Color & the in-camera image processing pipeline

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Scientist's view of photography

Photo by Uwe Hermann

Scientist’s view of photography

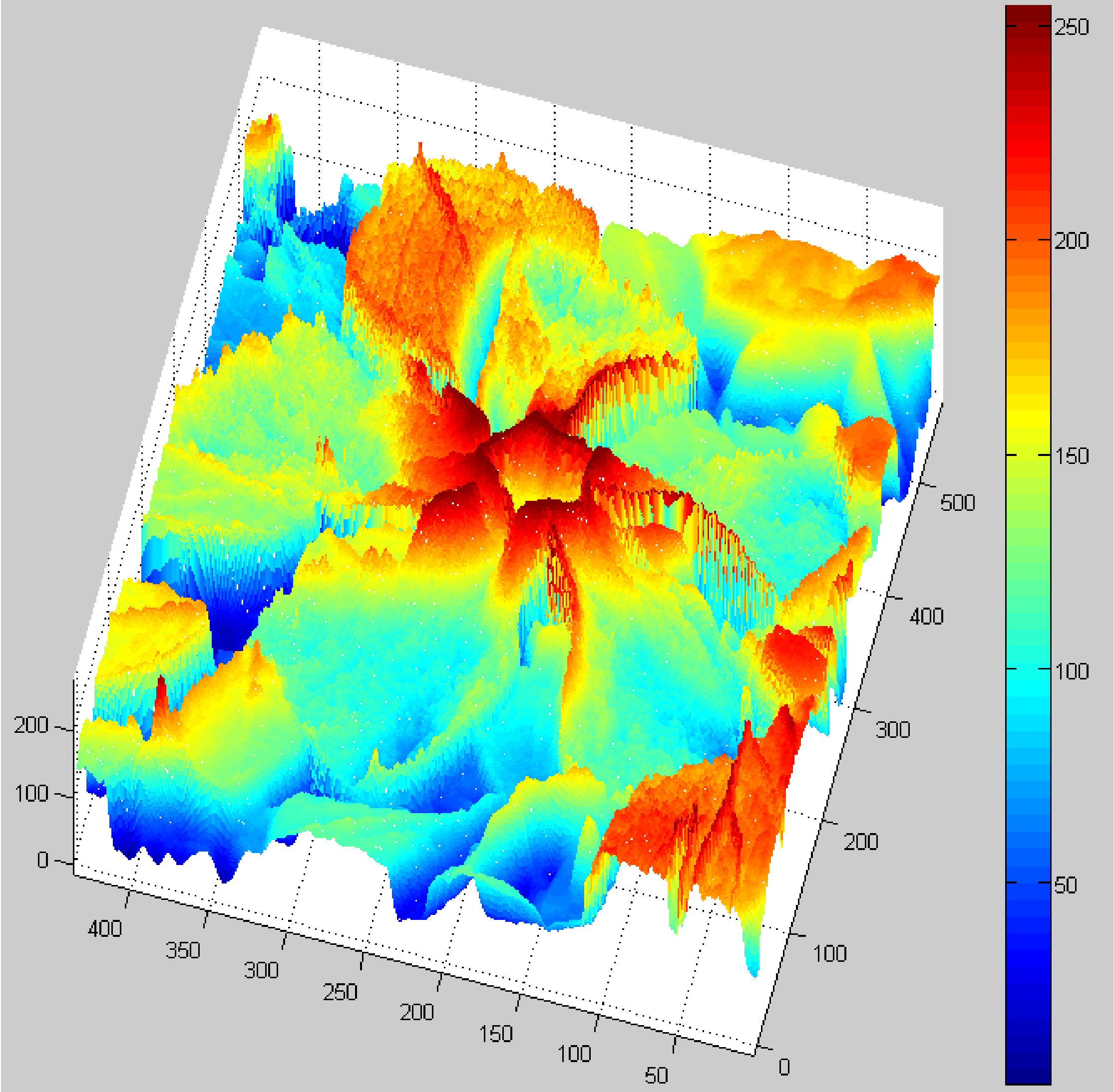
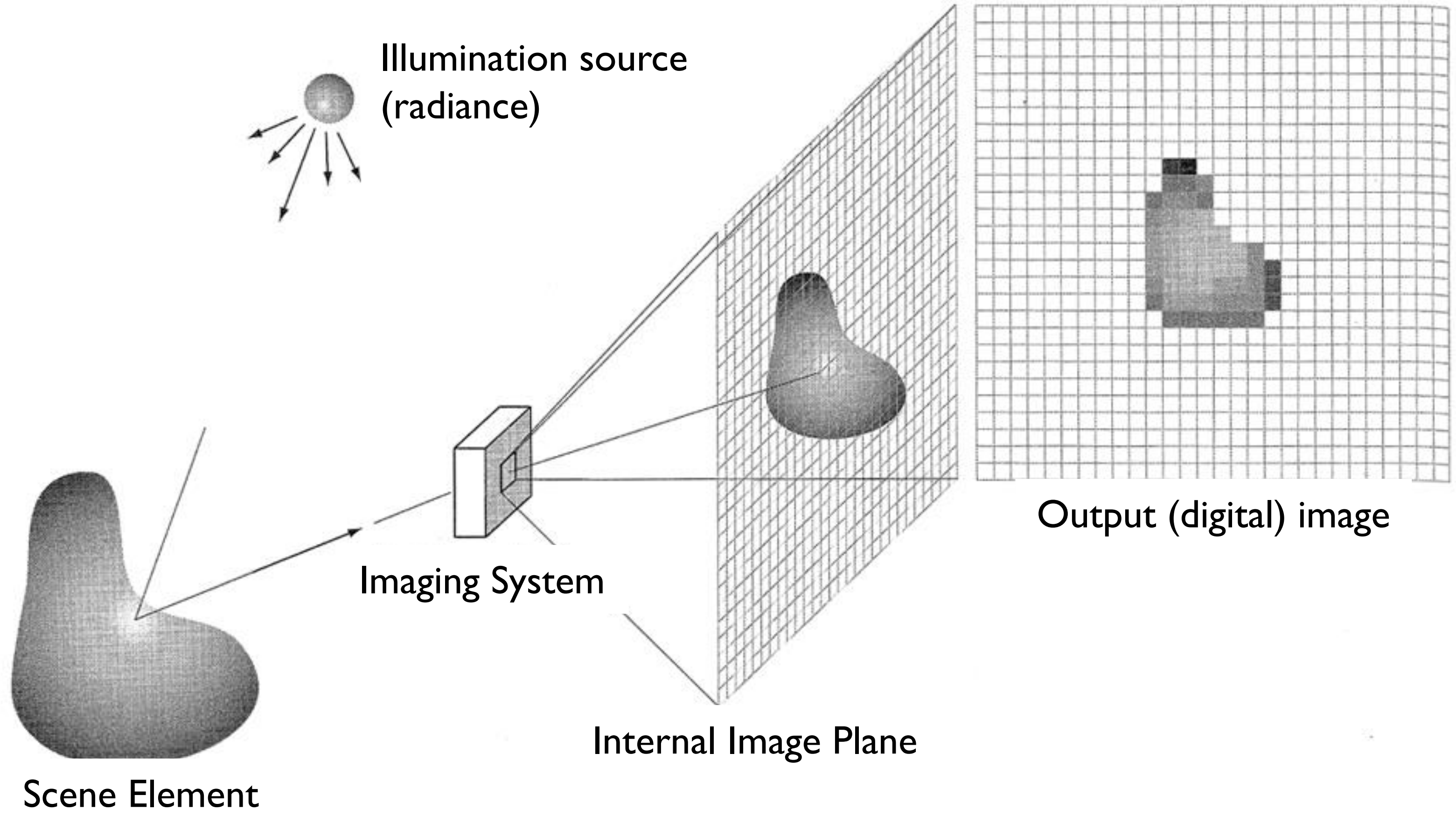


Photo by Uwe Hermann

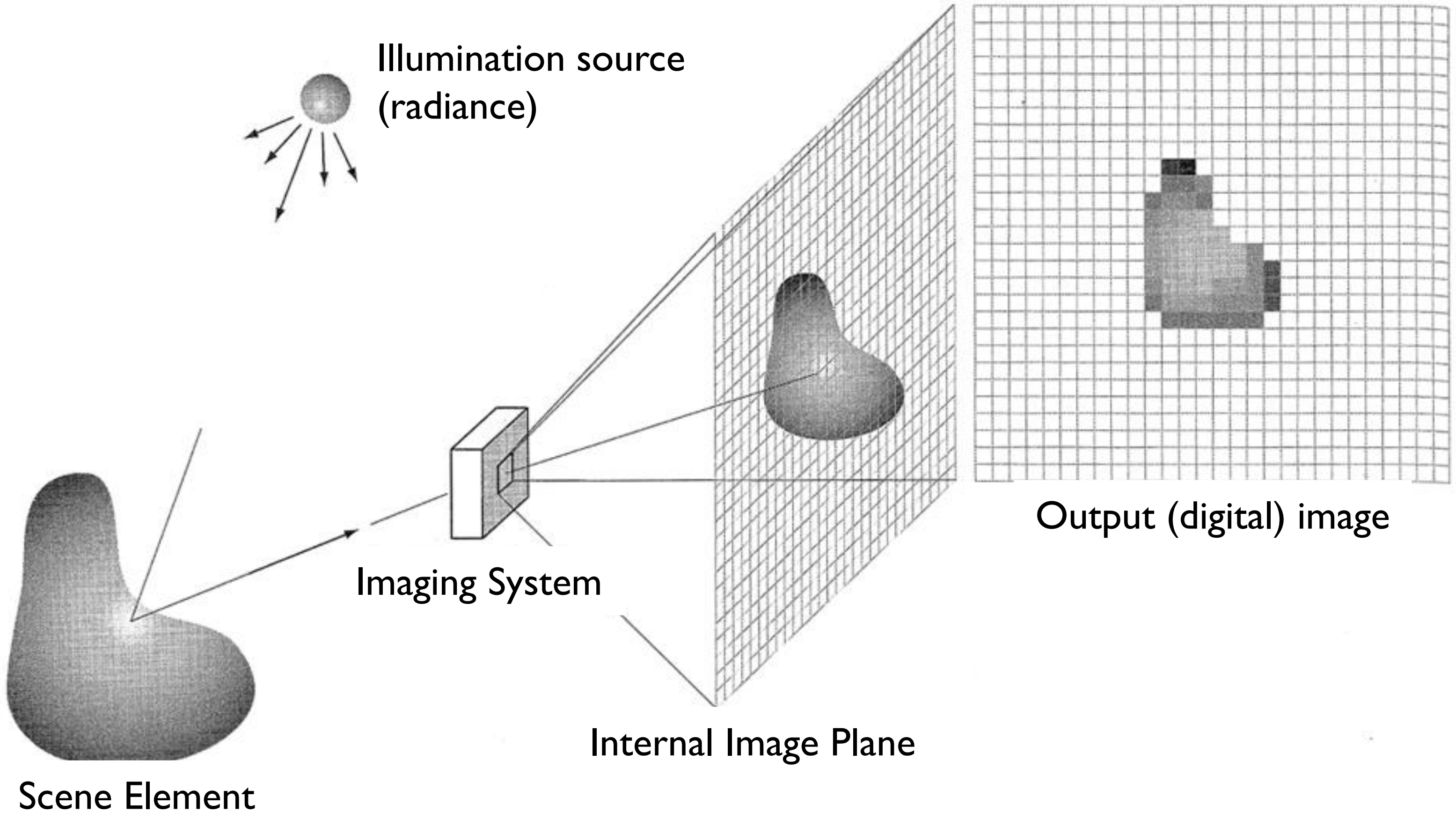
Camera = light-measuring device



Simple models of a camera assumes an image is a "quantitative measurement" of scene radiance.

Figure from Digital Image Processing, Gonzales/Woods

Image = radiant energy measurement



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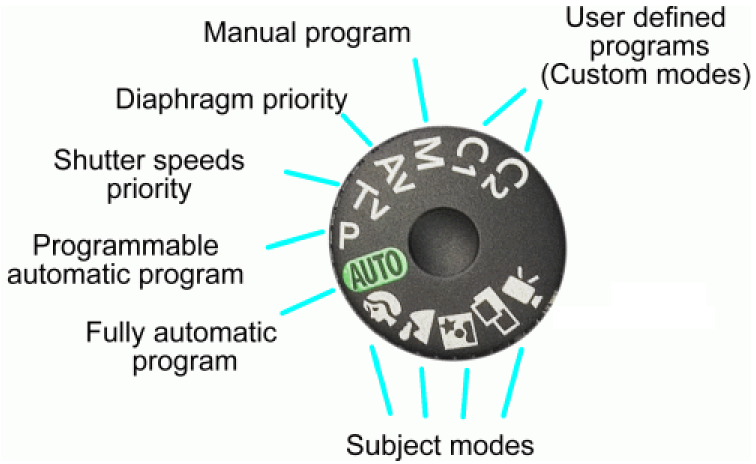
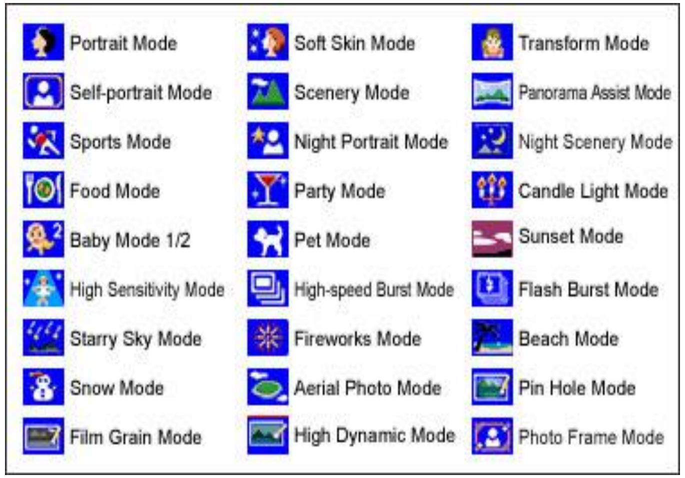
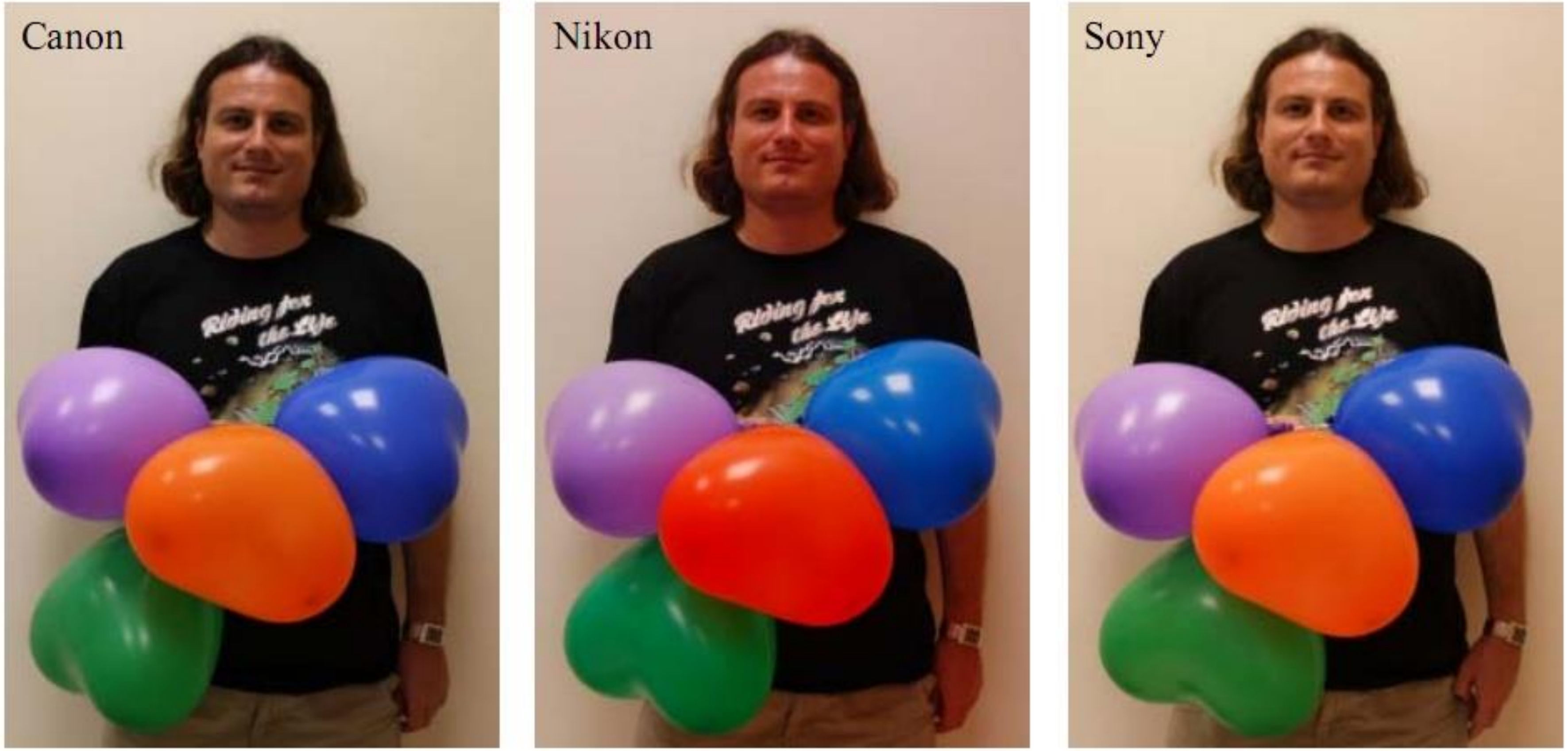
Camera = light-measuring device?





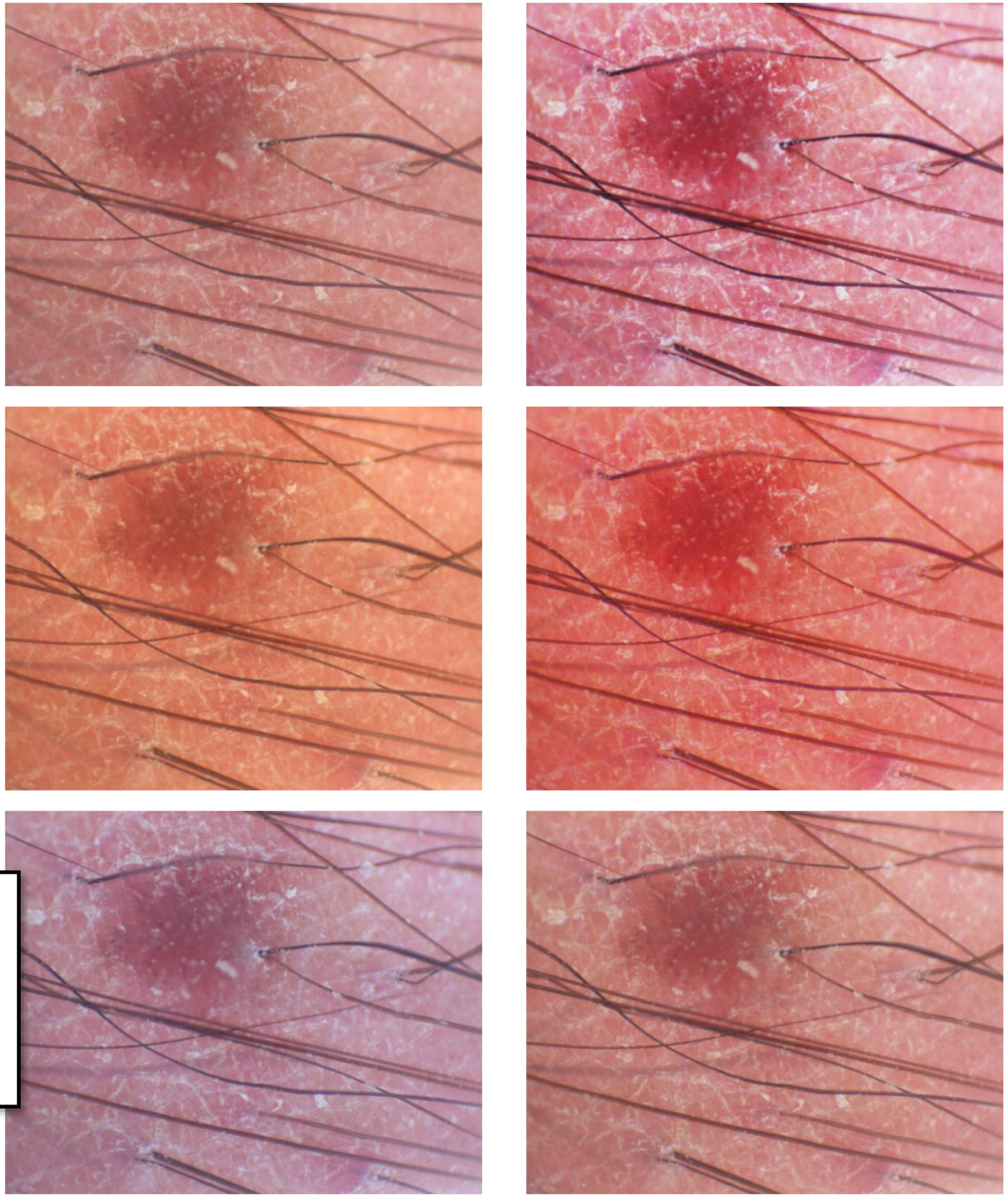
In-camera photo-finishing is the "secret recipe" of a camera



Photographs taken from three different cameras with the same aperture, shutter speed, white-balance , ISO, and picture style.

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

This type of processing is not suitable for scientific applications!



Which one is correct?

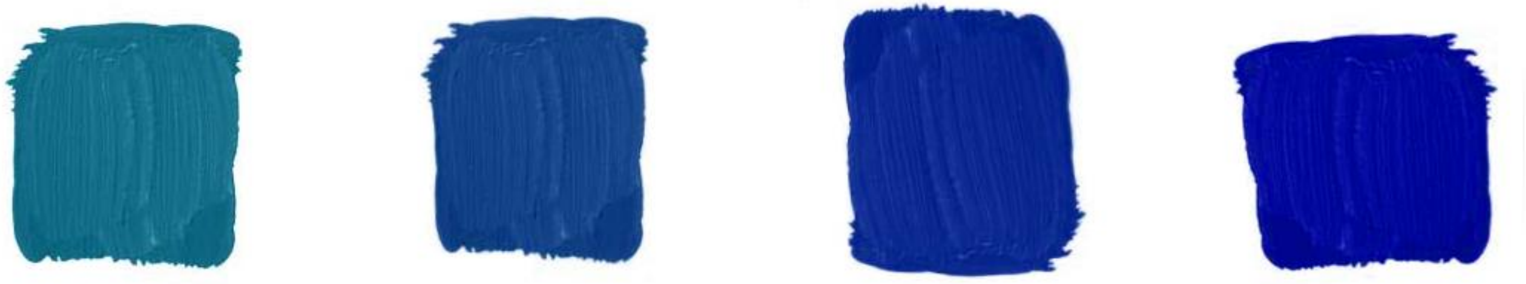
A talk in two parts

- **Part 1: Review of color**
  - CIE XYZ, chromatic adaption, color temperature, and output color spaces
  - In order to understand why your camera does what it does, you need to understand a few things about color
- **Part 2: Overview of a basic camera pipeline (ISP)**
  - The basic routines you'll find on any decent camera
  - Modern consumer cameras (e.g. smartphone cameras) will be more complicated, but have the basic workflow described here.

Part 1: “Crash Course” on Color & Color Spaces

Color is perceptual

- **Color is not** a primary *physical* property on an object
- Red, Green, Blue, Pink, Orange, Atomic Tangerine, Baby Pink, etc. . .
  - These are words we assign to human color sensations

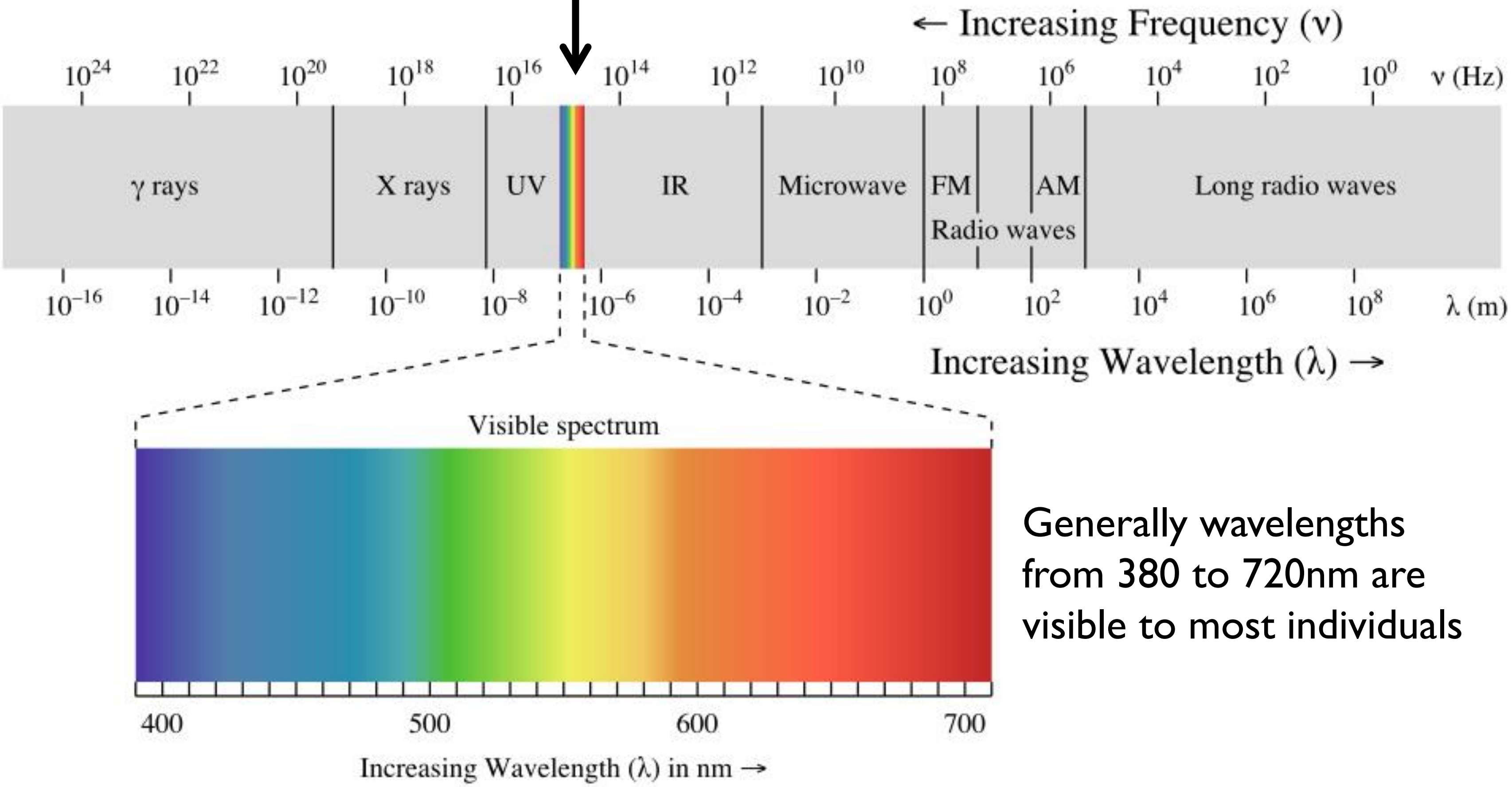


Which is the "true blue"?

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

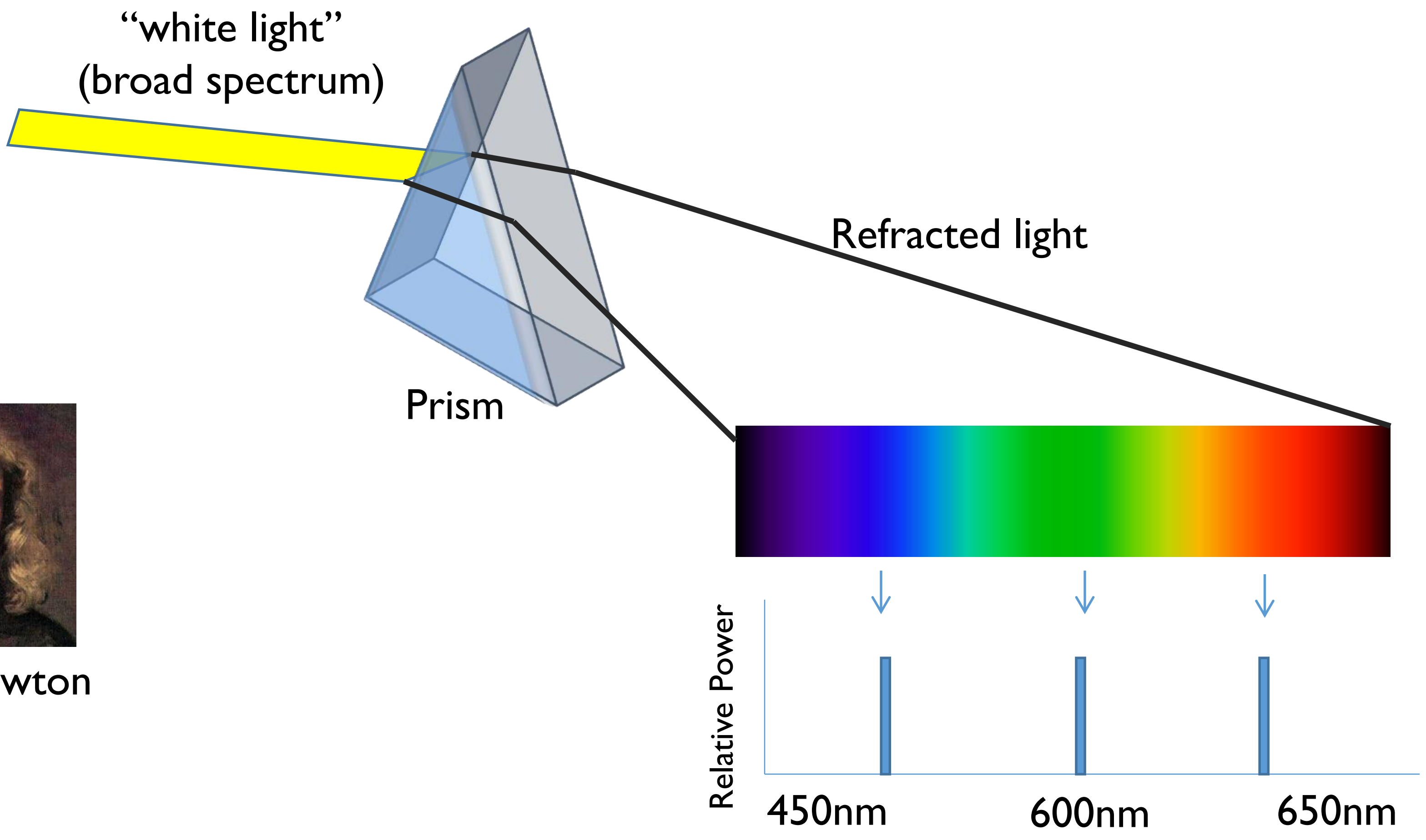
Where do "color sensations" come from?

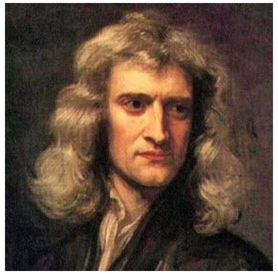
A *very* small range of electromagnetic radiation



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

White light through a prism

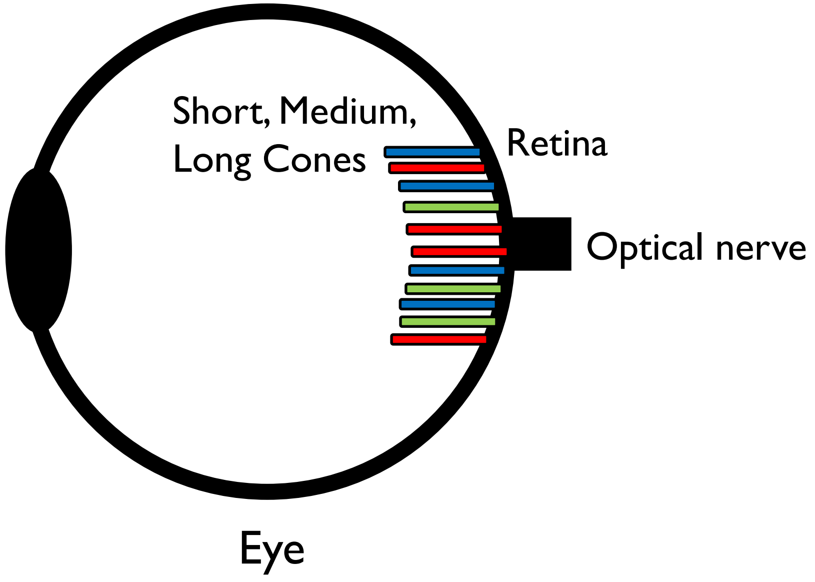


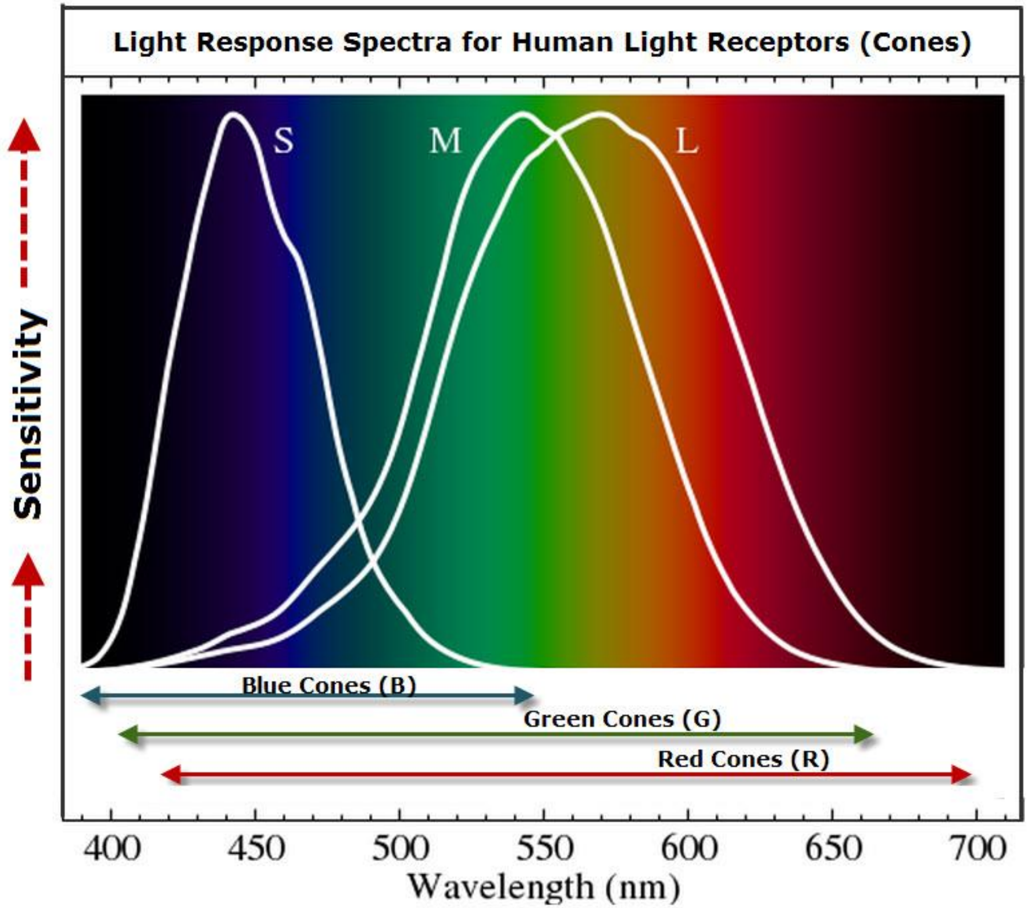

Isaac Newton

Light is separated into "monochromatic" light at different wave lengths.

