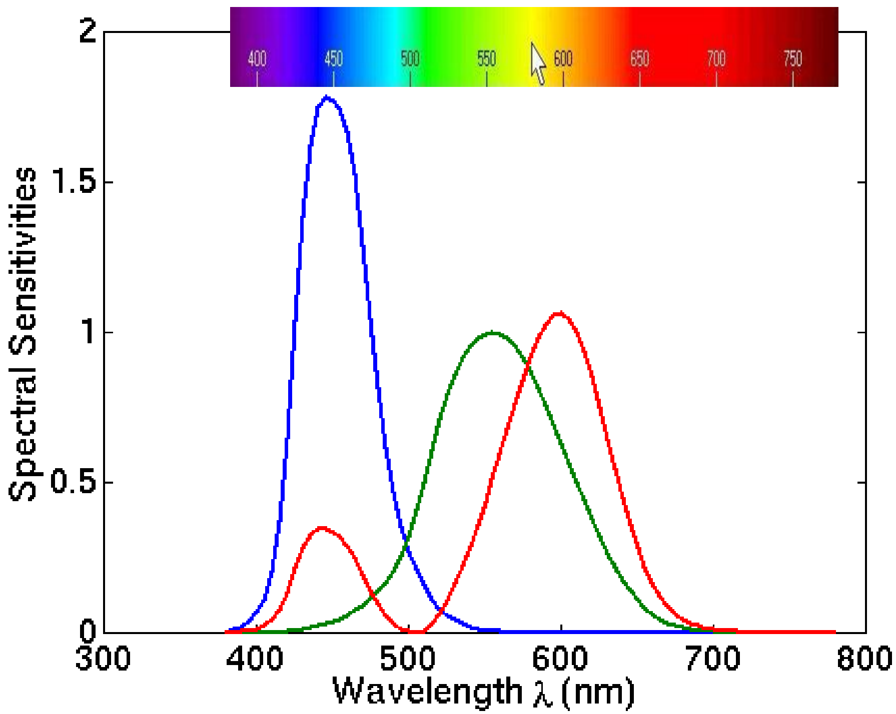
Intensity

U-Component

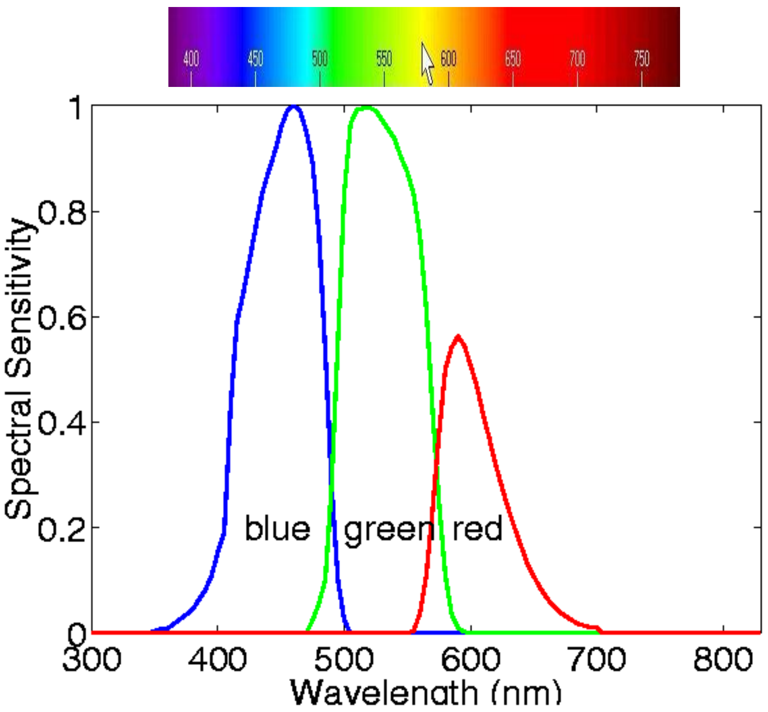
V-Component

Observer/Sensor

Eye Response



Camera Response



⇒ Reflected light spectrum is represented by a 3 element vector

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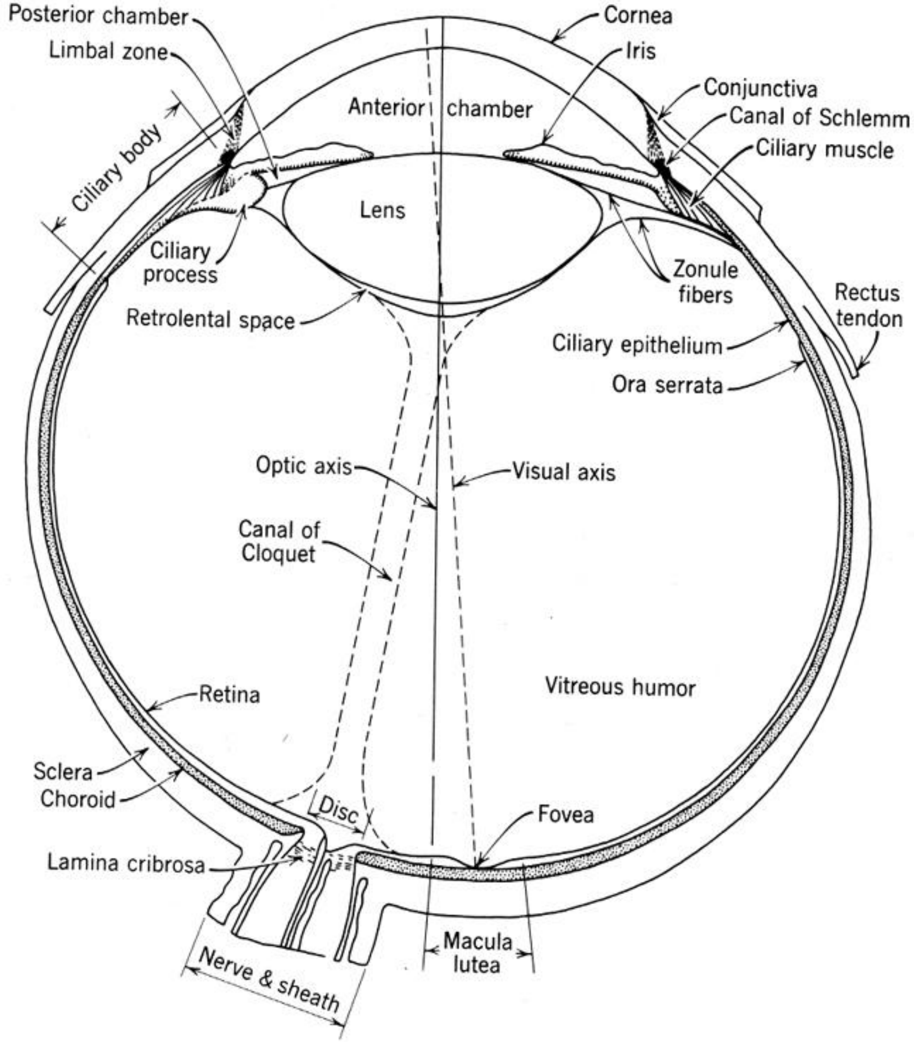
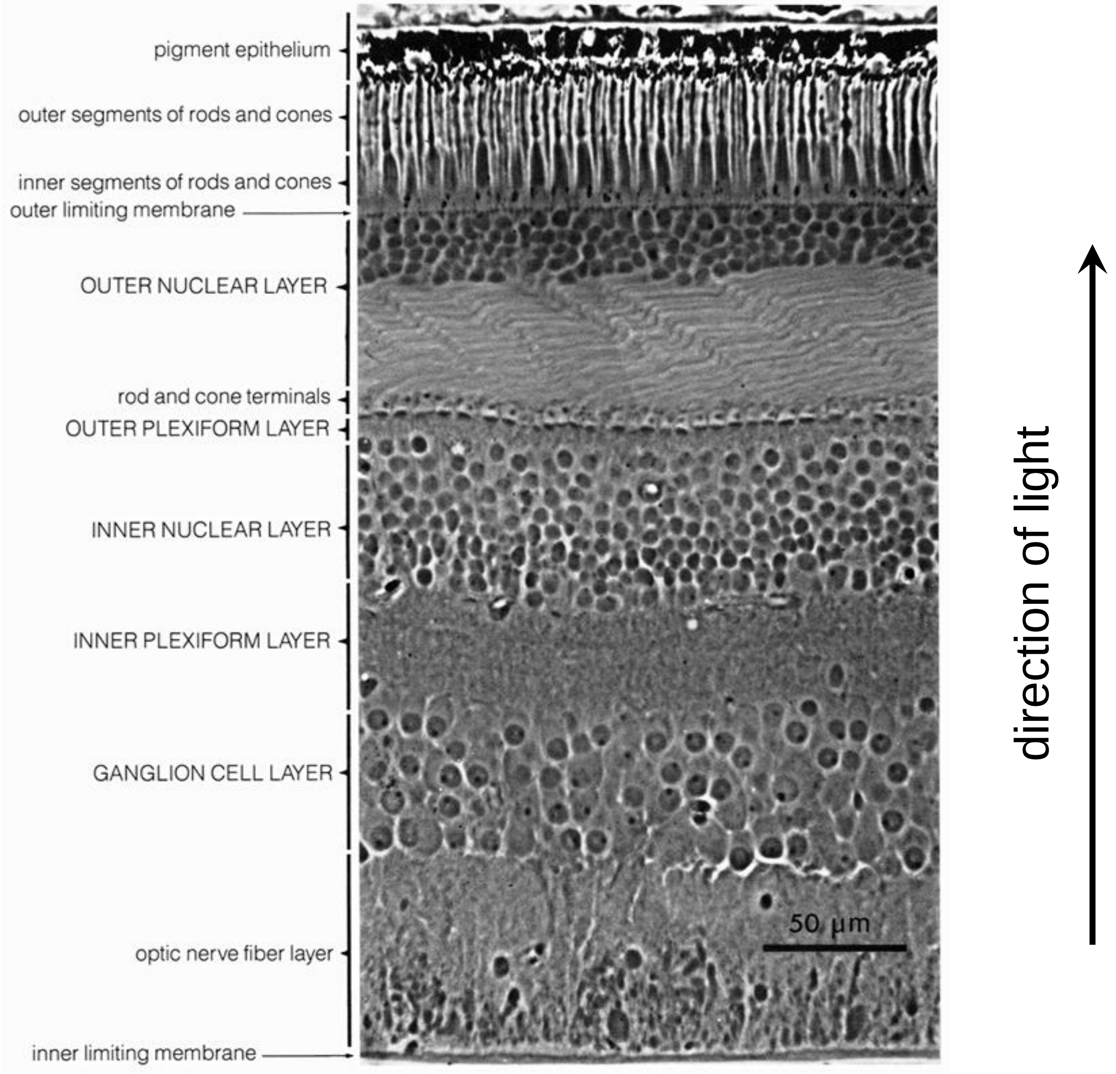
Human eye

