Advanced Color Machine Vision and Applications

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V09 March 26, 2014

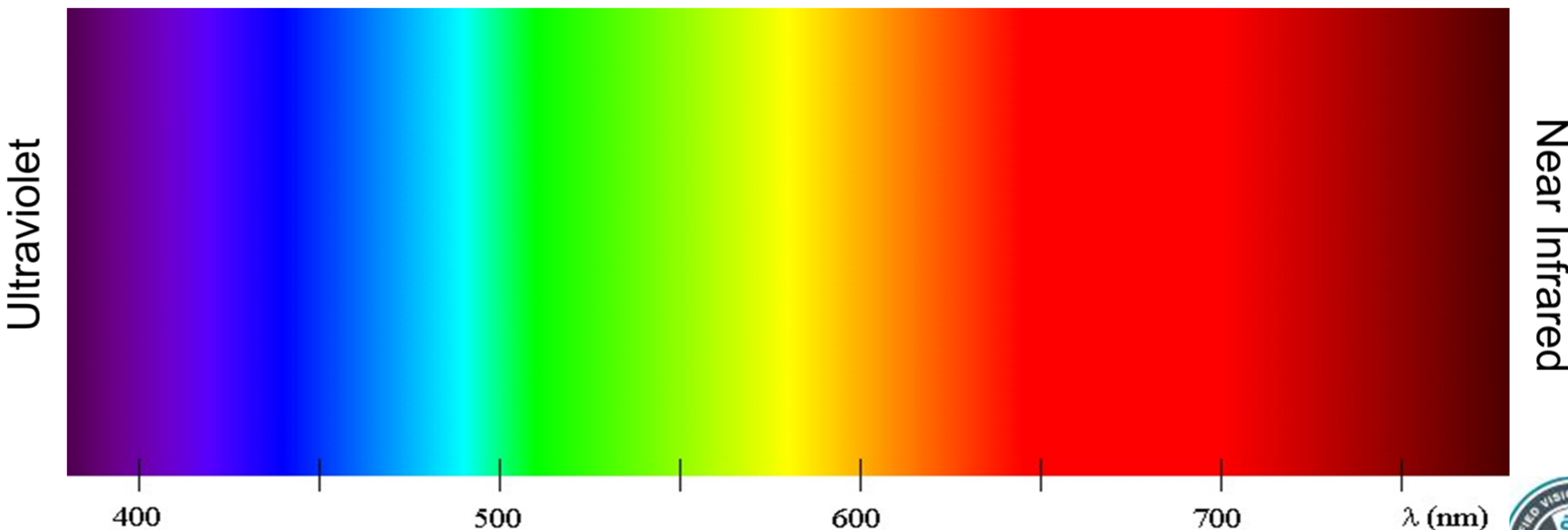
Welcome

- Why is color vision useful?
- Physics of color imaging
- Human color vision and measurement
- Color machine vision systems
- Basic color machine vision algorithms
- Computing application answers

-  Human vision  Machine Vision
- Important terms in **bold purple** (colorblind safe)
- Text and notes for study

What is Color?

- Our perception of wavelengths of light
  - About 360 nm to 780 nm (indigo to deep red)
  - "…the rays are not coloured…" - Isaac Newton
- Machine vision measures wavelengths
  - Can be calibrated to human color perception



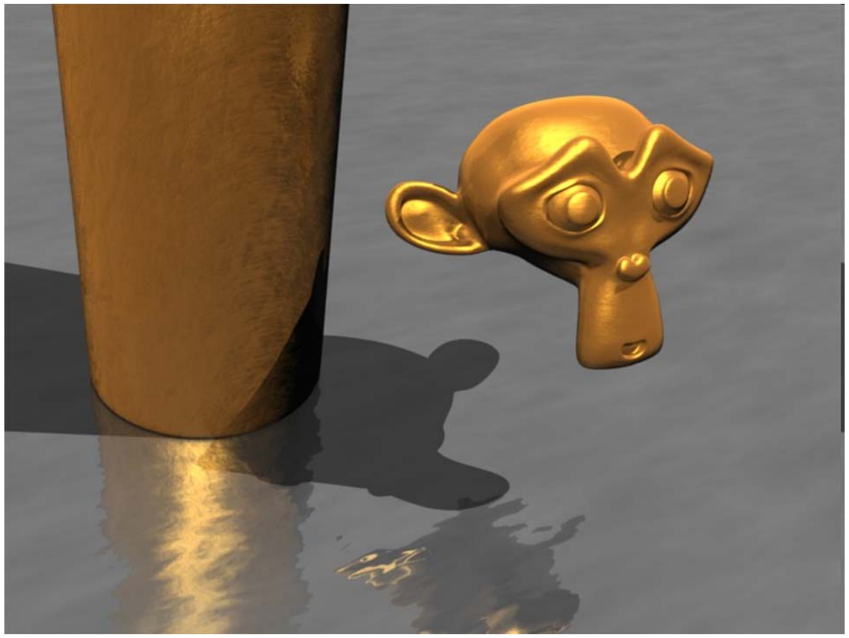
nm : nanometer = 1 billionth of a meter

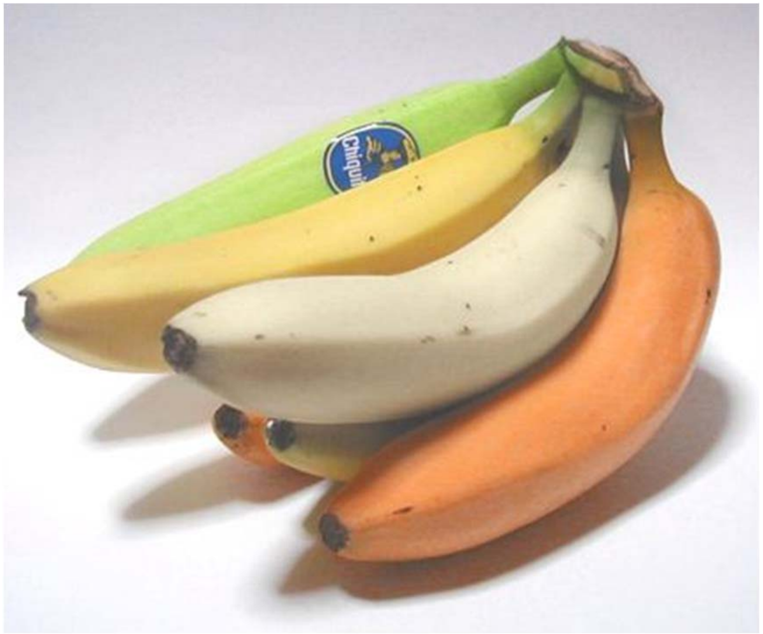
Important Uses of Color Vision

- Determining **material property** – help identify what something is made of or its state
  - What is that? Safe to eat it?
- Inspection and Sorting
  - Is the printing defective? Is the fruit damaged?
- Searching and Locating
  - Location? Orientation? Presence-absence?
- Measuring and Matching
  - What color is it? Right color? Does it match?
- Coding – Color labels and codes

Material Property

- Color is a **material property** – it helps tell what an object is made of, its state, etc.
  - Texture is also a material property



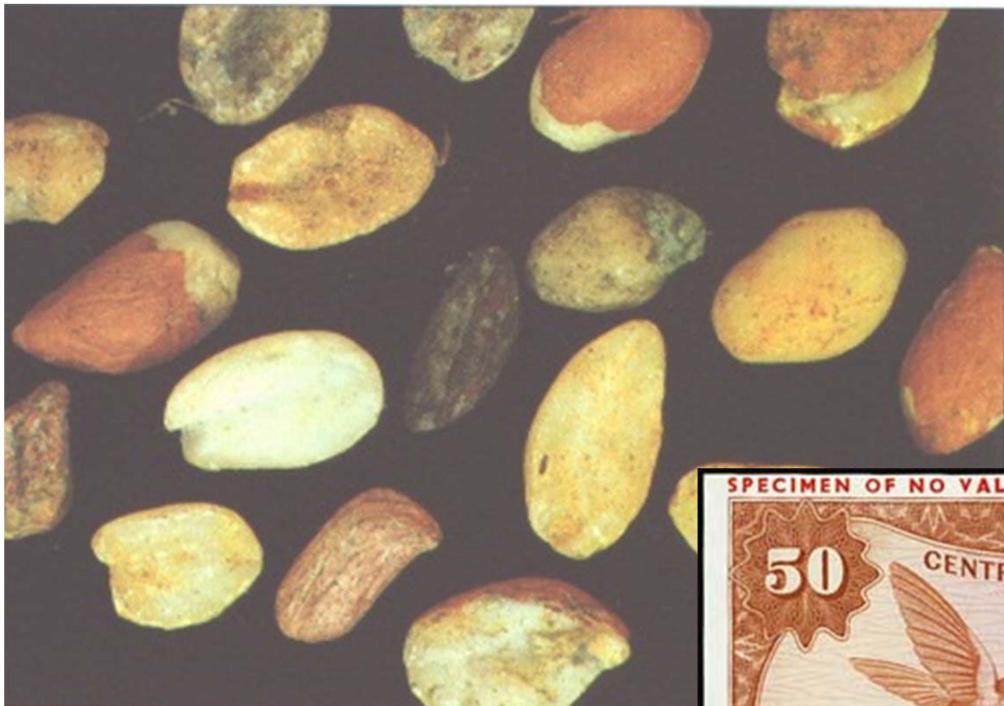


Which Cherries are Ripe?

With Color it is Easy!

Color Afterimage!

Color Inspection and Sorting



Which peanuts are bad? Is the currency good?

Searching and Locating

Which Sneakers are Light Blue?

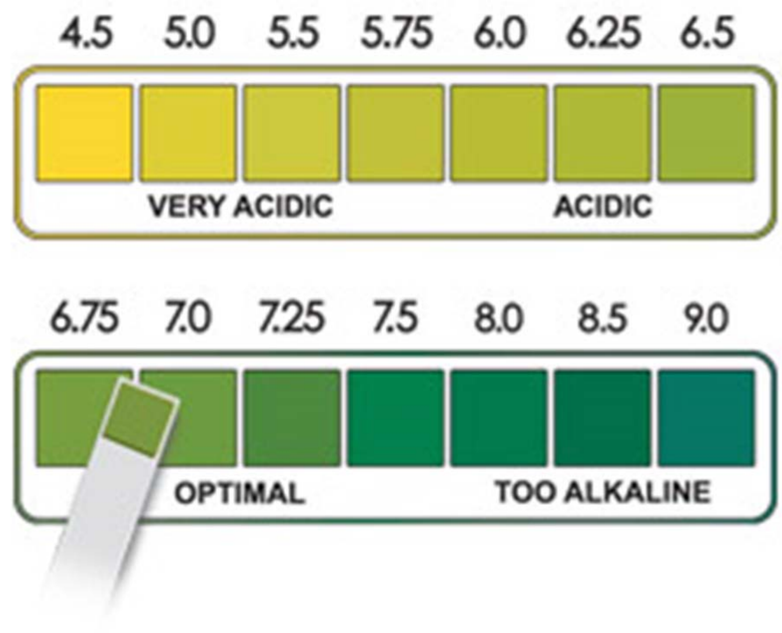
Importance of Fast Color Search

- Quickly identify hazards!
- Grab the food!


Milk snake – Batesian mimic of poisonous coral snake

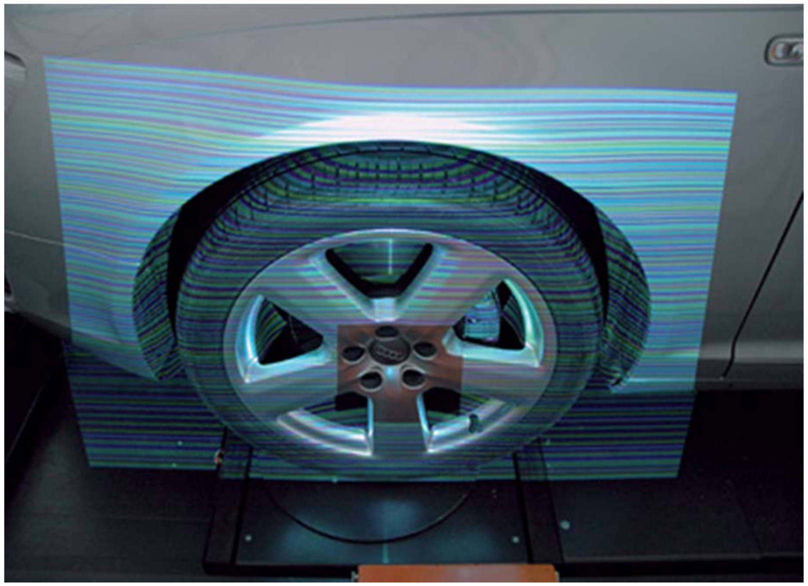
Color Measuring and Matching

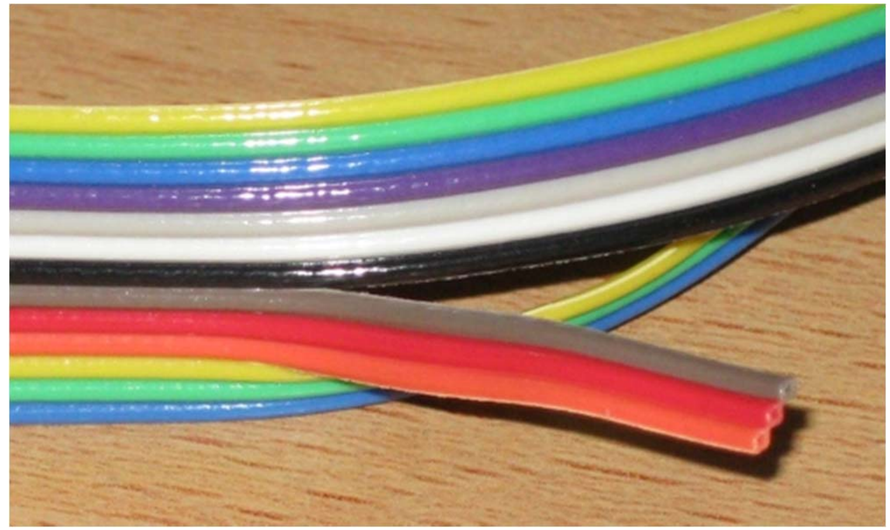
Color matching on car interior

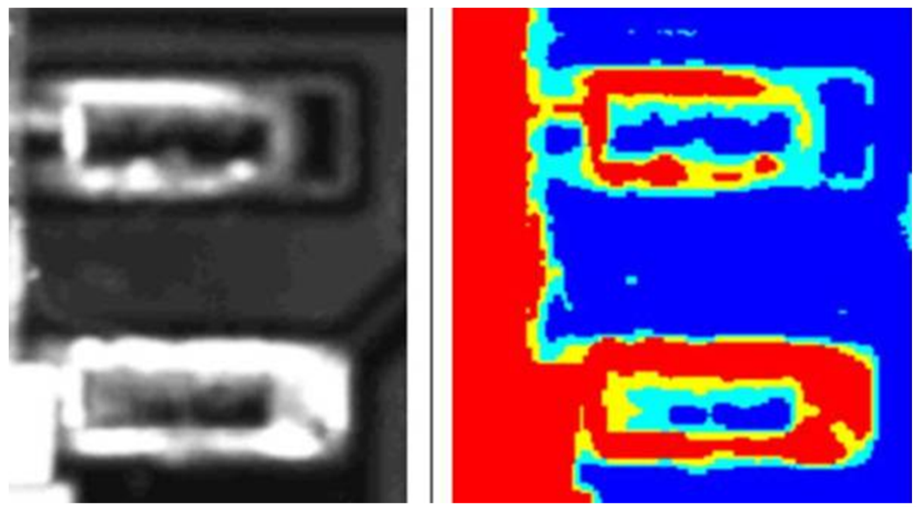


Medical diagnostics

Color Coding



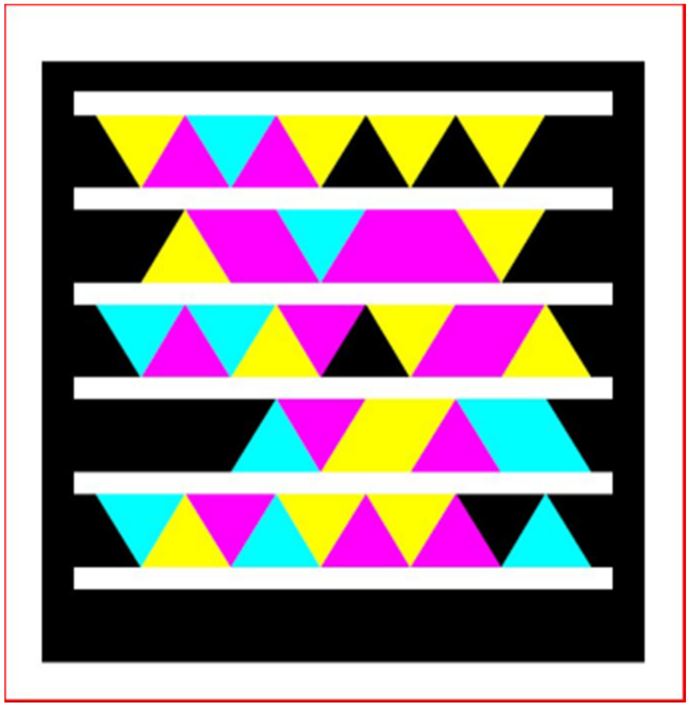


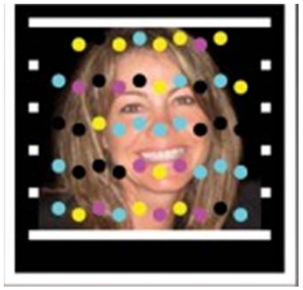


Pseudocolor

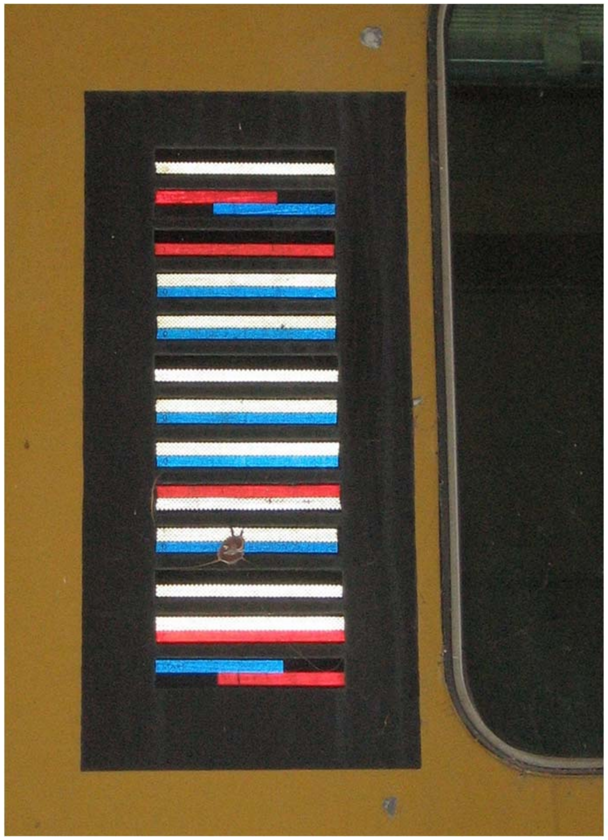
Bar Coding

- Microsoft MobiTags™, Railroad color barcodes





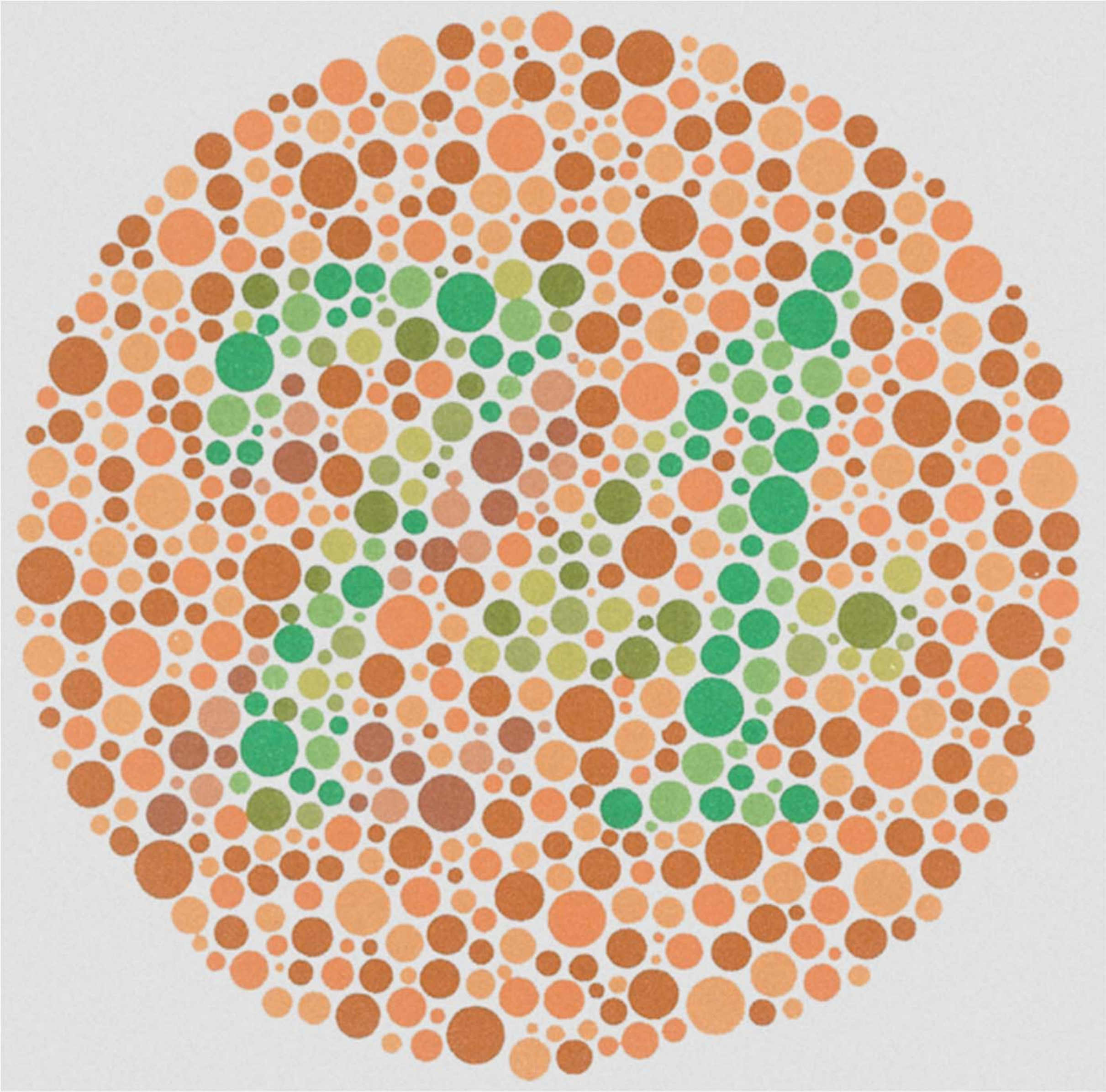
Computer Identics, 1970s



Human Color Vision

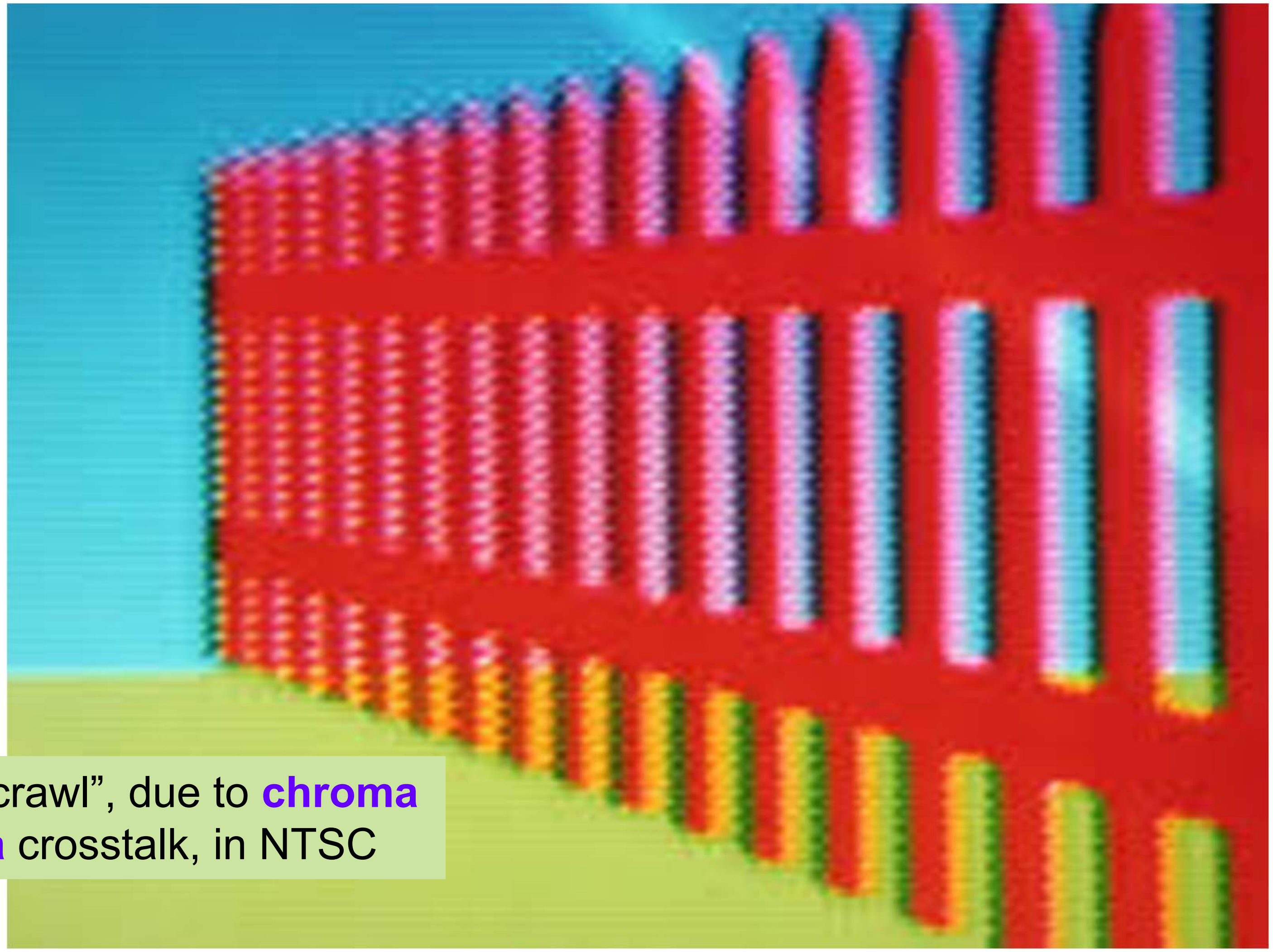
- **The standard for many color vision tasks**
- ✓ Stabile perceptions of objects despite uncontrolled lighting and viewing geometry
- ✓ Easy to train, flexible, “understands” images
- ✗ Slow, quickly tires, individuals differ, low resolution, hard to calibrate
- ✗ Color (not intensity!) is low spatial resolution
- ✗ Influenced by surroundings in time and space – **color contrast**
- **Optical illusions** show problems and give us clues as to how biological vision works

Individual Differences



An Ishihara test

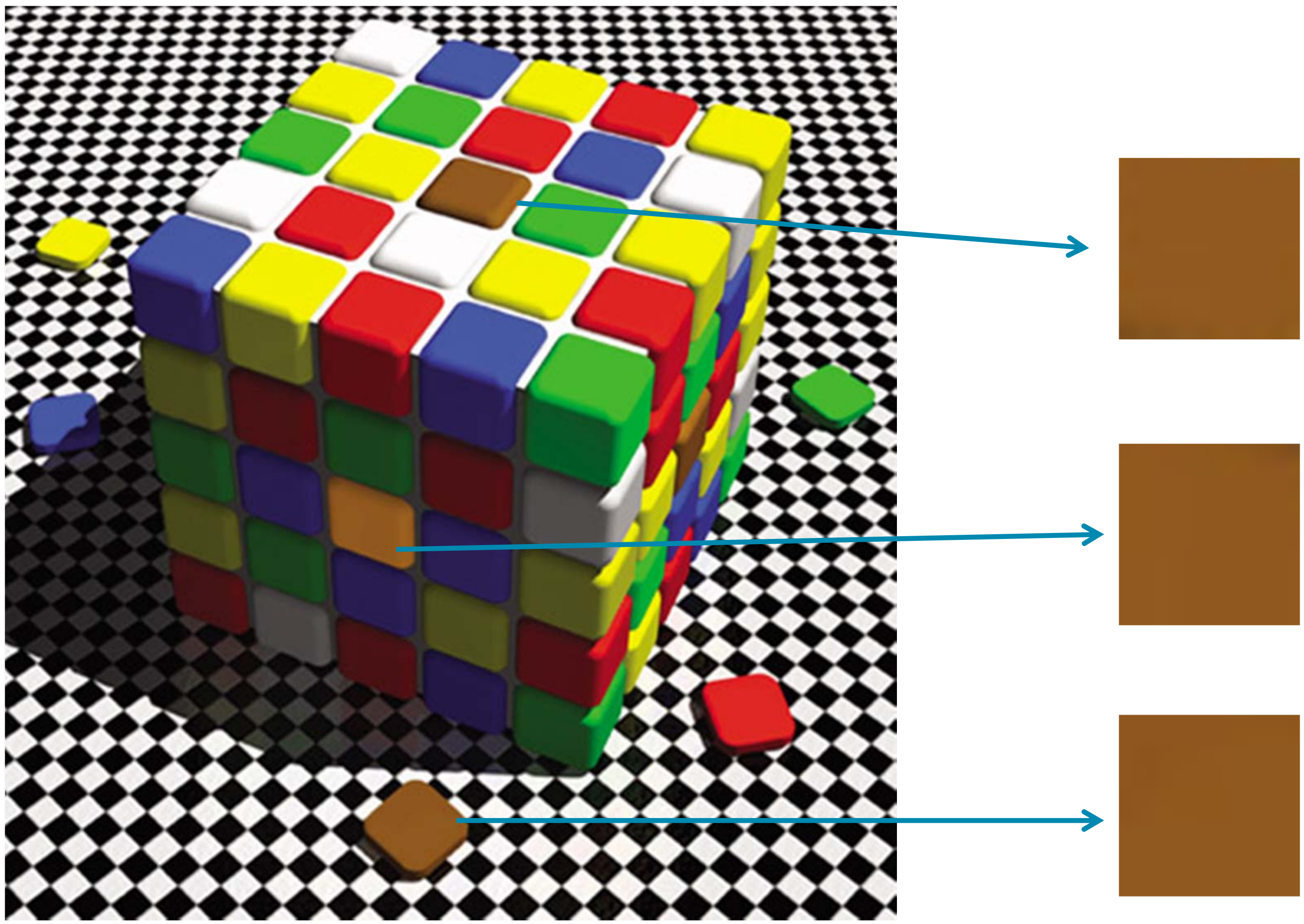
Color has Low Spatial Resolution



Chroma “crawl”, due to **chroma** and **luma** crosstalk, in NTSC

NOTE: Intensity changes have much higher spatial resolution

Influenced by Surroundings

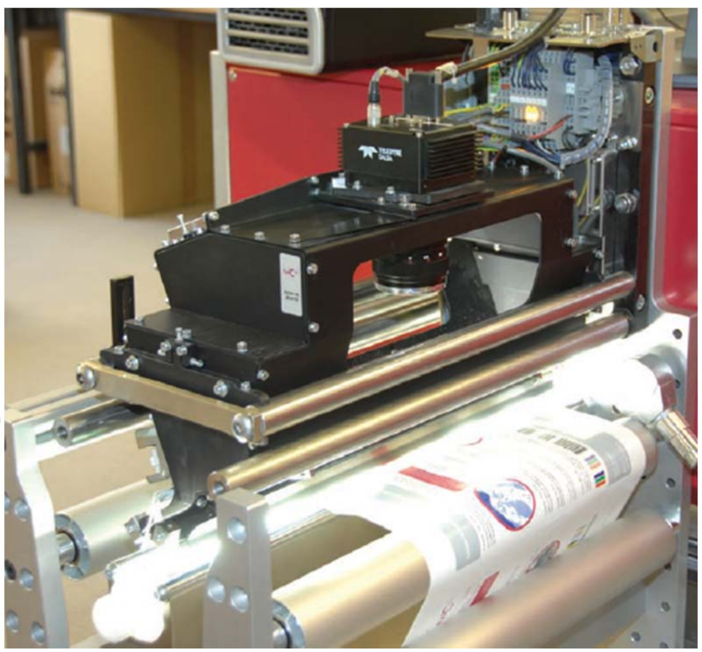


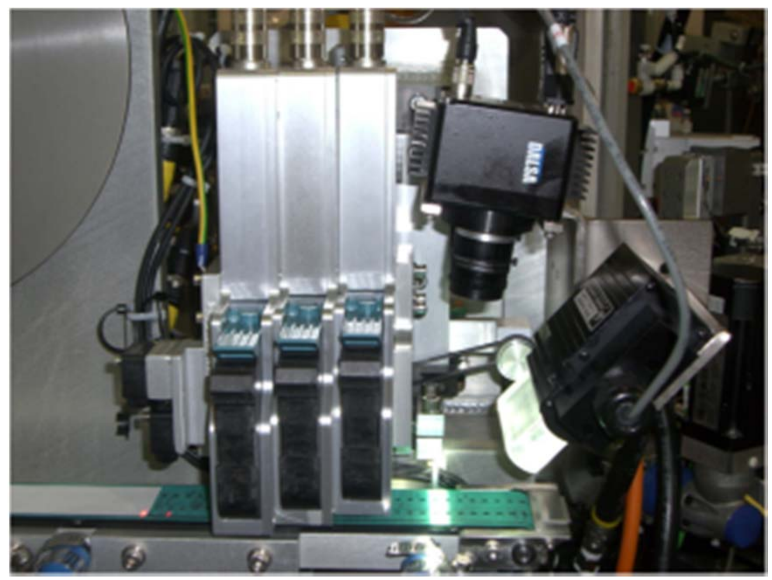
Dramatic example of **color contrast** effects
"Side effect" of our **color constancy** abilities?

Color Machine Vision (CMV)

- ✓ Replaces human vision on tasks that require fast, repeatable color vision. Never tires.
- ✓ Can calibrate to human color vision (sort of!)
- ✓ Can “see” wavelengths we can’t (IR, UV, etc.)

EyeC GmbH





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Color Machine Vision

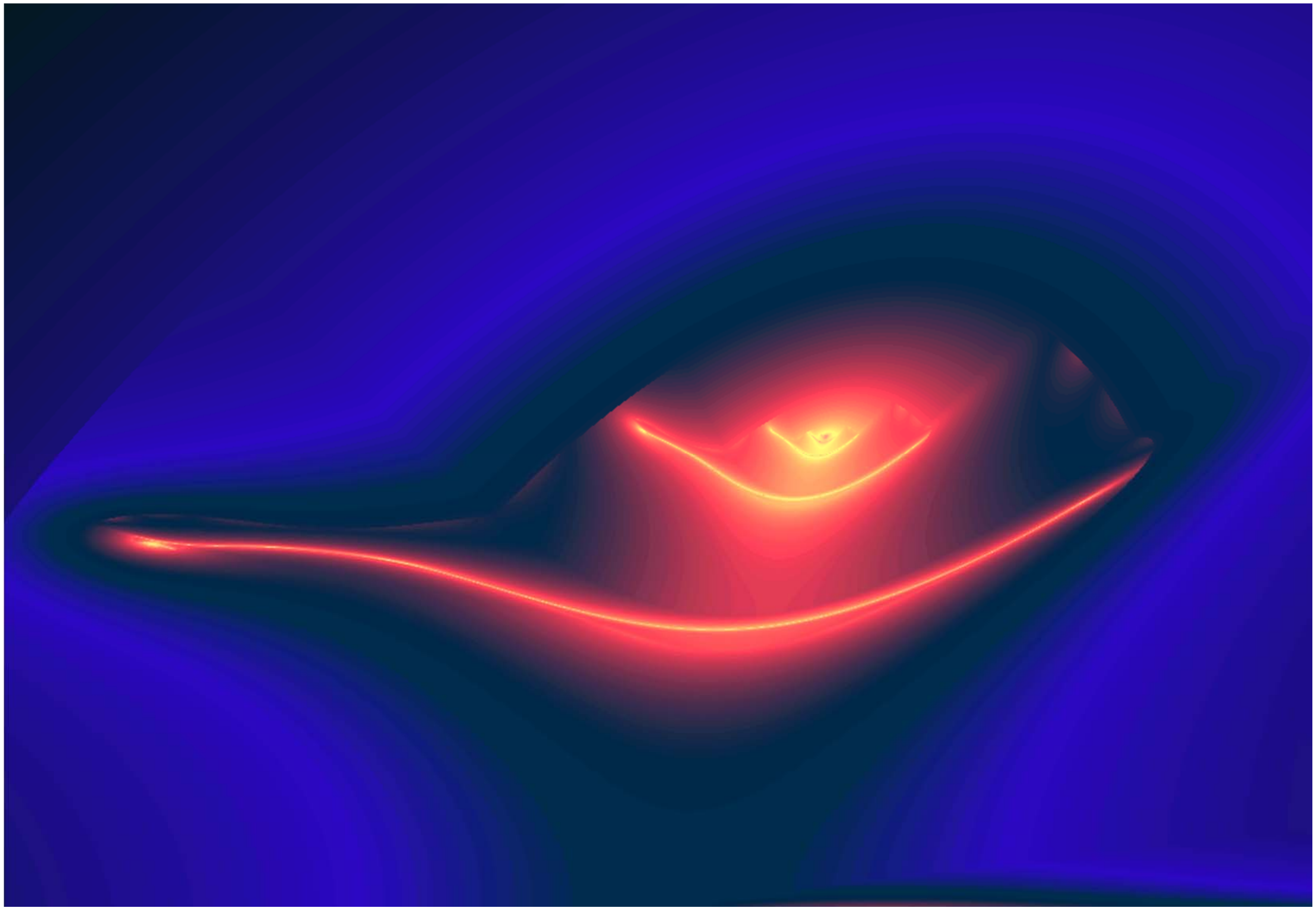
- Doesn’t “see” and understand the way you do!
- Requires exact set-up and instructions
- Difficult when vision task:
  - Requires extensive world or context knowledge
    - What does skin cancer look like?
  - Has poorly controlled lighting or part presentation
    - Mobile robots, agricultural automation, railroad barcodes
  - Is poorly defined
    - “Find all the defects!”

Some Markets for Color MV

- Food production and processing
- Pharmaceutical inspection
- Parts identification
- Inspecting or matching colored material

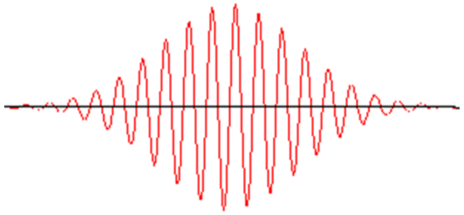
- Medical diagnostics
- Print and label inspection
- Sorting recycled materials
- Remote sensing, tracking
- Biometrics, traffic monitoring
- Measuring paints and pigments

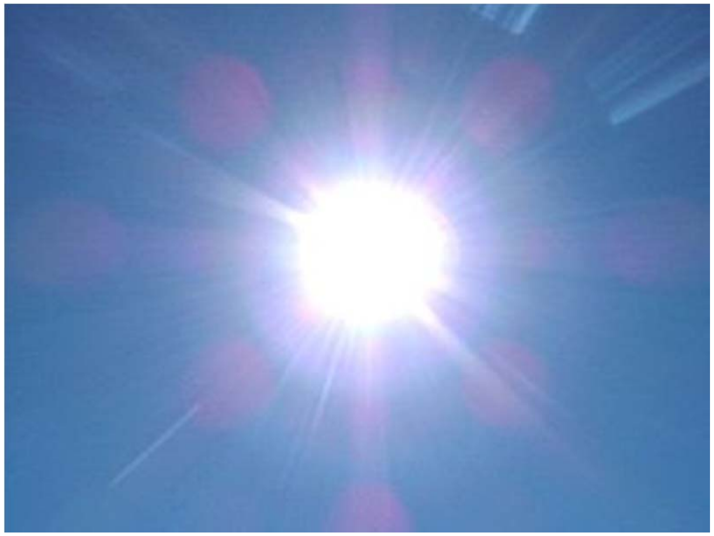
Physics of Color Imaging



Light

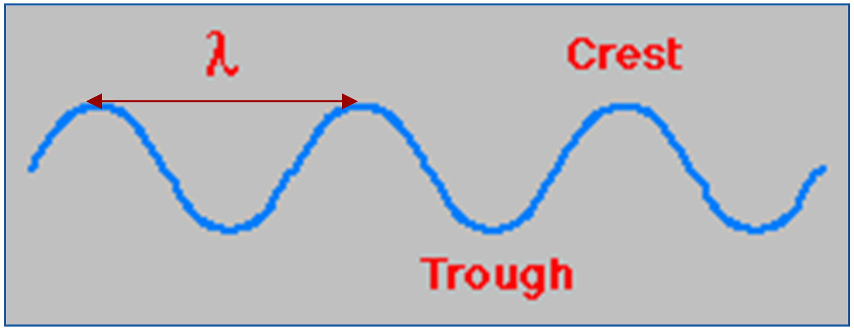
- Electromagnetic radiation
  - Quantized and transmitted as photons
  - Movement of electrons generates photons, absorption of photons moves electrons





- Described by:
  - **Wavelength** or **frequency**
  - **Energy** and **intensity**
  - **Spectrum**
  - **Polarization**
  - **Spatial configuration**

Wavelength or Frequency



- $v_p = c/n = \lambda f$
  - **c**: Velocity of light in vacuum or ~air (3×10^8 m/sec)
  - **n**: Index of refraction. e.g., 1 in vacuum, ~1.5 in glass
  - **λ**: Wavelength (780 to 360 nm – red through indigo)
  - **f**: Frequency (4×10^{14} to 8×10^{14} Hz) 600 THz
- Usually use wavelength

Energy and Intensity

- Photon energy is a function of wavelength

$$E = \frac{\hbar c}{\lambda} \qquad E = \frac{1.24}{\lambda(\mu m)}$$

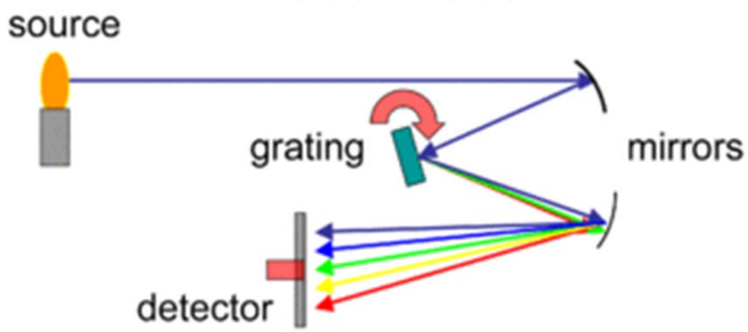
Red, 650 nm => 1.9 electron volts (eV)

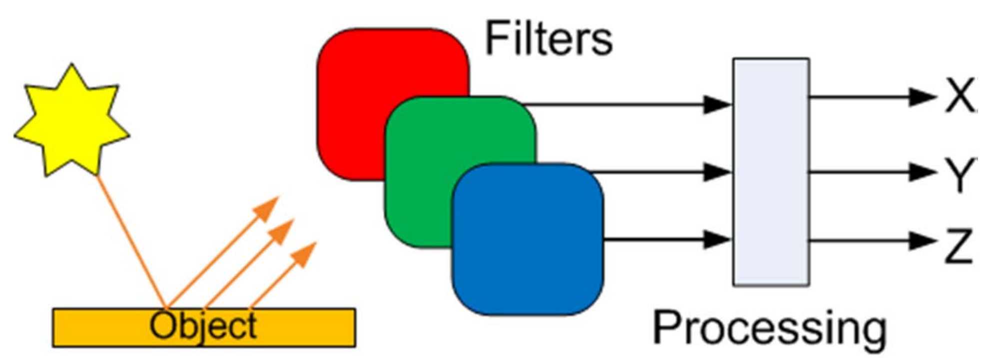
1 eV = 1.6 x 10^{-19} joules (J)

- Energy transfer rate increases with:
  - Photon energy (decreasing wavelength)
  - **Photon flux**: photons per second (intensity)
- **Spectral power**: E(λ) * flux
  - Watts per wavelength = J / sec / λ
- **Irradiance** = Watts / square area (W/m^2)
- These are **RADIOMETRIC** measures

Radiometric vs. Photometric

- **Radiometric** = Physical measurement of light
  - **Spectrometer**
- **Photometric** = Human response to light – *perceptual* brightness per wavelength.
  - **Tristimulus colorimeter** (or just **colorimeter**)
  - **Photometer**

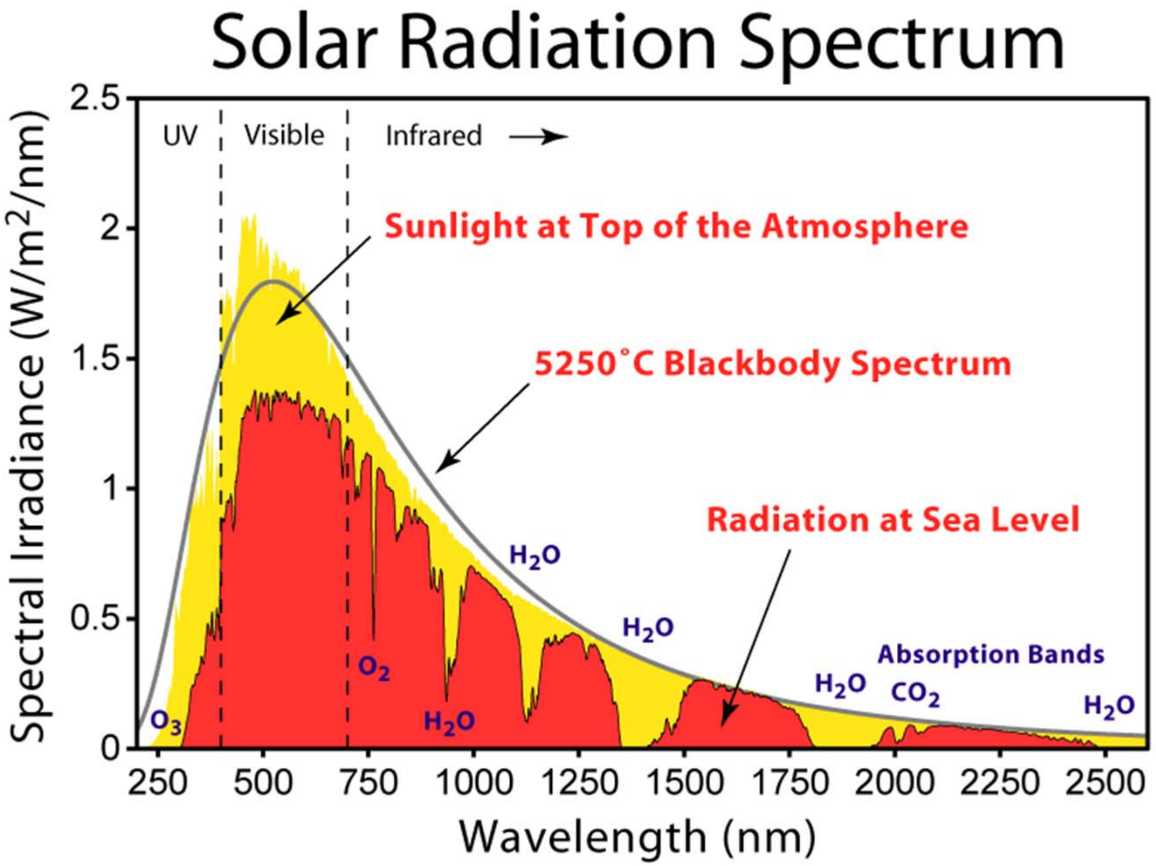




- ***Many*** different measures (~60?)

Spectrum (Radiometric)

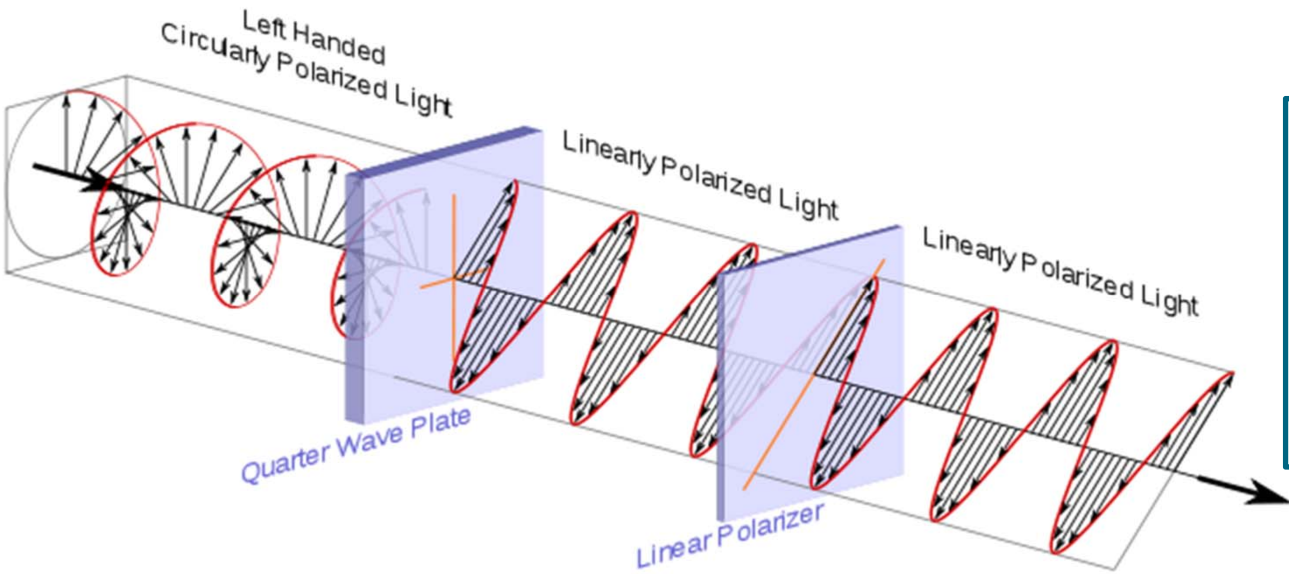
- A **spectrum** plots power or irradiance per wavelength



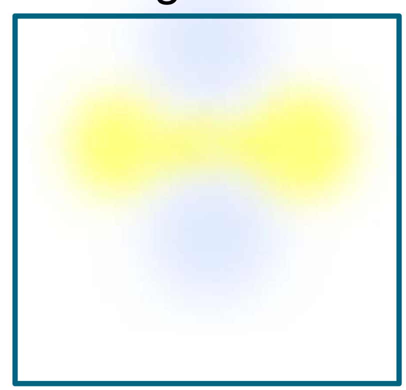
- Different than **spectral response** plot

Polarization

- Orientation of oscillating electromagnetic wave
- Some materials change color with polarization
  - Humans and MV Cameras insensitive to polarization
  - Some animals (bees, fish, etc.) detect polarization



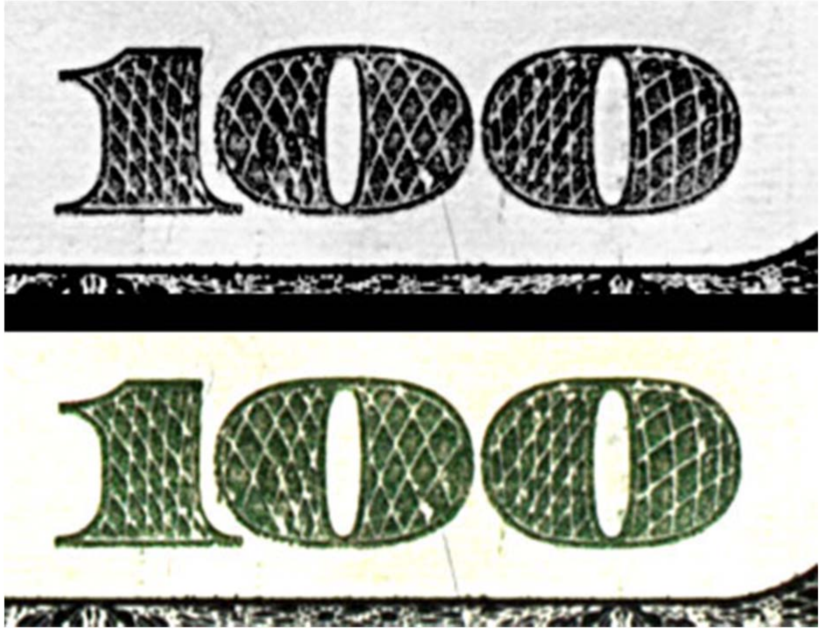
Haidinger's brush



Polarizers can reduce "highlights" or glare off of some surfaces and so help color detection.

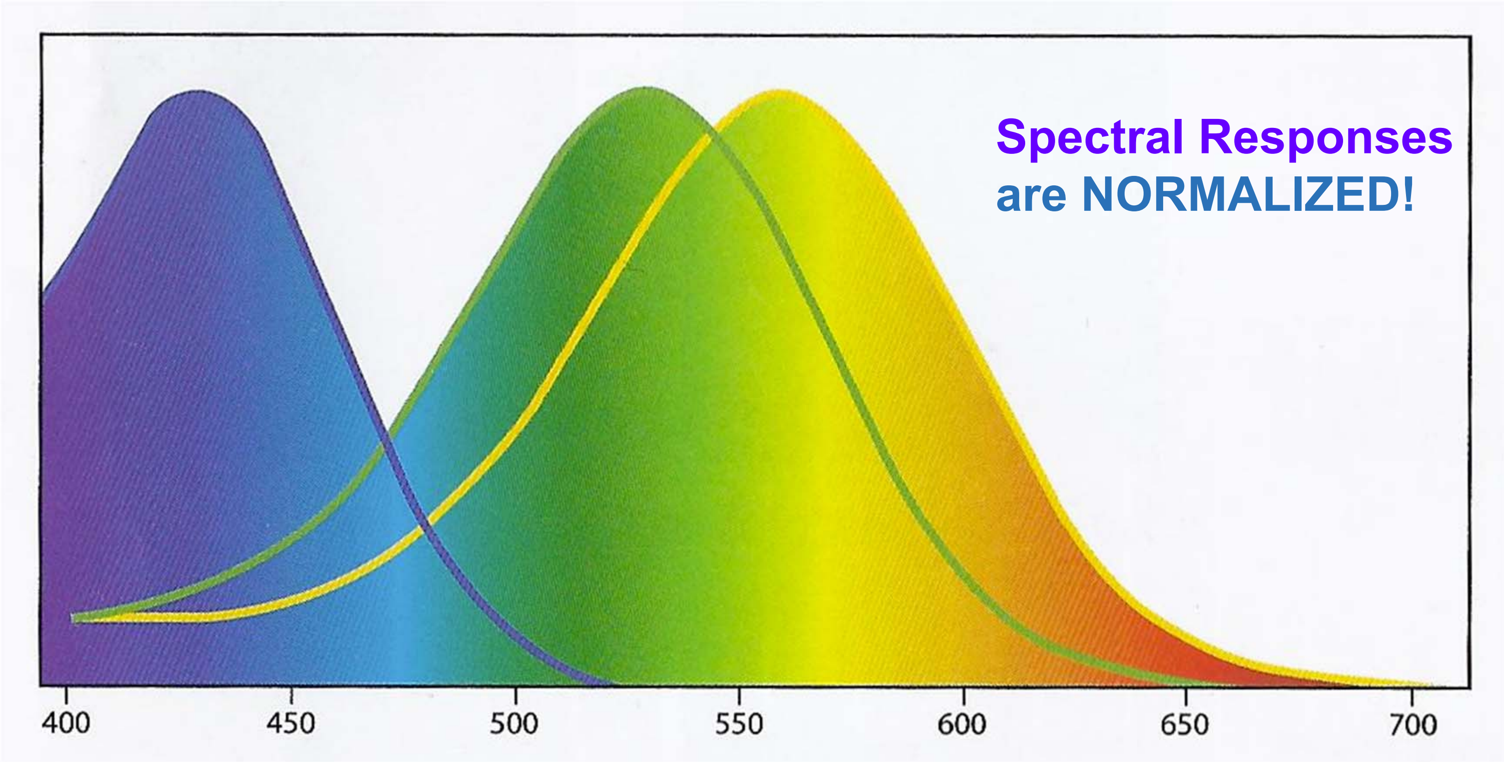
Spatial Configuration

- Position of lights relative to objects
- Can cause color appearance to change
  - Thin films, pigmented materials (Fresnel)



Ratios of Color Sensor Types

- Color vision requires two or more light **sensors types** with different **spectral responses**

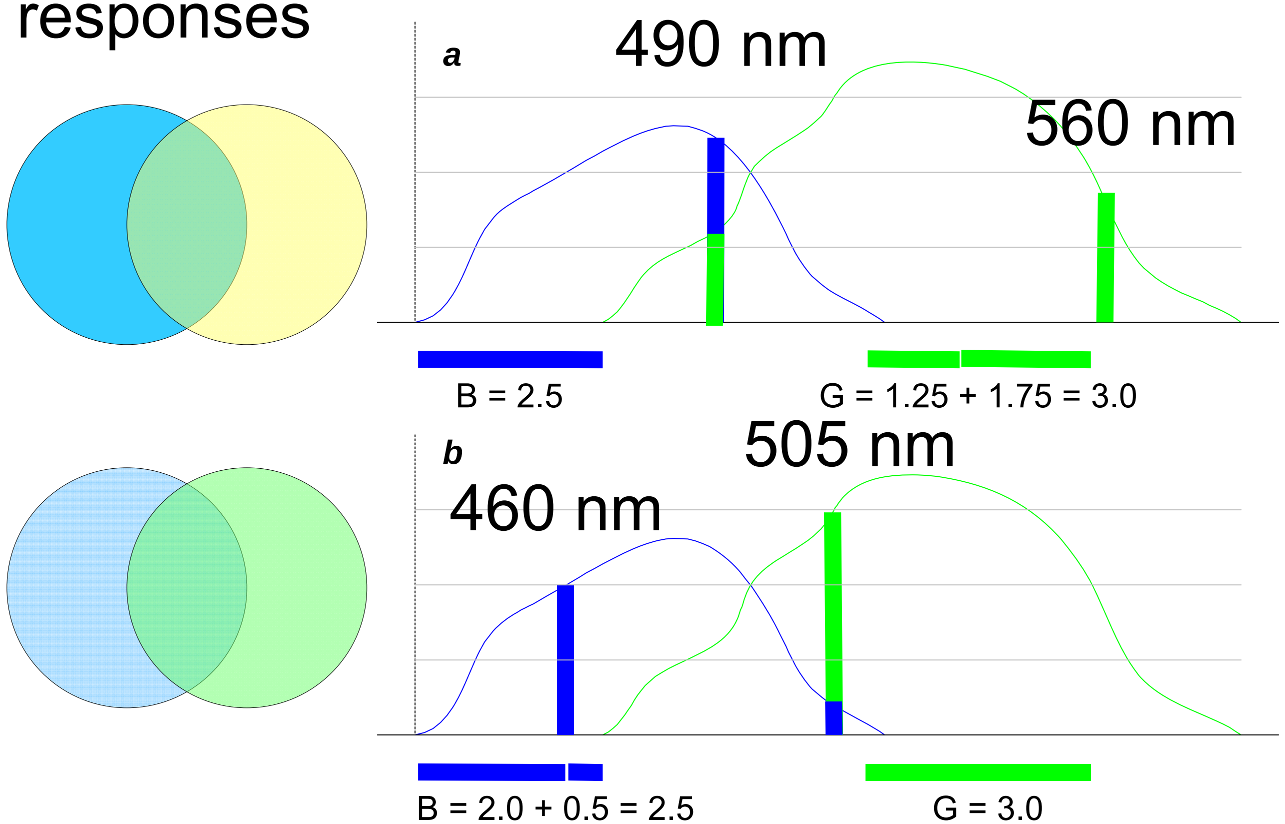


Why at least two sensor types?
Why overlapping spectral responses?