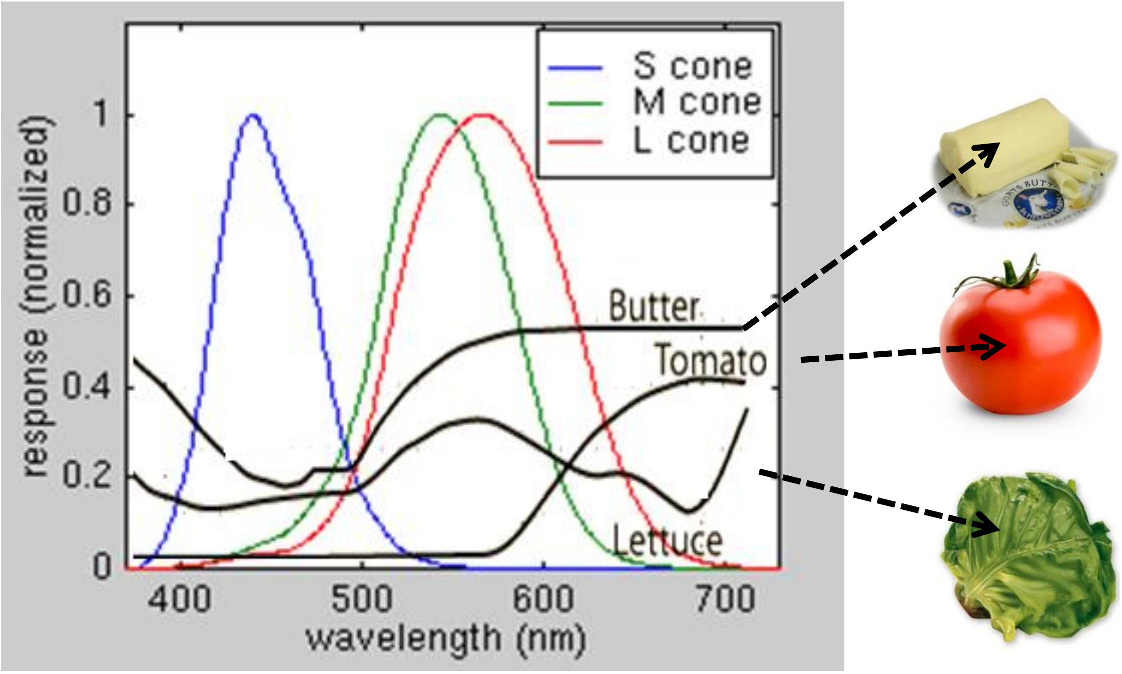
Biology of color sensations

- Our eye has three receptors (cone cells) that respond to visible light and give the sensation of color





Spectral power distribution (SPD)

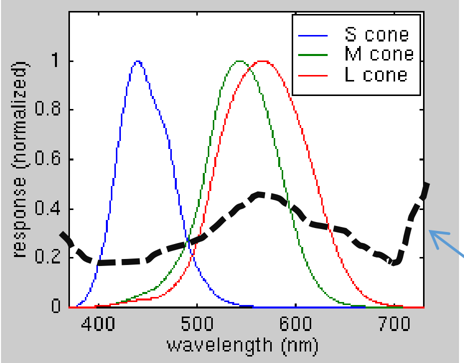


We rarely see monochromatic light in real world scenes. Instead, objects reflect a wide range of wavelengths. This can be described by a ***spectral power distribution*** (SPD) shown above. The SPD plot shows the relative amount of each wavelength reflected over the visible spectrum.

SPD relation to color is not unique

- Due to the accumulation effect of the cones, two different SPDs can be perceived as the same color (such SPDs are called "metamers").

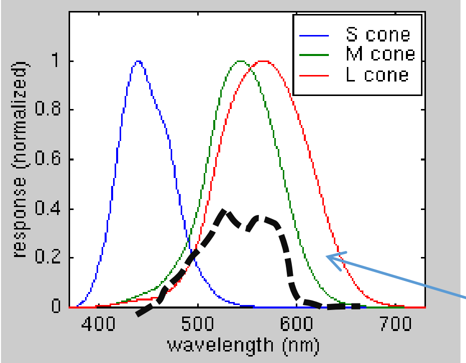
Lettuce SPD



Lettuce SPD stimulating S=0.2, M=0.8, L=0.8

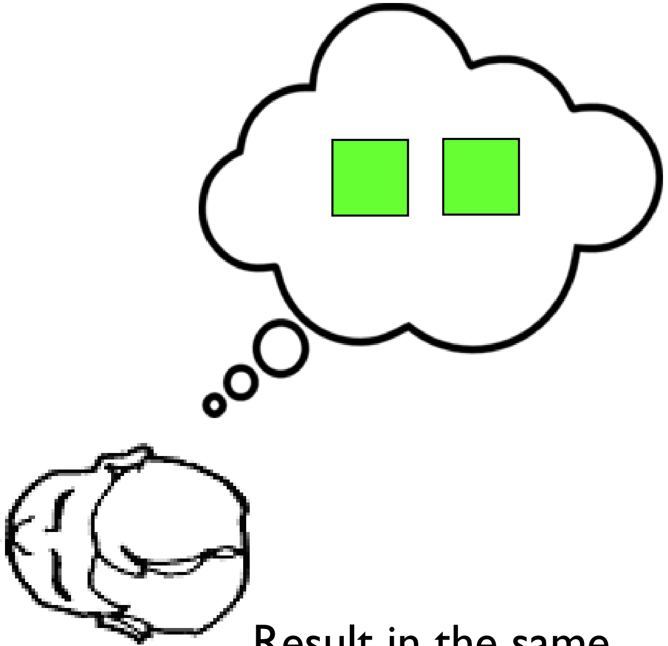
SPD of "real lettuce"

Green Ink SPD



Green ink SPD stimulating S=0.2, M=0.8, L=0.8

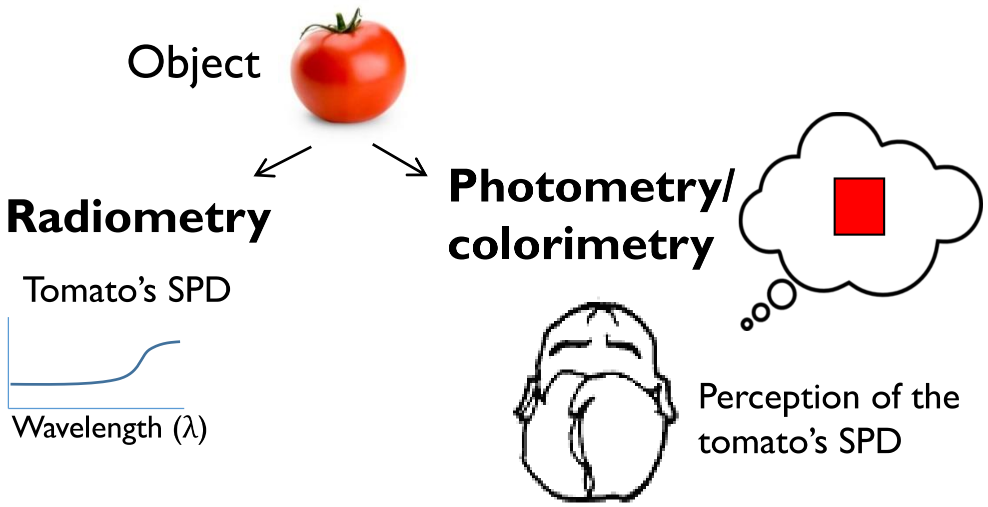
SPD of ink in a "picture of lettuce"



Result in the same color "sensation".

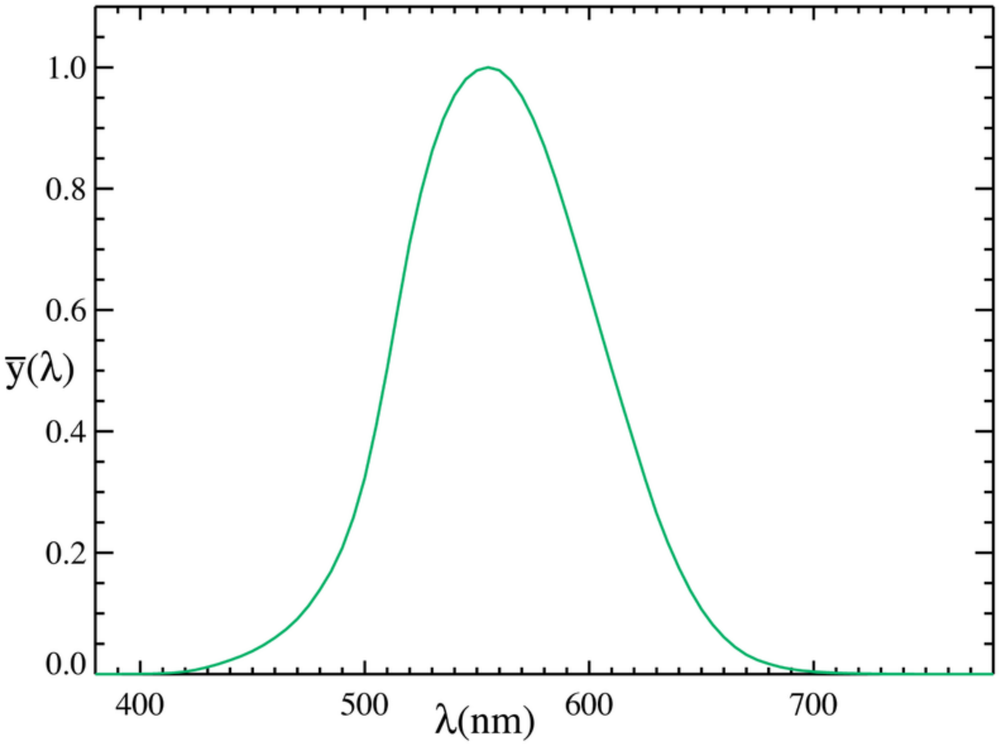
Radiometry vs. photometry

- **Radiometry**
  - Quantitative measurements of radiant energy
  - Often shown as spectral power distributions (SPD)
  - Measures either light coming from a source (radiance) or light falling on a surface (irradiance)
- **Photometry/ colorimetry**
  - Quantitative measurement of **perceived** radiant energy based on human's sensitivity to light
  - Perceived in terms of "brightness" (photometry) and color (colorimetry)



CIE (1924) Photopic luminosity function

If we invert the curve on the pervious slide, we get the luminosity function.



The Luminosity Function (written as $\overline{y}(\lambda)$ or $V(\lambda)$) shows the eye's sensitivity to radiant energy into luminous energy (or perceived radiant energy) based on human experiments (flicker fusion test).

International Commission on Illumination (CIE comes from the French name *Commission internationale e l'éclairage*) was a body established in 1913 as an authority on light, illumination and color . . CIE is still active today -- http://www.cie.co.at

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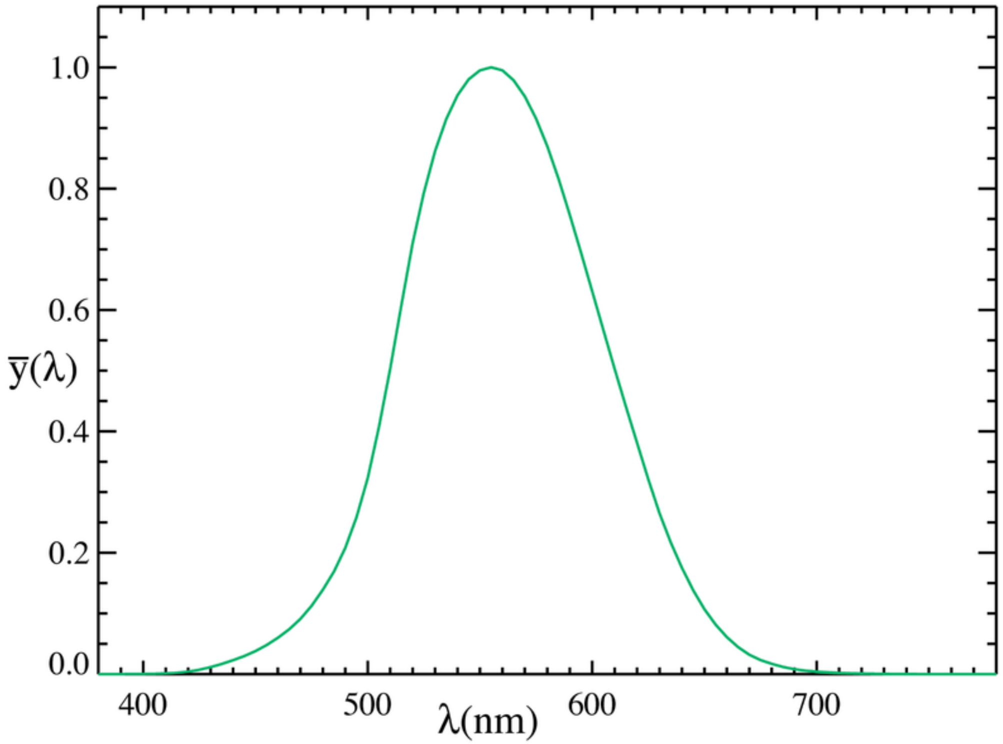

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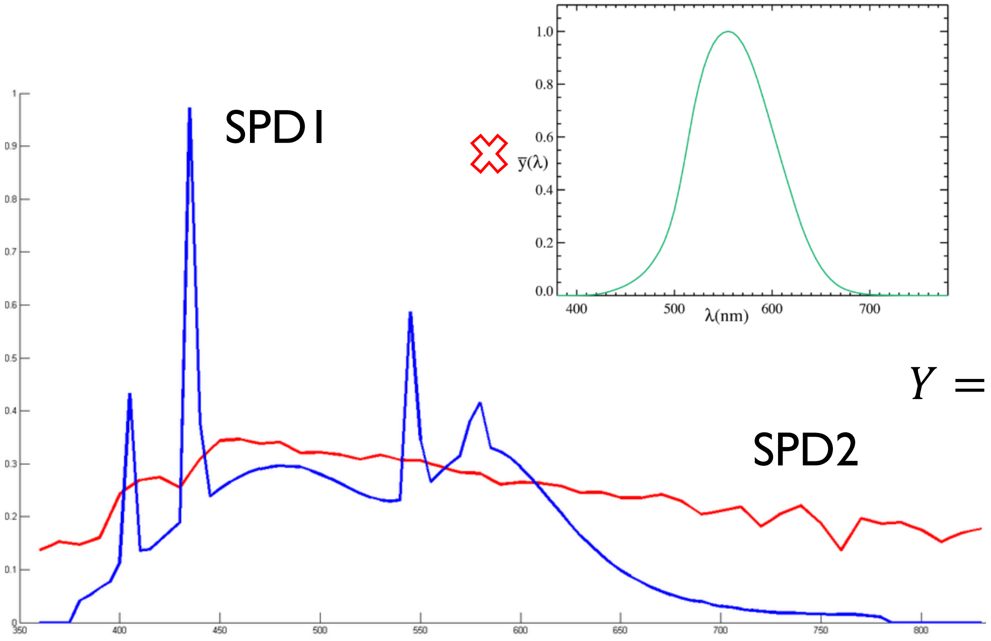
Radiometric to Photometric



Two SPDs

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

Which SDP is perceived brighter?

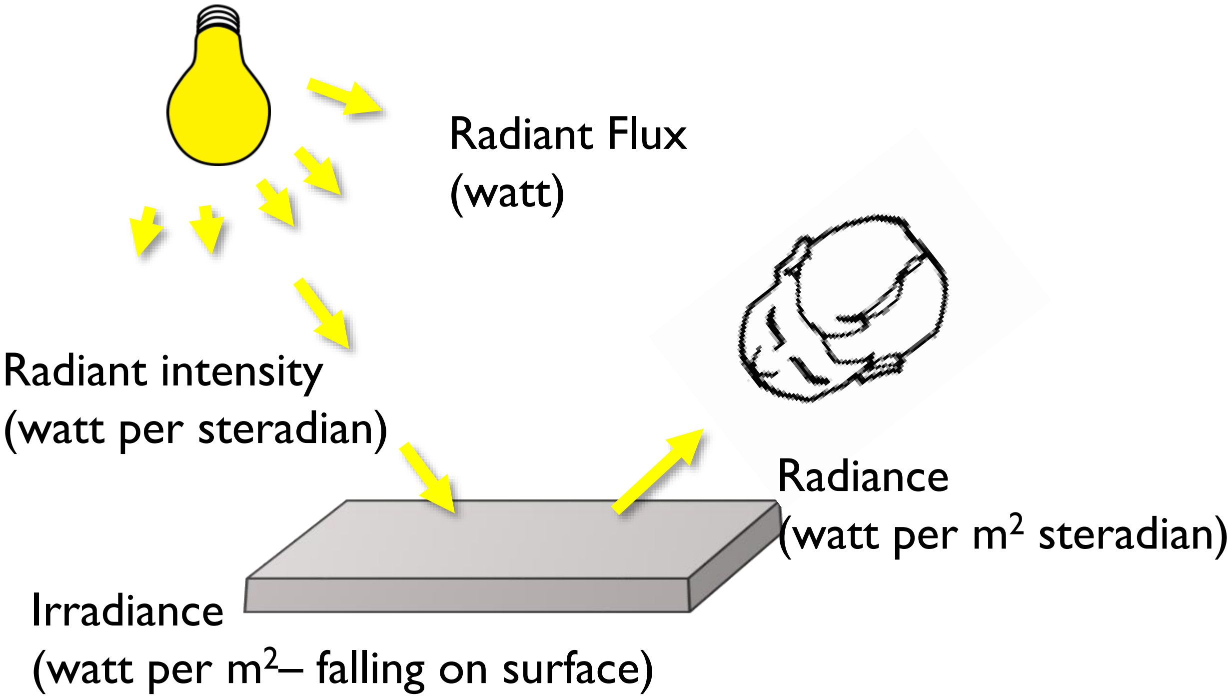
<u>SPD1</u>
Y=0.2989

<u>SPD2</u>
Y=0.2989

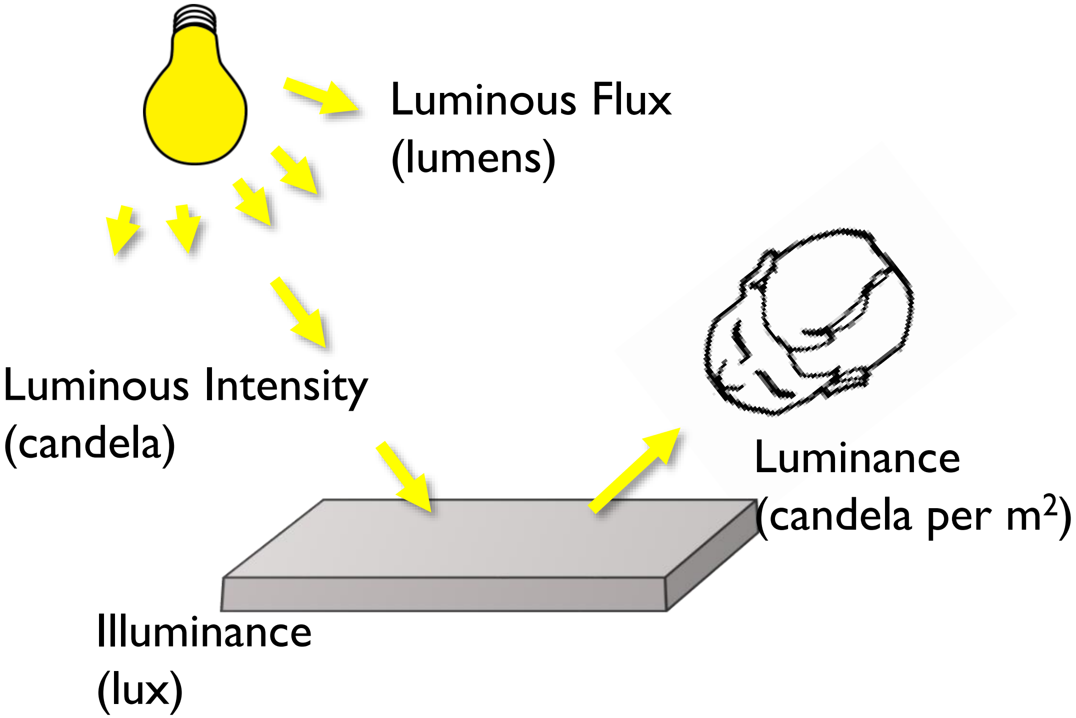
Radiometric **Photometric**

CIE Y gives a way to go from radiometric to photometric!
Now can quantify the perceived brightness of different light.

Radiometric vs. photometric units



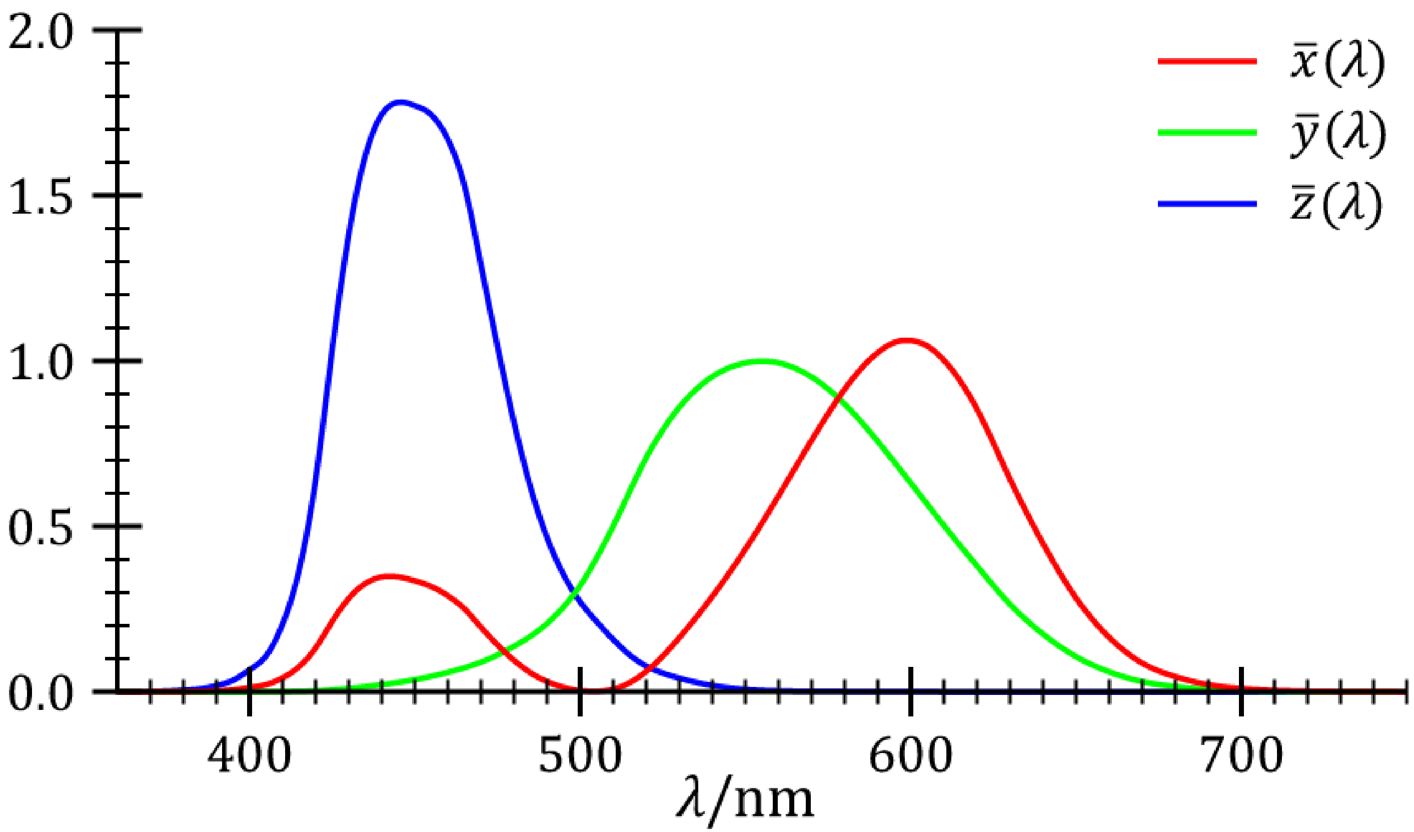
Radiometric values



Photometric values
(Radiometric values weighted by the Luminosity Function)

3100 lumens colour brightness

CIE 1931 XYZ



This shows the mixing coefficients $\overline{x}(\lambda), \overline{y}(\lambda), \overline{z}(\lambda)$ for the CIE 1931 2-degree standard observer XYZ basis computed from the CIE RGB data. Coefficients are all now positive. Note that the basis XYZ are not physical SPD like in CIE RGB, but linear combinations defined by the matrix on the previous slide.

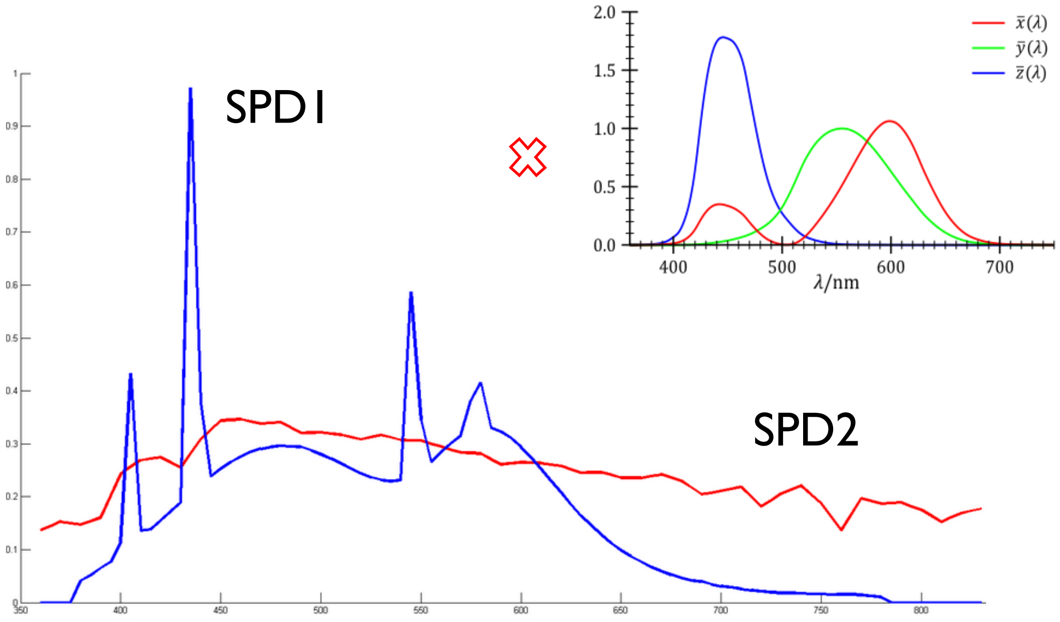
Using CIE 1931 XYZ functions

- **CIE XYZ provides a canonical color space to describe SPDs**
- Given an SPD, $I(\lambda)$, we can compute its mapping to the CIE XYZ space

$$X = \int_{380}^{780} I(\lambda)\bar{x}(\lambda)\, d\lambda \qquad Y = \int_{380}^{780} I(\lambda)\bar{y}\,(\lambda)\, d\lambda \qquad Z = \int_{380}^{780} I(\lambda)\bar{z}(\lambda)\, d\lambda$$

- Given two SPDs, if their CIE XYZ values are equal, then they are considered the same perceived color, i.e.
  - $I_1(\lambda), I_2(\lambda) \rightarrow (X_1, Y_1, Z_1) = (X_2, Y_2, Z_2)$ [perceived as the same color]

SPD to CIE XYZ example



Two SPDs

CIE XYZ Values

SPD1
X=0.2841
Y=0.2989
Z=0.3254

SPD2
X=0.2841
Y=0.2989
Z=0.3254

Radiometric **Colorimetric**

CIE XYZ gives a way to go from radiometric to colorimetric.
Imbedded is also the photometric measurement in the Y value.

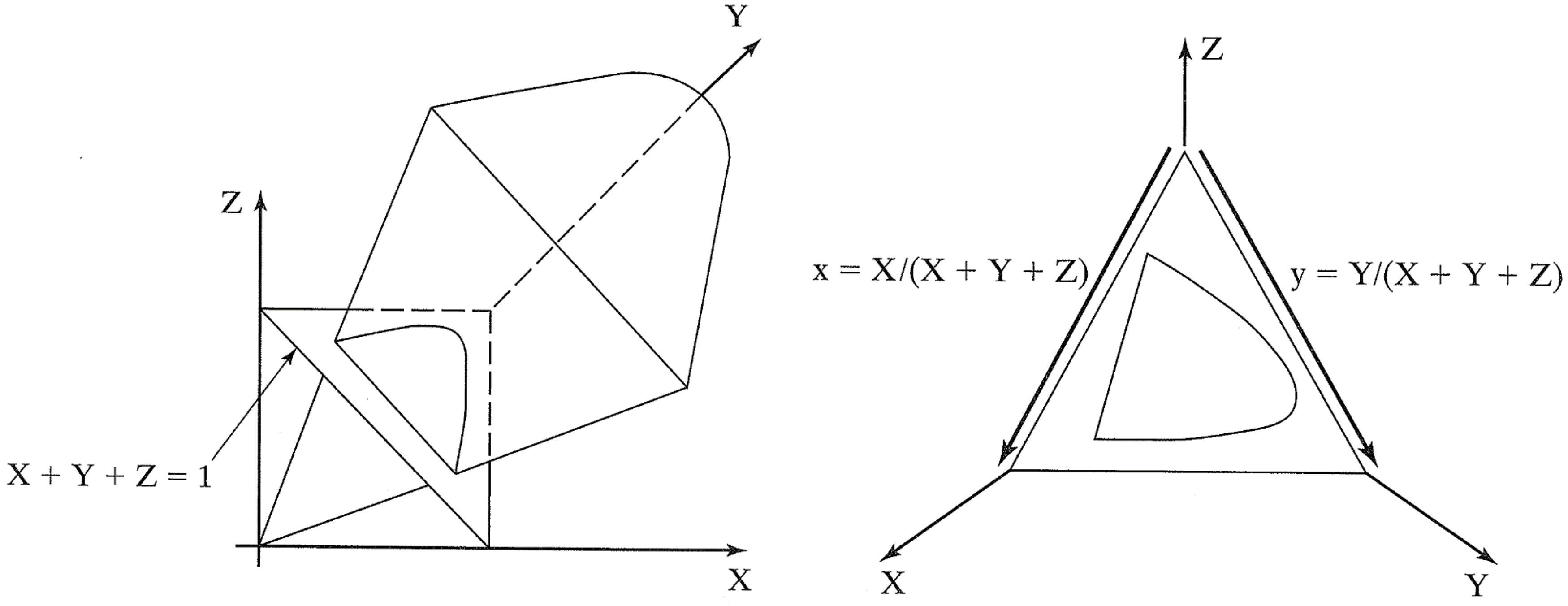
Usefulness of CIE 1931 XYZ

- CIE XYZ space is also considered "device independent" – the XYZ values are not specific to any device
- Electronic devices (e.g. cameras, flatbed, scanners, printers, displays) can compute mappings of their device specific values to the corresponding CIE XYZ values.
- This provides a canonical space to match between devices (at least in theory).

Luminance-chromaticity space (CIE xyY)

- CIE XYZ describes a color in terms of linear combination of three primaries (XYZ)
- Sometimes it is useful to discuss color in terms of luminance (perceived brightness) and chromaticity (we can think of as the hue-saturation combined)
- CIE xyY space is used for this purpose

Deriving CIE xyY



Project the CIE XYZ values onto the X=1, Y=1, Z=1 plane.

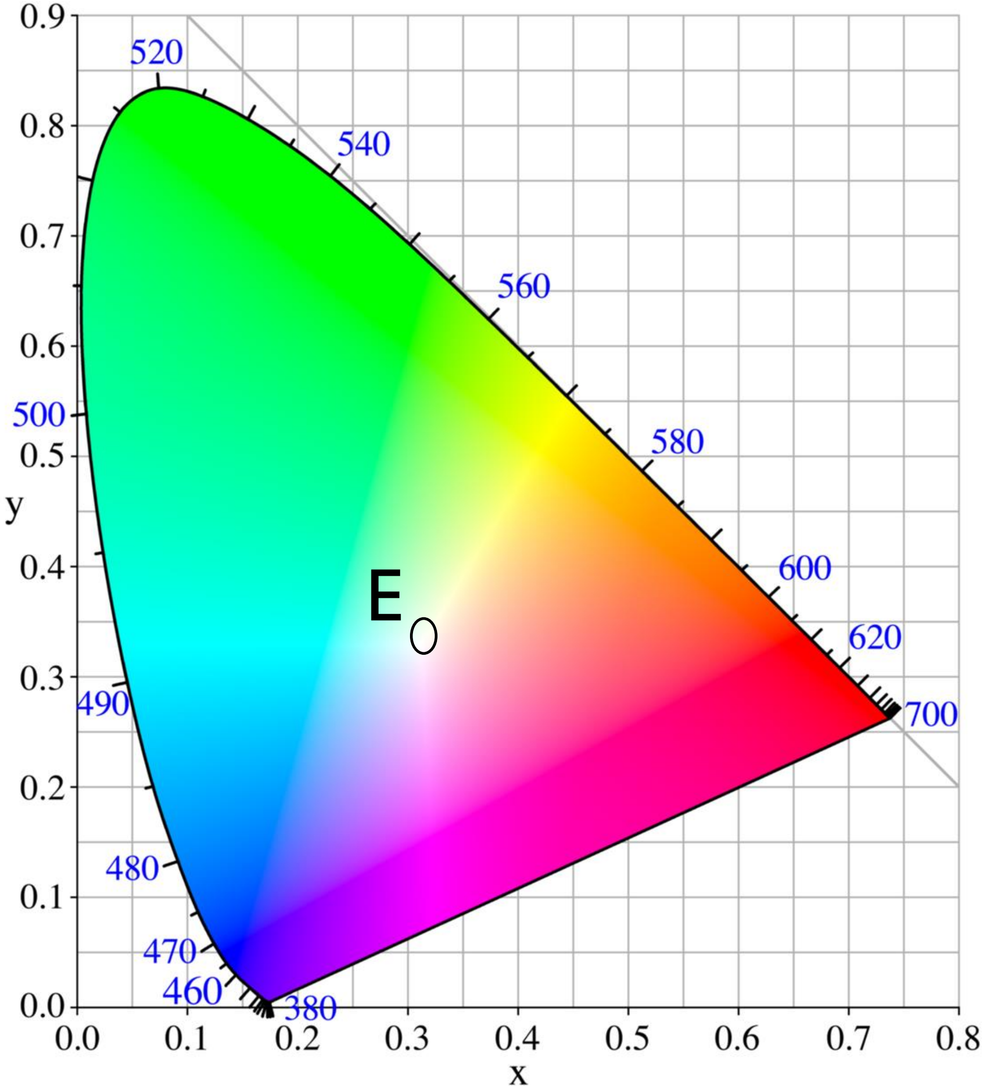
Figure from Ponce and Forsyth

CIE xy chromaticity diagram

This gives us the familiar horseshoe shape of visible colors as a 2D plot. Note the axis are x & y.

Point "E" represents where X=Y=Z have equal energy (X=0.33, Y=0.33, Z=0.33)

CIE XYZ "white point"



In the 1930s, CIE had a bad habit of over using the variables X, Y. Note that x, y are chromaticity coordinates, $\bar{x}$, $\bar{y}$ (with the bar above) are the matching functions, and X, Y are the imaginary SPDs of CIE XYZ.

A caution on CIE xy chromaticity

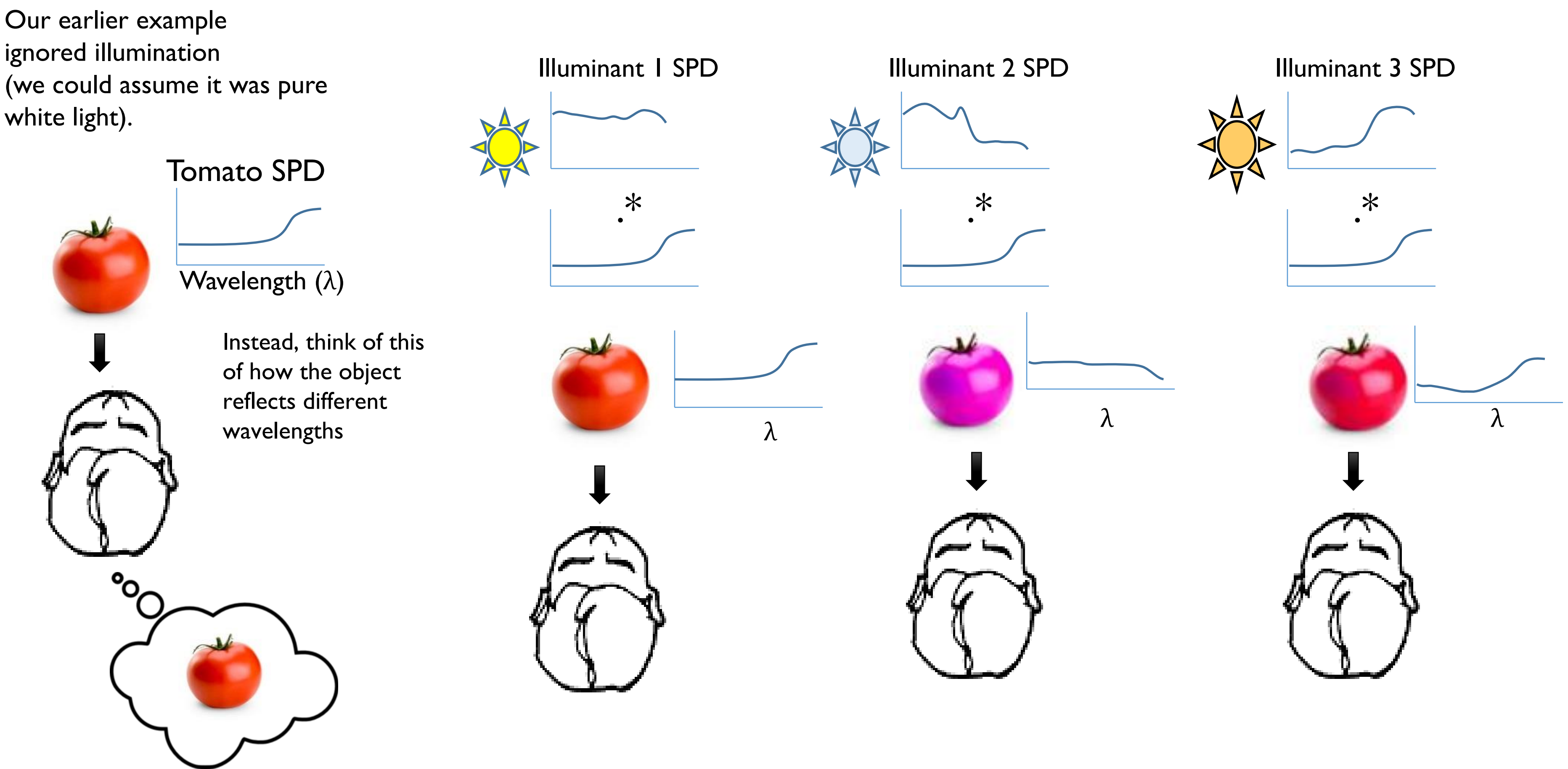
From Mark D. Fairchild book: "Color Appearance Models"

"*The use of chromaticity diagrams should be avoided in most circumstances, particularly when the phenomena being investigated are highly dependent on the three-dimensional nature of color. For example, the display and comparison of the color gamuts of imaging devices in chromaticity diagrams is misleading to the point of being almost completely erroneous.*"

Are we done with color?