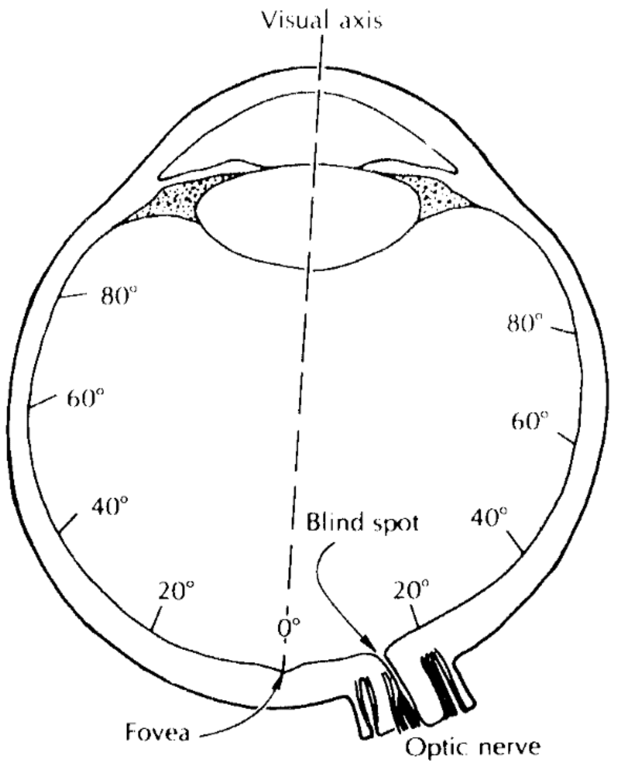


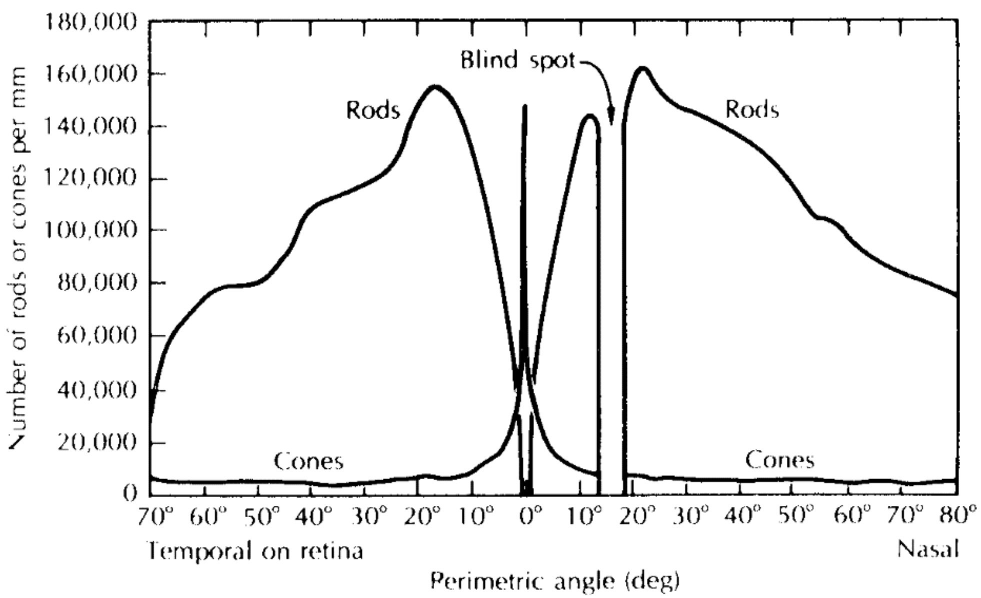
Posterior chamber
Limbal zone
Ciliary body
Anterior chamber
Cornea
Iris
Conjunctiva
Canal of Schlemm
Ciliary muscle
Lens
Ciliary process
Zonule fibers
Rectus tendon
Retrolental space
Ciliary epithelium
Ora serrata
Optic axis
Visual axis
Canal of Cloquet
Vitreous humor
Retina
Sclera
Choroid
Disc
Fovea
Lamina cribrosa
Macula lutea
Nerve & sheath

Cross section of human retina

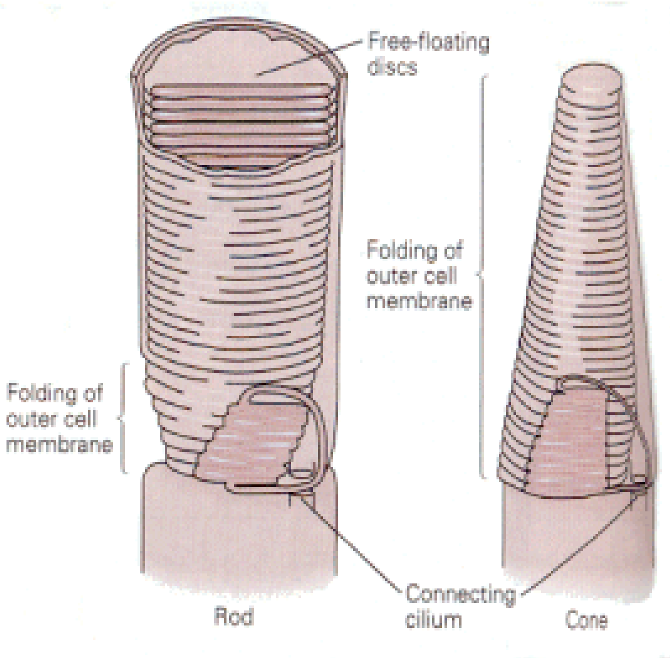


Cones and Rods



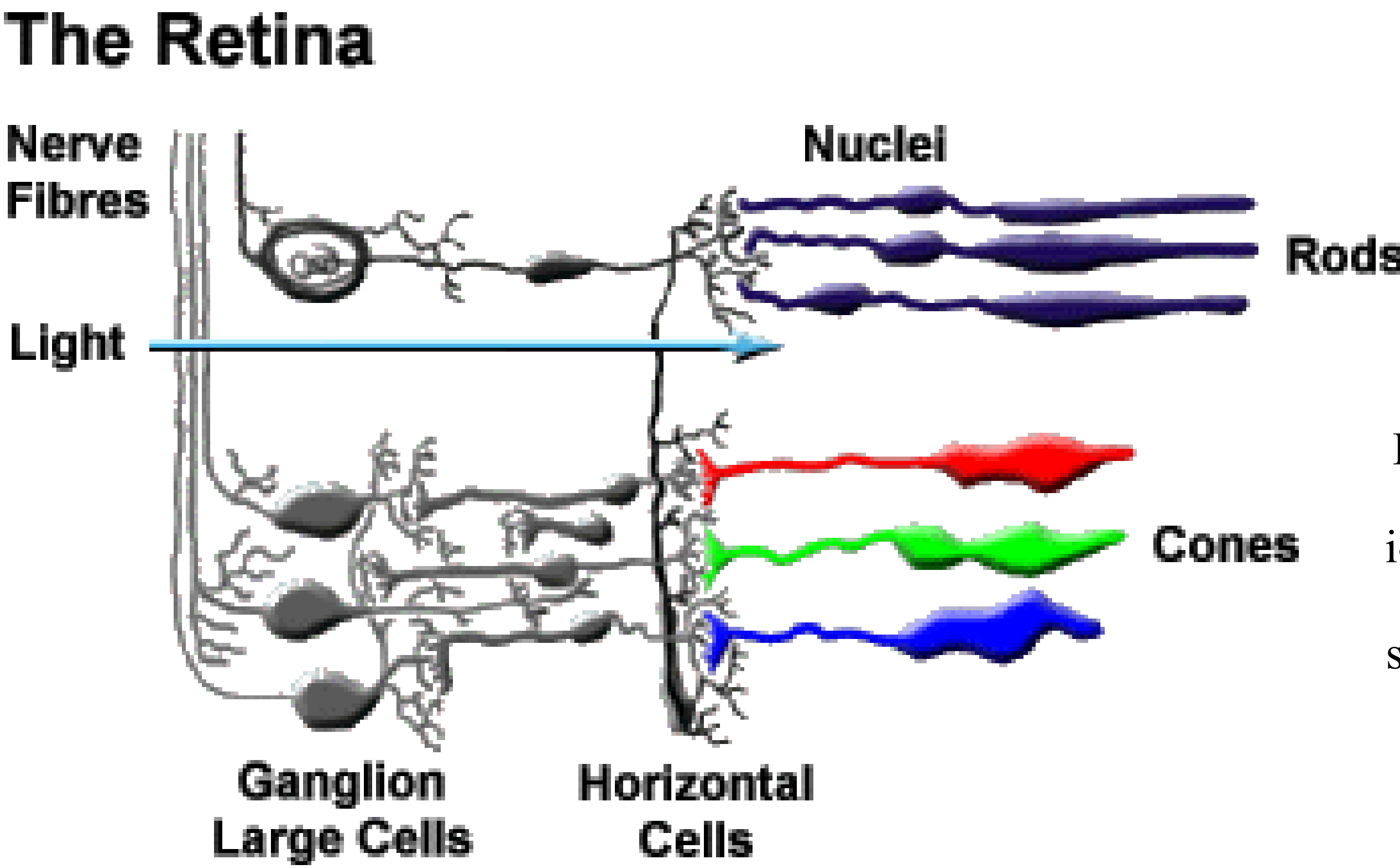


Rods and Cones



Rods	**Cones**
Achromatic: one type of pigment	Chromatic: three types of pigment
Slow response (long integration time)	Fast response (short integration time)
High amplification High sensitivity	Less amplification Lower absolute sensitivity
Low acuity	High acuity

Rods and Cones



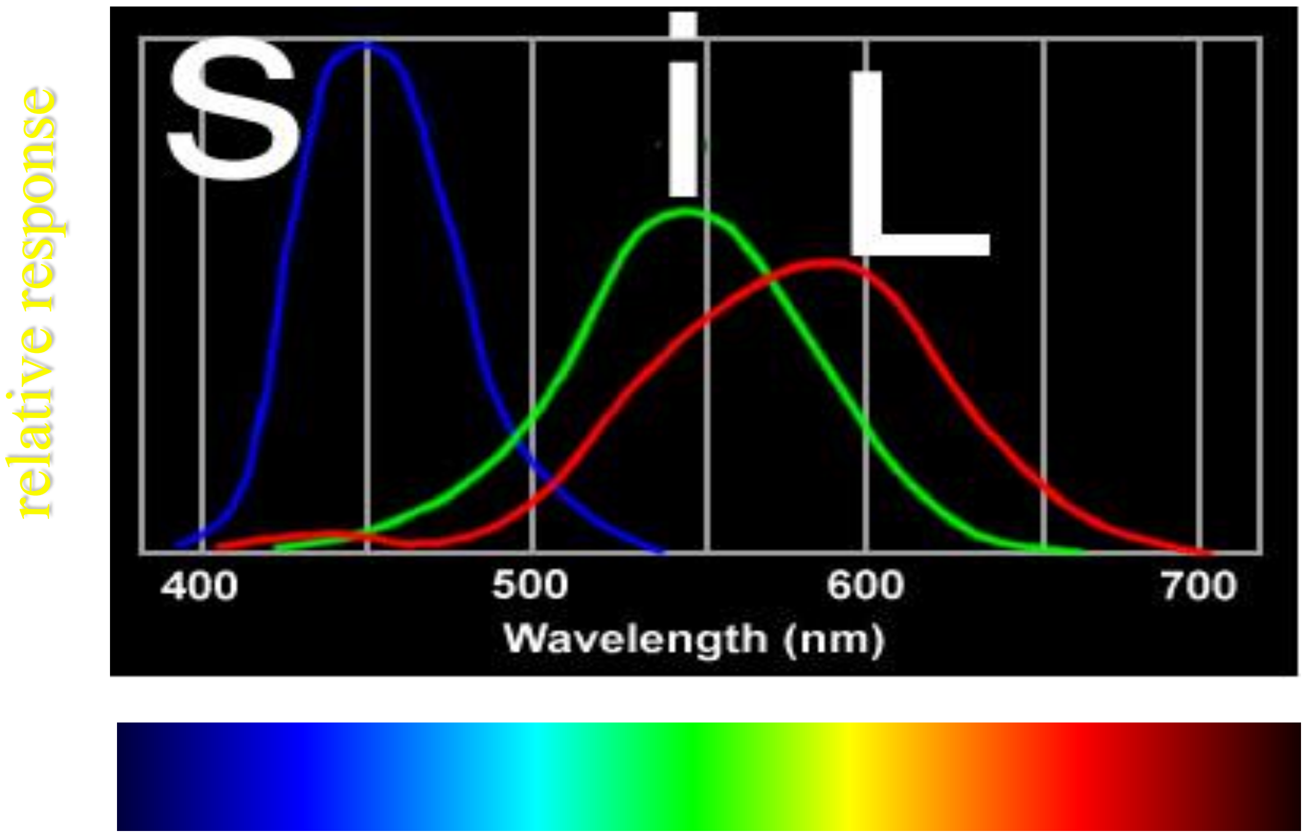
L-cones

i-cones

s-cones

Cone responses

Spectral *response of cones* in typical human eye



Cone responses

- *s-cones* absorb short wavelength light best, with peak response at 450 nm (blue)
- *i-cones* absorb intermediate wavelengths best, with peak response at 540 nm (green)
- *L-cones* absorb long wavelength light best, with peak response at 580 nm (red)

Cone responses

- Light at *any* wavelength in the visual spectrum from 400 to 700 nm will excite these 3 types of cones to a degree depending on the *intensity at each wavelength*.

- Our *perception* of which color we are seeing (*color sensation*) is determined by *how much s, i and L responses occur to light of a particular intensity distribution*.

Rule: To get the *overall response of each type of cone*, multiply the *intensity* of the light at each wavelength by the response of the cone at that wavelength and then add together all of the products for all of the wavenumbers in the intensity distribution.