Photometric units

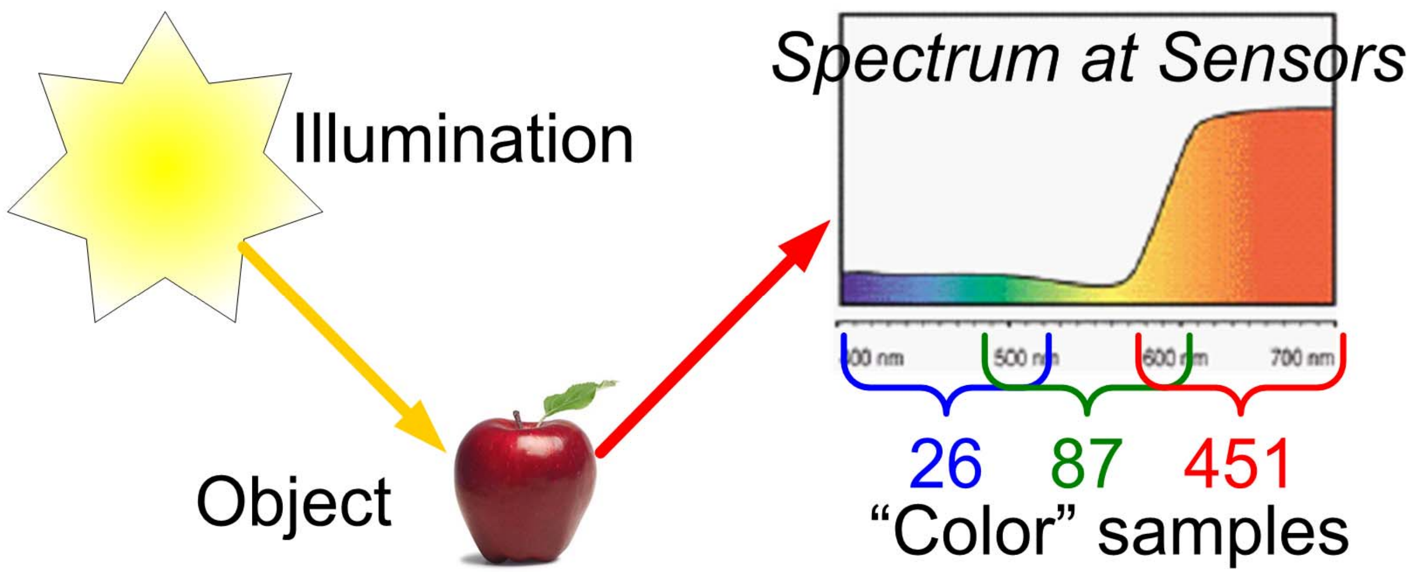
Metamers

- Same color response to different light spectra
  - Color vision can't distinguish some different spectra!
  - Due to broad, overlapped sensors' spectral responses



Model of Color Image Formation

- Modeled as the **product** of:
  - Illumination spectrum
  - Object transmission or reflection spectrum
  - Sensors' **spectral responses**



A Mathematical Model

- Output of a sensor type, P_i, is a **product** of:
  - Illumination spectrum: $E(\lambda)$
  - Material (object) reflectance spectrum: $R_m(\lambda,\theta,\varphi)$
  - Sensor response spectrum: $S_i(\lambda,\alpha)$

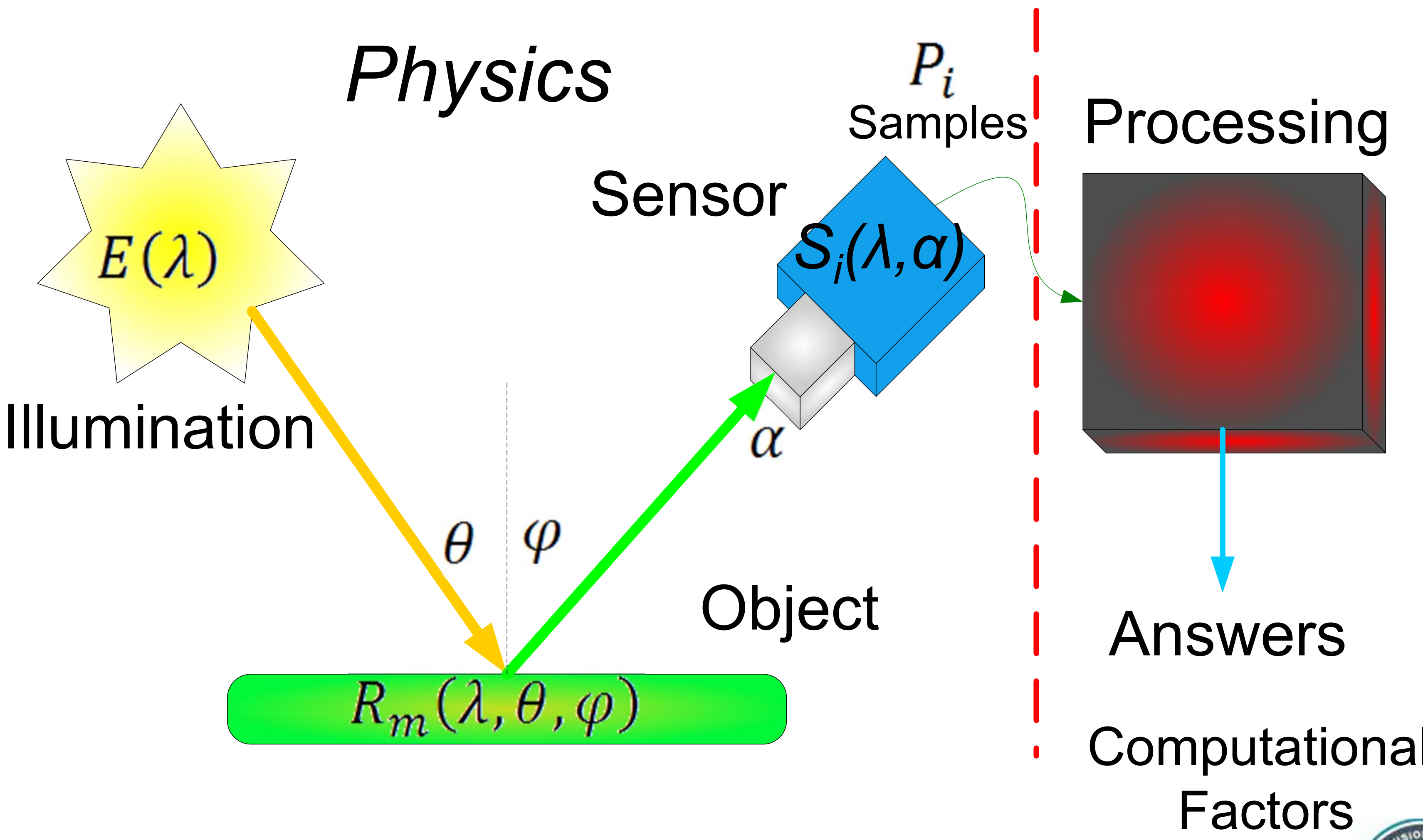
$$P_i = \iint E(\lambda) R_m(\lambda, \theta, \varphi) S_i(\lambda, \alpha) d\lambda d\alpha$$

- Sensor P_i output is a function of wavelength (*λ*), lighting and viewing **imaging geometry*** (*θ,φ),* and sensors' **acceptance angle** (*α)*

Greek Cheat Sheet: *λ* Lambda, *θ* Theta, *φ* Phi, *α* Alpha

*The term **imaging geometry** is a convenience and not in general use

Diagram of Imaging Model



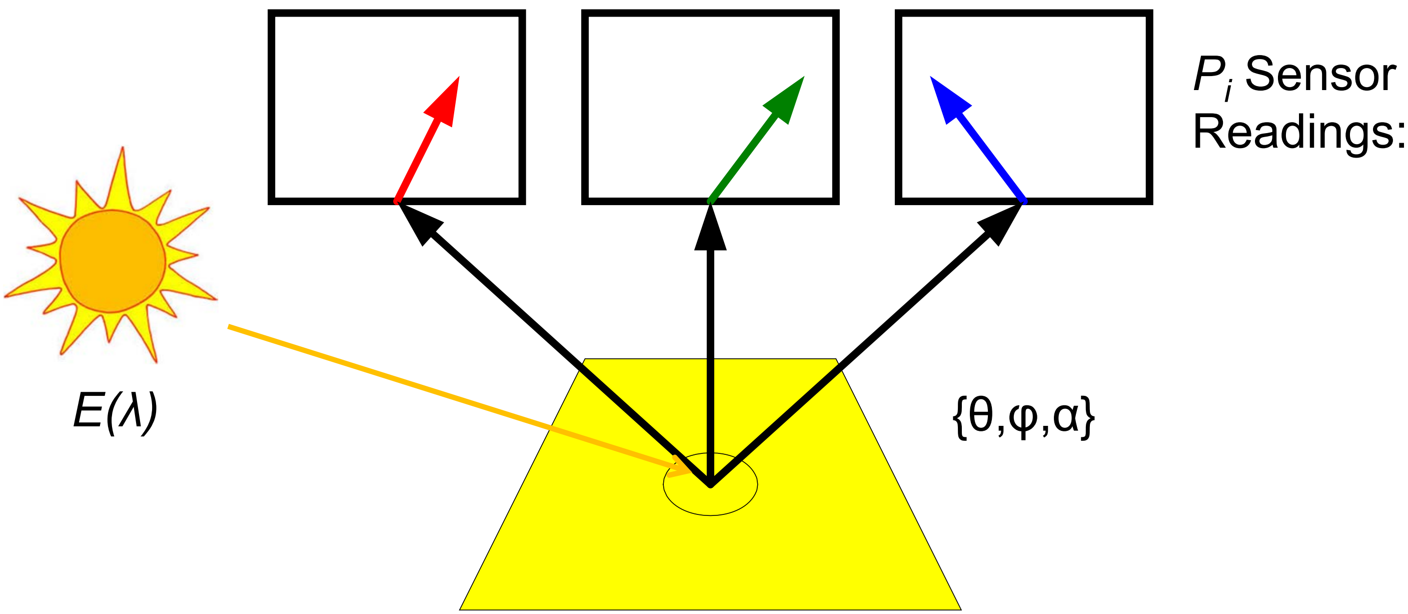
The Color Vision Problem

- Given broadband sensor types' outputs, P_i, recover object's spectrum, R_m

$$P_i = \iint E(\lambda) R_m(\lambda, \theta, \varphi) S_i(\lambda, \alpha)\, d\lambda\, d\alpha$$

- Must know or estimate $E(\lambda)$ and (θ, φ)

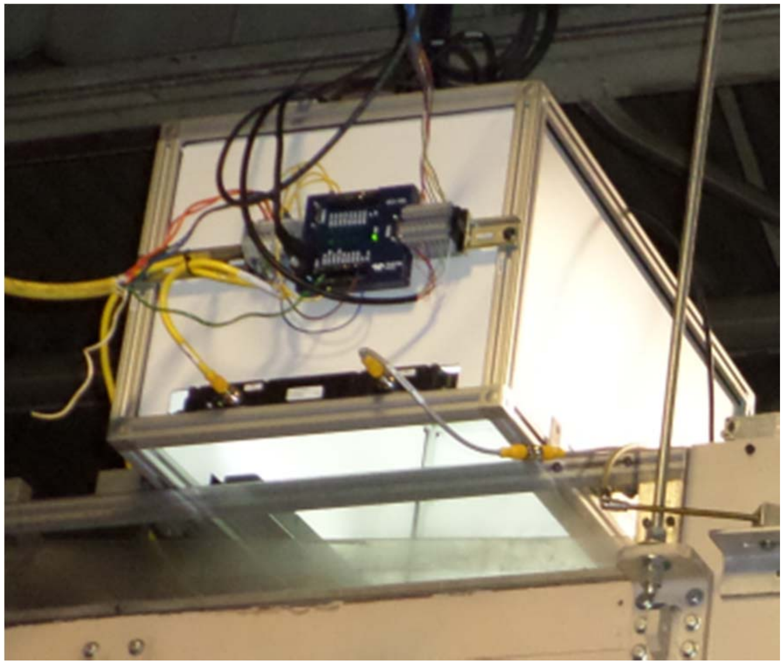
Is the material or light yellow??!



Recovering the Illuminant

- We know sensor responses and can know or estimate the imaging geometry *(θ,φ)*
- ➢ We must know or **recover the illuminant**, *E(λ)*
- Vision uses constraints and assumptions to "factor out" illumination and get object color

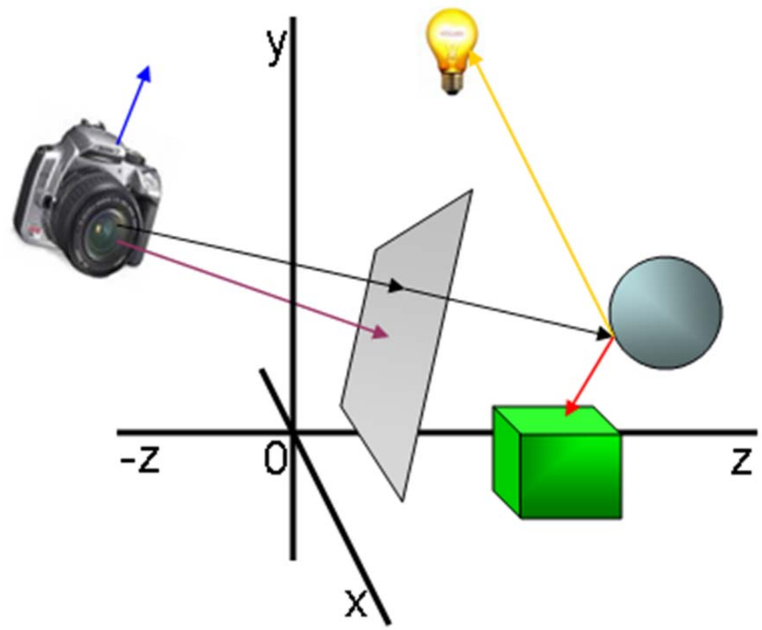
Example: MV uses constrained lighting and assumptions to **color balance** the image



Vision is Under-constrained

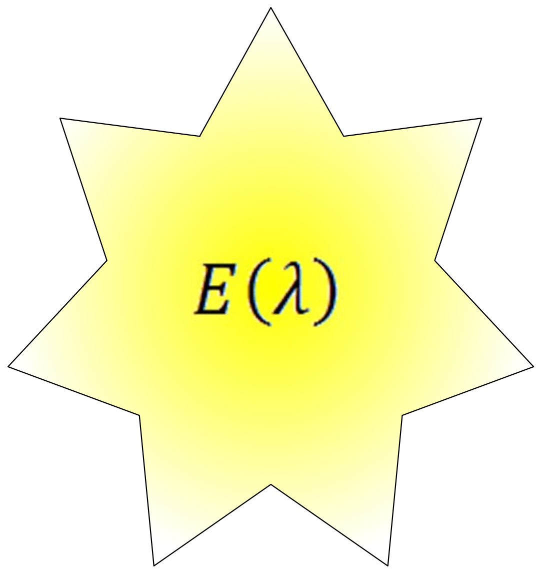
- Color is an under-constrained problem
  - More unknowns than measures
  - Multiple or no solutions
  - An "inverse" problem
- Need additional constraints and assumptions to reliably recover color

Computer graphics is a "forward problem" – you have information needed to generate P_is. This is much easier than an inverse.



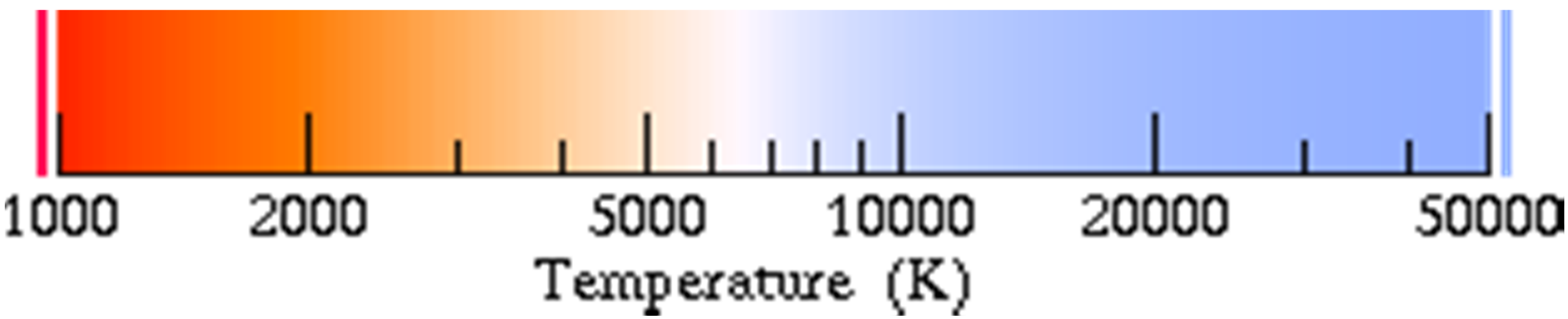
Illumination

Elements in color image formation
starting with illumination



Black Body Radiators

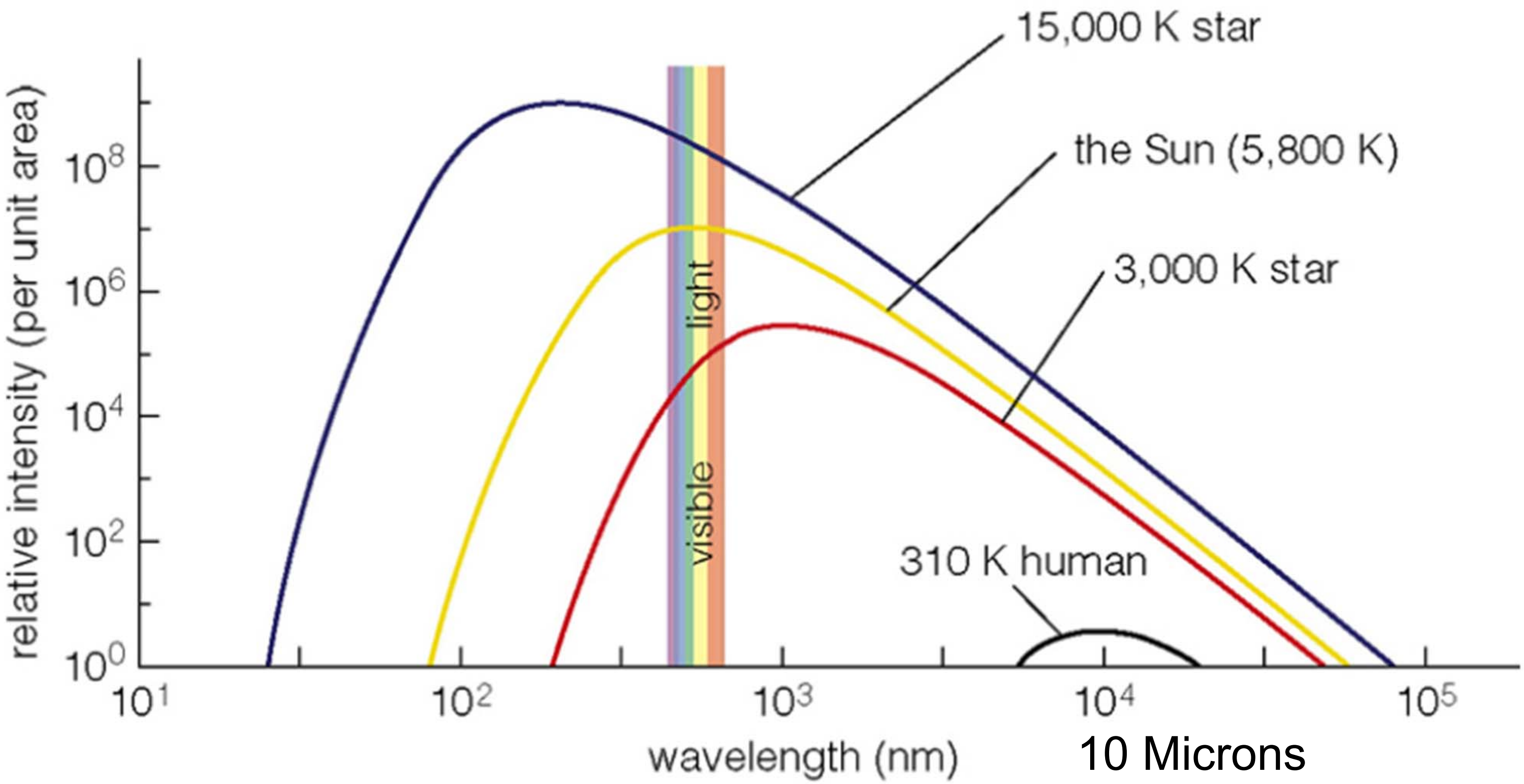
- **black body radiators**
  - Heat “jiggles” electrons to create broadband radiation
  - The sun, flames, people, incandescent lights
- Visibly glow at ~ 400 C (670 K) (750 F)
- Color shifts towards the blue as object heats up:



- Used as an illumination standard
  - Simple to described – function only of temperature

Black Body Radiation

- Spectrum is a function only of temperature, T

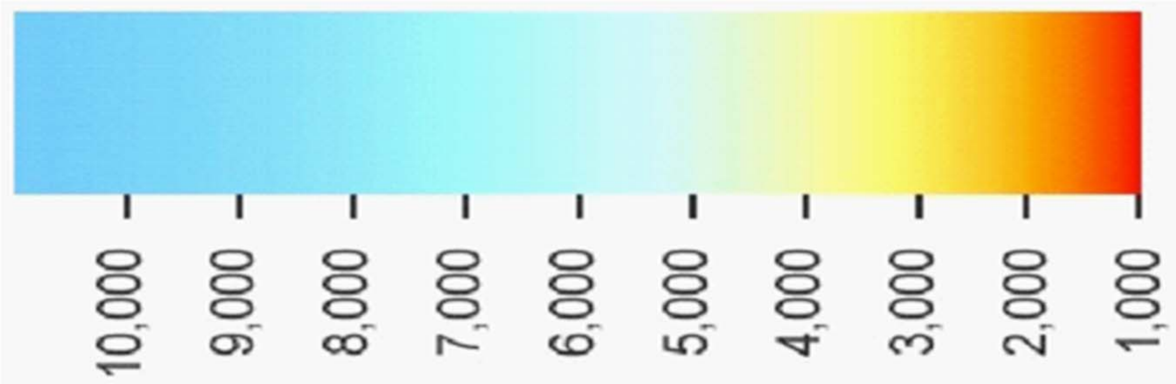


10 Microns
(Mid-IR)

K = Temperature in Kelvin

Color Temperature

- An illuminant's **Color Temperature** is the temperature of a black body radiator that matches the illuminant's **perceived** hue
  - For example D65 is daylight color from BB @ 6500 K
  - **Correlated color temperature** used for light sources that approximate black body (e.g. fluorescent lights)



Perceived color temperatures follow the **Planckian locus**

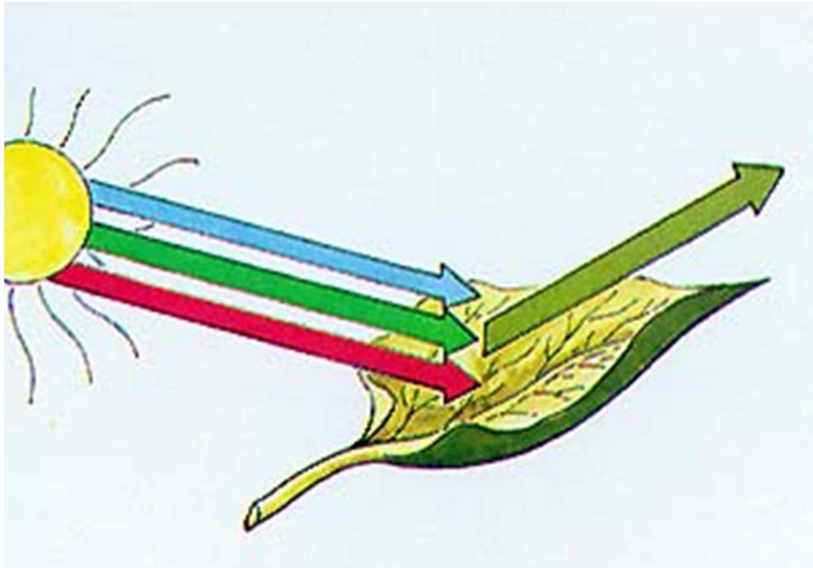
Correlated Color Temperature

CRI = Color Rendering Index ~ how close a match to “full” BB spectrum

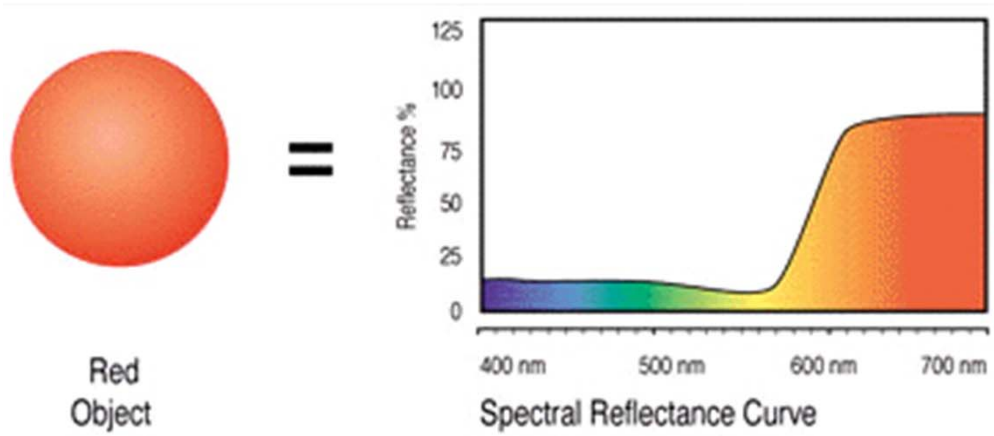
Objects

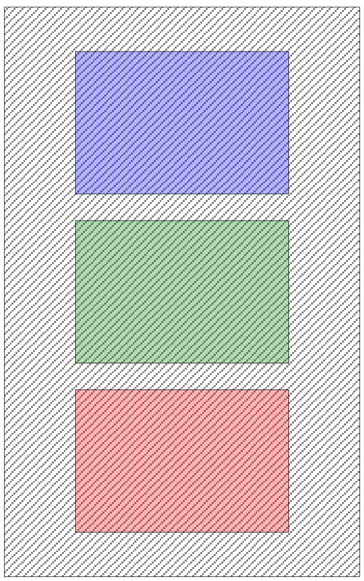
$$R_m(\lambda, \theta, \varphi)$$

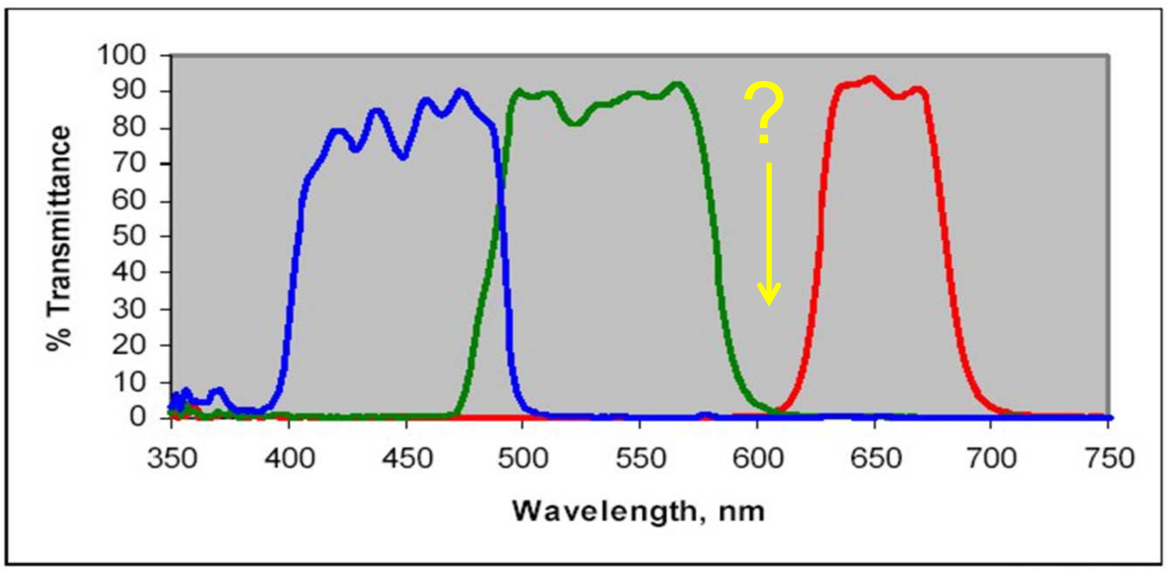
- Object color arises from the wavelengths (λ) the object reflects or transmits
- Color is also a function of the angles of object illumination and view (θ,φ)
  - Object color can vary with temperature (**thermochromic**). Very small effect for most (cool) materials.



Reflectance and Transmission



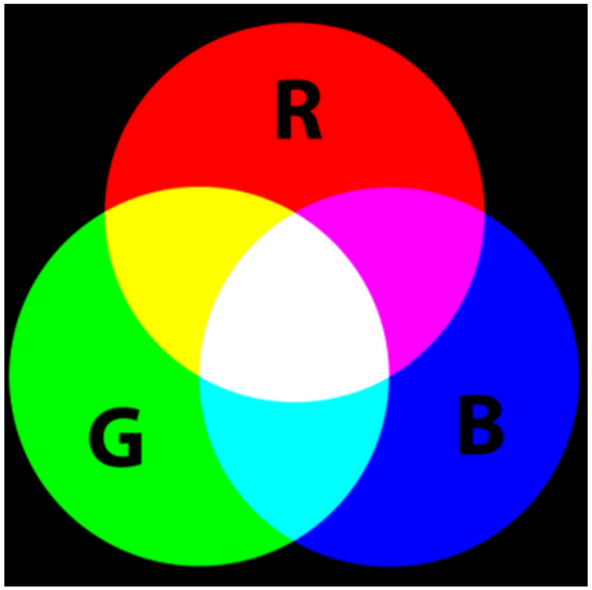


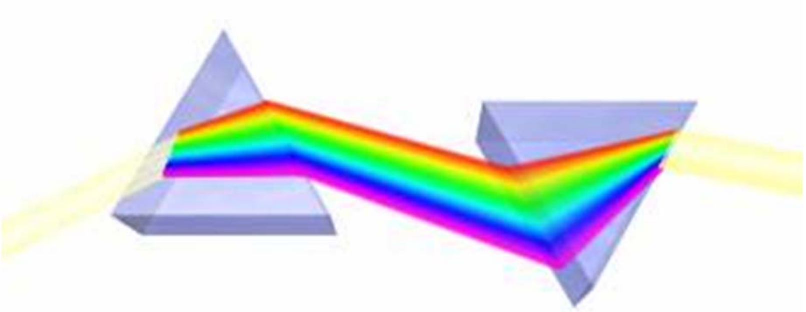


Filters' spectral transmission curves.
Why are these not good for color vision?

Additive color

- Light wavelengths add to give color
- Mixes **primary** colors of light
  - For example **green** + **blue** = **cyan**
- Use filters or prisms to create **primaries** from white light. LCD display, for example

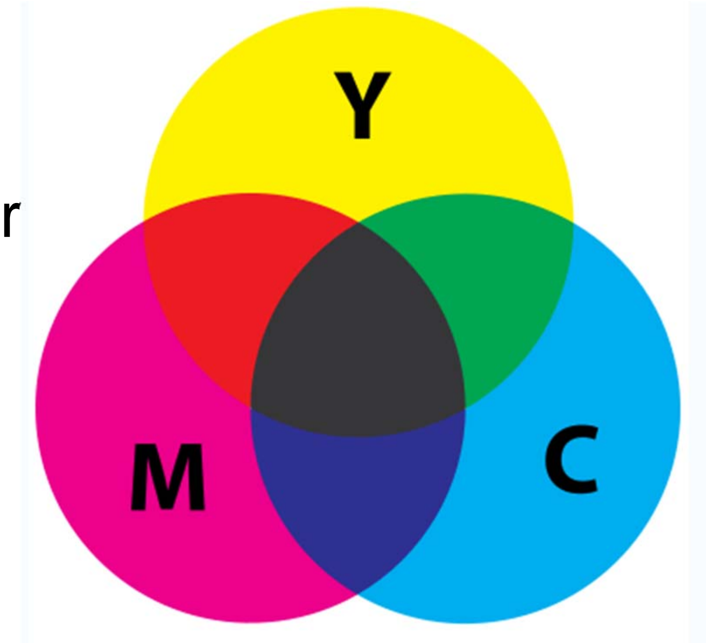


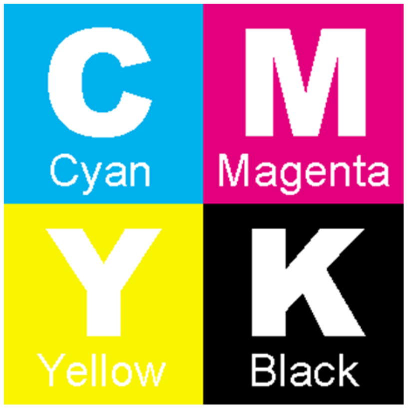


Newton's Experiment

Subtractive Color

- Pigments and filters selectively absorb (subtract) wavelengths
  - Remaining wavelengths give color
- Mix **primary** color pigments to get other colors
- For example, CMYK inks
  - white - **cyan** - **magenta** = **blue** (reflected)

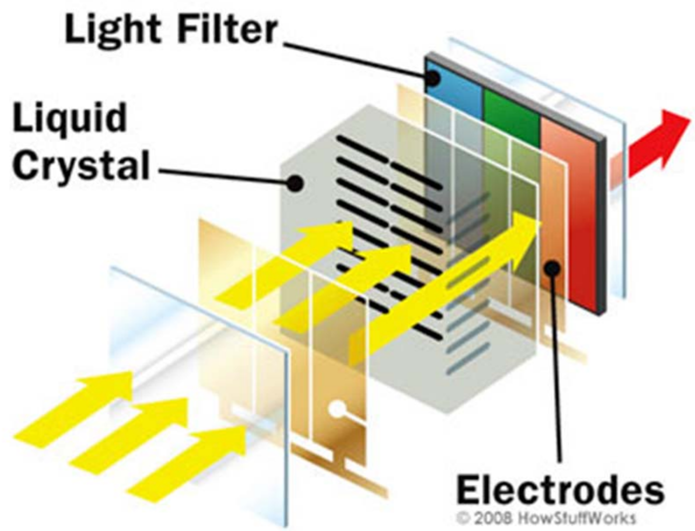




Most common, but we usually think in terms of **additive** color

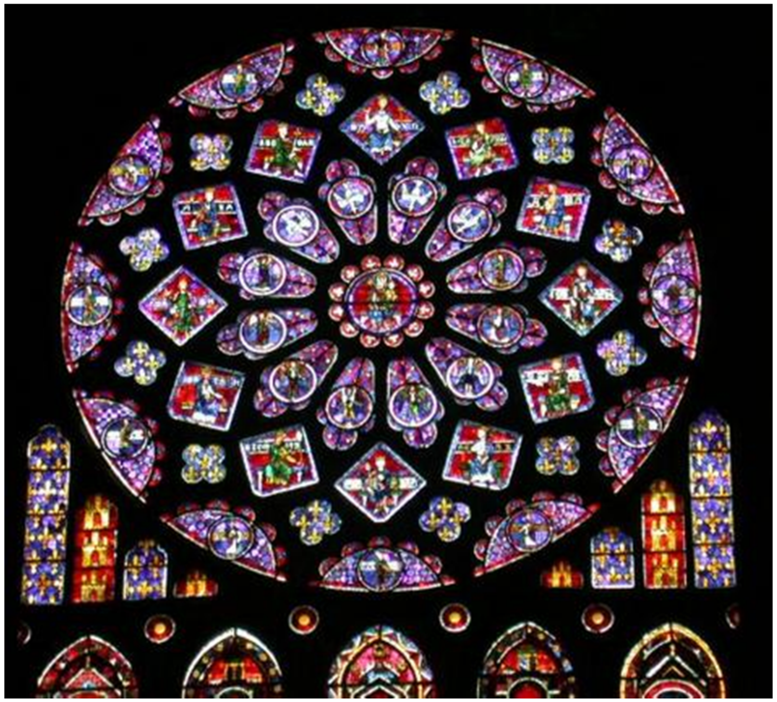
Example: LEDs and LCDs

- LEDs of different colors can be added to perceptually match a range (**gamut**) of colors
- LCD monitor filters white light to absorb all but a set of primaries (**subtractive**), eye mixes those primaries to get range of colors (**additive**)



Color Filters

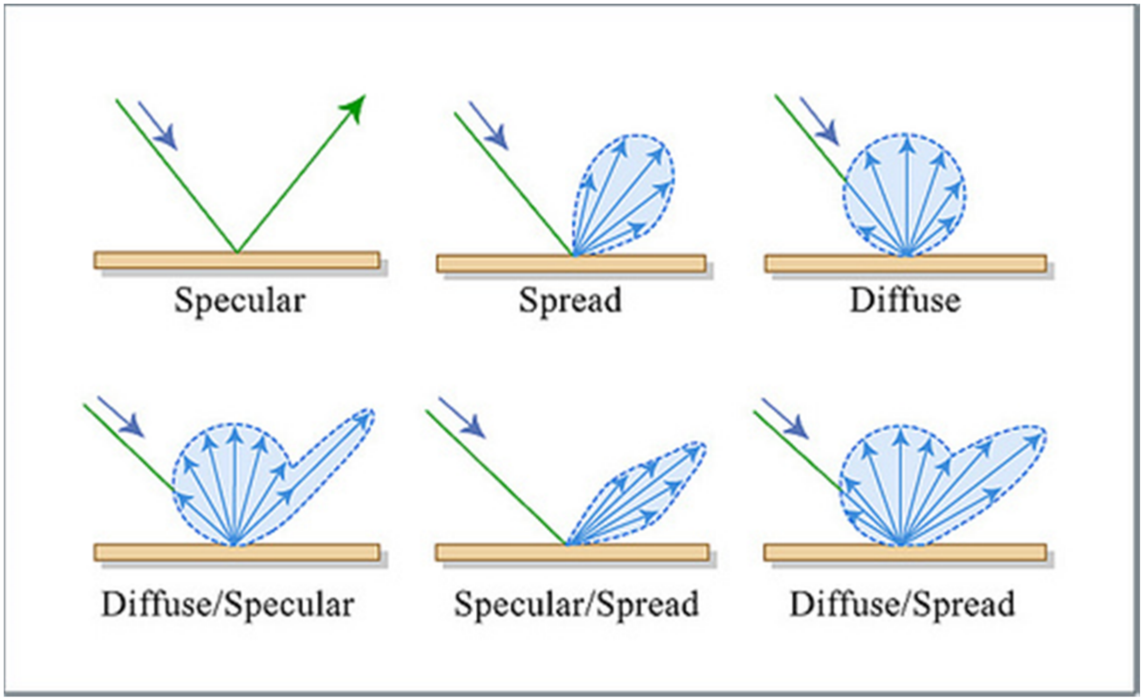
- Pigments (e.g., organic dyes)
- Thin-film interference coatings (e.g., dichroic)
- Surface plasmons in metal nanoparticles
  - Reradiates wavelengths



Issue: Color fading ("fugitive" colors)

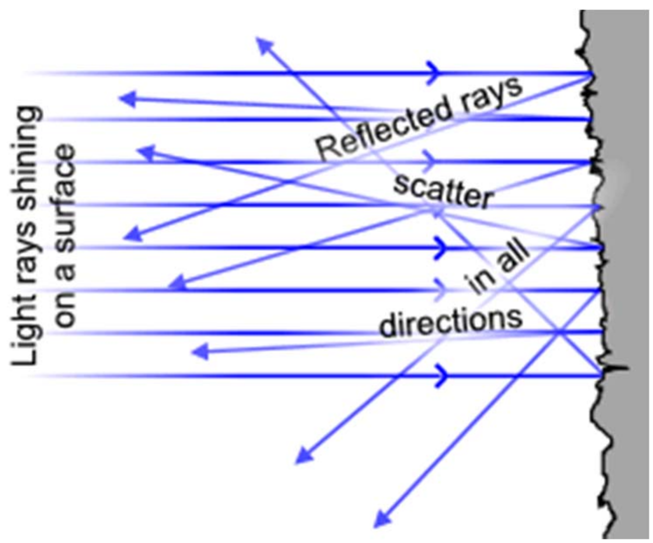
Material Reflectance

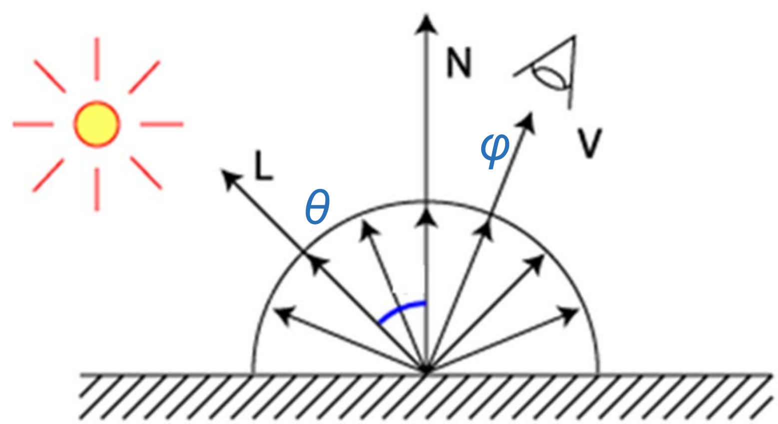
- A function of object's surface structure:
  - Rough => **Diffuse** reflection
  - Smooth => **Specular** (mirror-like) reflection
  - **Pigmented** => Complicated reflectance "spread"
  - Layered => **Interference** colors and patterns



Diffuse Reflectance

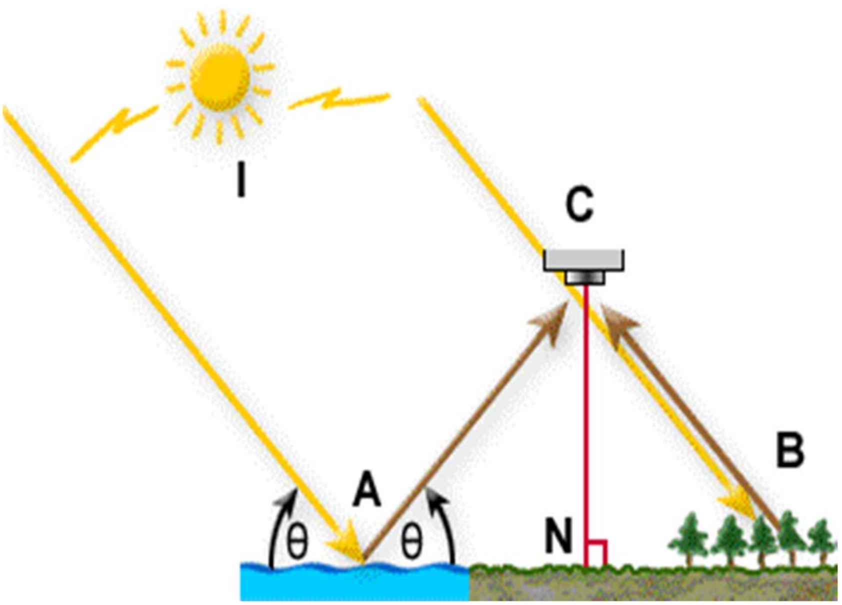
- Machine vision likes **Diffuse Reflection**
  - Incident light is reflected (nearly uniformly) over a wide range of angles
  - $R_m(\lambda,\theta,\varphi)$ (intensity) less dependant on θ,φ
    So imaging geometry less of an issue

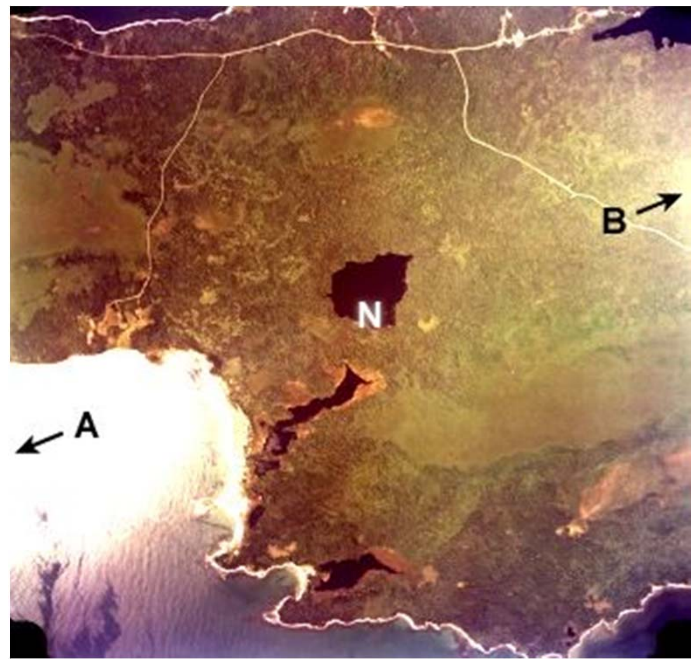




Specular Reflection

- MV generally doesn't like **Specular Reflection**
  - Angle of incidence = angle of reflection (mirror)
  - Gives "highlights", "hot-spots", "gloss", "shine"

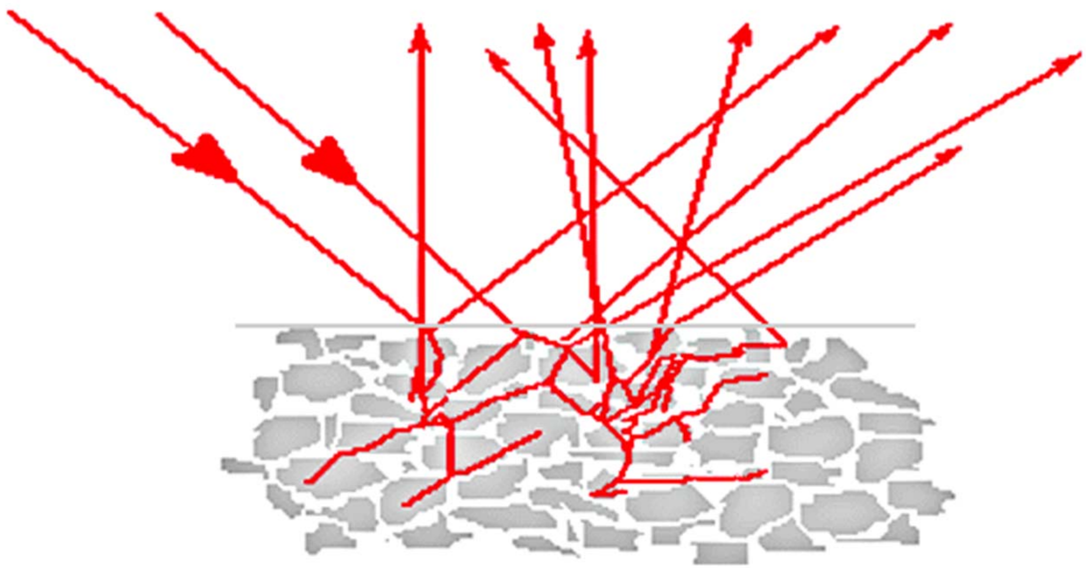




  - Shows the illuminant color which can be useful if it is consistent (very sensitive to angle)

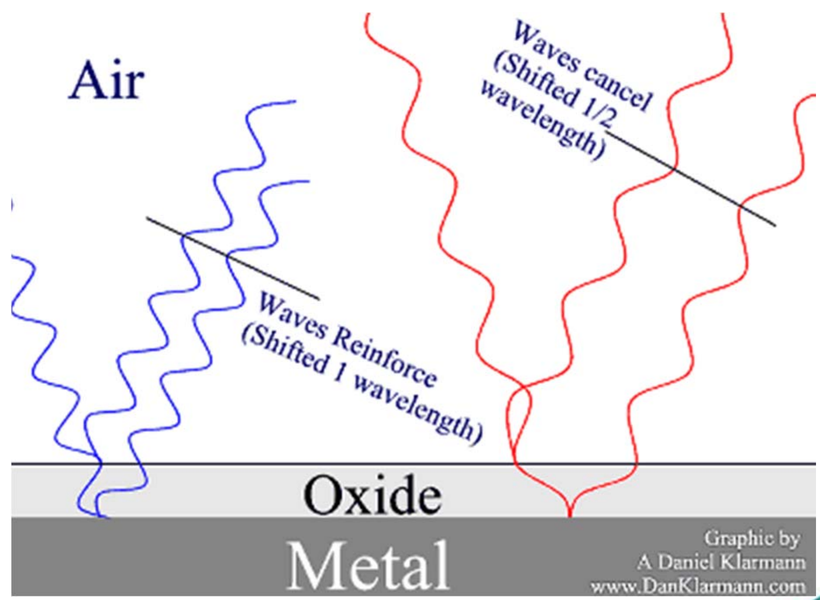
Pigmented Reflection (Fresnel)

- Paint, skin, agricultural products, printed labels
- Pigments in a binder absorb and reflect light
  - Could also have **interference** colors
- Complicated observed color and reflectance
- Color varies with illumination and view angles, illumination wavelength, and **polarization**



Interference Colors

- Thin layers of material can generate **interference colors** (**iridescence**)
  - Color (wavelength) variation with geometry
  - Coatings, semiconductors, some insects and birds
  - In controlled situations, can use to measure film thickness



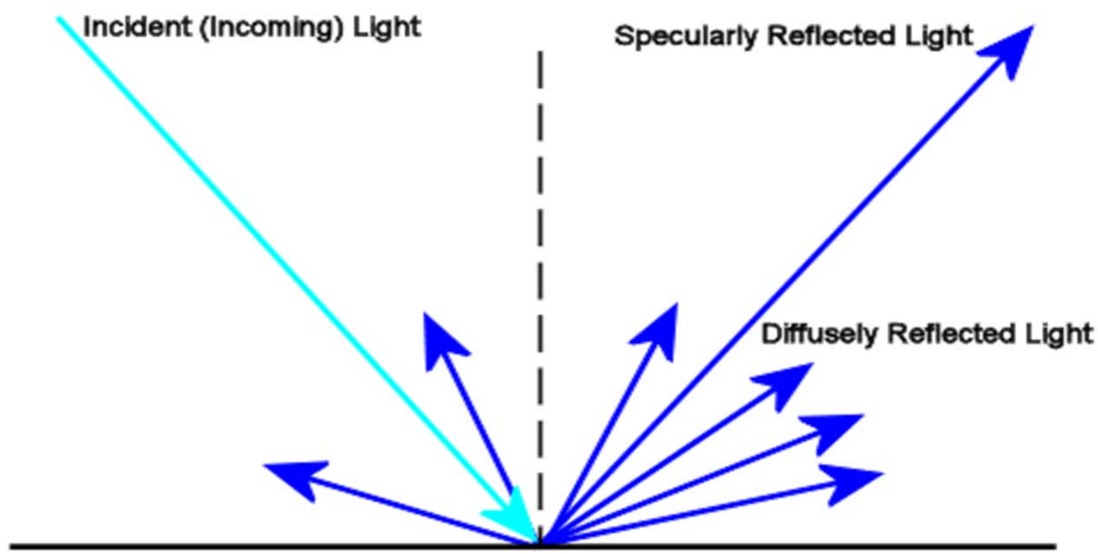
Color Shifts with Geometry

- Pigmented materials have intensity shifts and may have small spectrum shifts with change in angle
  - Again: fix illumination and view angles θ,φ
- **Iridescent** materials can have large wavelength shifts with angle – difficult to control

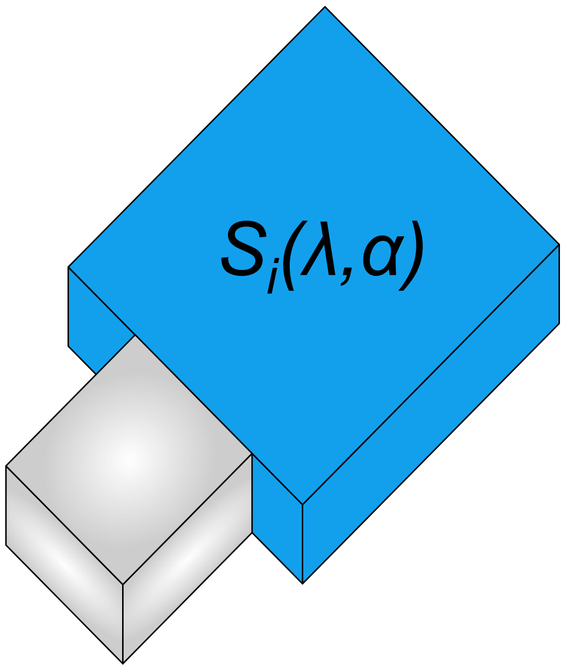
Color-shifting ink

Combination of Reflectance Types

- Most materials have a combination of reflectance types
- As examples, plastic and unpolished metal have both **diffuse** and **specular** components