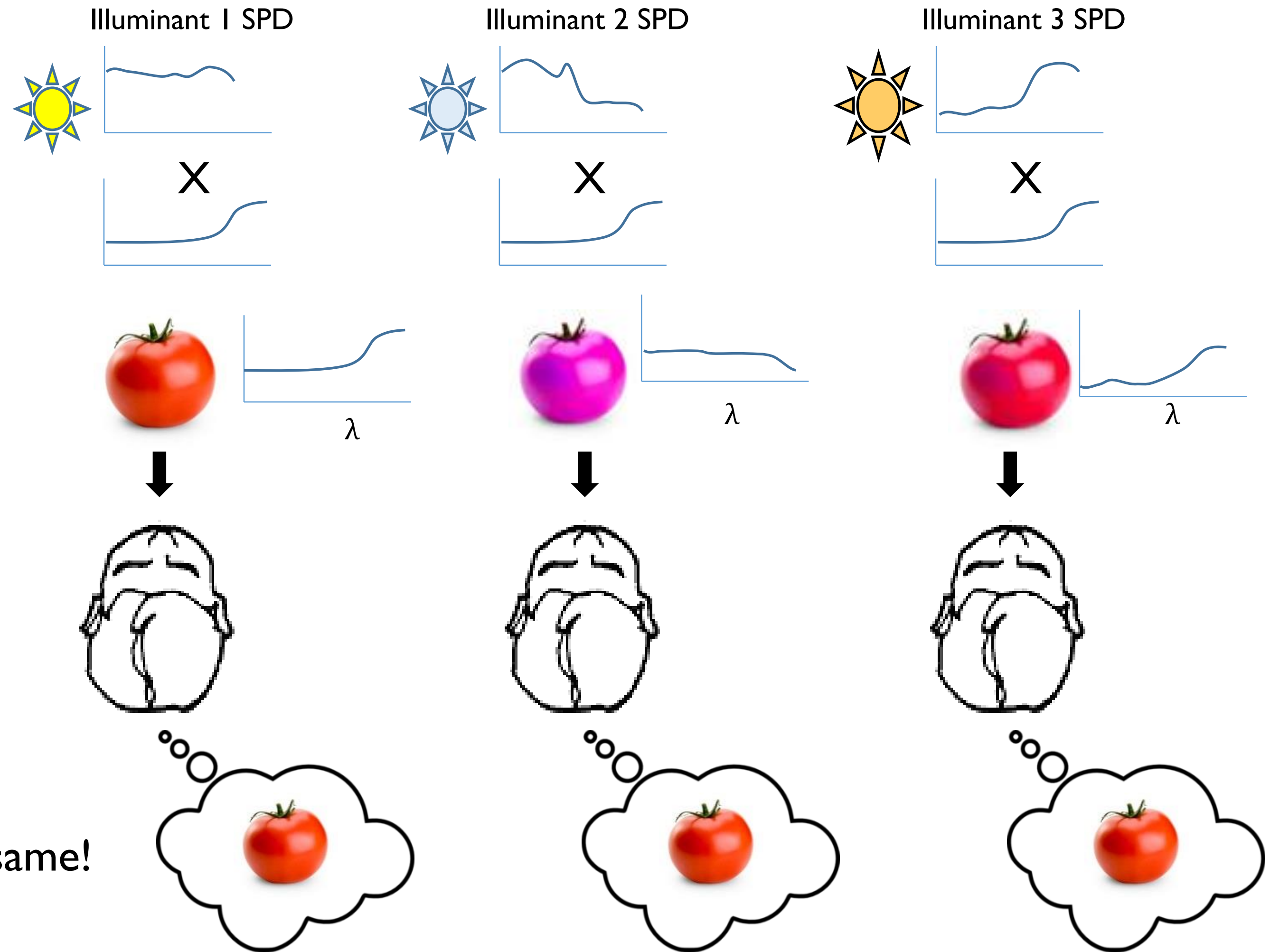
An object's SPD

- In a real scene, an object's SPD is a combination of its reflectance properties **and** scene illumination



Color constancy

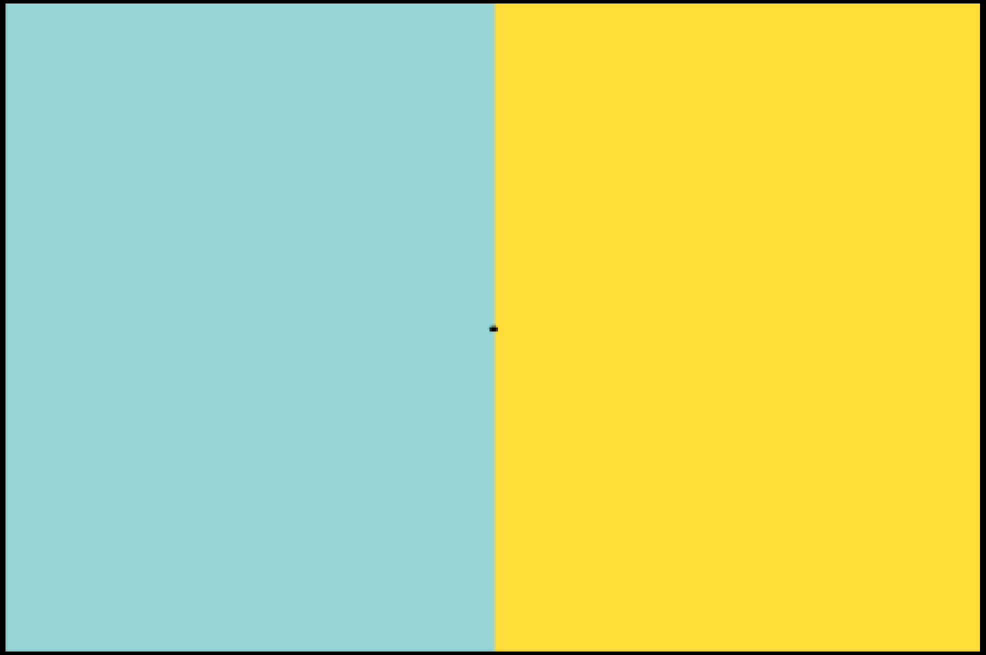
- Our visual system is able to compensate for the illumination



Looks the same!

Chromatic adaptation example

Chromatic adaptation example



Color constancy/chromatic adaptation

- Color constancy (also called *chromatic adaptation*) is the ability of the human visual system to adapt to scene illumination
- This ability is not perfect, but it works fairly well
- **Image sensors do not have this ability (it must be performed as a processing step, i.e. "white balance")**

Color constancy and illuminants

- To understand color constancy, we have to consider SPDs of different illuminants

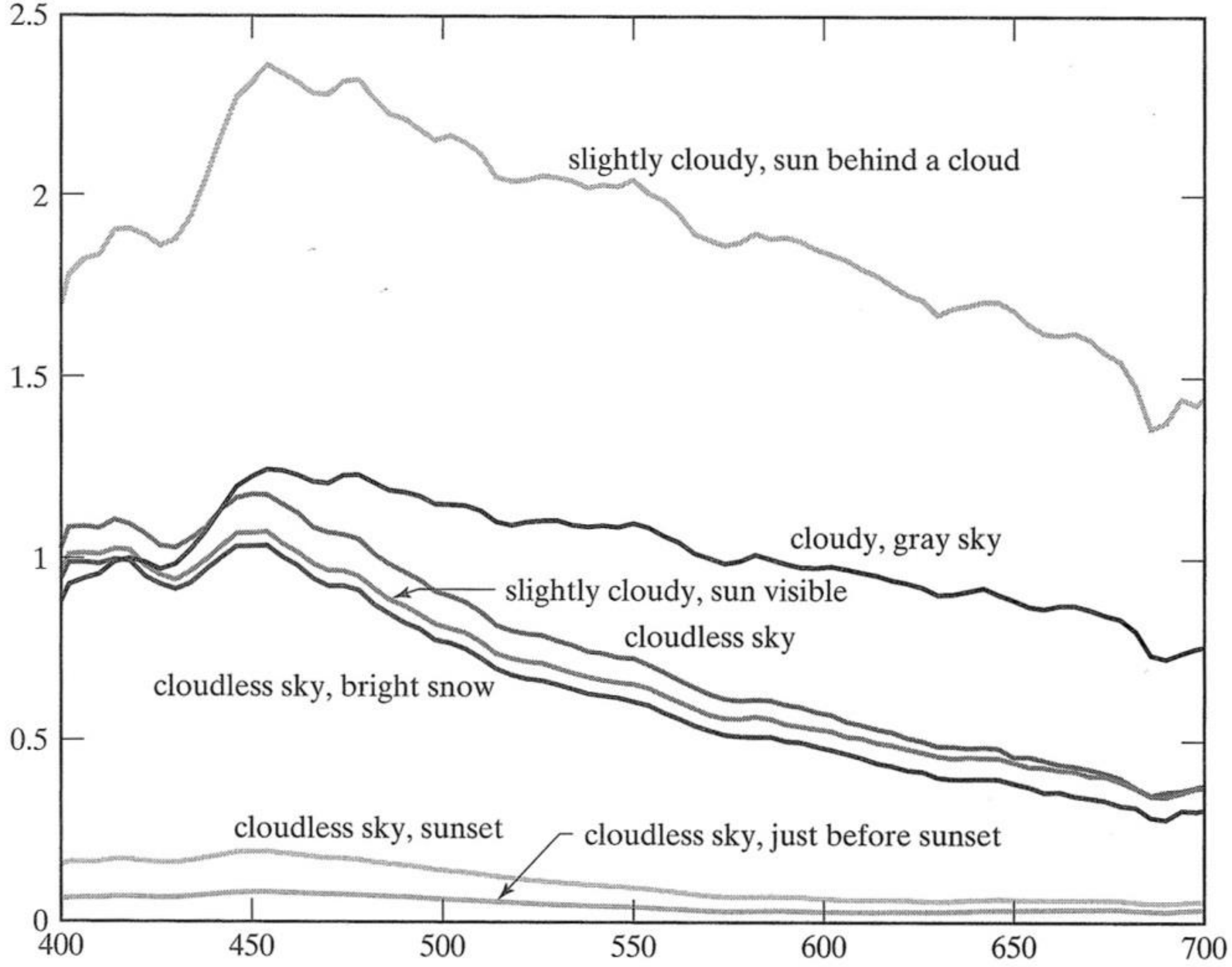
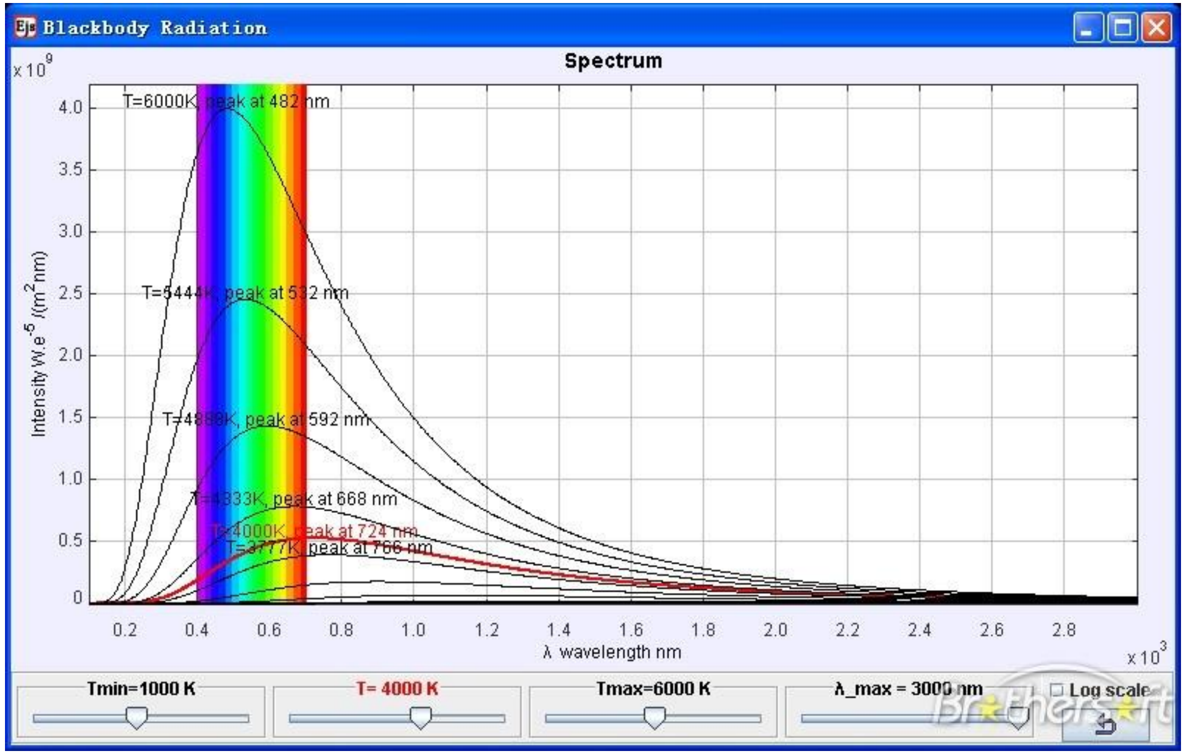


Figure from Ponce and Forsyth

Color temperature

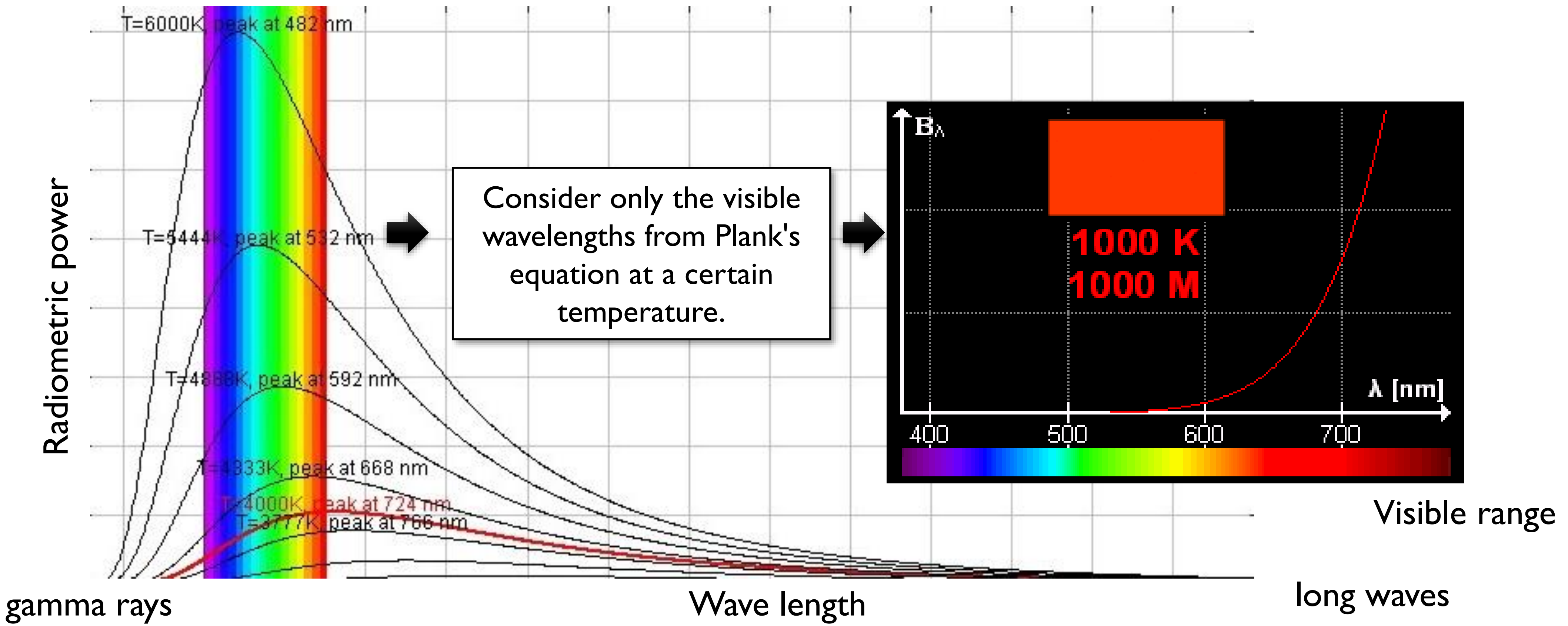
- Illuminants are often described by their "color temperature"
- This mapping is based on theoretical "blackbody radiators" that produce SPDs for a given temperature -- expressed in Kelvin (K)
- We map light sources (both real and synthetic) to their closest color temperature (esp in Photography/Video production)



$$B_\lambda(\lambda, T) = \frac{2hc^2}{\lambda^5} \frac{1}{e^{\frac{hc}{\lambda k_B T}} - 1}$$

Plank's law
Spectral density of electromagnetic radiation emitted by a blackbody radiator at a given temperature T.

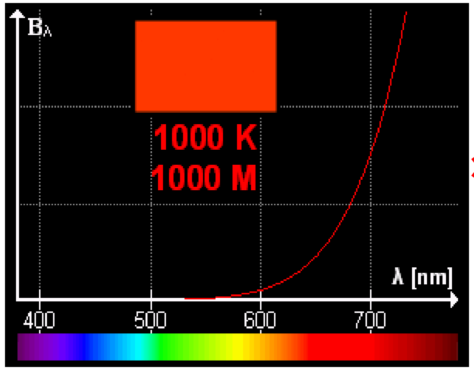
Visible range of a black body radiator

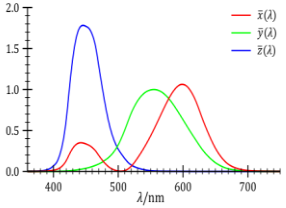


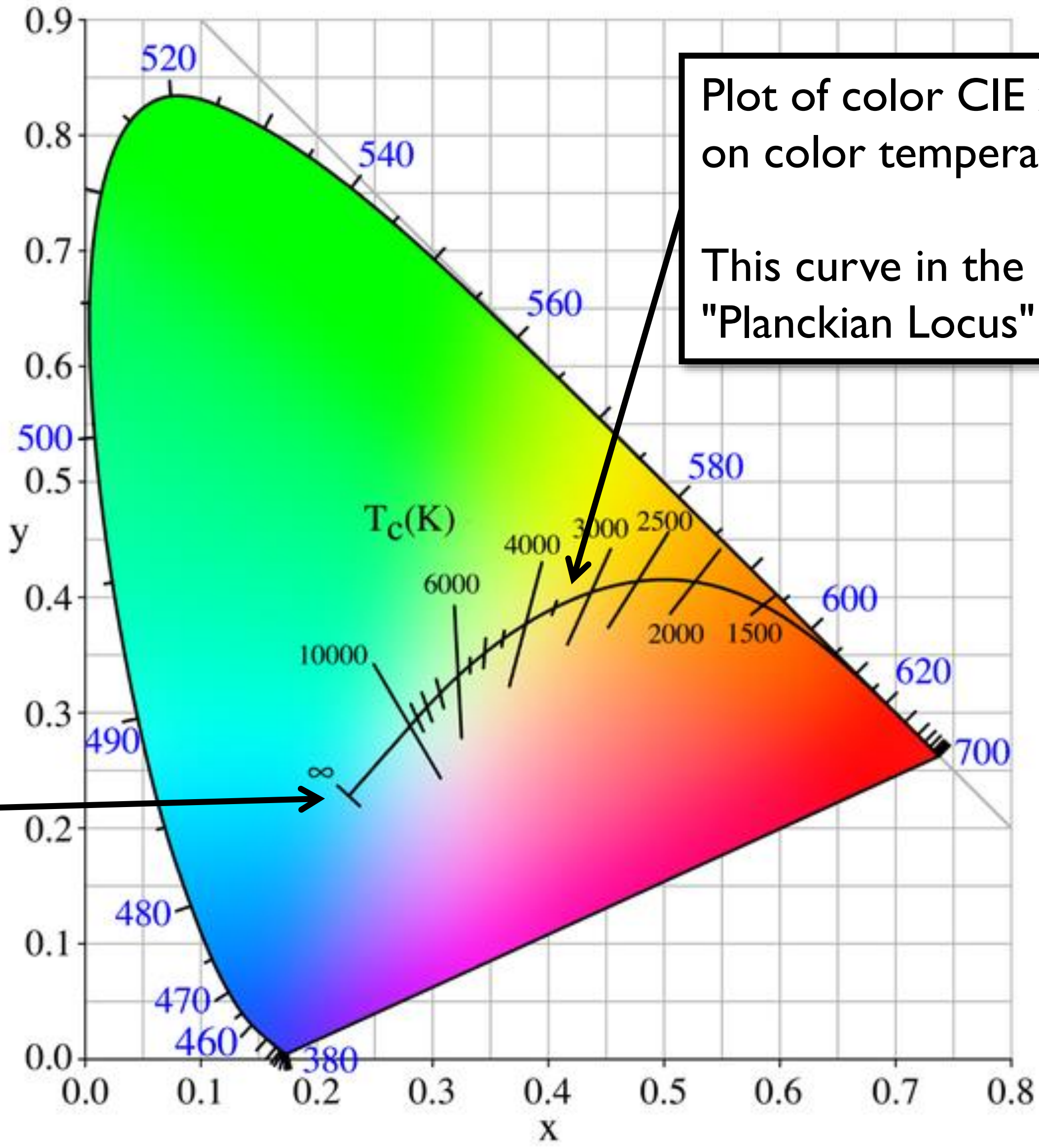
Black body radiator SPD for different color temperatures

Animation credit: Dariusz Kowalczyk

Plot visible SPDs in CIE xy chromaticity





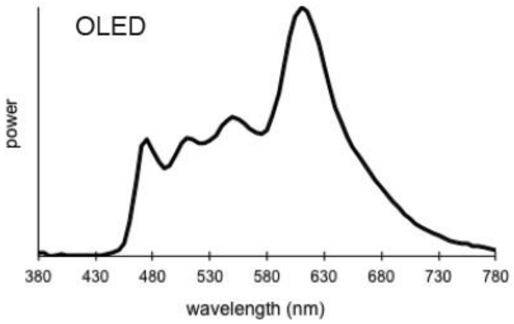


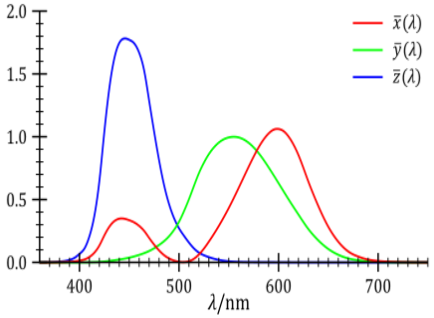
Plot of color CIE xy locations of SPDs based on color temperature.

This curve in the CIE xy plot of the "Planckian Locus" of color temperatures.

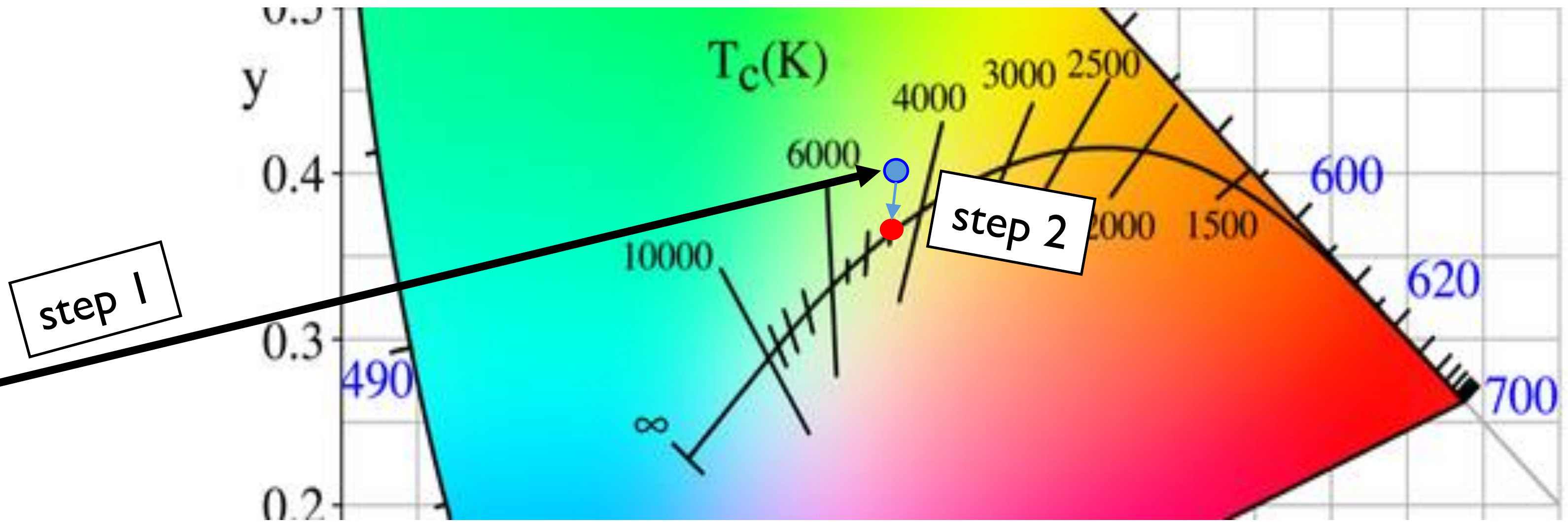
Color temperature of an SPD example

SPD of a light source



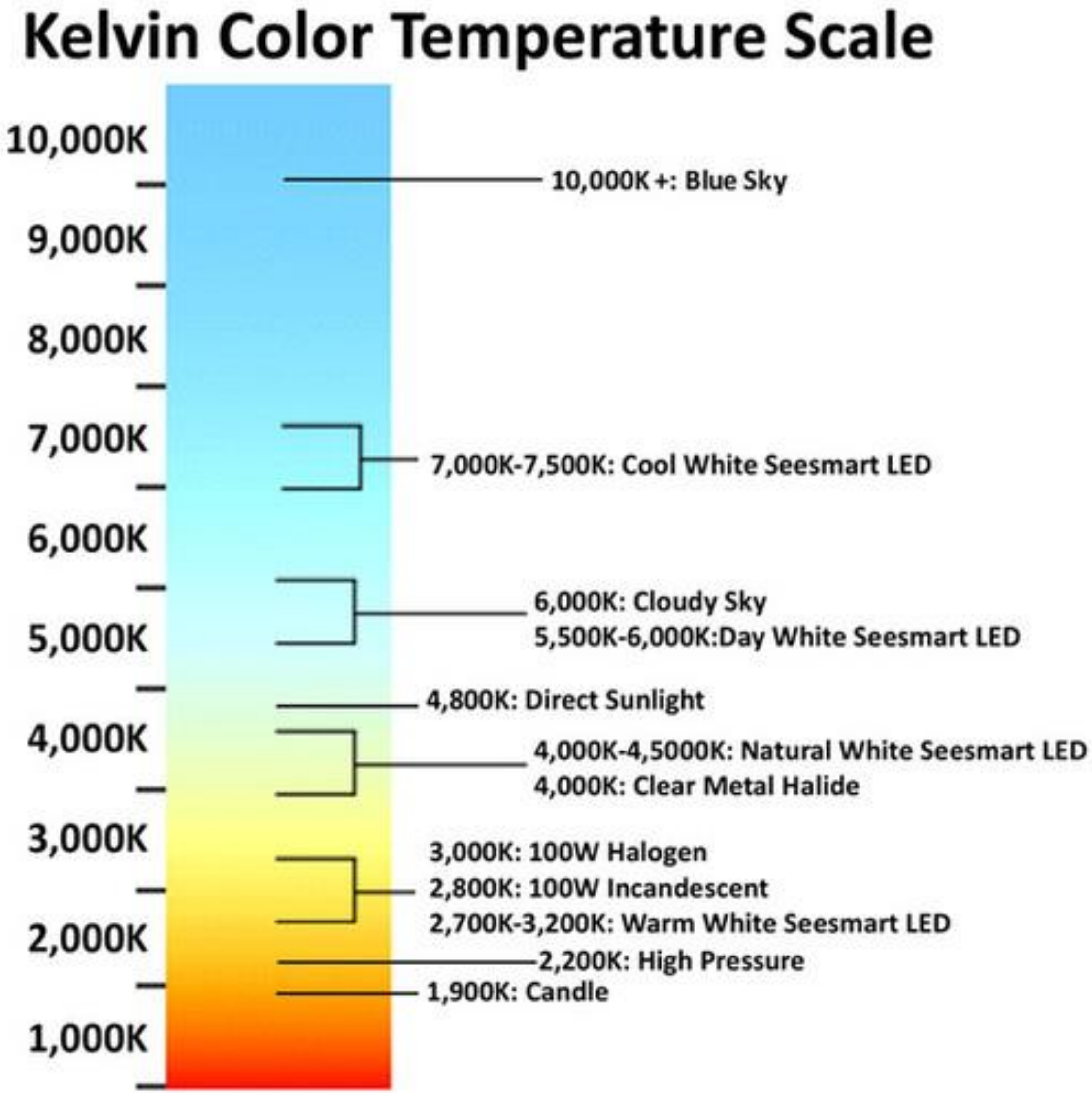


CIE 1931 mapping functions



(1) Find the light sources SPD mapping to CIE XYZ using the CIE 1931 mapping functions.
(2) Project the CIE xyY value to the Planckian locus line.

Color temperature



Typical description of color temperature used in photography & lighting sources.

From B&H Photo

Man made illuminants SPDs

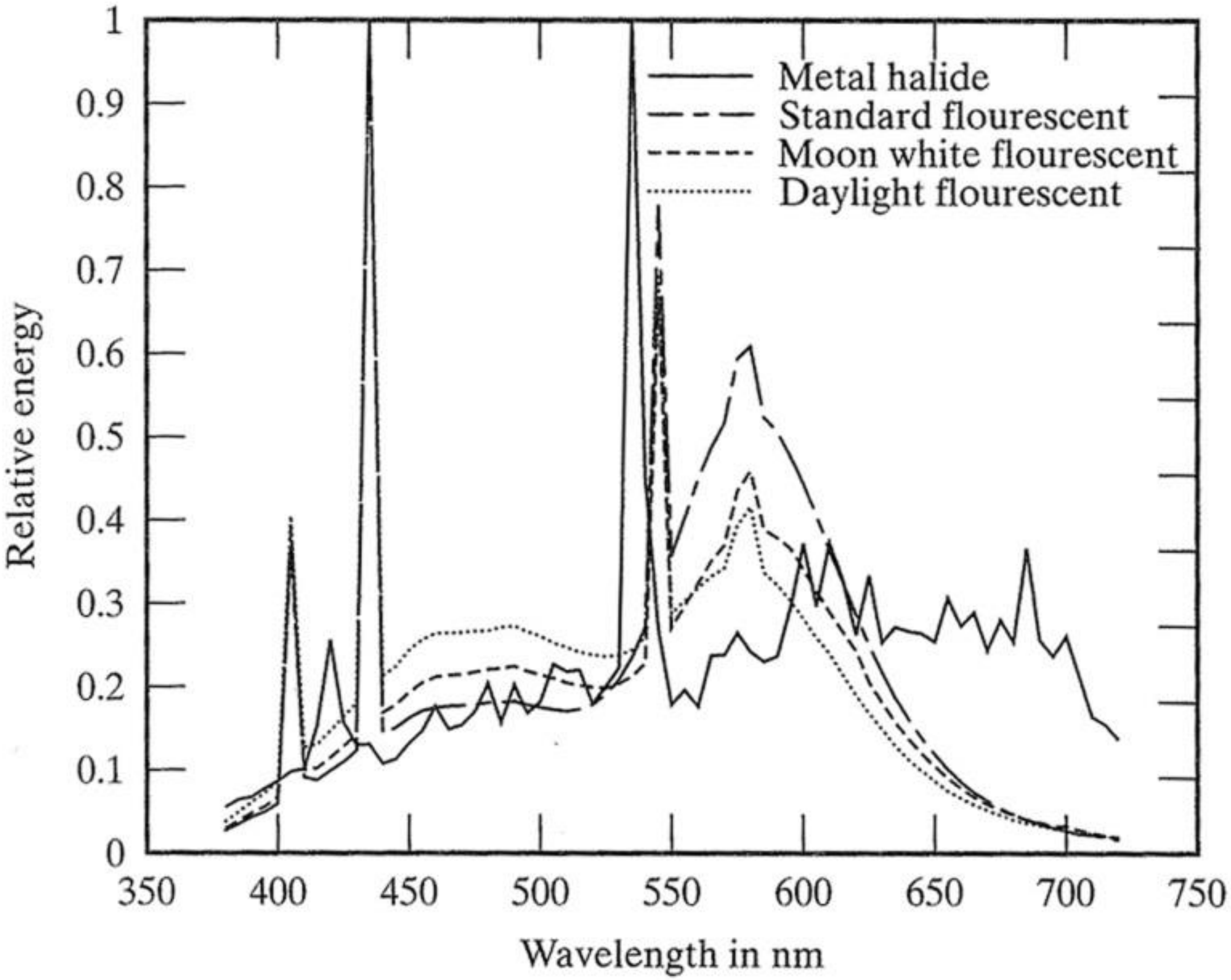


Figure from Ponce and Forsyth

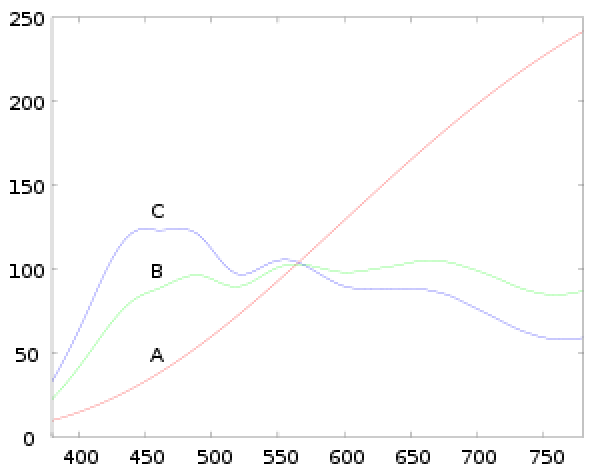
Lighting industry uses color temperature

Usage of correlated color temperature in these ads relate to the perceived color of the bulb's light. The heat output of a typical LED bulb is between 60C-100C (~333-373K).