Examples of two different ways we see white

Light color	Brightness	S-cone response	I-cone response	L-cone response
460 nm blue	1	60	5	2
575 nm yellow	1.66	0	1.66 x 33	1.66 x 35
Mixture (perceived as white)		60 + 0 = 60	5+1.66 x 33 = 60	2+1.66 x 35 = 60

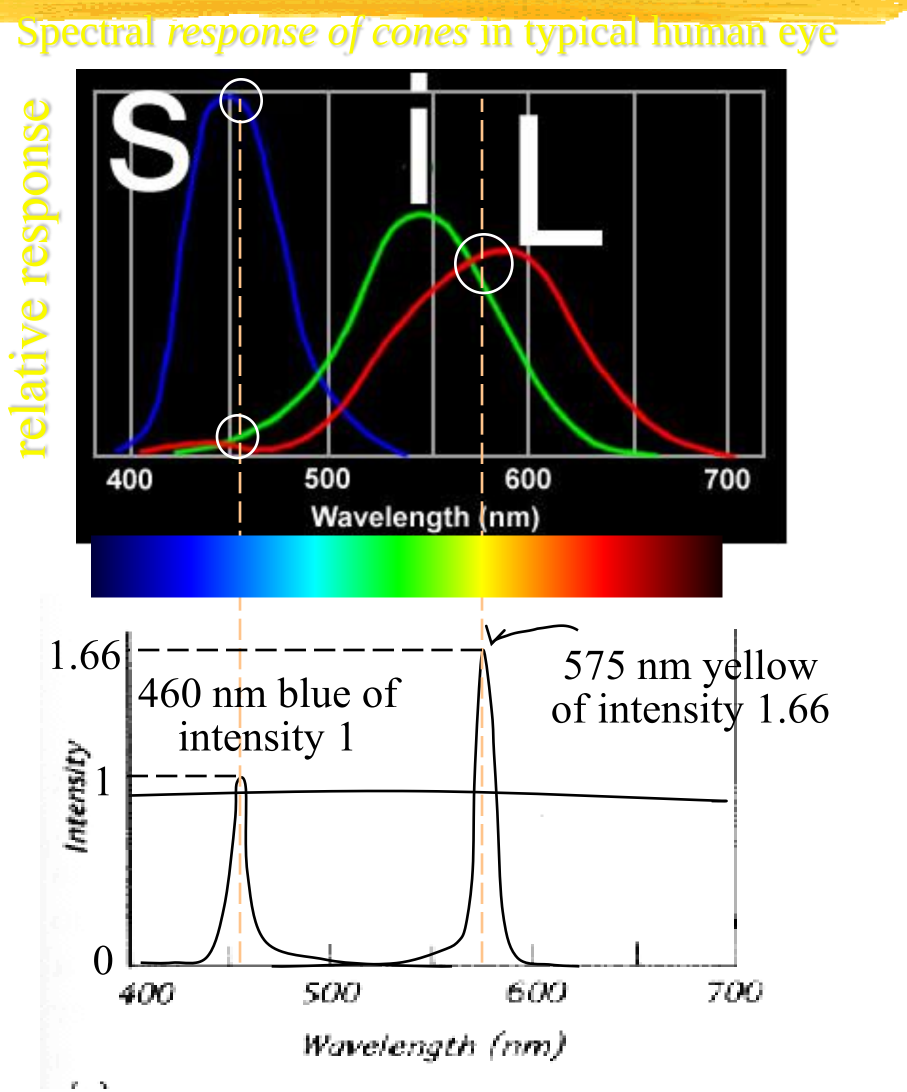
⌘Our *sensation* of color depends on how much *total S, i & L cone response* occurs due to a *light intensity-distribution*

⌘ *Multiply* the intensity distribution curve by each response curve to determine how much total S, i, and L response occurs

- E.g., 460 nm blue of intensity 1 and 575 nm yellow of intensity 1.66

Examples of two different ways we see white

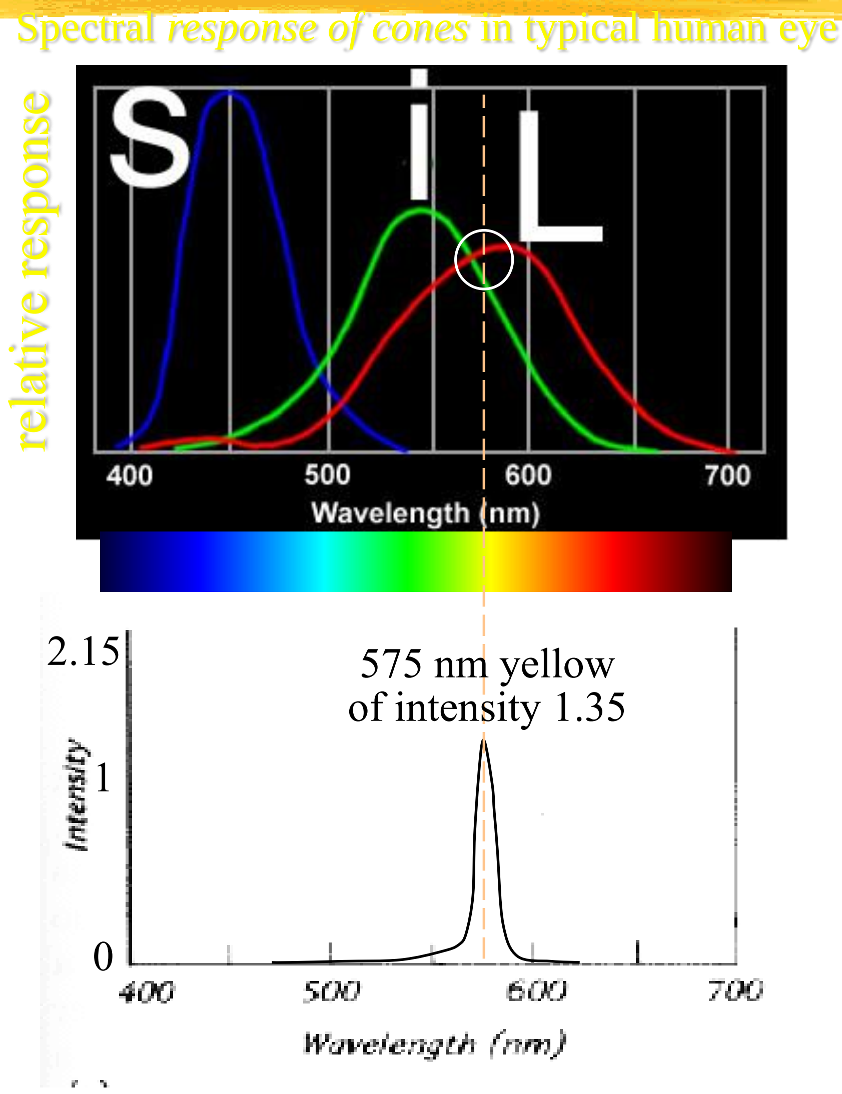
- We experience the sensation *white* when we have *equal* total S, i & L responses
- The blue excites mainly s-cones but also a bit of i-cones and a bit of L-cones
- The yellow excites i-cones and (slightly more) L-cones but no S-cones
- The result is an *equal response* of s-cones, i-cones and L-cones (details)



A normal person see yellow

- ⌘We also experience the sensation *yellow* when 575 nm light reaches our eyes

- ⌘What really gives us the sensation of *yellow* is the almost equal response of *i and L cones* together with *no* s-cones.

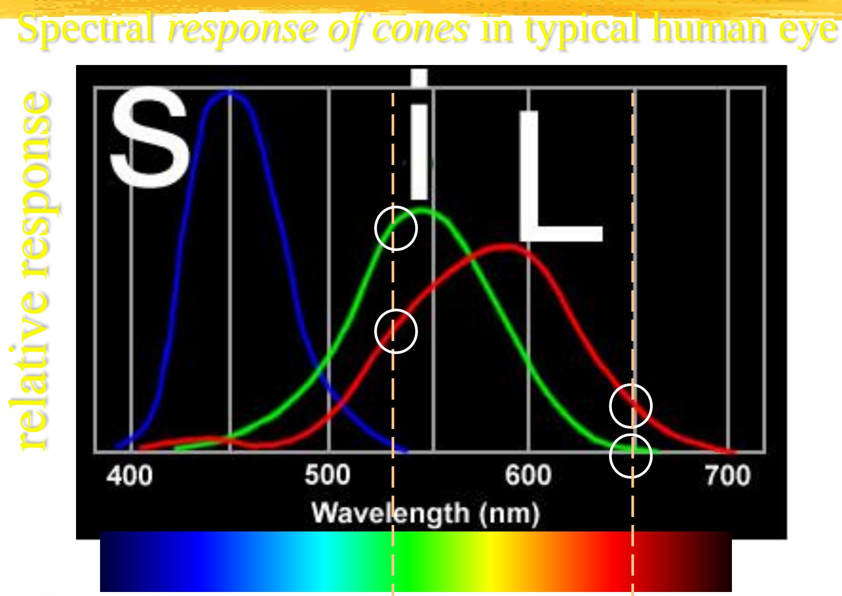


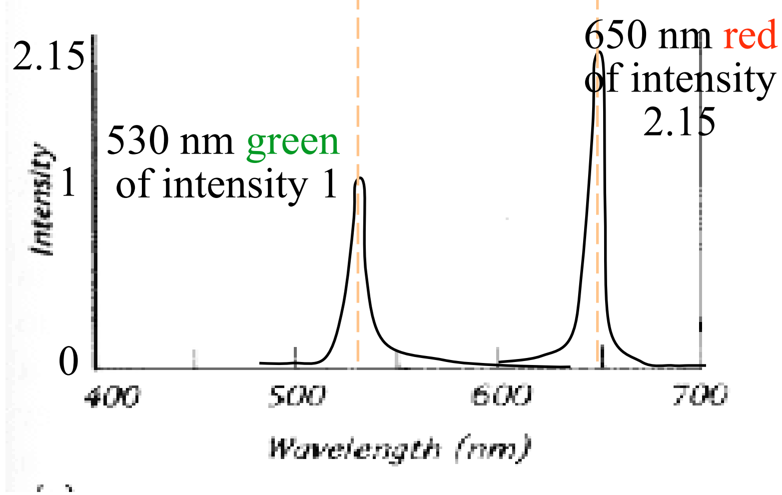
When only red and green lights are superimposed

Light color	Brightness	S-cone response	I-cone response	L-cone response
530 nm green	1	negligible	41	28
650 nm **red**	2.15	negligible	2.15 x 2	2.15 x 9
Mixture	(perceived as **yellow**)	negligible	41 +2.15 x 2 =45	28 +2.15 x 9 =47
575 nm yellow	1.35	negligible	1.35 x 33 = 45	1.35 x 35 = 47

When two lights are mixed

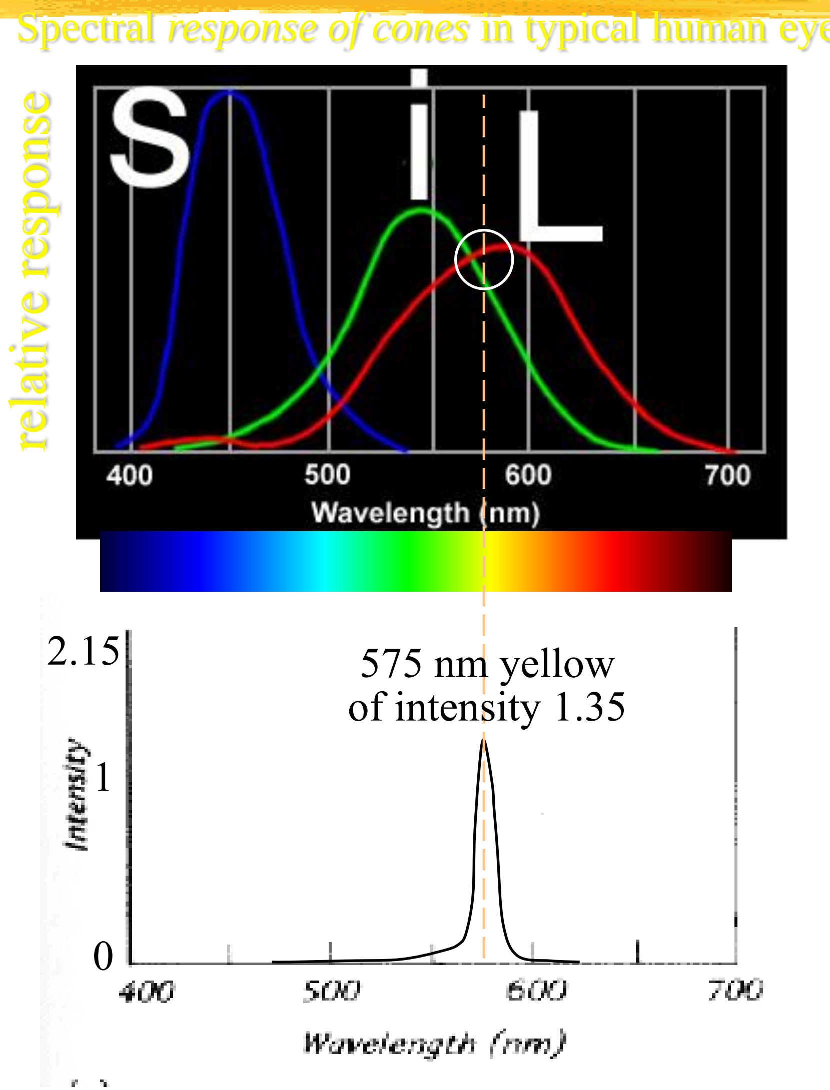
- 530 nm green of intensity 1 and 650 nm red of intensity 2.15
- The green excites mainly i-cones but also L-cones, while the red excites mainly L-cones but also i-cones
- The total respone of s & i-cones due to the spectral green and red is *the same as* the total response due to spectral yellow
- In general need 3 wavelength lights to mix to any color