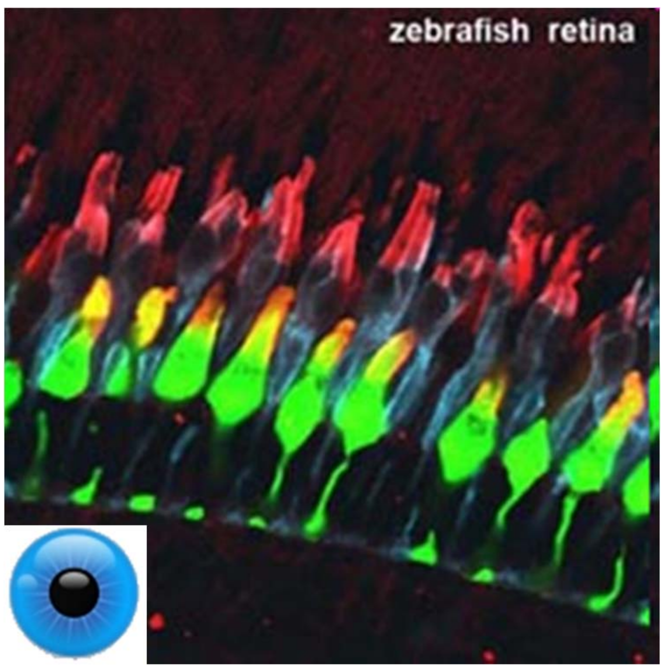


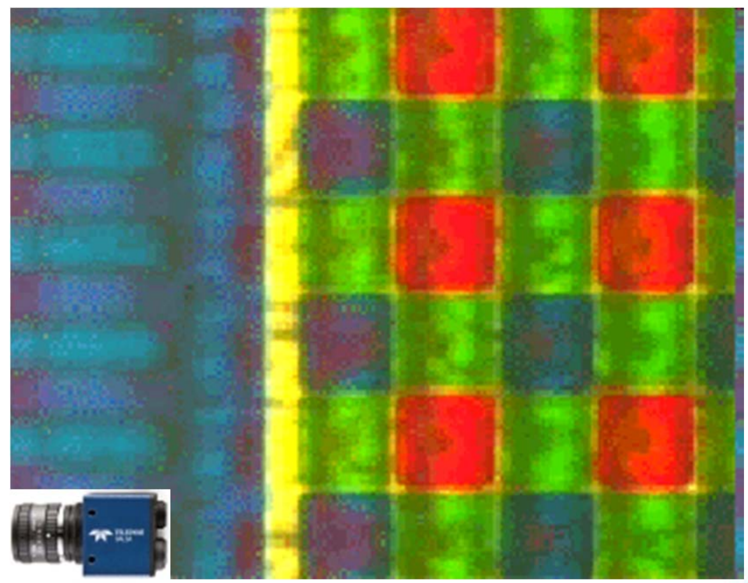
Sensor



Color Vision Sensors

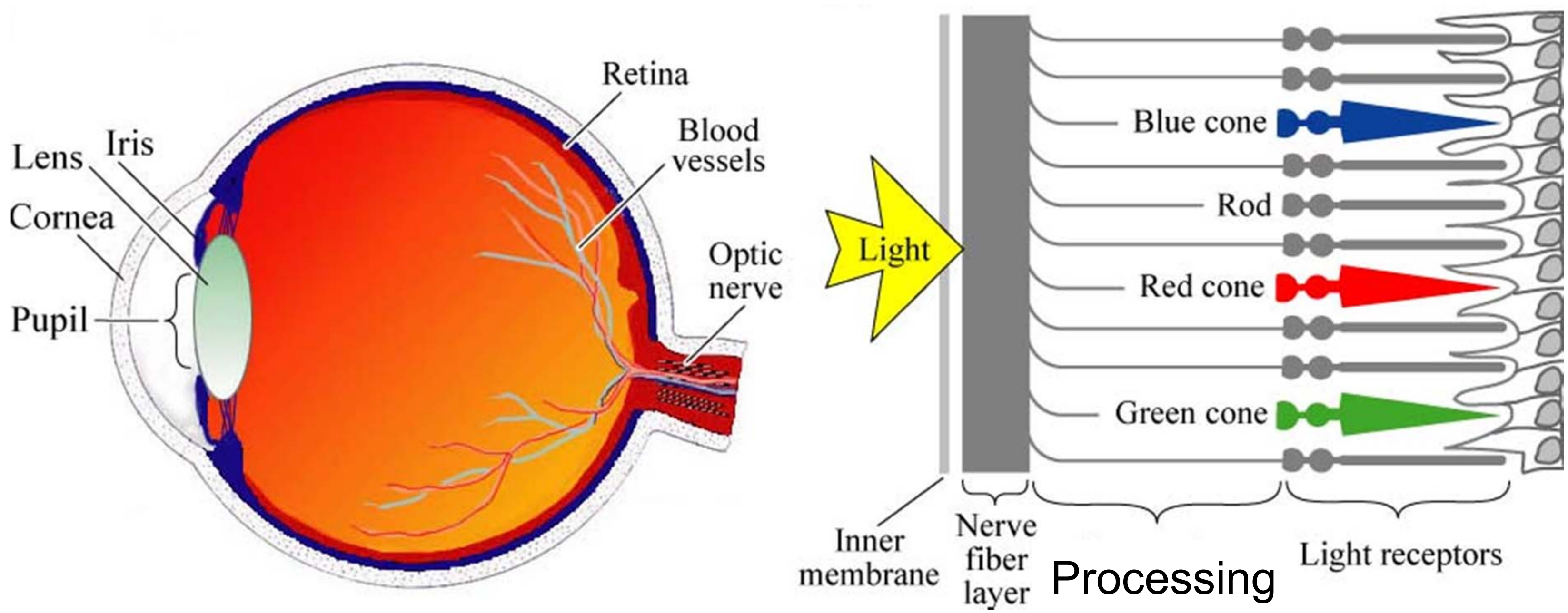
- *Color vision requires 2 or more sensor types with different spectral responses.*
  - More types gives better color discrimination
- We and most CMVs have 3 (N=3) sensor types with broad spectral responses





Sensels

Human Eye

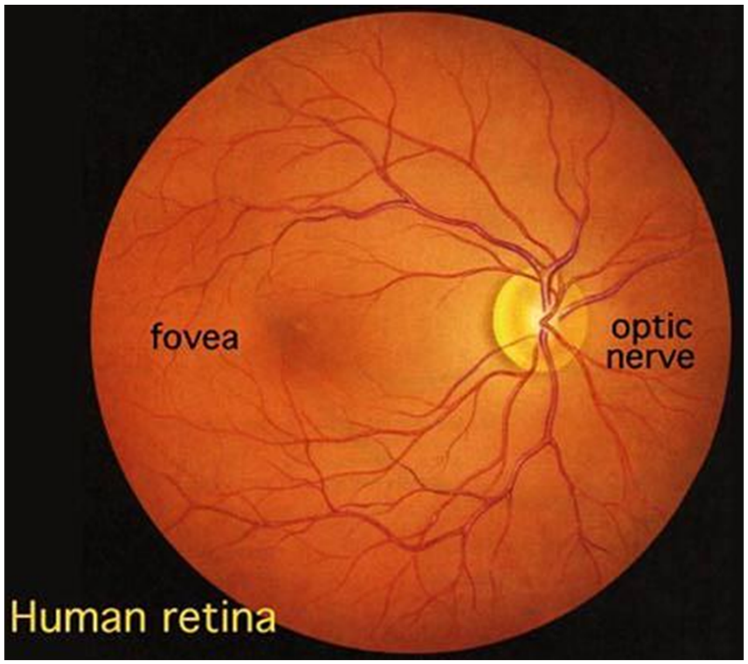


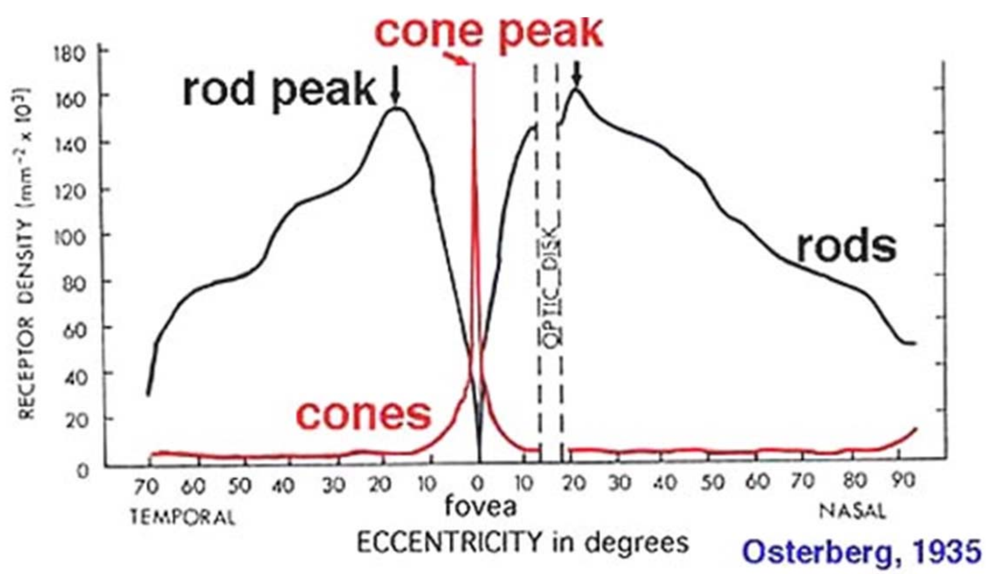
Why are "wires" on top of "sensors"?

- **Rods** = Monochrome
  - **Scotopic** (dim light, "nighttime") vision, less "sharp"
- **Cones** = Color (and detailed, "sharp" vision)
  - **3** Sensor types: Long, Medium, Short (or ~ Red, Green, Blue)
  - **Photopic** (bright light, "daytime") vision – mnemonic: photo

Retina and Fovea

- **Retina**: Light sensitive neural layer of eye
- **Fovea**: Area of retina with high density of cones

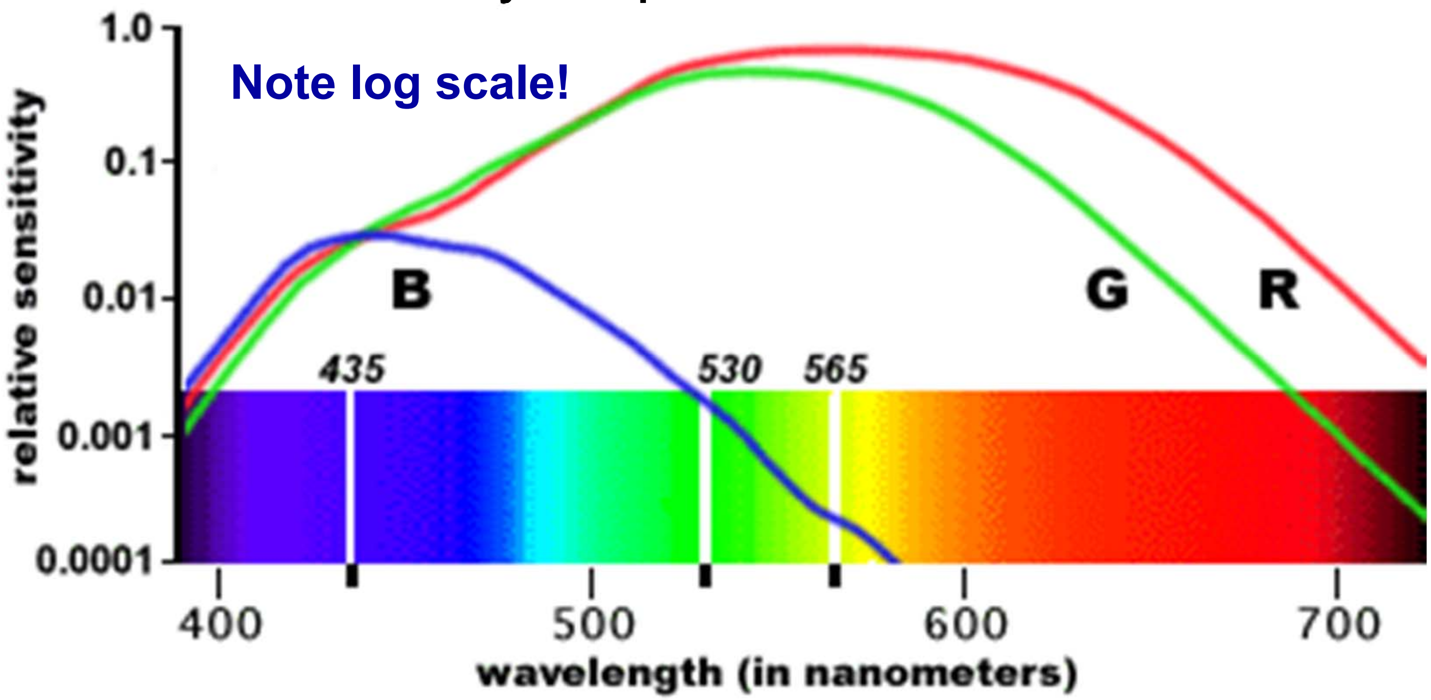




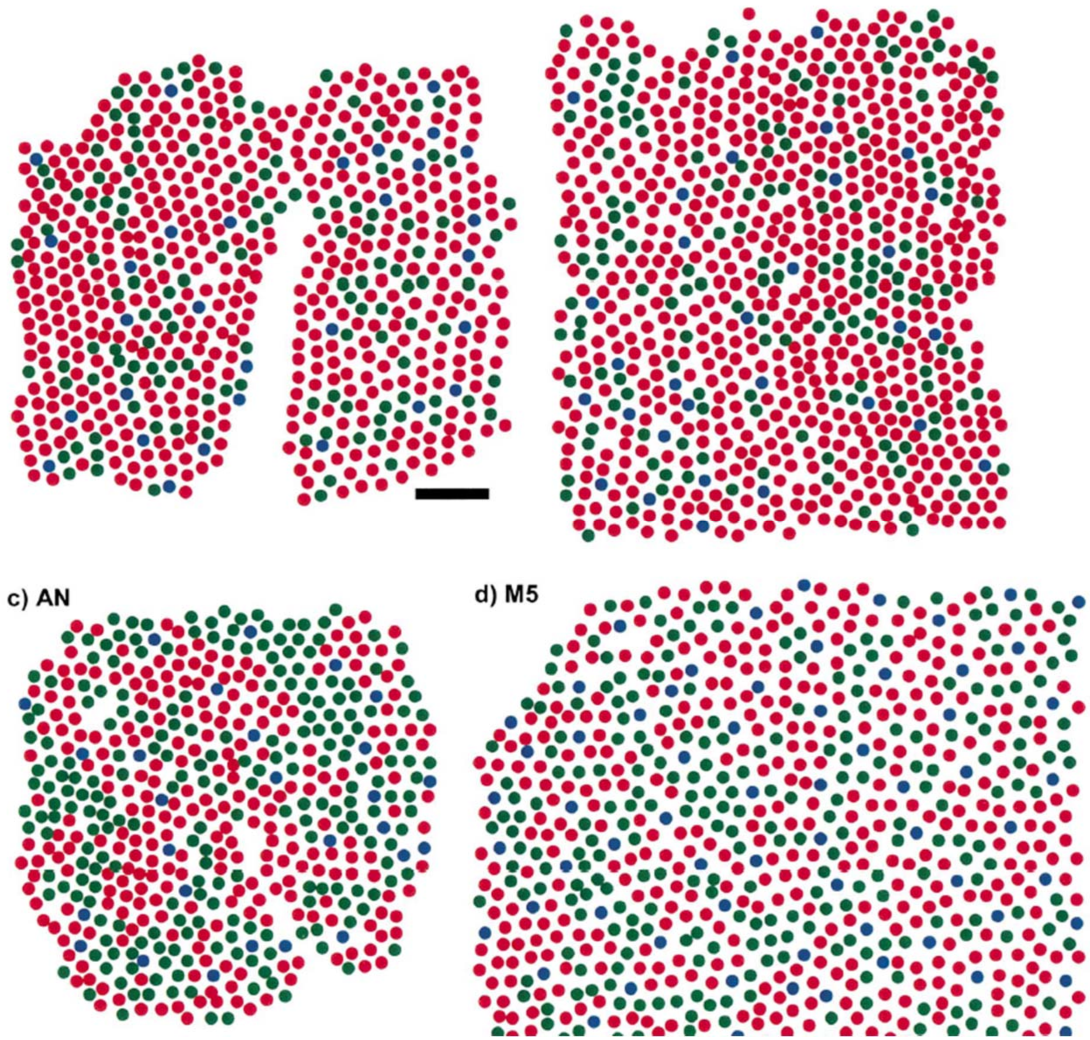
- 6-7 million cones, mostly in fovea (sharp vision)
  - About 64% “red”, 32% “green”, ***only*** 4% “blue”
- 120 million rods mostly outside fovea

Human Cone Sensor Types

- Broad wavelength sensitivity, with peaks in Long, Medium, Short (~R,G,B) wavelengths
  - Cone responses set by pigments (photopsins)
  - Electrochemically amplified



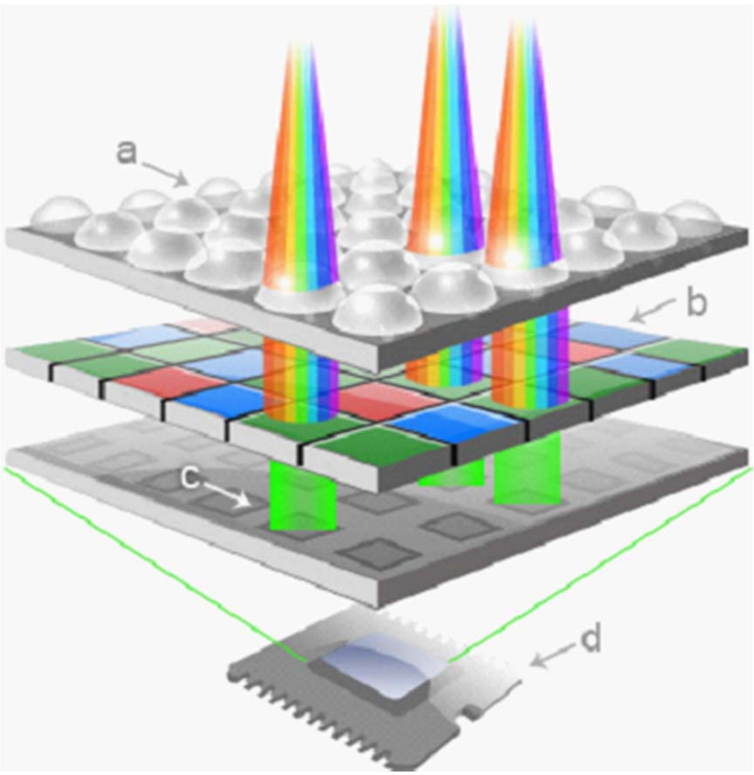
Cone Distribution



Random distribution, ~hexagonal packing
Individual differences, blue cones are special

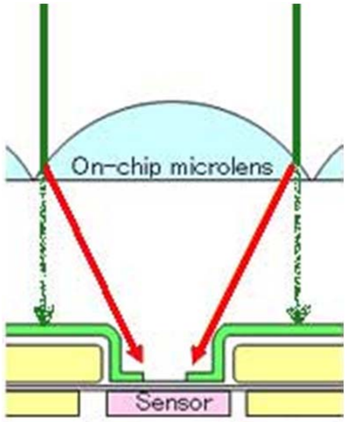
Camera Color Sensors

- Color sensors use a monochrome sensor overlaid with (typically) **3** types of color filters
  - **Bayer** (BUY-er) pattern of color filters most common



a. Microlenses
b. Color filter mosaic
c. Sensor pixels
d. Packaging (IC)

Correct lens action->

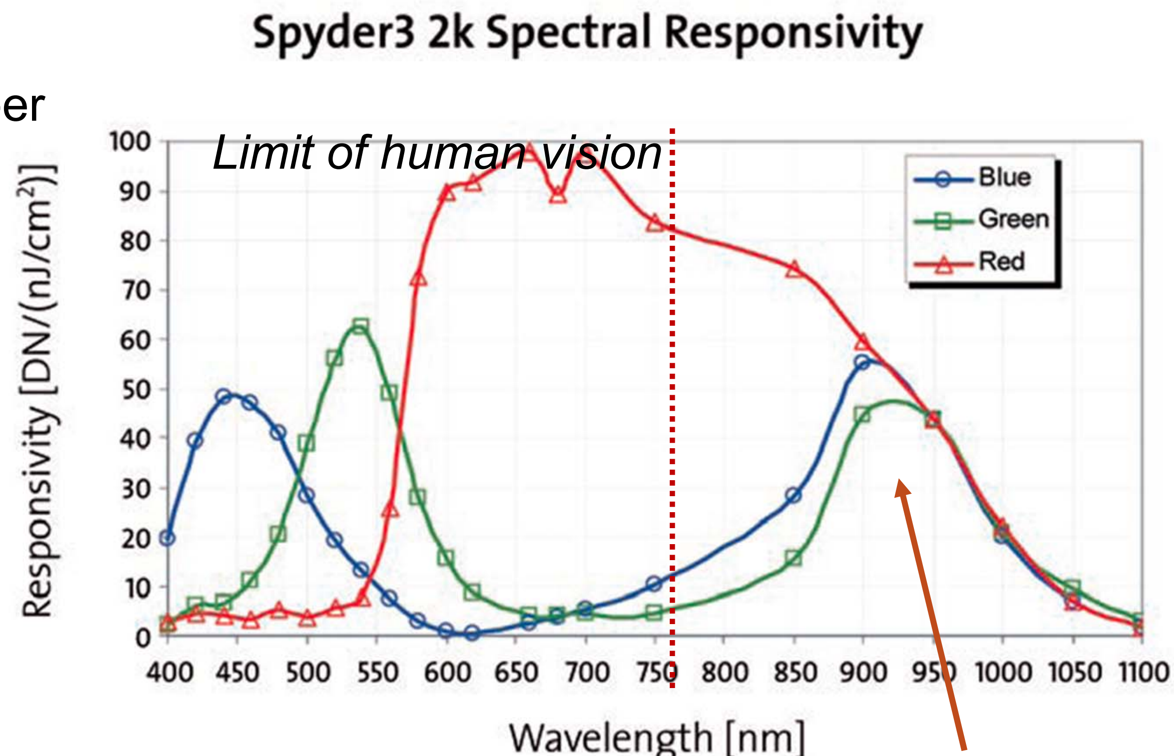


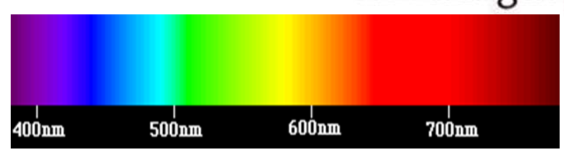
- Fill Factor
- Acceptance angle

Camera Sensors' Responses

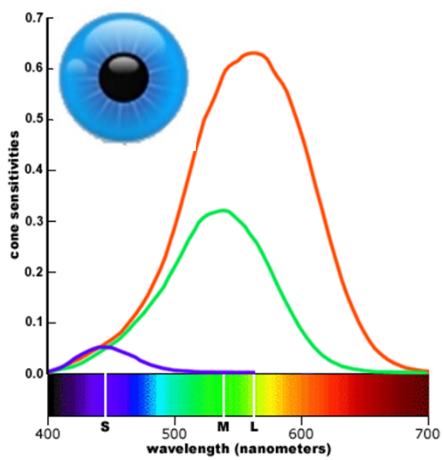
DN = Digital Number

Teledyne DALSA Spyder™ 3





"Bump" in IR causes problems!



<- Human Spectral Response (not normalized)

Human Color Vision

If human vision is to be used as a standard, need to measure it.
Also gives us ideas for color machine vision processing.

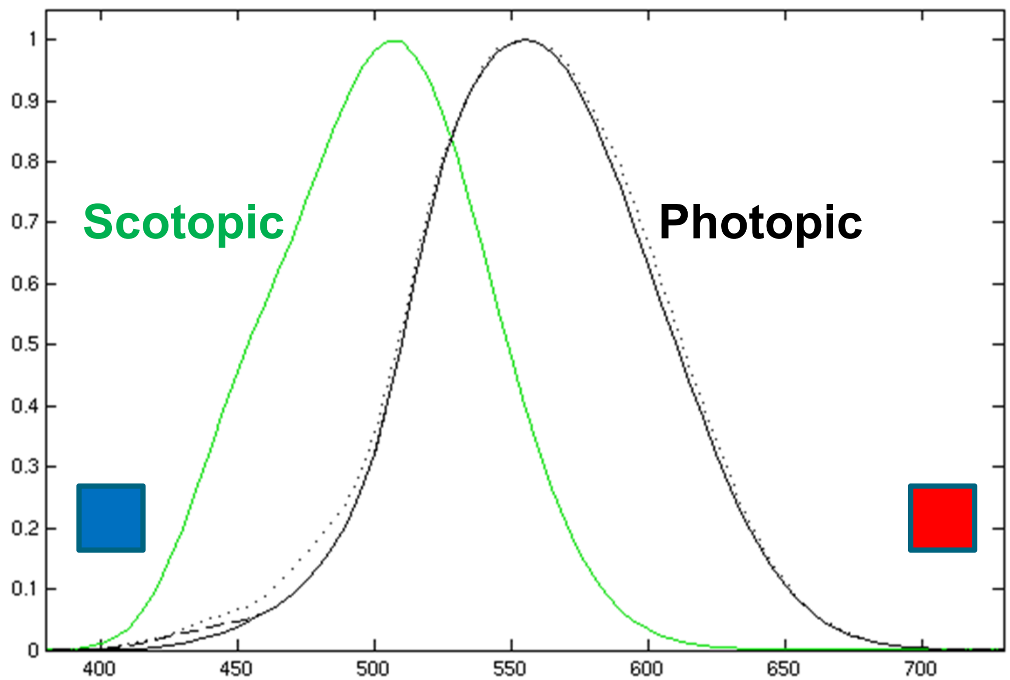
Pop Quiz!

- Define: rods, cones
- How many sensor types does the eye have*
- Name three (or more) properties of light
- What is a metamer?
- When we say color is a material property, what does that mean?
- Name some factors in color image formation
- Name two (or more) types of reflectance
- What is color temperature?

* Trick Question!

As the Sun Goes Down…?

- Below are normalized scotopic and photopic brightness spectral responses
- What happens to colors' brightnesses as it gets darker?

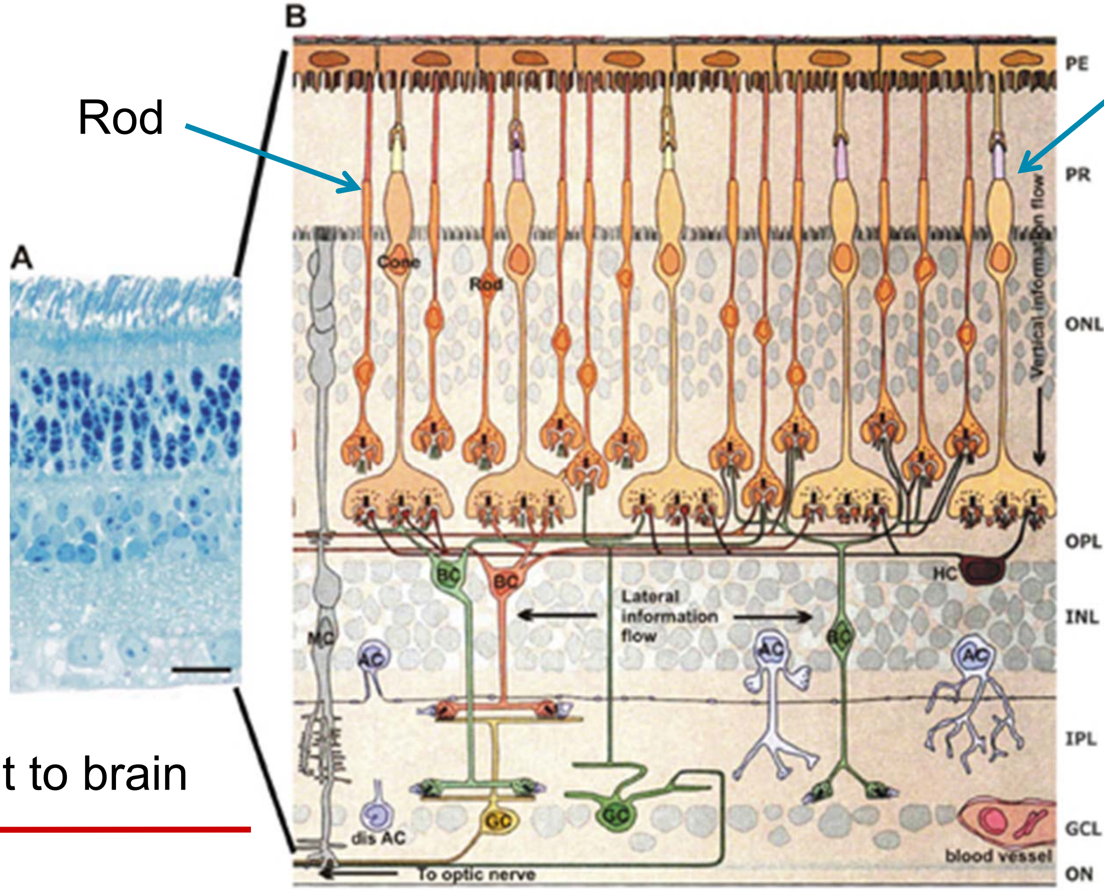


Purkinje Shift

Retinal Processing

- Retina performs a huge amount of “analog” processing on rod and cone outputs

Rod



Cone

Sensors

Light from pupil

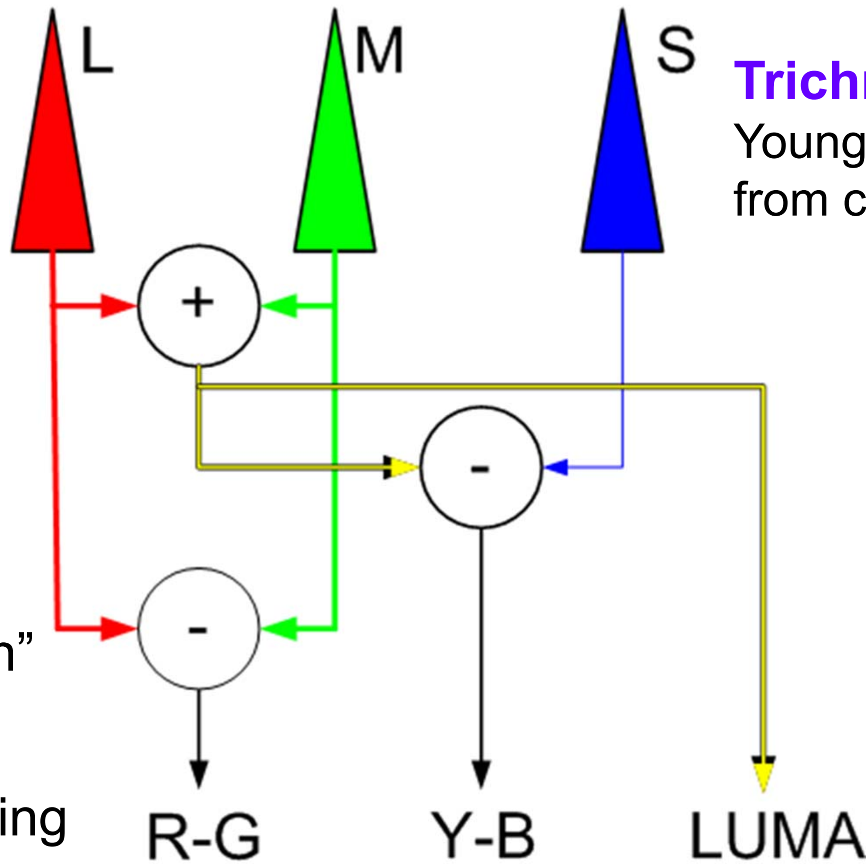
Local processing

Digital Output to brain

Retinal Processing of Colors

Very simplified model:

Sensors are ~ logarithmic response so -,+ become /,*



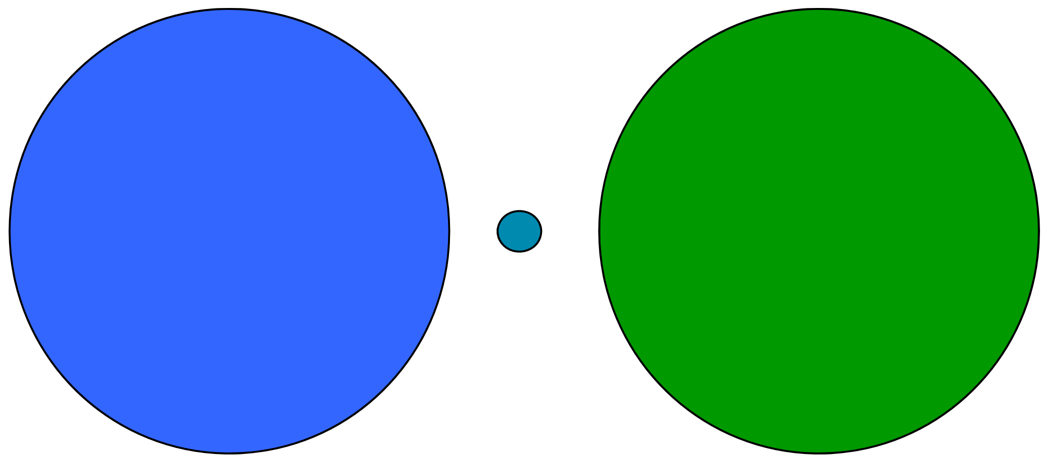
Trichromatic – Young, Helmholtz, from color matching

There is no "reddish-green" or "bluish-yellow"

Color opponents - Hering

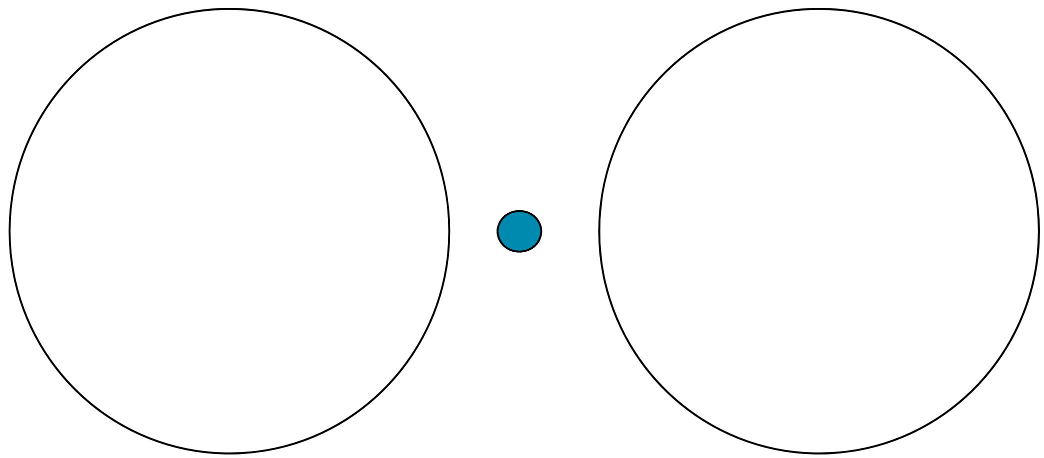
Brightness (**Luma**) is separated from **color opponents**

Color Opponency Demo



Demonstrates **color opponency** by **adapting** (fatiguing) **trichromatic** sensors

How’s Your Hering?



Perceptual Color Terms

- **Hue** = "pure" color
- **Saturation** or **Chroma** = colorfulness relative to the brightness of a similarly illuminated white

- **Brightness** or **Luma** = intensity of light
- Unfortunately, these are not consistently used
  - In particular, Chroma can mean Hue + Saturation
- My use of the term **color** should be clear from the context…

Human Color Sensitivity

- Cones encode **local differences** to ~7 or 8 bits
- How many different colors can we distinguish?
  - About ~120 “pure” **hues** (resolution varies with λ)
  - But with **saturation** and **brightness**, ~1,000,000+ colors
- Many color names “Blushing peach”?...
  - Culturally learned, so consistent between people

Some Retinal Processing

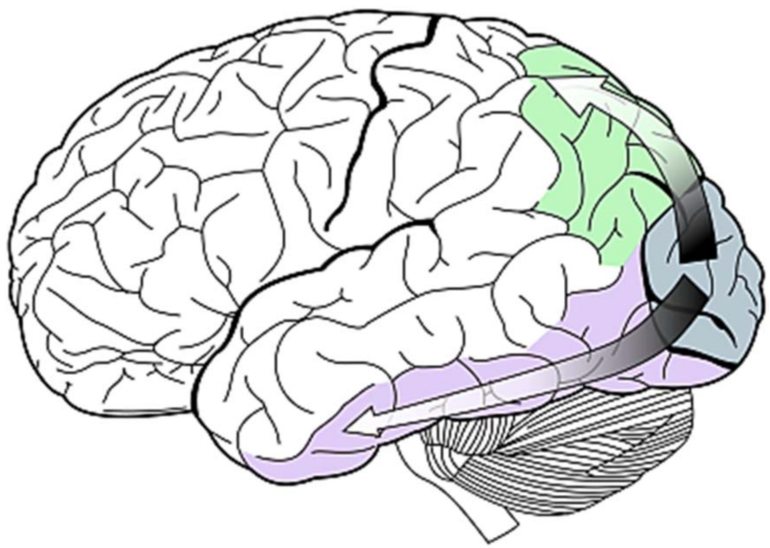
- Cone and rod response is ~ logarithmic
- RGB separated into R-G, B-Y color and luma
- Adjusts to environment (lighting)
  - Adaptation in space and time; cones & rods, etc.
- Digitized to 7 to 8 bits
- Extracts <u>information</u> (compressive)
  - ~100 to 1 sensor to output compression
  - Compression ratio increases away from fovea
  - Local adaptation and balance selects for sending changes in light input (spatial & temporal patterns)
  - Color is sent at lower resolution than luma
  - Luma encodes motion, intensity, detail (edges)

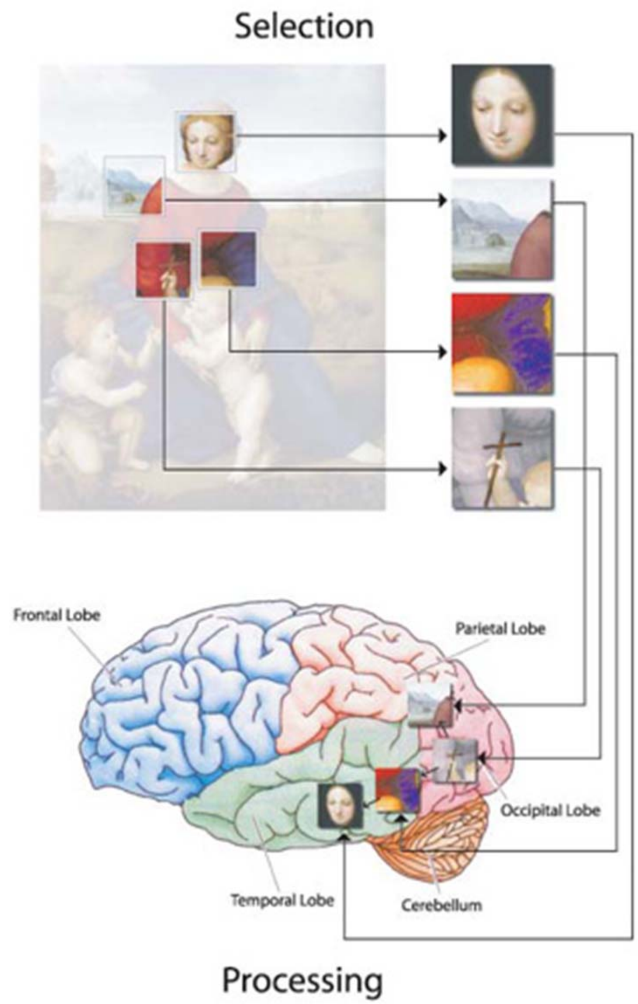
Retinal and Cortical Processing

- Recovery of (factoring out) the illumination is done, in part, at the retina
  - Color **aftereffects** suggest retinal adaptation
    - Not always, as we will see
- Color influenced by surroundings (**color contrast**) suggests retinal and cortical processing

Color Processing Paths

- Eye -> LGN -> Cortex
- Cortical areas specialized for different processing





How do they get unified into our perceptions?

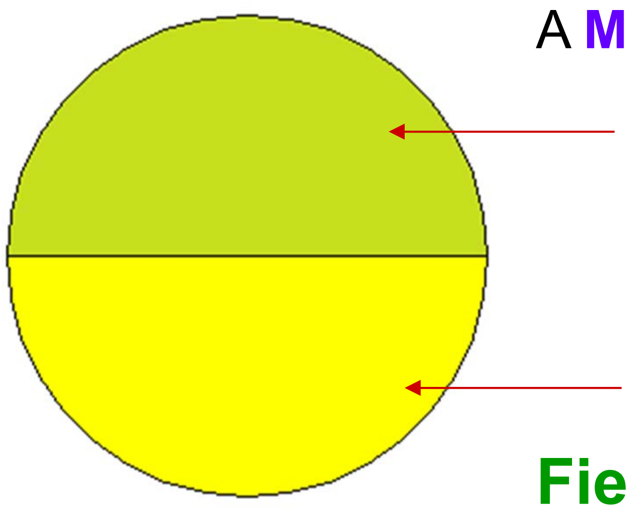
Psychophysics

- **Psychophysics** measures observers' responses to physical stimuli
- Example measures:
  - Minimum detectable color differences
  - Color response, averaged over many people
  - Range of color vision (**gamut**)

Measuring Human Color Vision

- Select primaries whose axes span all colors
  - The CIE "XYZ" primaries are the standard
- Observer views bipartite (two-part) field
  - One half is a known, fixed **Test Color**
  - The primary colors in the other half are adjusted by the observer to match the Test Color

A **METEMERIC** match



Match color – observer can adjust intensity of color components to match test color, e.g. 560 nm + 630 nm

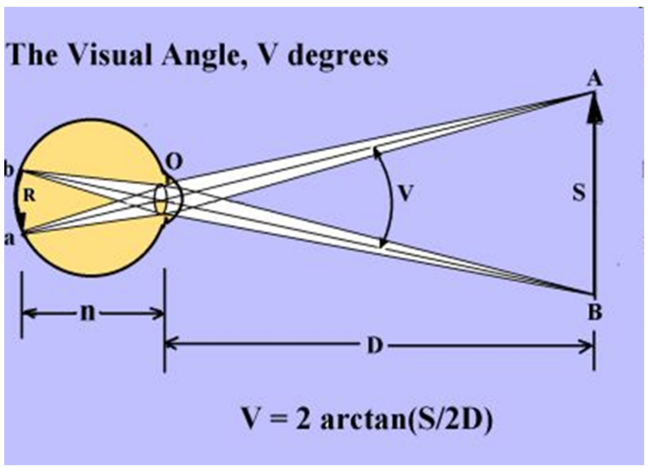
Test Color – fixed color, e.g. monochromatic 580 nm (yellow)

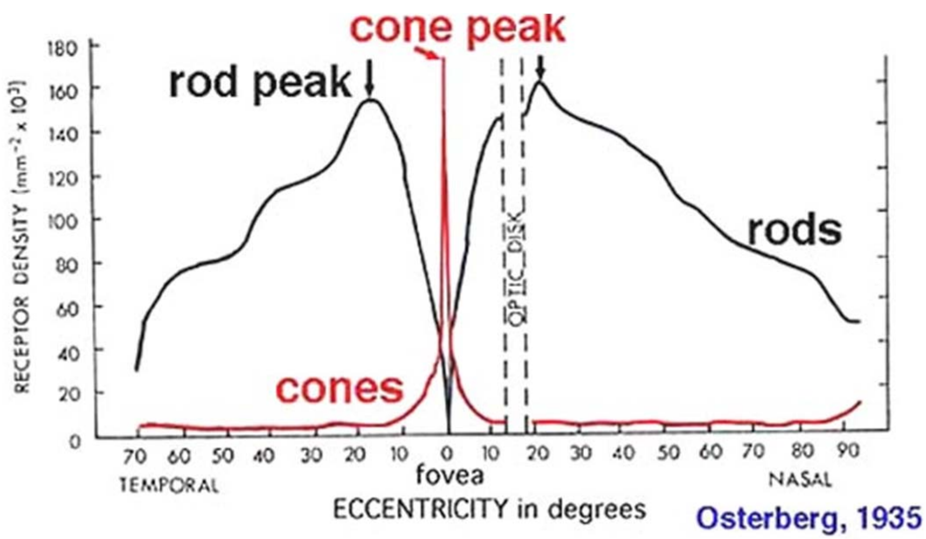
Field size matters!

Surround matters!

Dependence on Field of View

- Human color vision response depends on the size and position of the field of view (FOV) used
  - Measured in degrees of visual angle (arc)
  - 2 and 10 degrees of arc are common FOV sizes





Held at arm's length:
fingernail = ~1 degree
thumbnail = ~1.5 degrees
thumb width = ~2 degrees (retinal size of most detailed vision)

CIE Color Matching Functions

- Constructed from many observers' matches
  - Think of them as the spectral sensitivity curves of 3 linear light sensor types, yielding XYZ values
  - $\bar{x}(\lambda), \bar{y}(\lambda), \bar{z}(\lambda)$ provided as numerical tables

$$X = K \int_{380}^{780} S(\lambda)\, \bar{x}(\lambda)\, R(\lambda)\, d\lambda$$

$$Y = K \int_{380}^{780} S(\lambda)\, \bar{y}(\lambda)\, R(\lambda)\, d\lambda$$

$$Z = K \int_{380}^{780} S(\lambda)\, \bar{z}(\lambda)\, R(\lambda)\, d\lambda$$

$$K = \frac{100}{\int_{380}^{780} S(\lambda)\, y(\lambda)\, d\lambda}$$

where

$S(\lambda)$: Relative spectral power distribution of the illuminant

$x(\lambda)$, $y(\lambda)$, $z(\lambda)$: Color-matching functions for CIE 2° Standard Observer (1931)

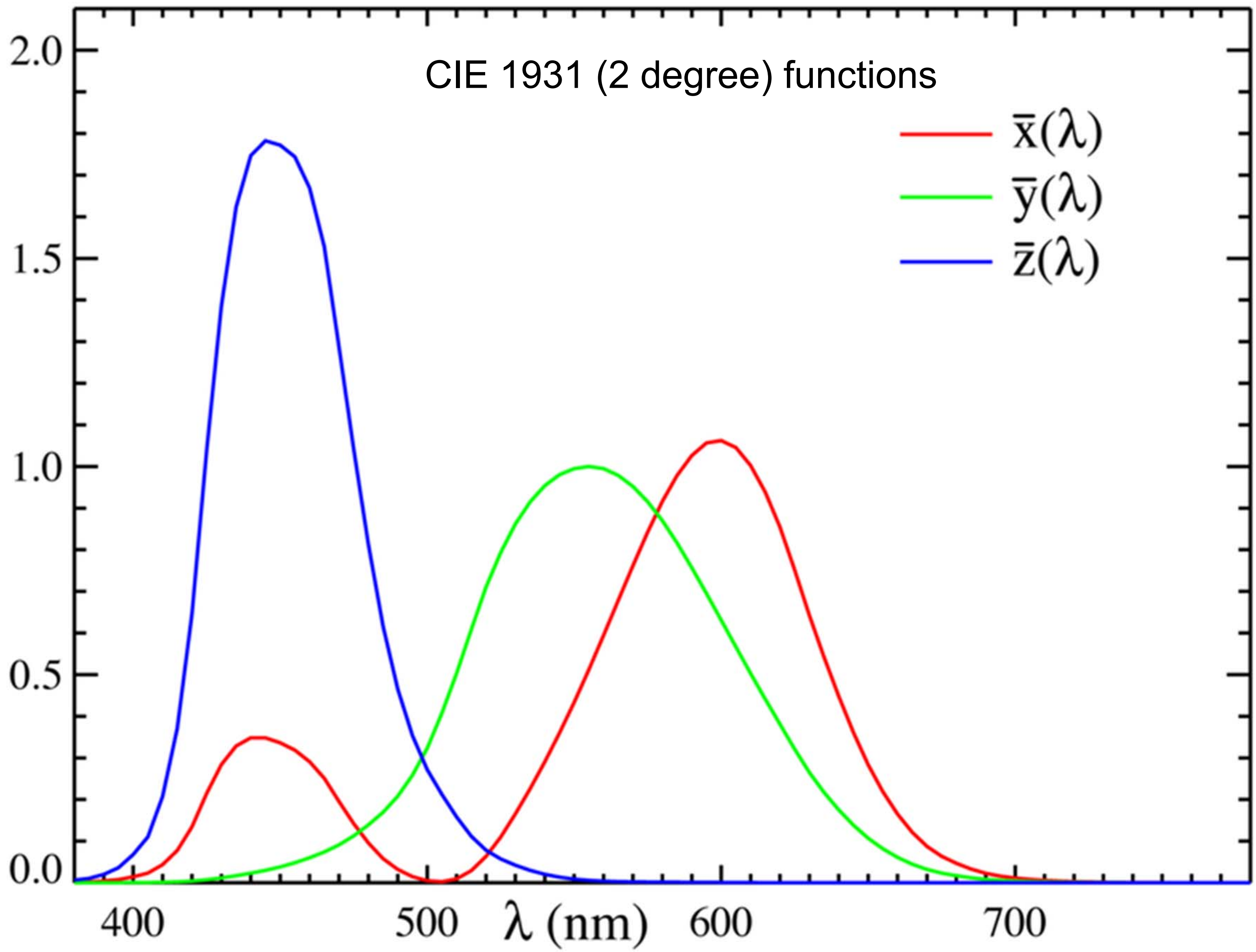
$R(\lambda)$: Spectral reflectance of specimen

Inner products of matching functions and S(λ)

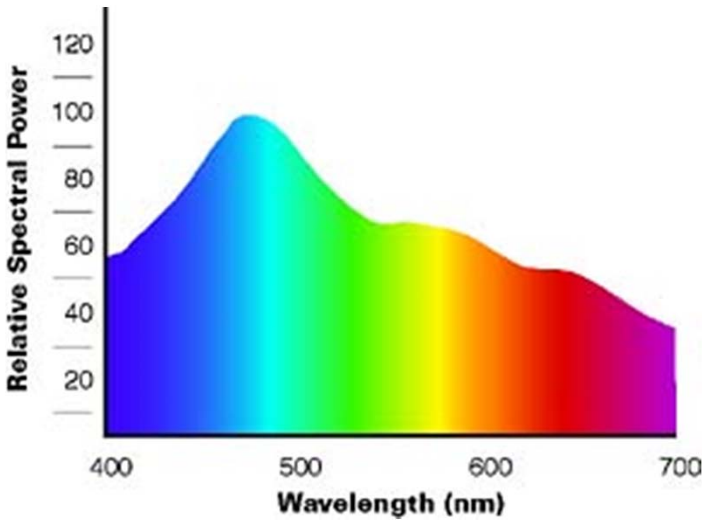
Y is, effectively, LUMA
~= green response

Given a light with S(λ) power (**radiometric**) distribution, these equations give the XYZ coordinates for that light.
Note: 2 degree (1931) and 10 degree (1964) versions

CIE Color Matching Functions

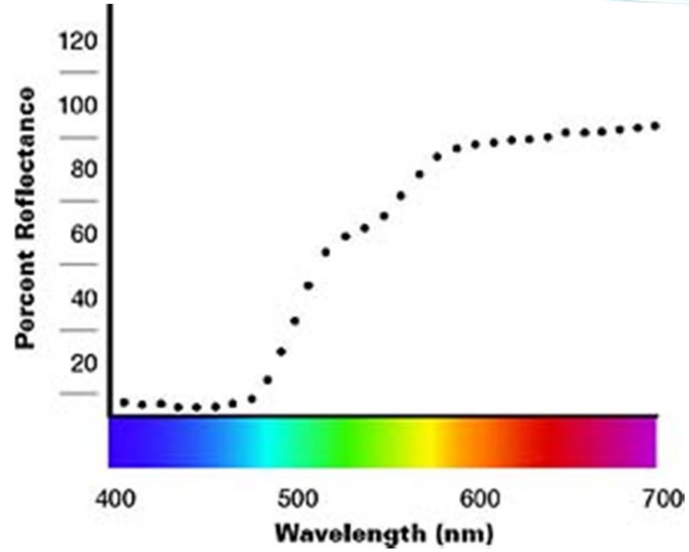


Measuring XYZs



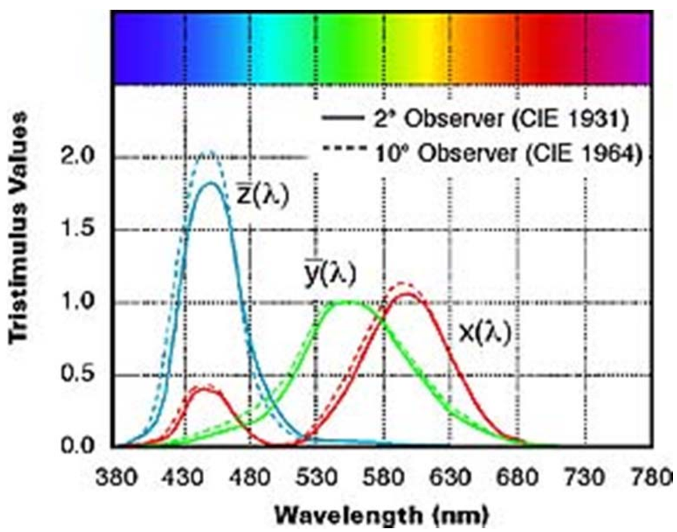
D65 illuminant

X



Object Spectral Reflectance

X



"Sensor" Responses

=

X = 62.04
Y = 69.72
Z = 7.34

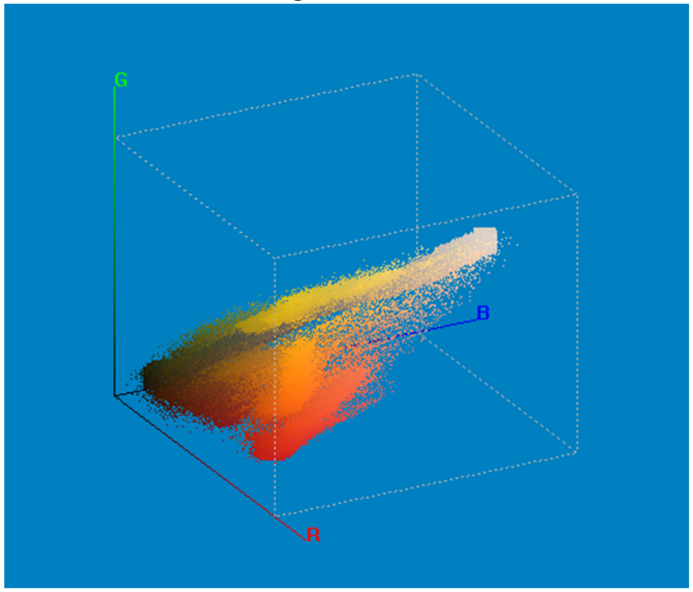
XYZ Measures

Inner products

www.xrite.com

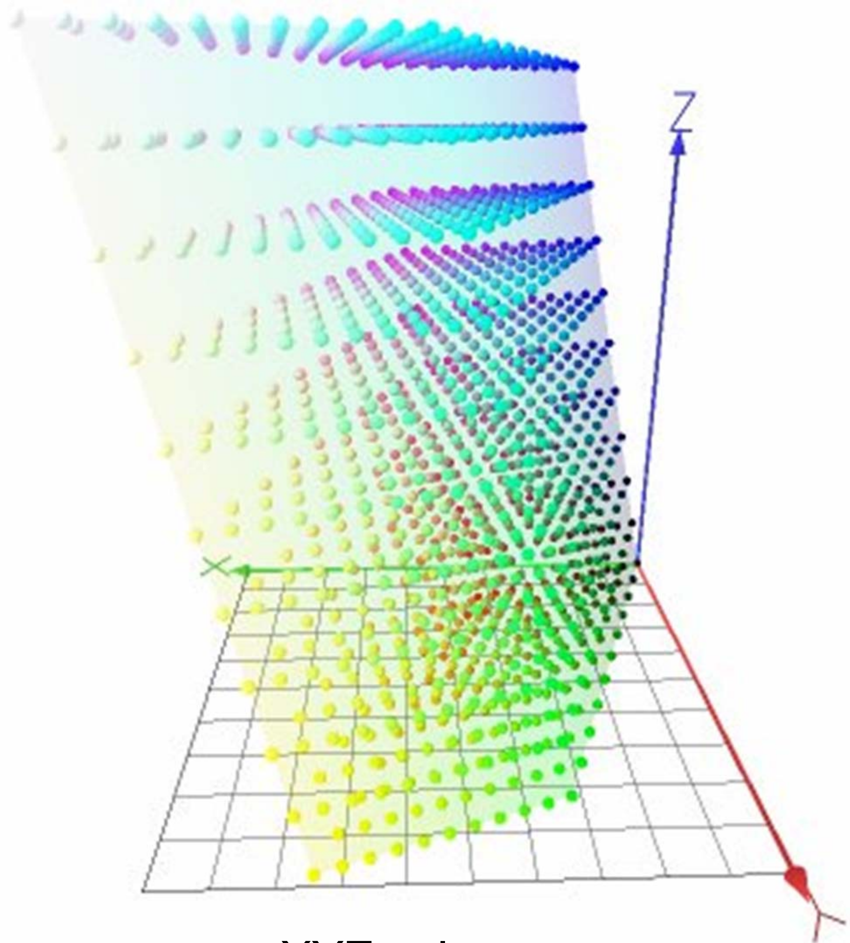
Color Space

- A **color space** represents (maps) possible colors vision system can detect
  - Possible colors (**gamut**) might not fill the space
- Axes are color space's **primaries**, e.g. R,G,B
- Can be a non-linear space, e.g. cylindrical
- Term also used for graphic display of colors



CIE XYZ Color Space

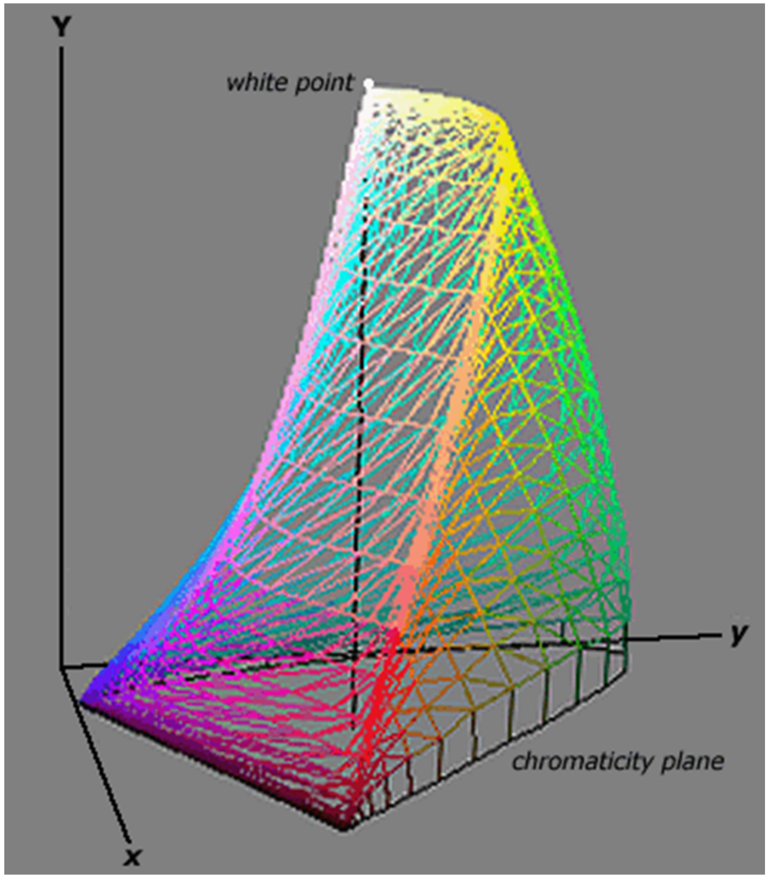
- Gamut of human color vision in XYZ primary color space



XYZ color space

CIE xyY Color Space

- Divide X,Y by (X+Y+Z) to get xyY
  - **Chromaticity** (x,y) and luma (Y)
- Separates color **(chromaticity)** and **luma**
  - Like retinal processing?