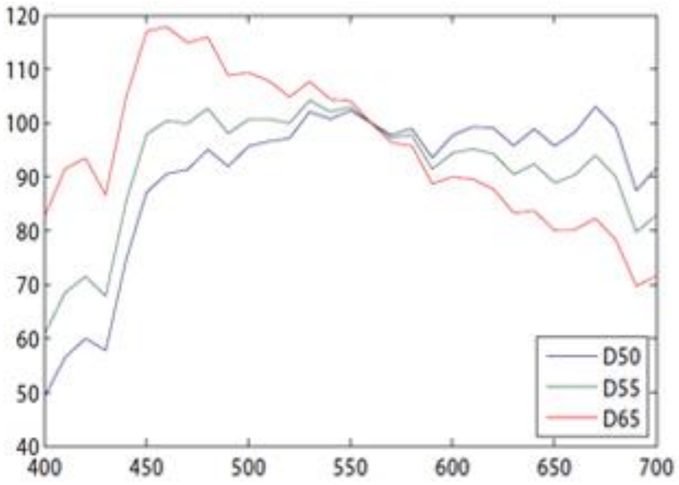
CIE standard illuminants

- CIE established several “synthetic” SPDs that serve as proxies for common real illuminants
- Illuminant A
  - tungsten-filament lighting (i.e. a standard light-bulb)
- Illuminant B
  - noon sunlight
- Illuminant C
  - average daylight
- Illuminant D series
  - represent natural daylight at various color temps (5000K, 5500K, 6500K), generally denoted as D50, D55, D65
- Illuminant E
  - idea equal-energy illuminant with constant SPD
  - does not represent any real light source, but similar to D55
- Illuminant F series
  - emulates a variety of fluorescents lamps (12 in total)

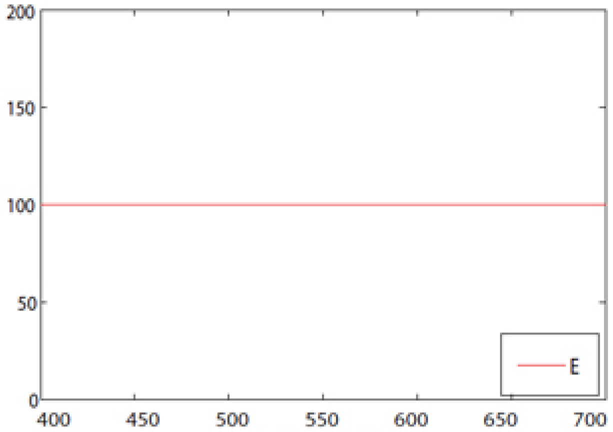
CIE standard illuminants



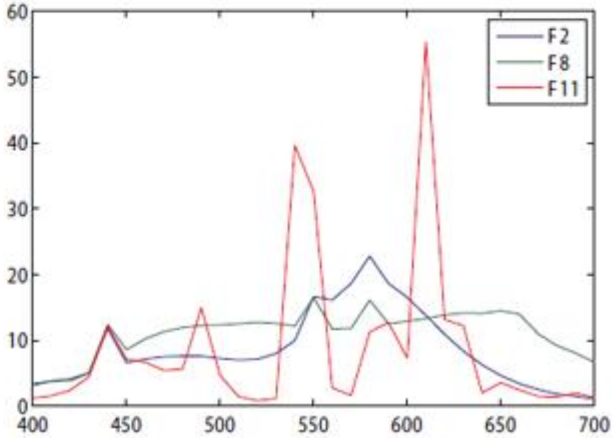
SPDs for CIE standard illuminant A, B, C



SPDs for CIE standard illuminant D50, D55, D65



SPDs for CIE standard illuminant E



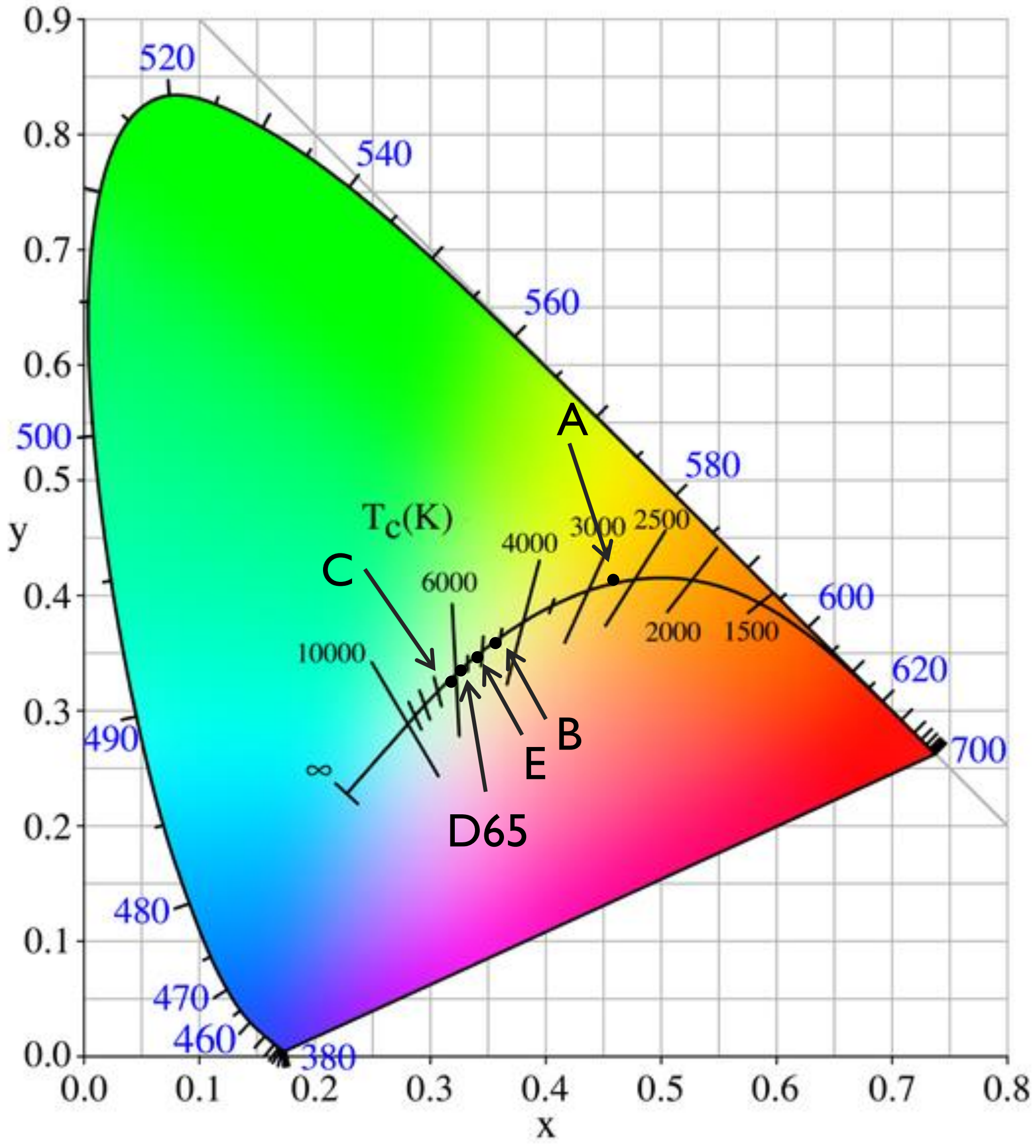
SPDs for CIE standard illuminants F2, F8, F11

D, E, and F series images from http://www.image-engineering.de

White point

- A white point is a CIE XYZ or CIE xyY value of an ideal "white target" or "white reference"
- This is essentially an illuminants SPD in terms of CIE XYZ/CIE xyY
  - We can assume the white reference is reflecting the illuminant
- The idea of chromatic adaptation is to make white points the same between scenes

White points in CIE xy chromaticity



CIE Illuminants

A, B, C, D65, E in terms of CIE xy

CIE	**x**	**,**	**y**
A	0.44757	,	0.40745
B	0.34842	,	0.35161
C	0.31006	,	0.31616
D65	0.31271	,	0.32902
E	0.33333	,	0.33333

Color constancy (at its simplest)

Johannes von Kries

- (Johannes) *Von Kries* transform
- Compensate for each channel corresponding to the L, M, S cone response

$$\begin{bmatrix} L_2 \\ M_2 \\ S_2 \end{bmatrix} = \begin{bmatrix} 1/L_{1w} & 0 & 0 \\ 0 & 1/M_{1w} & 0 \\ 0 & 0 & 1/S_{1w} \end{bmatrix} \begin{bmatrix} L_1 \\ M_1 \\ S_1 \end{bmatrix}$$

L_2, M_2, S_2 is the new LMS response with the illuminant divided "out". In this case white is equal to [1,1,1]

L_{1w}, M_{1w}, S_{1w} is the LMS response to "white" under this illuminant

L_1, M_1, S_1 are the input LMS space under an illuminant.

Illuminant to illuminant mapping

- More appropriate would be to map to another illuminant's LMS response (e.g. in the desired viewing condition)
- $(LMS)_1$ under an illuminant with white-response (L_{1w}, M_{1w}, S_{1w})
- $(LMS)_2$ under an illuminant with white-response (L_{2w}, M_{2w}, S_{2w})

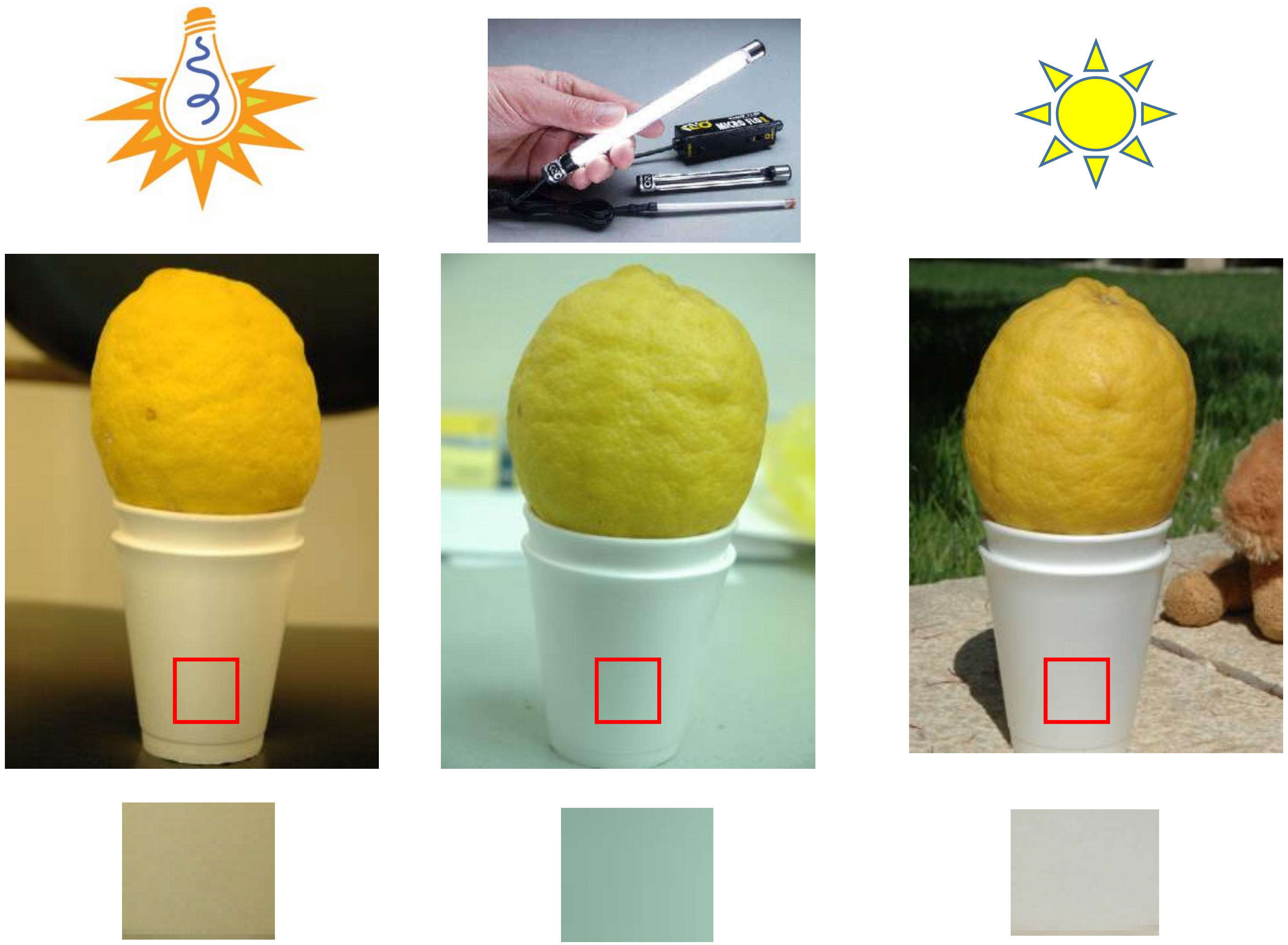
$$\begin{bmatrix} L_2 \\ M_2 \\ S_2 \end{bmatrix} = \begin{bmatrix} L_{2w}/L_{1w} & 0 & 0 \\ 0 & M_{2w}/M_{1w} & 0 \\ 0 & 0 & S_{2w}/S_{1w} \end{bmatrix} \begin{bmatrix} L_1 \\ M_1 \\ S_1 \end{bmatrix}$$

L_2, M_2, S_2 is the new LMS response with the illuminant divided "out" and scaled to LMS_2 illuminant

L_{1w}, M_{1w}, S_{1w} is the LMS response to "white" the input illuminant, L_{2w}, M_{2w}, S_{2w} response to "white" of output illuminant

L_1, M_1, S_1 are the input LMS space under an illuminant.

Example

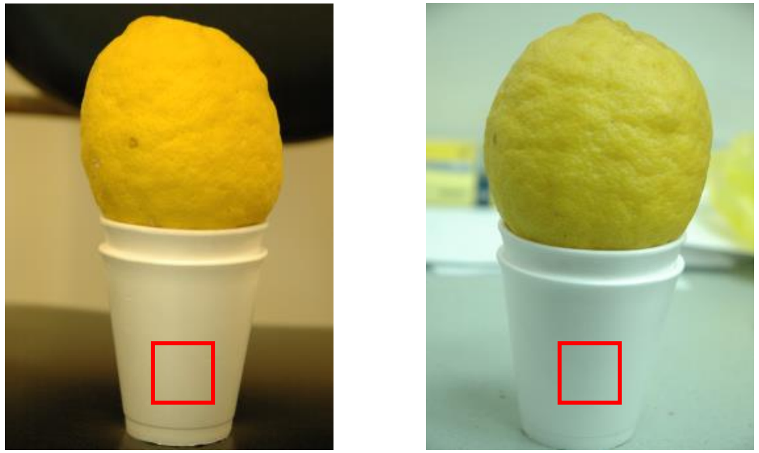


Simulation of different "white points" by photographing a "white" object under different illumination.

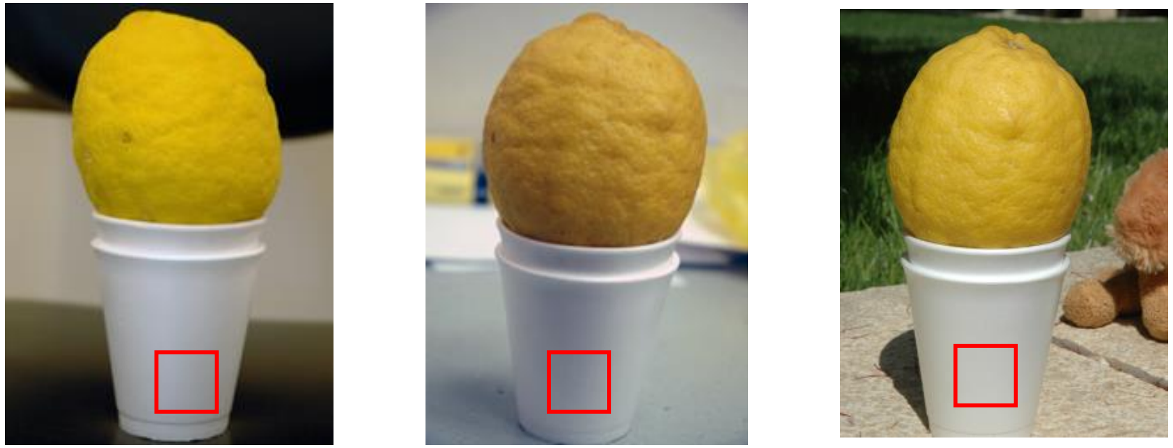
Images courtesy of Sharon Albert (Weizmann Institute)

Example

Input



Adapted to
“target”
illuminant

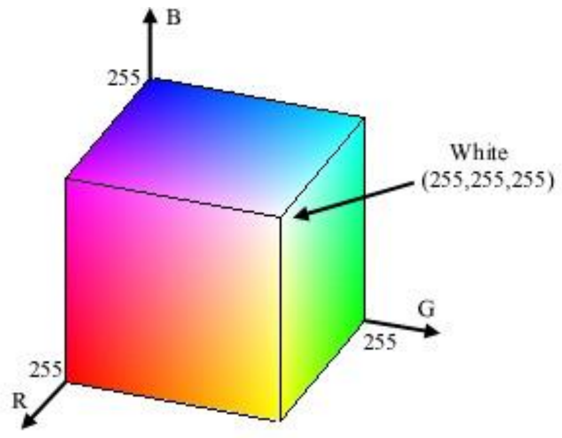


Before After Before After Target Illumination

Now we are finally done with color?

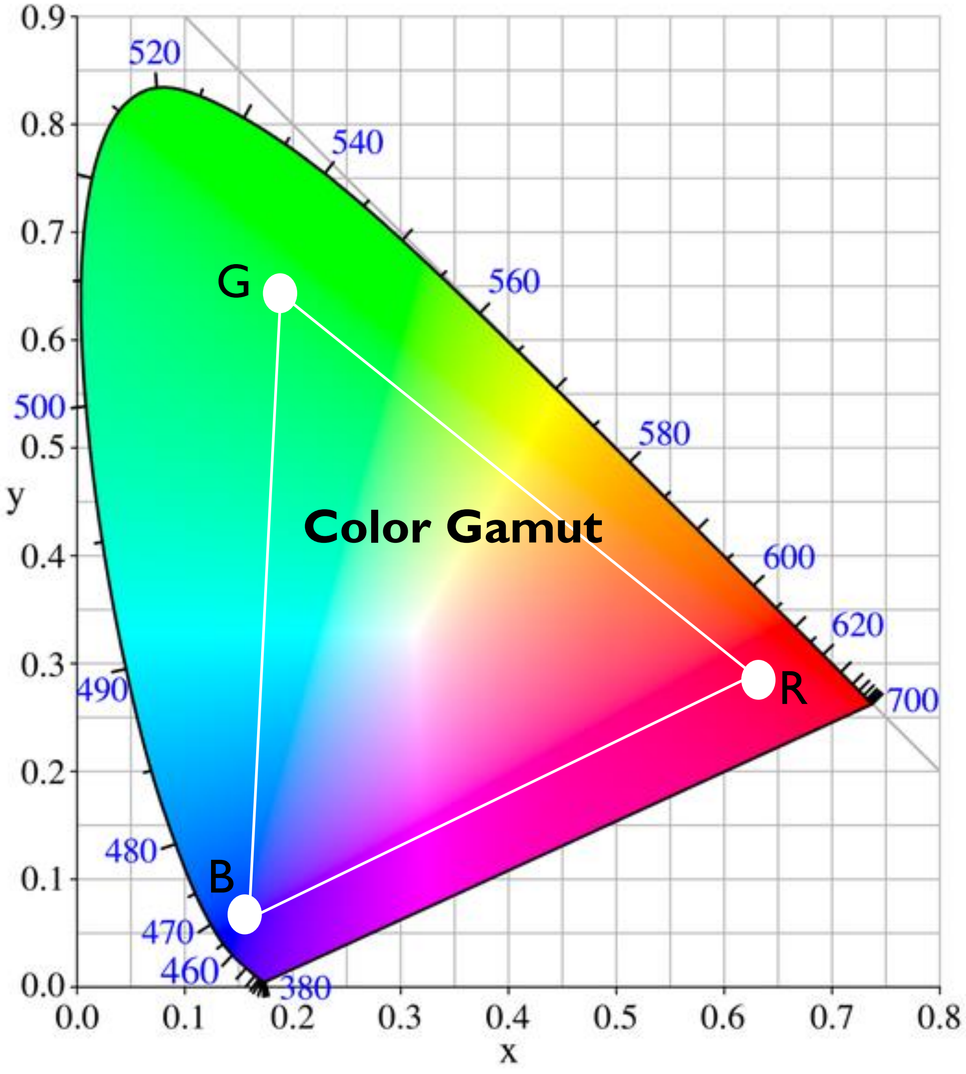
CIE XYZ and RGB

- While CIE XYZ is a canonical color space, images/devices rarely work directly with XYZ
- XYZ are not real primaries
- RGB primaries dominate the industry
- We are all familiar with the RGB color cube



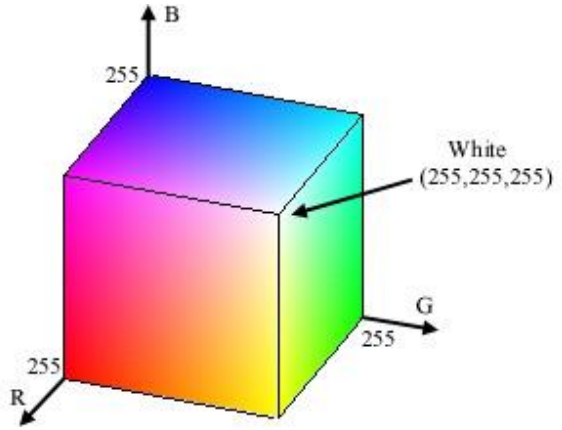
But by now, you should realize that Red, Green, Blue have no quantitative meaning. We need to know their corresponding SPDs or CIE XYZ values

Device specific RGB values

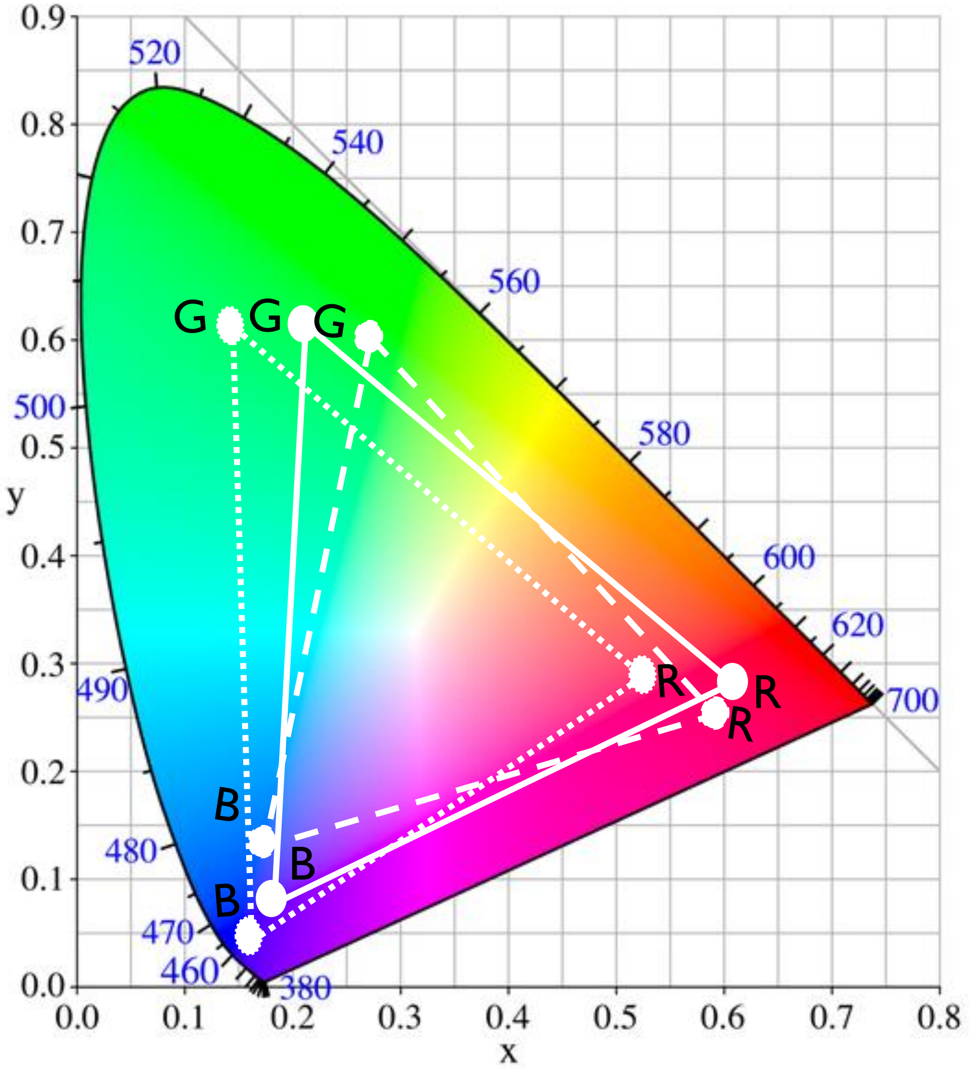


The RGB values span a subspace of CIE-XYZ to define the devices gamut.

If you have RGB values, they are specific to a particular device .



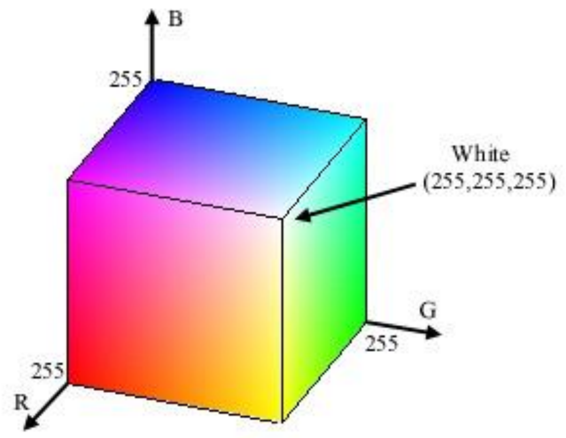
Trouble with RGB



Device 1 ——

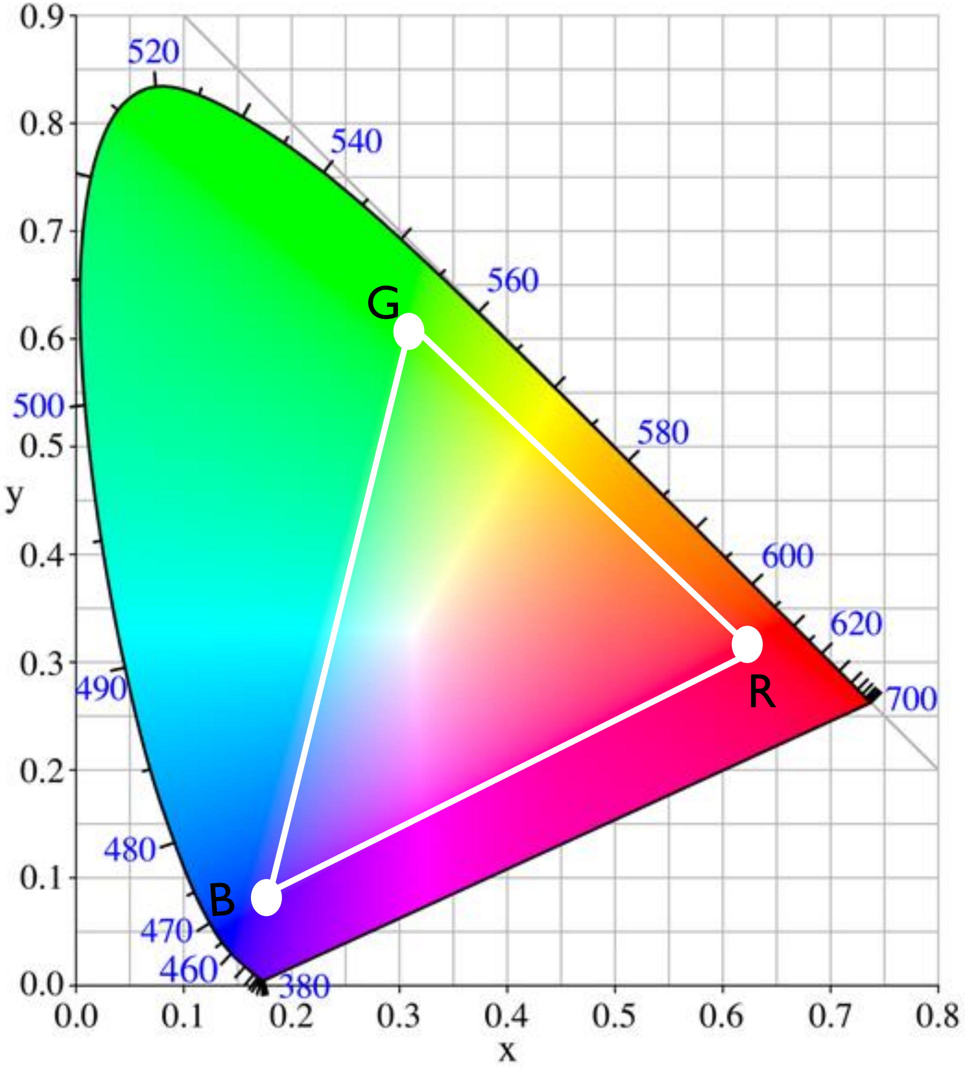
Device 2 ··········

Device 3 - - - -



RGB values have no meaning
if the primaries between devices
are not the same! This is a
huge problem for color reproduction
from one device to the next.

Standard RGB (sRGB) – Rec.709



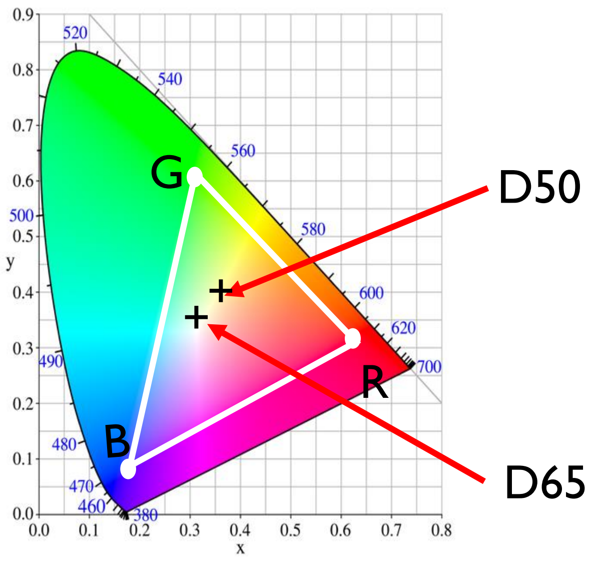
In 1996, Microsoft and HP defined a set of "standard" RGB primaries.
R=CIE xyY (0.64, 0.33, 0.2126)
G=CIE xyY (0.30, 0.60, 0.7153)
B=CIE xyY (0.15, 0.06, 0.0721)

This was considered an RGB space achievable by most devices at the time.

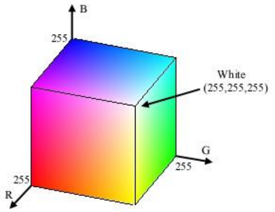
White point was set to the D65 illuminant**. This is an important thing to note.** It means sRGB has built in the assumed viewing condition (6500K daylight).

sRGB's white point

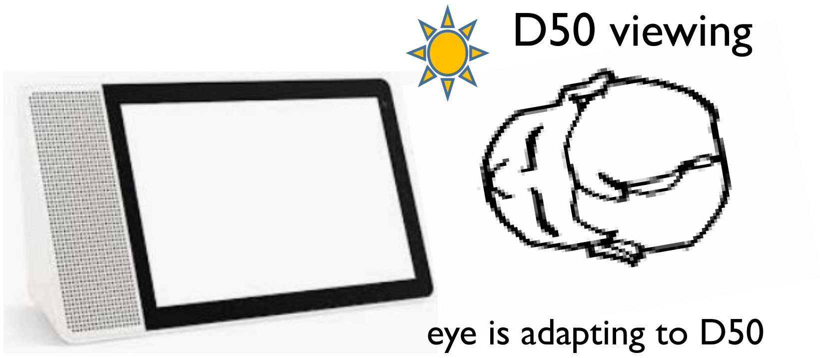
- When we map from CIE XYZ to a color space, we need to specify the white point, --i.e., what is the CIE XYZ of "white" where we will view our image.
- This is to match the assumed viewing condition of my device
  - While in my sRGB color space, the white-point is r=g=b, it was transform from CIE XYZ at a particular white-point



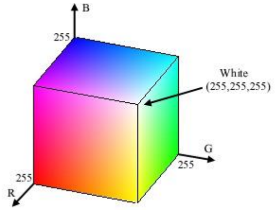
CIE XYZ



sRGB (D50 whitepoint)



eye is adapting to D50 environment light.



sRGB (D65 whitepoint)

eye is adapting to D65 environment light.

The positions of the white-point locations are exaggerated here.

CIE XYZ to sRGB conversion

Matrix conversion:

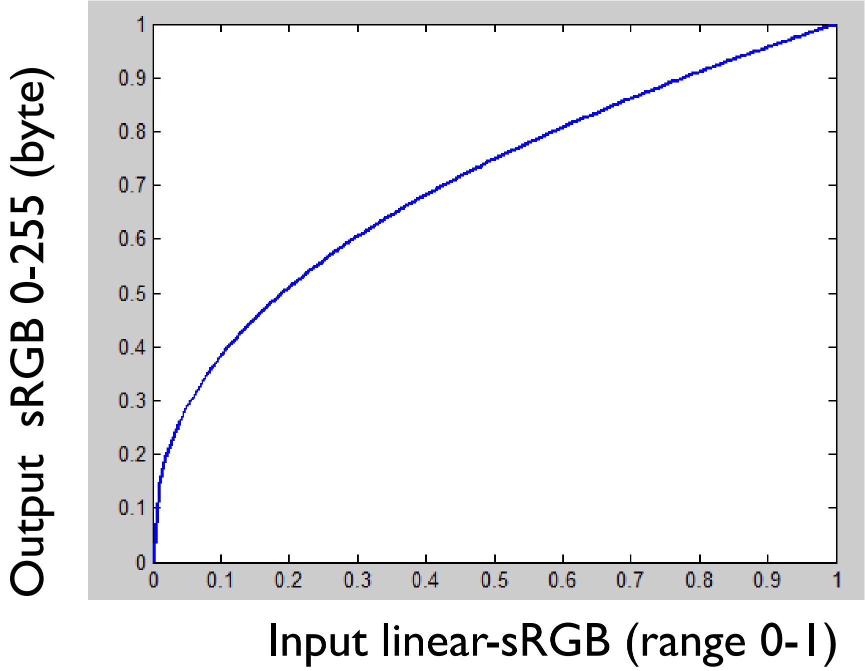
$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} 3.2404542 & -1.5371385 & 0.4985314 \\ -0.9692660 & 1.8760108 & 0.0415560 \\ 0.0556434 & -0.2040259 & 1.0572252 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}$$

Linearized sRGB (D65)

CIE XYZ

- D65 is taken as the white-point
- This is the linear-sRGB space
- sRGB also specifies a gamma correction of the values
- The CIE refers this as the Recommendation 709 color space – or Rec.709

sRGB gamma curve



This is a close approximation of the actual sRGB gamma

Actual formula is a bit complicated, but effectively this is gamma ($I' = 255*I^{(1/2.2)}$), where I' is the output intensity and I is the linear sRGB ranged 0-1, with a small linear transfer for linearized sRGB values close to 0 (not shown in this plot).

Stevens' power law

- Physical stimulus vs. perceptual sensation
- Stevens' Power Law

$$S = kI^{a}$$

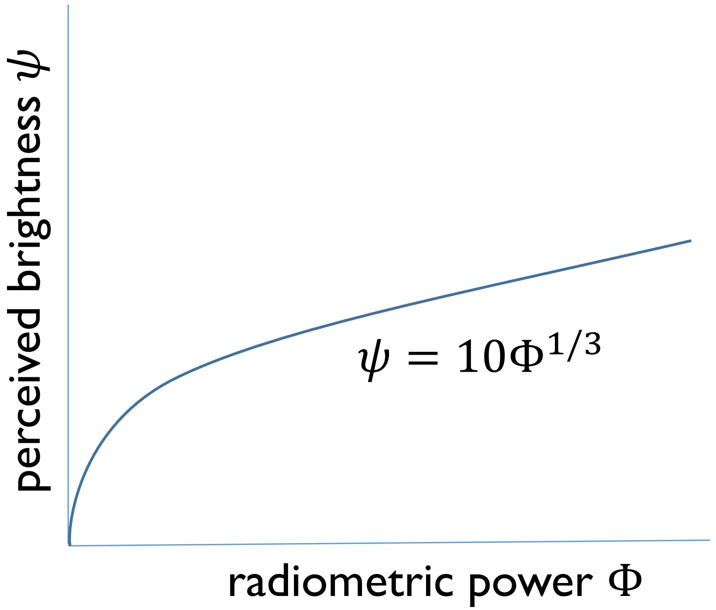
Human sensation

Constant

Stimulus intensity

power exponent

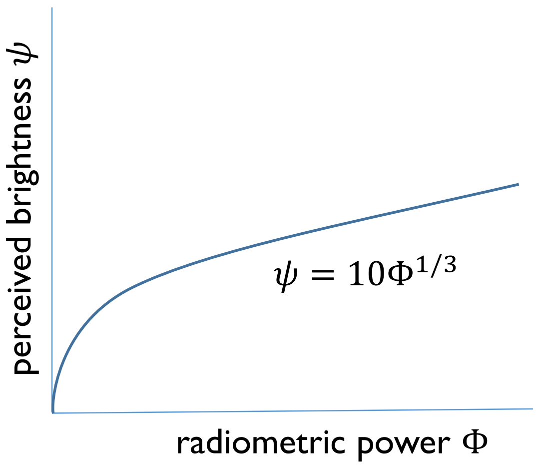
Dr. Stanley Stevens showed that most human sensations follow a power-law relationship between stimuli and sensation.