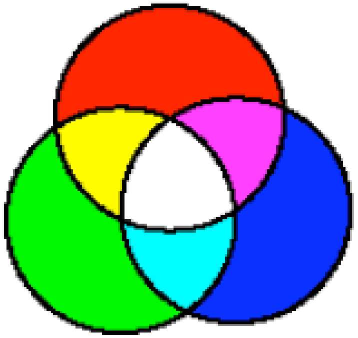


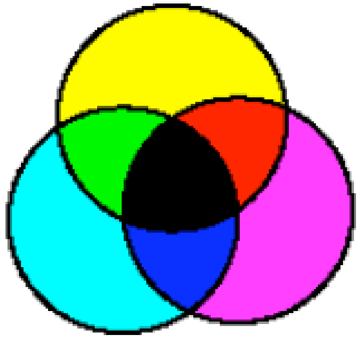
A normal person see it as yellow

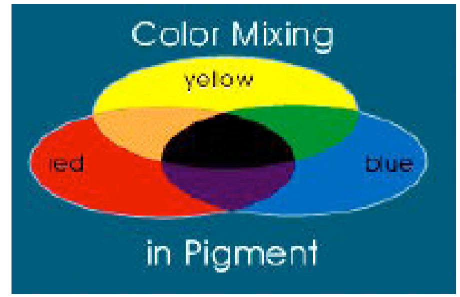
- We also experience the sensation *yellow* when 575 nm light reaches our eyes

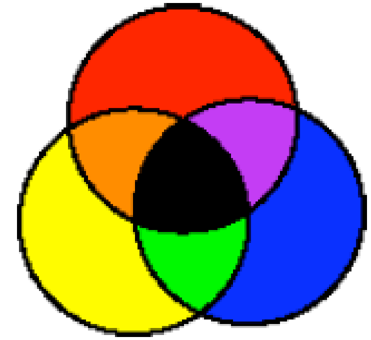


FOUR PRIMARY COLOR GROUPS









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Psychological colors consist of red, yellow, blue, green and the achromatic pair, black and white. This is the group we were taught as children. All colors can be described verbally as a mixture o: these four psychological primaries.

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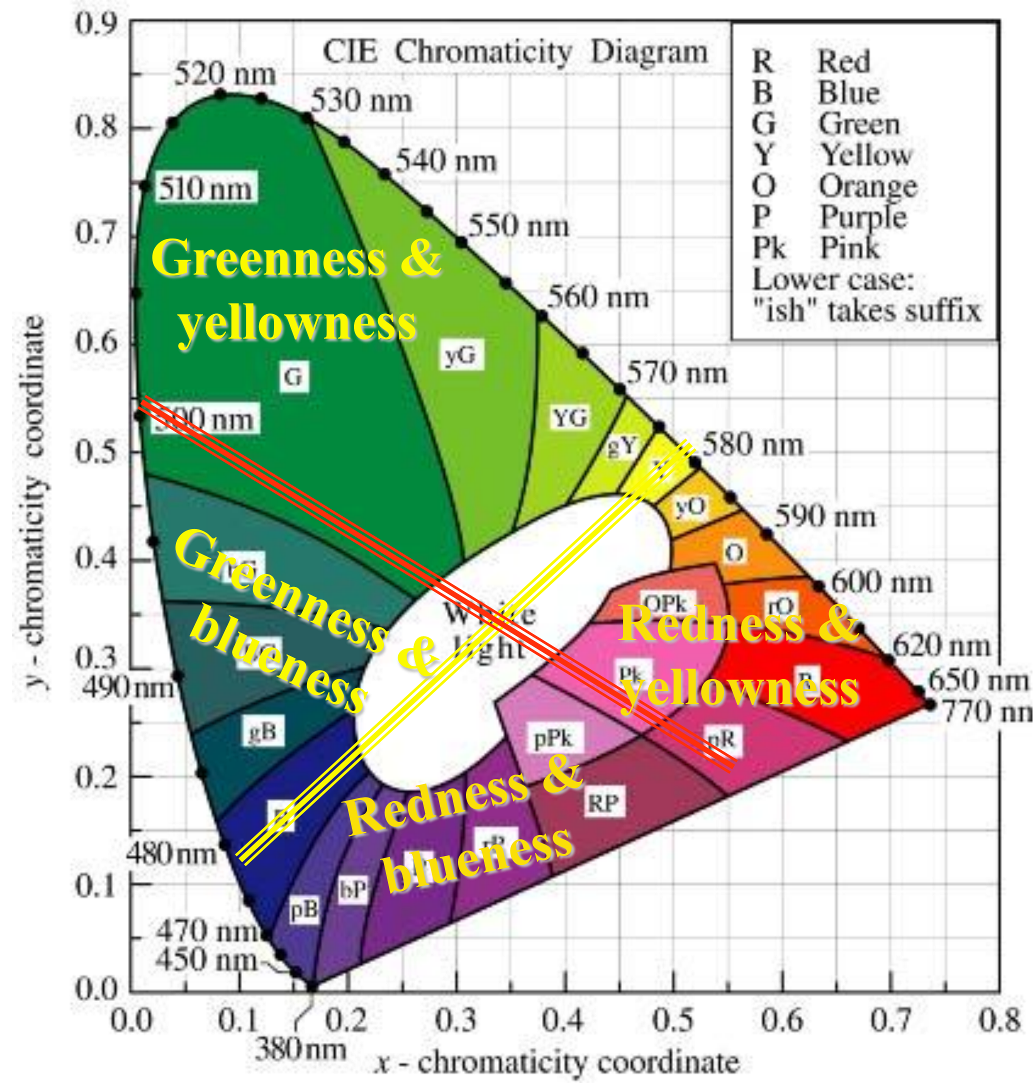
The four psychological primaries

- In addition to the additive primaries (RGB) and the subtractive primaries (CMY) there is another set of (4) primary colors, called the psychological primaries
  - Blue
  - Green
  - Yellow
  - Red (really closer to magenta)
- All *hues* can be *verbally described* as combinations of these colors. For example,
  - Yellowish red or green
  - Bluish green or red
- BUT we don't recognize hues (forbidden colors) such as
  - Reddish green
  - Yellowish blue
- *Opponent hues*
  - Red and green
  - Yellow and blue

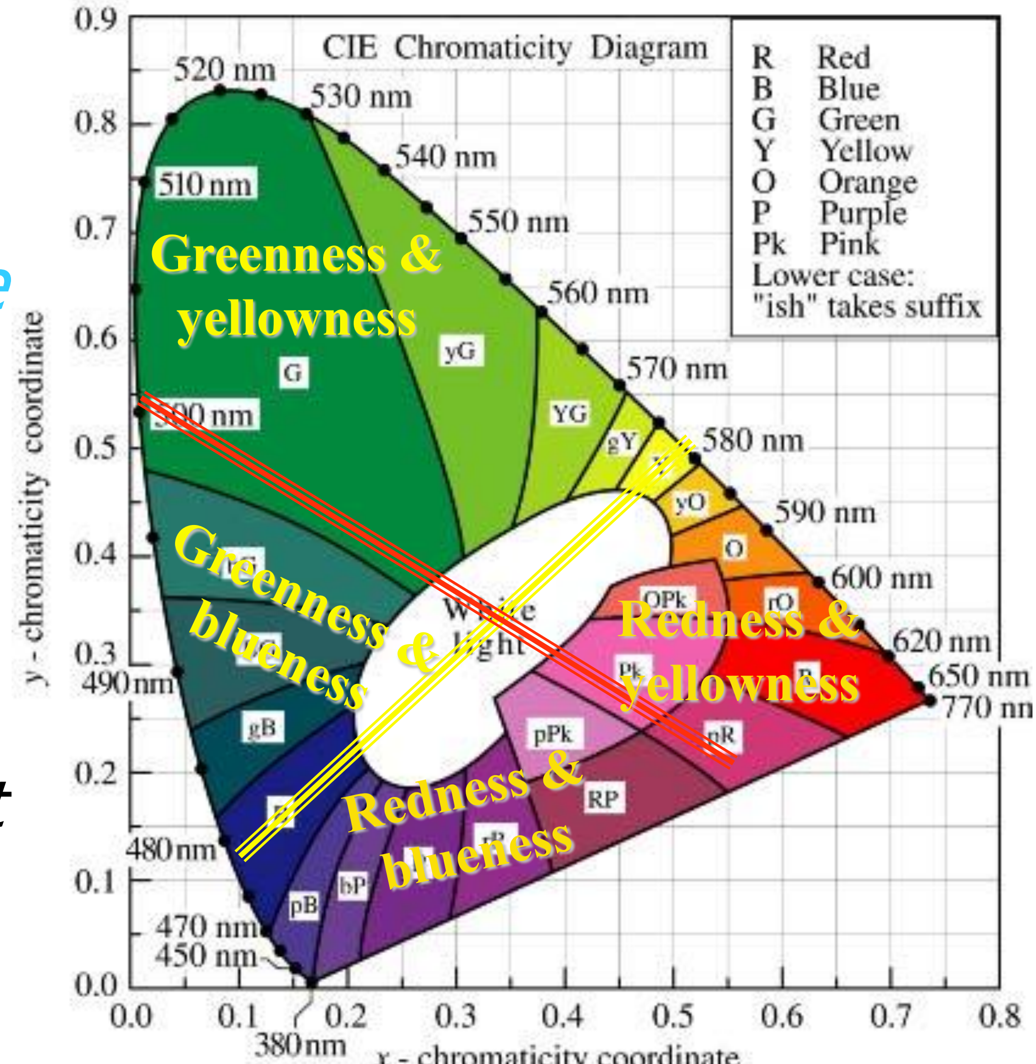
Color naming of hues on the chromaticity diagram

- ⌘Hue: how much green, red, blue or yellow is "in" them
- ⌘We don't need orange, purple or pink:
  - ☒orange can be thought of as yellow-red
  - ☒purple can be thought of as red-blue
  - ☒pink has the same hue as red but differs only in lightness



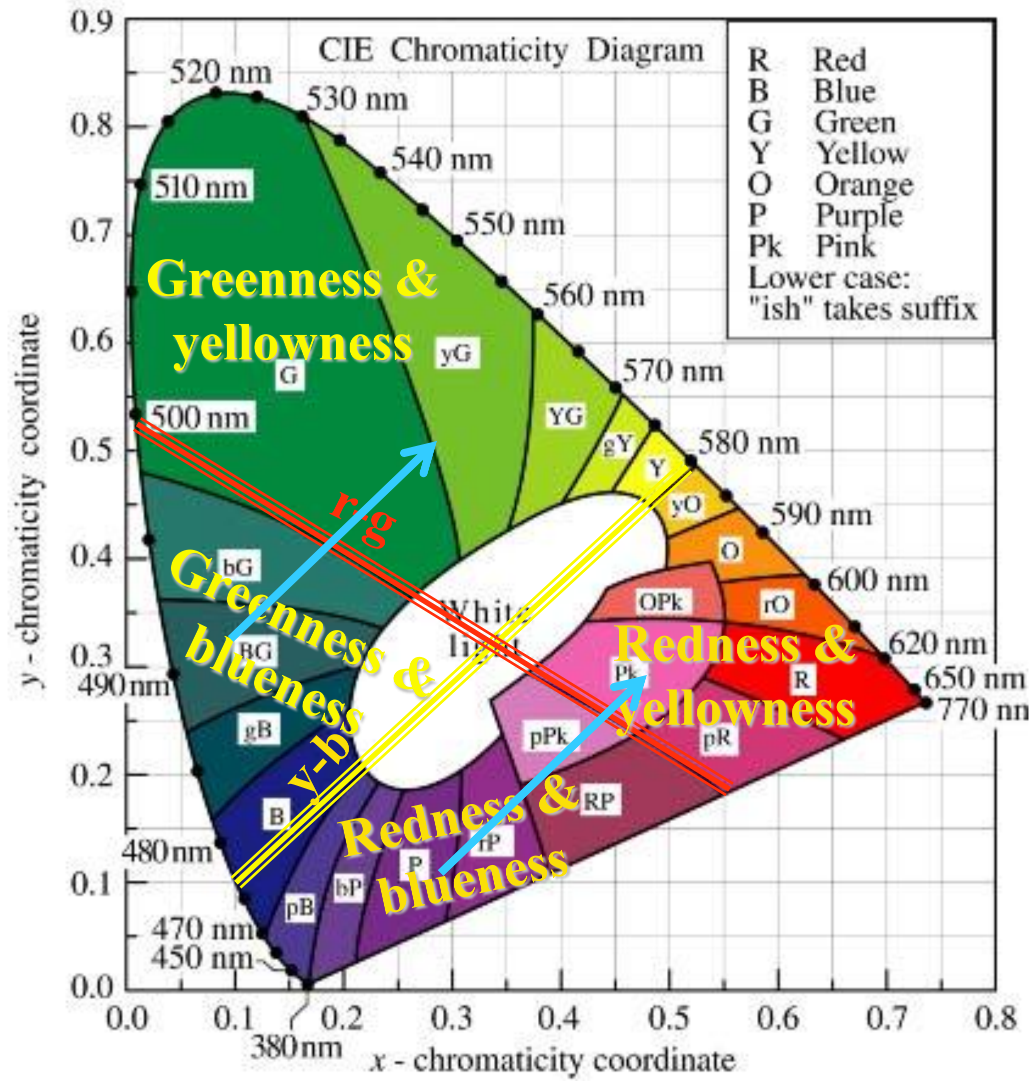
Color naming of hues on the chromaticity diagram