Projection onto xy

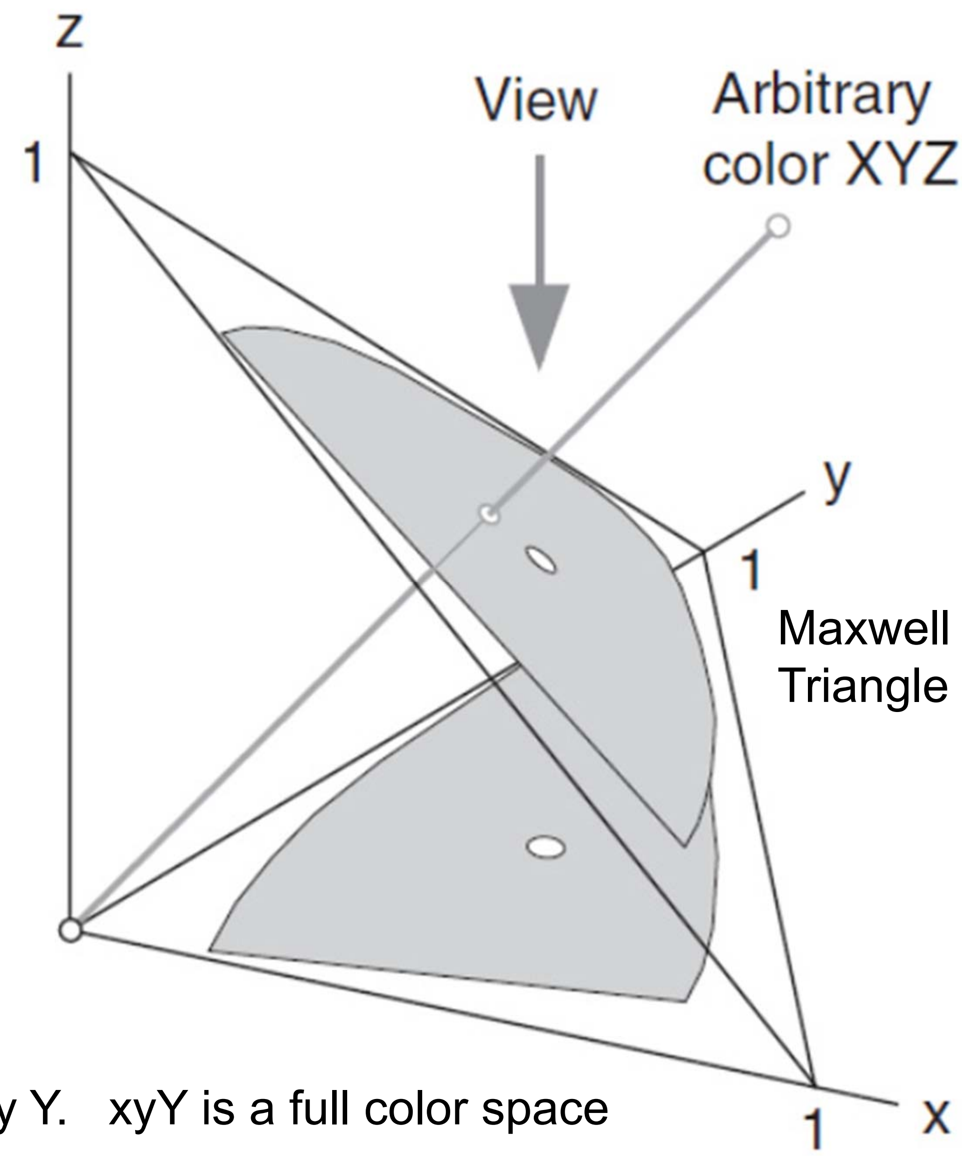
Project plane defined by x+y+z = 1 onto x,y plane to get CIE **Chromaticity Diagram**

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

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

$$z = \frac{Z}{X+Y+Z} = 1-x-y$$

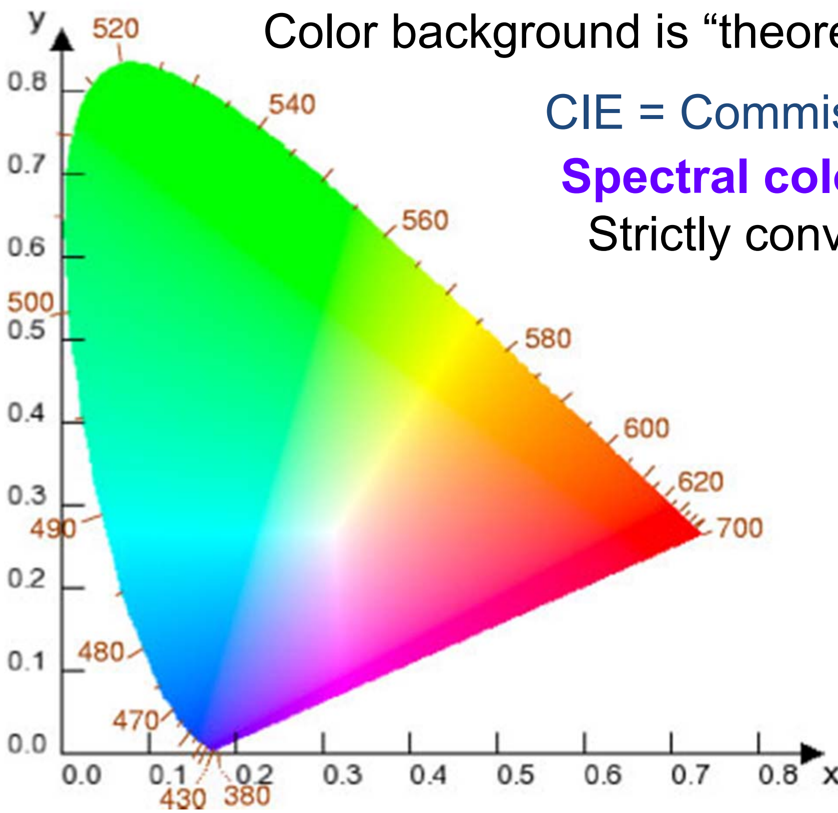
z is implicit



To recover XYZ, need to specify Y. xyY is a full color space

CIE Chromaticity Diagram

- 2D representation of just (x,y) color space
- A convenient way to show device **gamut**

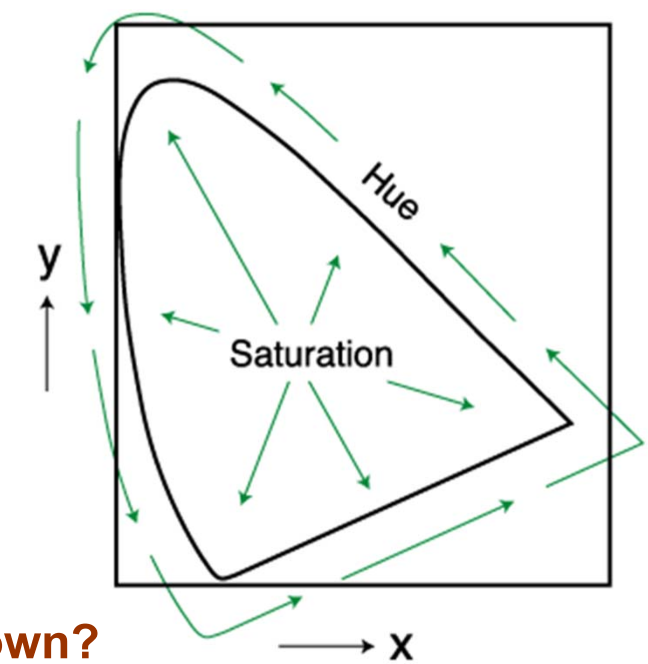


Color background is “theoretical” because display gamut is limited

CIE = Commission Internationale de l'Éclairage

Spectral colors around “horseshoe” edge

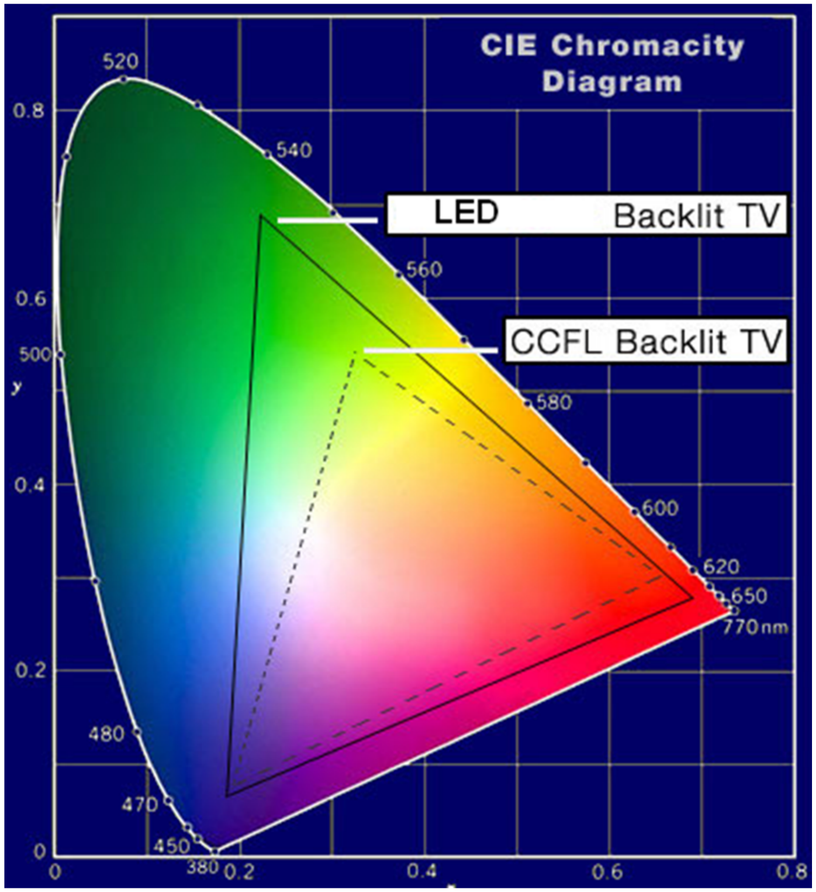
Strictly convex



What wavelength is magenta? Brown?

Gamut

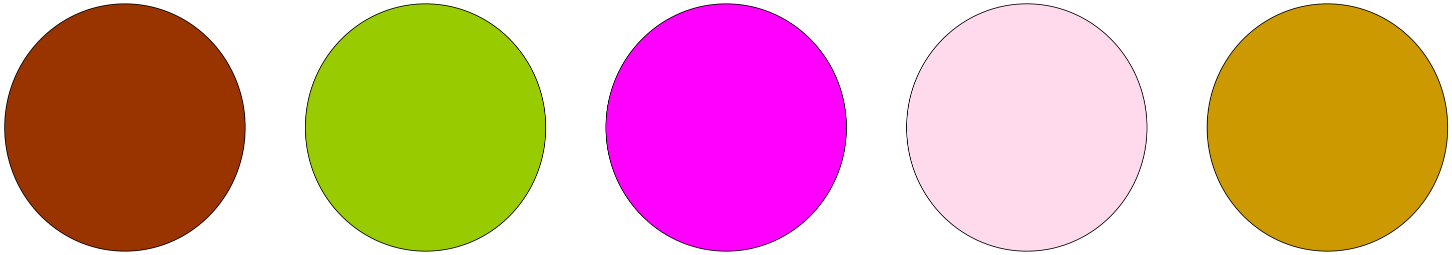
- **Gamut** – range of colors that a device (light, camera, human etc.) can generate or detect
- Often plotted in CIE Chromaticity space.



What happens to gamut as the color image is processed through a "chain" of devices? e.g. camera, printer, eye

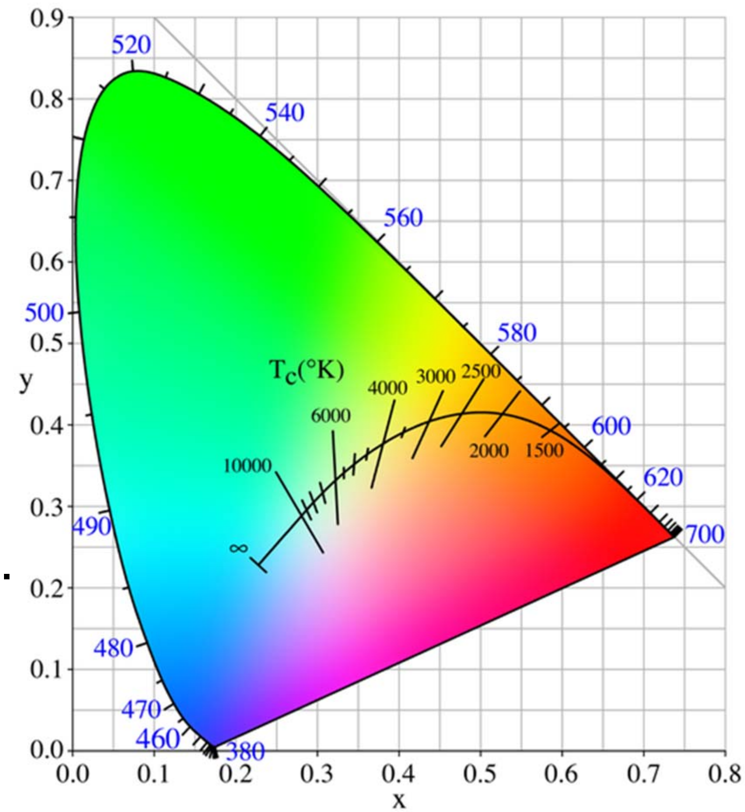
Non-Spectral Colors

- **Spectral colors**
  - Pure colors from spectrum; around CIE x,y “horseshoe”
- **Non-spectral colors**
  - Add dimensions of brightness and saturation
  - All colors arise from neural processing
- **Saturation** = amount of color relative to color’s brightness; colorfulness; radial on CIE xy
  - Pink, tan, olive, brown are **desaturated** and low intensity colors. Need Y component to show
- Magenta (red + blue) can be saturated



Why is CIE Color Important?

- Color spaces derived from CIE XYZ give a standard way to specify process colors
  - Colorants, Object colors
  - Light sources
- CIE XYZ calibrates (links) **photometric** to **radiometric** measures



Example: Specifying Illumination. The **Planckian Locus** is the locus of blackbody color temperatures on the CIE chromaticity diagram.

Example: CIE L*a*b*

- An **color opponent** and **perceptually uniform** color space derived from CIE XYZ
  - Common way to specify process color
  - L* = Lightness; a*,b* = color components

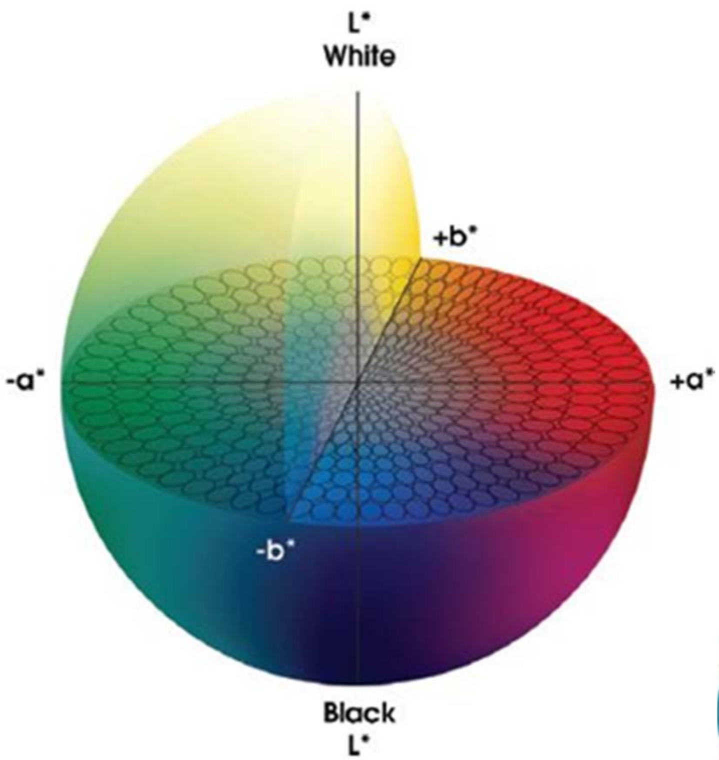
$$L^* = 116\left(\frac{Y}{Y_r}\right)^{1/3} - 16$$

$$a^* = 500\left[\left(\frac{X}{X_r}\right)^{1/3} - \left(\frac{Y}{Y_r}\right)^{1/3}\right]$$

$$b^* = 200\left[\left(\frac{Y}{Y_r}\right)^{1/3} - \left(\frac{Z}{Z_r}\right)^{1/3}\right]$$

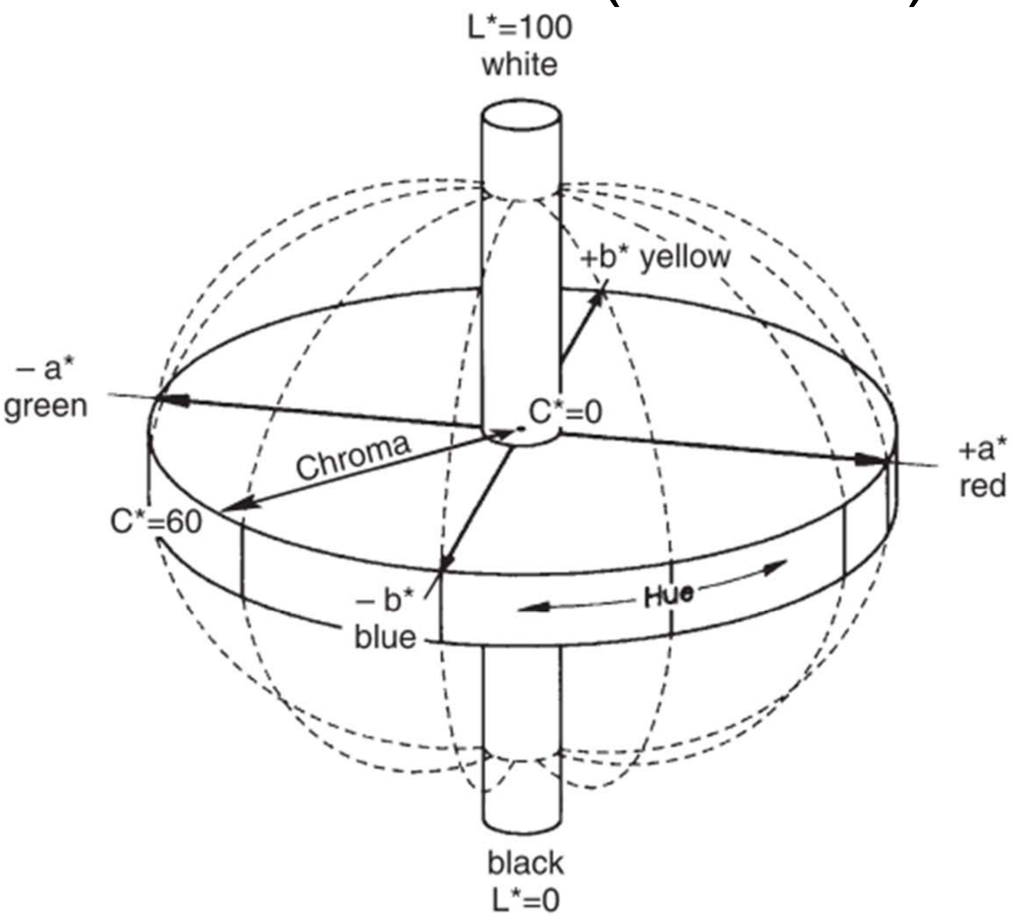
Simplified!

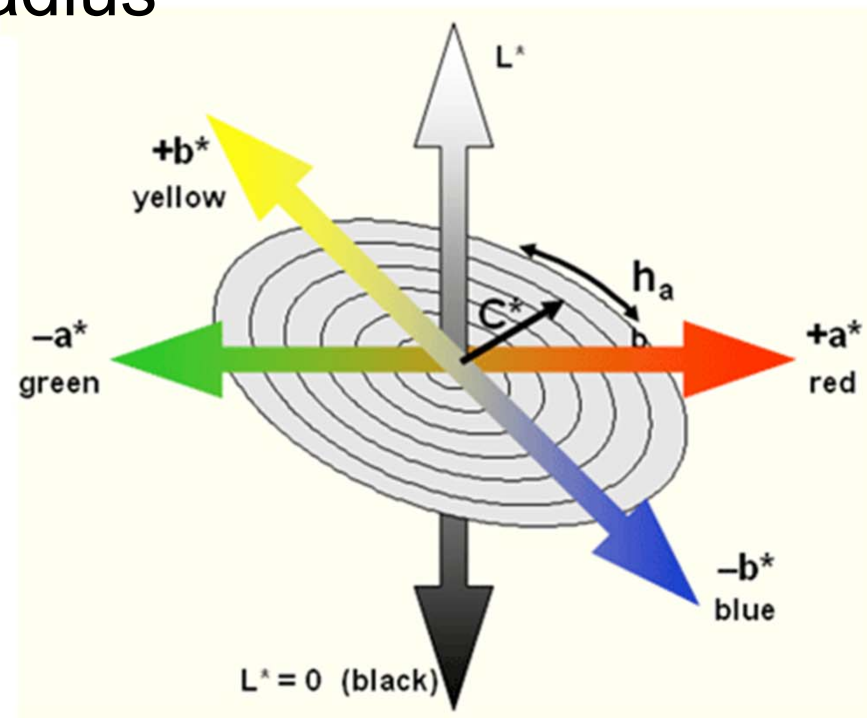
X_r ,Y_r , Z_r are reference white values used



Another View of CIE L*a*b* Axes

- L (**lightness** or **luma**) vertical axis
- **Hue**: around circumference
- **Saturation** (**Chroma**): radius





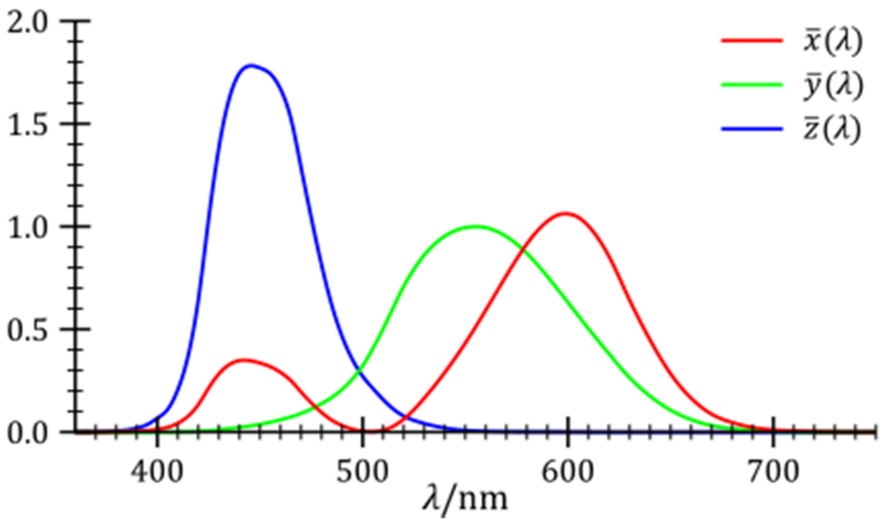
Calibrating MV to CIE

- Difficult!
  - Variations in illumination, geometry, optical and camera response over image area and time.
  - Camera's spectral response is different than CIE's
- Try using a **tristimulus colorimeter** to calibrate RGB limits around colors of interest
- Some tips:
  - Use an IR block filter (discussed later)!
  - Limit the field of view (FOV) to center of image!
  - Control your lighting and geometry!
  - Periodically recalibrate!

Tristimulus Colorimeter

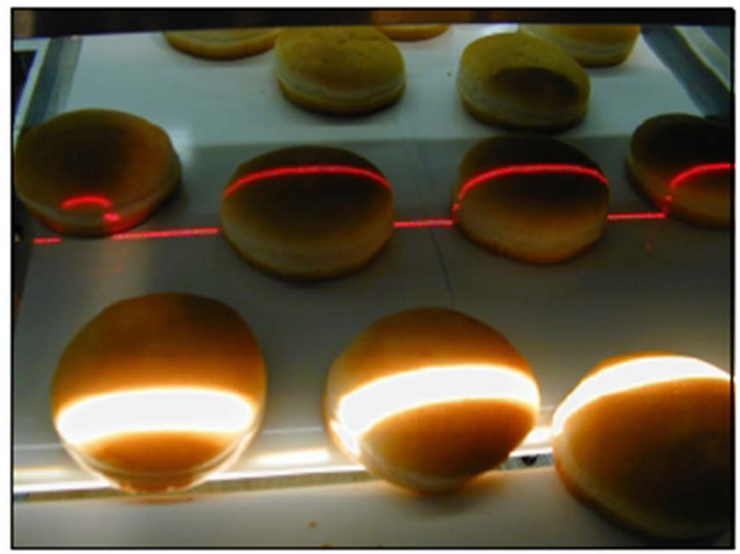
- Controlled illumination and geometry
- Three sensor types, approximate CIE **color matching functions**
- Small field of view

ElektroPhysik



Inspecting Baked Goods

- Cooked in continuous process
- Check 3D shape and color(s)



www.montrose-tech.com

English Muffin "Toast Mark"

- Check toast mark color, specified in L*a*b*
- Difficult with an RGB color MV camera

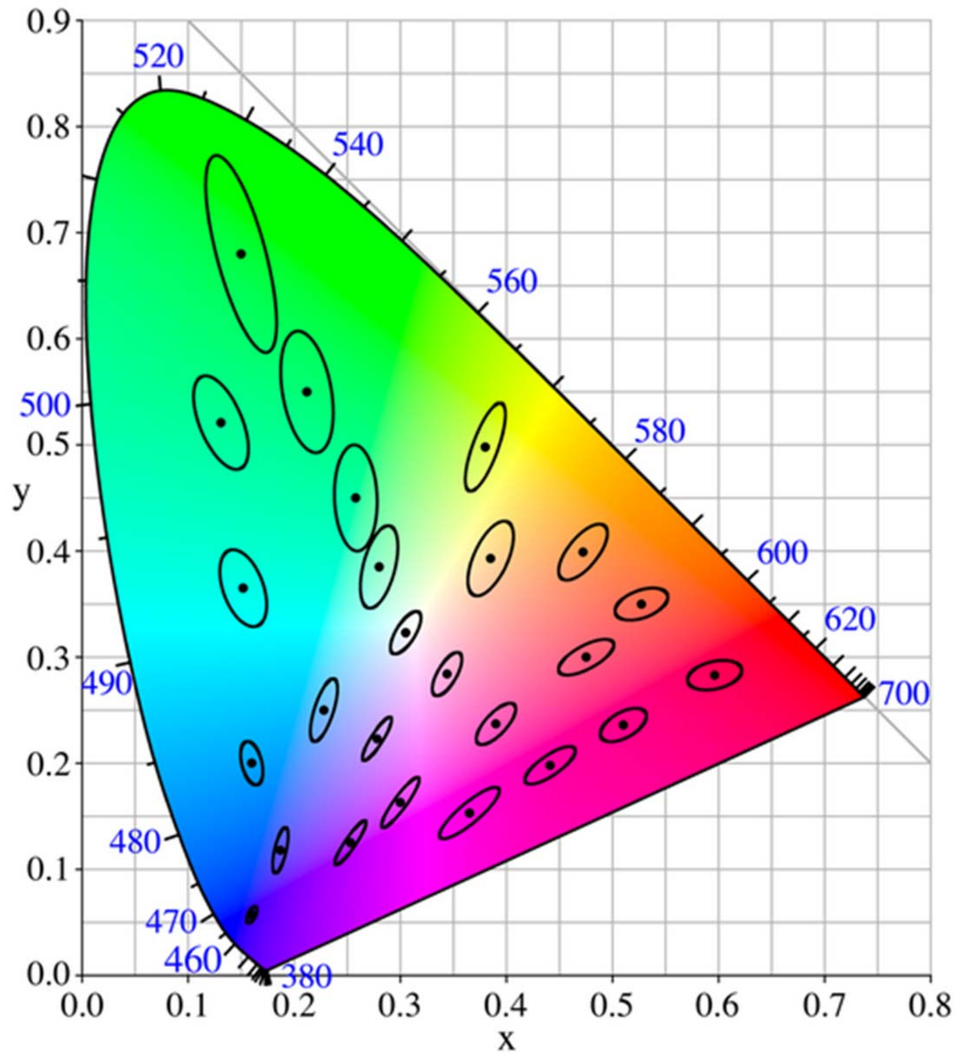
Why do we care about a toast mark anyway?

Muffin Inspection Details

- RGB camera, white LED illumination
  - Controlled using a **white reference patch**
- RGB limits set by CIE L*a*b* specifications
- **Not full calibration**
  - Periodic recalibration of RGB limits using tristimulus photometer
  - RGB limits might not = L*a*b* limits, but close enough
- Browns are difficult colors to measure
  - Low brightness and **desaturated** red-orange
- Toast mark is to meet consumer expectations!

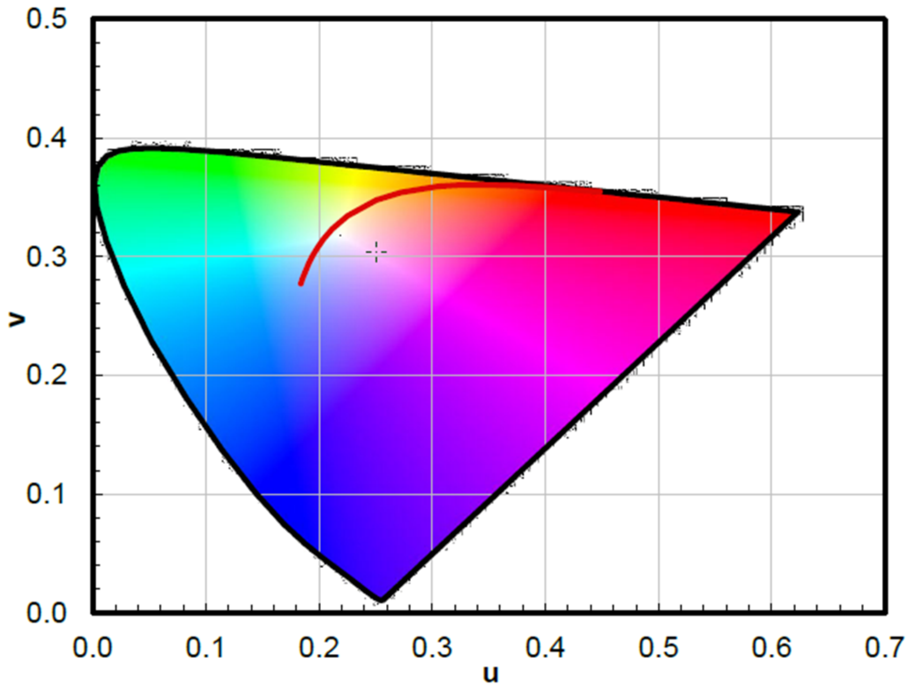
Perceptually Uniform Color Spaces

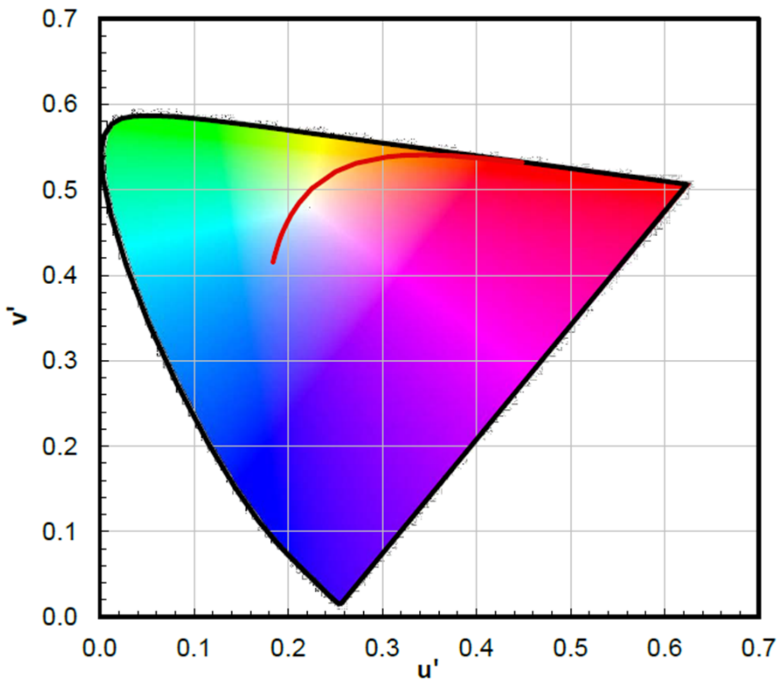
- **MacAdam Ellipses**: how much a color has to change to be seen as different
- Note different sizes - CIE x,y is not a **perceptually uniform** color space where a Δ change in component gives an equivalent perceptua change. L*a*b* is.



Making xy Perceptually Uniform

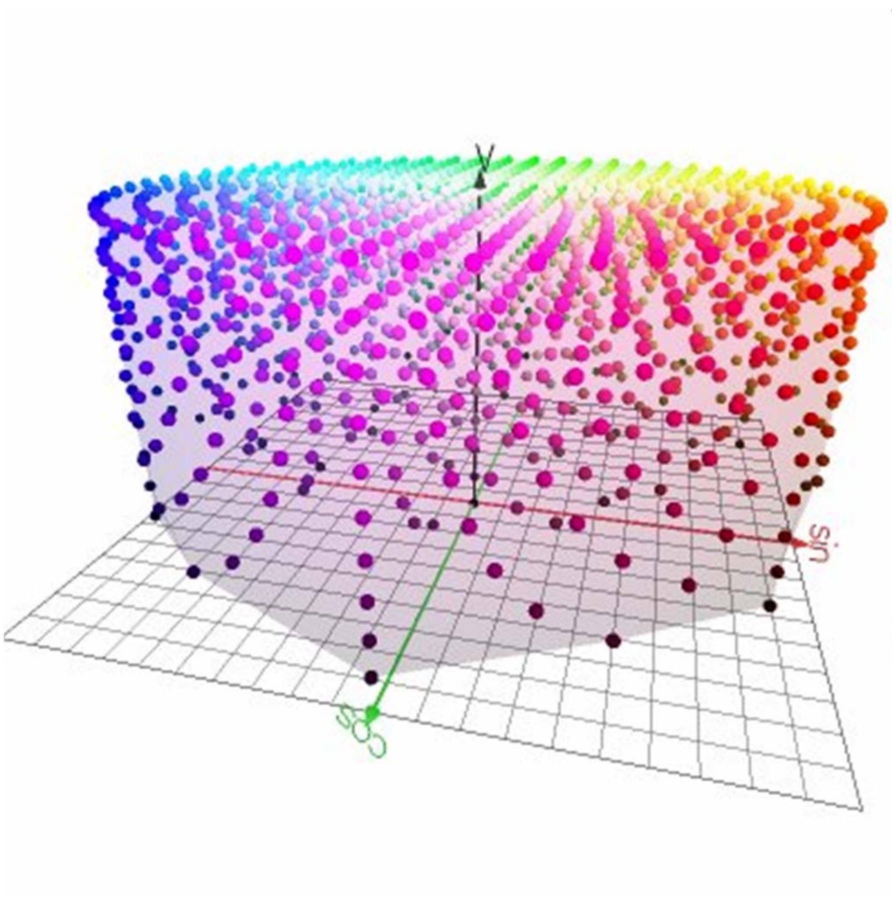
- Transformations make CIE chromaticity more perceptually uniform
  - CIE 1960 u,v – a linear transform
  - CIE 1976 u’,v’ – a similar linear transform
- But non-linear representations can do better





Non-Linear, Perceptually Uniform

Non-linear spaces claim to have better **perceptual uniformity**
L*a*b* is one we've discussed…
Here is another:

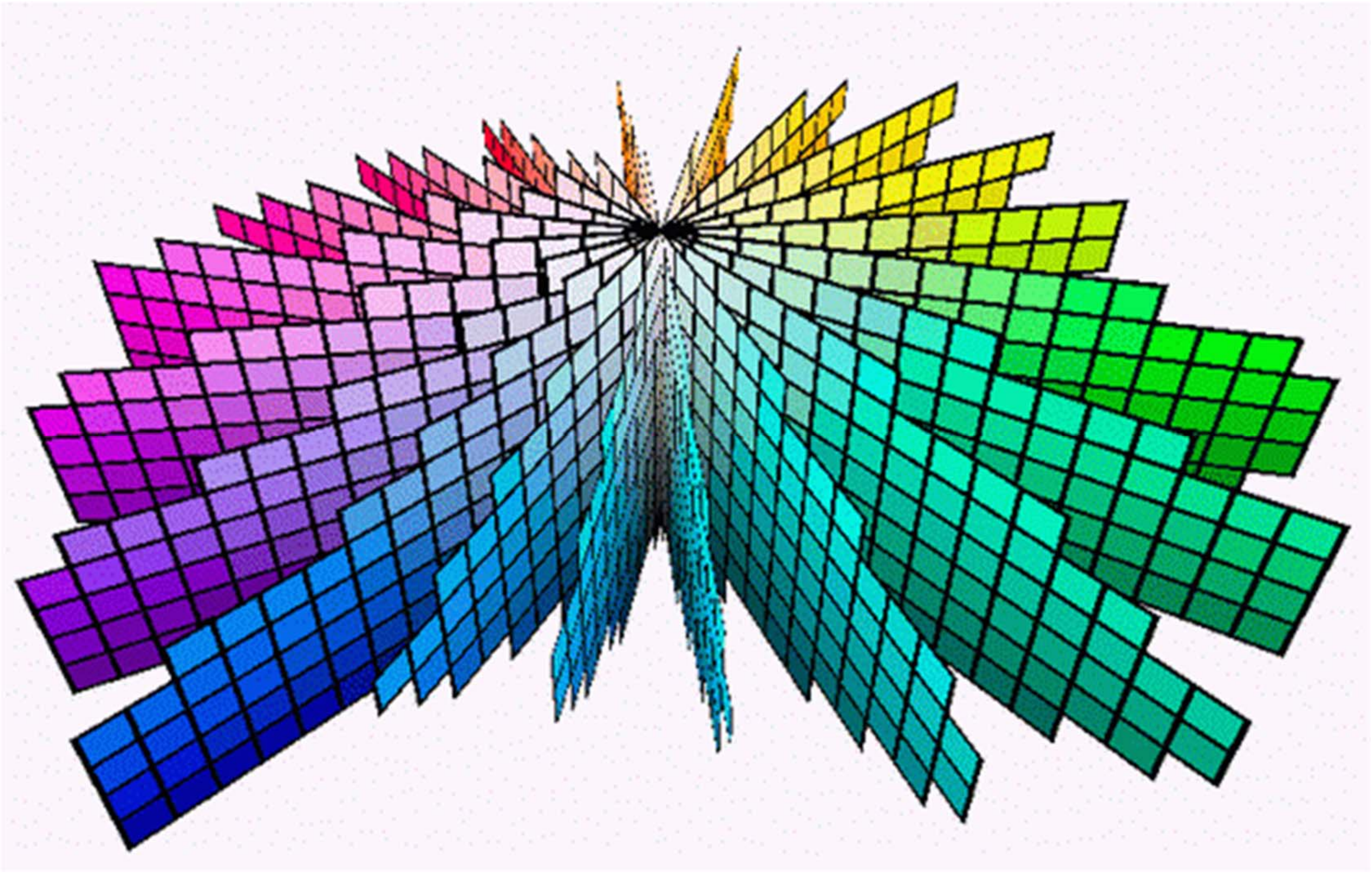


HSV (Hue, Saturation, Value)
V = Intensity
Similar: HSI, I = Intensity
Similar: HSL, L = Intensity

Large number of variations!

Munsell Color Space

- Perceptual, non-linear. Typically used for colorant (e.g., paint) selection and matching



Converting from MV's RGB

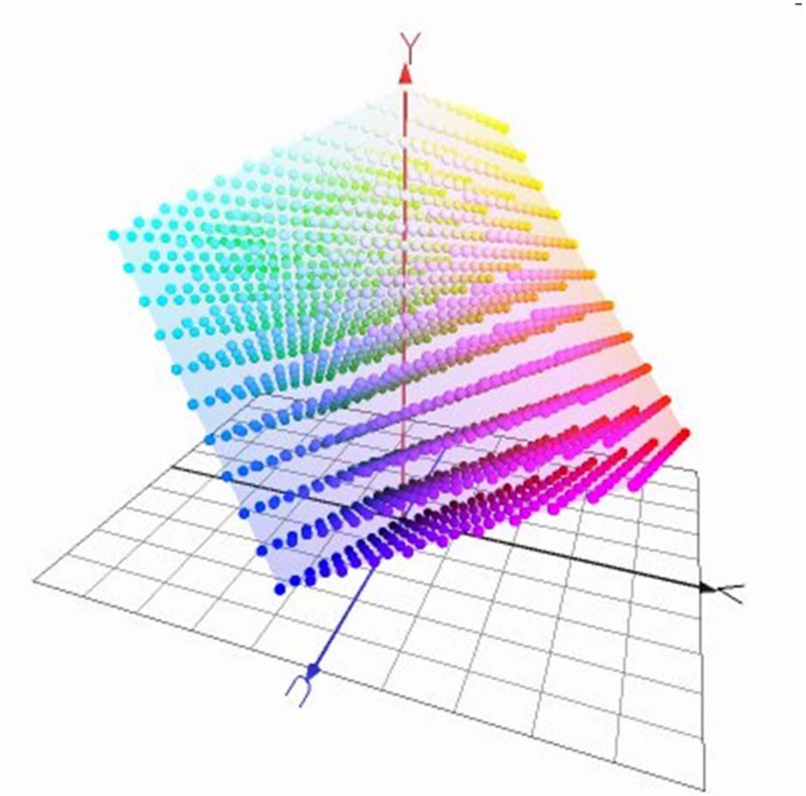
- Cameras output R,G,B values from sensors with poorly specified spectral responses
- Can transform camera RGB to any color space
  - Limited by RGB's gamut and range of digital values
  - Costs: computation time and added noise
  - Many transforms; based on **gamma**, lighting, display

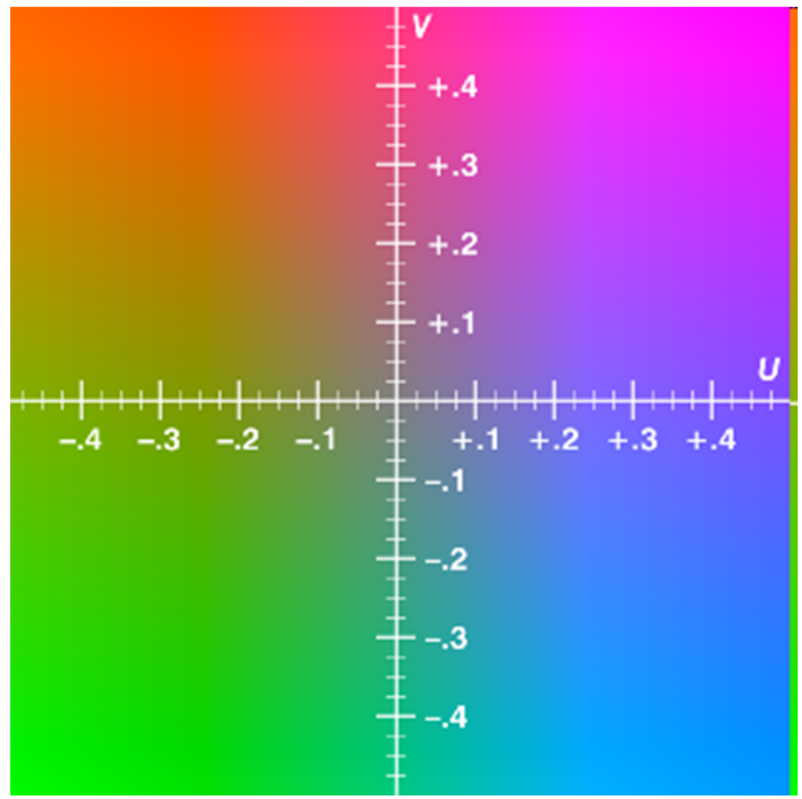
$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} 0.49 & 0.31 & 0.2 \\ 0.17697 & 0.8124 & 0.01063 \\ 0 & 0.01 & 0.99 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

- **Transformation does not mean calibration**

Example: YUV (linear from RGB)

Essentially a matrix rotation of the RGB color space to make the RGB space diagonal into the Y (luma) component

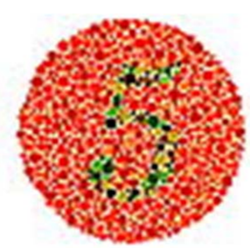


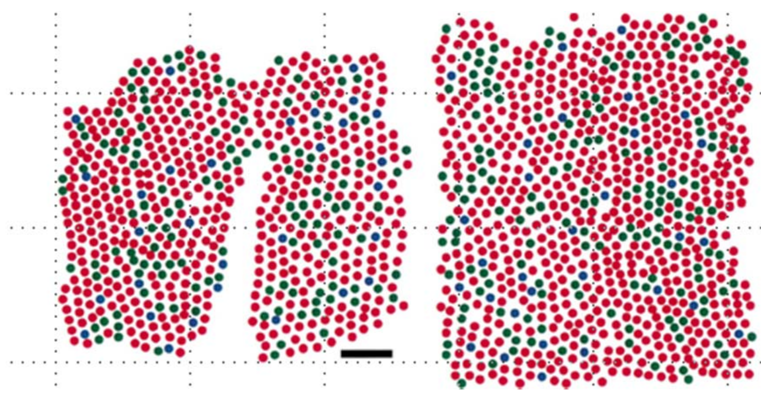


Luma (Y) axis is square root of 3 ~= 1.73 in length, so scale all components to fit in 0..1 range – loss of resolution in digital images

More on Individual Differences

- Color perception varies between individuals and over time, context, retinal location and adaptation
  - Makes creating a **standard observer** difficult
  - Color names are learned associations and so are stable
- Color blindness
- Individual’s distribution of sensor types
- Age, toxins, adaptation to light and surroundings

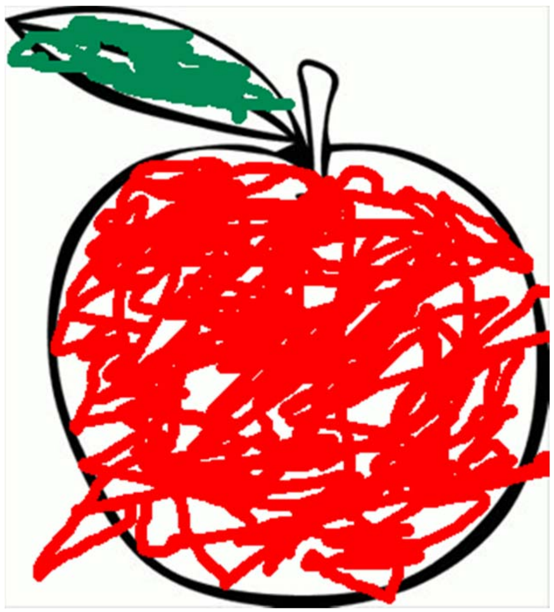




6% males are deuteranomolus (mutated medium pigment towards red)

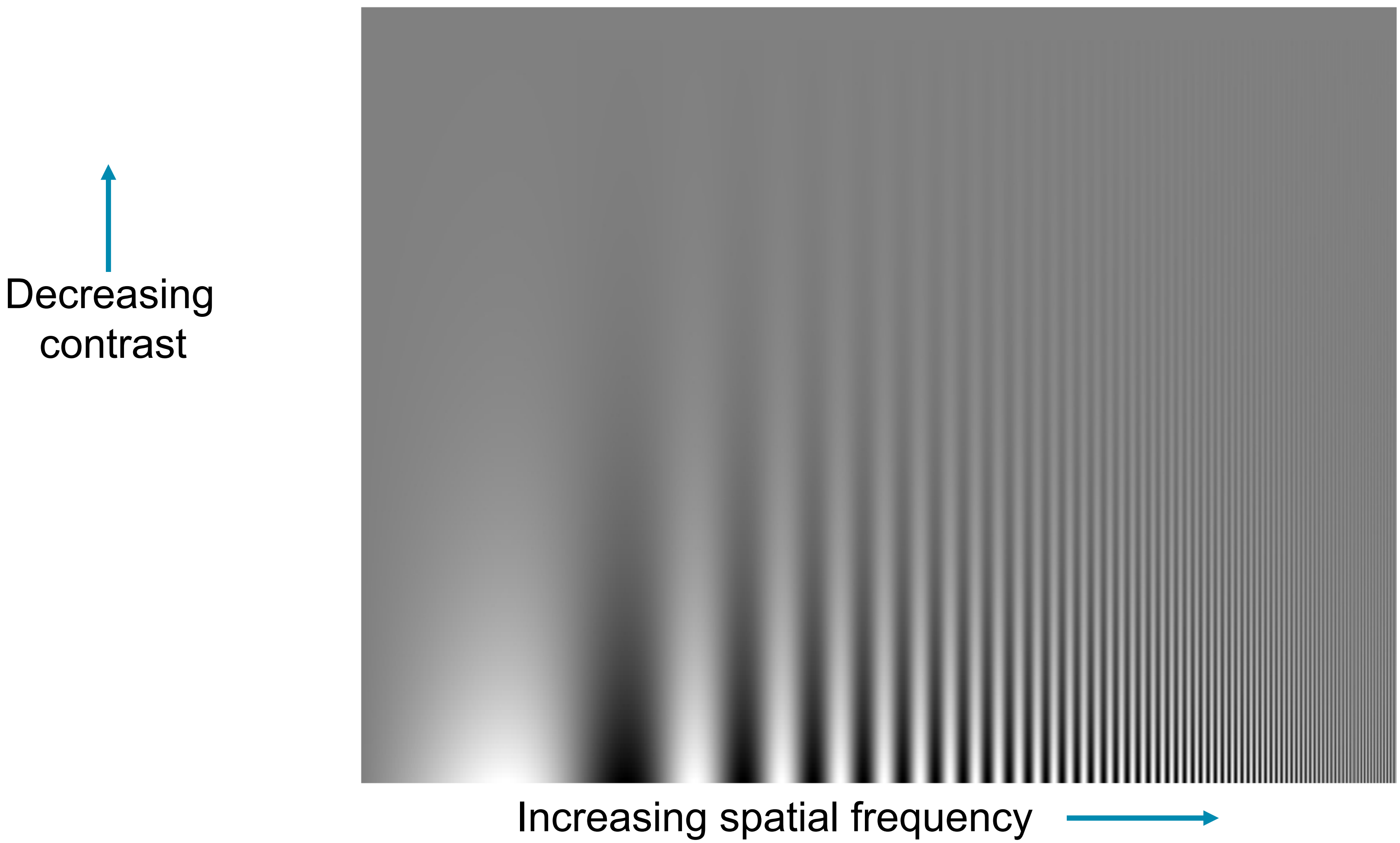
Color Fills Luma Edges

- Color information is low **spatial frequency** and fills in objects defined by luma edges
  - “Analog” color television (NTSC, PAL, SECAM)
- Are there color-only edges?
  - Unlikely in human vision, but could have in machine vision



Spatial Frequency

- Cycles per unit distance
  - Line pairs per mm, cycles per degree, etc.