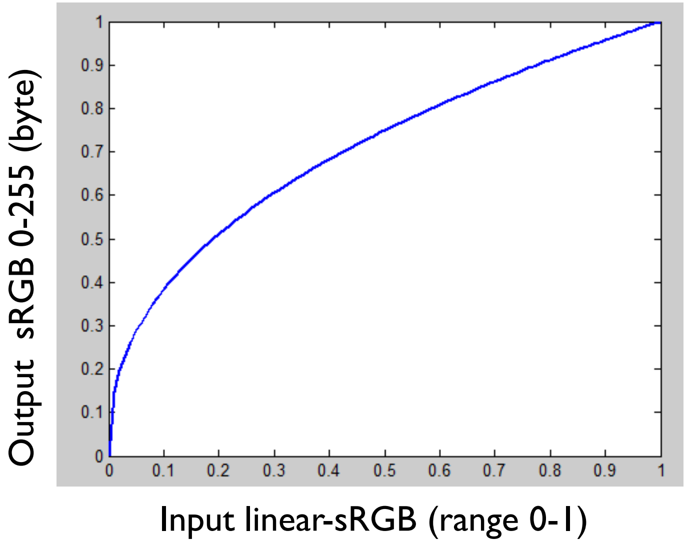


Stevens' model stated that human perception to brightness followed a cube-root power-law.

sRGB gamma

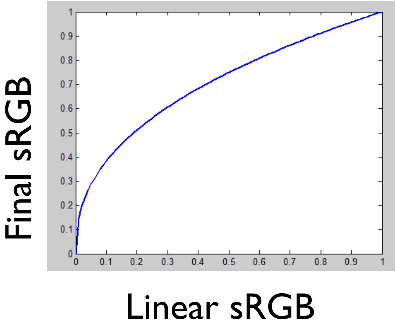
- The sRGB gamma encoding is related to the Steven's power-law
- The sRGB gamma is approximately a √3 power-law





Before (linear sRGB) & after (sRGB)

Linear sRGB

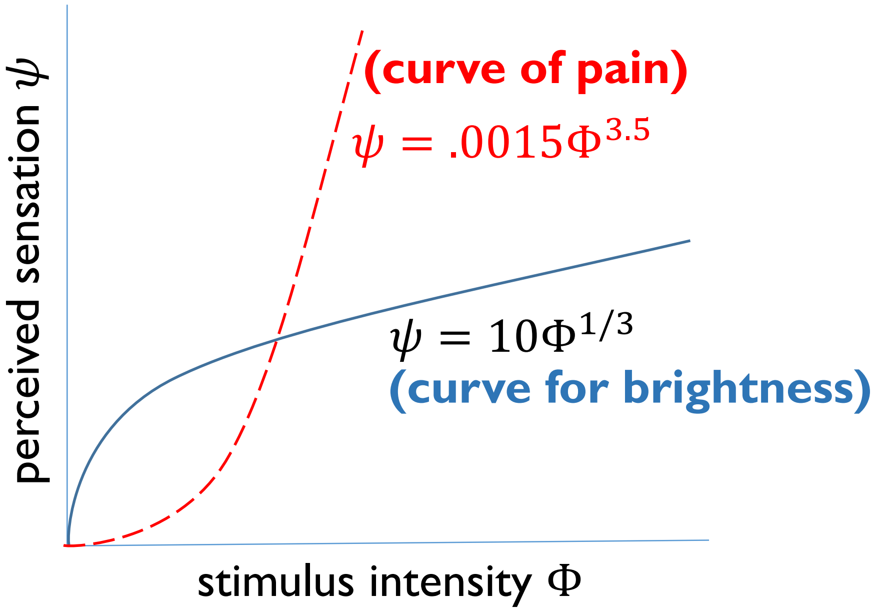


Final sRGB

An additional fun fact

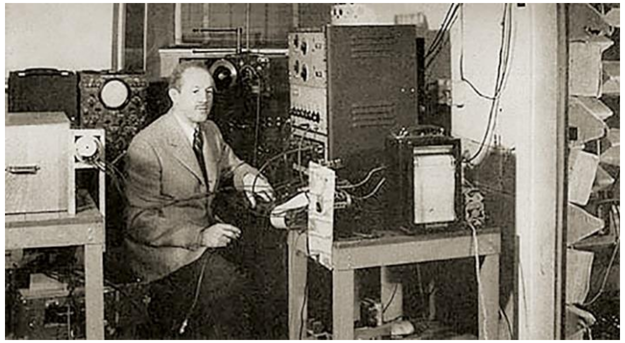
- Physical stimulus vs. **human** sensations
- Stevens' Power Law

$$\underbrace{S}_{\text{Human sensation}} = \underbrace{k}_{\text{Constant}}\,\underbrace{I}_{\text{Stimulus intensity}}^{\overbrace{a}^{\text{power exponent}}}$$

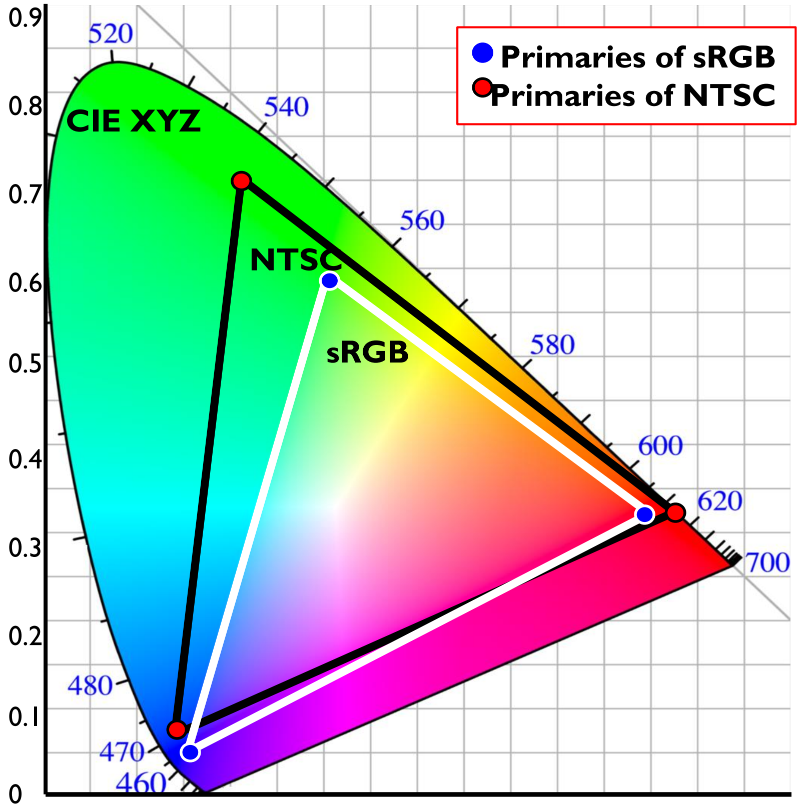


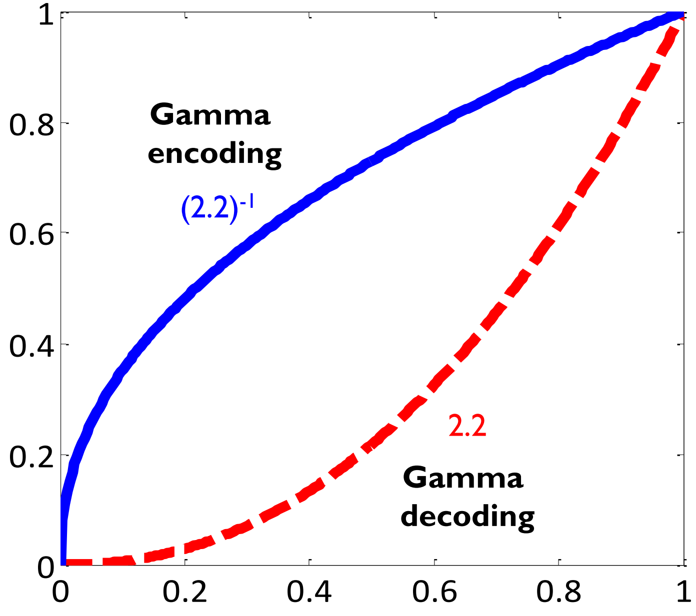
Dr. Stanley Stevens introduced showed that most human sensations follow a power-law relationship between stimuli and sensation.

Stevens also did experiment on the **pain sensation** of electrical shock! Turns out our sensitivity is the opposite than with radiometric power to brightness.



Standardization is not new - NTSC/PAL





Both NTSC and sRGB used gamma encodings.

CIE XYZ $\leftrightarrow$ NTSC/sRGB
(know your color space!)

It is important to known which color space your image is in.

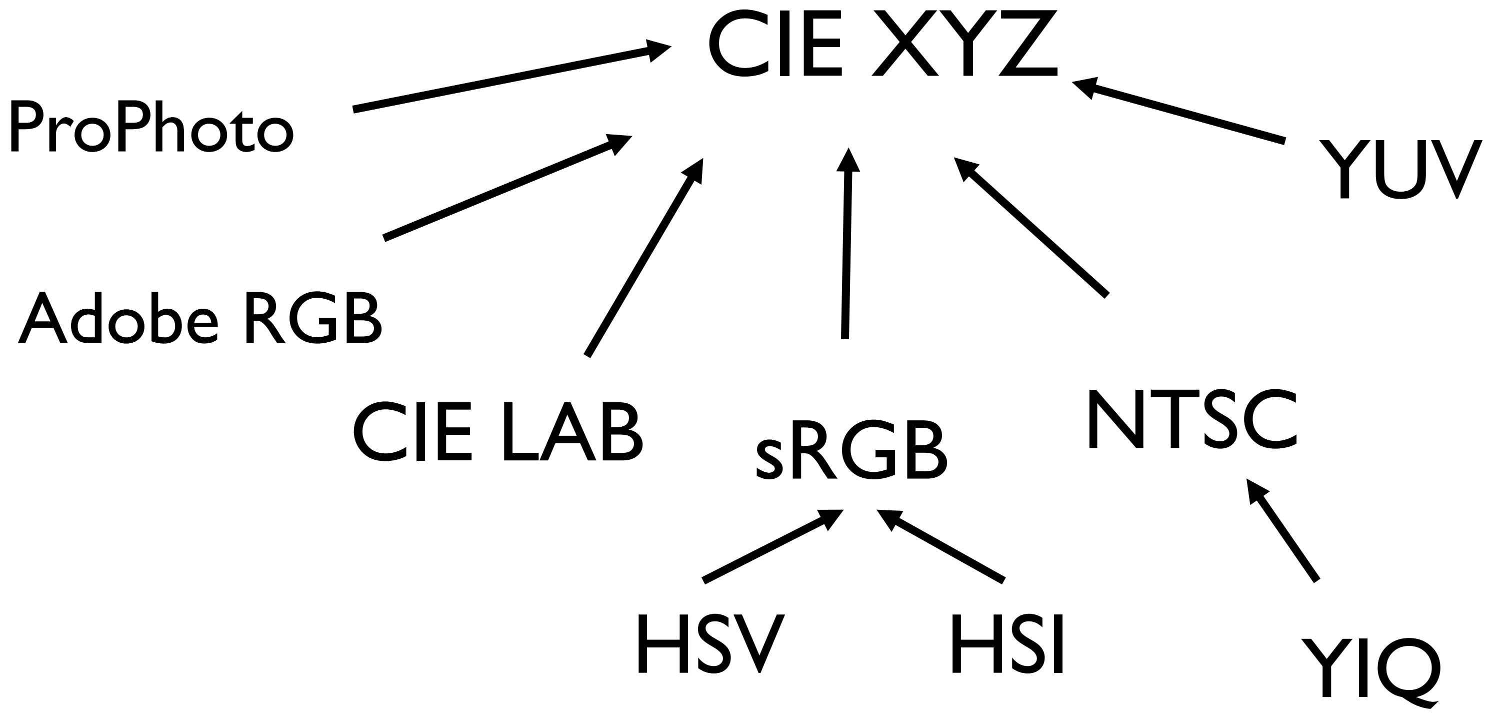
Linear-sRGB back to XYZ

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} 0.4124 & 0.3576 & 0.1805 \\ 0.2126 & 0.7152 & 0.0722 \\ 0.0193 & 0.1192 & 0.9505 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

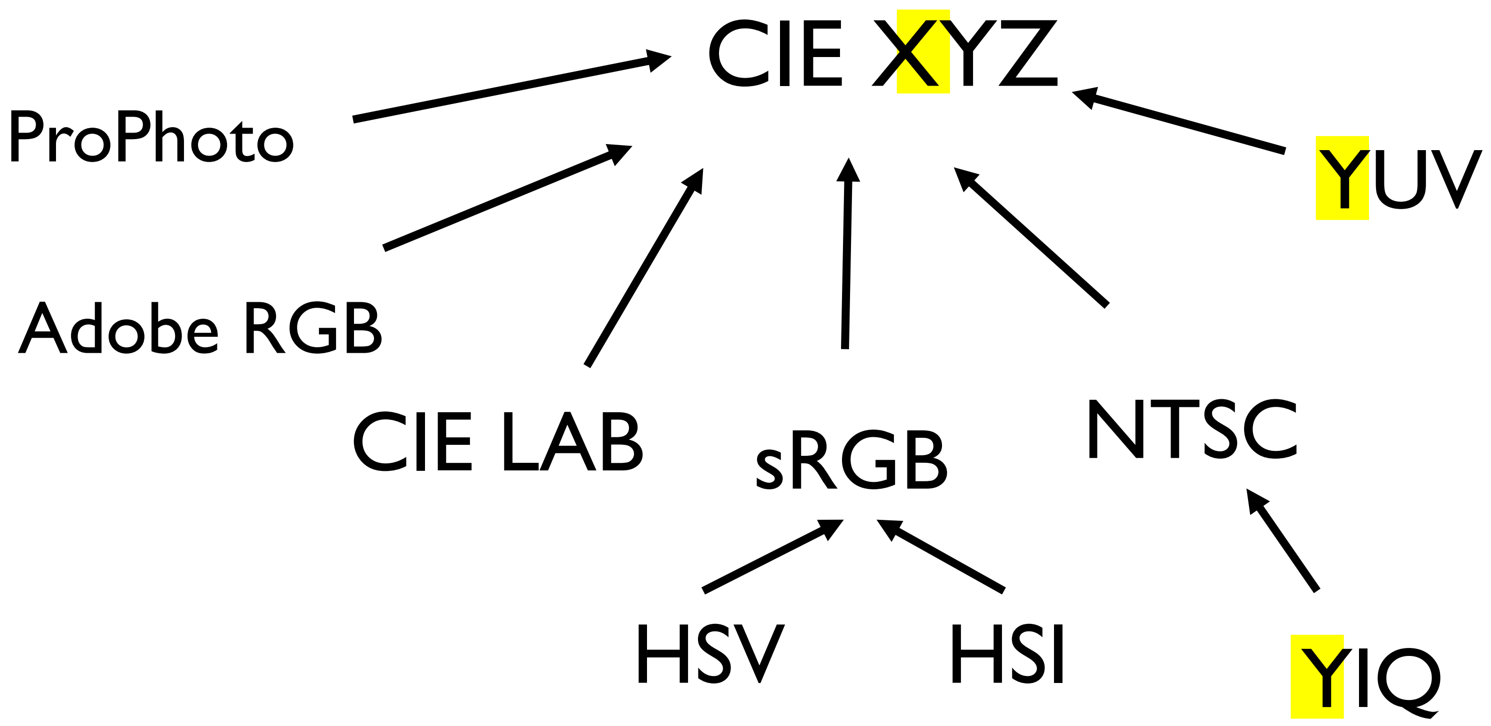
Linear-NTSC back to XYZ

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} 0.6071 & 0.1736 & 0.1995 \\ 0.2990 & 0.5870 & 0.1140 \\ 0.0000 & 0.0661 & 1.1115 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

CIE XYZ: The mother of color spaces
grand



CIE XYZ: The mother of color spaces
grand



Be careful, not all Y's are the same!

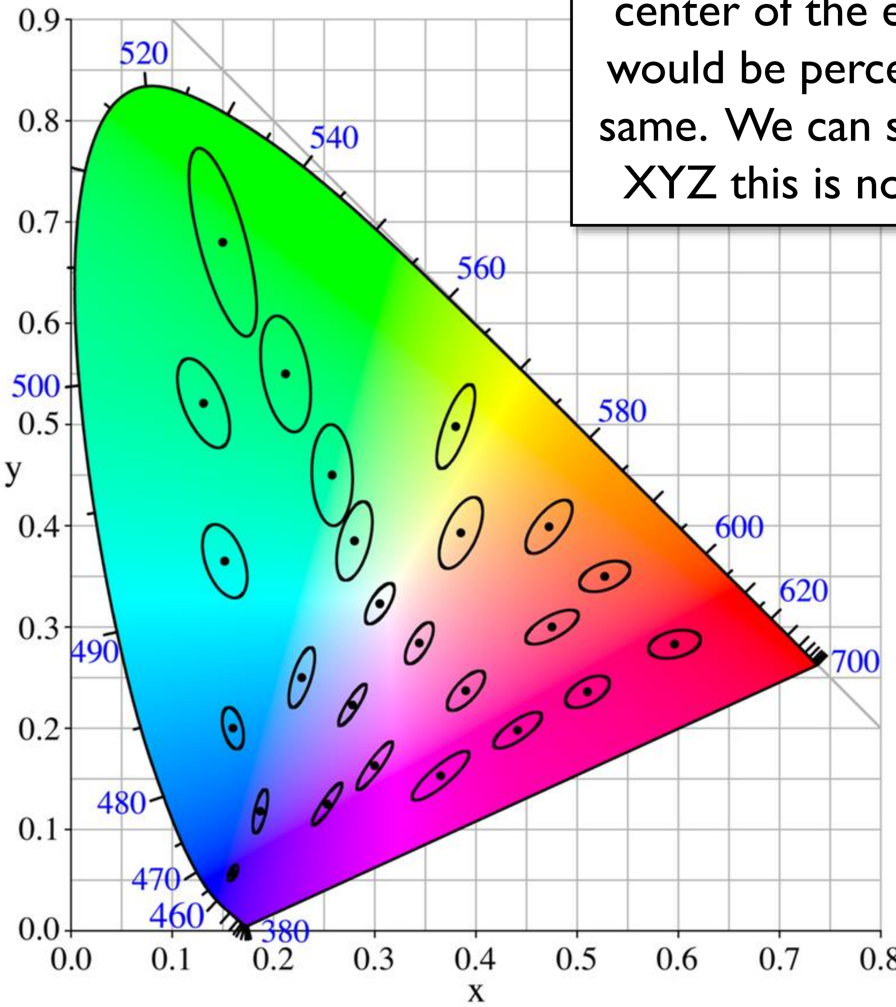
Other common color spaces

This tutorial does not go into the details of the mathematical transformations to other color spaces (we'd need another tutorial for that). You can find the transforms online.

The goal here is to explain the rationale behind each transform so you understand why the other color spaces are introduced.

CIE LAB space

- CIE LAB space (also written as CIE $L^*a^*b^*$) was introduced as a perceptually uniform color space
- **Why?**
    - CIE XYZ provides a means to map between a physical SPD (radiometric measurement) to a colorimetric measurement (perceptual)
    - However, a uniform change in CIE XYZ space does result in an uniform change in perceived color difference (see diagram)
- CIE Lab transforms CIE to a new space where color (and brightness) differences are more uniform.



The ellipses shows the range of colors (around the center of the ellipse) that would be perceived as the same. We can see that CIE XYZ this is not uniform.

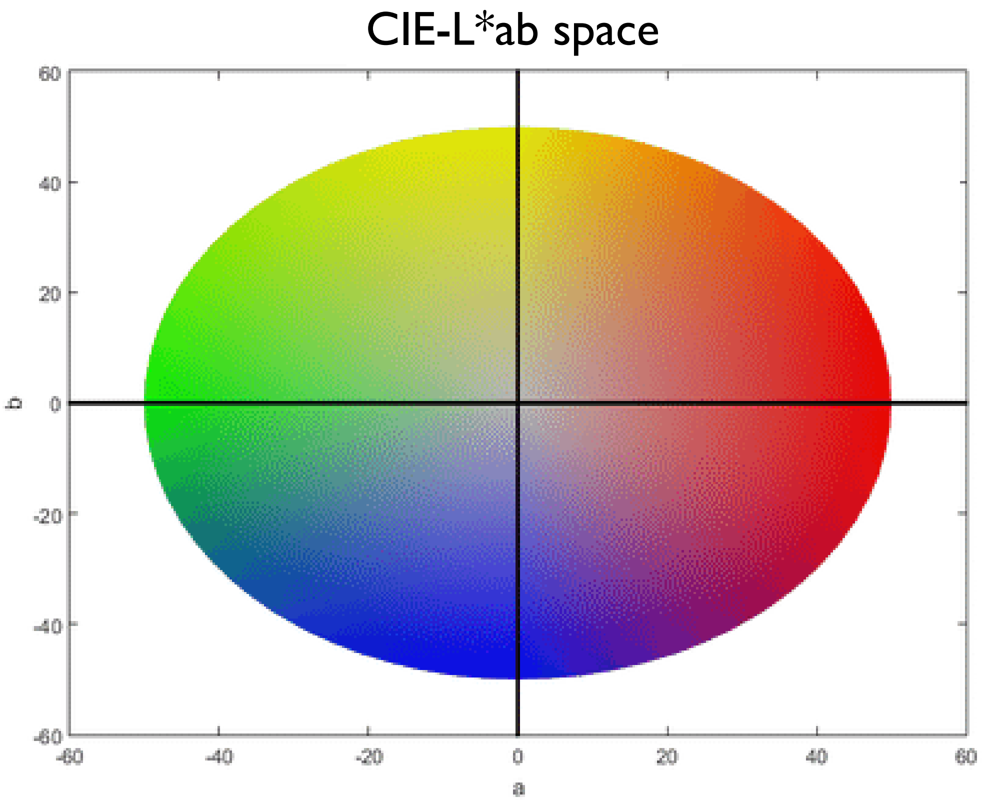
David MacAdam performed experiments into color perception. This plot is known as the MacAdam ellipses.

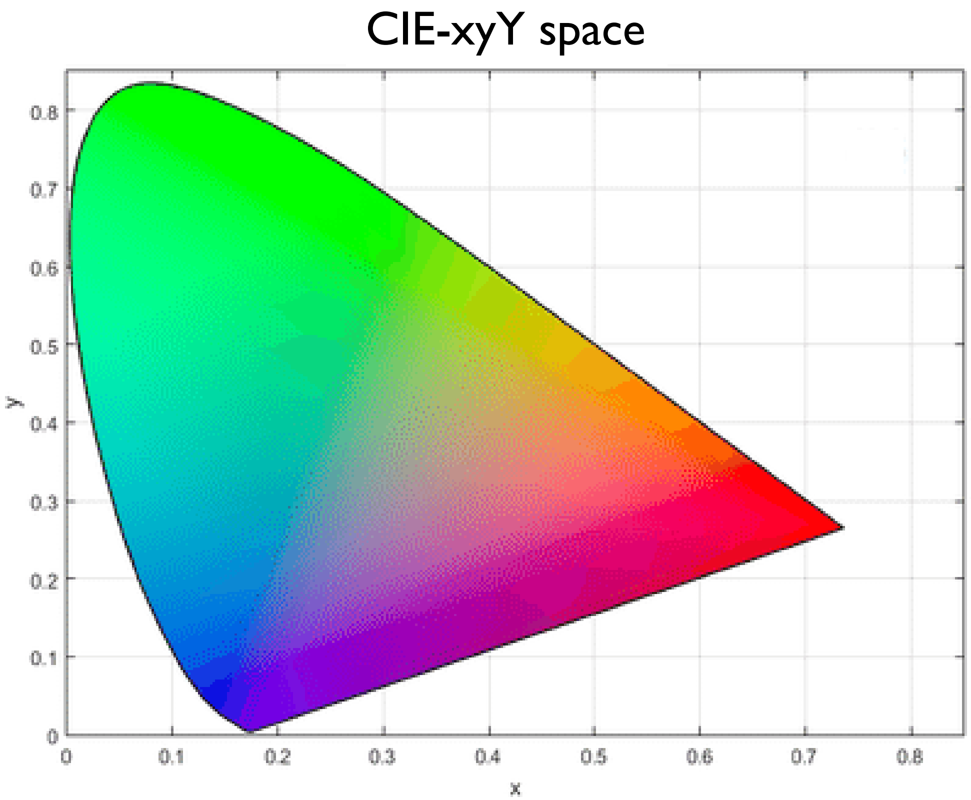
CIE 1976 LAB

- Considering the MacAdam experiments and the Steven's power-law, CIE LAB was derived in 1976 by applying various transformations to the CIE XYZ values that result in the following:
- L* represents a perceptual brightness measure between 0-100
  - L* is a non-linear transformation of the Y component of CIE XYZ.
  - L is approximately a cube root of Y (directly from Steven's power law)
- a* and b* (often range ±100)
  - Both have similar non-linear transformations applied, and represent approximately:
  - a* values lying along colors related to red and green
  - b* values lying along colors related to yellow and blue
  - a*=b*=0 represents neutral grey colors

NOTE: CIE LAB requires the white-point to be specified for the transformation.
The default white-point is D65.

CIE LAB





Chromaticity comparison's between CIE LAB and CIE XYX

Image from Bagdasar et al ICSTCC'17

Y'UV, Y'IQ, Y'CrCb

- These spaces are color decompositions that separate the RGB space into a "brightness-like" component and chrominance (color) components.
- The Ys in these color spaces are *not defined* on linear-sRGB or linear-NTSC
- They are defined on the ***gamma encoded*** sRGB and NTSC color spaces
- These Y are referred to as "Luma", not Luminance
- It should be written as Y' but they are typically written as only Y

$$\begin{bmatrix} Y' \\ U \\ V \end{bmatrix} = \begin{bmatrix} 0.2126 & 0.7152 & 0.0722 \\ -0.09991 & -0.33609 & 0.436 \\ 0.615 & -0.55861 & -0.05639 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

Gamma encoded (nonlinear) sRGB values

* Treating Y from YUV, YIQ, and YCrCb as CIE Y luminance is a common mistakes in the computer vision community.

Color error metric – CIE 2000 Delta E (ΔE)

- The CIE defined a color error metric in 2000 based on the CIE LAB space. This returns a color error between 0-100.
- You will see this referred to as CIEDE2000, CIEDE, ΔE, Delta E, DE, ..
- Delta E 2000 interpretation:

Delta E	Perception
<= 1.0	Not perceptible by human eyes.
1 - 2	Perceptible through close observation.
2 - 10	Perceptible at a glance.
11 - 49	Colors are more similar than opposite
100	Colors are exact opposite

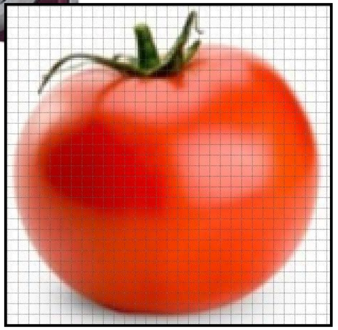
In general, DE of 2 or less is considered to be very good. It means a standard observer could not tell that two colors are different unless they observed them very closely.

Table from
https://zschuessler.github.io/DeltaE/learn/

Congratulations!

Standard color spaces are great

"The real scene"



Camera
sRGB Image

sRGB -> CIE XYZ -> CMYK -> printer ink (ICC Profi

sRGB -> CIE XYZ -> Display (ICC Profile)

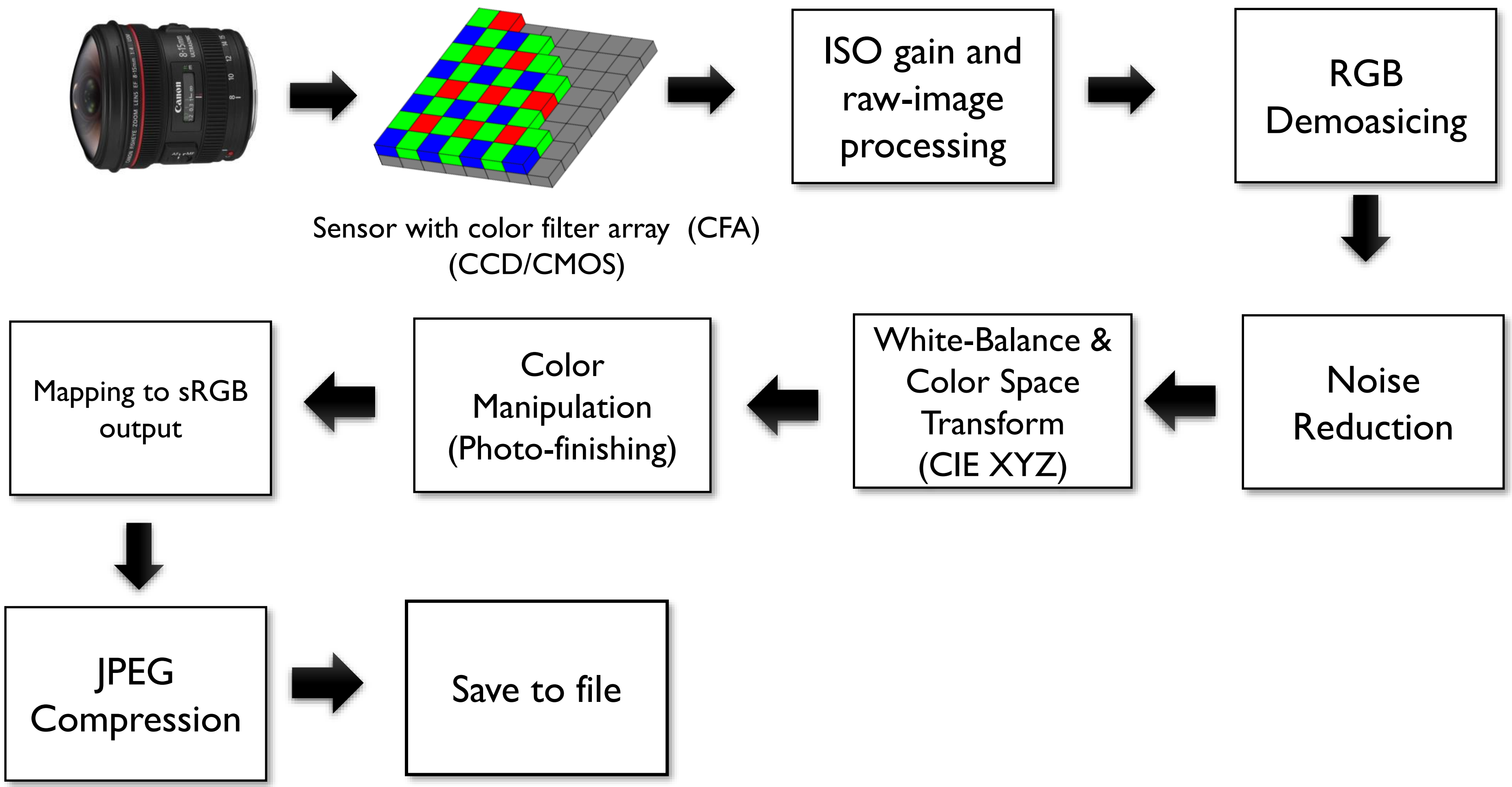
sRGB -> HSV -> Image Editing Software

Part 1: Overview of the Camera Imaging Pipeline

Integrated signal processor (ISP)

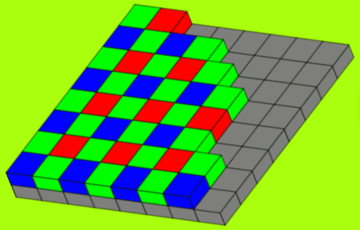
- You will hear the term "ISP" associated with camera pipelines
- An ISP is dedicated hardware used to process the sensor image to produce the final output (JPEG image) that is saved on your device
- The ISP is usually integrated as part of a system on a chip (SoC) that has other modules
- Companies such as Qualcomm, HiSilicon, Intel (and more) sell ISP chips
  - An ISP can be customized by the customer (Samsung, Huawei, LG, Apple, etc)
- Note that it is also possible to perform operations common on an ISP on your device's CPU and GPU

A typical color imaging pipeline



NOTE: This diagram represents the steps applied on a typical consumer camera pipeline. ISPs may apply these steps in a different order or combine them in various ways. A modern camera ISP will undoubtedly be more complex, but will almost certainly implement these steps in some manner.

A typical color imaging pipeline



Sensor with color filter array (CFA)
(CCD/CMOS)

ISO gain and raw-image processing

RGB Demoasicing

Noise Reduction

White-Balance & Color Space Transform (CIE XYZ)

Color Manipulation (Photo-finishing)

Mapping to sRGB output

JPEG Compression

Save to file

Camera sensor

CMOS sensor

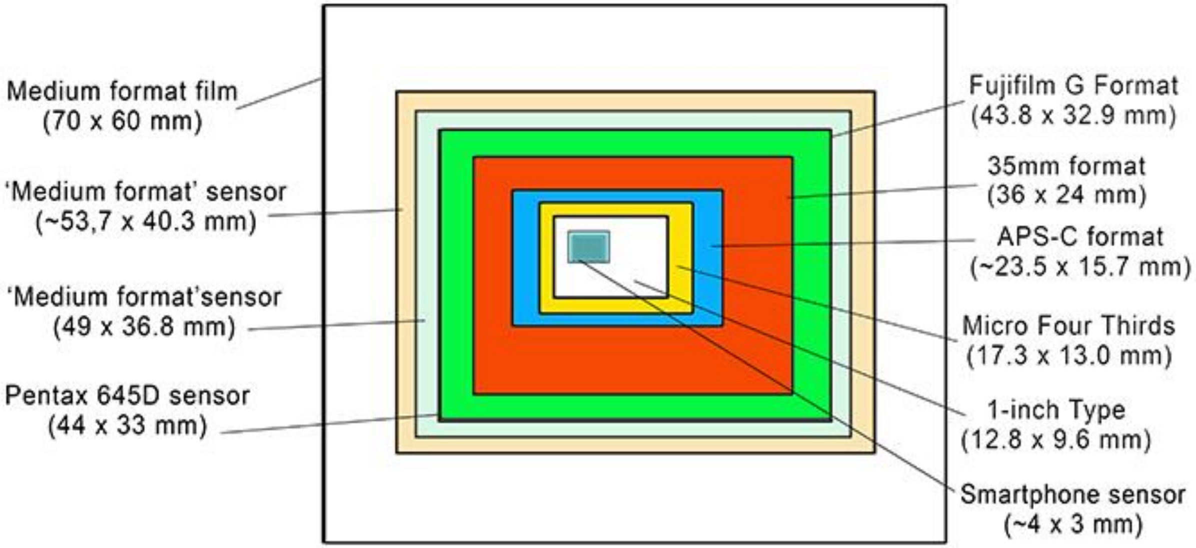
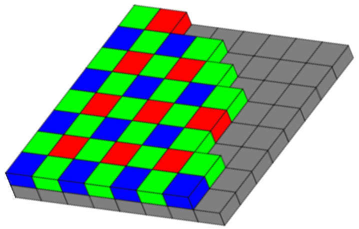


Figure from Photo Review website.

Almost all consumer camera sensors are based on complementary metal-oxide-semiconductor (CMOS) technology.

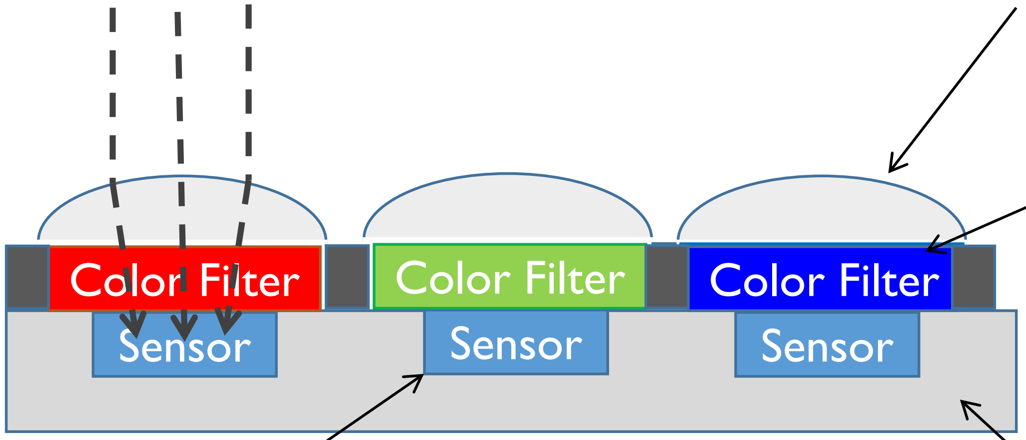
We generally describe sensors in terms of number of pixels and size. The larger the sensor, the better the noise performance as more light can fall on each pixel. Smart phones have small sensors!

Camera sensor RGB values



Color filter array
or "Bayer" pattern.

Light



Micro-lenses are placed over the diode to help increase light collection on the sensor

Color filters place over the sensor. This forms a Color Filter Array (CFA) also called a "Bayer Pattern" after inventor Bryce Bayer.

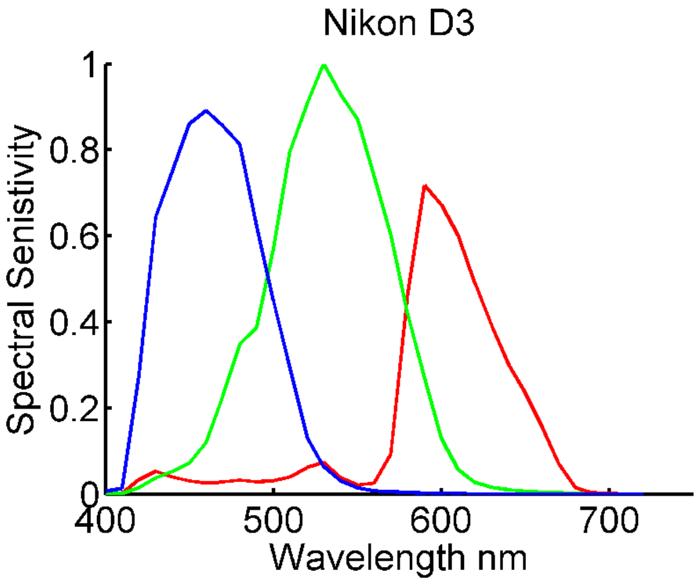
Photodiode
Photons hit the diode and force out electrons. This design is similar to a solar cell!