- Break up the diagram into 4 different regions by drawing two lines whose *endpoints are the psychological primary hues*
  - 580 nm "unique" yellow and 475 nm "unique" blue
  - 500 nm "unique" green and the other is "red" (*not* unique or spectral - really more like *magenta*)



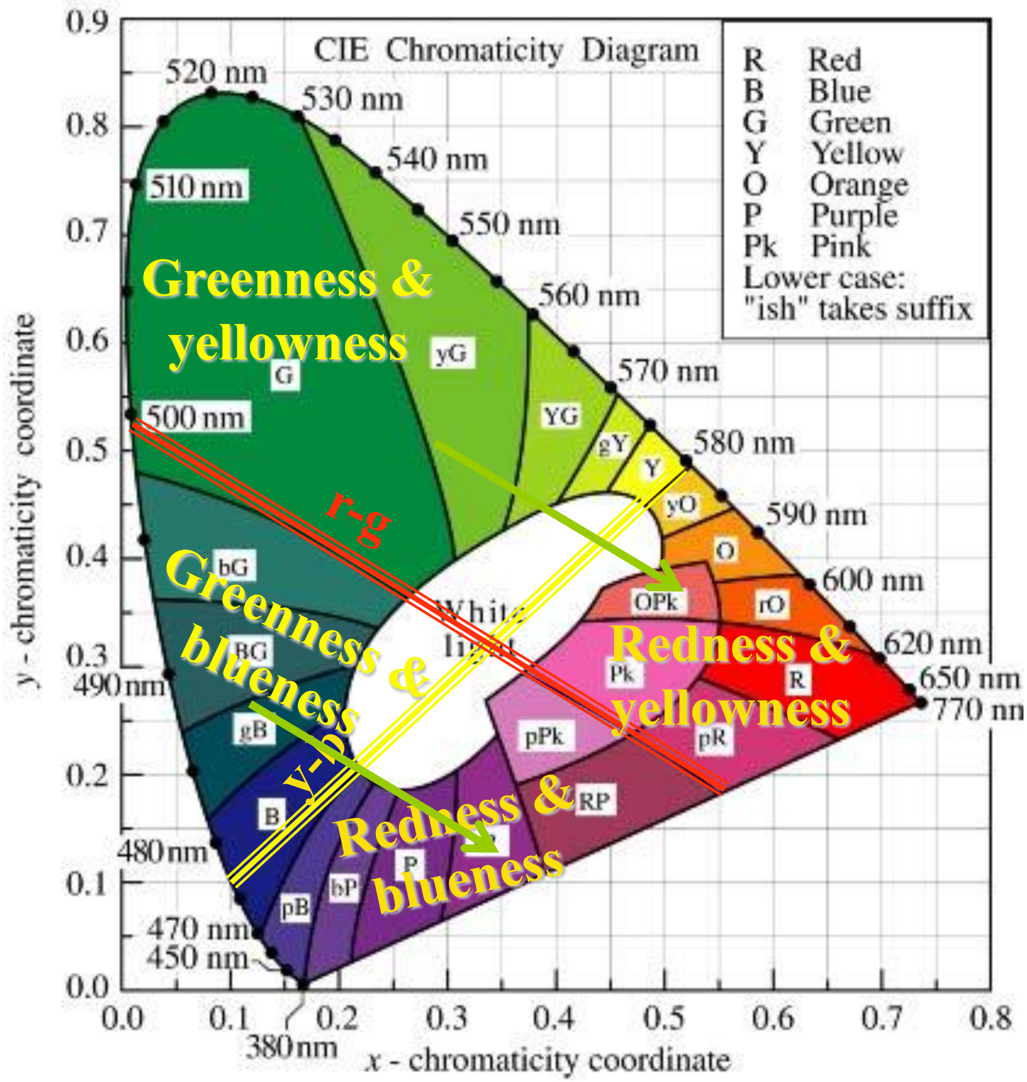
Opponent nature of yellow-blue perception

- In the direction of the yellow line from 475 nm blue towards 580 nm yellow, we see more yellowness of each color and less blueness.
- We call this perception our *y-b channel*
- Yellow & blue are *opponents*



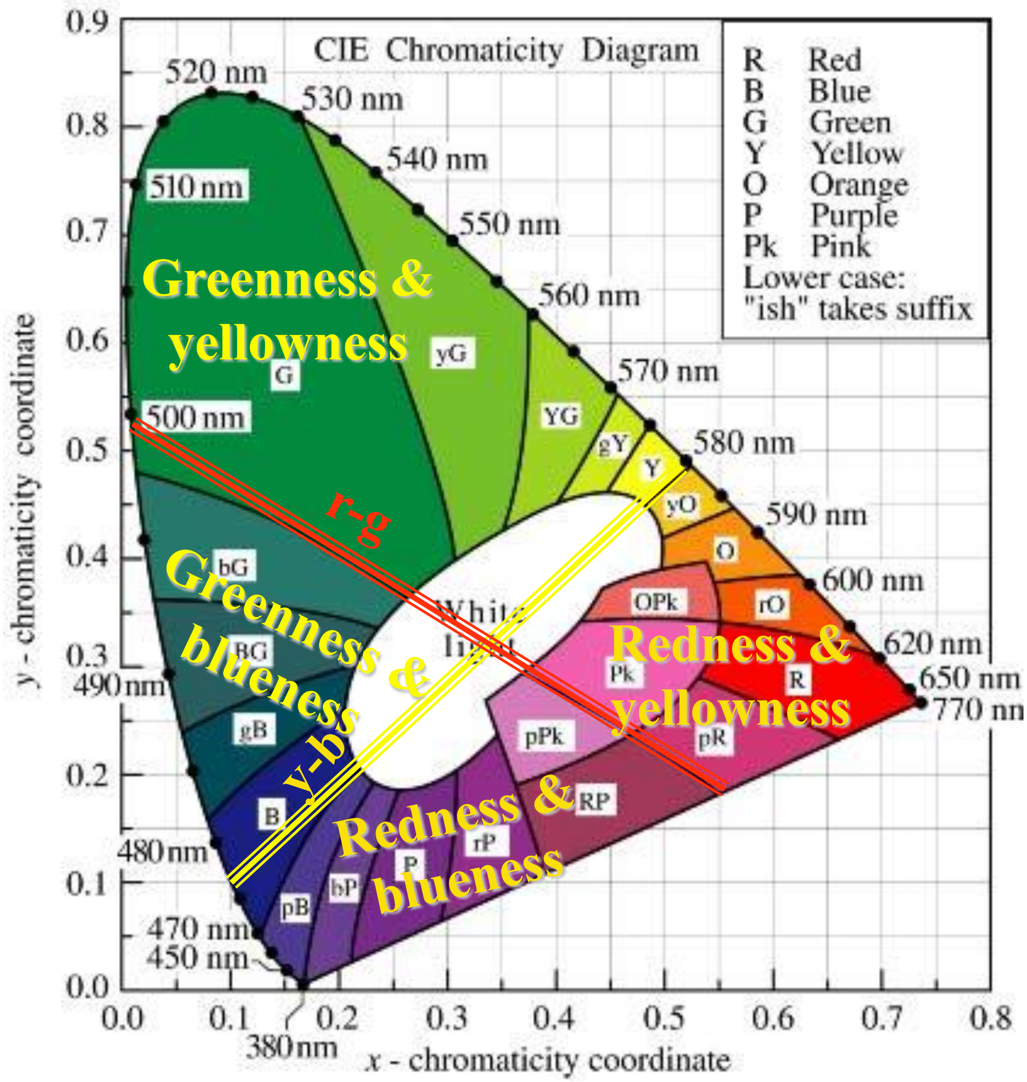
Opponent nature of red-green perception

- Moving parallel to the red line from 500 nm green towards nonspectral red we see more redness in each color and less greenness.
- We call this perception our *r-g channel*
- Red and green are *opponents*



Opponent nature of yellow-blue perception

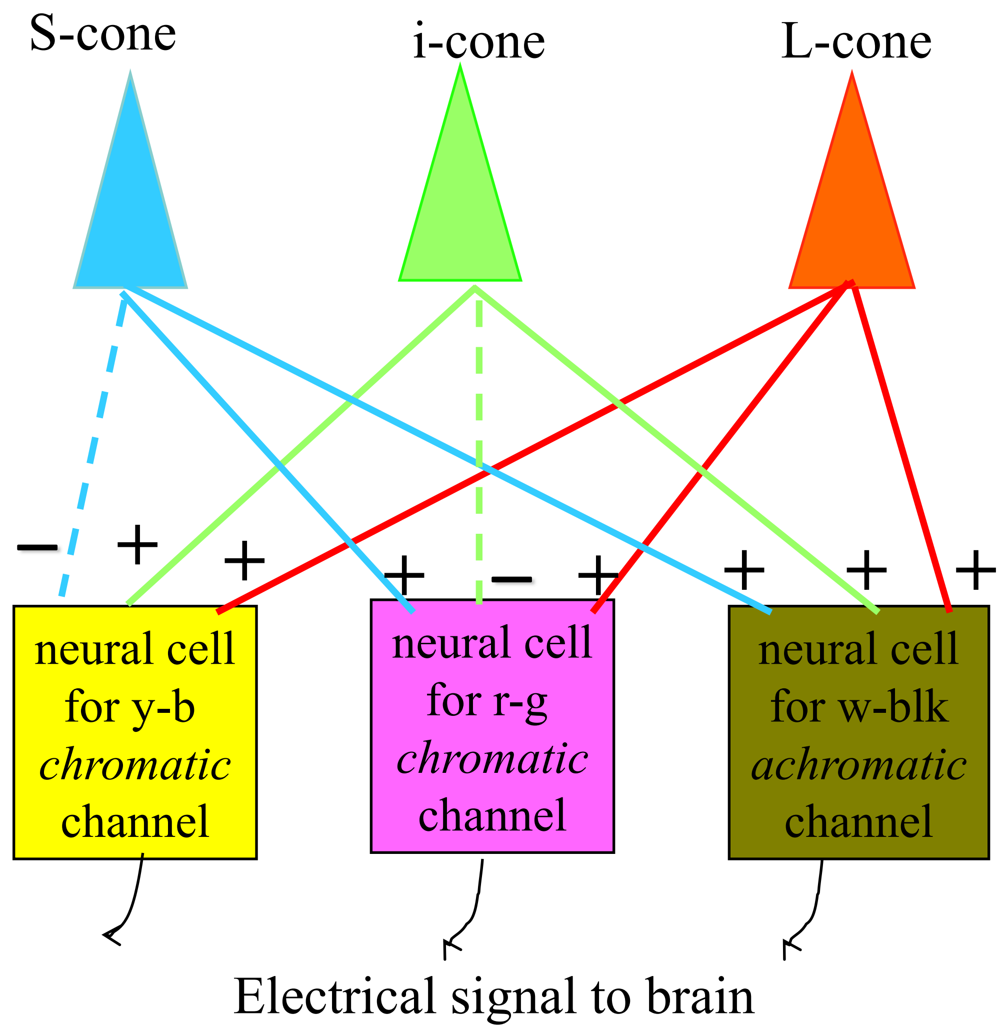
- The lines *cross* at *white*, where both y-b & r-g are *neutralized*



How might the *three types of cones* be "wired" to neural cells to account for our perception of hues

- The 3 kinds of cones are related to r-g and y-b by the way they are connected to neural cells (such as ganglion cells)
- Cones of each kind are attached to *3 different neural cells* which control the two *chromatic* channels, y-b and r-g, and the white vs black channel called the *achromatic* channel (lightness)