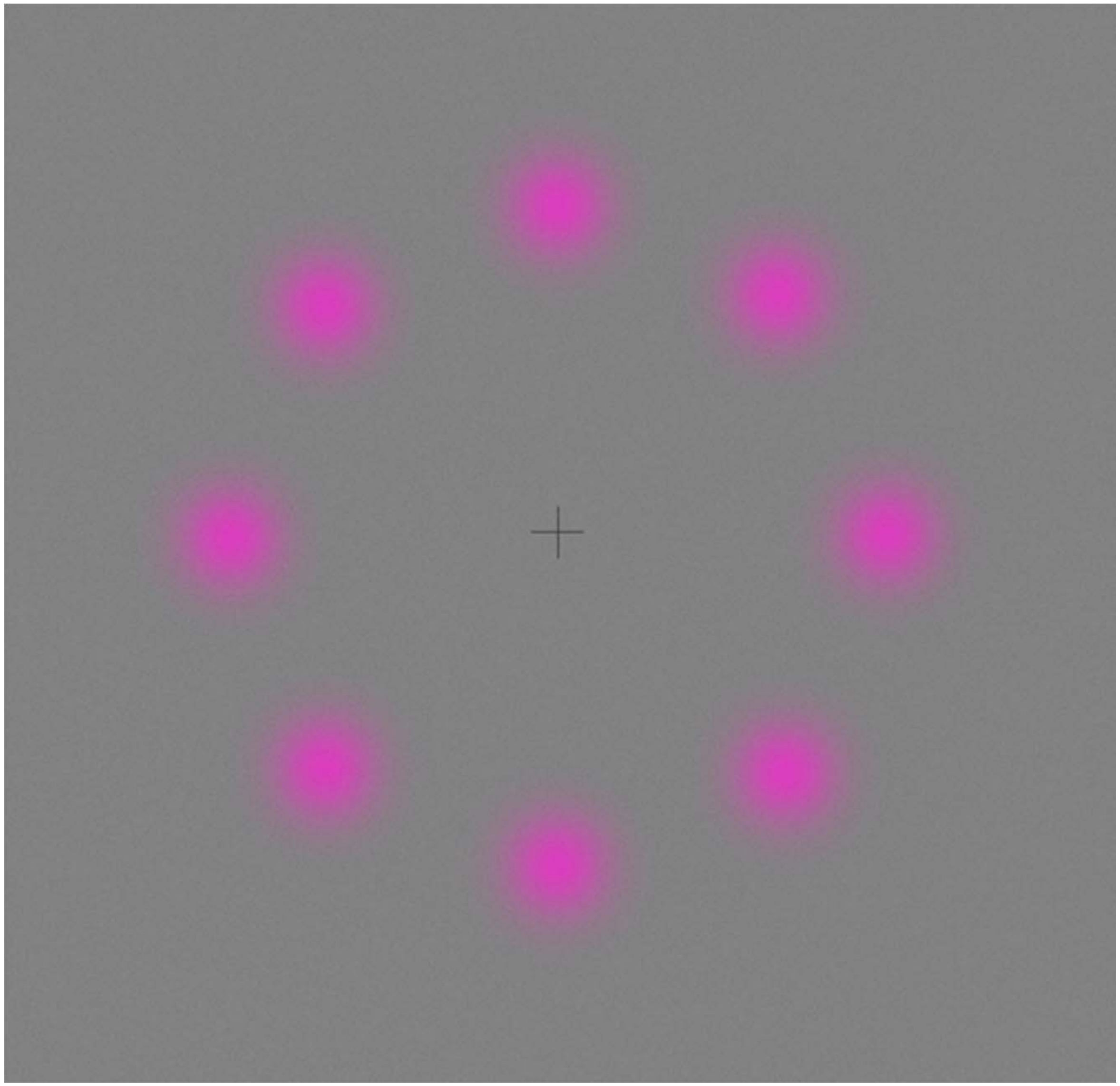
Color Constancy

- We **recover the illumination** to make colors appear about the same as lighting changes
- Improves reliability of identifying objects and estimating material property by color

Adaptation

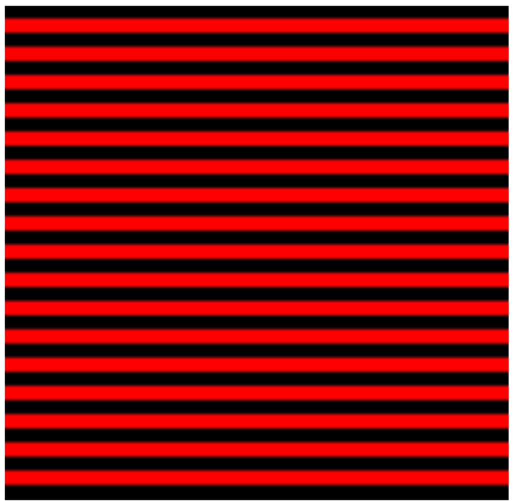
- Human vision constantly adjusts its “operating points” as environment changes – it “adapts”
- Short term and long term **adaptation**
  - Color aftereffects, dark adaption (cone to rod vision)
- Attenuates constant colors, amplifies spatial and temporal differences
  - Stabilizes information extraction, e.g. color constancy
  - Compresses visual data by mostly sending changes

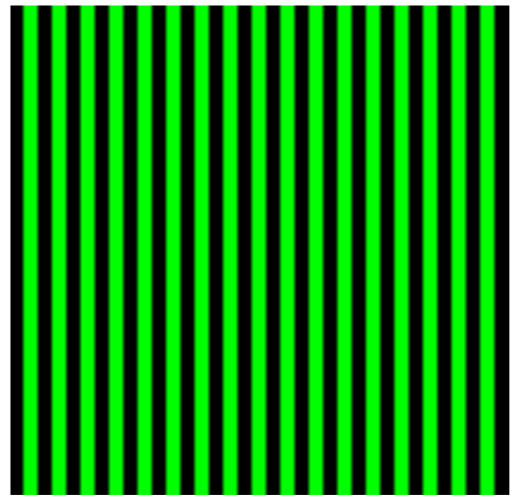
Adaptation Example



McCollough Effect

- Dramatic example of neural adaptation and aftereffect





Gaze at these while you take a break!

Mom Quiz!

- Define gamut
- What is a color space?
- Name a non-spectral color on CIE x,y edge
- What are some retinal processing functions?
- Name a perceptually uniform color space
- Why is CIE calibration of a MV system difficult?
- What is color constancy?

Let’s Choose a Paint Color…

- (a) Paint on the wall doesn’t look the same as the samples in the store (b) You and your mate disagree on how the colors look
- What could cause these problems? How to fix?

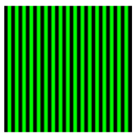
Towards Painting Harmony

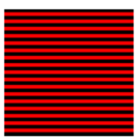
- Lighting differences between store and home
  - **Color constancy** might reduce this
- Individual differences
- **Color Contrast**: influence of surrounding colors
  - Kirshmann's "laws" of color contrast (1891)
    - Smaller the test, the larger the effect
    - The larger the surrounding, the larger the effect
    - Effect decreases with distance between colors
    - Effect increases as brightness contrast decreases
    - Effect increases with saturation of the surrounding

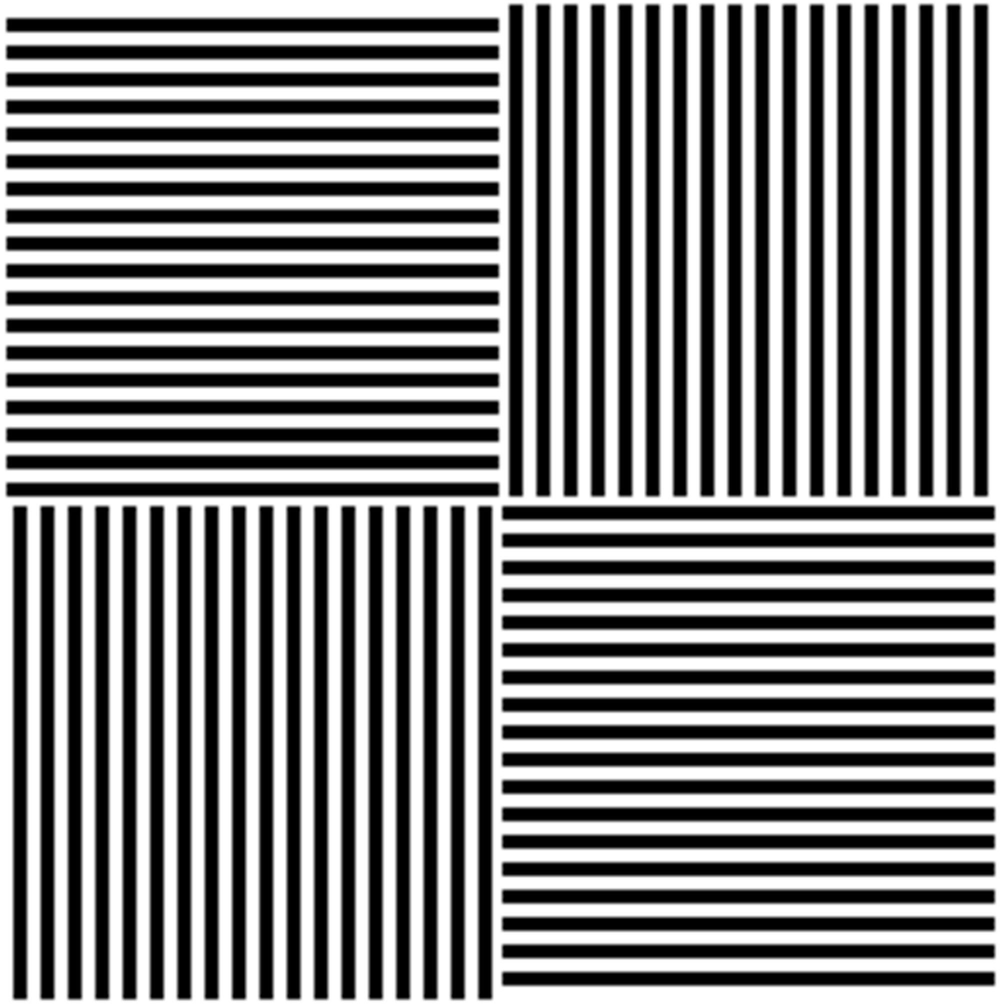
➢ Bring large (30 cm or more) samples home!

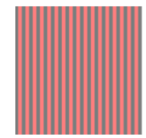
➢ View in expected light and surroundings!

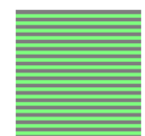
McCollough Effect Test







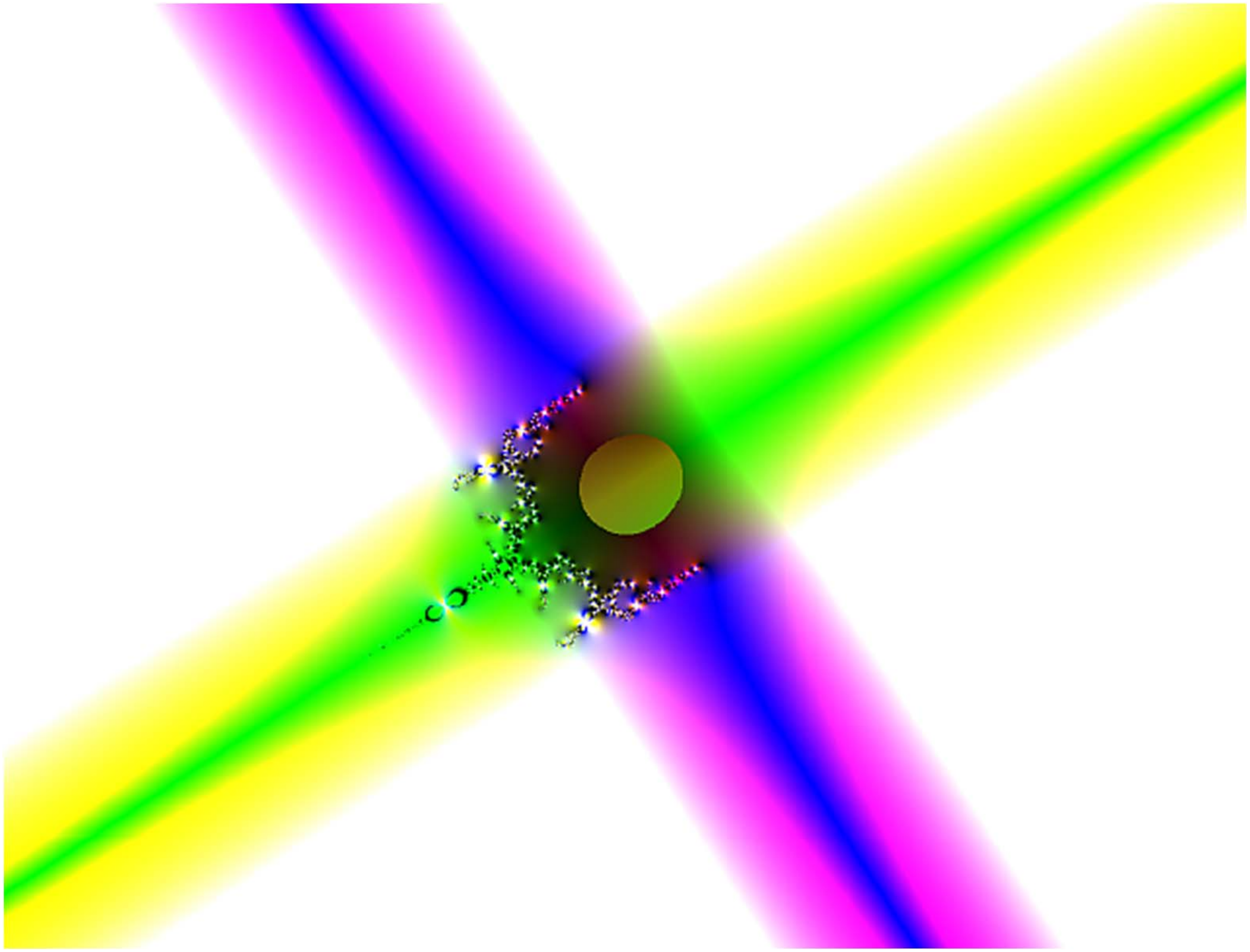




Induction

Result

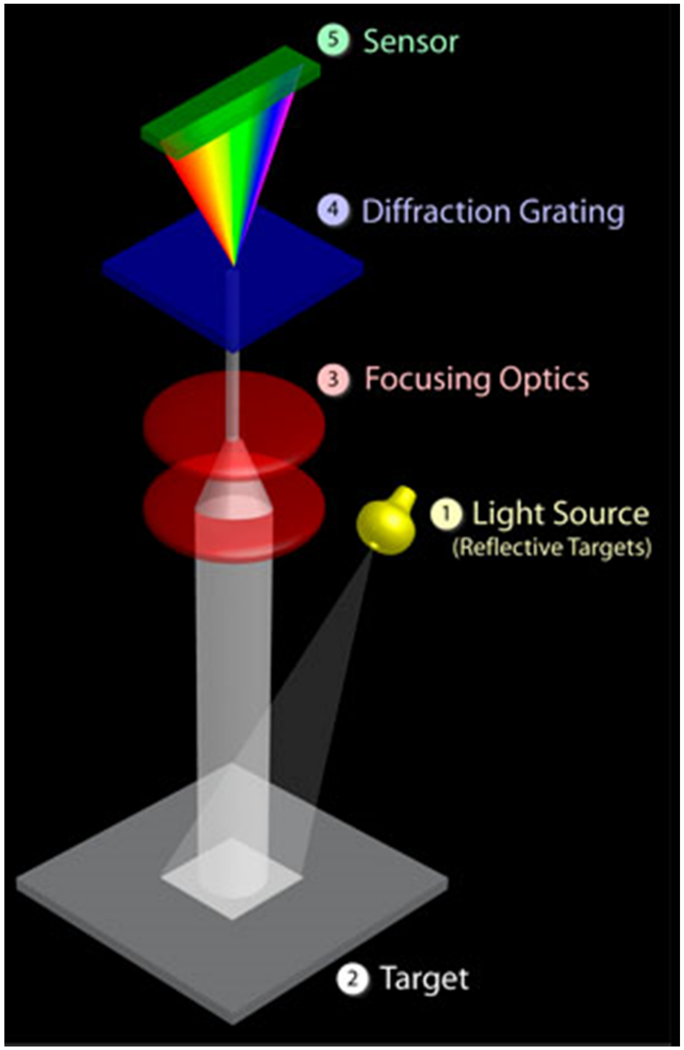
Color Machine Vision Systems



Color Measurement Tools

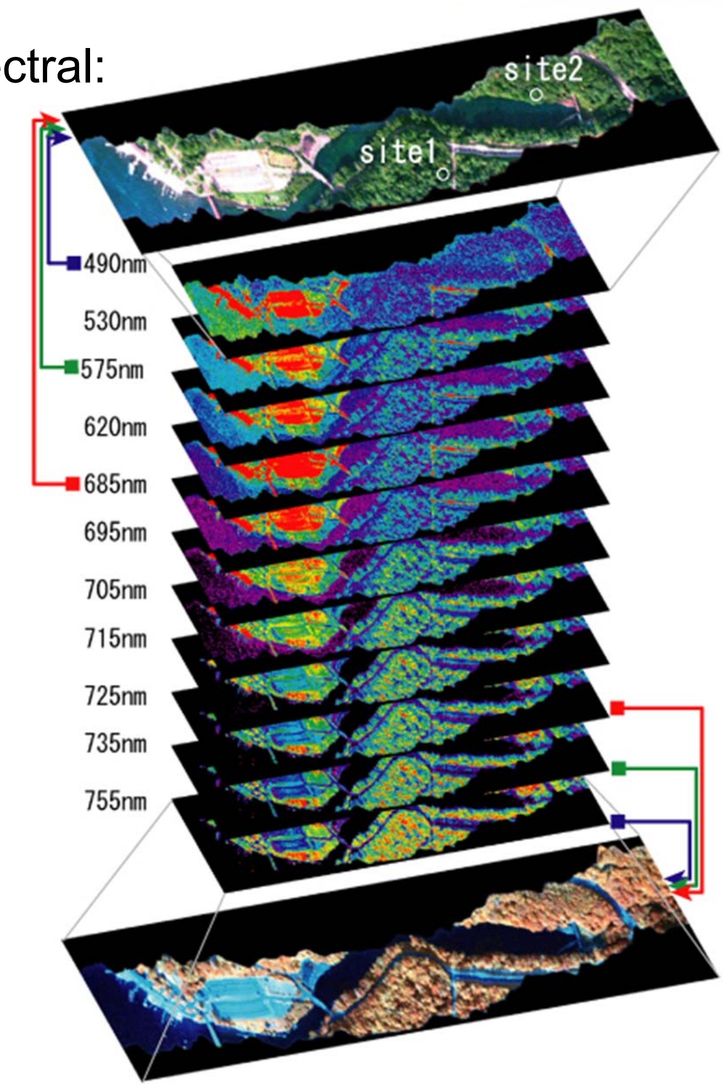
- **Tristimulus Colorimeter** *already described*
  - Calibrated to CIE, controlled light & geometry
  - Measures color at a single point on object
  - Paints, pigments, etc.
- **Spectrometer** – detailed color spectrum
  - Recover object's reflection or transmission spectrum
  - Moisture, cure, chemicals, remote sensing etc.
- **Color sensors and vision systems**
  - Measure color at point or area
  - Can be approximately calibrated to human vision
  - Have to control lighting and imaging geometry

Spectrometer and Hyperspectral



Single spot

Hyperspectral:



False Color

Color Sensors

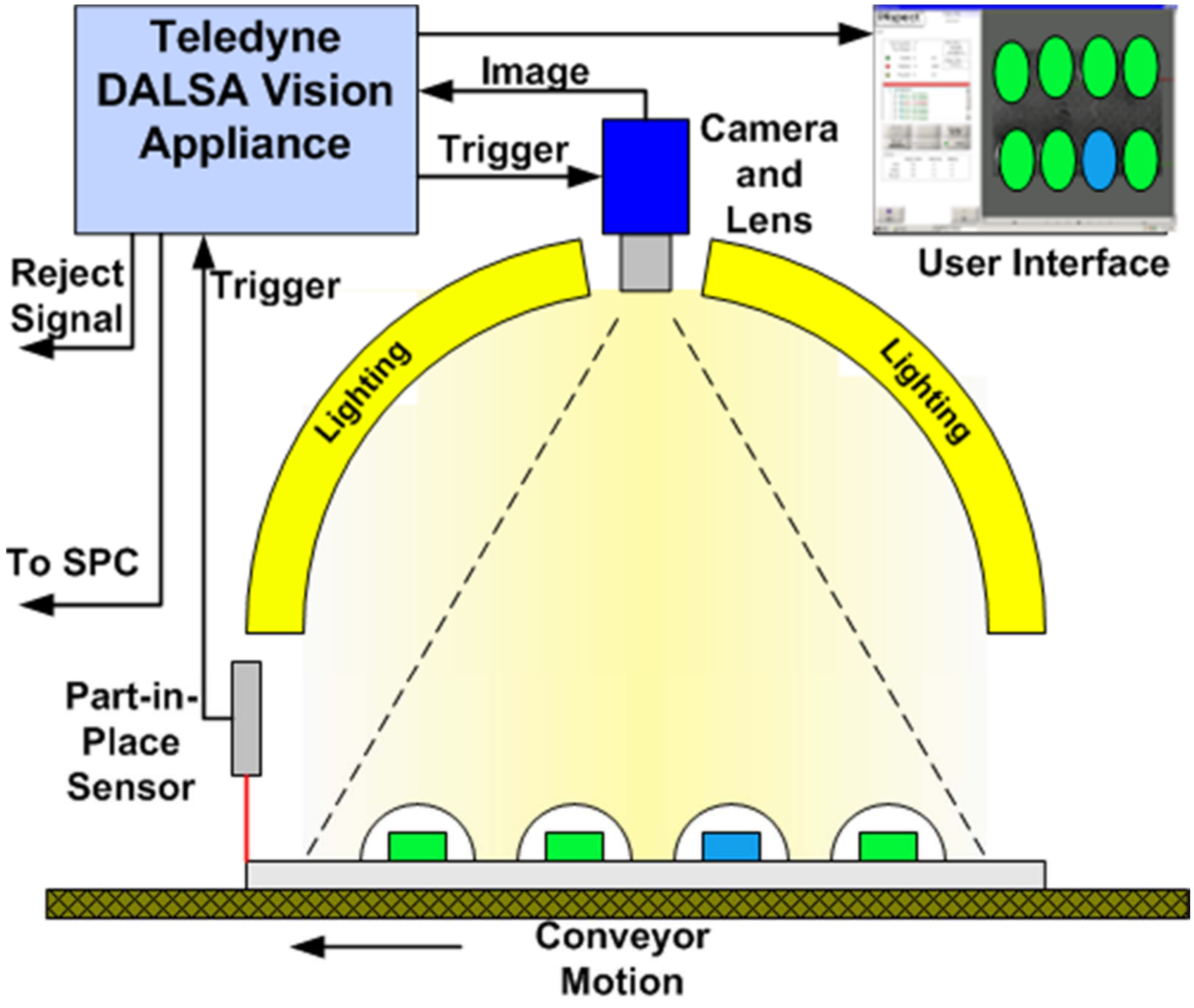
- **Single point** measurement of color
- Easy to set up
- If provides lighting, might give CIE calibrated results
- Might have limit "switches" or other simple processing

KEYENCE

Color Machine Vision Systems

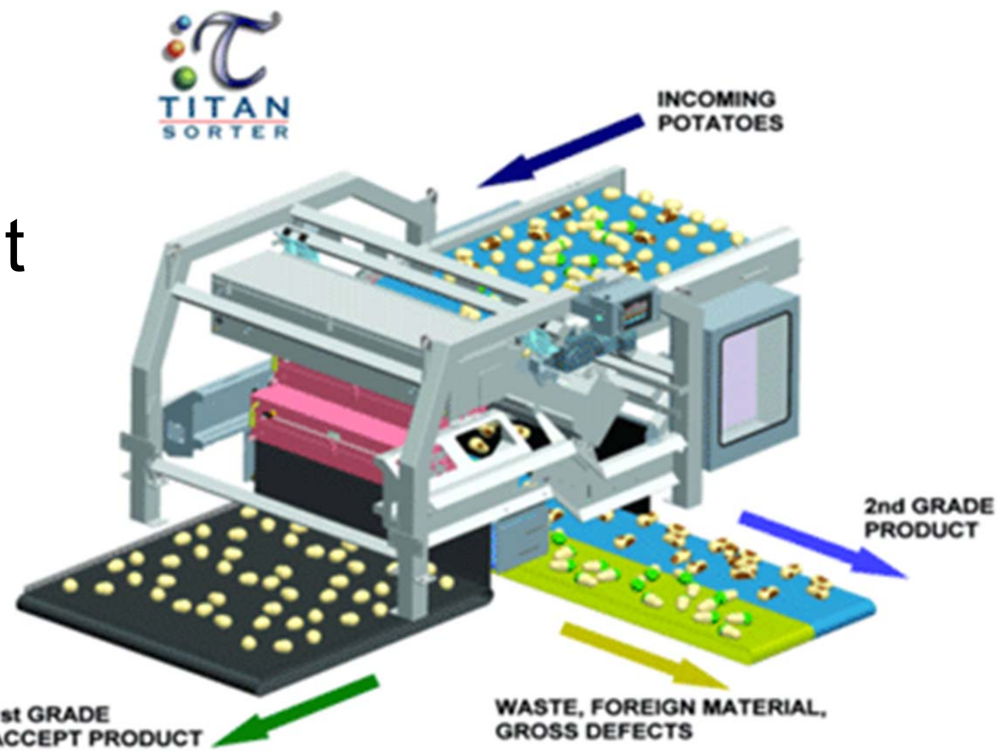
- Color camera measures color over an <u>area</u>
  - Usually not CIE calibrated measures
- "Smarts" built in or in an attached processor
  - Can have very sophisticated decision making
- *Some CMVS components:*
  - Part presentation, environmental control
  - Lighting, filters, lenses
  - Processors, algorithms (might include hardware)
  - Software, developer interface, user interface
  - Reporting, factory integration (not covered here)

CMVS Example: Gelcap Inspection



Part Presentation & Environment

- Positions parts in the camera's field of view
- Fixes viewing geometry
  - Limit color shifts
  - Best view of defects
- Control Environment
  - Light Shield
  - Lighting regulation
  - Cooling, safety, etc.



Desired Illumination for CMV

- “White” light at a specified color temperature
  - Smooth, full spectrum, like a Black Body radiator
- Spectrum covers sensors’ gamuts
- Stabile intensity and spectrum

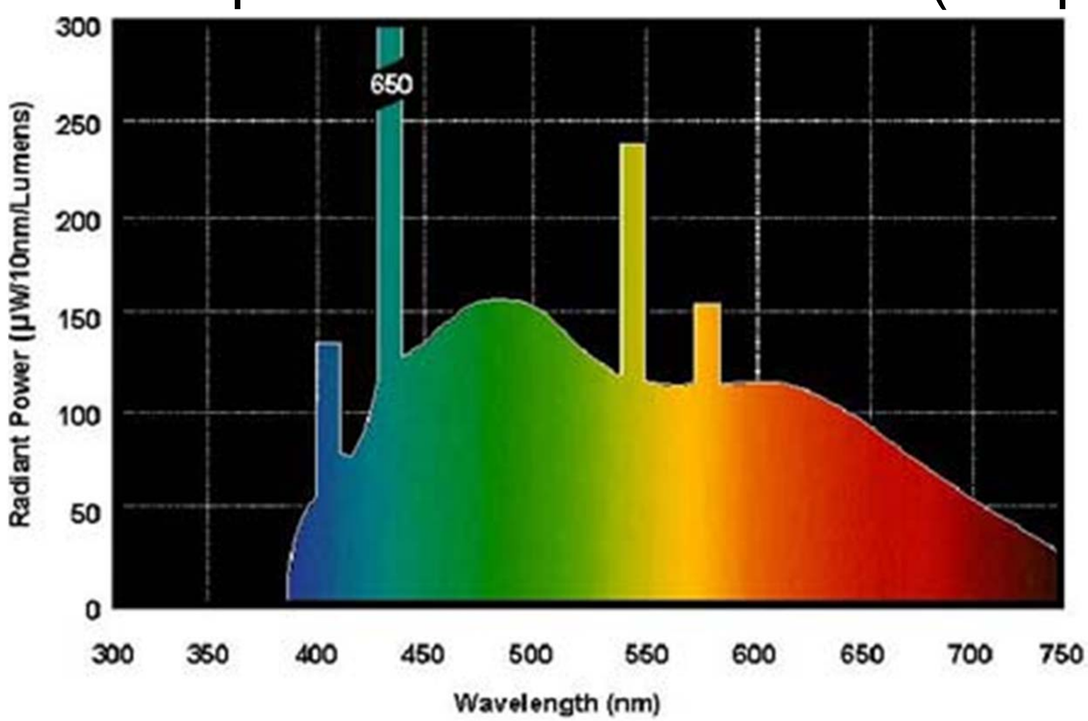
Noon sunlight is best…

Why (not) use Incandescent?

- ✓ Incandescent light has a “natural” spectrum
  - Smooth spectrum, black body radiator
  - Useful for human color matching
- ✗ Color temperature varies with current
  - Regulated DC supply and feedback
- ✗ Short life span
- ✗ Poor energy efficiency
- ✗ Heat removal

Fluorescent Lights

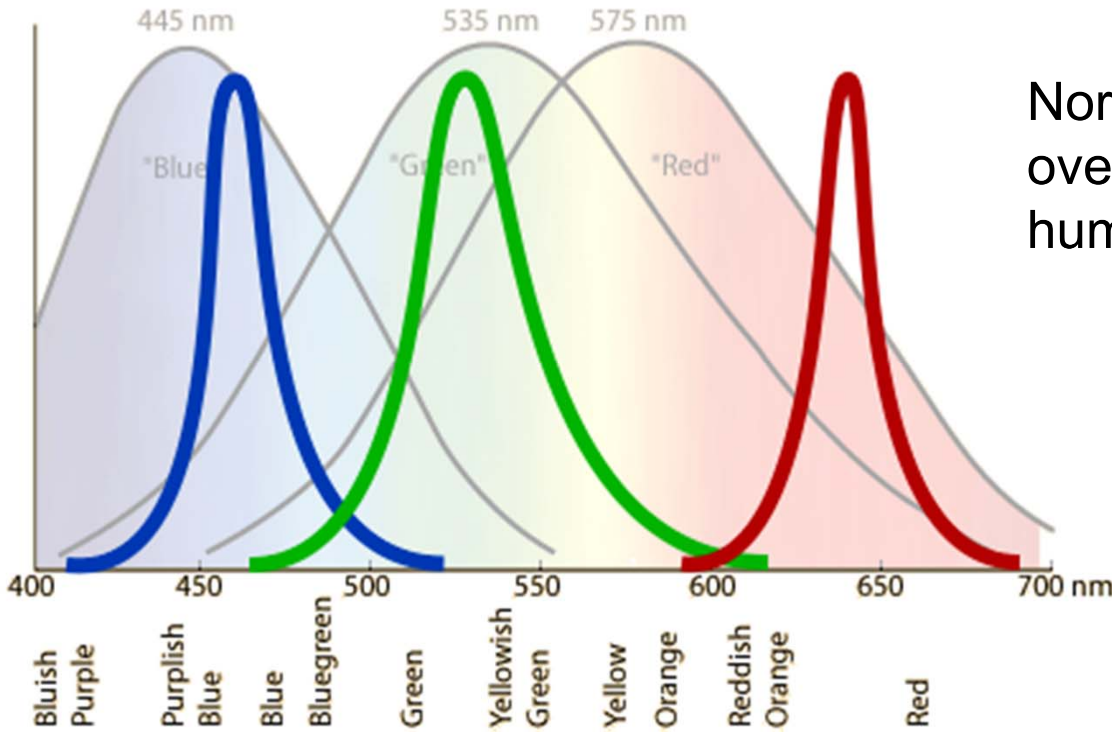
- Spectrum is OK for many CMV tasks
  - Not Black Body but characterized by **correlated color temperature** – again, perceptual color match
  - Spectrum depends on phosphors used
  - Spectrum shifts over time (UV phosphor damage?)



Use high frequency drive to avoid beating against camera's shutter. Still a problem if using fast line-scan cameras.

RGB “White” LEDs

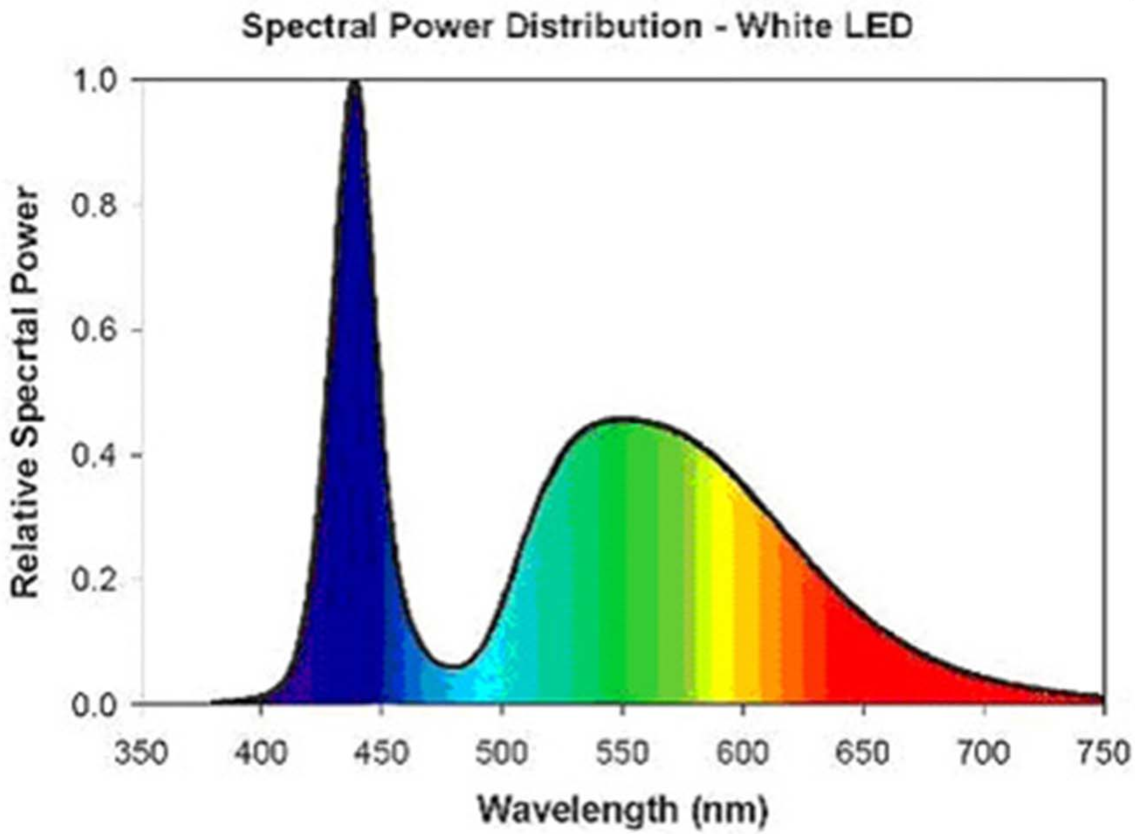
- Combine R,G,B LEDs to get “white” light
- Wide Gamut, adjustable color temperature
- Difficult to make spatially uniform white light



Normalized LED outputs overlaid on normalize human cone responses

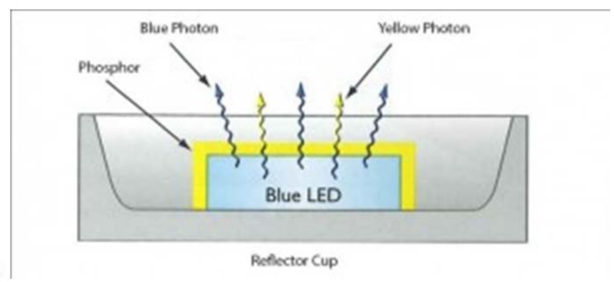
White Phosphor LEDs

- LED emits at ~ 440 nm, phosphor “down converts” some light to longer wavelengths
- Peaks in blue and yellow; dip in blue-green

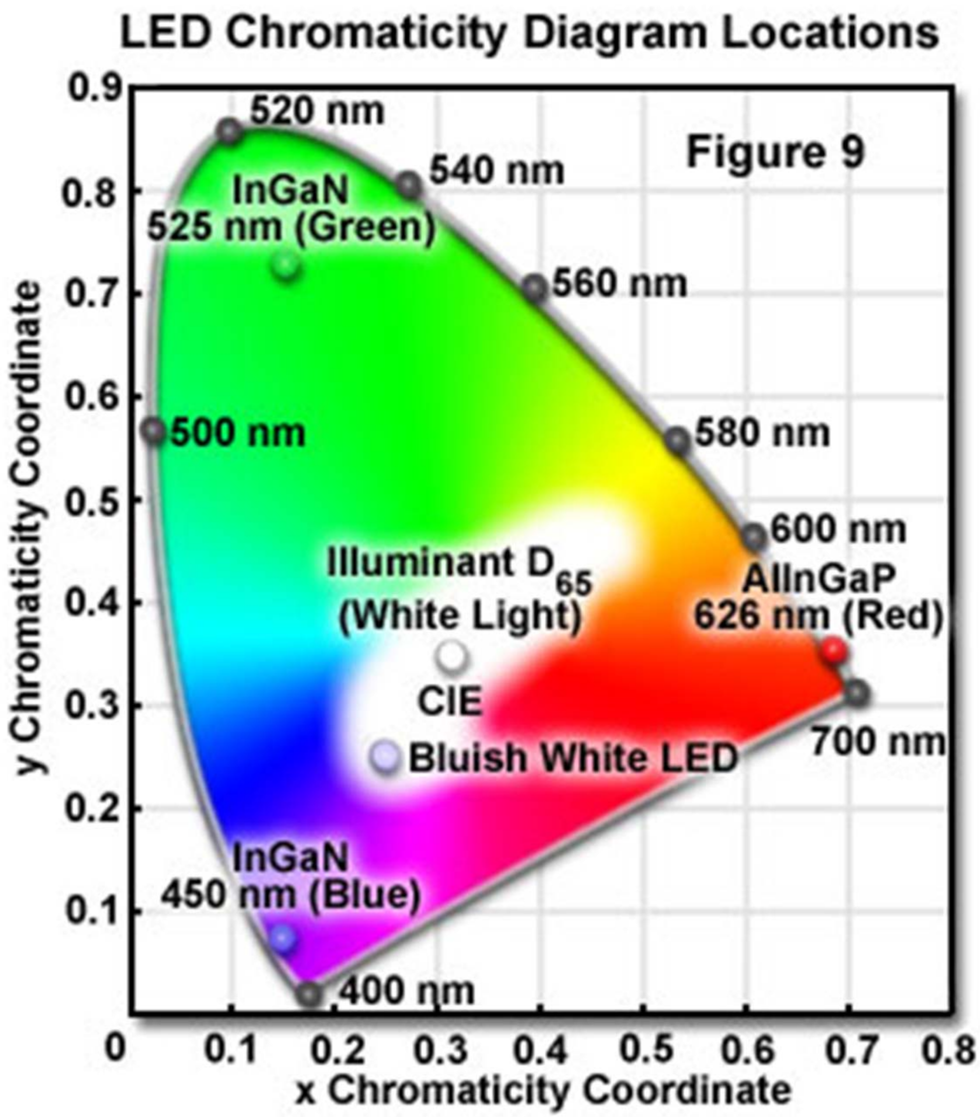


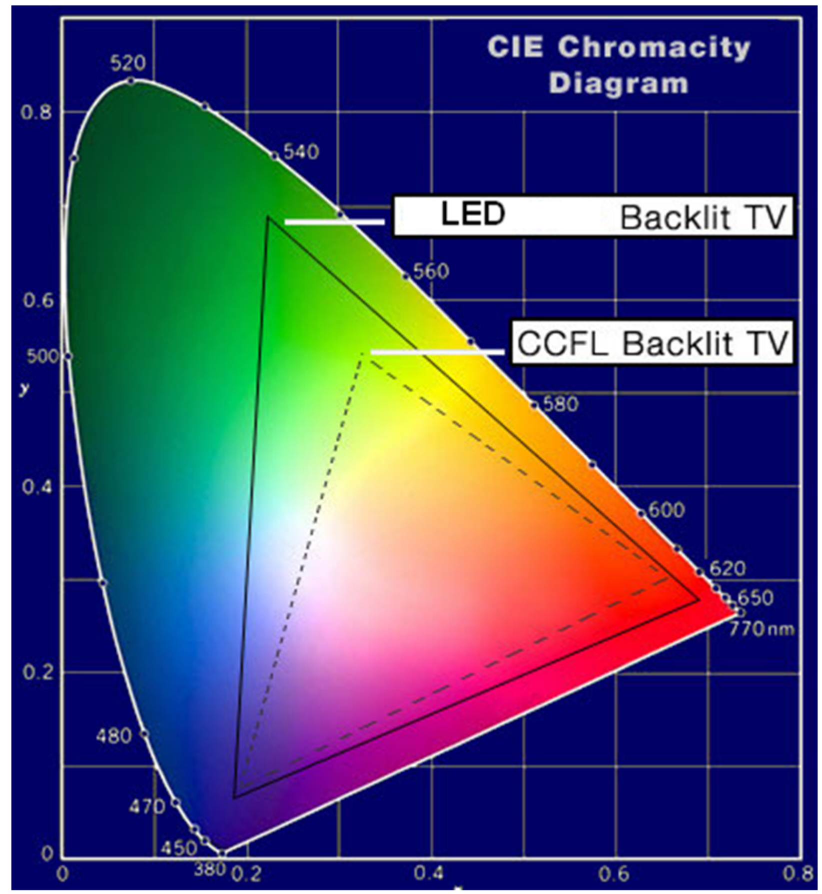
Higher color temperature than sun; very different spectrum.

Spectrum is OK for many CMV tasks.



LEDs in Chromaticity Diagram



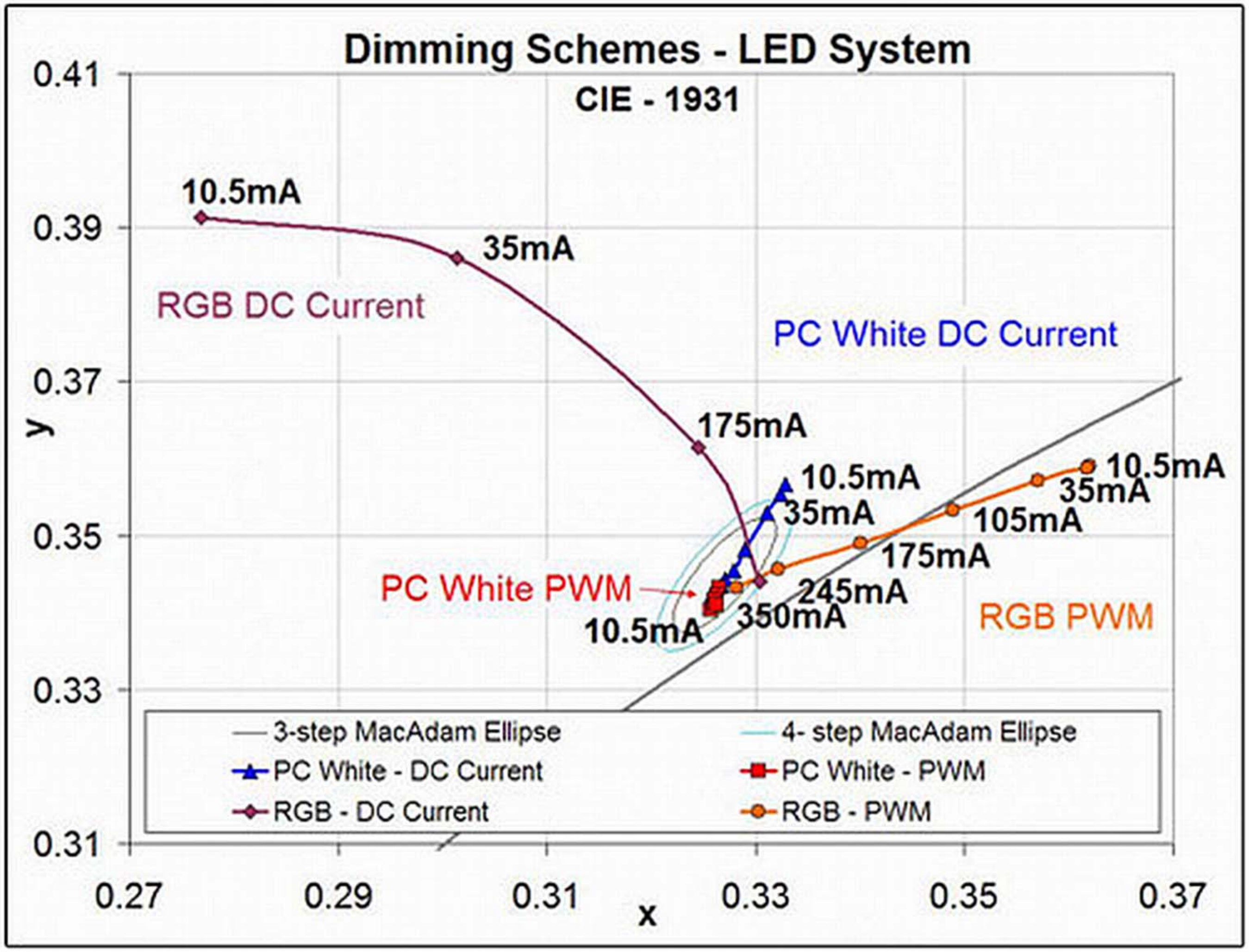


RGB LED Illumination

Why (not) LEDs?

- ✓ Long life, low power
- ✓ Good gamut on RGB, acceptable on white
- ✘ R,G,B colors shift with current, temp. and time
- ✘ White LED color changes with time (phosphors)
- ✘ White LED has limited gamut
- ✘ Life span decreased by heat
  - White: ~10K hours (~1 year), R,G,B: ~50K hours
  - Strobe lights to increase flux and lifetime
- ✓ Use RGB LEDs for high gamut color tasks, white LEDs for just about everything else

LED Color Changes with Current



Some White LED Lights

Advanced illumination
www.advill.com

Filters

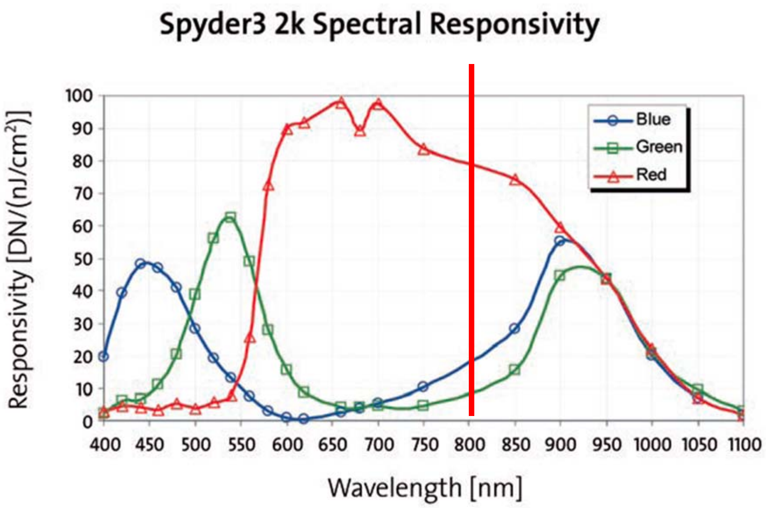
- Limit spectrum as a function of wavelength

MIDOPT

Midwest Optical Systems
www.midopt.com

Why Filter a Color Image!?

- White balance – change illumination spectrum
- Remove or allow IR, UV, or selected color range. Silicon sensors respond out to 900+ nm
  - Remember "IR Bump" on camera response?
  - Makes camera white or color balance impossible!
- Color filters and monochrome camera(s)
  - Higher spatial, spectral resolution



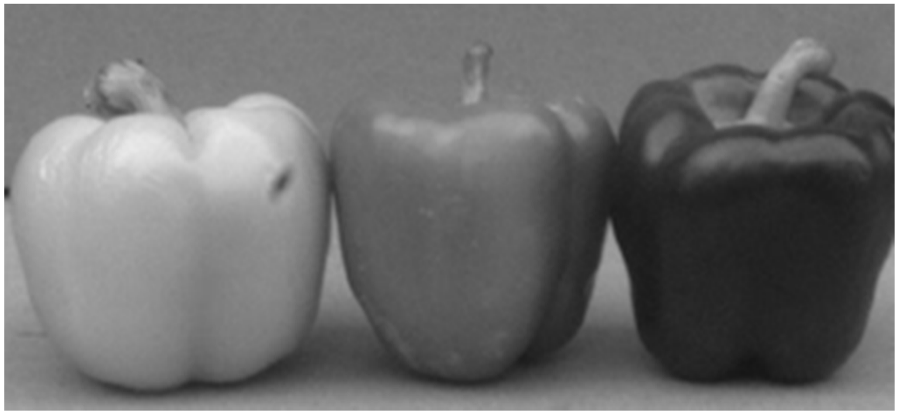
Monochrome “Color Imaging”

A single filter makes an inexpensive, limited “color” detector

Color Image

Monochrome

Midwest Optical Systems
www.midopt.com



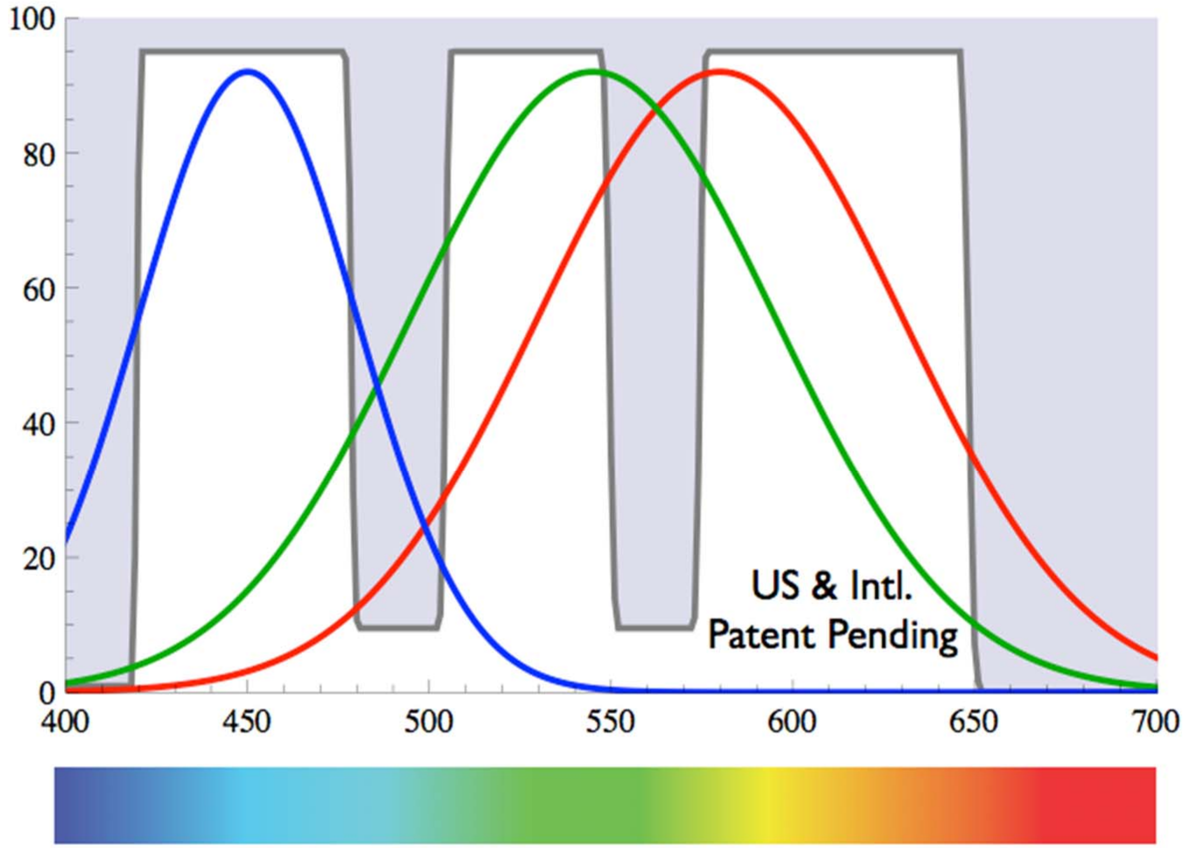
All metamers!

Monochrome Camera with Green Filter

What if part light intensity or part reflectance changes?