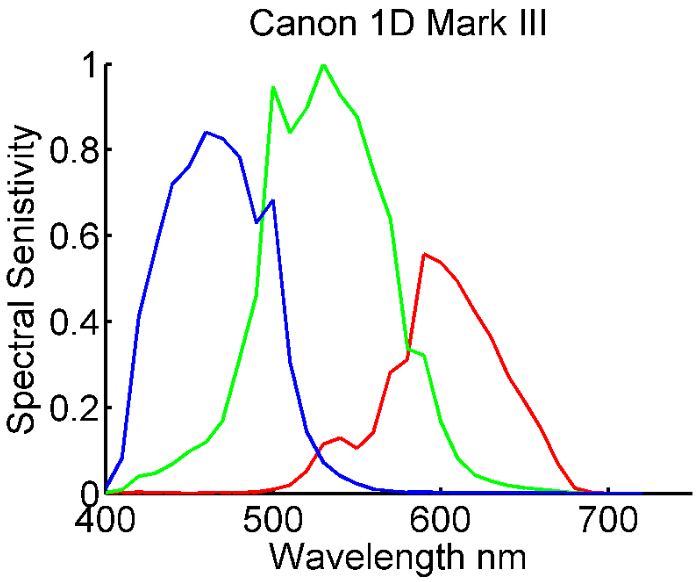
Silicon/Circuitry

Bryce Bayer

Camera RGB sensitivity

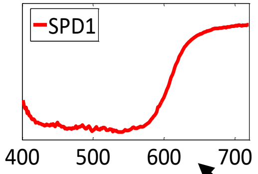
- The color filter array (CFA) on the camera filters the light into three *sensor-specific* RGB primaries

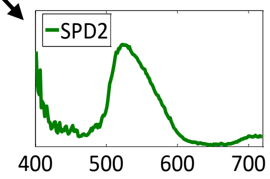




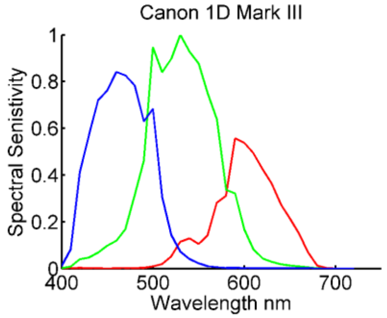
Plotted from camera sensitivity database by Dr. Jinwei Gu from Rochester Institute of Technology (RIT). Dr. Gu is now at SenseTime (USA). http://www.cis.rit.edu/jwgu/research/camspec/

Sensor raw-RGB image





Remember: physical world is measured by radiometric spectral power distributions.



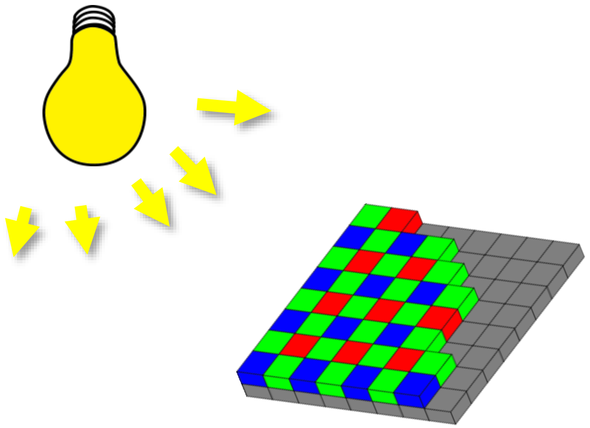
Color Matching Functions
CIE XYZ

Your camera sensor RGB filter is sensitive to different regions of the incoming SPD.

raw-RGB represents the physical world's SPD "projected" onto the sensor's spectral filters.

Sensors are linear to irradiance

- Camera sensors are decent light measuring devices
- If you double the amount of light hitting a sensor's pixel, the digital value output of that pixel will double

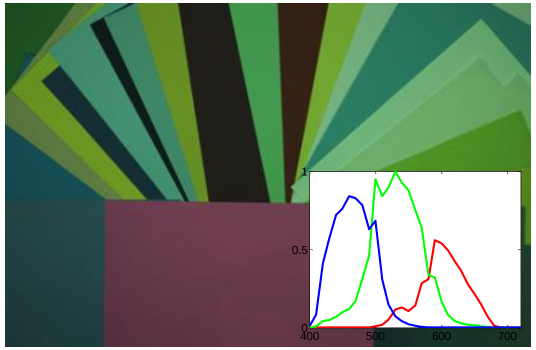


Sensor output is linear with respect to irradiance falling over the sensor over a certain amount of time.

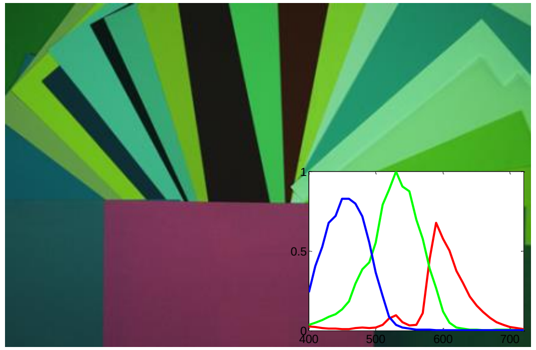
$$I = i * t$$

Digital value I is a linear function of irradiate i and exposure t.

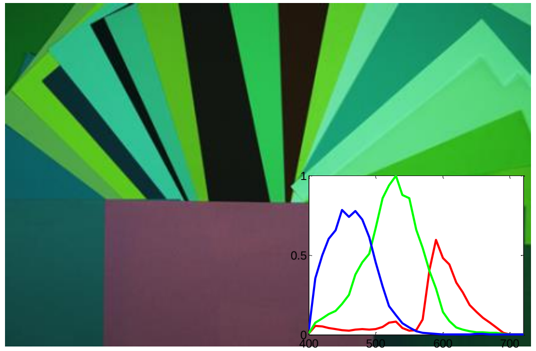
IMPORTANT: raw-RGB sensor images are <u>not</u> in a standard color space



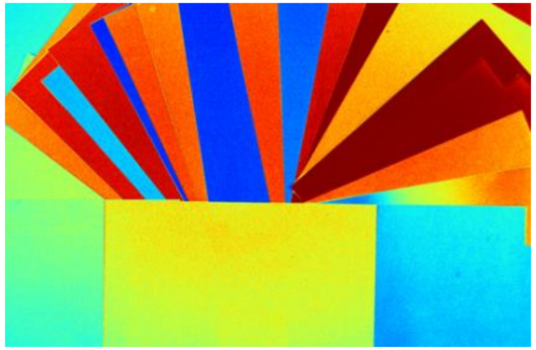
Canon 1D



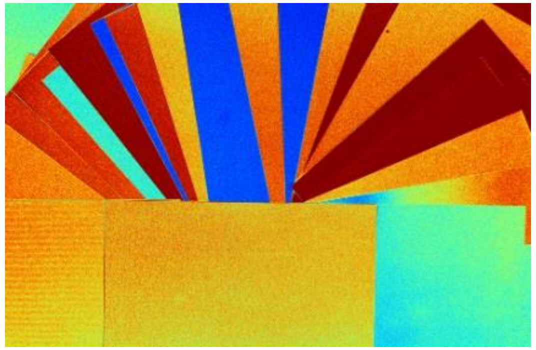
Nikon D40



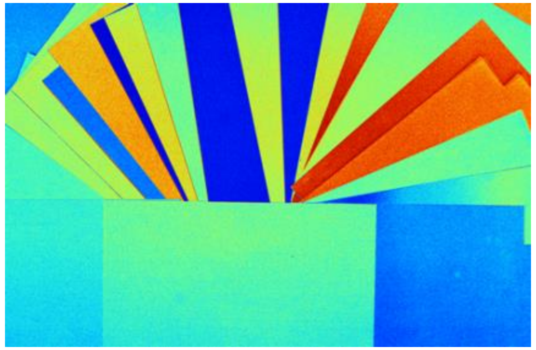
Sony $\alpha 57$



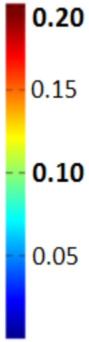
||Canon 1D – Nikon D40||$_2$



||Canon 1D - Sony $\alpha 57$||$_2$



||Nikon D40 - Sony $\alpha 57$||$_2$



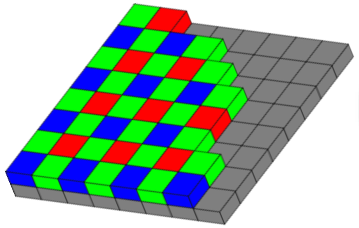
Color plots show L2 distance between the raw-RGB values with different cameras.

Displaying raw-RGB images

- Inserting a raw-RGB image in your slides, research paper, etc will result in strange colors.
- Why? Our devices (computers, printers, etc) expect the image to be in a standard color space like sRGB.

This is a raw-RGB image. Why does it look bad?
Because the RGB values are not sRGB values.
Knowing your color space is important!

A typical color imaging pipeline



Sensor with color filter array (CFA)
(CCD/CMOS)

ISO gain and raw-image processing

RGB Demoasicing

Noise Reduction

White-Balance & Color Space Transform (CIE XYZ)

Color Manipulation (Photo-finishing)

Mapping to sRGB output

JPEG Compression

Save to file

ISO signal amplification (gain)

- Imaging sensor signal is amplified and digitized
- Amplification to assist A/D conversion
  - Need to get the voltage to the range required to the desired digital output
- This gain is used to accommodate camera ISO settings
  - Gain to signal applied on sensor
  - Note – gaining the signal also gains image noise

Different ISO settings (note: the exposure will be shorter for higher ISO)

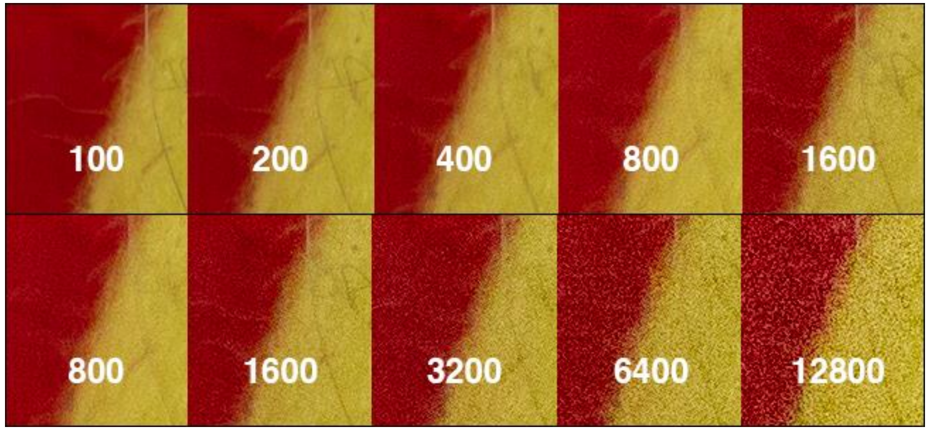


Image: Harry Guinness

ISO gain and raw-image processing

Pixel "intensity"

- We often talk about a pixel's intensity, however, a pixel's numerical value has no *unit*

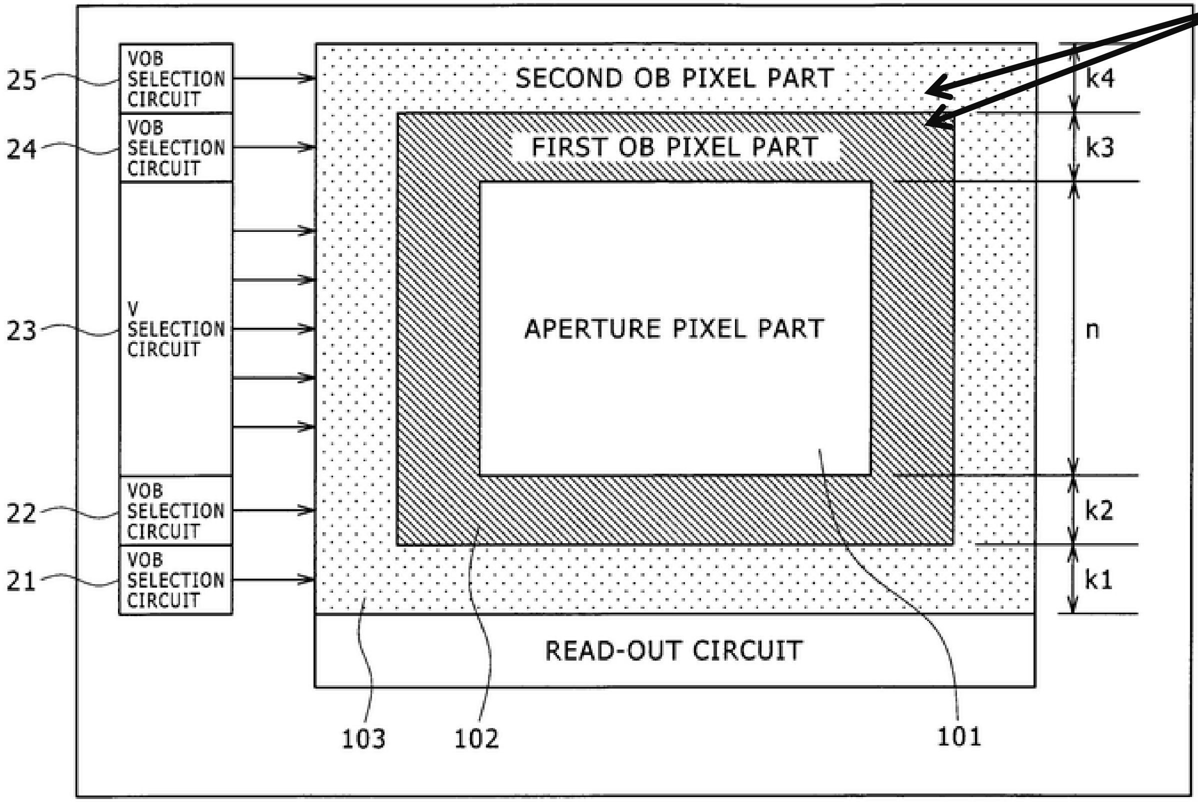
- The digital value of a pixel is based on several factors
  - Exposure (which is a function of both shutter speed and exposure)
  - Gain (ISO setting on the camera)
  - Camera hardware that digitizes the signal

- We typically rely on the ***relative*** digital values in the image and not the absolute digital values

Black light subtraction

- Sensor values for pixels with "no light" should be zero
- This is not the case due to sensor noise
  - The black level often changes as the sensor heats up
- This can be corrected by capturing a set of pixels that do not see light
- Place a dark-shield around sensor
- Subtract the level from the "black" pixels

Optical black (OB)



Sensor area(s) capturing "optical black"

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

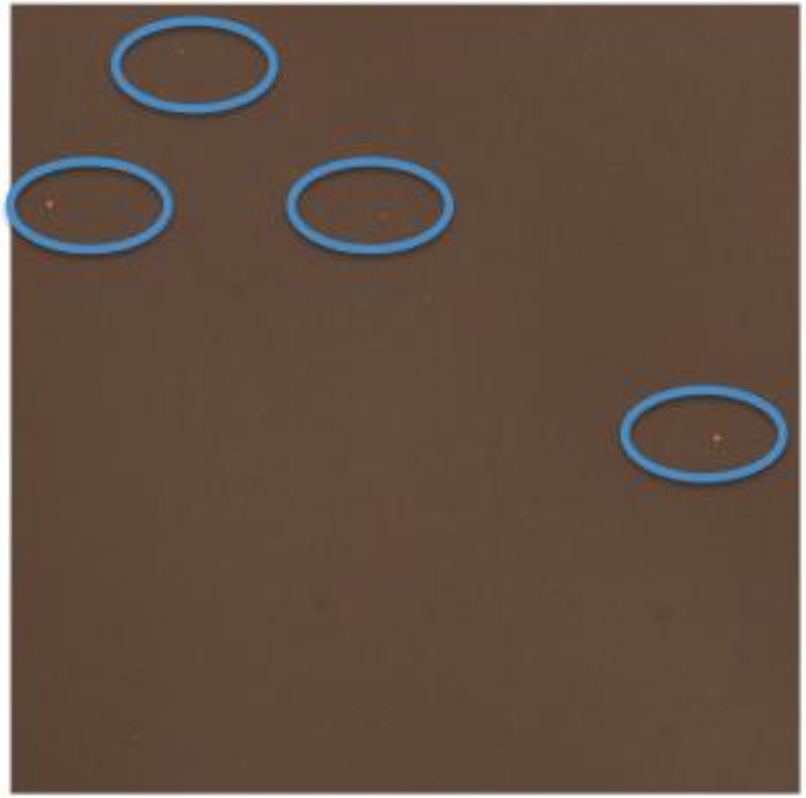
ISO gain and raw-image processing

Defective pixel mask

- CMOS have pixels that are defective
- Dead pixel masks are pre-calibrated at the factory
  - Using "dark current" calibration
  - Take an image with no light
  - Record locations reporting values to make "mask"
- Bad pixels in the mask are interpolated

ISO gain and raw-image processing

Defective pixel mask example



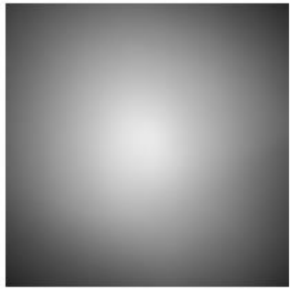
Identifying "dead pixels"

After interpolation

ISO gain and raw-image processing

Image courtesy of Lu Zheng and Moshe Ben-Ezra

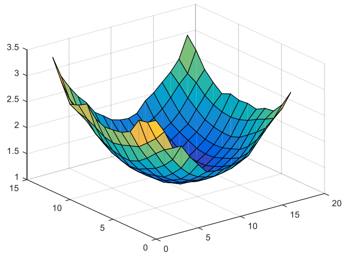
Flat-field correction



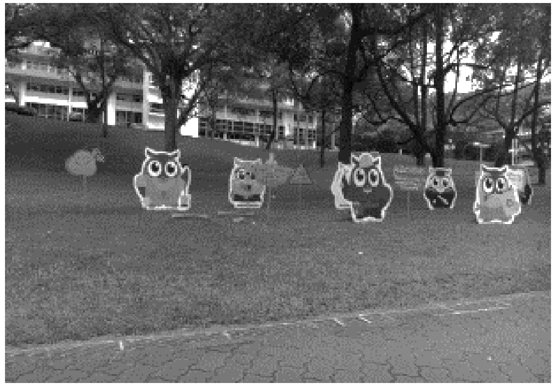
Uniform light falling on the sensor may not appear uniform in the raw-RGB image. This can be caused by the lens, sensor position in the camera housing, etc.

We want to correct this problem such that we get a "flat" output.

Before correction



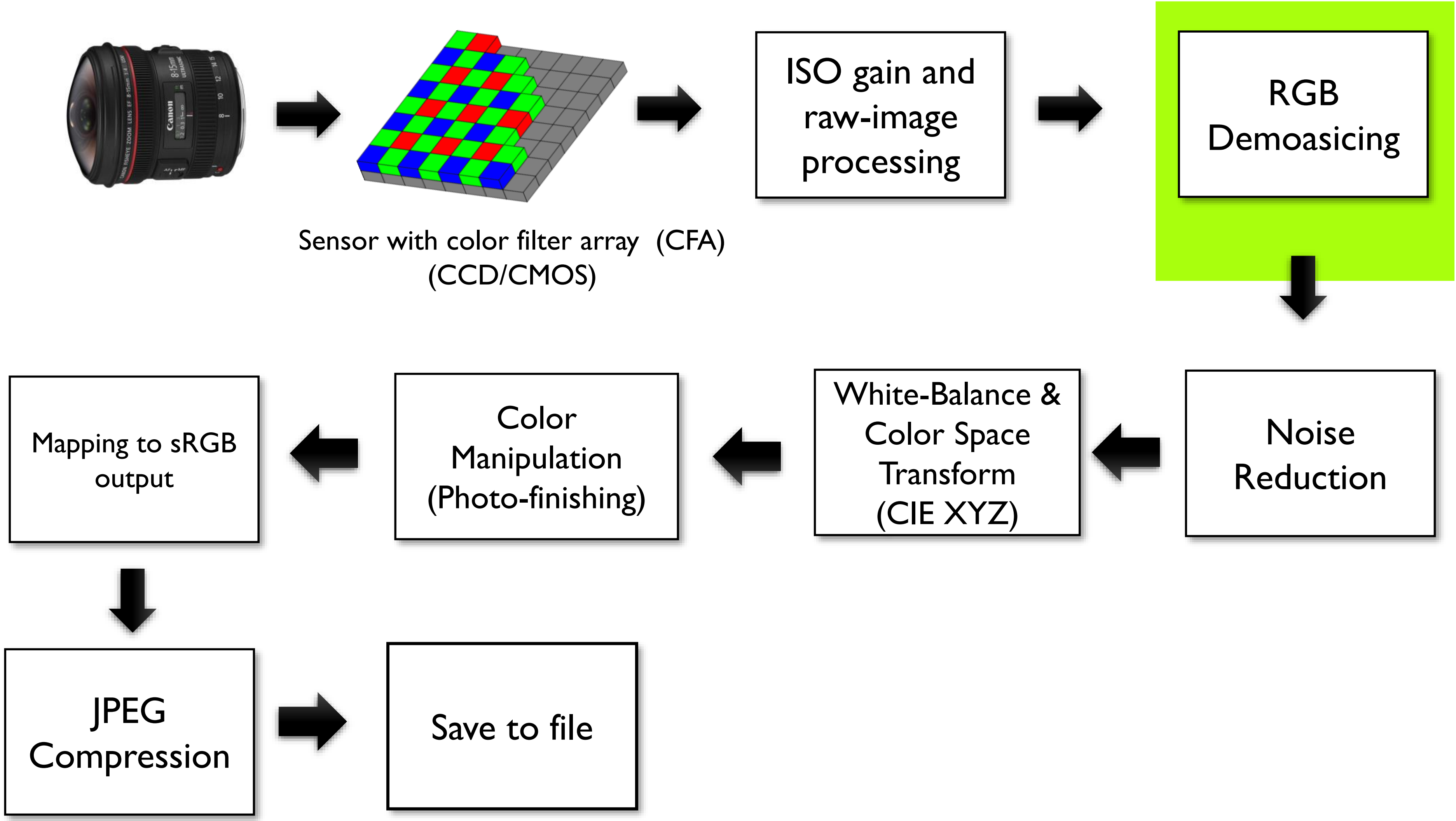
Apply a correction gain over the sensor values.



After correction

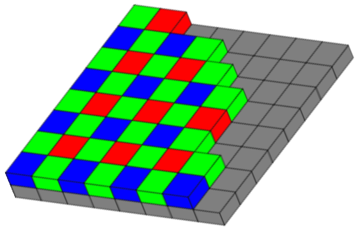
This operation can also be called "lens shading" correction.

A typical color imaging pipeline

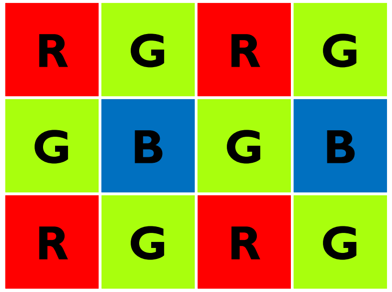


CFA/Bayer pattern demosaicing

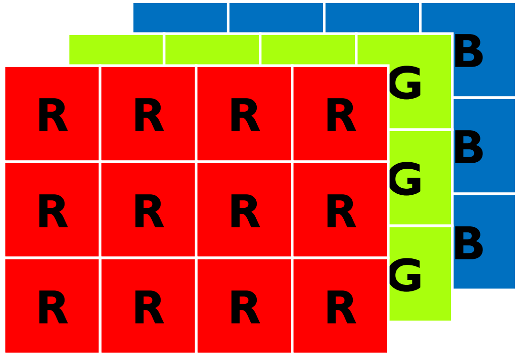
- Color filter array/Bayer pattern placed over pixel sensors
- We want an RGB value at each pixel, so we need to perform interpolation



Sensor with color filter array (CMOS)



Sensor RGB layout

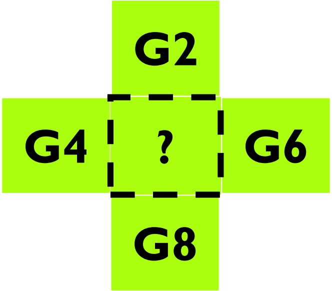


Desired output with RGB per pixel.

This is a zoomed up version of the Bayer pattern.

Simple interpolation

B1	G2	B3
G4	R5	G6
B7	G8	B9



At location R5, we have a red pixel value, but no Green or Blue pixel.

We need to estimate the G5 & B5 values at location R5.

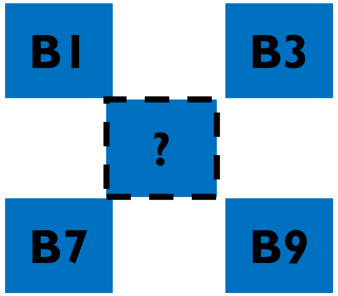
R5

G5 ?

B5 ?

$$G5 = \frac{G2 + G4 + G6 + G8}{4}$$

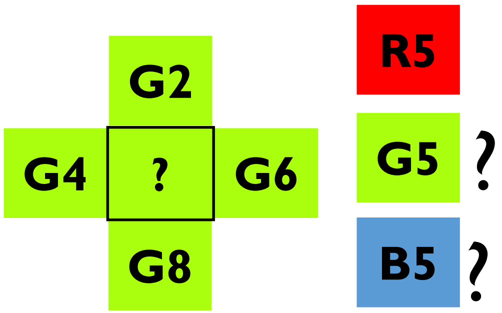
$$B5 = \frac{B1 + B3 + B7 + B9}{4}$$



RGB Demoasicing

Simple "edge aware" interpolation

B1	G2	B3
G4	R5	G6
B7	G8	B9



If (|G2–G8) && |(G4-G8)| both < Thres):

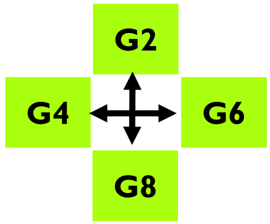
$$G5 = \frac{G2 + G4 + G6 + G8}{4}$$

elseif (|G2-G8| > Thres):

$$G5 = \frac{G4 + G6}{2}$$

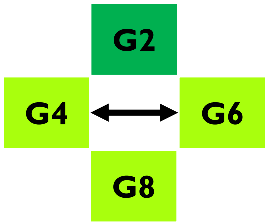
else:

$$G5 = \frac{G2 + G8}{2}$$



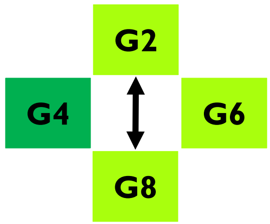
Case 1

All about the same.



Case 2

G2 and G8 differ – ignore them in the interpolation



Case 3

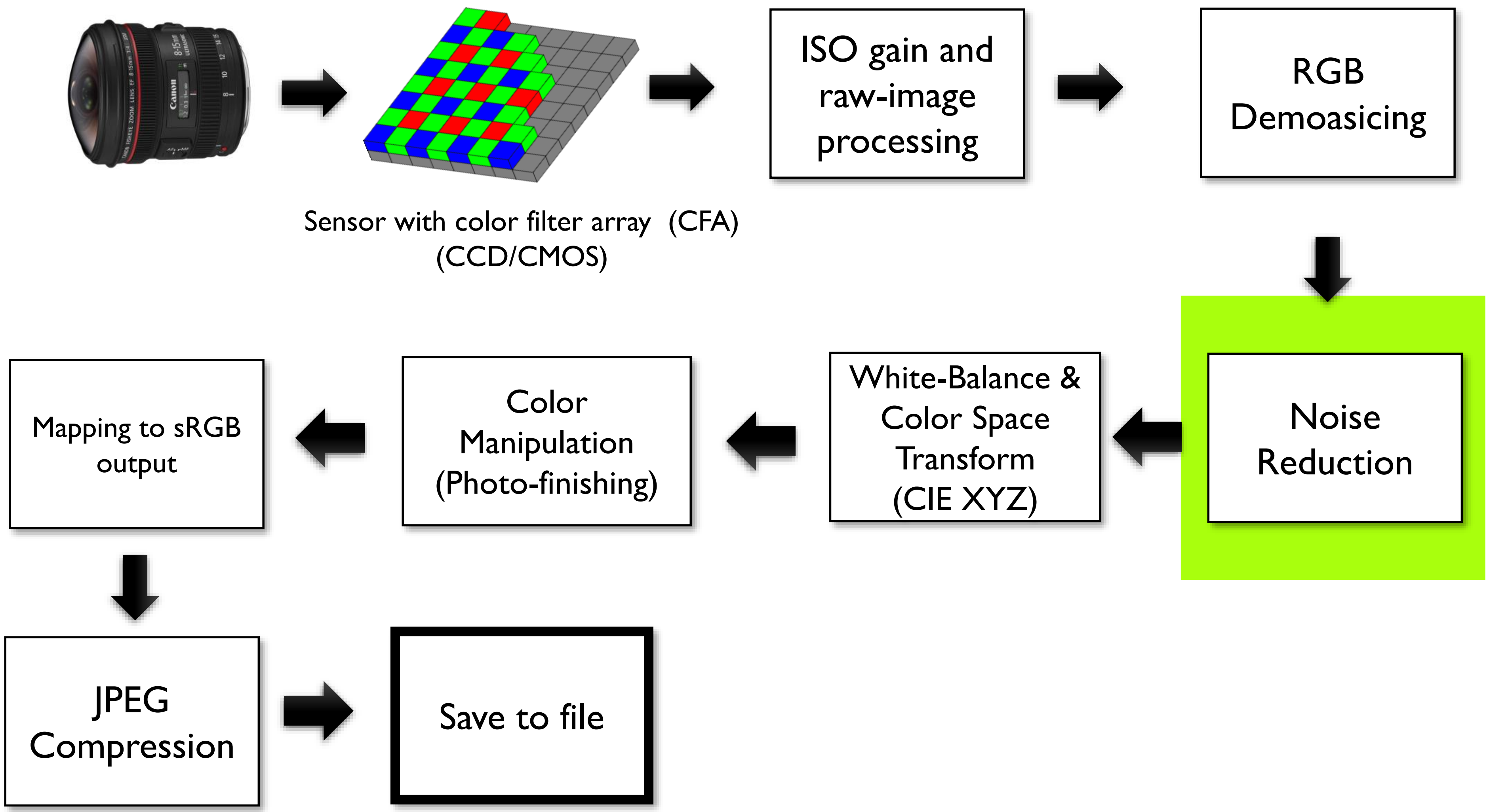
G2 and G8 differ – ignore them in the interpolation

Do this procedure also for the blue pixel, B5.

Demosaicing in practice

- The prior examples are illustrative algorithms only
- Camera IPSs use more complex and proprietary algorithms.
- Demosaicing can be combined with additional processing
  - Highlight clipping
  - Sharpening
  - Noise reduction

A typical color imaging pipeline



* Note that steps can be optional (e.g. noise reduction) or applied in slightly different order.

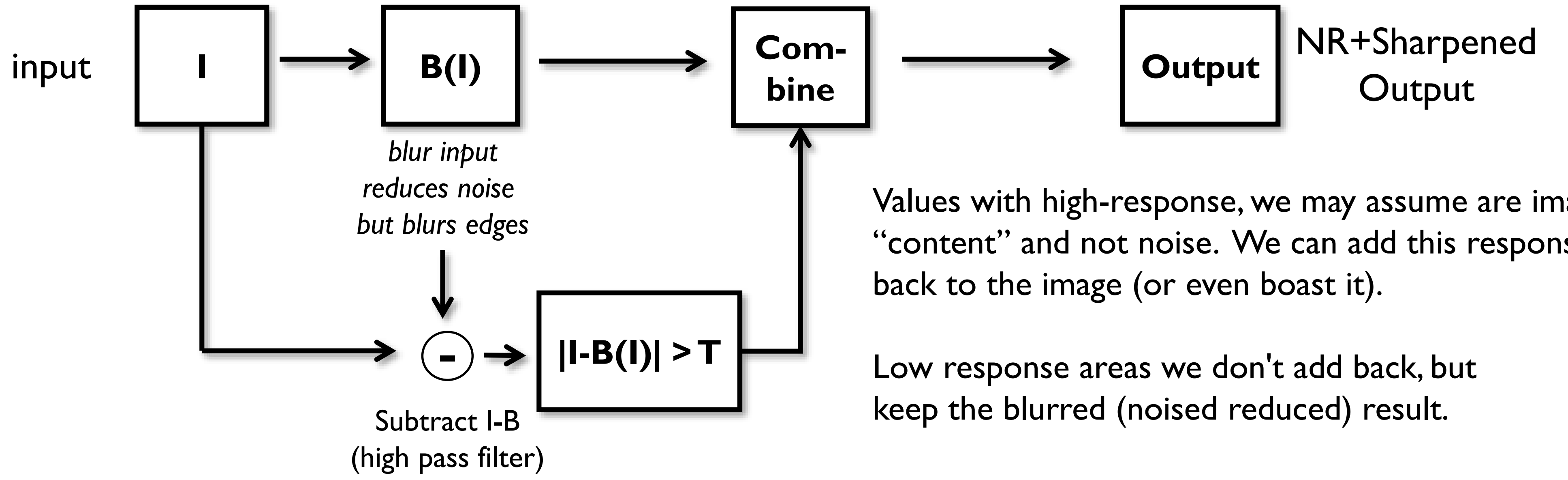
Noise reduction (NR)

- All sensors inherently have noise
- Most cameras apply additional NR after A/D conversion
- A simple method is described in the next slide
- For high-end cameras, it is likely that cameras apply different strategies depending on the ISO settings, e.g. high ISO will result in more noise, so a more aggressive NR could be used
- Smartphone cameras, because the sensor is small, apply aggressive noise reduction.