How might the *three types of cones* be "wired" to neural cells to account for our perception of hues



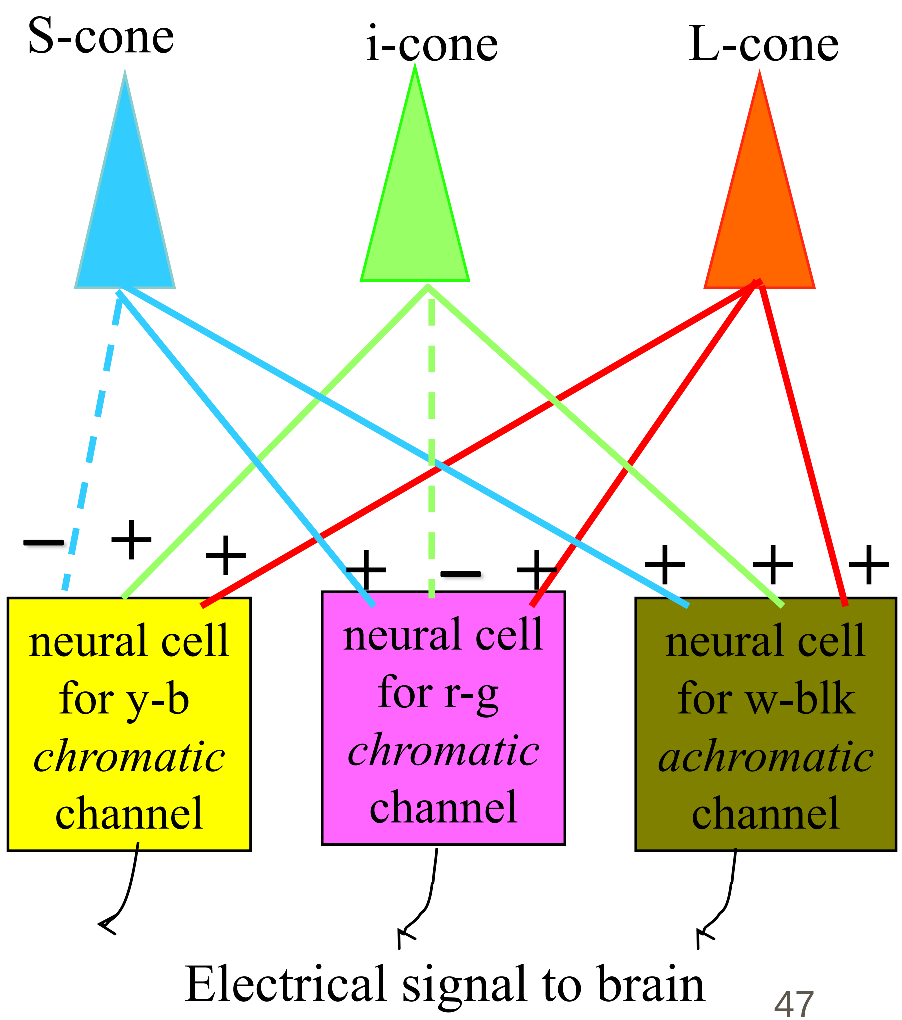
How might the *three types of cones* be "wired" to neural cells to account for our perception of hues

⌘"wiring" is the following:

- When light falls on the *L-cones* they tell all 3 neural cells to *increase* the electrical signal they send to the brain
- When light falls on the *i-cones* they tell the r-g channel cell to decrease (inhibit) its signal but tell the other cells to increase their signal
- When light falls on the *s-cones* they tell the y-b channel cell to decrease (inhibit) its signal but tell the other cells to increase their signal

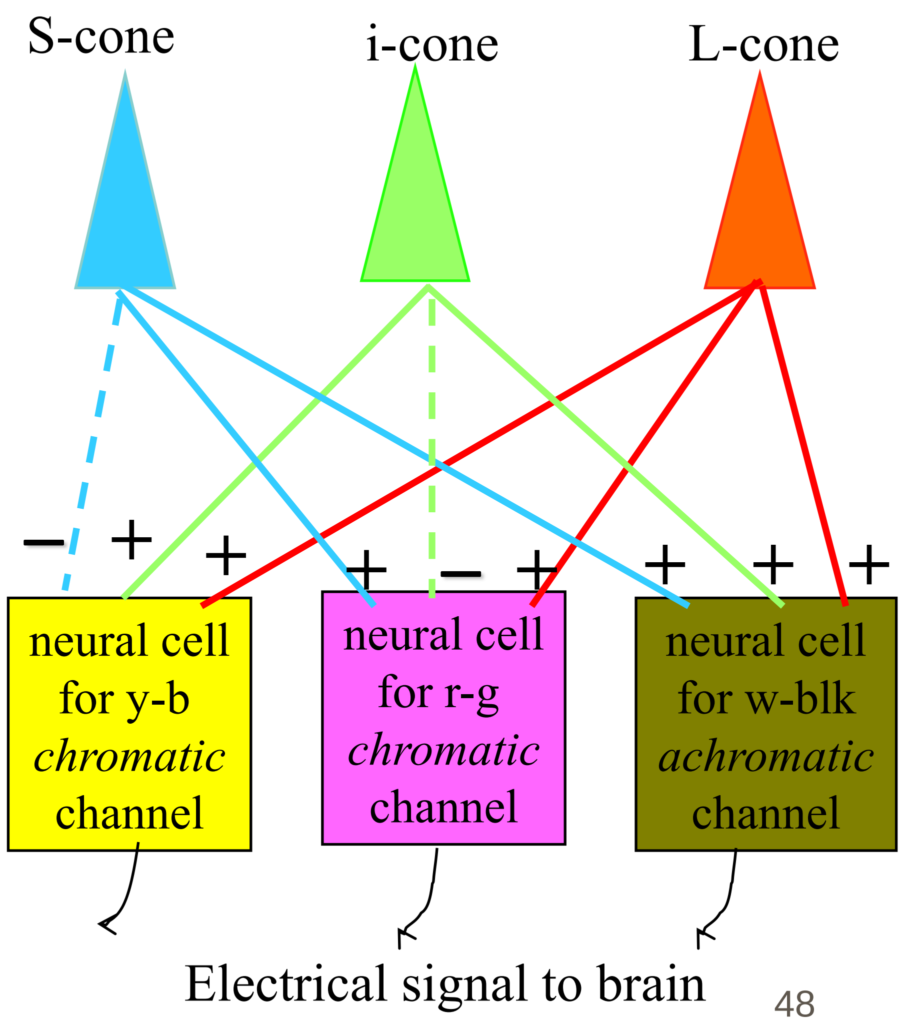
Yellow-Blue channel

- The neural cell for the y-b *chromatic* channel has its signal
- *inhibited* when (bluE) light excites the s-cone INTERPRETED AS BLUE
- *enhanced* when light excites the i & L cones INTERPRETED AS YELLOW



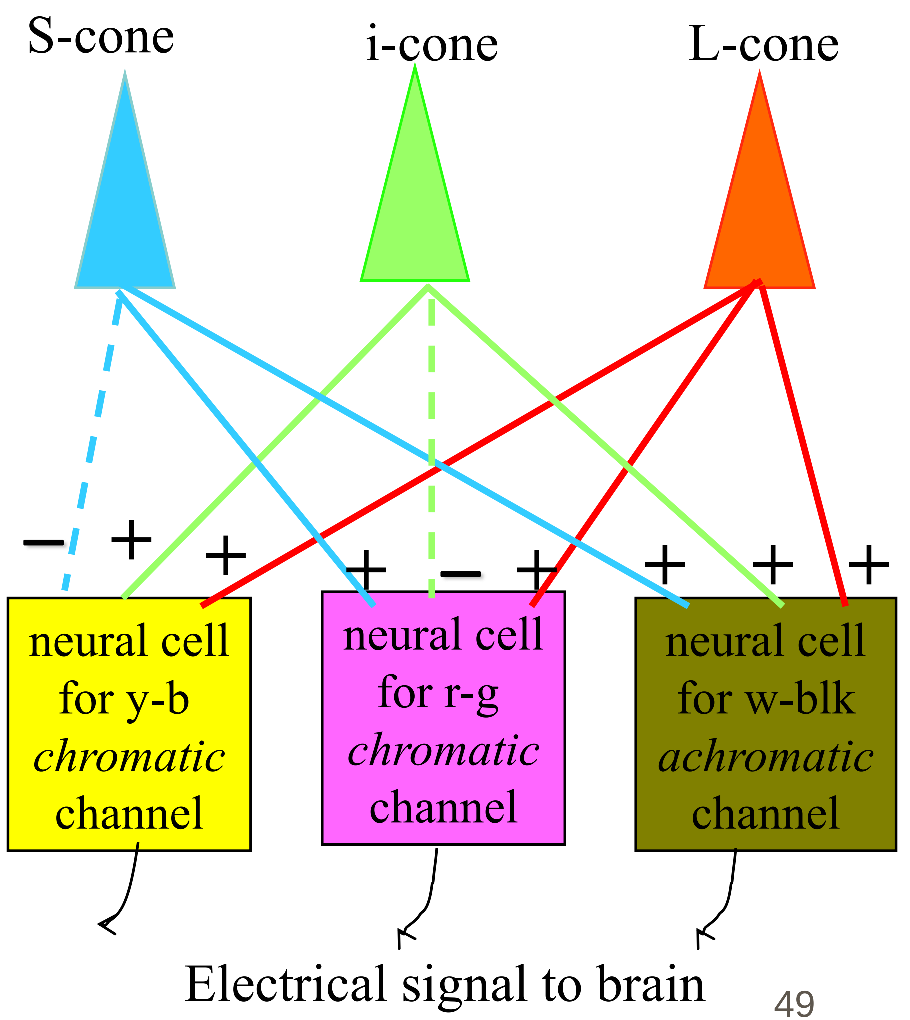
Red-Green channel

- The neural cell for the r-g *chromatic* channel has its signal
- *inhibited* when (green) light falls on the i-cone INTERPRETED AS GREEN
- *enhanced* when light excites the s and L cone INTERPRETED AS MAGENTA (Psychological red)



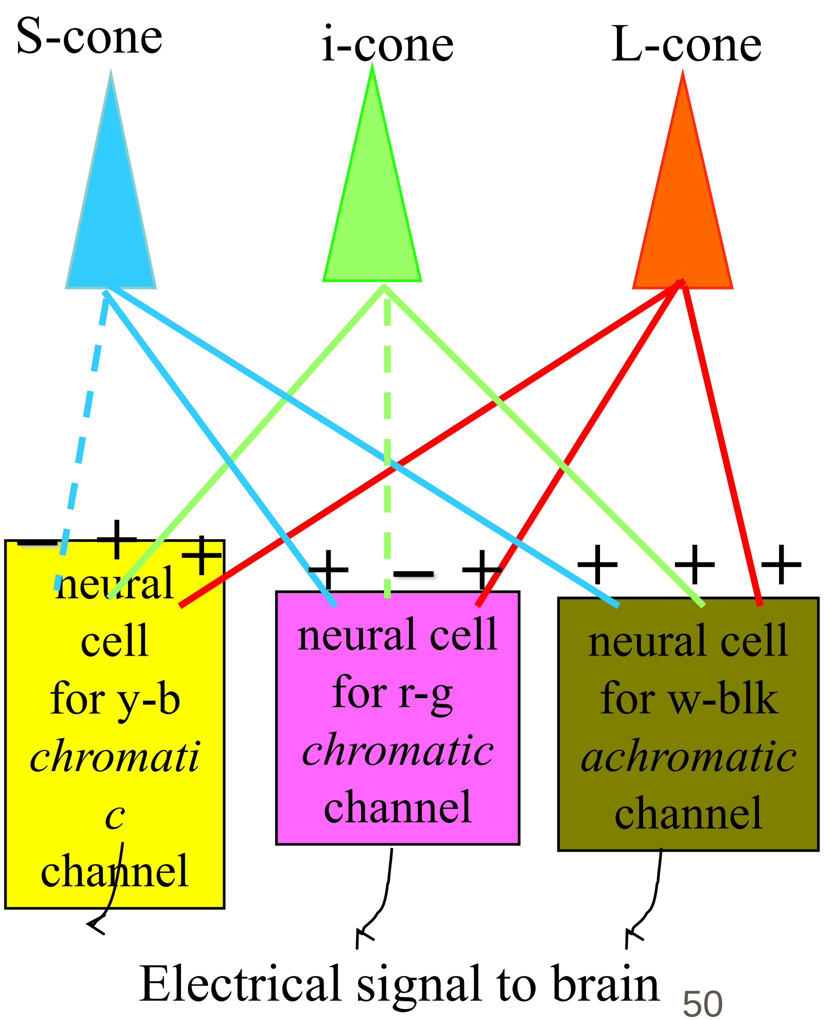
Achromatic channel

- The neural cell for the achromatic channel has its signal enhanced when light excites *any* of the cones



Hue changes

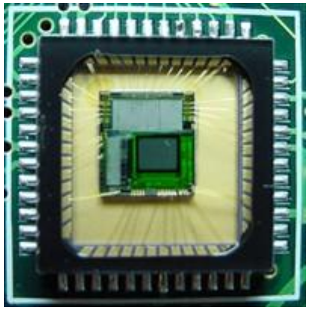
- The gradual changes in hue: pure red→ yellowish red (oranges)→ pure yellow→ greenish yellow→ pure green→bluish green→ pure blue→ reddish blue (purples)→pure red. Also note, that many hues are non-spectral (pure red, purples).