"Correcting" Some Color Blindness

- Sunglasses with a spectral "notch" filters that separates cones' spectral responses



EnChroma Cx with Digital Color Boost™

http://enchroma.com/

Lenses for CMVS

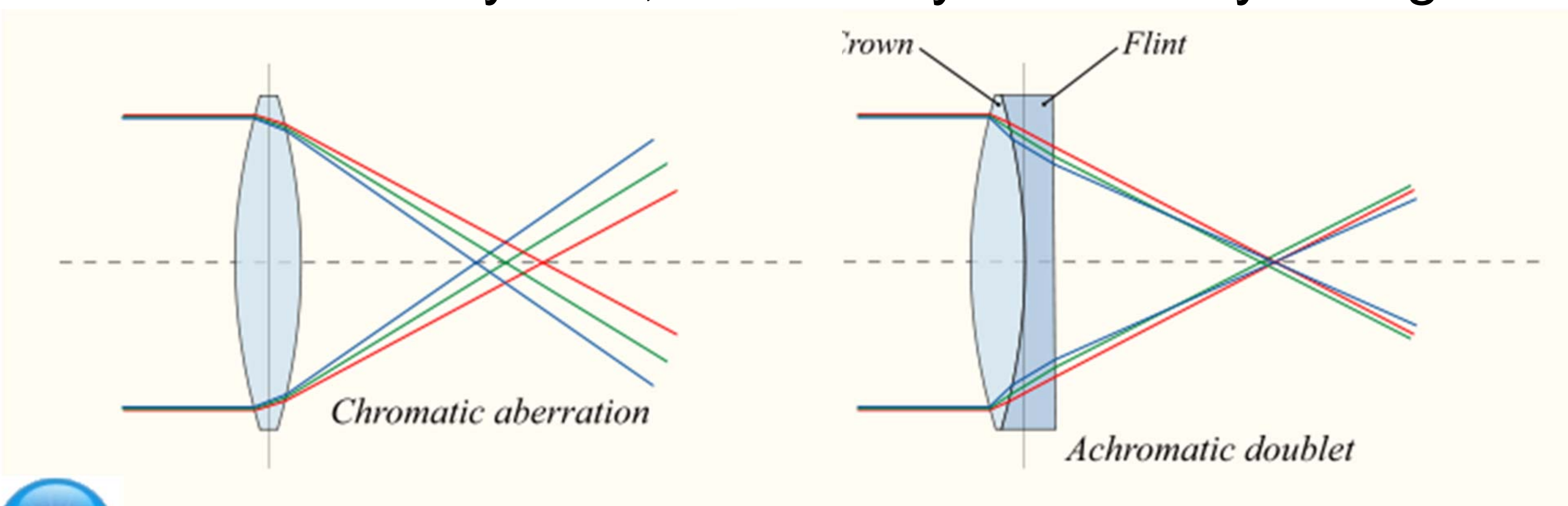
- Brings object into focus on the sensor plane
- Lenses must be **color corrected** for chromatic aberration

Schneider OPTICS

www.schneideroptics.com

Lens Chromatic Aberration

- **Chromatic Aberration**: Focus point shifts with wavelength
  - Most MV lenses are well **color corrected** for **visible light**, so usually not a problem
- Near IR and UV light are "fuzzy" and attenuated
  - Block IR by filter; UV usually blocked by lens glass



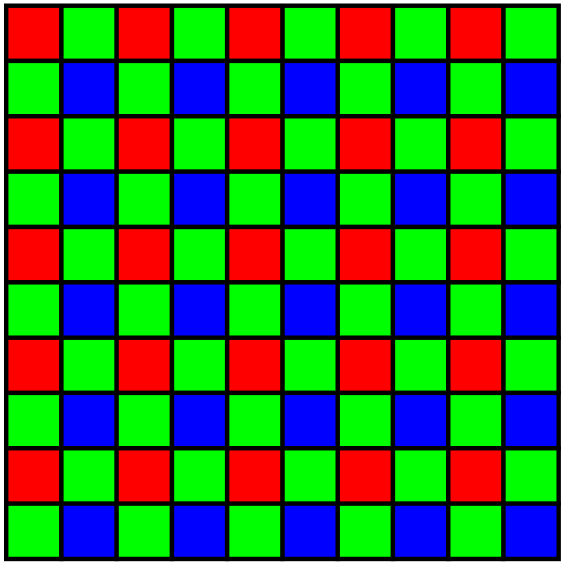
Eye has limited blue cones and has a yellow filter in central fovea

Color Cameras

- Usually three sensor types
  - *Approximates* spectral responses of eye's sensors
  - Color computed from the relative responses of the sensor types, as with the eye
- Warning: Outputs could shift with temperature

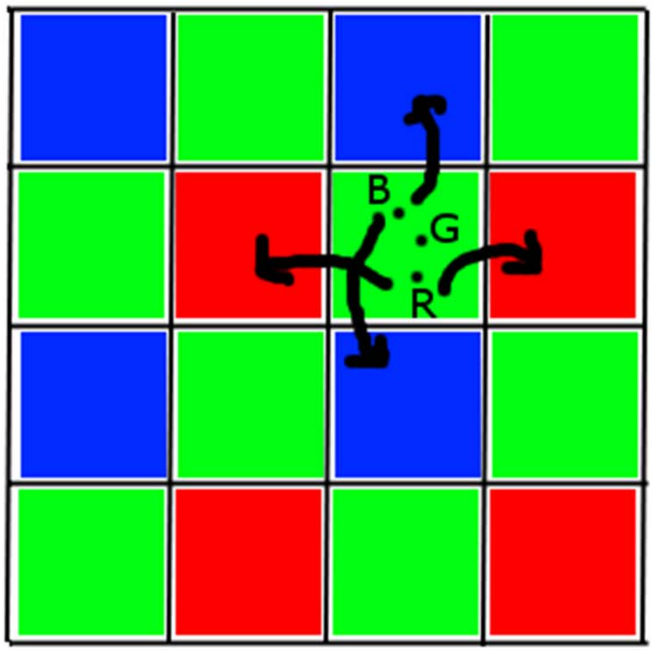
Bayer Pattern Cameras

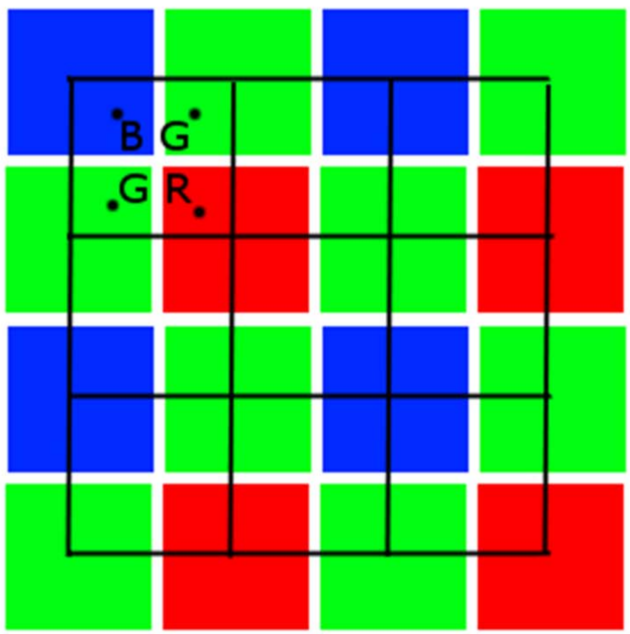
- Color filters over a monochrome camera’s pixels
  - Reduces cost… and spatial resolution
- Colors interpolated to RGB values at each pixel
  - Interpolation of missing samples gives color noise, particularly at edges
  - Lower spatial resolution can give **color aliasing**



Bayer Pattern "Removal"

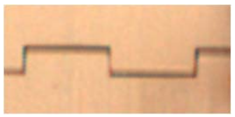
- Interpolate colors to get "full" RGB color image
  - But really at ½ resolution
- Done in the camera or in CPU
  - Many algorithms available, none can be perfect…





Bayer Pattern Color Noise

- Interpolating color generates color “noise”, especially noticeable across intensity edges

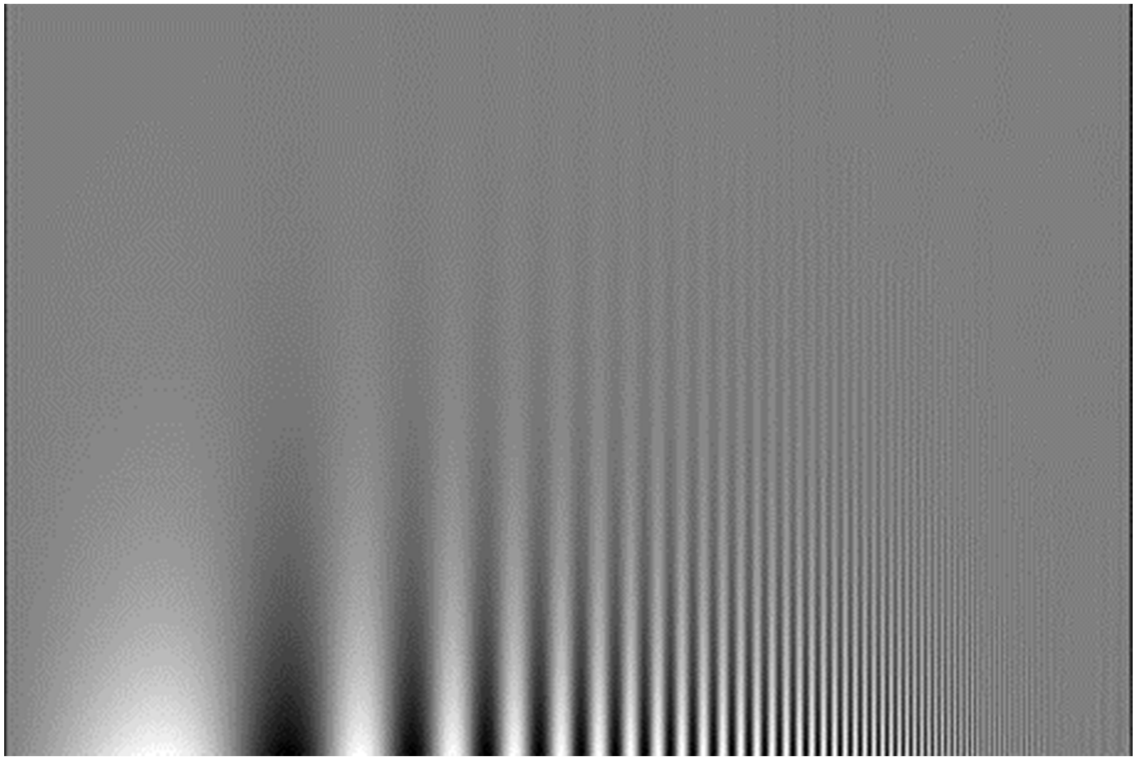


An innocent-looking section of conveyer belt

Zoomed in shows color artifacts from Bayer pattern

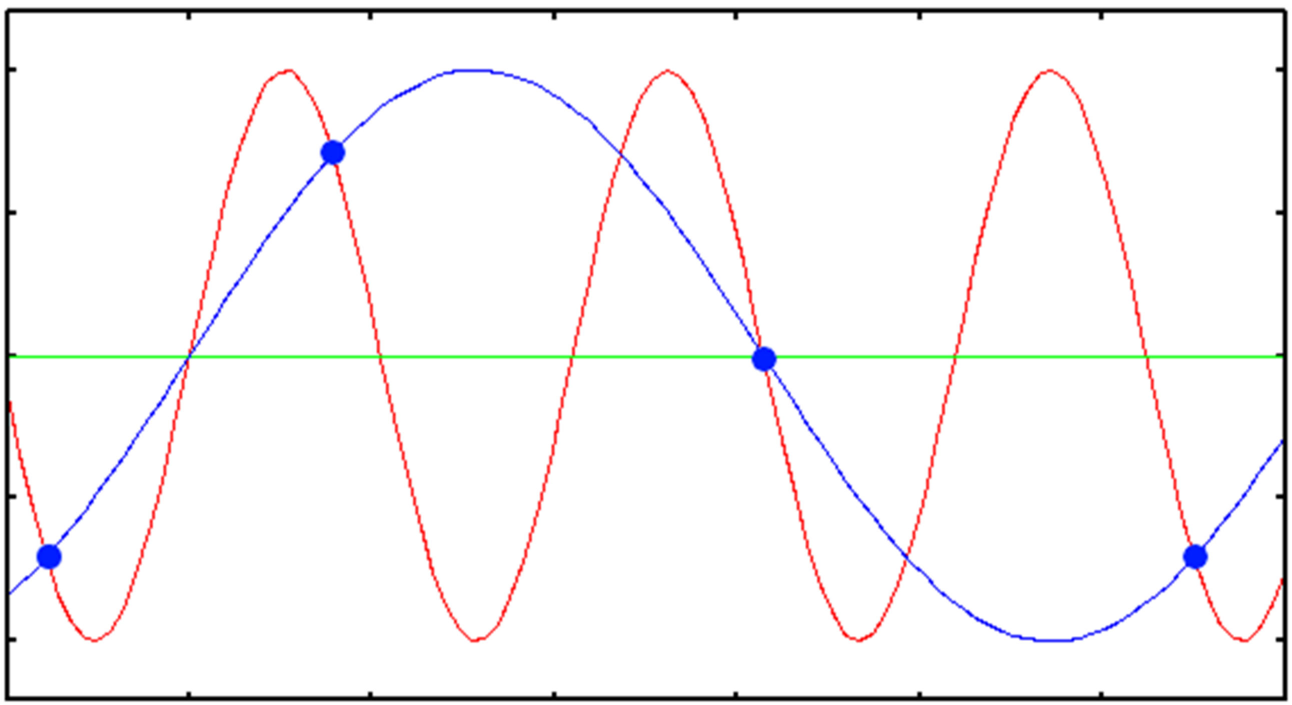
Spatial Frequency Response

- Imaging systems can be characterized by their **spatial frequency response**
  - Higher spatial frequencies correspond to more details or more “sharpness” in the image



Digital Sampling & Aliasing

- Object details < 2 **sensels** can produce bogus spatial frequencies in the digital image
  - Appears as incorrect colors or intensity in image
  - Limit object's spatial frequency to avoid aliasing



Color Aliasing

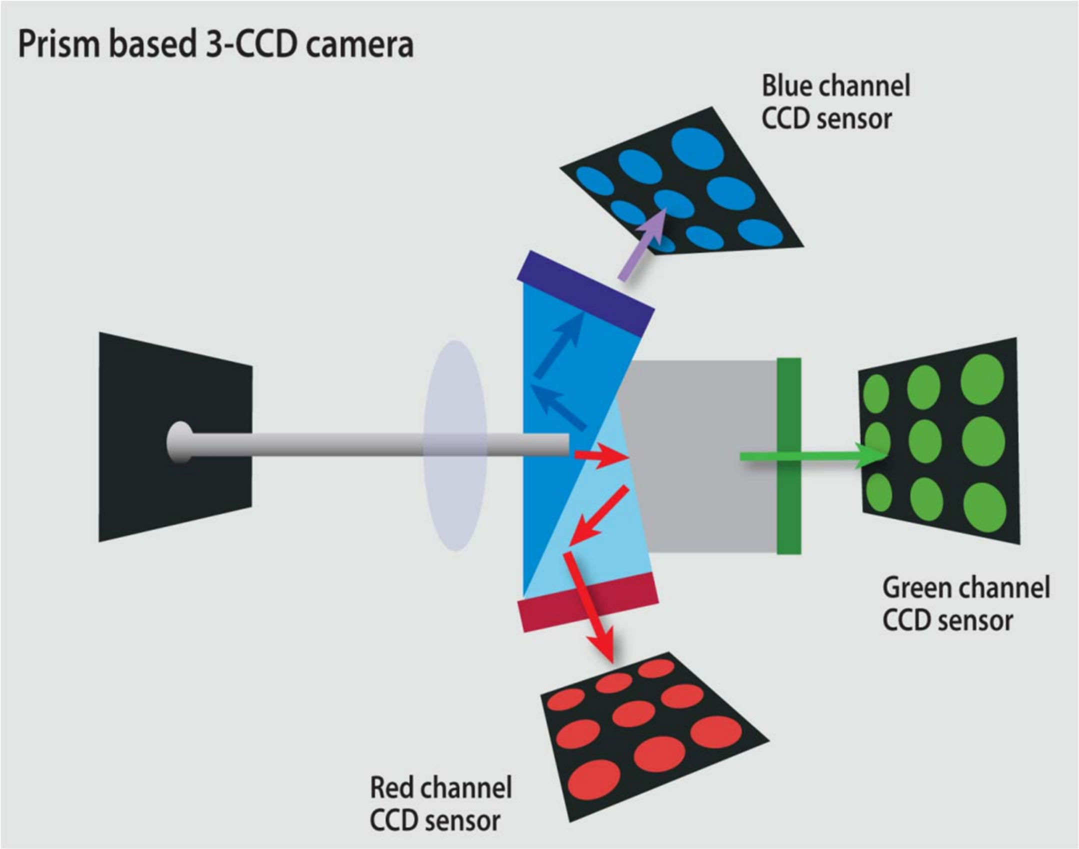
- Bayer filter pattern cameras can exhibit aliasing
  - Beat or color moiré patterns on high spatial frequencies
- Some cameras include an optical low-pass filter
  - Spreads light rays into a 2x2 pixel square

Color vs. Resolution

- Bayer pattern cameras trade spatial resolution (details) for spectral resolution
- In human vision, color "fills in" edges defined by intensity so lower color resolution looks OK
  - But not to a machine vision system!
- Bayer pattern makes it difficult to use edges for dimensioning objects
  - Reduced resolution
  - Color artifacts when computing edge position
  - More likely to get color aliasing

3 CCD Cameras (1)

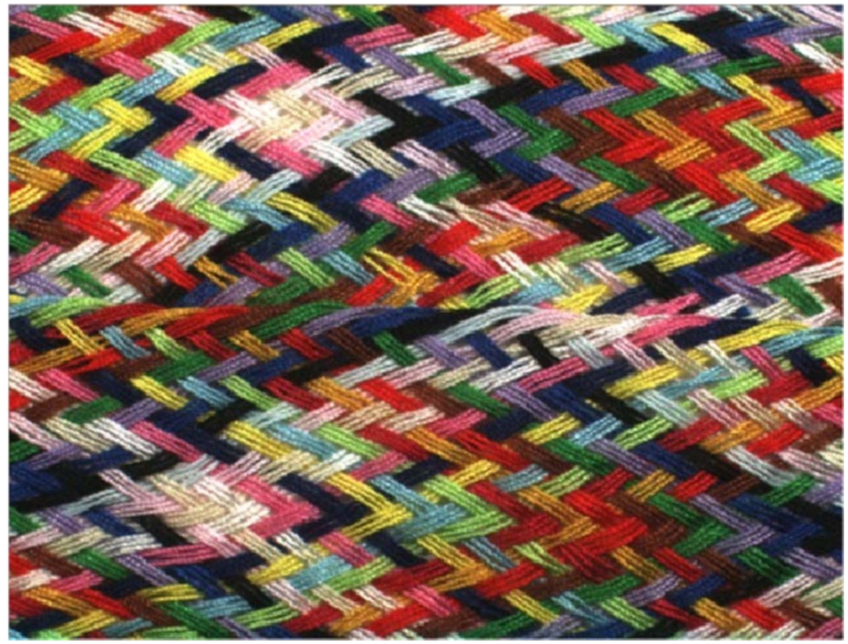
- A 3-sensor (CCD) camera has no spatial sub-sampling and so reduces the chance of aliasing



www.jai.com/en

3 CCD Cameras (2)

- Improves color resolution and contrast

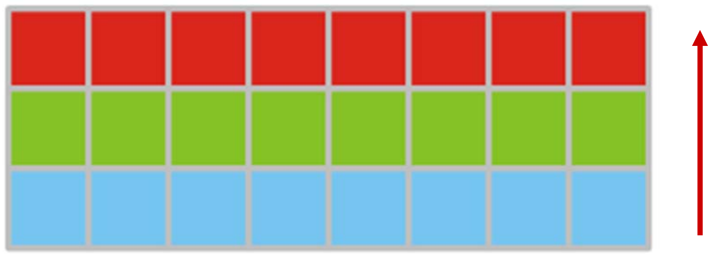


- Expensive, higher data rate
  - Hard to align the three sensor chips

www.jai.com/en

Color Line Scan Cameras

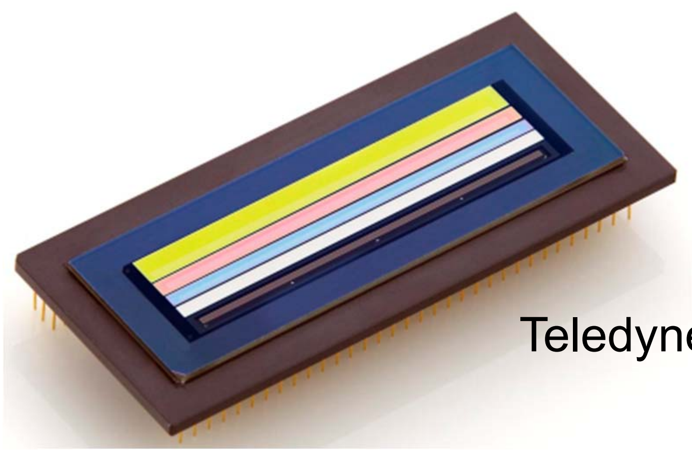
- Long rows of different sensor types



Delay outputs to align colors

  - For continuous inspections of moving objects
  - Large images with no defects, no Bayer pattern issues
  - Ideal for print inspection, continuous web processes

Sensor surface must be parallel to object surface – Why?

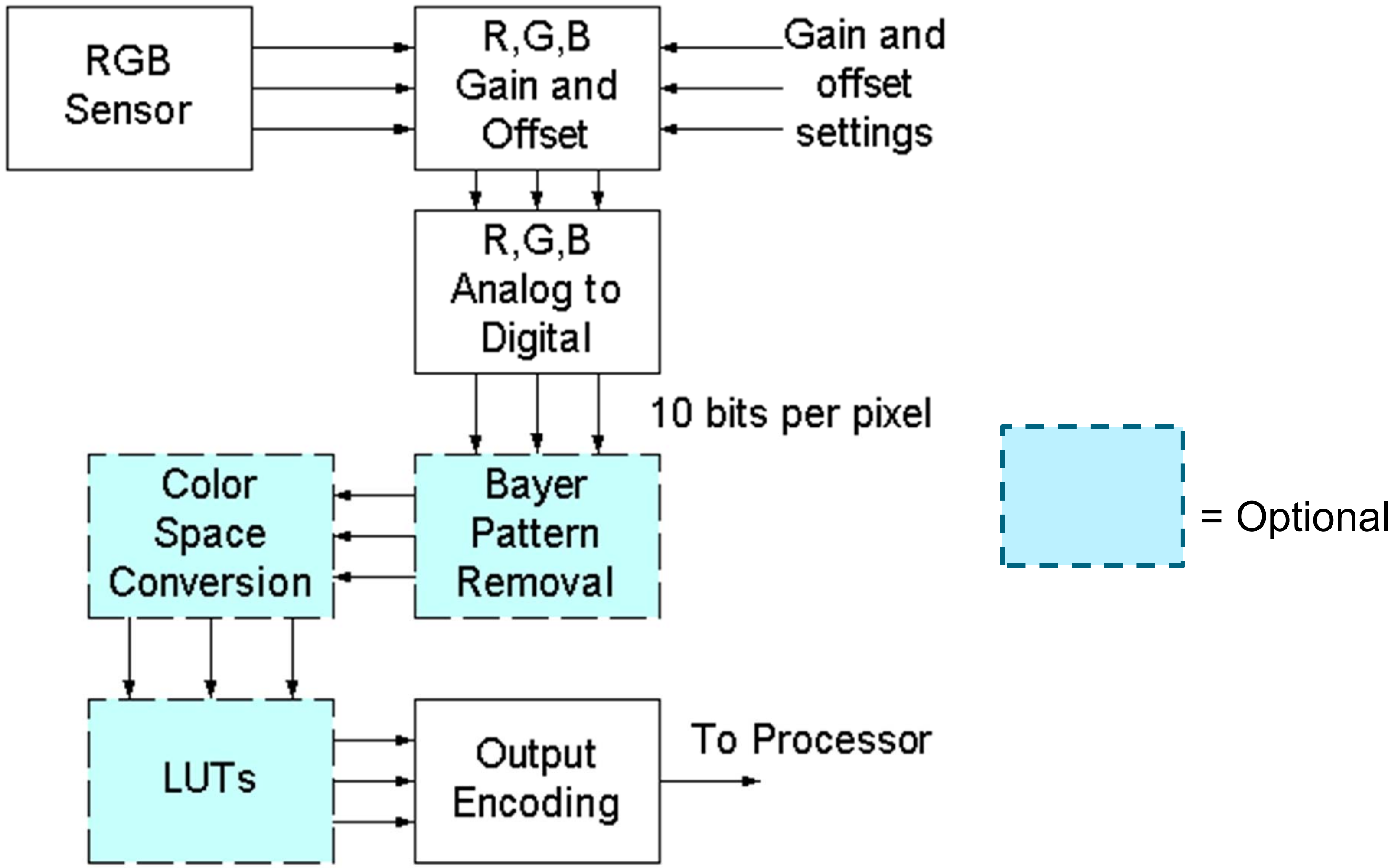


Teledyne DALSA – CMYK line scan sensor

Living with the Bayer

- **It's low cost**
- Use a better camera if you need edge or detail measures (e.g. print defect detection)
  - Higher resolution, line-scan, or 3-sensor
- Customized interpolation software
- Measure areas and averages, not details

In-Camera Processing

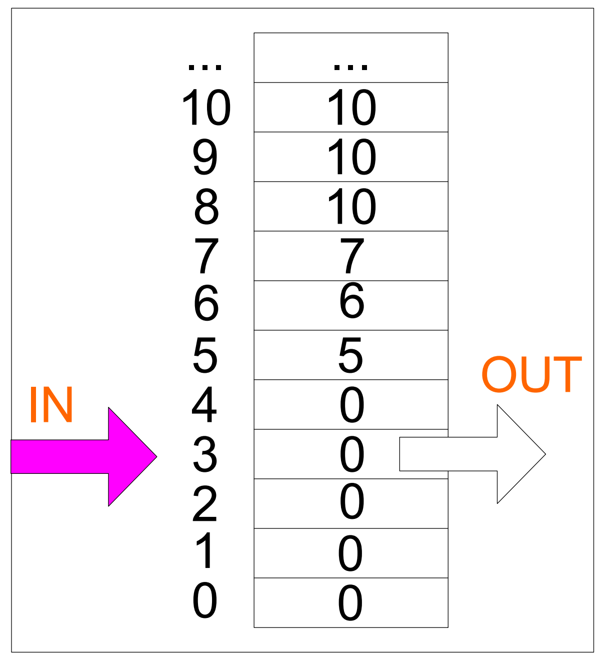


Gain and Offset, A to D

- Changes gain and offset for each channel
  - Out = gain * input + offset
  - Done in analog to preserve maximum working range
  - Adjust for maximum output gamut
- Used to approximately **white balance** or **color balance** the image (*discussed later*)
- Analog to digital conversion of 10 bits gives you "headroom" for Bayer pattern removal, etc.
  - Each digital multiply introduce ~0.5 bit of error
  - Digital dynamic range is limited

Color Space Conversion, LUTs

- Color machine vision cameras rarely have color space conversion (usually a matrix multiplier)
- Many have Look-up Tables (LUTs), for things like:
  - **Gamma correction**
  - **White and color balance**
  - Could use for thresholds and other algorithms, but usually done by processor



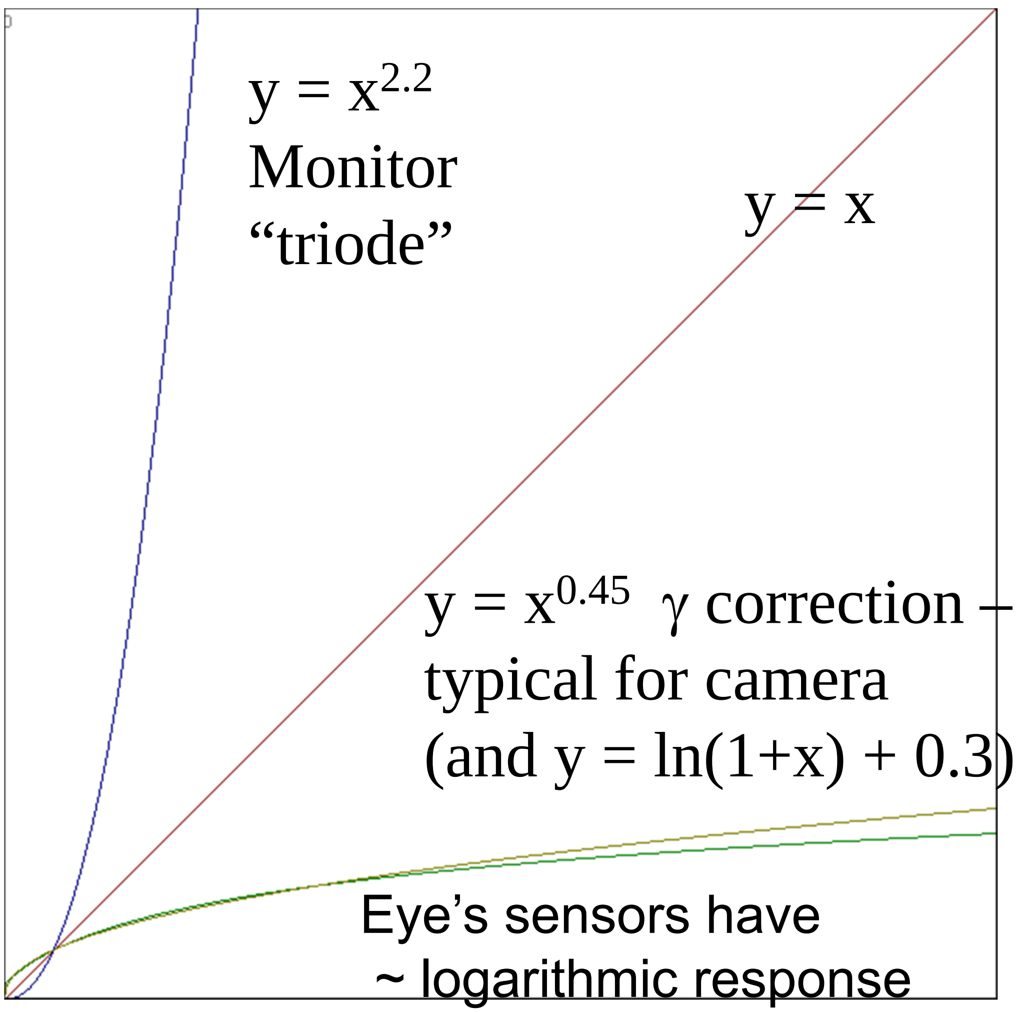
The Curse of Gamma

- Old TV cameras compressed intensity $I_o = I_i^{\gamma}$
- Uncompressed by CRT “triode” response
    - LCD displays fake a CRT response with LUTs
- Digital cameras can mimic old TV cameras
- Messes up MV – **turn it off** in most cases
    - Will make the displayed image “dark”

Gamma off

Gamma on

Gamma Curves



Color MV Processors

- Smart cameras
  - Low cost, good performance, easy to set up
- PC Based
  - Higher performance, familiar work environment
- Attached processor (boards)
  - For high-speed applications such as web inspection
  - FPGAs, large LUTs, parallel processors, etc.
- High-speed, custom processors
  - CT, MRI, remote sensing
  - Huge data rates

Color "Smart Cameras"

- RGB Camera combined with processor
  - Small size, low cost, easy mounting, easy to use
  - Programmed and controlled over network

Teledyne DALSA BOA

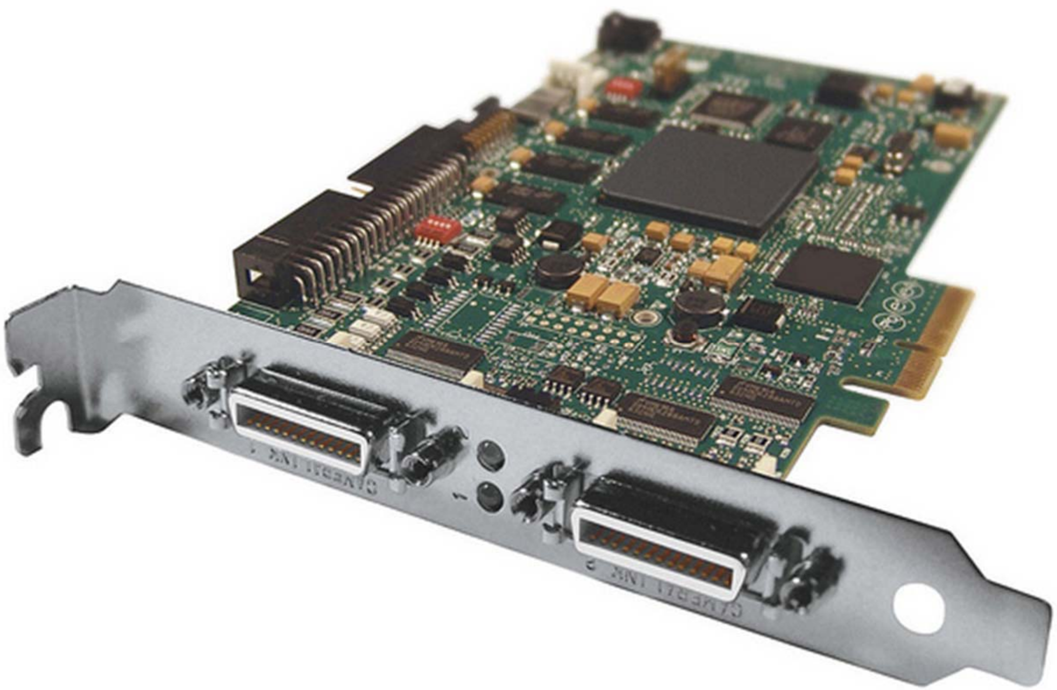
PC-Based Processors

- General purpose computer
- Small to industrial rack-mount PC size
- Range of performance and flexibility
- Familiar software environment

Teledyne DALSA
GEVA 3000

Attached Processor

- PC with attached processor
  - Offloads computationally intensive operations
    - Color space conversion, color correction, calibration
- For demanding applications
  - High-speed line scan processing



Teledyne DALSA
Xcelera-CL PX4

TIPS (1)

- Make sure the camera resolution is sufficient
- Avoid CIE calibration with RGB camera
- Control lighting, imaging geometry
- Use white LED or fluorescent lighting
- Use a color reference spot in FOV (TBD)
- Use an IR block filter on camera (2 reasons)
- Control camera temperature (+/- 5 F is good)
- Avoid making edge-based measures, e.g. calipers, with low-resolution Bayer cameras

Basic Color MV Algorithms

- Algorithms are implemented by Lighting, Optics, Hardware and Software

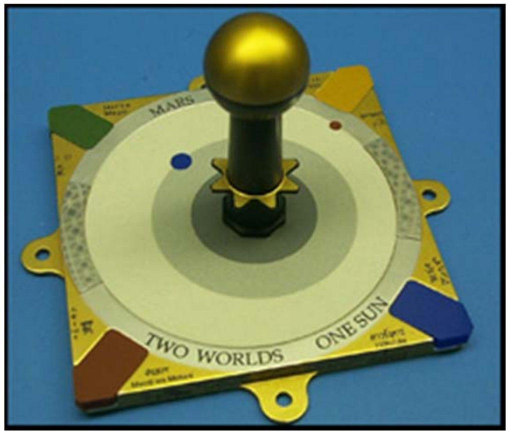
Camera Setup

- Three terms, often confused:
- **White Balance** (or gray or neutral balance)
  - Removes color cast so whites appear white
  - Compensate for illumination's color temperature
- **Color Balance**
  - As above, but applied to correcting range of colors
    Used for human viewing (usually with gamma on)
- **Color Calibration**
  - Adjusts camera's outputs to get values expected from known colors.
  - **Standard** (e.g. CIE) or **Comparative** (to object colors)
    - These are my terms and not generally in use!

White Balance Example

Color Balance for Human Viewing

- CMV presents images for human viewing
  - High-speed printing, remote sensing
- We use a **color chart** and adjust gain, offset and **gamma** of R,G,B channels so display closely matches the chart's colors



Comparative Calibration

- **Compare** measured colors with color values of known good parts
  - Avoids **standardized** calibration
  - Good enough for many MV tasks
- Example: Color on can label
  - Customers won't buy if "faded" color
  - Compare production colors to colors measured on a know good can
  - Reject cans that are outside limits
  - Fix the ink supply!

All need to Recover the Illuminant

- To **White Balance**, **Color Balance** or **Calibrate** color we need to know or recover the illuminant
  - Use color temperature, if known
  - Use a **white reference** patch in the field of view, to reflect illumination spectrum
    - Preferred method in machine vision
    - Adapts to lighting changes
  - Computational methods for **color constancy** try to "factor out" the illuminant

X-Rite

Color Constancy (again)

Human vision uses constraints and computation to give stabile color perception despite illumination changes

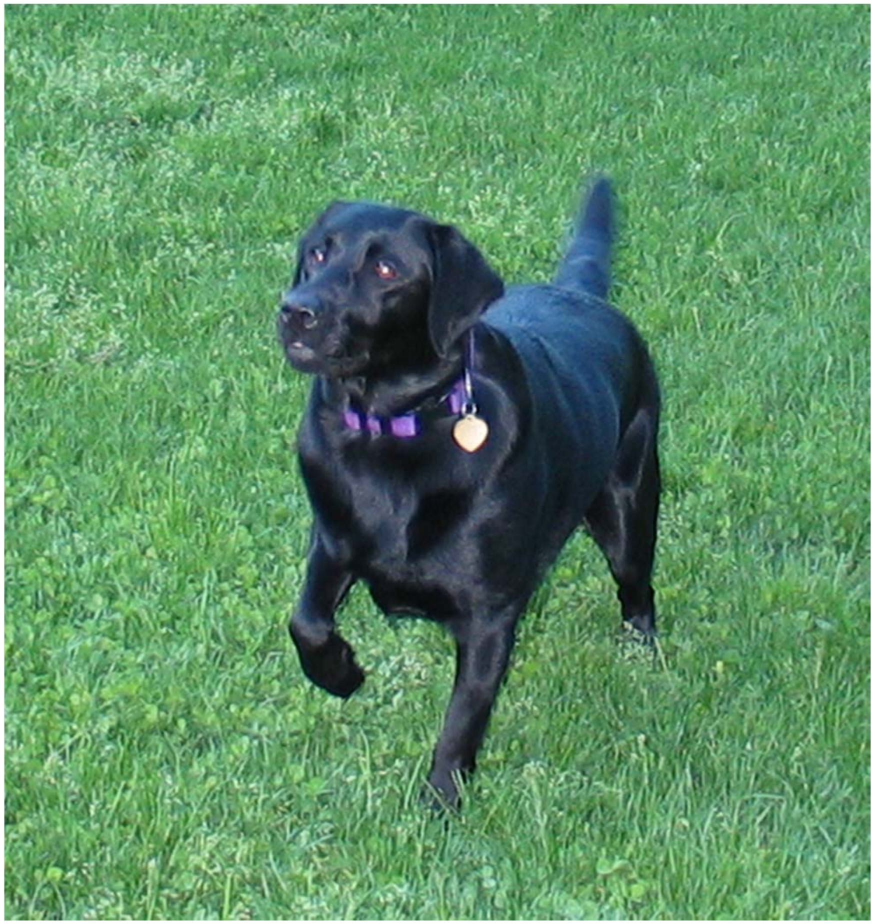
White Balance Methods

- Assume maximums of R,G,B are the color of the illuminant
  - Limited camera range usually clips
  - Can be confused by unstable highlights
- Assume gray average world color (**gray world**)
  - Average of R,G,B image values: R_a, G_a, B_a
  - Assume any differences between these averages are due to illumination color (e.g. "world" should average to gray, $R_a=G_a=B_a$, if lighting is white)
  - Scale image values so averages are equal, thus removing effects of illumination color

When (and why) will this fail?

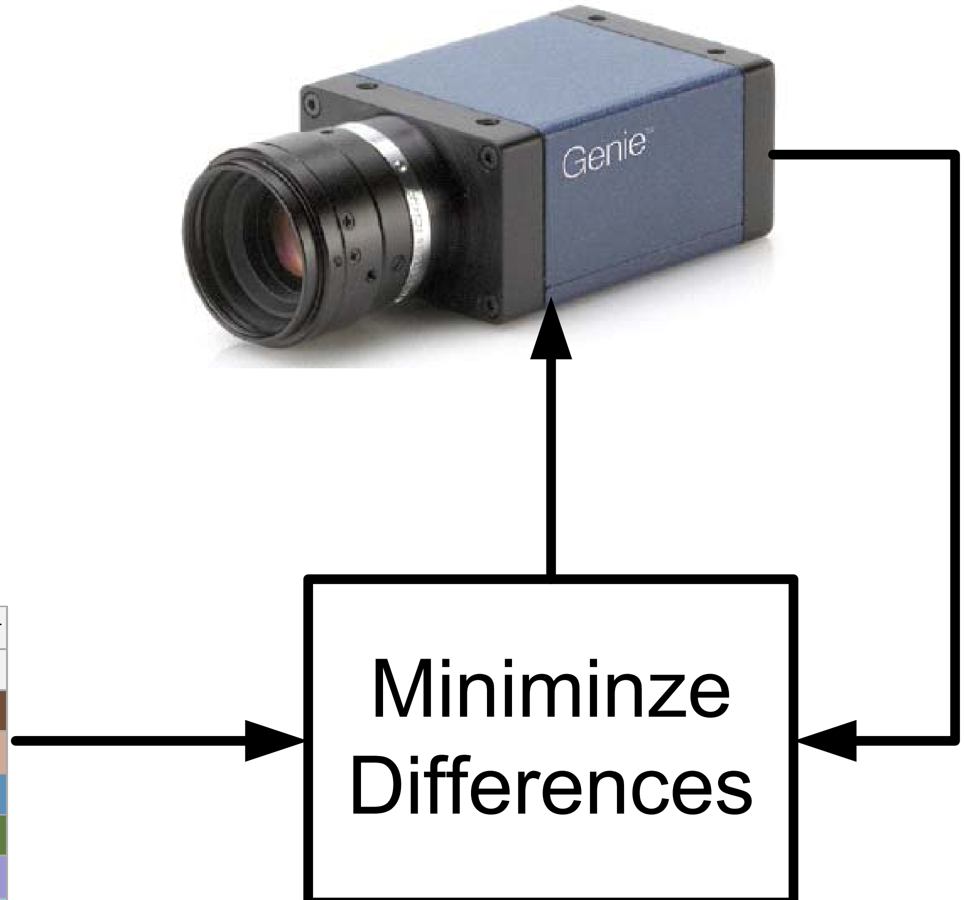
Violating Gray World Assumption

When "average world color" isn't gray…



Color Balance

Index	Description	Munsell Notation	CIE xyY	Approximate RGB color
Row 1: Natural colors				
1	Dark skin	3 YR 3.7/3.2	0.400 0.350 10.1	#6f4f38
2	Light skin	2.2 YR 6.47/4.1	0.377 0.345 35.8	#ceaa99
3	Blue sky	4.3 PB 4.95/5.5	0.247 0.251 19.3	#5e8fb8
4	Foliage	6.7 GY 4.2/4.1	0.337 0.422 13.3	#607c43
5	Blue flower	9.7 PB 5.47/6.7	0.265 0.240 24.3	#9b97d2
6	Bluish green	2.5 BG 7/6	0.261 0.343 43.1	#8ddad6



Color Balance Methods

- Includes white balance
- Seek function(s) to minimize the difference between camera output and color standards
  - Usually automated and provided by vendor
- Some minimization functions:
  - Adjust gain and offset and gamma (in camera)
  - Matrix multiplication (3x3 or 4x4)
    - Rotates and scales input color space
  - Piecewise linear look-up table (LUT)
  - Full R x G x B lookup
    - Does a good job but hard to set 16 million values

Color Balance Examples

Method 1: Gain / Gamma

Original Image

Method 2: Matrix (linear)

Retinex Algorithms

- Portmanteau of “retina” and “cortex” (brain)
- Assume that sudden changes in color are edges of color objects
- Compute illumination compensation based on relatively constant colors between changes
- Variety of algorithms claiming to be “Retinex”!

Best Use a Reference Patch!

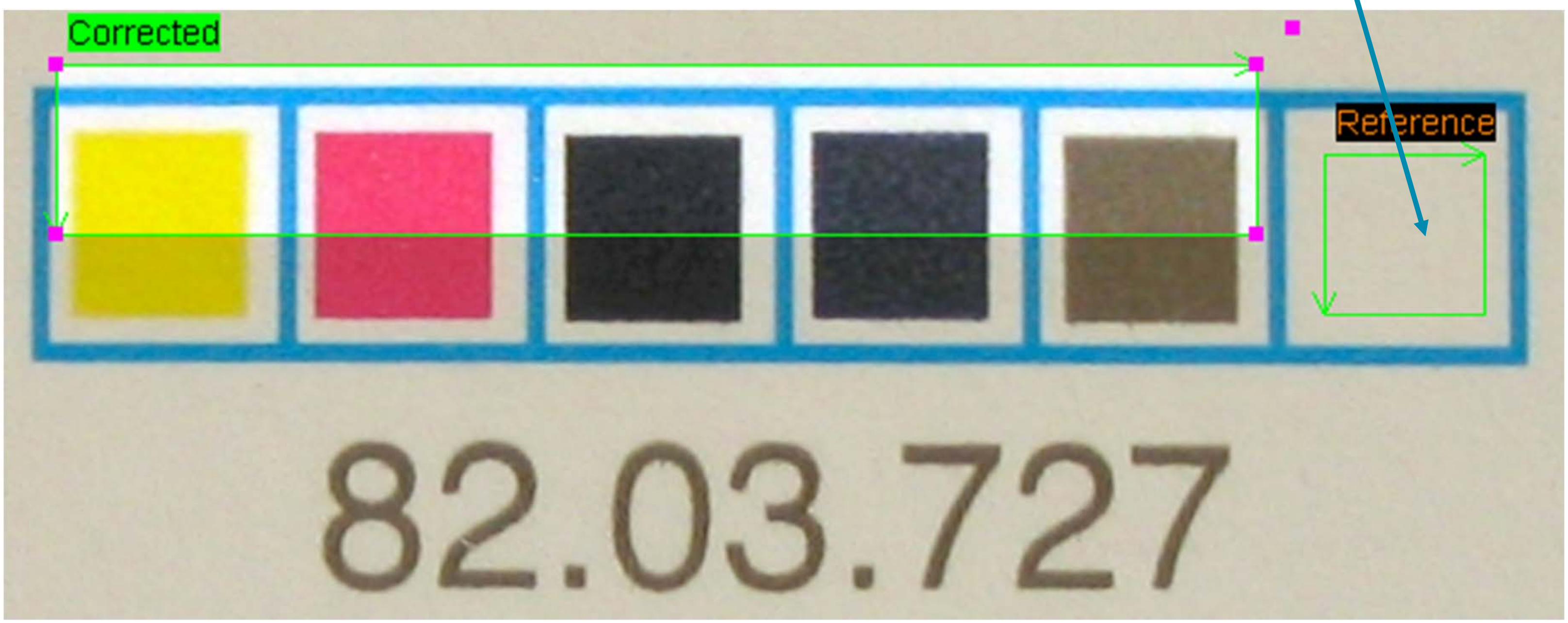
- White and/or colored patches in field of view
  - PTFE, sanded plastic, ceramic, metal oxides
- Tracks changes in camera and illumination
- Example: Ceramic tiles
  - High-quality color reference; some thermochromism

www.ceram.com

Reference Patch Example

- Safe to use **gray world** method on gray patch
- Corrects for illumination and (in this case) background color

White Reference

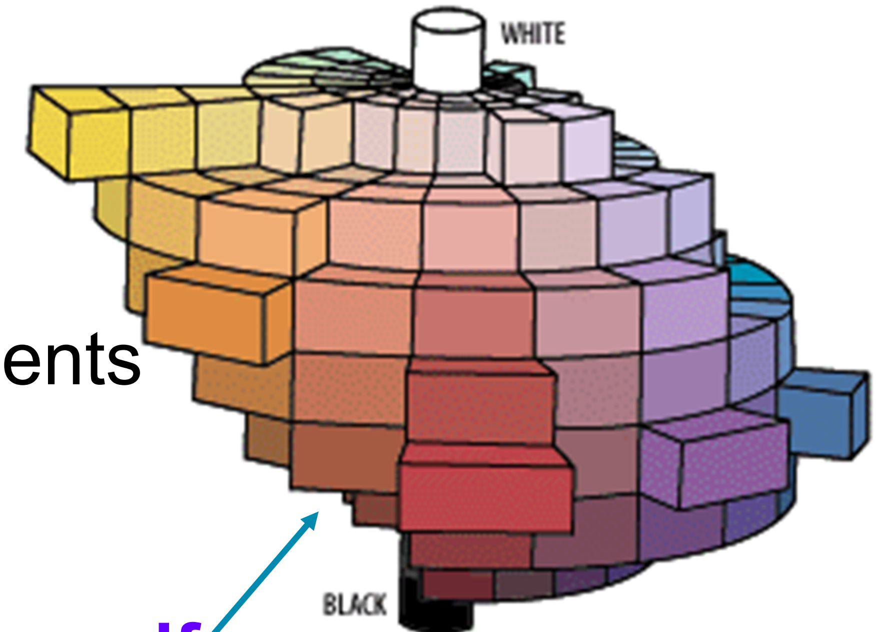


Why is this a good and bad white reference?

Color Space Conversions

- Sometimes want a color space other than RGB

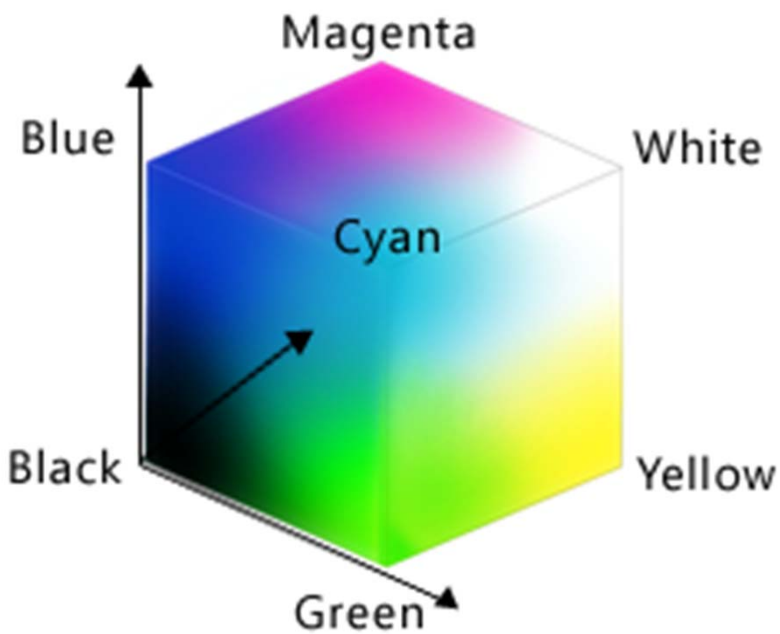
Three common types:

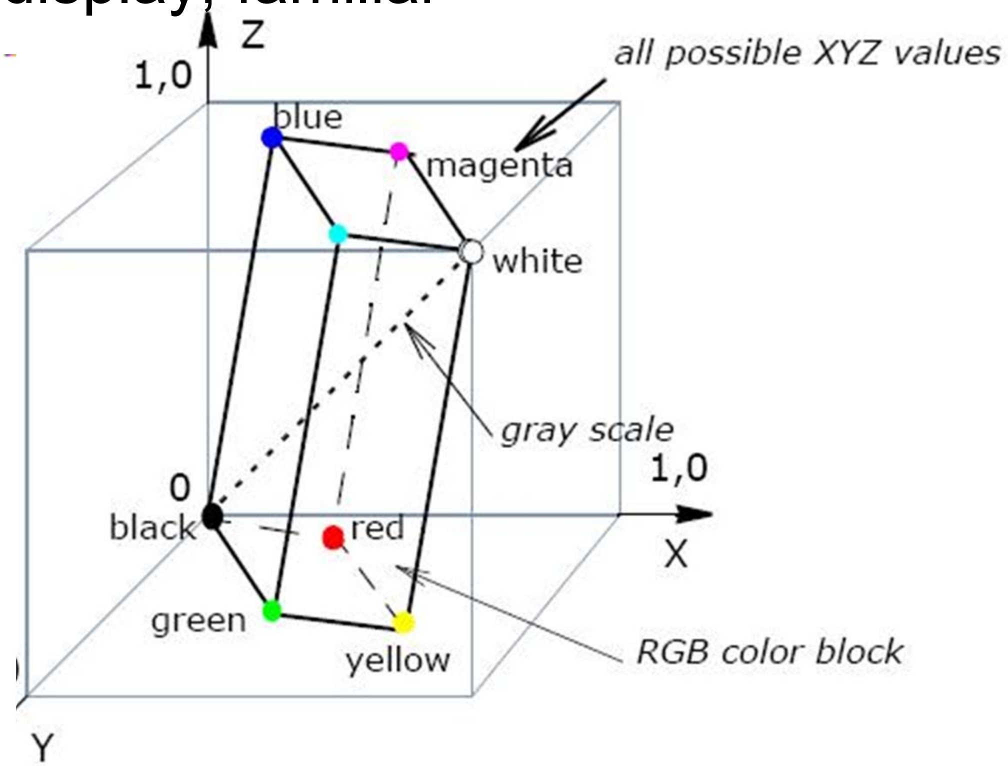


- Linear, 3 color
  - RGB, CIE XYZ etc.
- Luma + 2 color components
  - Linear: YCrCb, YUV, etc.
  - Non-Linear: CIE xyY
- Non-linear, **perceptually uniform**
  - L*a*b, HIS, HSL, HSV, Munsell, etc.

Linear, 3 Color

- RGB space is most commonly used in CMV
  - No loss of data from R,G,B sensor outputs
  - Easy to process and display; familiar

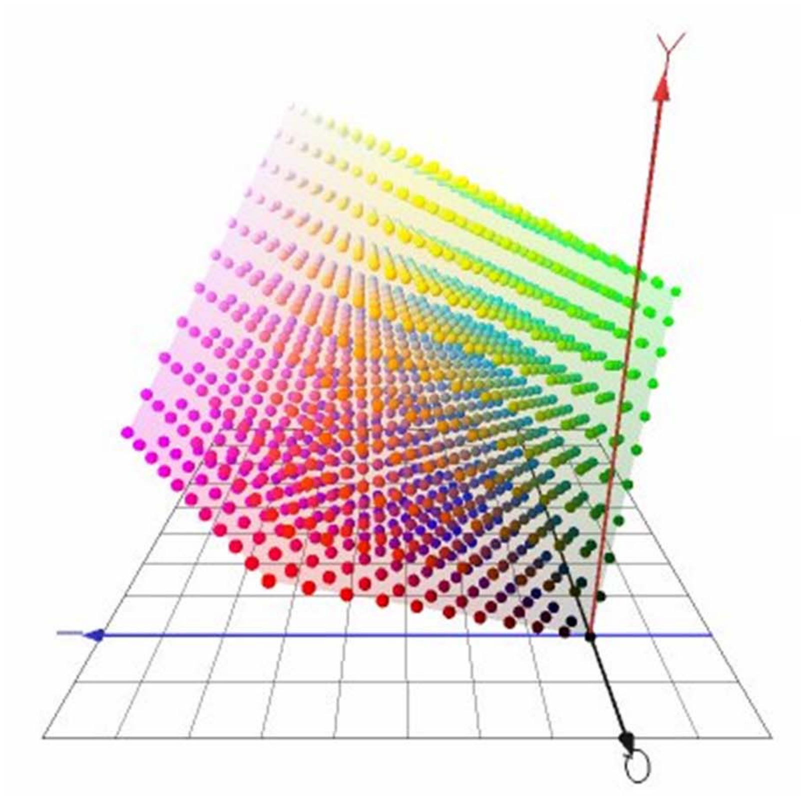




Luma + 2 Color Components

- Separate luma (Y) from color components
  - Removes some effects of intensity variations
  - Color can be coded at a lower data rate, e.g., for TV
  - Similar to what human vision does
- Linear: YUV, YCrCb, YIQ, etc.
  - Matrix rotate RGB color space so luma is diagonal
- Non-Linear: CIE xyY, etc.
- Issues with clipping and round-off noise in digital images

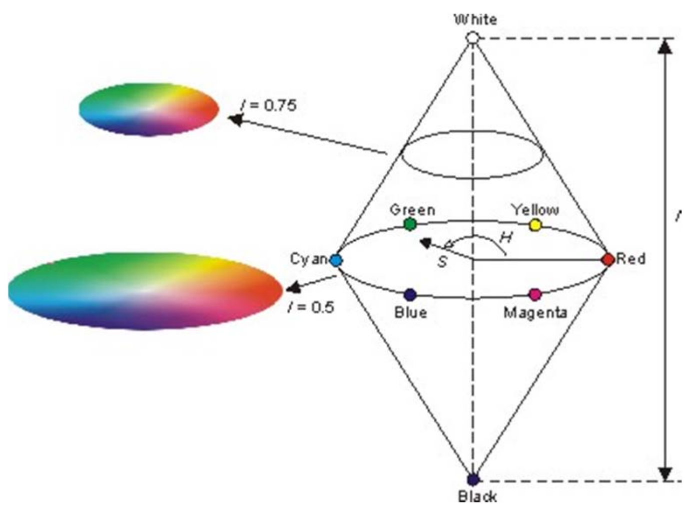
Example: YIQ (linear)



$$\begin{cases} Y &= 0.299 \times R + 0.587 \times G + 0.114 \times B \\ I &= 0.596 \times R - 0.274 \times G - 0.322 \times B \\ Q &= 0.212 \times R - 0.523 \times G + 0.311 \times B \end{cases}$$

Non-Linear, Perceptually Uniform

- Attempt to match "metrics" of human vision
- Natural spaces for color matching & adjustment?
- HSI, HSL, HSV : Hue, Saturation, and {Intensity, Lightness, Value} Many variations!



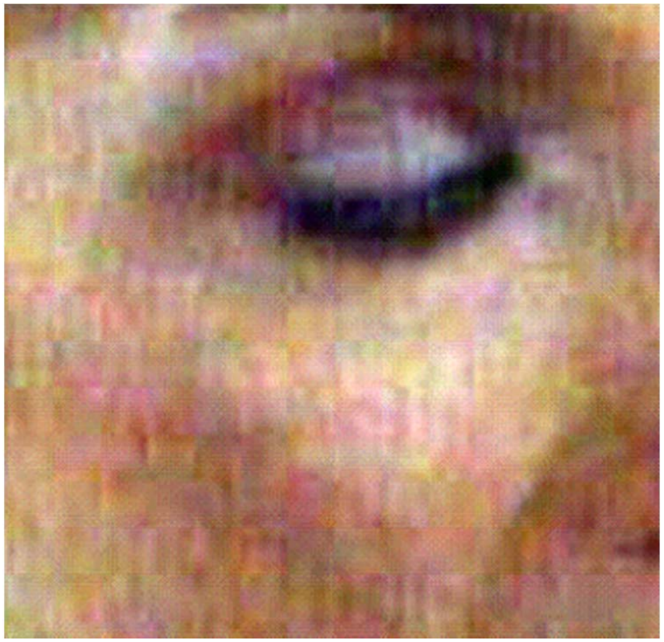
$$\begin{cases} H &= \arctan(\frac{\beta}{\alpha}) \\ S &= \sqrt{\alpha^2 + \beta^2} \\ I &= (R+G+B)/3 \end{cases}$$

With

$$\begin{cases} \alpha = R - \frac{1}{2}(G+B) \\ \beta = \frac{\sqrt{3}}{2}(G-B) \end{cases}$$

Color Space Conversion Issues

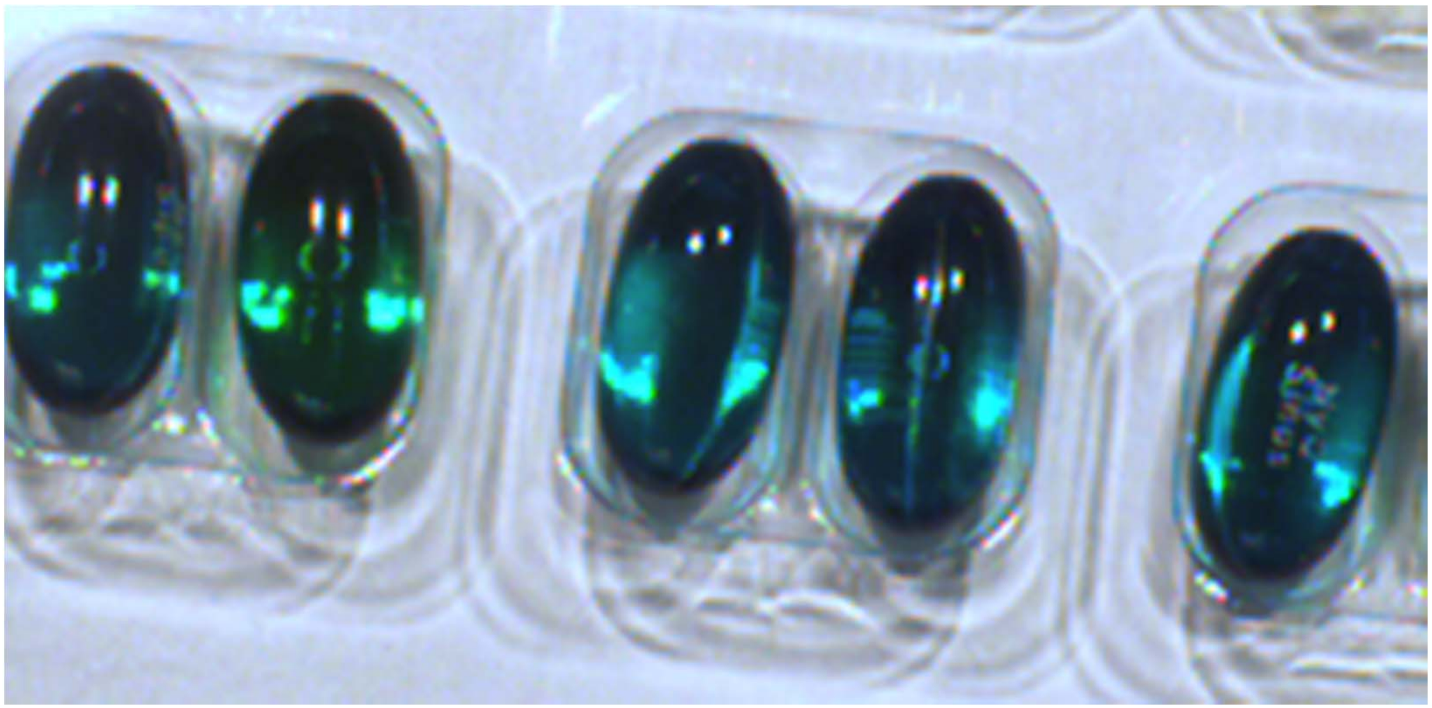
- Conversions take time
- Conversions adds round-off noise to image
- In separate luma spaces (e.g., YUV), **low** luma pixels exhibit **color chatter*** – noise in the color component(s)
  - Shadows, part edges
- Value truncation when conversion goes outside 8-bit color range



*__Color chatter__ is my term and not in common use.
Caused by image noise appearing in color when intensity is low

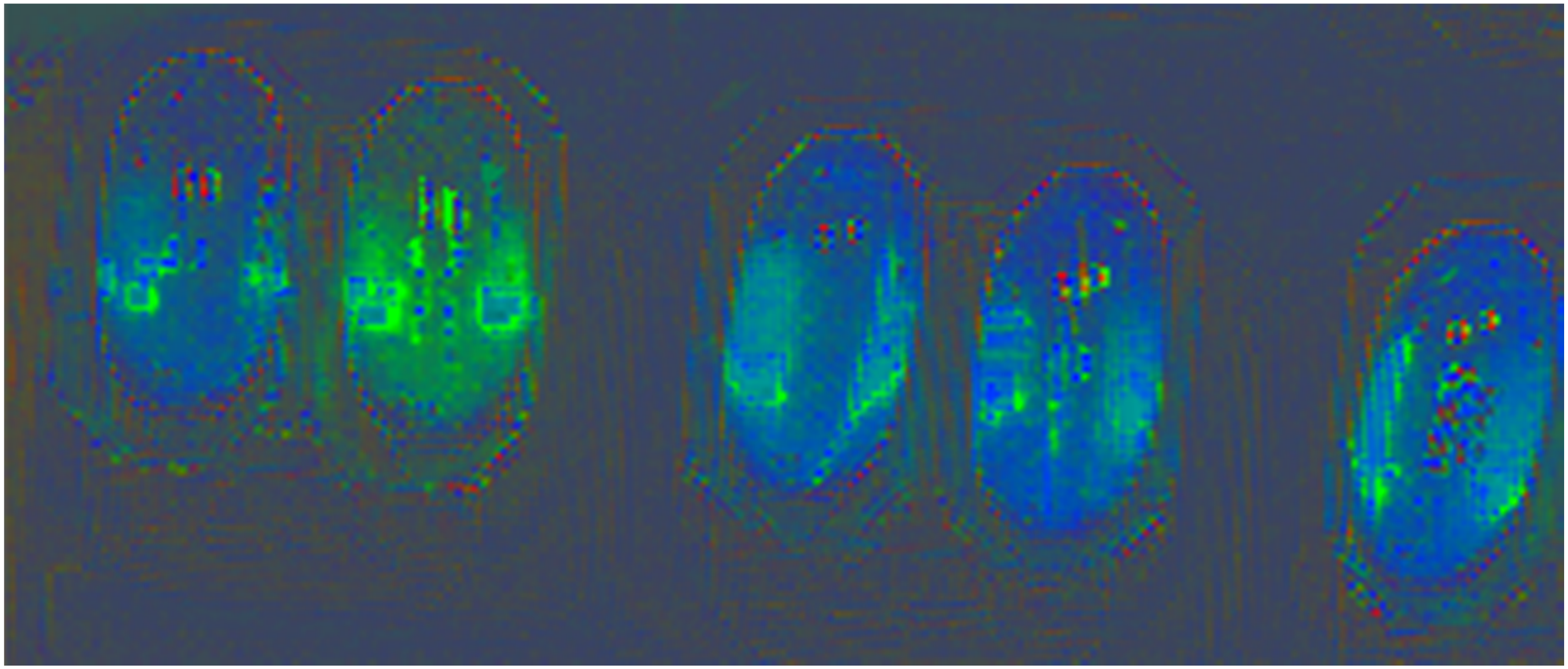
Example: Gelcaps

- Can you see the incorrect color gelcap?