A simple noise reduction approach

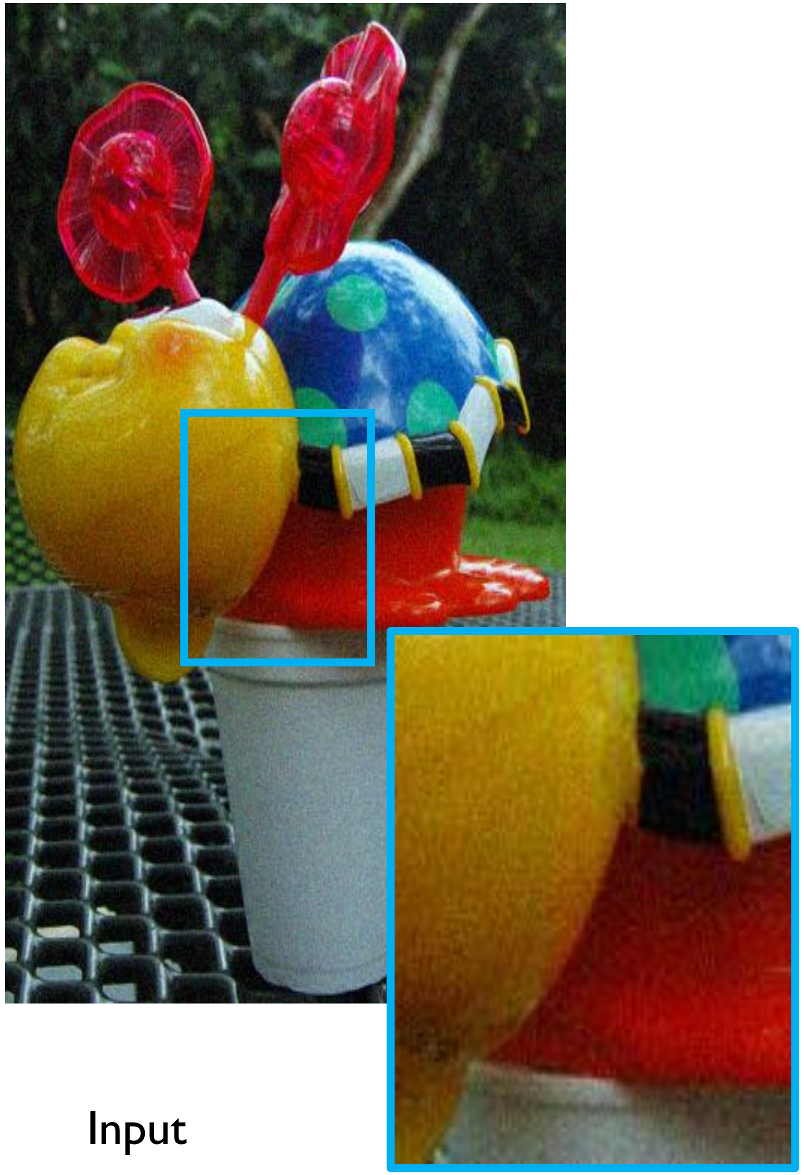
- Blur the image based on the ISO setting (higher ISO = more blur)
- Blurring will reduce noise, but also remove detail.
- Add image detail back for regions that have a high signal. We can even boost some parts of the signal to enhance detail (i.e. "sharpening")

Sketch of the procedure here

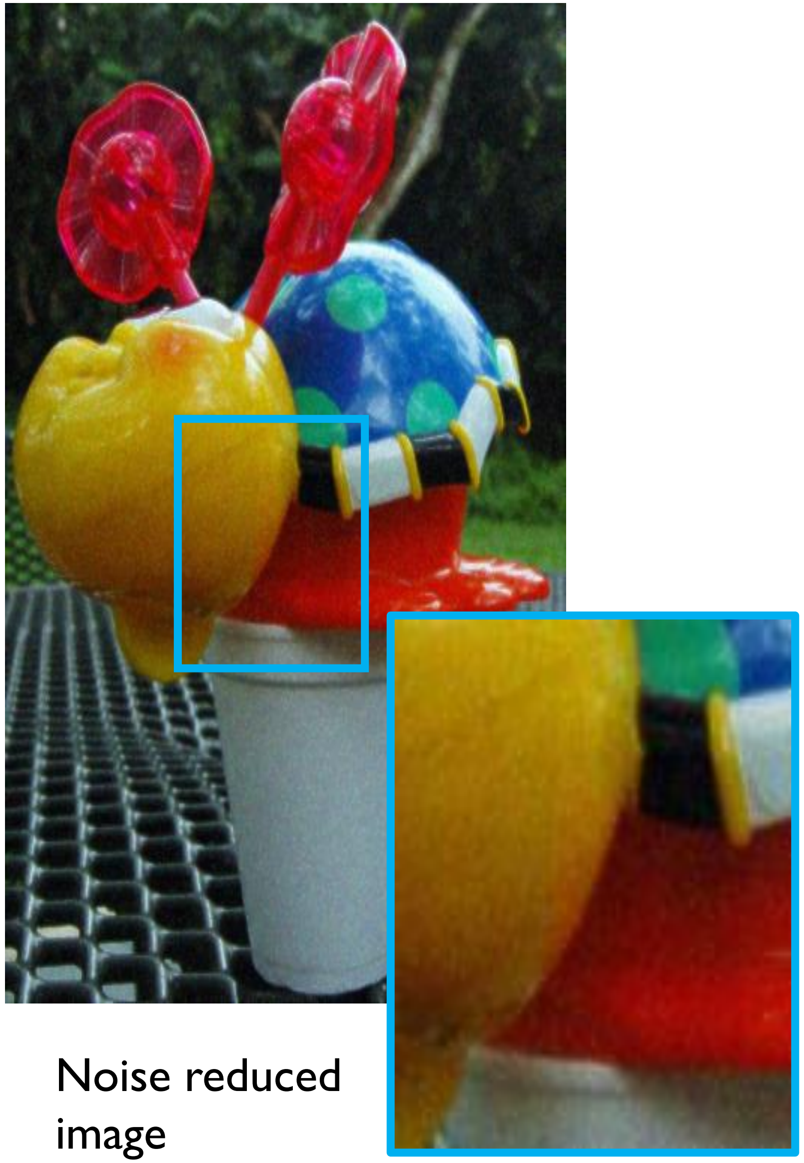


Values with high-response, we may assume are image "content" and not noise. We can add this response back to the image (or even boast it).

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

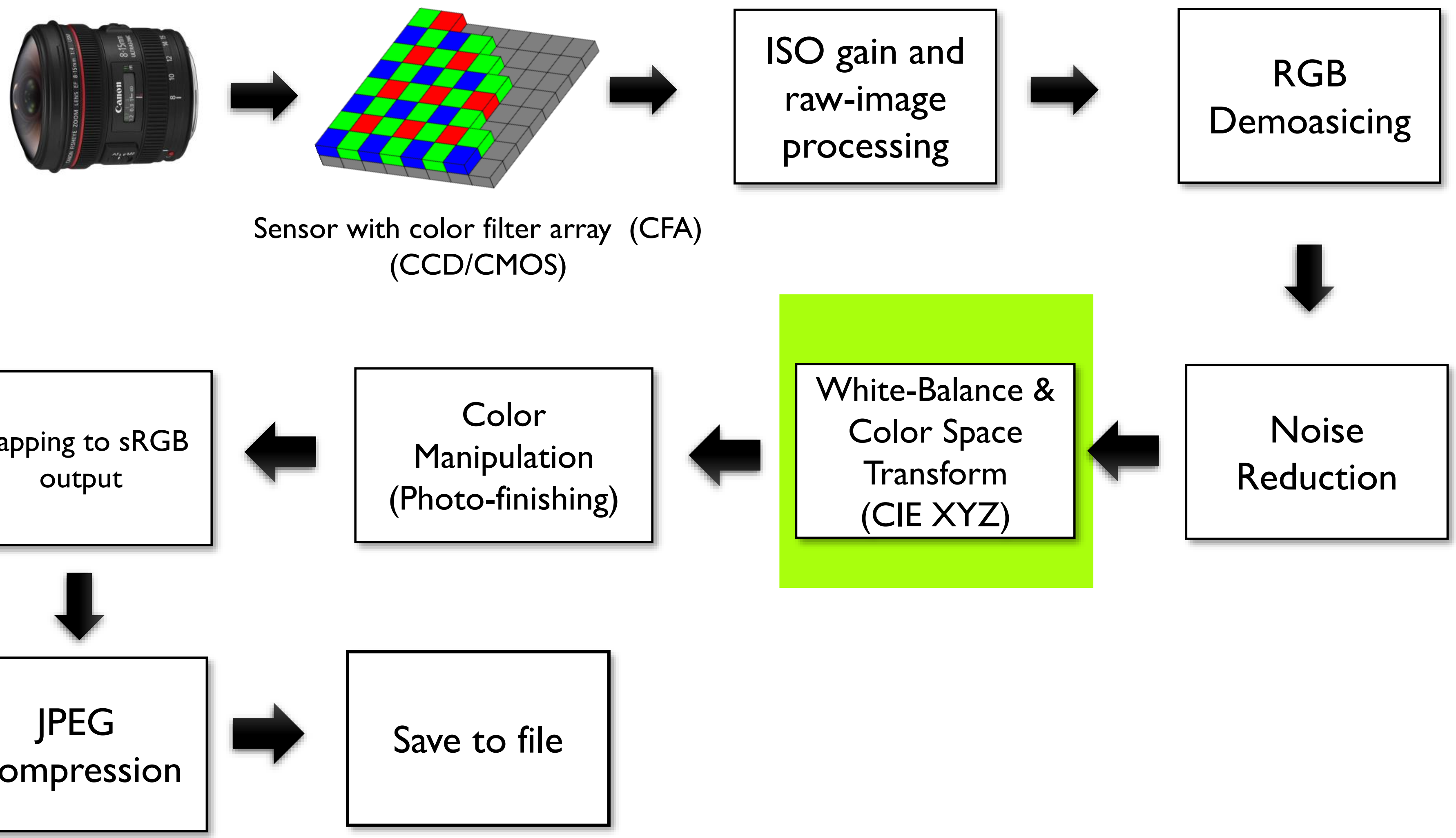


Input



Noise reduced image

A typical color imaging pipeline

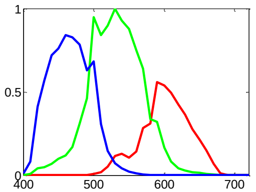


Color mapping/colorimetric stage

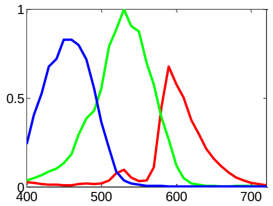
- This step in the IPS converts the sensor raw-RGB values to a device independent color space

Camera sensors have their own spectral response.

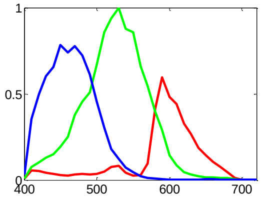
We need to map it into a standard response (CIE XYZ).



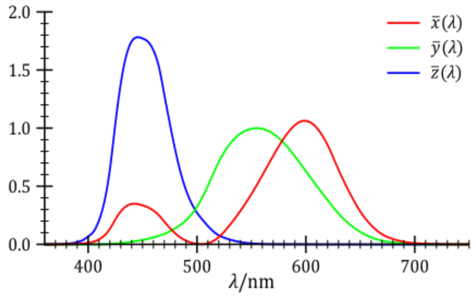
Canon 1D



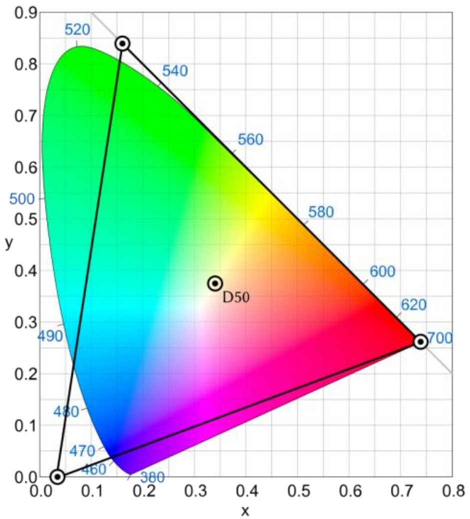
Nikon D40



Sony α57



CIE XYZ



ProPhoto RGB

We will use CIE XYZ in this tutorial, but most cameras use a related space called ProPhoto.

White-Balance & Color Space Transform (CIE XYZ)

Two step procedure

(1) apply a white-balance correction to the raw-RGB values

(2) map the white-balanced raw-RGB values to CIE XYZ

White balance

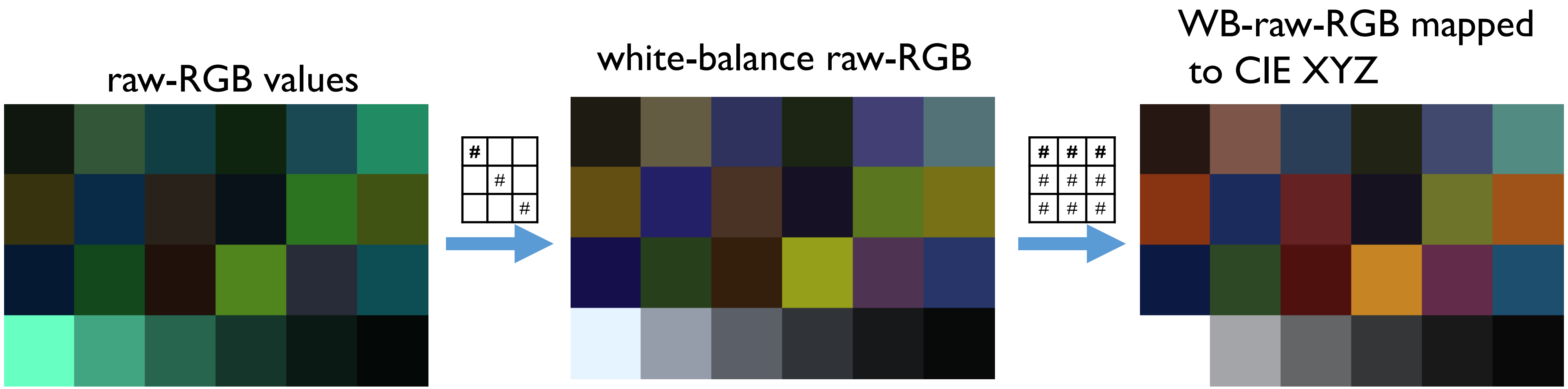
#		
	#	
		#

3x3 diagonal matrix

Color space transform (CST)

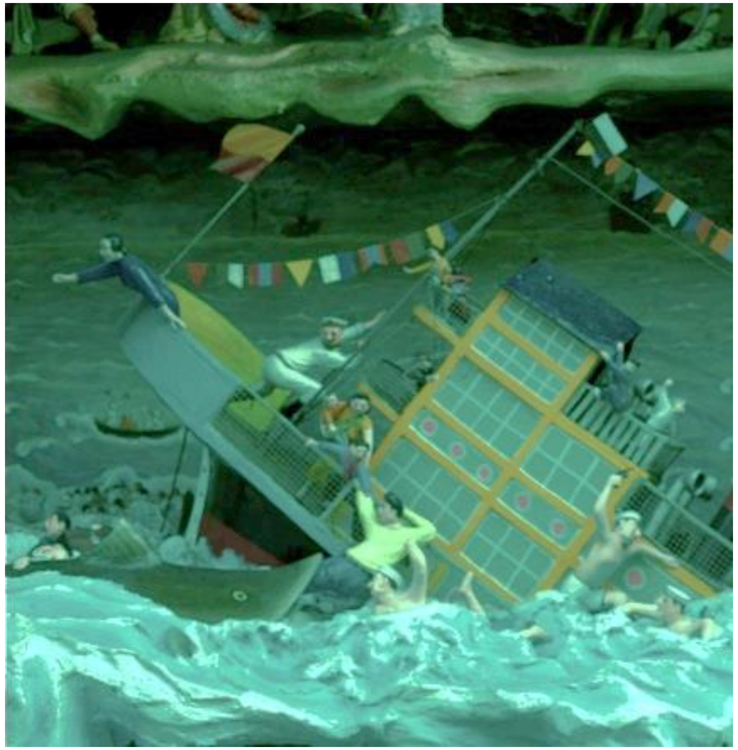
#	#	#
#	#	#
#	#	#

3x3 full matrix (or polynomial function)



White-Balance & Color Space Transform (CIE XYZ)

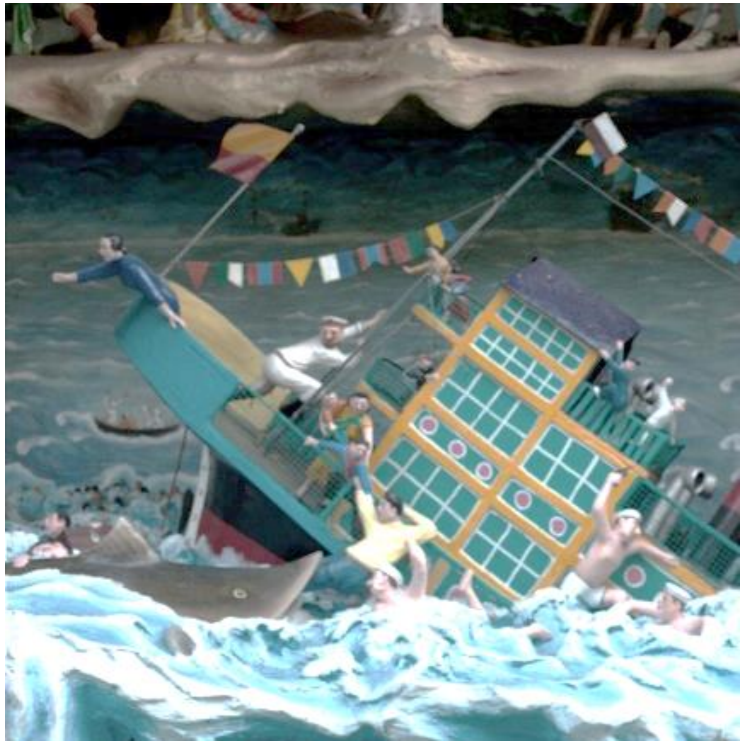
How does white balance (WB) work?



raw-RGB sensor image
(pre-white-balance correction)

Sensor's
response to
illumination (ℓ)

$$\begin{bmatrix} \ell_r \\ \ell_g \\ \ell_b \end{bmatrix} = \begin{bmatrix} 0.2 \\ 0.8 \\ 0.8 \end{bmatrix}$$



"White-balanced"
raw-RGB image

White-balance
diagonal matrix

$$\begin{bmatrix} r_{wb} \\ g_{wb} \\ b_{wb} \end{bmatrix} = \begin{bmatrix} 1/\ell_r & 0 & 0 \\ 0 & 1/\ell_g & 0 \\ 0 & 0 & 1/\ell_b \end{bmatrix} \begin{bmatrix} r \\ g \\ b \end{bmatrix}$$

White-Balance &
Color Space
Transform
(CIE XYZ)

White balance
(computational color constancy)

- **The challenging part for white-balance is determining the proper white-balance setting!**
- Users can manually set the white balance
  - Camera specific white-balance matrices for common illuminations
  - These can be manually selected by the user
- Otherwise auto white balance (AWB) is performed
  - In computer vision, we often refer to AWB as "illumination estimation"
  - Since the hard part is trying to determine what the illumination in the scene is.

White-Balance & Color Space Transform (CIE XYZ)

WB manual settings

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

Cameras can pre-calibrate their sensor's response for common illuminations.

Typical mapping of WB icons to related color temperate.

Image from ExposureGuide.com

Examples of manual WB matrices

Nikon D7000

Sunny

$$\begin{bmatrix} 2.0273 & 0 & 0 \\ 0 & 1.0000 & 0 \\ 0 & 0 & 1.3906 \end{bmatrix}$$

Incandescent

$$\begin{bmatrix} 1.3047 & 0 & 0 \\ 0 & 1.0000 & 0 \\ 0 & 0 & 2.2148 \end{bmatrix}$$

Shade

$$\begin{bmatrix} 2.4922 & 0 & 0 \\ 0 & 1.0000 & 0 \\ 0 & 0 & 1.1367 \end{bmatrix}$$

Canon 1D

Daylight

$$\begin{bmatrix} 2.0938 & 0 & 0 \\ 0 & 1.0000 & 0 \\ 0 & 0 & 1.5020 \end{bmatrix}$$

Tungsten

$$\begin{bmatrix} 1.4511 & 0 & 0 \\ 0 & 1.0000 & 0 \\ 0 & 0 & 2.3487 \end{bmatrix}$$

Shade

$$\begin{bmatrix} 2.4628 & 0 & 0 \\ 0 & 1.0000 & 0 \\ 0 & 0 & 1.2275 \end{bmatrix}$$

Sony A57K

Daylight

$$\begin{bmatrix} 2.6836 & 0 & 0 \\ 0 & 1.0000 & 0 \\ 0 & 0 & 1.5586 \end{bmatrix}$$

Tungsten

$$\begin{bmatrix} 1.6523 & 0 & 0 \\ 0 & 1.0000 & 0 \\ 0 & 0 & 2.7422 \end{bmatrix}$$

Shade

$$\begin{bmatrix} 3.1953 & 0 & 0 \\ 0 & 1.0000 & 0 \\ 0 & 0 & 1.2891 \end{bmatrix}$$

White-Balance &
Color Space
Transform
(CIE XYZ)

Pre-calibrated white-balance matrices for different brands of cameras.

Auto white balance (AWB)

- If manual white balance is not used, then an AWB algorithm is performed
- AWB needs to determine the sensor's raw-RGB response to the scene illumination from an arbitrary image
- This is surprisingly hard and AWB still fails from time to time (see next slide)

White-Balance & Color Space Transform (CIE XYZ)

AWB is not easy

raw-RGB input image before white-balance

Given an arbitrary raw-RGB image, determine what is the camera's response to the illumination.

The idea is that something that is *white** is a natural reflector of the scene's illuminations SPD.

So, if we can identify what is "white" in the raw-RGB image, we are observing the sensor's RGB response to the illumination.

* It doesn’t have to be "white", but grey – sometimes we call these scene points "achromatic" or "neutral" regions.

AWB: "Gray world" algorithm

- This methods assumes that the average reflectance of a scene is achromatic (i.e. gray)
  - Gray is just the white point not at its brightest, so it serves as an estimate of the illuminant
  - This means that image average should have equal energy, i.e. R=G=B
- Based on this assumption, the algorithm adjusts the input average to be gray as follows:

First, estimate the average response:

$$R_{avg} = \frac{1}{Nr}\sum Rsensor(\mathrm{r}) \quad G_{avg} = \frac{1}{Ng}\sum Gsensor(\mathrm{g}) \quad B_{avg} = \frac{1}{Nb}\sum Bsensor(\mathrm{b})$$

r = red pixels values, g=green pixels values, b =blue pixels values
Nr = # of red pixels, Ng = # of green pixels, Nb = # blue pixels

Note: # of pixel per channel may be different if white balance is applied to the RAW image before demosaicing. Some pipelines may also transform into another colorspace, e.g. LMS, to perform the white-balance procedure.

AWB: "Gray world" algorithm

- Based on the image average R/G/B value, white balance can be expressed as a matrix as:

$$\begin{bmatrix} R' \\ G' \\ B' \end{bmatrix} = \begin{bmatrix} G_{avg}/R_{avg} & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & G_{avg}/B_{avg} \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

White-balanced sensor RGB

Sensor RGB

Matrix scales each channel by its average and then normalizes to the green channel average.

White-Balance & Color Space Transform (CIE XYZ)

AWB: "White patch" algorithm

- This methods assumes that "highlights" (bright spots) represent specular reflections of the illuminant
  - This means that maximum R, G, B values are a good estimate of the white point
- Based on this assumption, the algorithm works as follows:

$$R_{max} = max(Rsensor(\mathrm{r})) \qquad G_{max} = max(\,Gsensor(\mathrm{g})) \quad B_{max} = max(\,Bsensor(\mathrm{b}))$$

r = red pixels values, g=green pixels values, b =blue pixels values

White-Balance & Color Space Transform (CIE XYZ)

AWB: "White patch" algorithm

- Based on RGB max, white balance can be expressed as a matrix as:

$$\begin{bmatrix} R' \\ G' \\ B' \end{bmatrix} = \begin{bmatrix} G_{max}/R_{max} & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & G_{max}/B_{max} \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

White-balanced sensor raw-RGB

Sensor raw-RGB

Matrix scales each channel by its maximum value and then normalizes to the green channel's maximum.

White-Balance & Color Space Transform (CIE XYZ)

AWB example

Input

Gray World

White Patch

White-Balance & Color Space Transform (CIE XYZ)

Better AWB methods

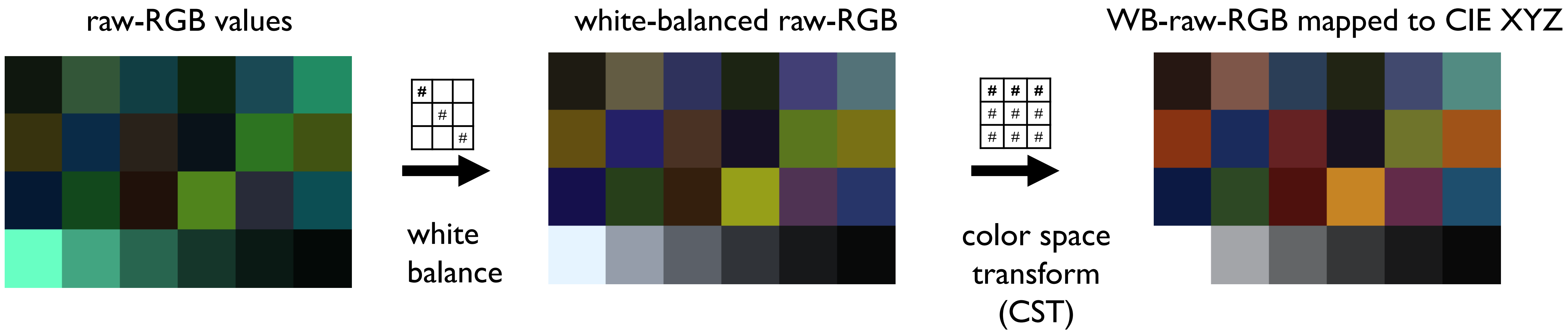
- Gray world and white patch are *very basic* algorithms
  - These both tend to fail when the image is dominated by large regions of a single color (e.g. a sky image)
- **There are many AWB methods in the literature**
- Camera's often use their own proprietary white-balanced
- Note – they may not use the exact scene illumination, but a slightly different result to leave a small color cast in the image for aesthetic reasons.

White-Balance & Color Space Transform (CIE XYZ)

Color space transform – part 2

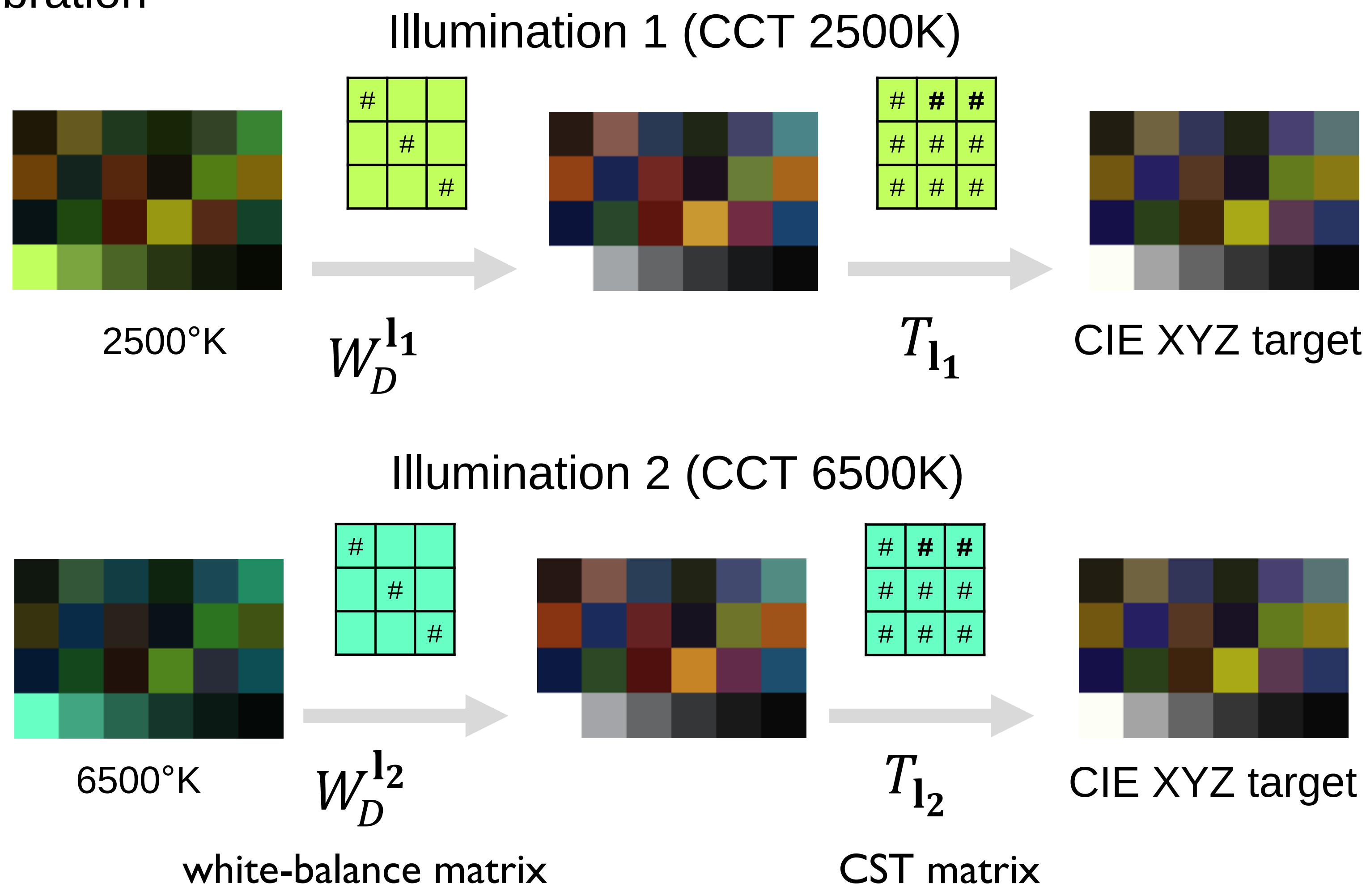
- Process used on cameras involves interpolation from factory presets
- **The need for interpolation is relate to white-balance only approximating true color constancy**

Color space transform is applied after the white balance. In fact, the matrix we use to perform the CST is based on the white-balance CCT.



Color space transform (1/3)

Factory pre-calibration

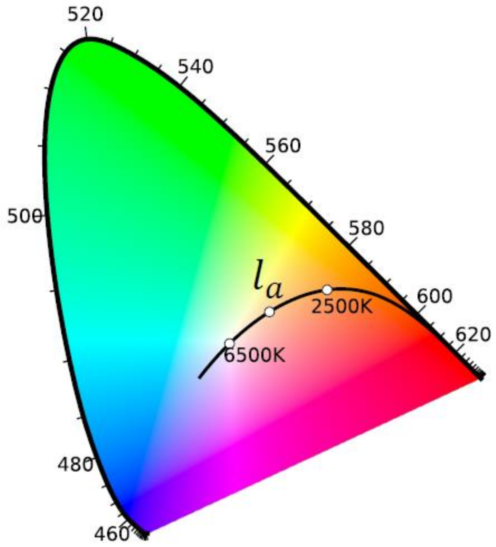


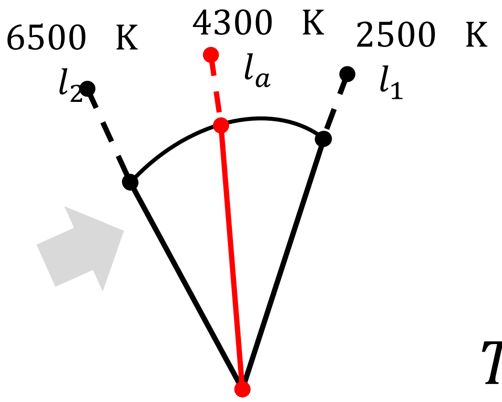
White-Balance & Color Space Transform (CIE XYZ)

CST matrices ($T_{\mathbf{l_1}}$ and $T_{\mathbf{l_2}}$) are calibrated for two different illuminations (l1 and l2). Depending on the temperature of the white-balance, we use the corresponding CST.

Color space transform (2/3)

Interpolation process





$$g = \frac{\mathrm{CCT}_{\mathbf{l_a}}^{-1} - \mathrm{CCT}_{\mathbf{l_2}}^{-1}}{\mathrm{CCT}_{\mathbf{l_1}}^{-1} - \mathrm{CCT}_{\mathbf{l_2}}^{-1}}$$

$$T_{\mathbf{l_a}} = gT_{\mathbf{l_1}} + (1-g)T_{\mathbf{l_2}}$$

New input (4300°K) $\Phi_{\mathbf{cam}}^{\mathbf{l}_a}$ $W_D^{\mathbf{l_a}}$ $T_{\mathbf{l_a}}$

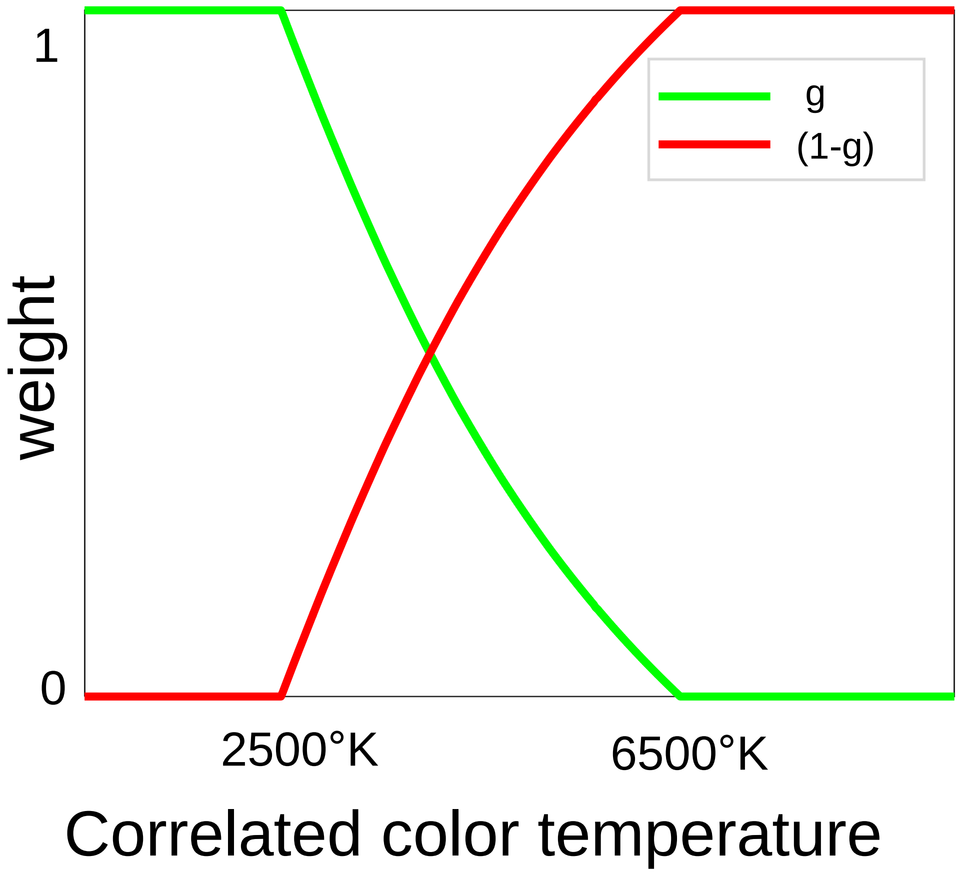
Given a new illumination (la) and its estimated correlated color temperature (CCT), we construct a CST matrix by blending the two factory pre-calibrated matrices.

Color space transform (3/3)

Weighting functions

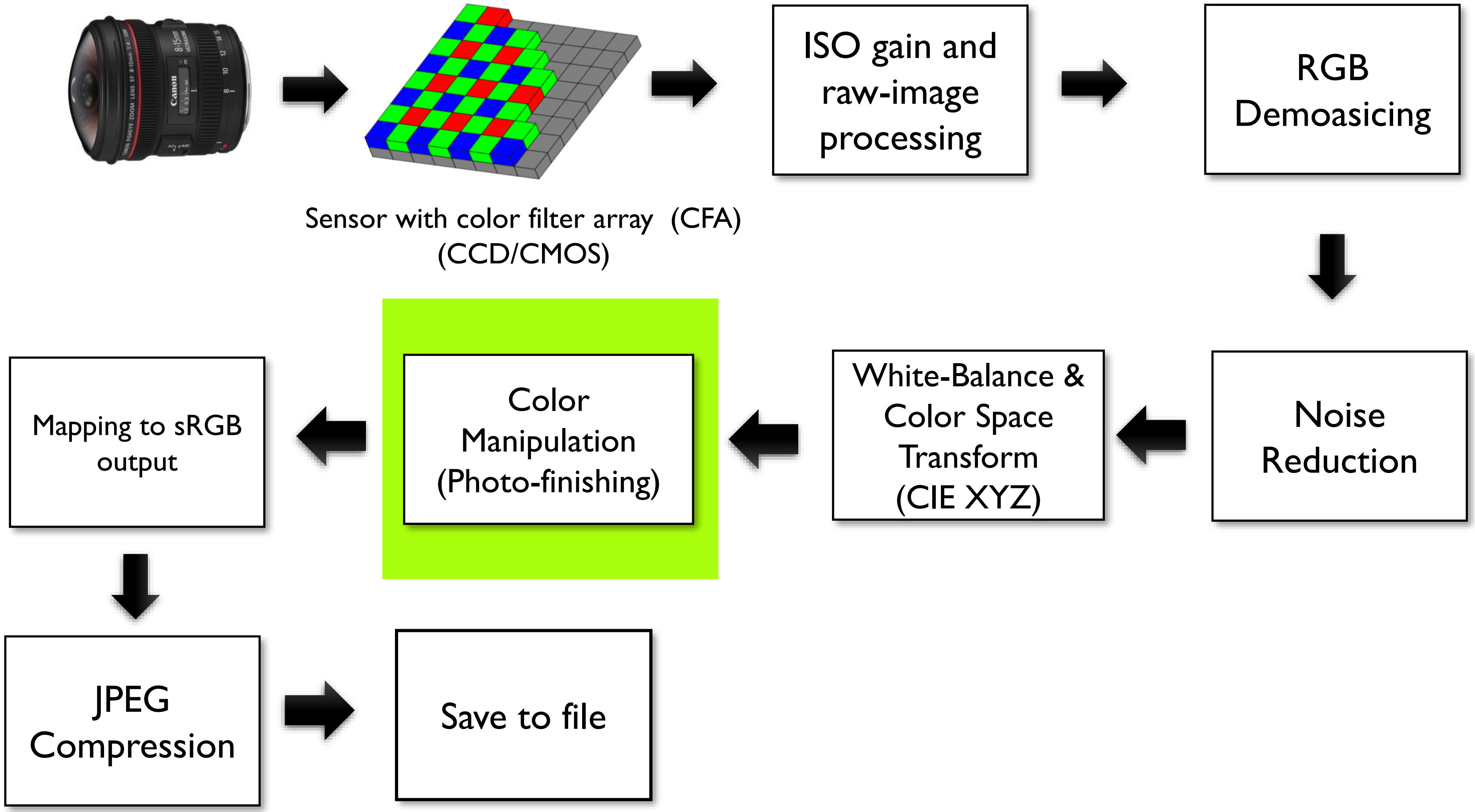
$$g = \frac{\mathrm{CCT}_{\mathbf{l_a}}^{-1} - \mathrm{CCT}_{\mathbf{l_2}}^{-1}}{\mathrm{CCT}_{\mathbf{l_1}}^{-1} - \mathrm{CCT}_{\mathbf{l_2}}^{-1}}$$

$$T_{\mathbf{l_a}} = gT_{\mathbf{l_1}} + (1-g)T_{\mathbf{l_2}}$$



White-Balance & Color Space Transform (CIE XYZ)

Typical color imaging pipeline



Color manipulation

- This is the stage were a camera applies its "secret sauce" to make the images look good
- This procedure can be called by many names:
  - Color manipulation
  - Photo-finishing
  - Color rendering or selective color rendering
  - Yuv processing engine
- DSLR will often allow the user to select various photo-finishing styles
- Smartphones often compute this per-image
- Photo-finishing may also tied to geographical regions!