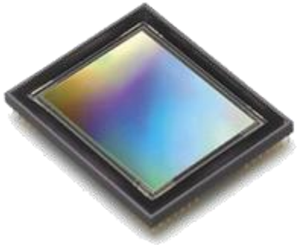
How is image formed?

There are basically three types of light receptors (imagers) used within all generally available digital cameras at present:

- Imagers
  - CCD - Charge Coupled Device
  - CMOS - Complementary Metal Oxide Semiconductor
  - Foveon - a chip of transparent quartz containing 3 layers of CMOS

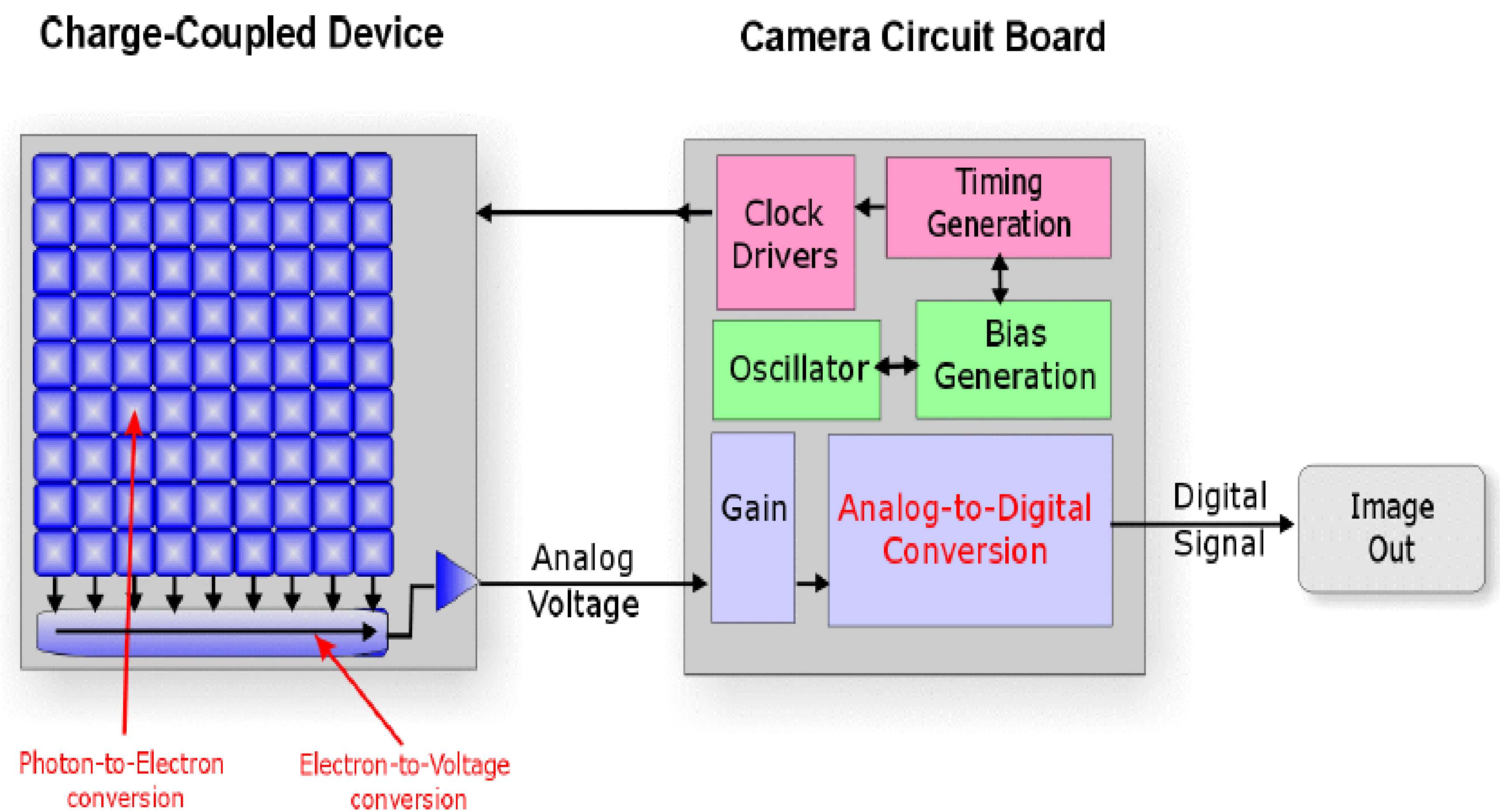


A CMOS image sensor



A CCD sensor

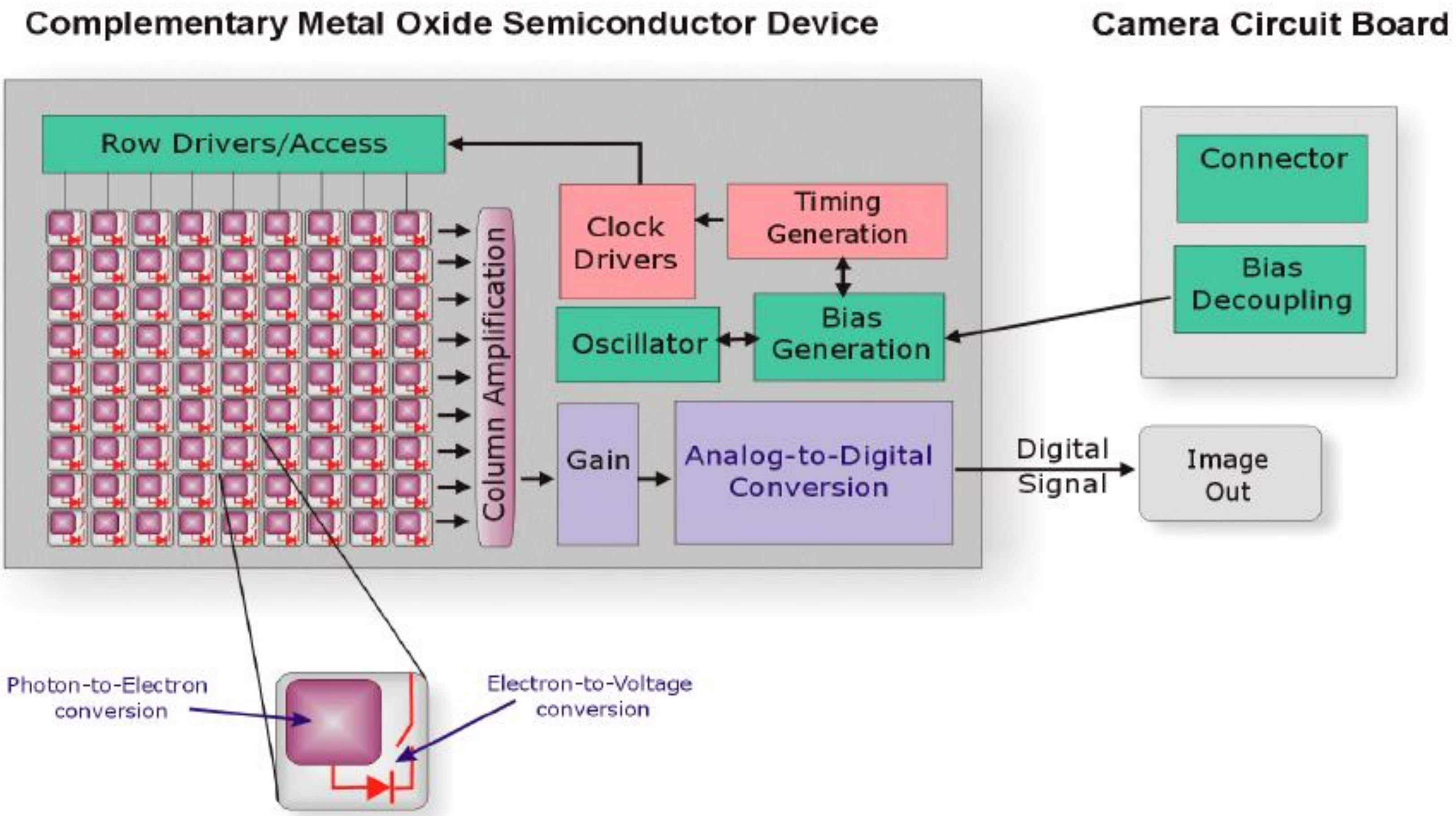
CCD (Charge-Coupled Device)



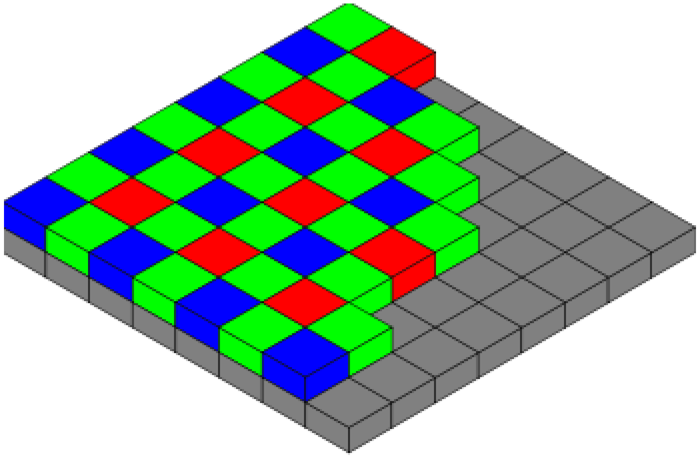
CMOS

- With the CMOS imager both the ‘Photon-to-Electron’ conversion and the ‘Electron-to-Voltage’ conversion is done within the pixel, leaving less room for the light receptive part of the sensor. This means the CMOS chip has less area to actually receive the light and normally some form of micro-lens is needed to capture the light the pixel would otherwise miss.

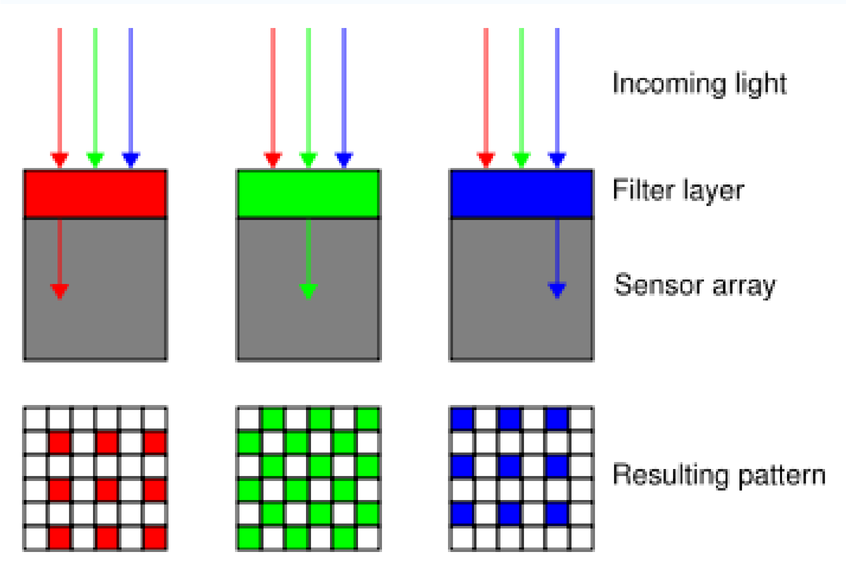
CMOS (Complementary Metal Oxide Semiconductor)