Remove Luminance

- Divide color components by pixel luminance, like CIE XYZ to xyz color space conversion
- Removes luma to reveal color differences

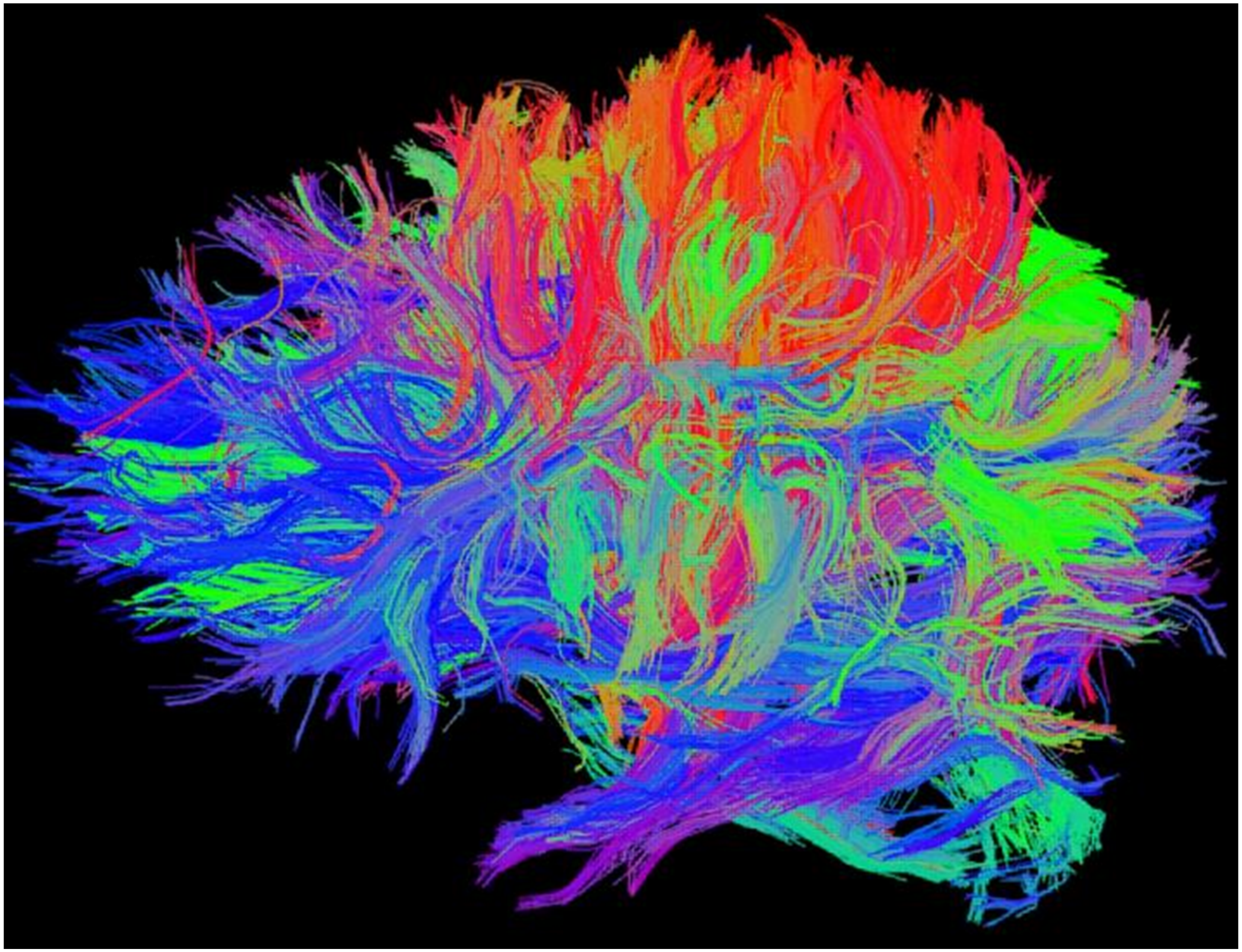


Some Bayer pattern noise & color chatter, but improved color detection

Tips (2)

- Comparative calibration OK for many MV tasks
- White balance: Use reference patch in FOV
  - Used to remove lighting and camera variations
- Color (and white) balance
  - Generally done “off line” and for human viewing
  - Unless done in camera analog doesn’t improve data
- Use RGB space when possible
  - Color space conversion adds noise and time
- Separate luma + 2 color components
  - Reduces effects of luma change
  - Can introduce color chatter at low luma

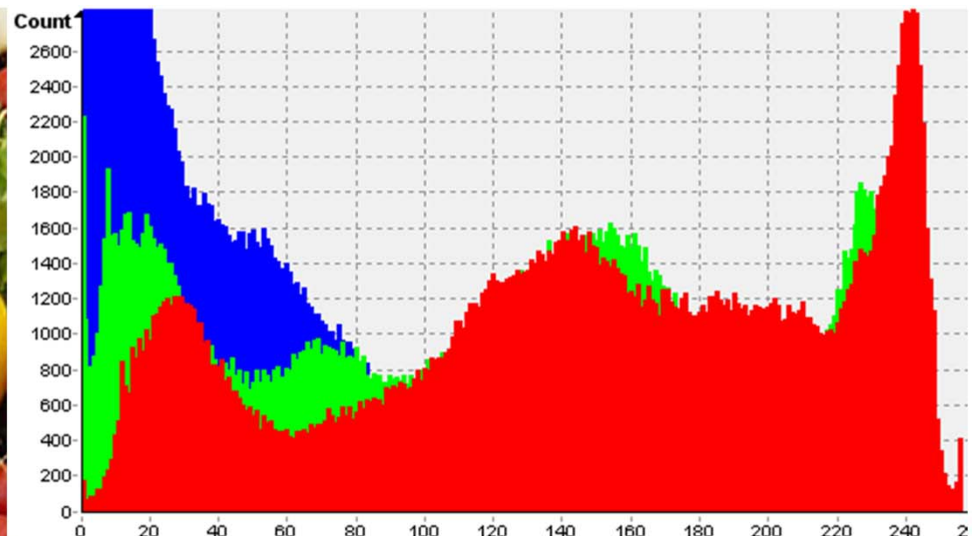
Computing Application Answers



(Credit: Photo © Neuron)

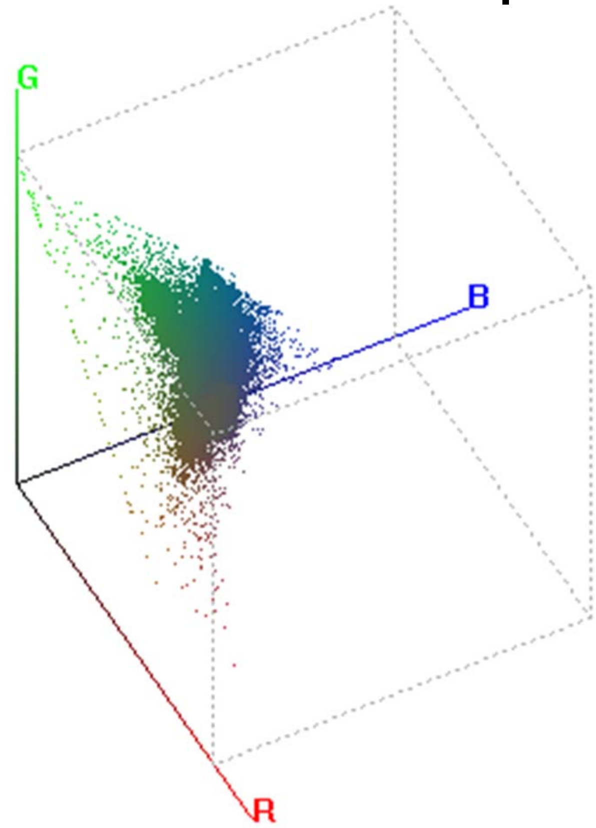
Color Statistics

- Simple way to compare colors, detect defects
- Histogram (mostly for setup)
- Counts, Minimums, Maximums, Means, Variances
- Per channel or joint statistics



Joint Statistics

- Statistics based on 2 or more colors (axes)
- Covariance, marginal density distributions
- Centroid and other moments in color space
- Color space density
- Color textures

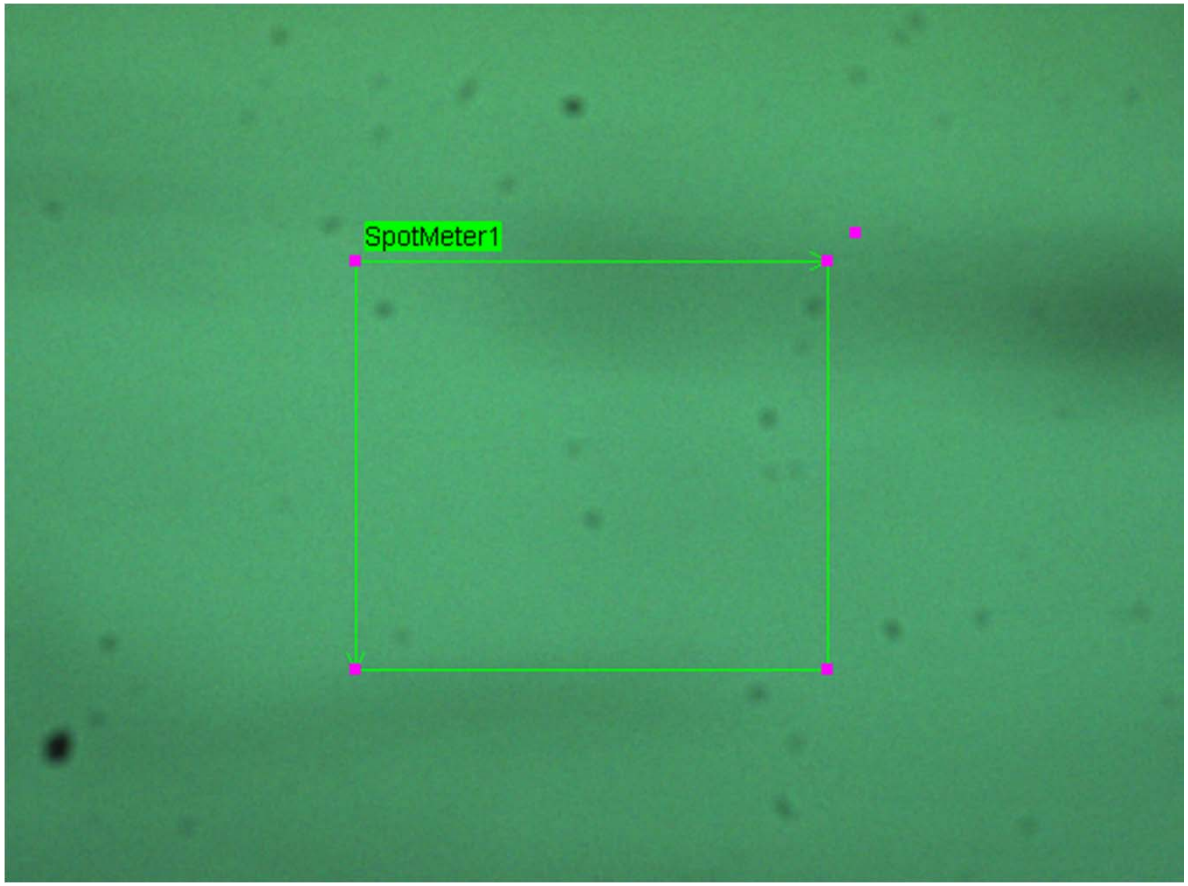


Color Spot Meter

- Color statistics over an area of image
  - Computed on a per-component (RGB) basis
  - Measures means, maximums, and variances
- Used for:
  - Checking color range (go / no-go)
  - Correct part present, based on color
  - Matching colors (not very accurate)
  - Checking part orientation by color “swatch” location
- Good When:
  - Parts have uniform color areas at known positions
  - Large color differences between parts’ colors

Example: Mouthwash

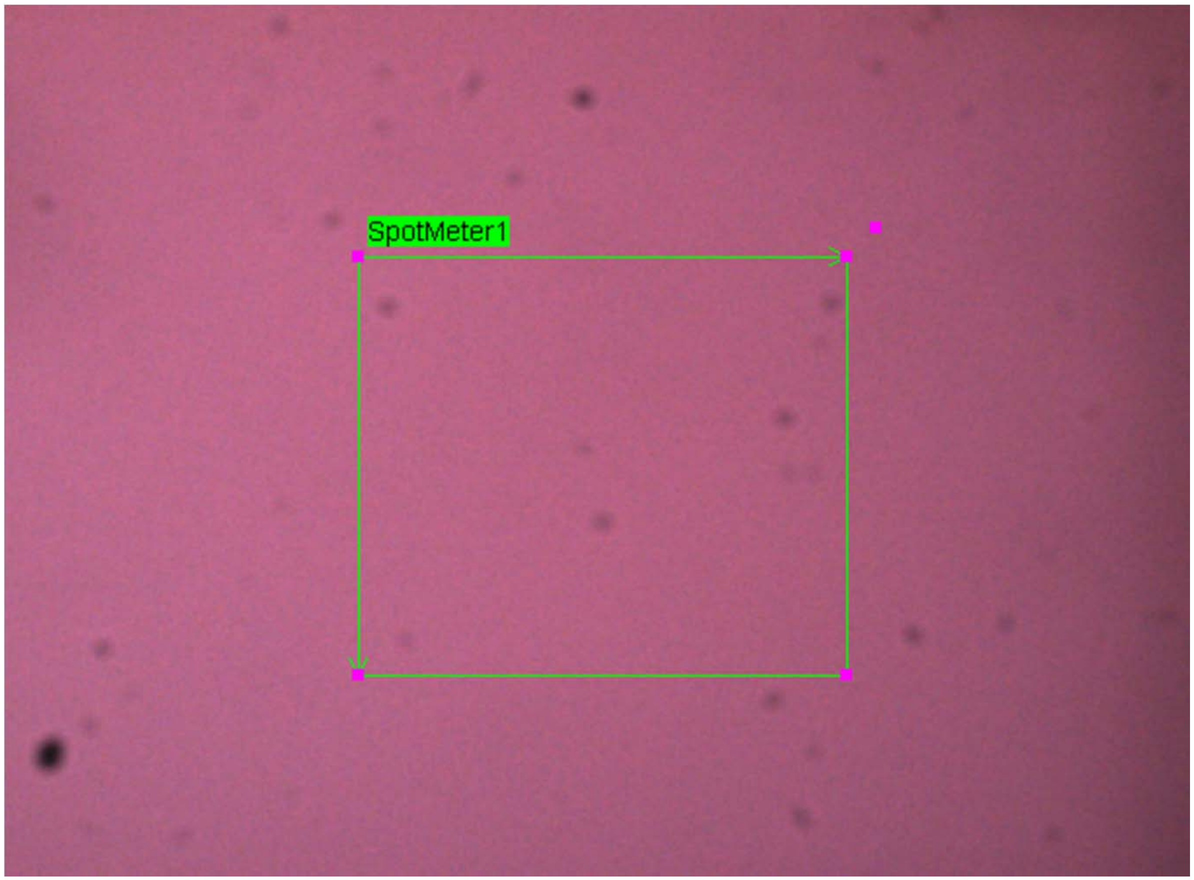
- Right color? Completely flushed?
- Compare RGB values to known good samples



Red = 76
Green = 162
Blue = 109

More Mouthwash

- Set limits to distinguish green vs. magenta



Red = 180
Green = 96
Blue = 129

What are those dark spots?

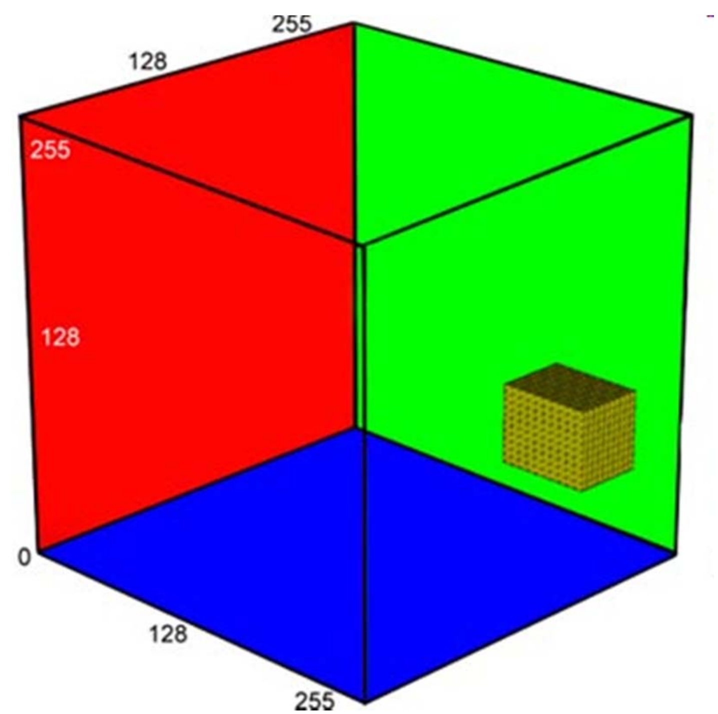
Color Classifiers

- **Key algorithm for many CMV applications**
- Pixels assigned to “classes” based on their color
- **Class assignment functions*** (CAFs) divide a color space into smaller volumes
  - Each volume represent a color of interest (e.g. “good”)
- CAFs are difficult to specify “by eye”, so the classifier learns the classes “by example”
- Classified pixels can be “tagged” with their class number, to be used for further processing

* This is my term and not in general use

Threshold Classifier

- Thresholds or limits specify a cuboid (3D rectangle) in the color space, containing the colors in the class

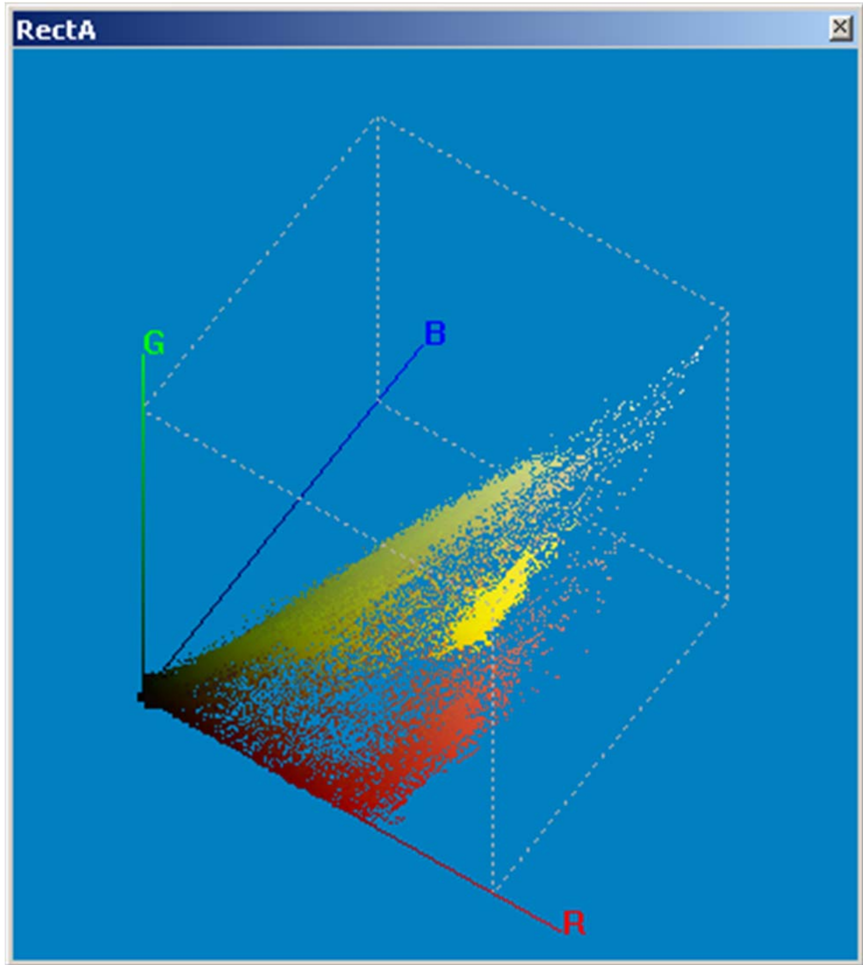


Threshold Classifier Example

- CAFs are cuboids in color space

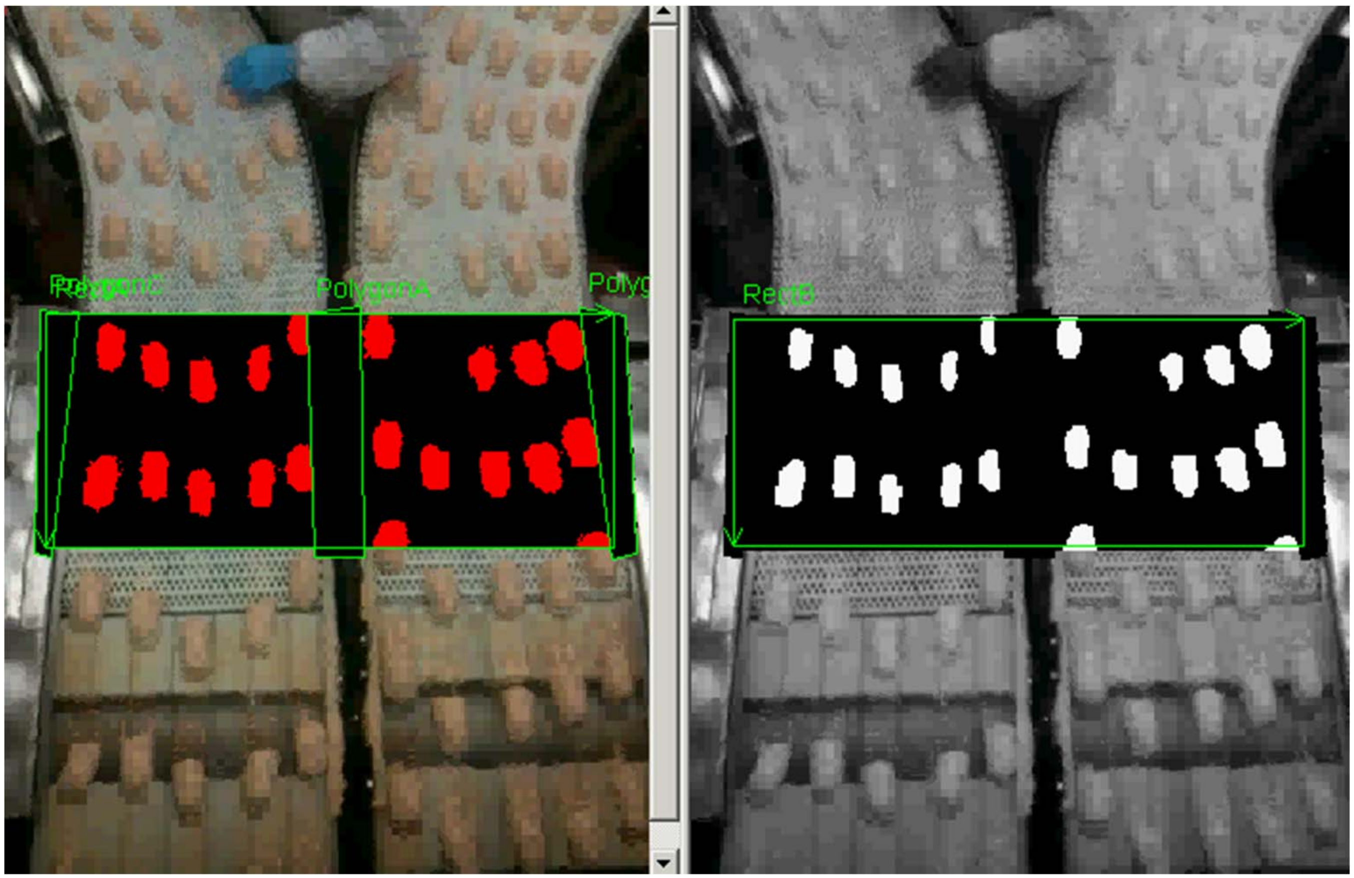
Threshold CAFs' Poor Performance

Most objects' color ranges don't fit a cuboid!



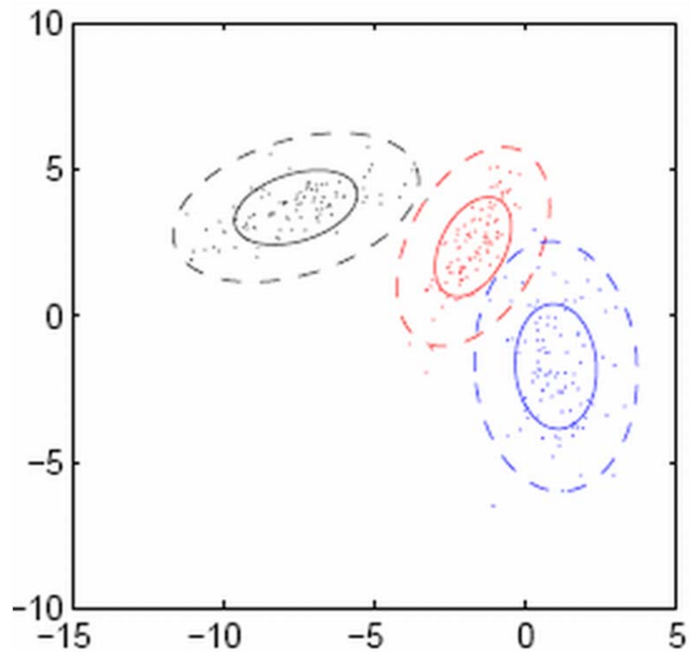
Part Location by Color

- Counting chicken breasts
- Threshold CAF works OK because only red channel drives classification



Gaussian CAFs

- Ellipsoids in 3D color space
  - Defined by center and covariance matrix
- Better color classification than rectangles
  - Closer to how colors distribute in natural images

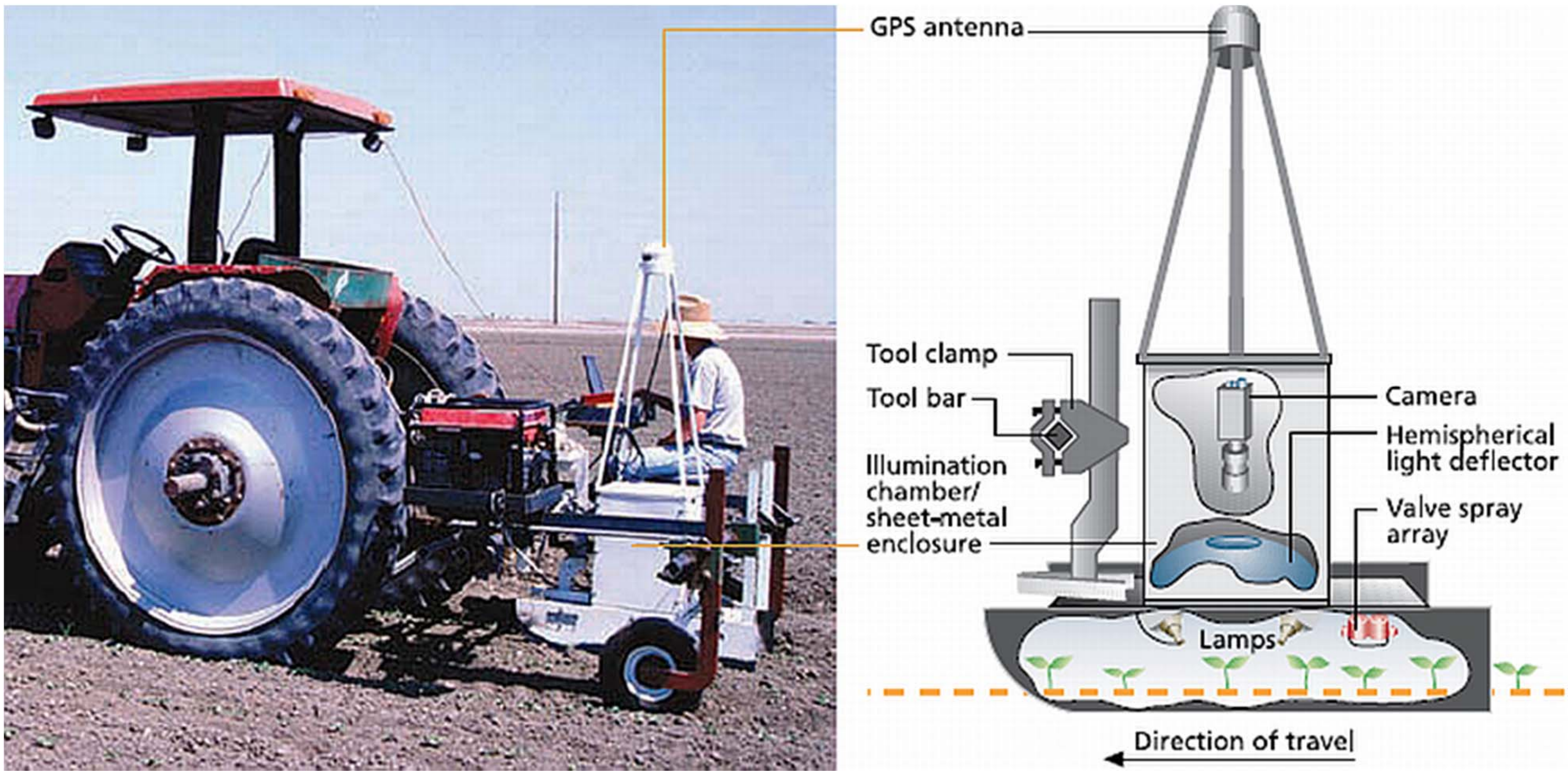


Automated Weeding

Gaussian CAF works OK to separate plant from dirt

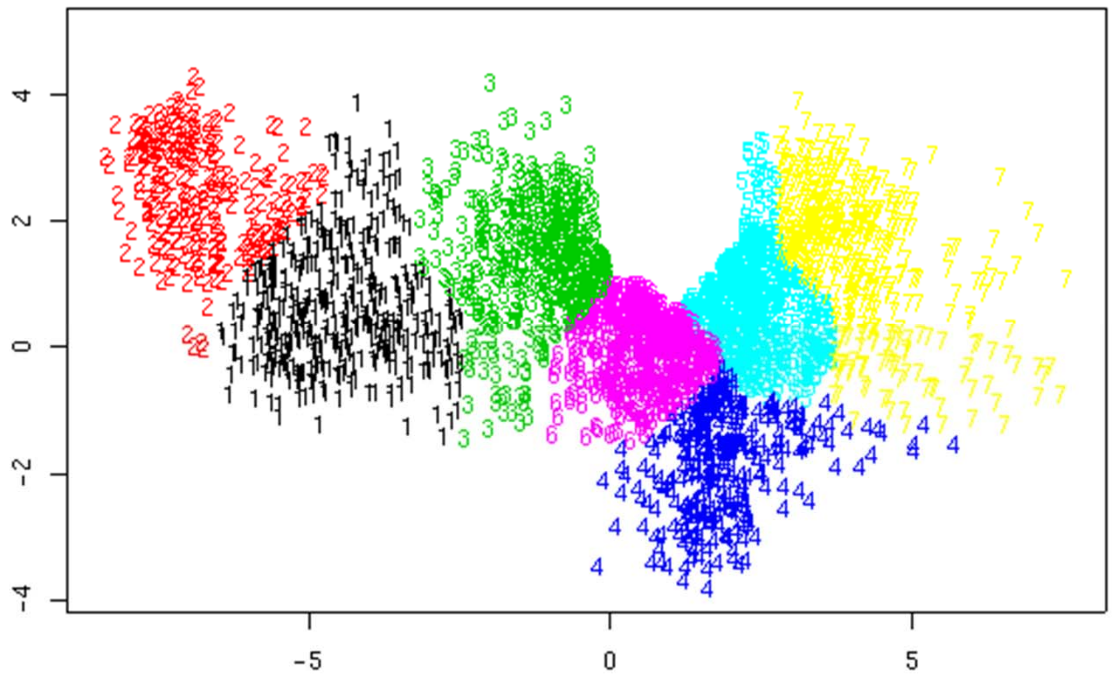
Automated Weeding System

Color alone is not sufficient – need shape, etc.



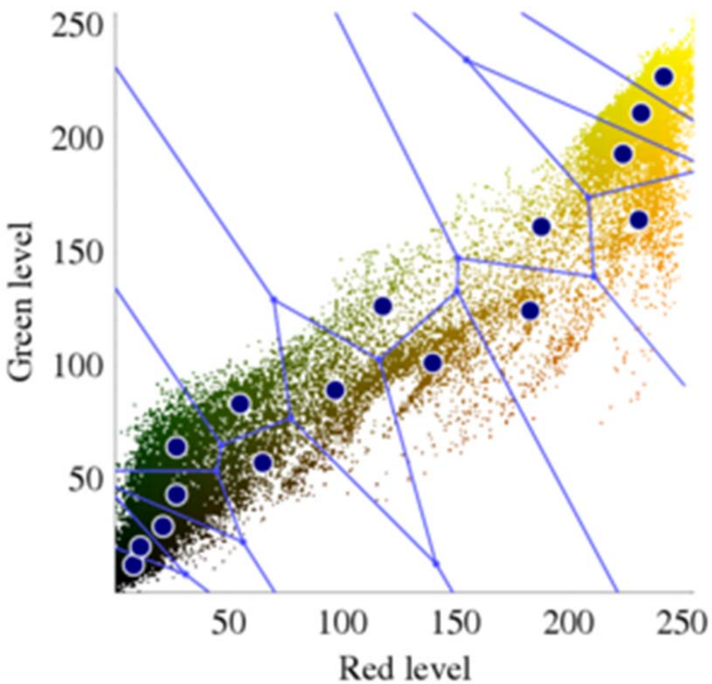
Radial Basis CAFs

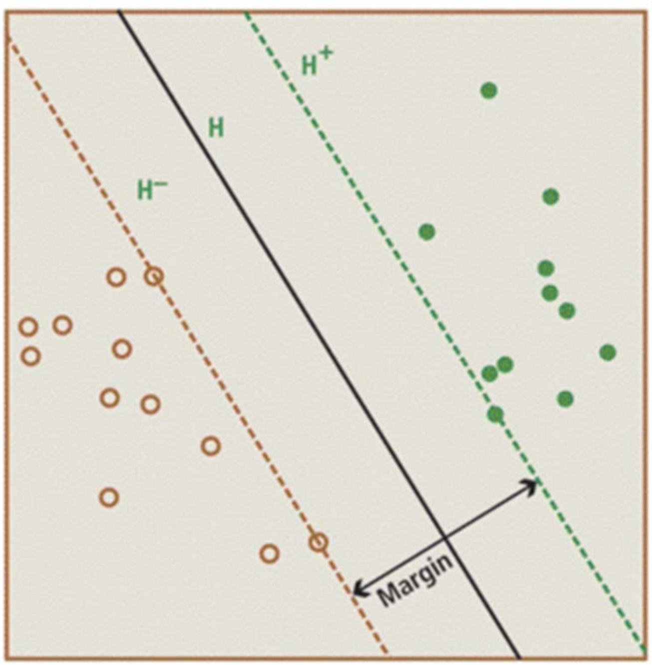
- Decision surfaces expand, like balloons, and push against each other to divide up the space
- A form of Artificial Neural Network (ANN)



Support Vector Machines

- CAFs try to maximize the margin (~ distance) between classes



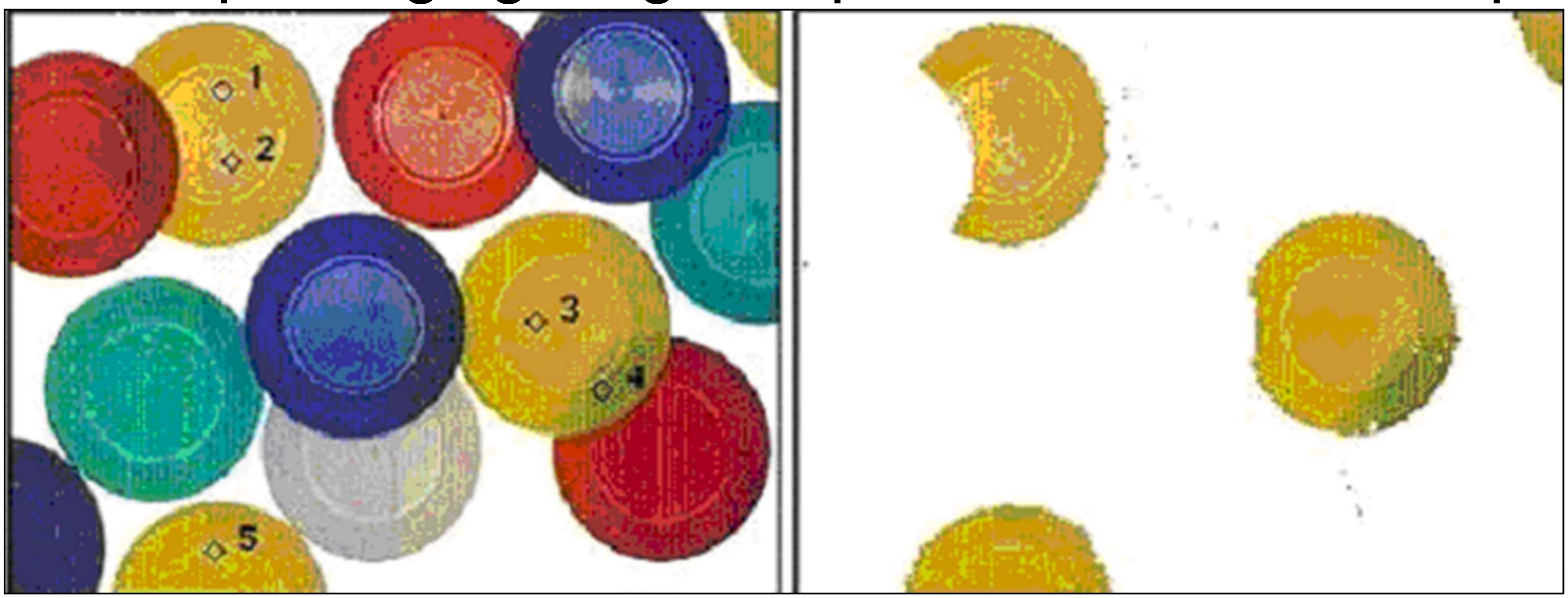


Class Probability

- Some classifiers return probabilities of a color being in a class (e.g. how close is a particular color to the centroid of that class's volume).
- Allows you to use prior information (e.g., a Bayesian classifier) and / or "cost functions" to improve classification results
- Example: Sorting oranges and apples, if oranges are expected 80% time then we bias our apple vs. orange decision towards oranges

Misclassification

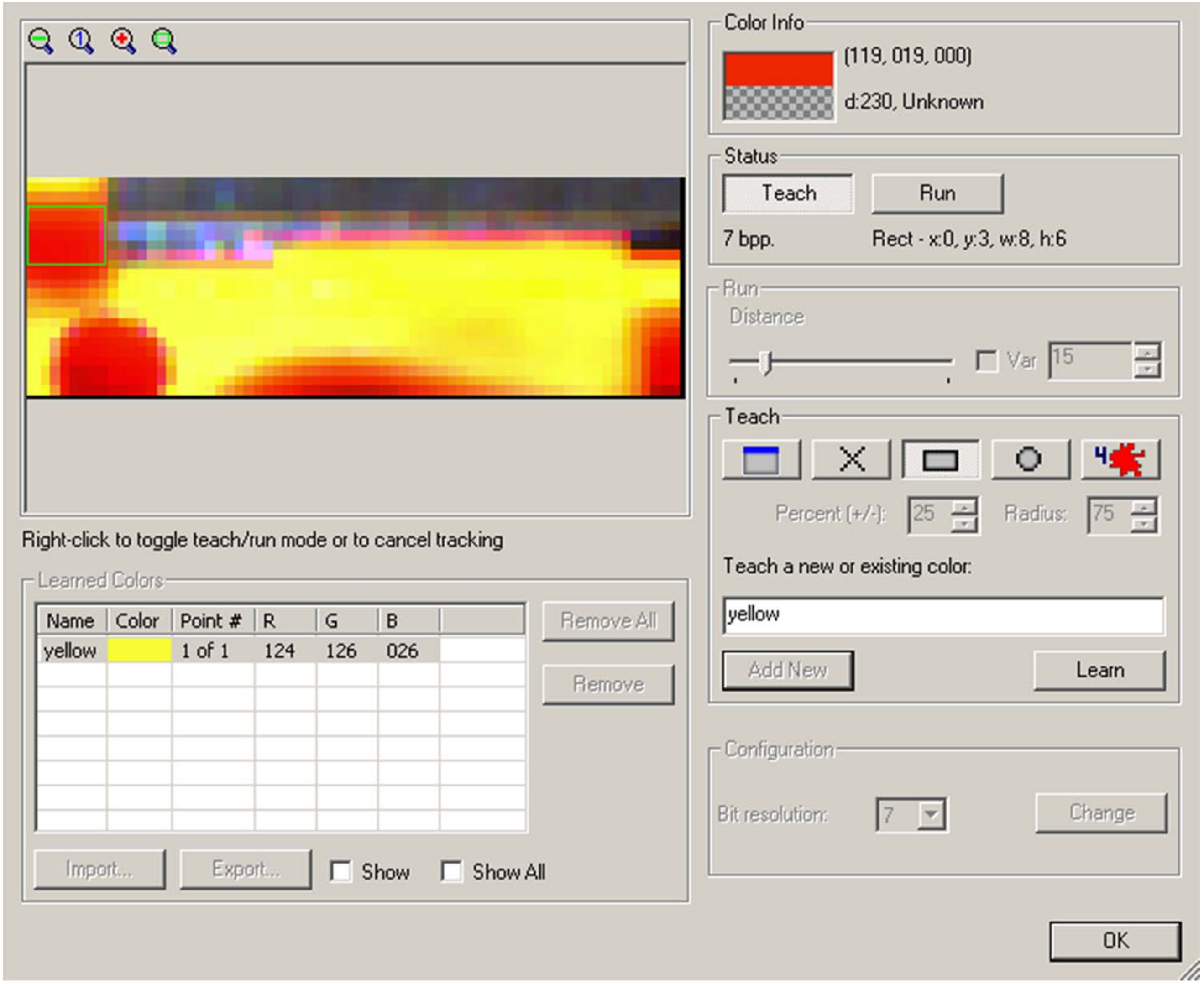
- Part colors often overlap in color space
- Shadows and noise (Bayer) are problems
- Additional classifier training might help… or not
- Improving lighting and presentation often helps



Training a Classifier

- Pick examples of each part color you want to train
- Show the classifier each set of examples and give each set a class name (e.g., “red”, “good”, etc.)
- How many examples to use?
  - Too many => “over train” so poor generalization
  - Too few => some wanted colors might not be classified
- Have an “out class” for colors that haven’t been trained (usually provided by algorithm)

Training a Color Classifier

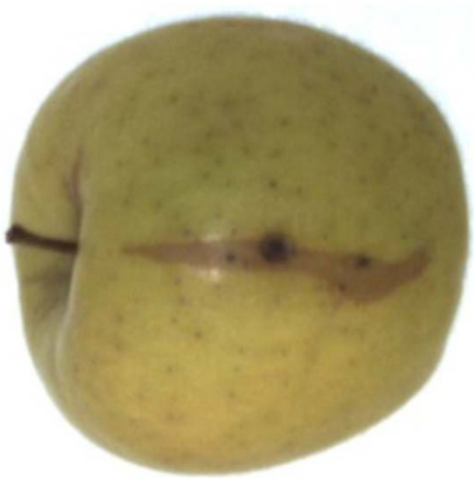


Thresholds and Error Costs

- A classifier defines decision thresholds (e.g. a surface in color space) for different classes.
- The decision is often not perfect because sample colors might overlap class boundaries
- False Accept (**escape**) – Classifier says color is “good” but it isn’t
- False Reject (**false alarm**) – Classifier says color is “bad” but it isn’t
- If you have a measure of classification certainty, you can use it to weight the decision
  - Weighting is called a **cost function**

Cost Functions

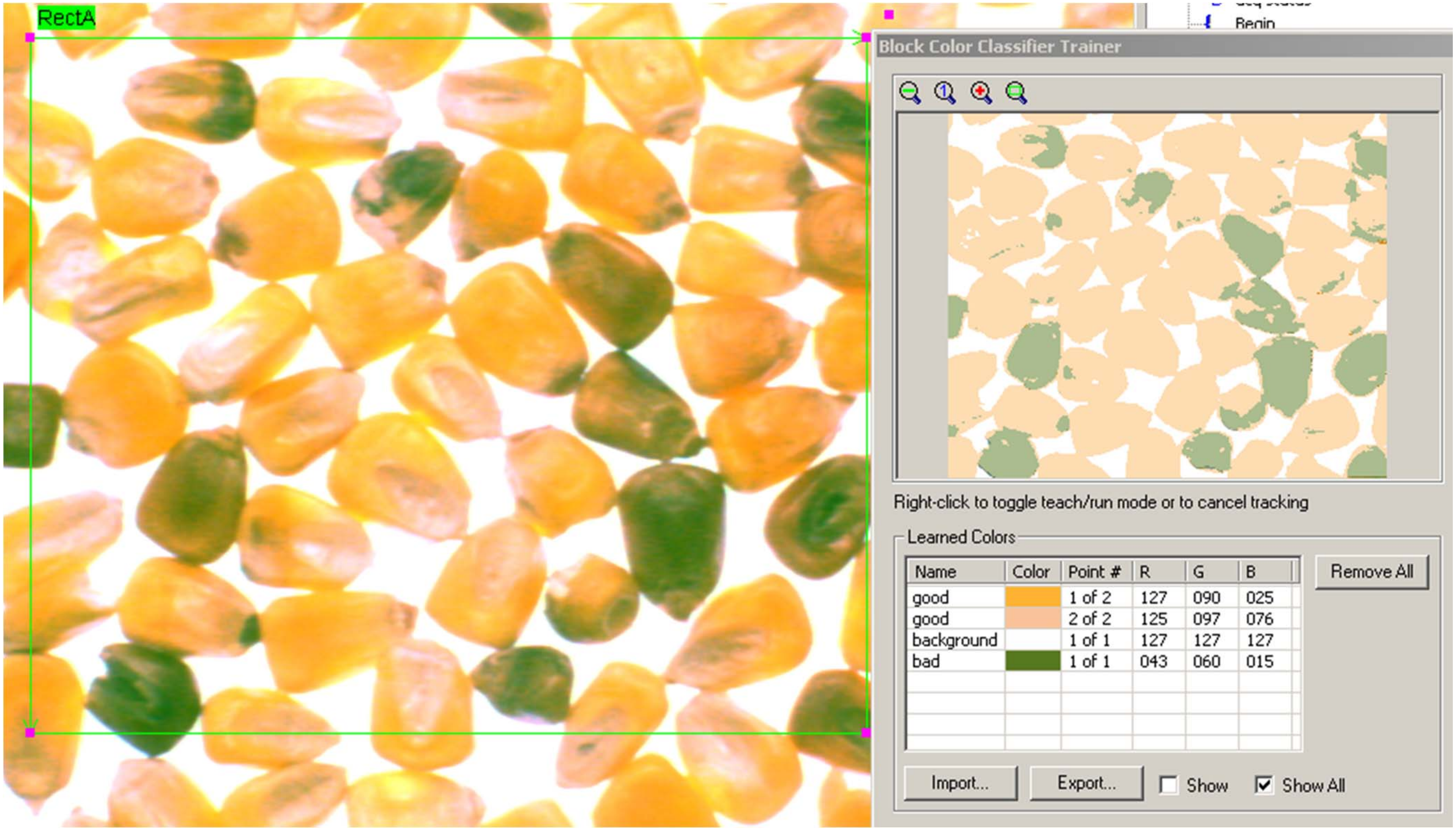
- Example: Cheaper to have falsely reject good food than have a lawsuit. So set to reject even if only a few pixels are classified as “bad”



Obviously bad…

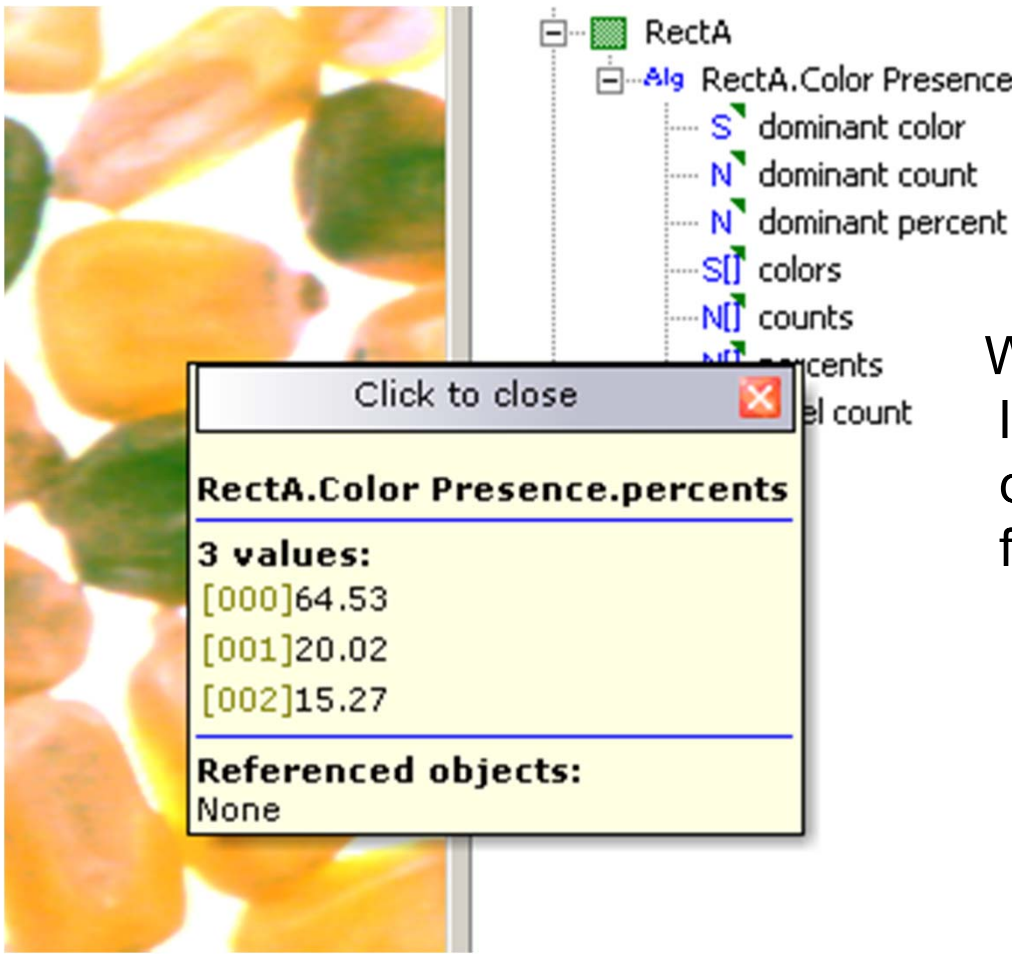
How about this?