Mosaic Images

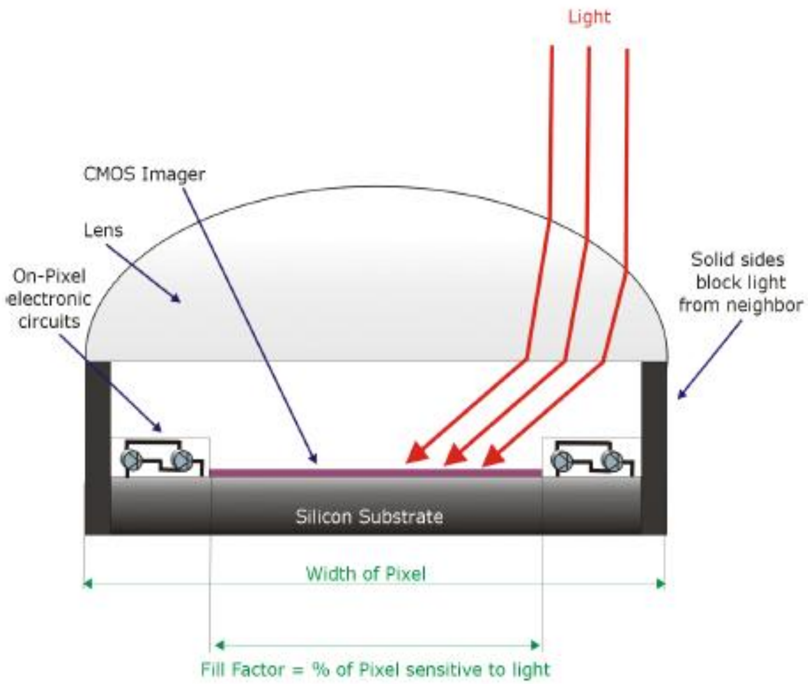


Bayer Pattern



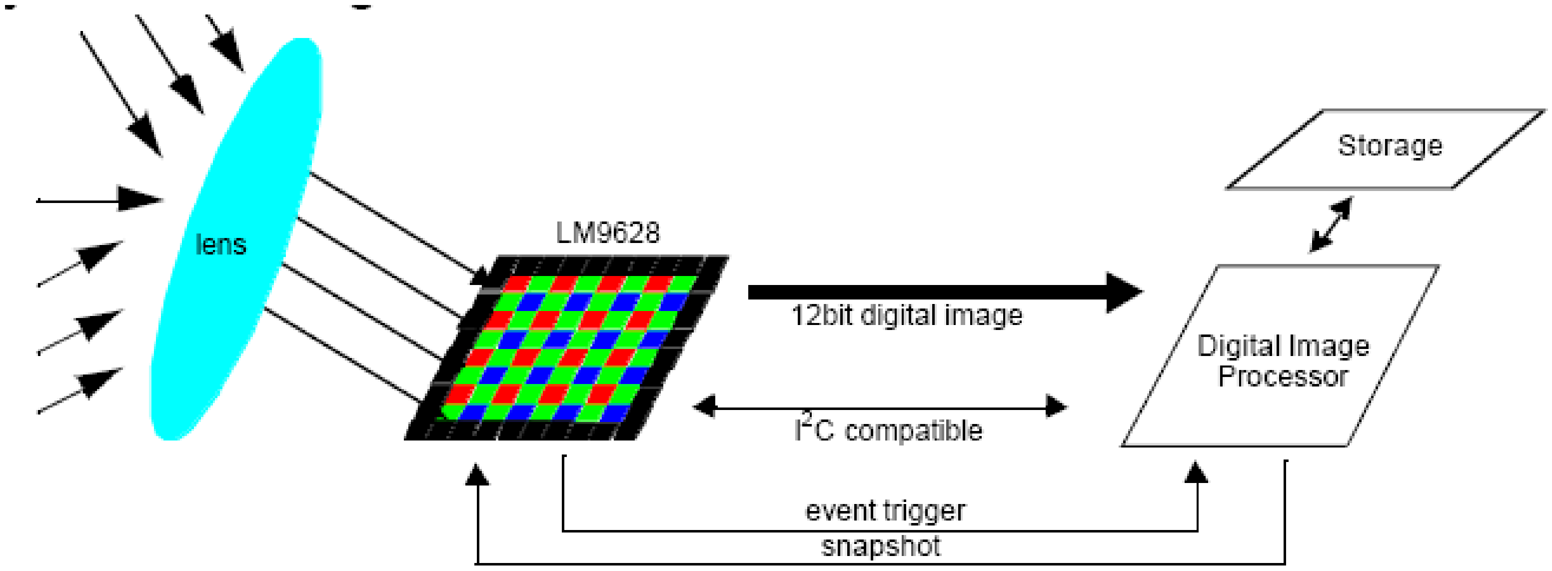
- Digital cameras capture images using a color filter array (CFA)
- Only 1 color is captured in each sensor
- Most commonly used CFA pattern - Bayer Pattern

Micro-lens



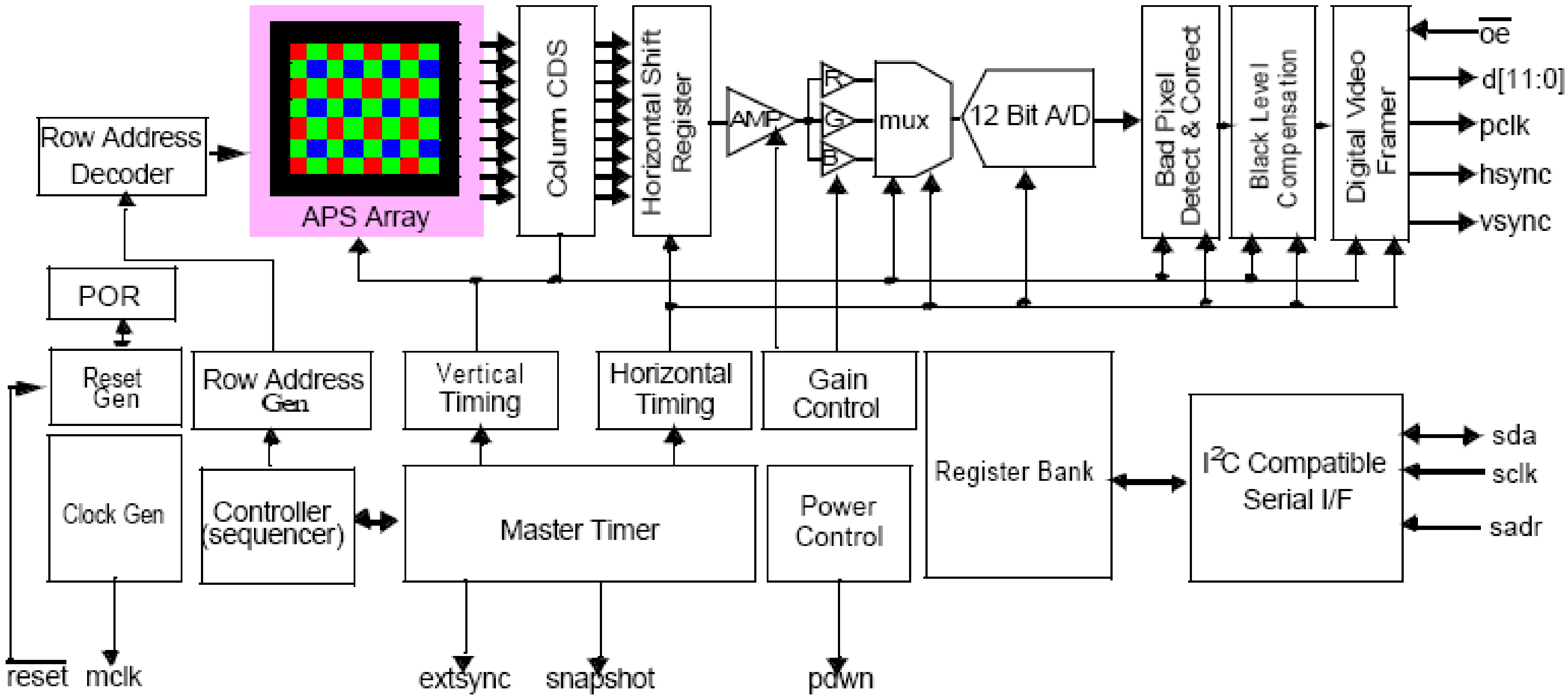
- Micro-lens technology is used to help capture more light and bend it away from the circuitry on the chip and towards the light sensitive parts of the pixel.

How is a digital image generated?

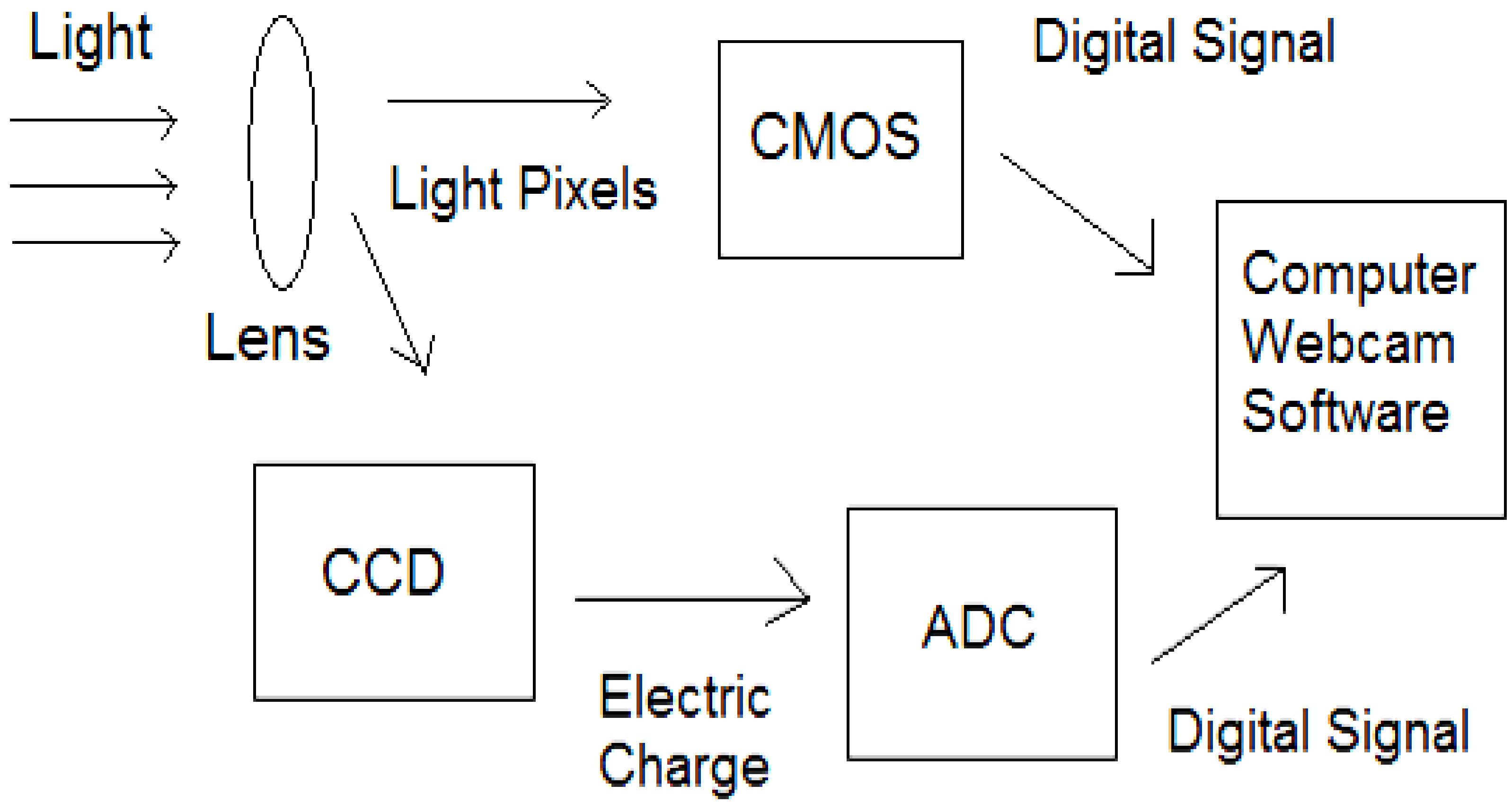


•normally, a simple linear interpolation is used to get the “missing” color values

… and in some more detail…



CMOS vs CCD



Light
Lens
Light Pixels
CMOS
Digital Signal
Computer Webcam Software
CCD
Electric Charge
ADC
Digital Signal

Comparison of CCD and CMOS image sensors:

CCD	CMOS
Long history of high quality performance	Lower performance in past, but now providing comparable quality
High Dynamic range	Moderate Dynamic range
Low noise and best dMax	Noisier, but getting better quickly
Well established technology	Newer technology
High power consumption	Relatively low power consumption
Moderately reliable	More reliable due to integration of chip
Small pixel size (small sensors – best to develop new cameras and lenses)	Larger pixel size (larger sensors – easier to use within current camera technology)
Needs lots of external circuitry	All circuitry on chip
High Fill Factor	Lower Fill Factor
CCD creates analogue signal that is digitised off the chip	CMOS creates a digital signal on chip