Example: Grading Seed Corn



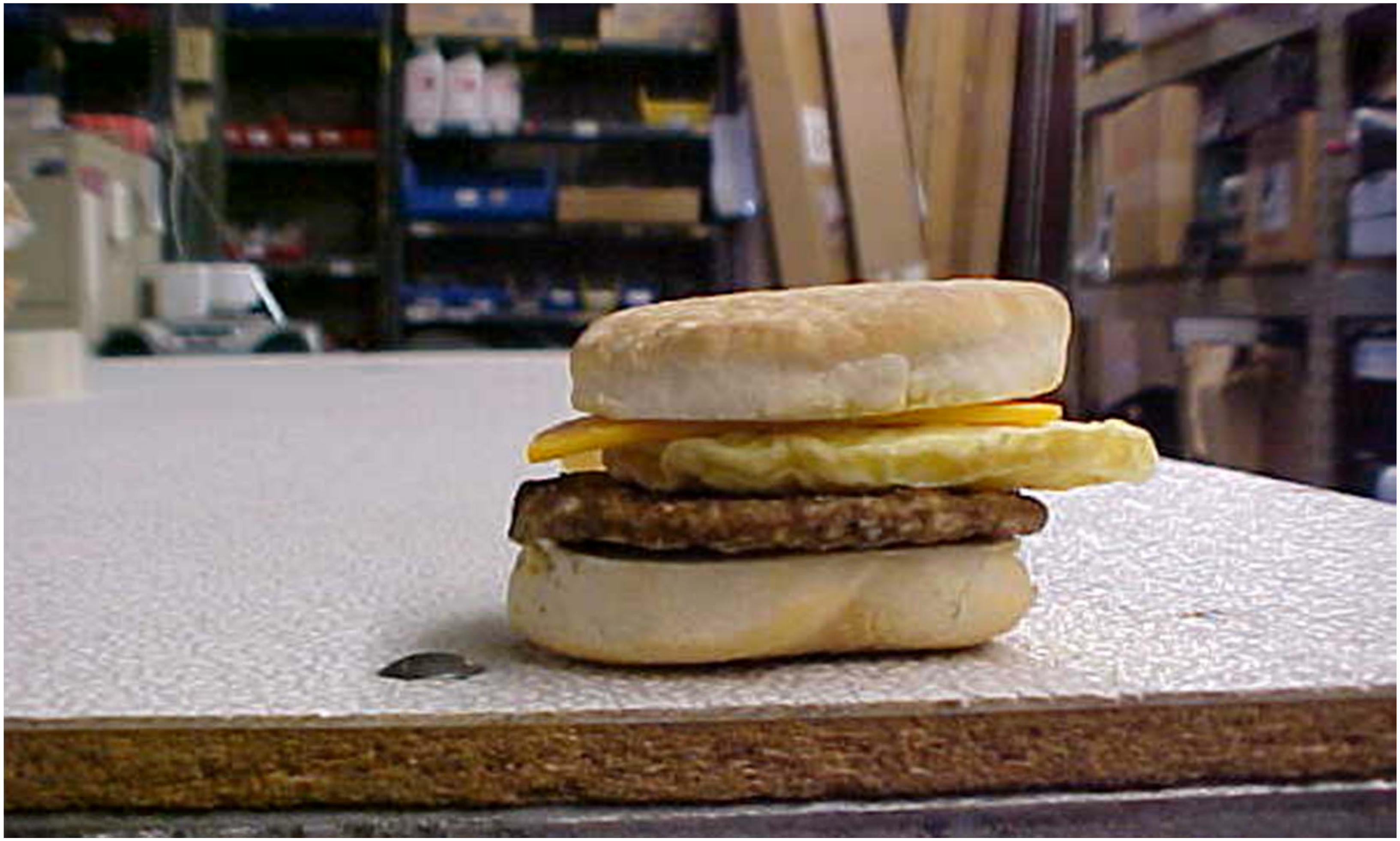
Seed Corn Grading

- Use percent of {good, background, bad} colors to compute percent good kernels -> $ value



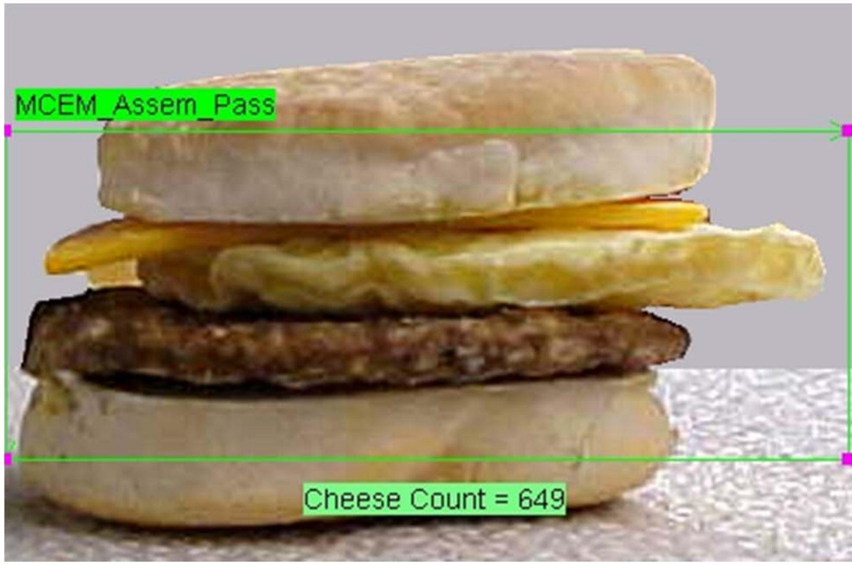
Well separated classes and low cost for wrong decision, so no need for a cost function

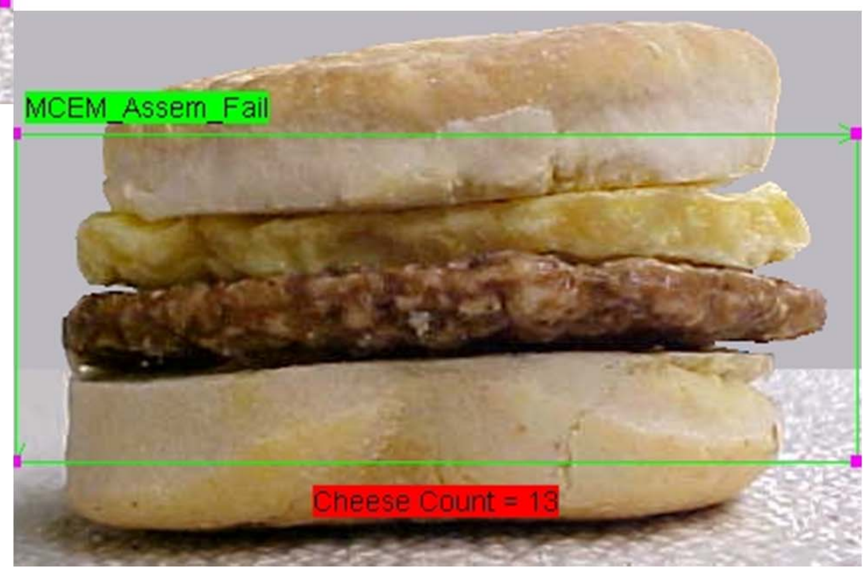
Breakfast Meal Check



Use classifier to count pixels
with {cheese, egg, or meat} values

Assembly Checking





Hand assembled, so this is a quality control check.
Vision system false alarms require human checking.
Greatly reduces human effort.

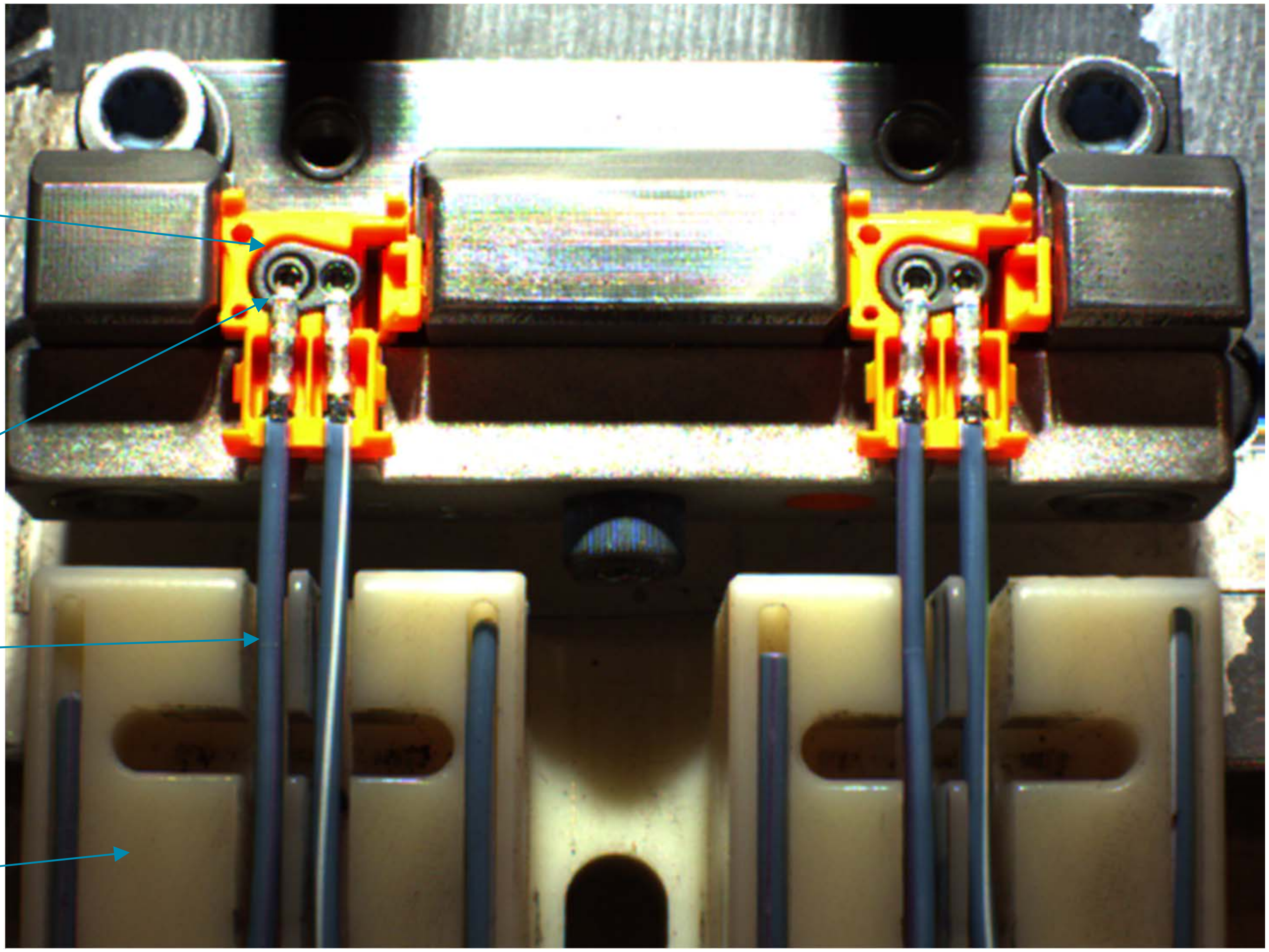
Automotive Verification

Plastic Housing

Ferrite Bead

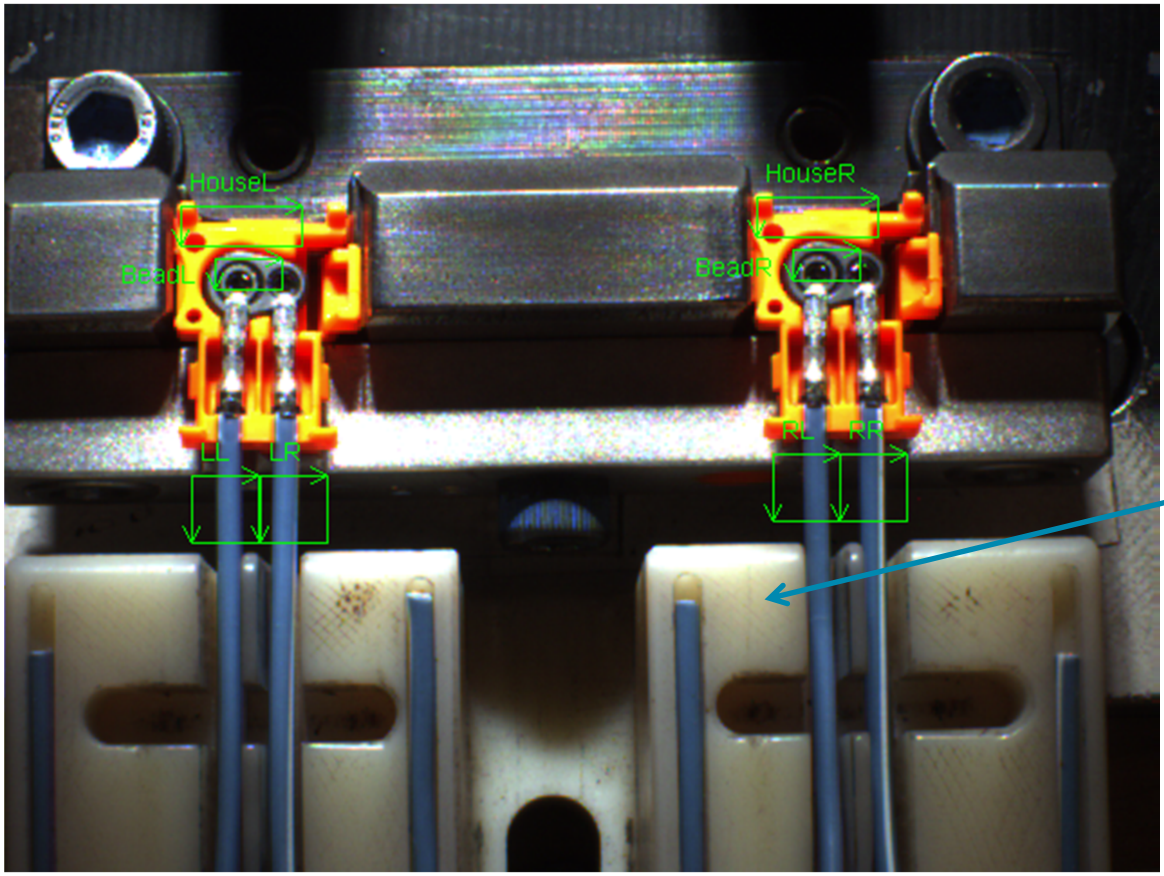
Wire

Polyethylene



Assembly Verification

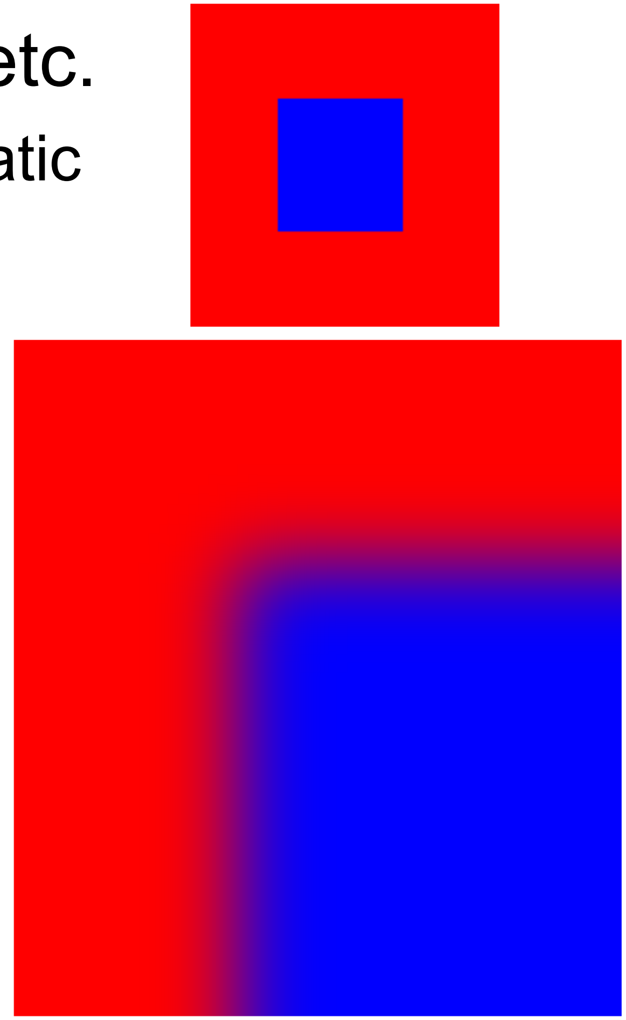
- Are the wire colors correct? Is the housing present? Is the ferrite bead in place?



What about using this as a white reference?

Difficult Algorithms for Color

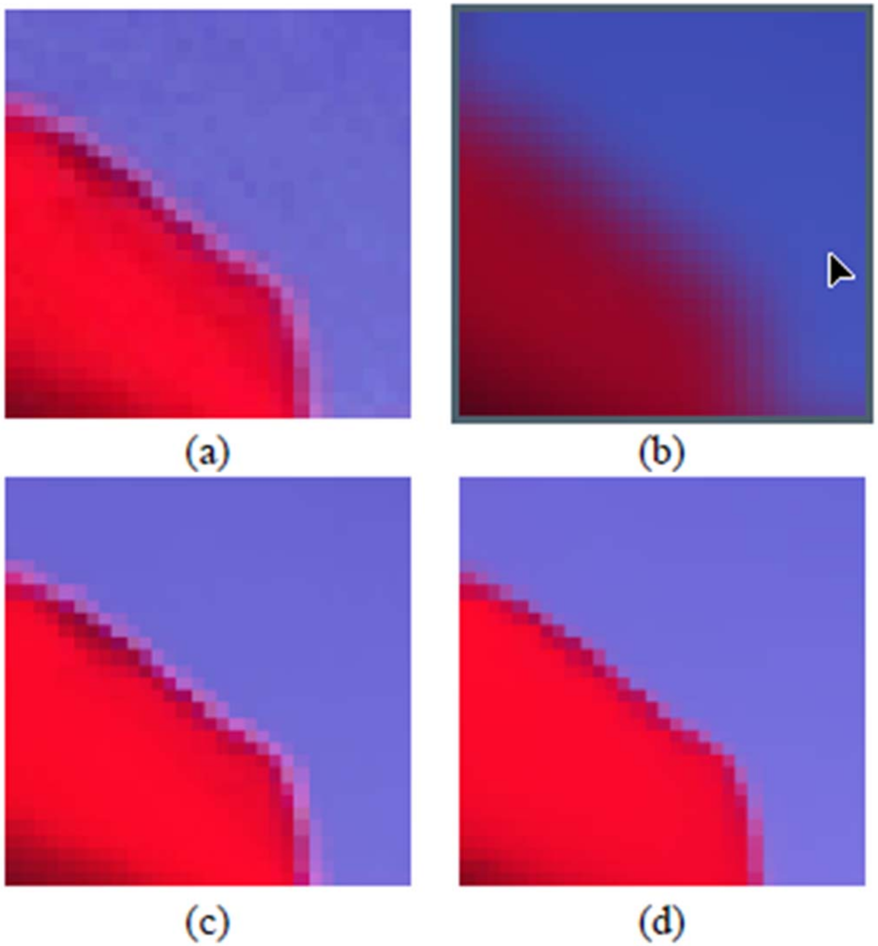
- Edge detection, morphology, etc.
  - Any kernel operation is problematic
- Use luminance and then "add in" color information
- Dimensioning is hard
  - Due to Bayer pattern
  - Have to define what a chromatic edge is
- Use the unique capabilities of color instead!



Color artifacts

Bilateral Filtering

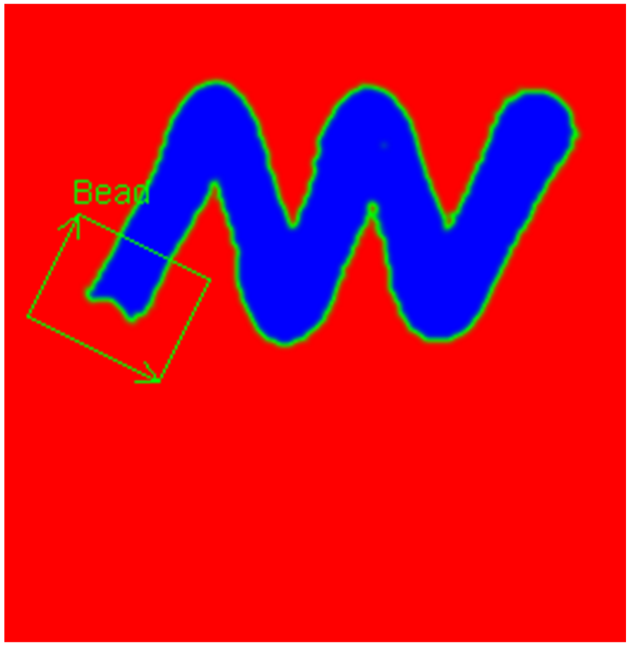
- Only smooth color <u>away</u> from edges



a. Original with noise
b. Low-pass smoothing (kernel)
c. Bilateral filter smoothes, but leaves the pink artifact
d. Bilateral filtering in CIE Lab space gives excellent results

Color Map from Classifier

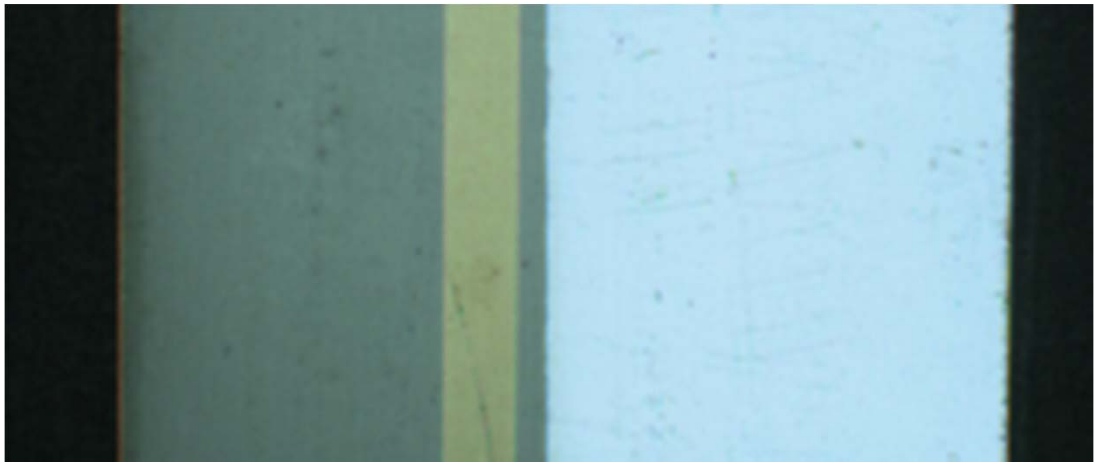
- Number each pixel by its color class
- Could display as a gray-scale, but hard to see
  - Use **pseudocolor** to visualize



Allows processing color image with some monochrome tools

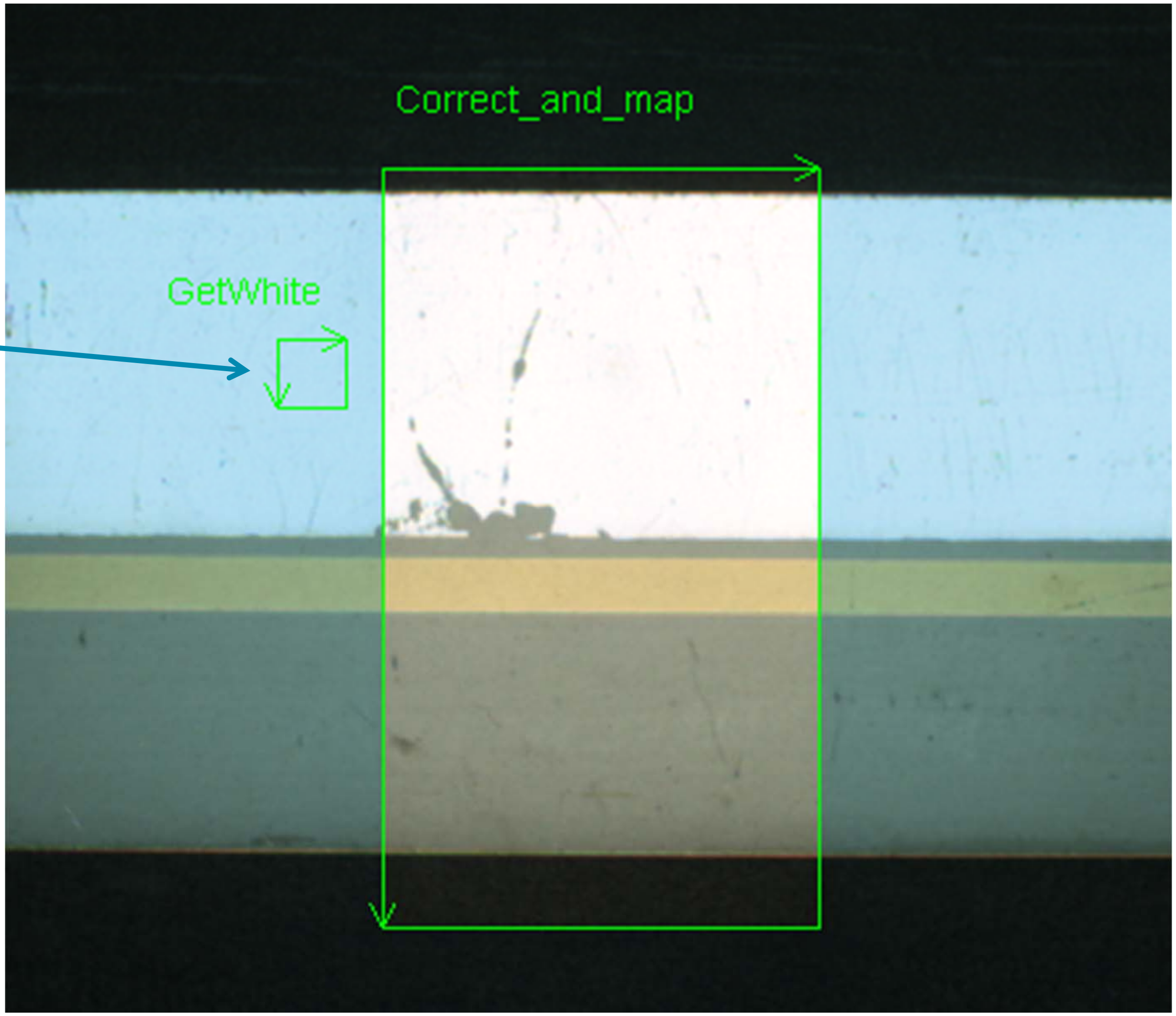
Color Defects and Dimensioning

- Defects and dimensions of colored material
  - If dimensioning or gauging, have color edge issues
  - Practical limit of perhaps +/- 1 pixel
- Use a **color map** to label colors and then apply monochrome defect and dimensioning tools
- Example: Metal strips plated with nickel, silver and gold



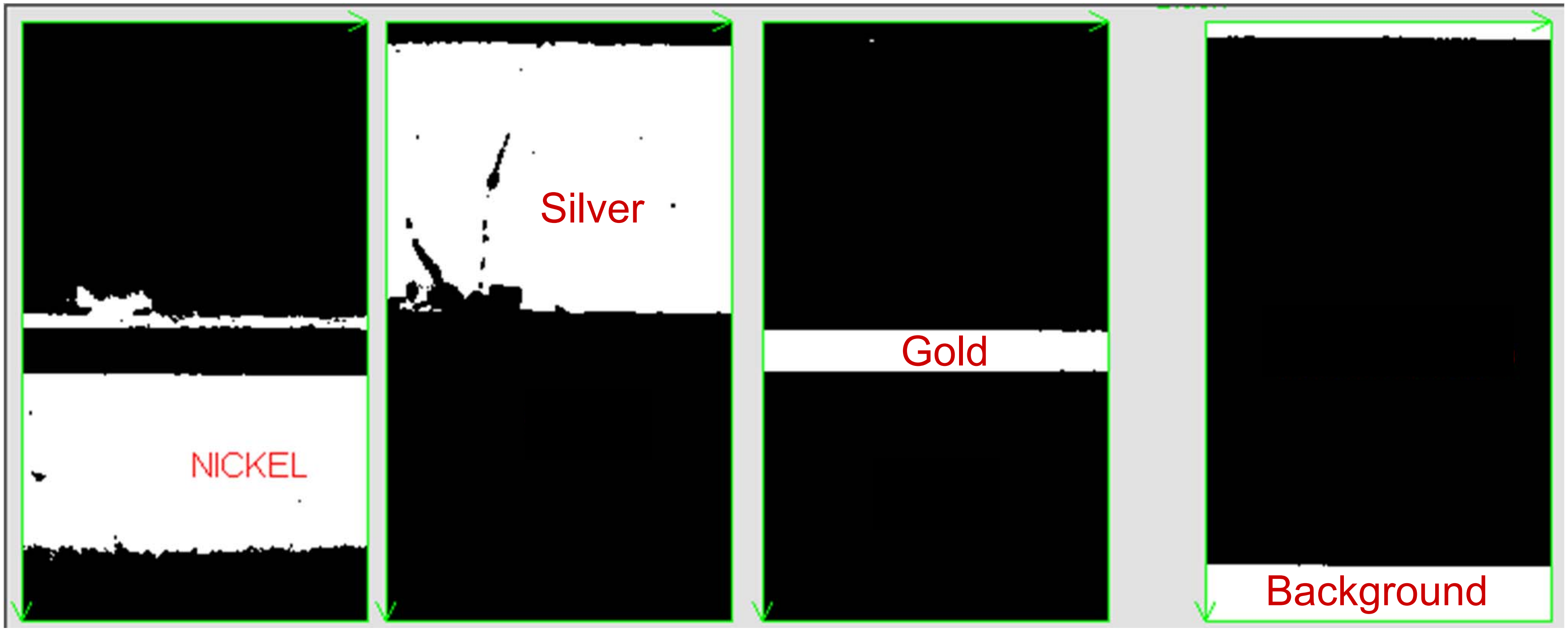
Plating Inspection – White Balance

Why is this white reference unreliable?

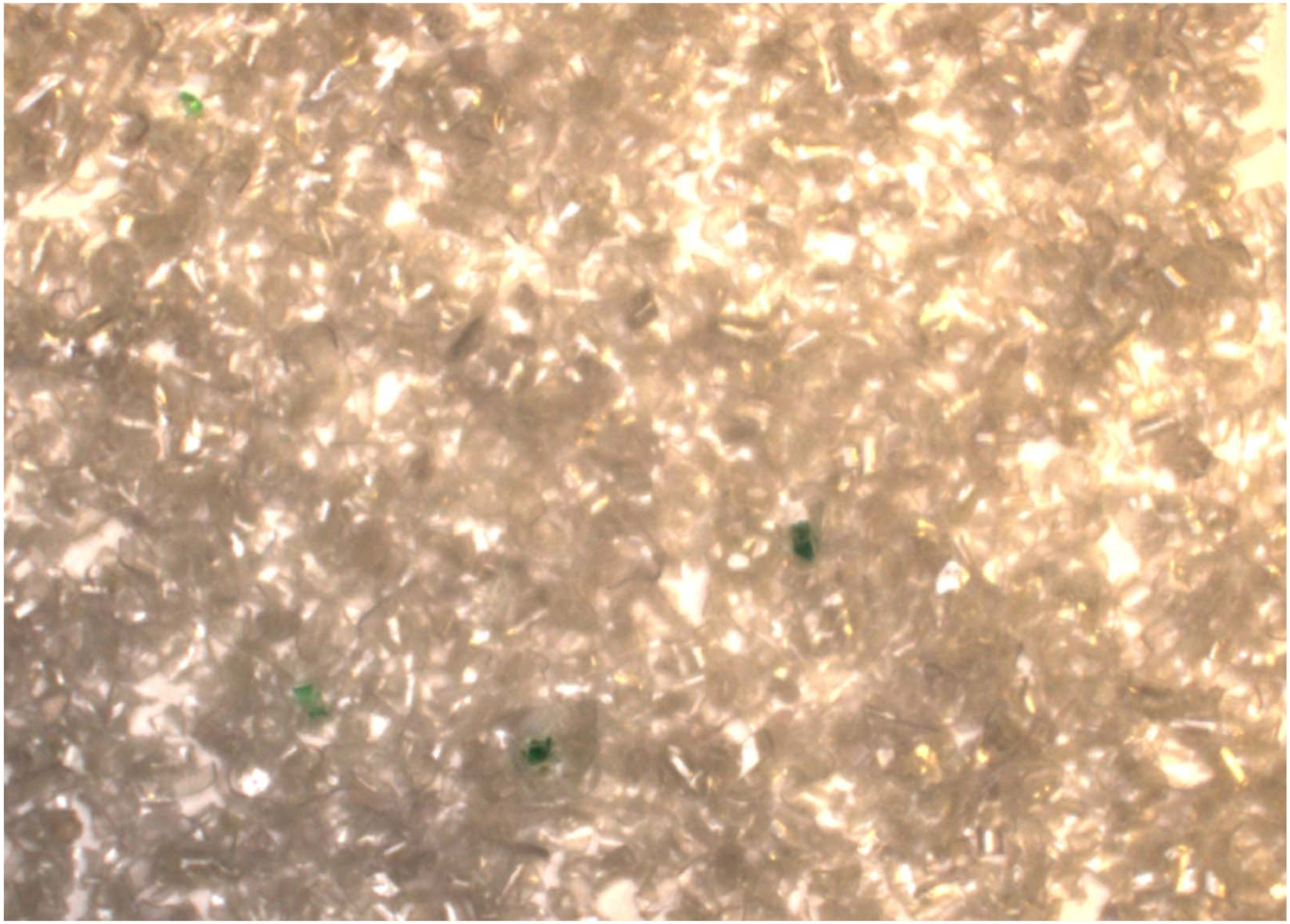


Plating Inspection – Find Defects

- Threshold to display color map label values
- Use monochrome blob and edge detectors for dimensioning and defect detection

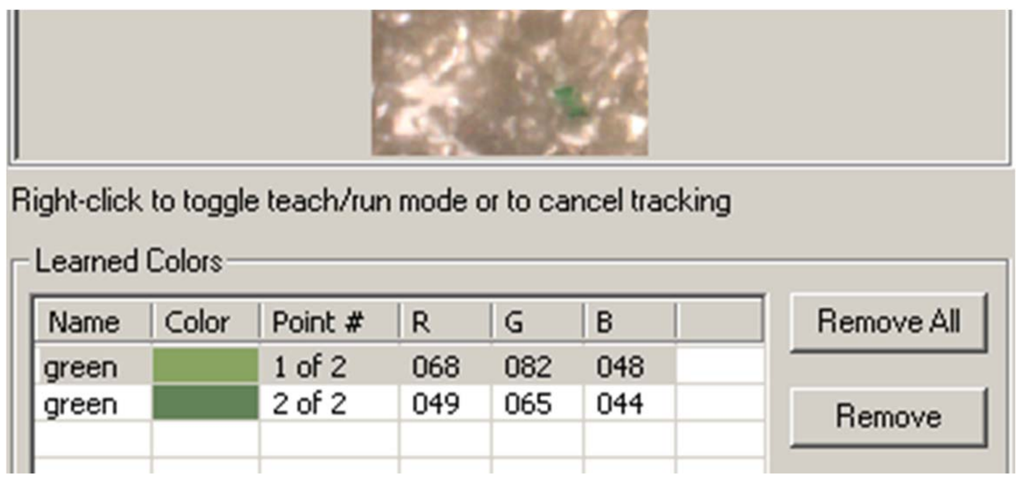


Sorting Recycled Plastic

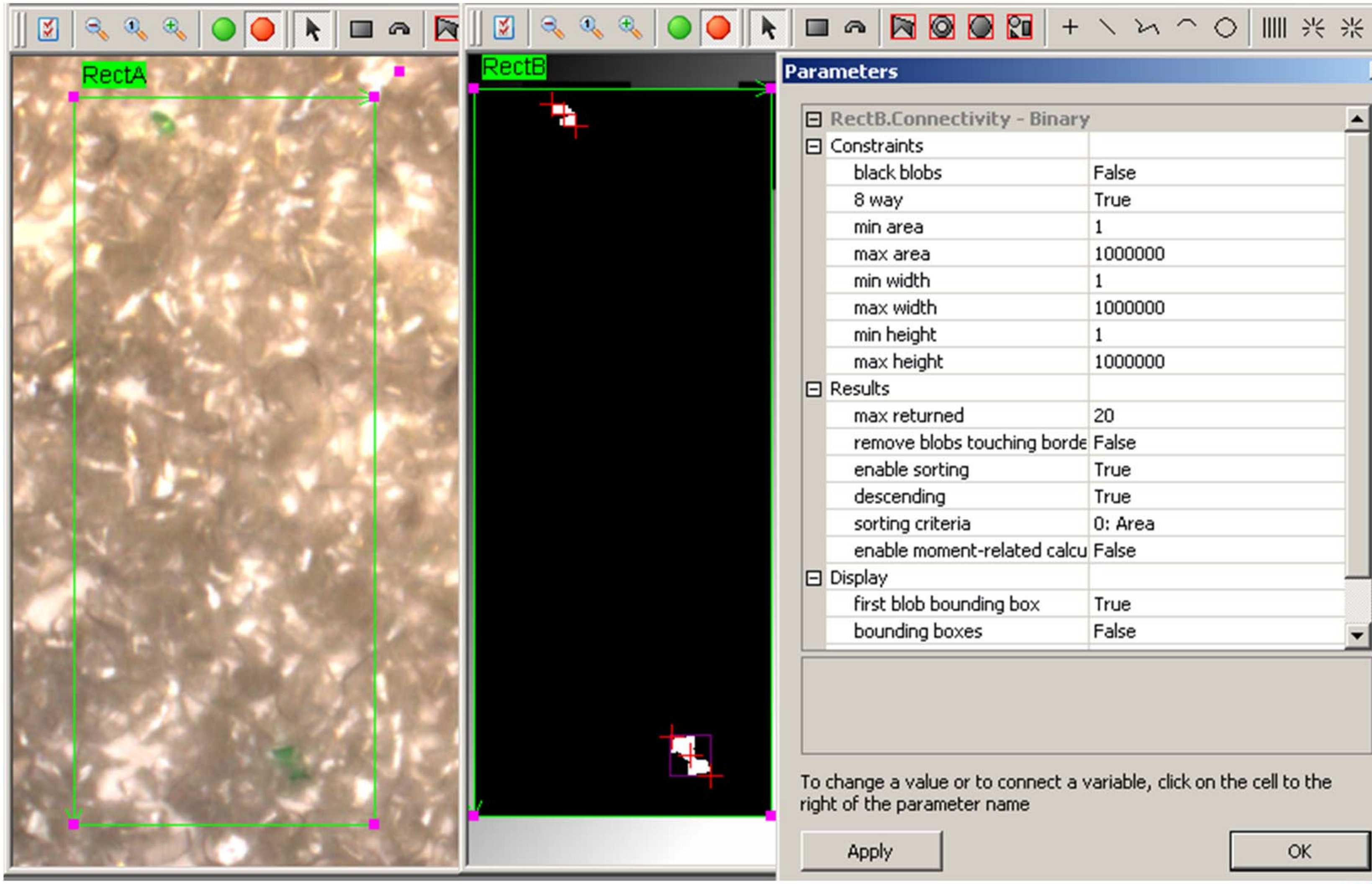


Use a Color Map

- Monochrome image values represent different color materials, 0 represents clear plastic
- Then apply standard monochrome machine vision tools to this map
- Count connected pixels of same class for color plastic detection
- Air knife out colored plastic



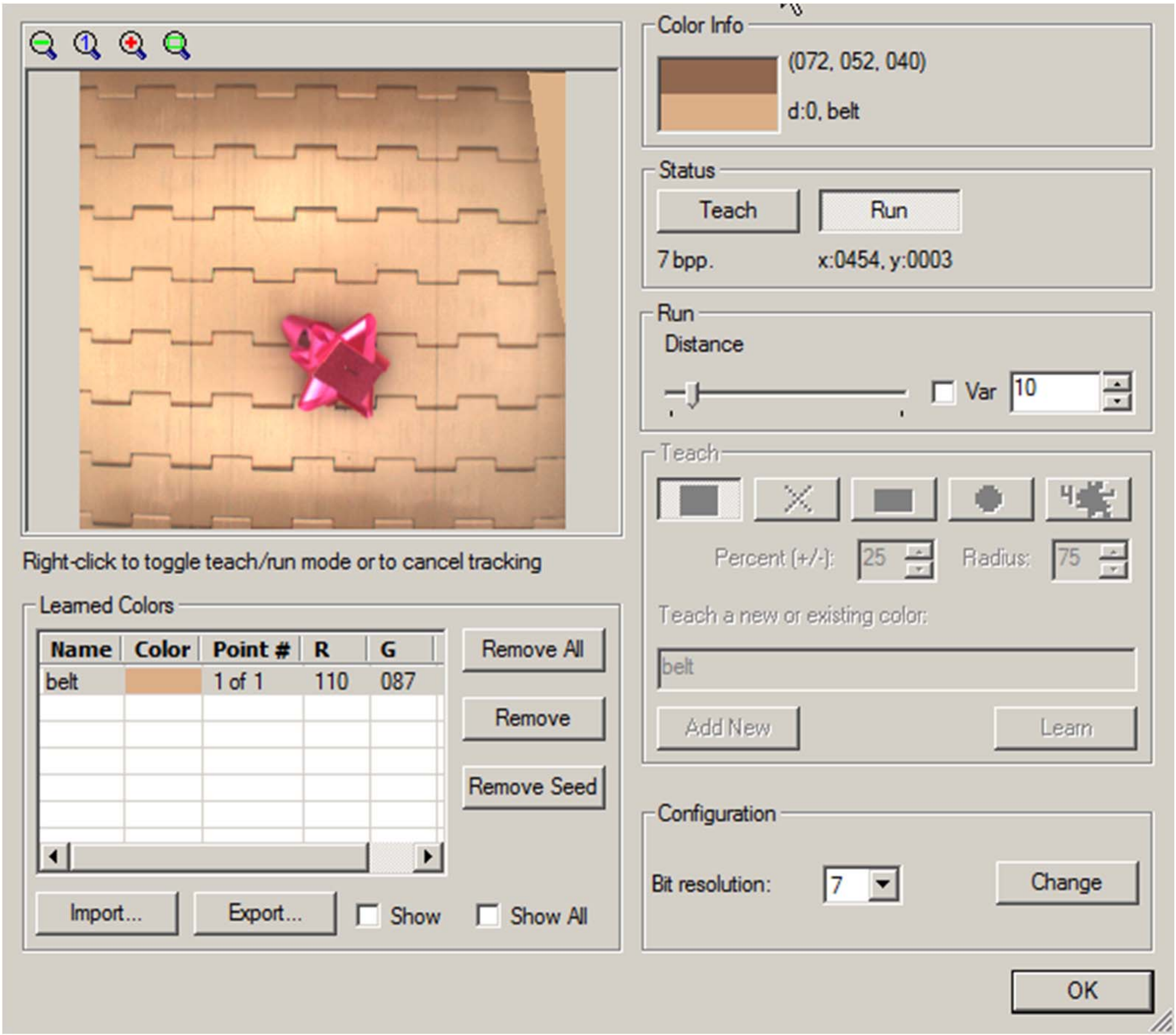
Color Map Blob Analysis



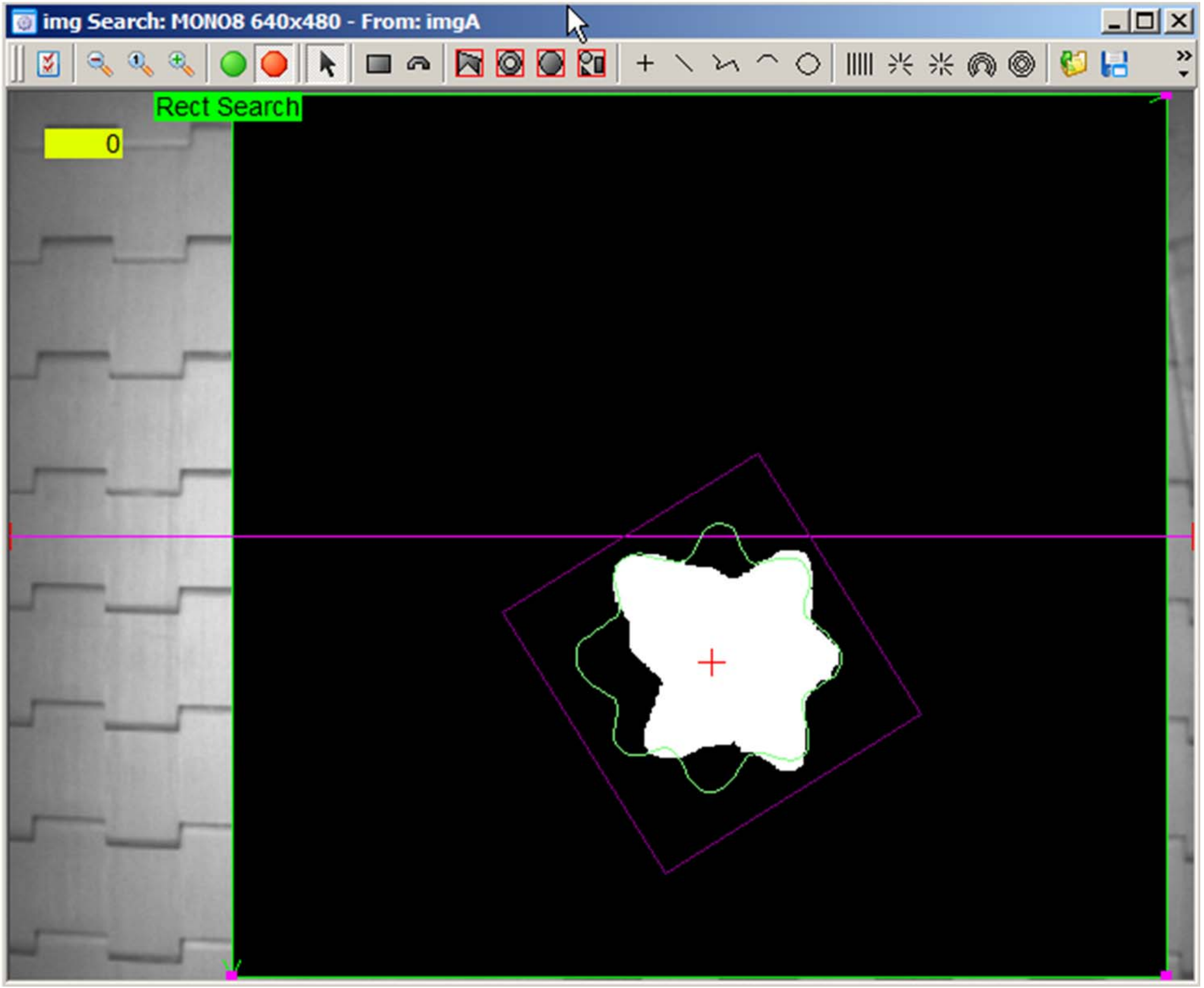
Counting Bows

- Count bows as they fly by (6’ a second)
- All colors, various sizes, right-side or upside down
- Variable position, can be touching or piled up
- Got any ideas how?

Color Classify BACKGROUND



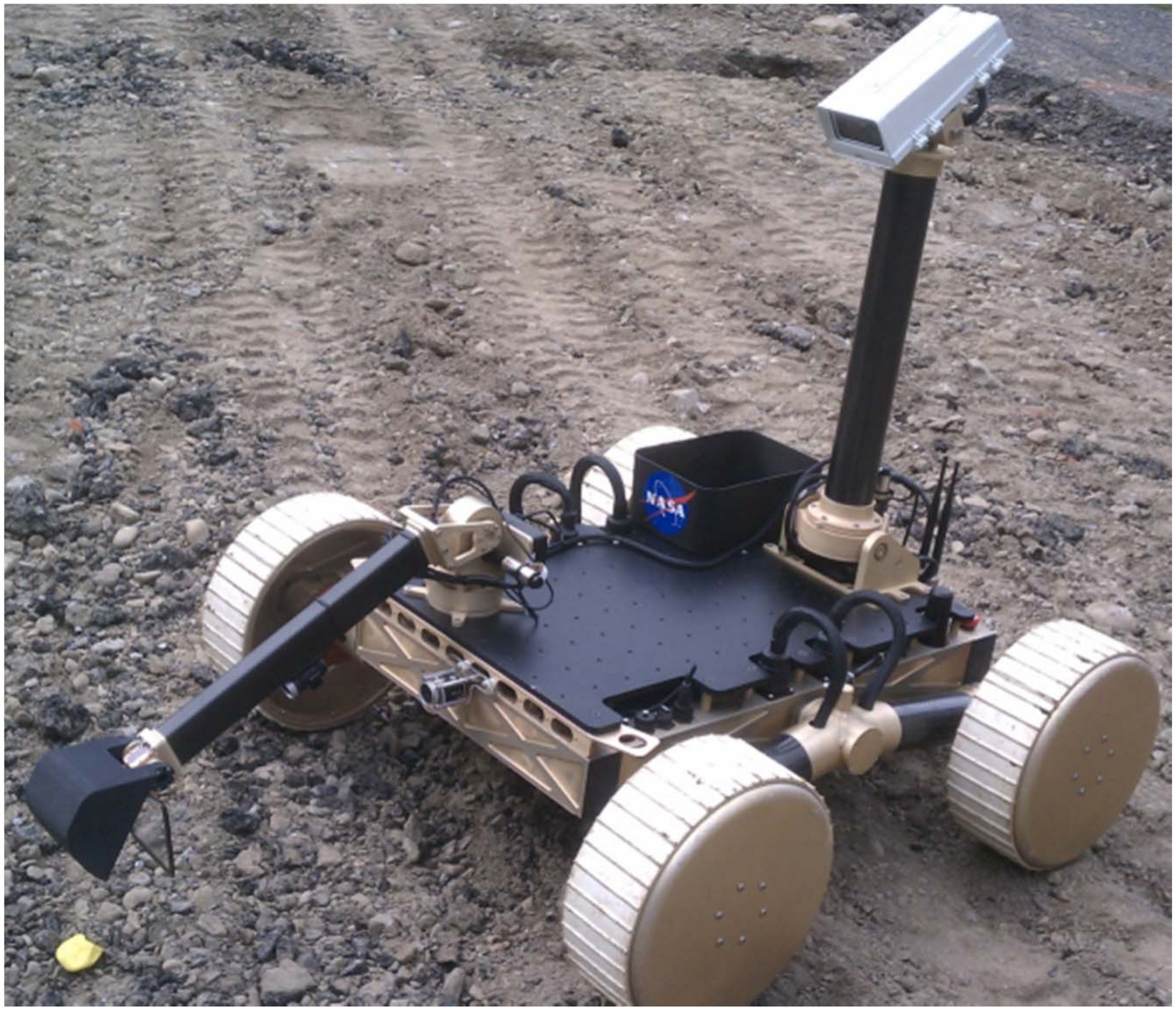
Use Color Map to Show Only Bows



Find by “sloppy” pattern matching;
Count when crosses the purple “count line”

Mars Rocks and Rovers Roll

- NASA sponsors a student competition to build "rovers" that find and pick up colored rocks

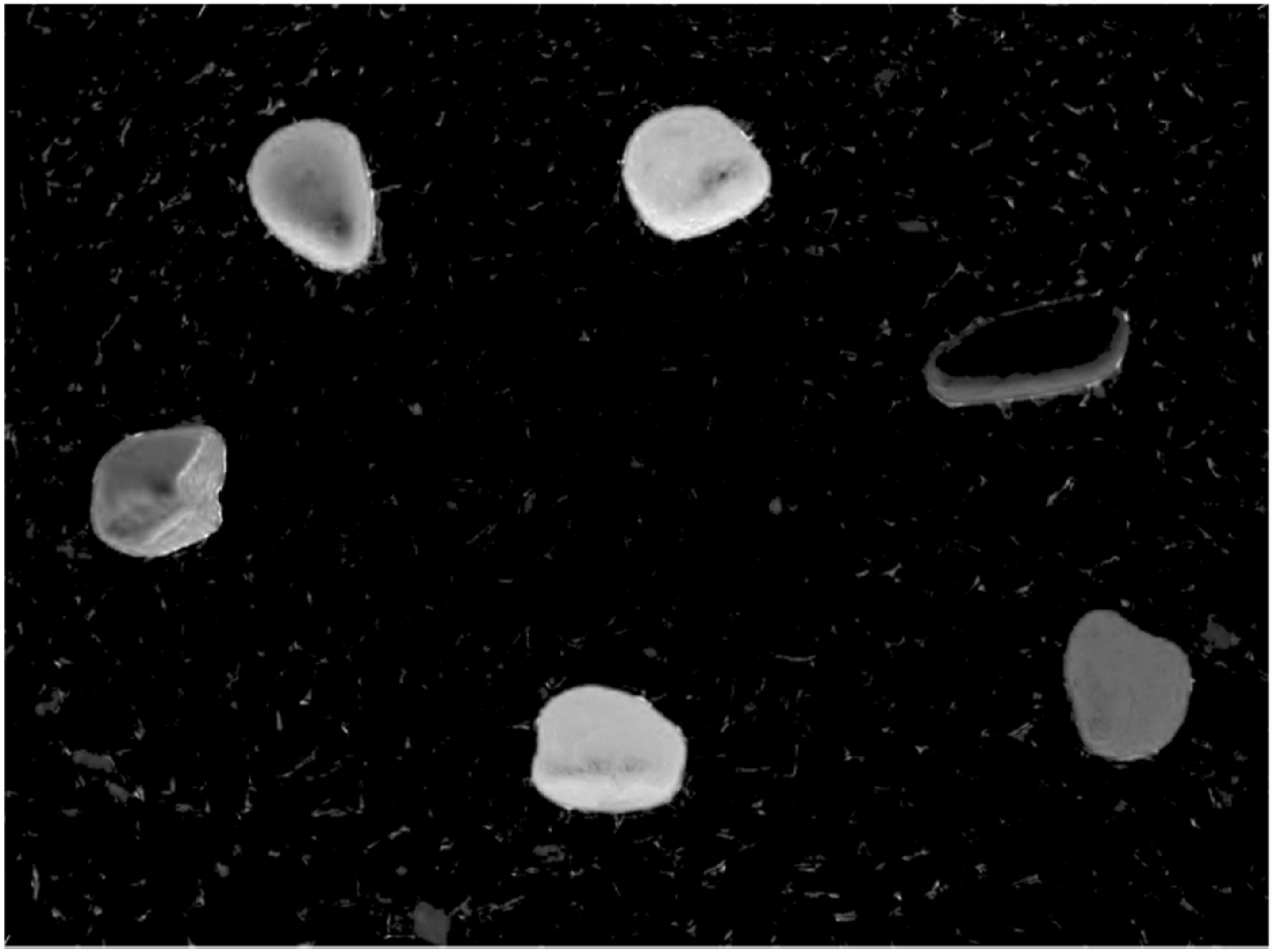


Sample Rocks

- Variety of color backgrounds with low saturation

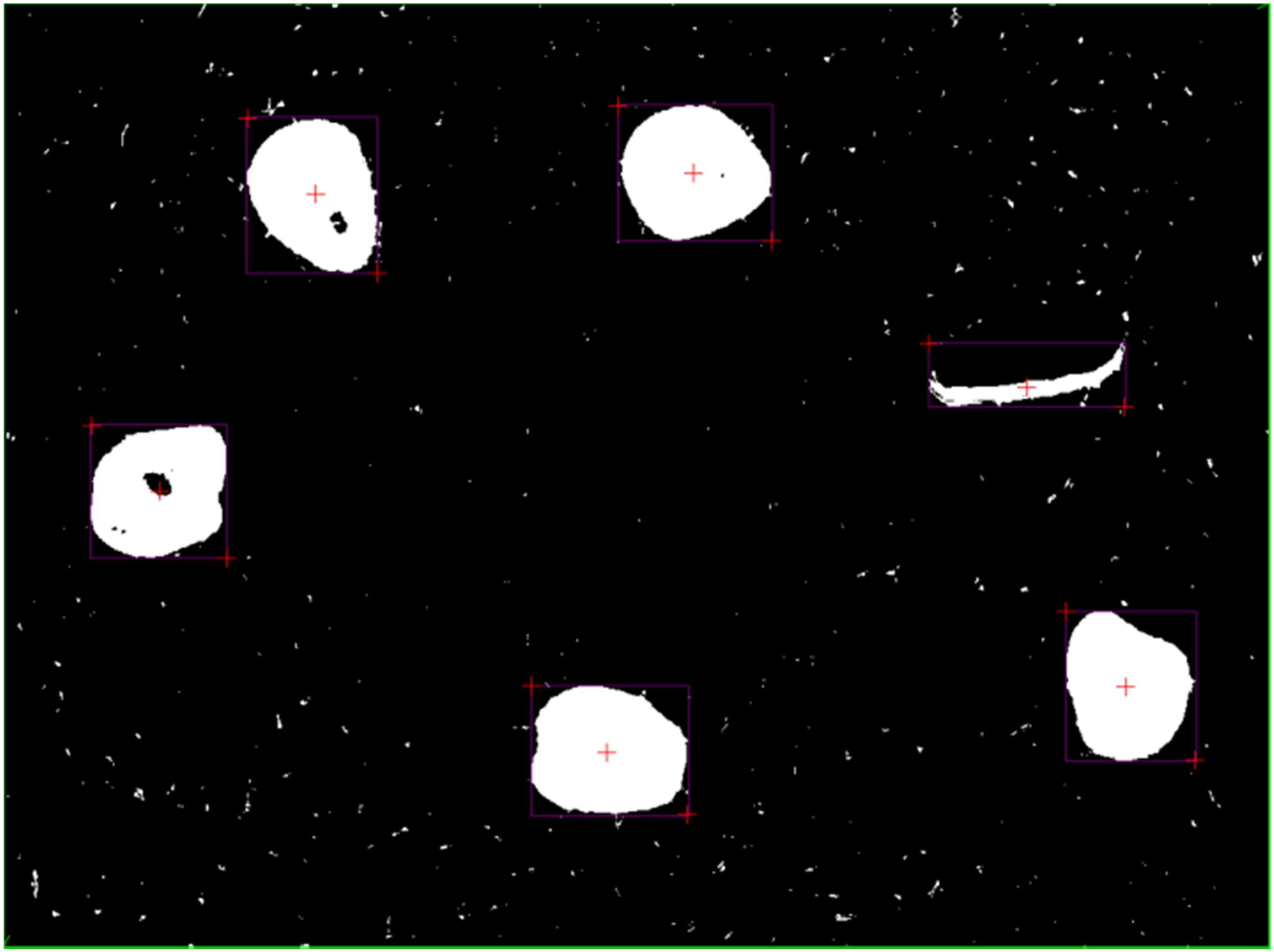
HSV's Saturation Works Well

- Color space transform to extract S is used



Clean up and “Blob Detect”

- Assume rocks > background texture



A Difficult Color Vision Problem

Coming soon (we hope) https://www.facebook.com/MITRobotics

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