DSLR "picture" styles

From Canon’s user manual

Standard

Glowing prints with crisp finishes.
It is the basic color of EOS DIGITAL.

Portrait

For transparent, healthy skin for women and children

Landscape

Crisp and impressive reproduction of blue skies and green trees in deep, vivid color

Neutral

Subjects are recorded in rich detail, giving the greatest latitude for image processing

Faithful

Accurate recording of the subject’s color, close to the actual image seen with the naked eye

Monochrome

Filter work and sepia tone with the freedom of digital monochrome

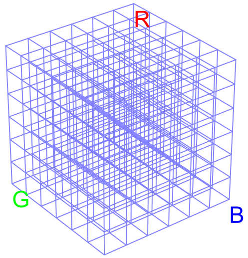
Picture styles

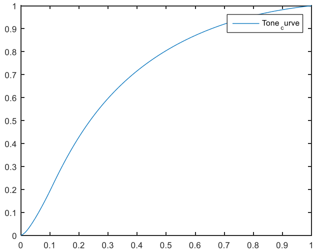



Color Manipulation (Photo-finishing)

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

Nonlinear color manipulation





3D Look up table (LUT)

1D Tone Curve

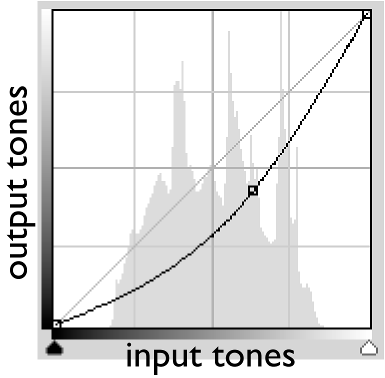
Color manipulation can be implemented using a 3D look up table (LUT) and a 1D LUT tone-curve.
The 3D LUT table acts like a 3D function: $f(X,Y,Z) \rightarrow X',Y',Z'$
The 1D LUT table is applied per channel: $g(X) \rightarrow X', g(Y) \rightarrow Y', g(Z) \rightarrow Z'$

The 3D and 1D LUT can change based on picture style.

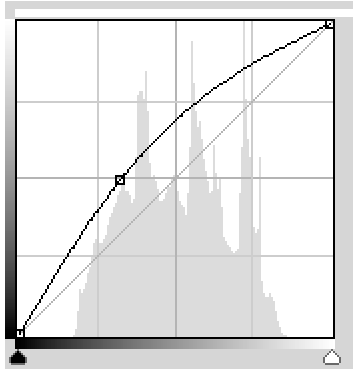
Color Manipulation (Photo-finishing)

Global tone map example (1D LUT)

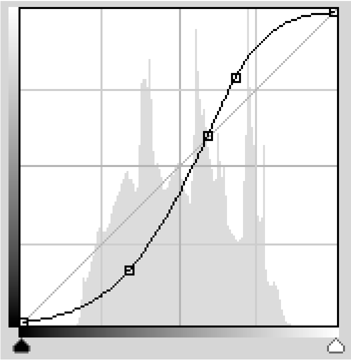
Input



Darkening the image

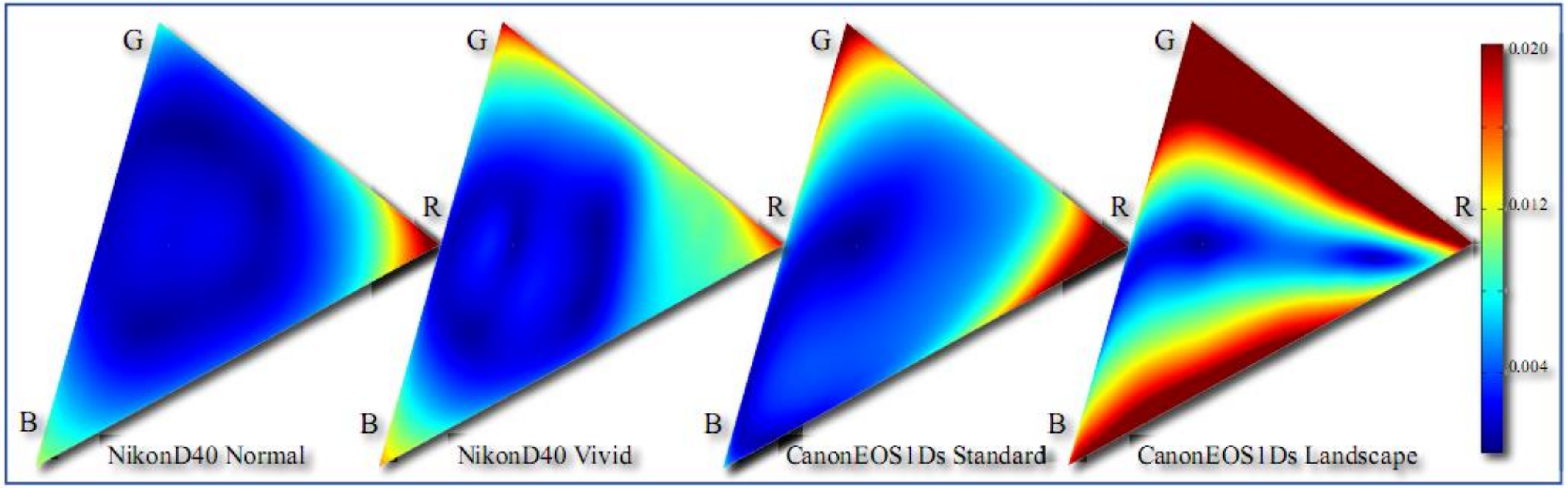


Brightening the image

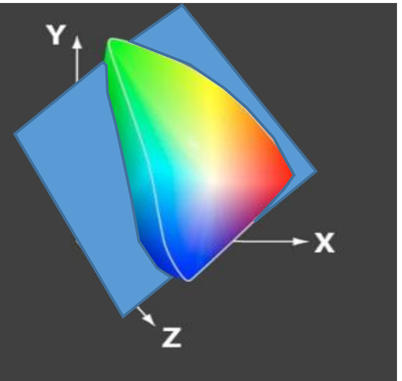


Enhancing contrast (called an S-curve)

3D LUT color manipulation visualization



Visualization as a **displacement map** of a *slice*
of the 3D LUT mapping, warping an input and output value

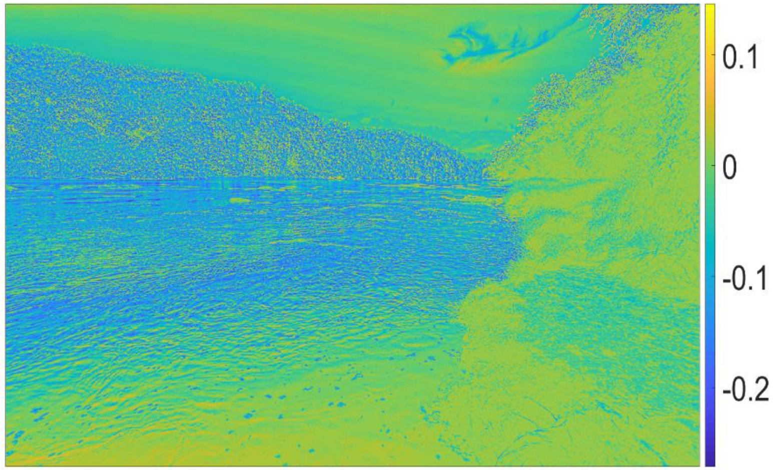


Local tone mapping (LTM)

Global tone-mapping
Camera mode - Manual

Local tone-mapping
Camera mode - Auto

NOTE: On many cameras, esp smartphones, a local tone map is applied as part of the photo-finishing. This helps bring out highlights in the image.



Difference map between image before and after LTM

Color Manipulation (Photo-finishing)

Selective Color Manipulation

- "Select" colors can be manipulated, especially skin tone

Selected color regions
can be manipulated.

Color Imaging Conference 2020

- Papers addressing preferred skin color

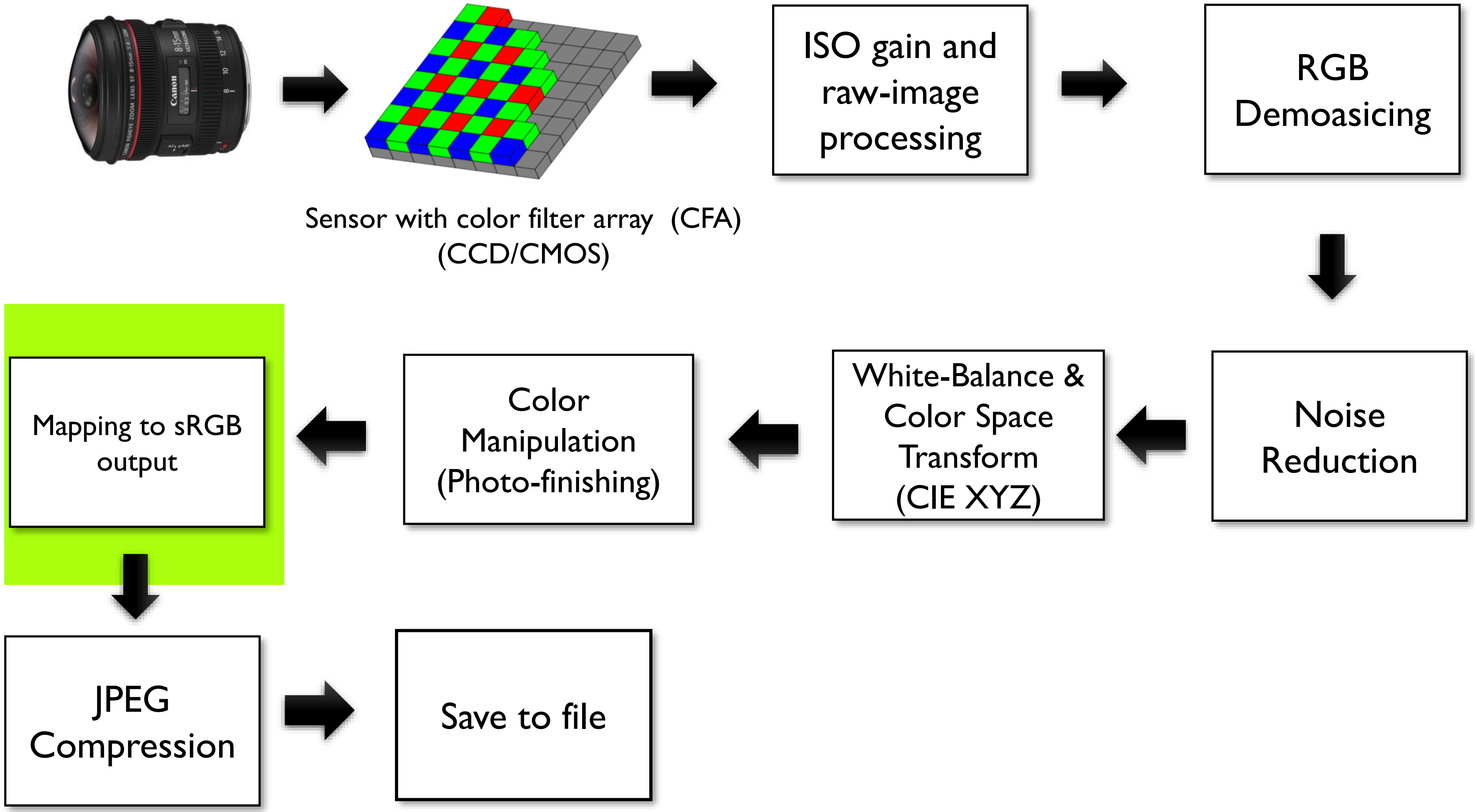
Investigation of Effect of Skin Tone to Facial Attractiveness, *Yan Lu[1], Jie Yang[1], Kaida Xiao[1], Michael Pointer[1], Changjun Li[2], and Sophie Wuerger[3]; [1]University of Leeds (UK), [2]University of Science and Technology Liaoning (China) and [3]University of Liverpool (UK)*

Preferred Skin Colours Observed by Three Ethnic Groups under different Ambient Lighting Conditions, *Mingkai Cao, Ming Ronnier Luo, Rui Peng, Yuechen Zhu, and Xiaoxuan Liu, Zhejiang University, and Guoxiang Liu, Huawei Technologies Co, Ltd. (China)*

Preferred Skin Reproduction Centres for Different Skin Groups, *Rui Peng, Ming Ronnier Luo, Mingkai Cao, Yuechen Zhu, and Xiaoxuan Liu, State Key Laboratory of Modern Optical Instrumentation, and Guoxiang Liu, Hisilicon (China)*

Are We Alike? Skin Color Perception in Portrait Image and AR-based Humanoid Emoji, *Yuchun Yan and Hyeon-Jeong Suk, KAIST (South Korea)*

Typical color imaging pipeline

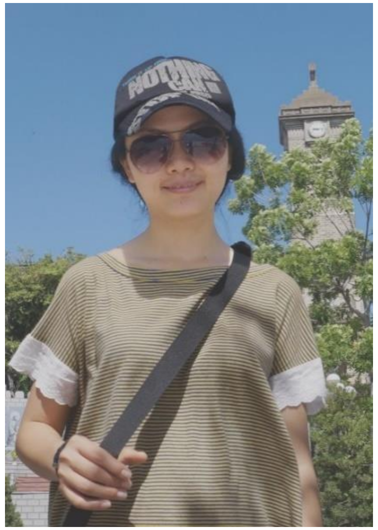


Re-scaling image and sRGB conversion

- The image can be rescaled here

Full frame

rescaled for view-finder



rescaled for preferred output size

Final sRGB conversion (or other color space)

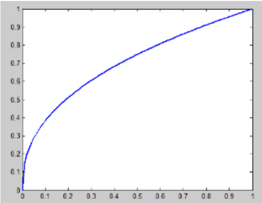
- Map from *photo-finished* CIE XYZ image to sRGB
- Apply the sRGB $(2.2)^{-1}$ gamma encoding

Photo-finished CIE XYZ

Covert to linear sRGB

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

Apply sRGB gamma

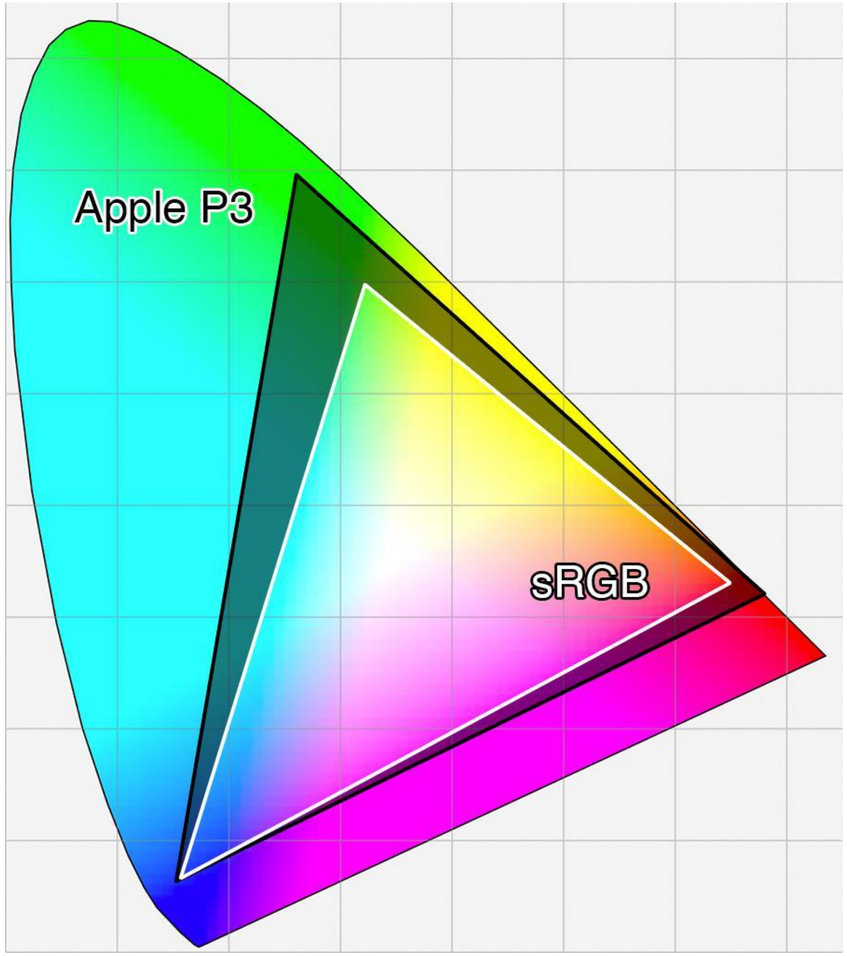


Map to sRGB output

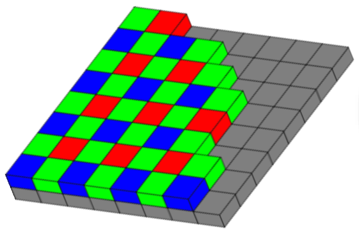
sRGB is known as an "output-referred" or "display-referred" color space. It is intended for use with display devices.

Note: sRGB/JPEG is slowly being replaced

- sRGB was developed for monitors in the 1990s – it is an old standard.
- High Efficient Image Encoding (HEIC)
  - Better compression than JPEG
- Apple iPhone has started to use HEIC to *replace JPEG*
- HEIC supports multiple color spaces. Apple uses Display P3 – a variation on a Digitial Cinema Initiative P3 space.
- The P3 gamut is 25% wider than sRGB
- There is also a gamma encoding similar to sRGB.
- Samsung phones have supported this in the past.



Typical color imaging pipeline



Sensor with color filter array (CFA)
(CCD/CMOS)

ISO gain and raw-image processing

RGB Demoasicing

Noise Reduction

White-Balance & Color Space Transform (CIE XYZ)

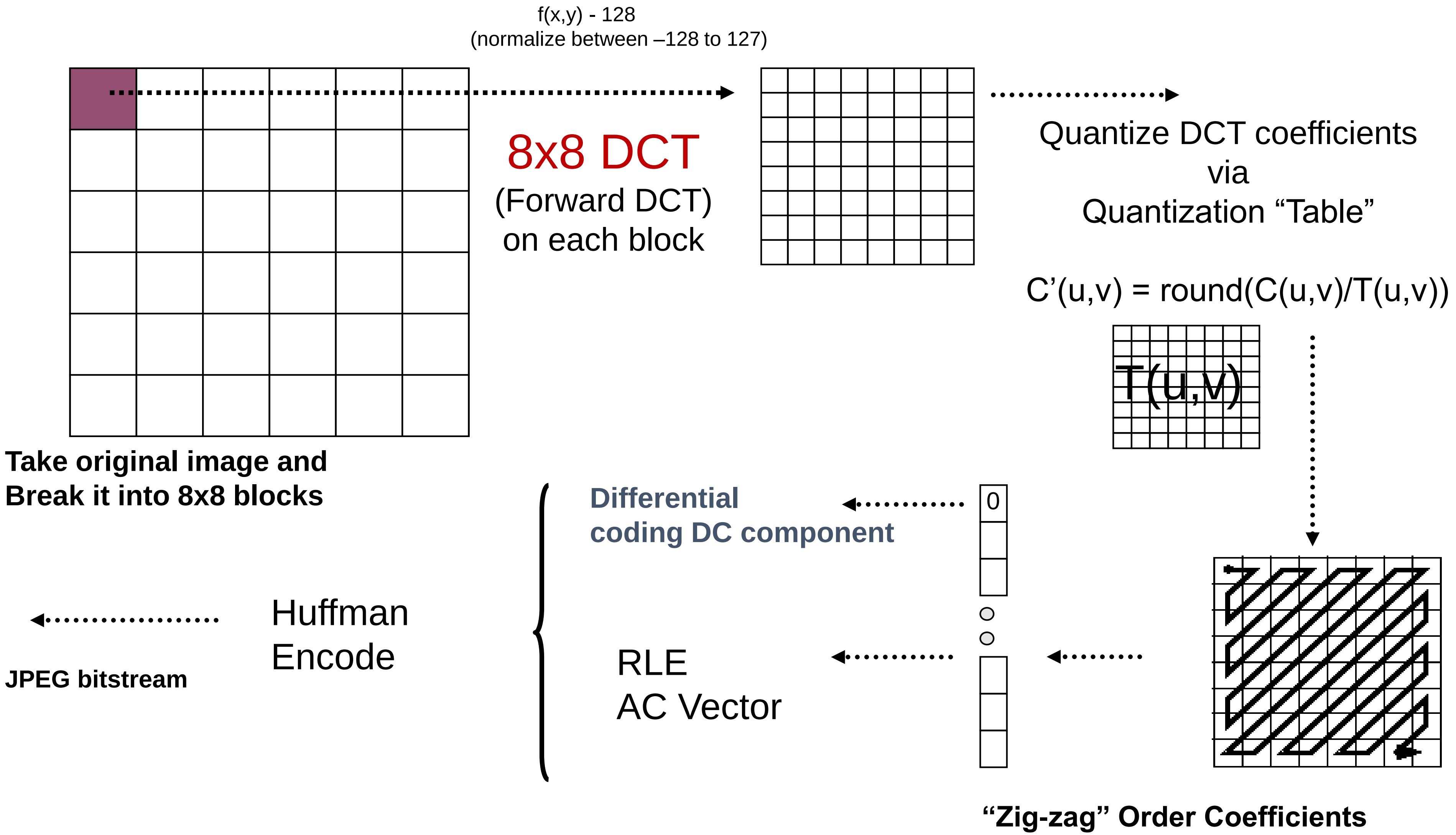
Color Manipulation (Photo-finishing)

Mapping to sRGB output

JPEG Compression

Save to file

JPEG compression scheme



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

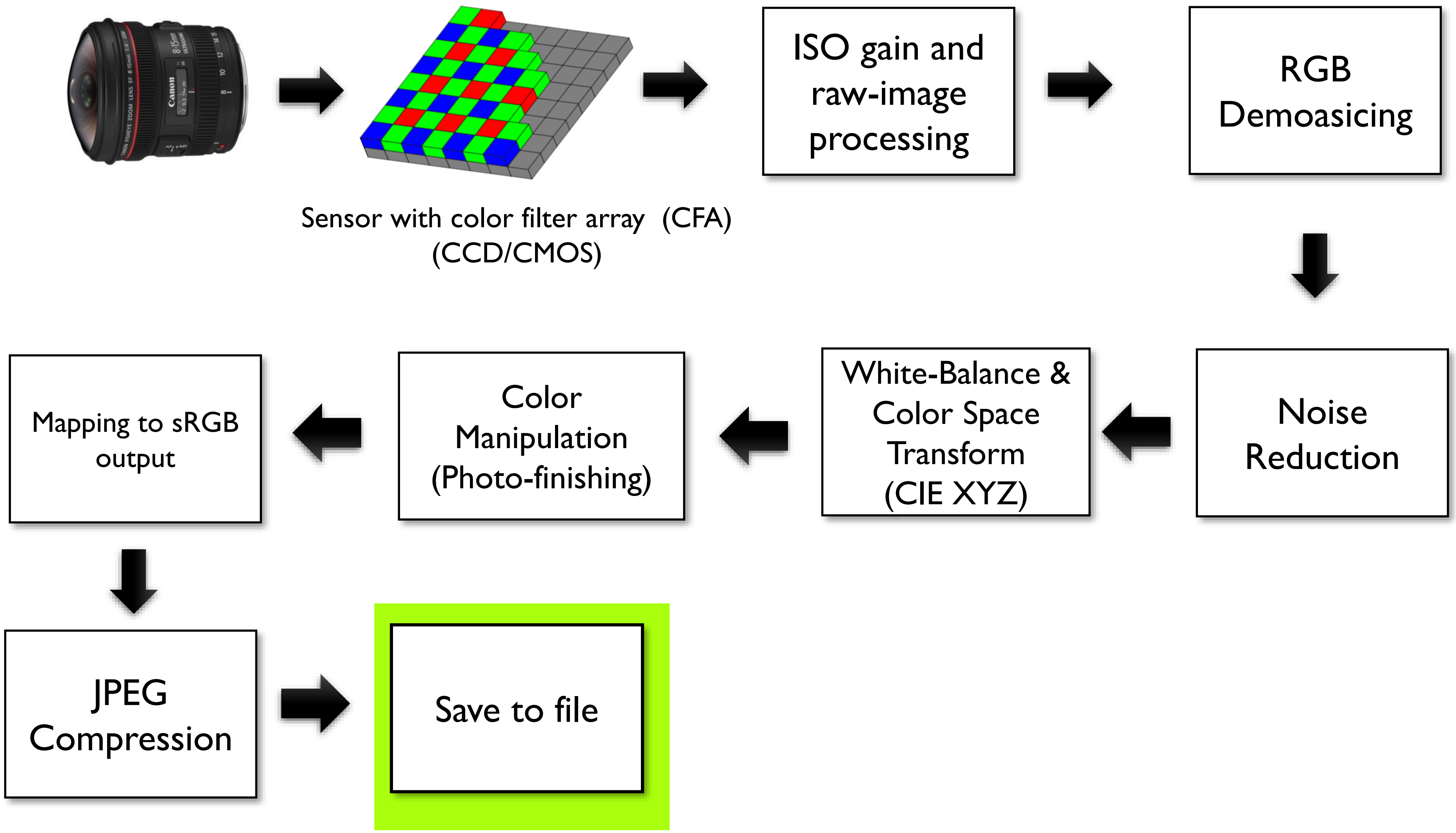
JPEG quality

- The amount of quantization applied on the DCT coefficients amounts to a "quality" factor
  - More quantization = better compression (smaller file size)
  - More quantization = lower quality
- Cameras generally allow a range that you can select

Image from nphotomag.com

JPEG Compression

Save to storage and we are done!



Exif metadata

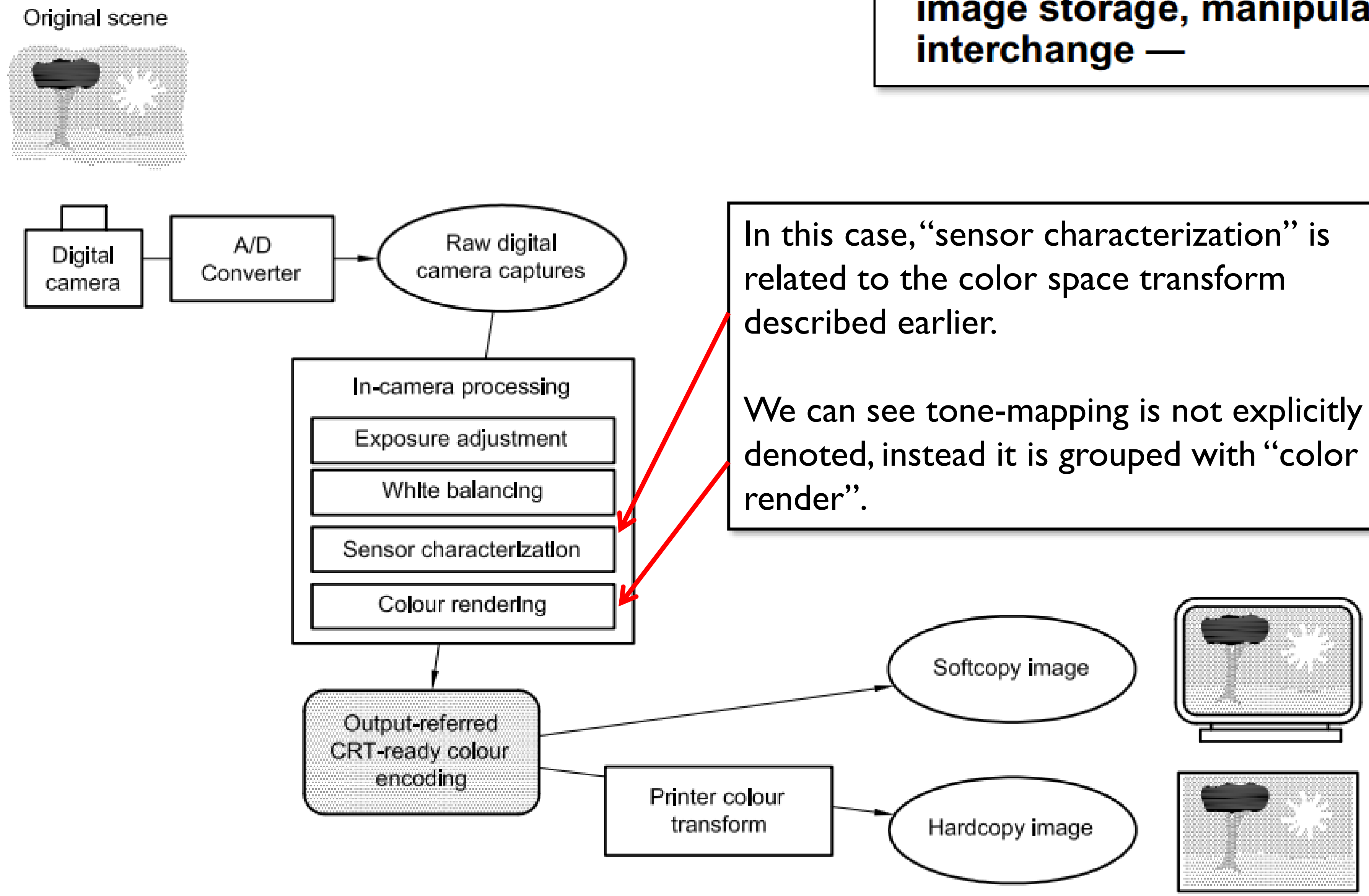
- Exchangeable image file format (Exif)
- Created by the Japan Electronics and Information Technology Industries Association (JEITA)
- Associates meta data with images
  - Date/time
  - Camera settings (basic)
    - Image size, aperture, shutter speed, focal length, ISO speed, metering mode (how exposure was estimated)
  - Additional info (from in some Exif files)
    - White-balance settings, even matrix coefficients of white-balnace
    - Picture style (e.g. landscape, vivid, standard, portrait)
    - Output color space (e.g. sRGB, Adobe RGB, RAW)
    - GPS info
    - More . . .

ICC and color profiles

- International Color Consortium (ICC)
  - In charge of developing several ISO standards for color management
- Promote the use of ICC profiles
- ICC profiles are intended for device manufacturers to describe how their respective color spaces (e.g. sensor RGB) map to canonical color spaces called Profile Connection Spaces (PCS)
- PCS are similar to linking all devices to CIE XYZ, but are more flexible allowing for additional spaces to be defined (beyond CIE XYZ)

From the ICC-ISO 22028

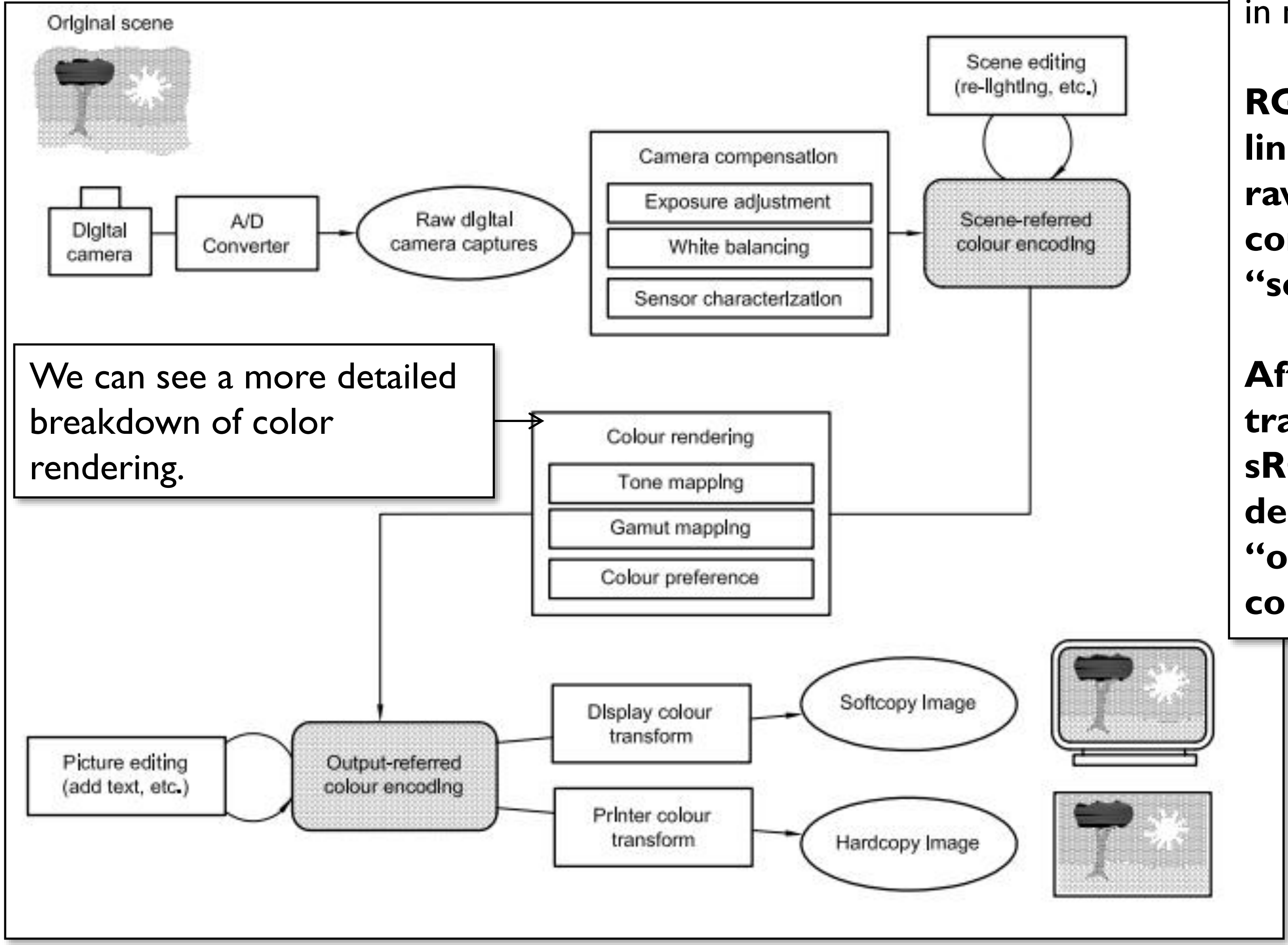
Photography and graphic technology — Extended colour encodings for digital image storage, manipulation and interchange —



In this case, "sensor characterization" is related to the color space transform described earlier.

We can see tone-mapping is not explicitly denoted, instead it is grouped with "color render".

From the ICC-ISO 22028



We can see a more detailed breakdown of color rendering.

This describes a basic digital camera pipeline in more detail.

RGB values linked to the raw-RGB are considered "scene referred".

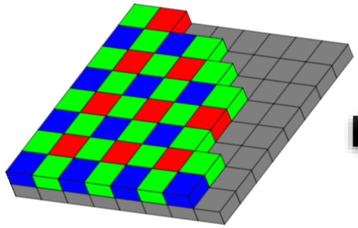
After the color transform to sRGB they are denoted as "output referred" color encodings.

Pipeline comments

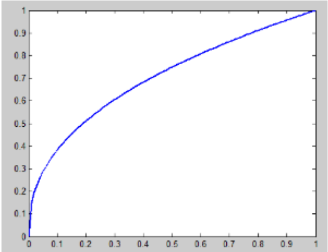
- **Again, important to stress that the exact steps mentioned in these notes only serve as a guide of what takes place in a camera**
- Modern pipelines are more complex, however, you will find steps similar to what was described
- Note: for different camera makes/models, the operations could be performed in different order (e.g. white-balance after demosaicing) and in different ways (e.g. combining sharpening with demosaicing)

What about machine vision cameras?

- Some industrial/machine vision cameras provide minimal ISP processing
- For example, some will only perform white-balance and apply a gamma to the raw-RGB values.
- This means the output is in a camera-specific color space



ISO gain and raw-image processing → RGB Demoasicing → White-Balance (per-channel gain) →



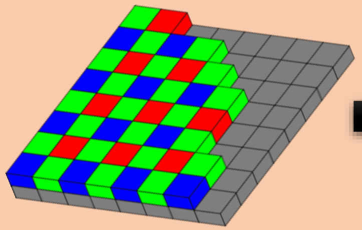
per-channel gamma

Typical machine vision pipeline

Point grey grasshopper camera.

ISP organization

Bayer-Processing Front-End



CMOS
with color filter array

ISO gain and raw-image processing

RGB Demoasicing

Noise Reduction

White-Balance & Color Space Transform (CIE XYZ)

Image-Processing Engine (Photo-Finishing)

Color Manipulation (Photo-finishing)

Mapping to sRGB output

JPEG Compression

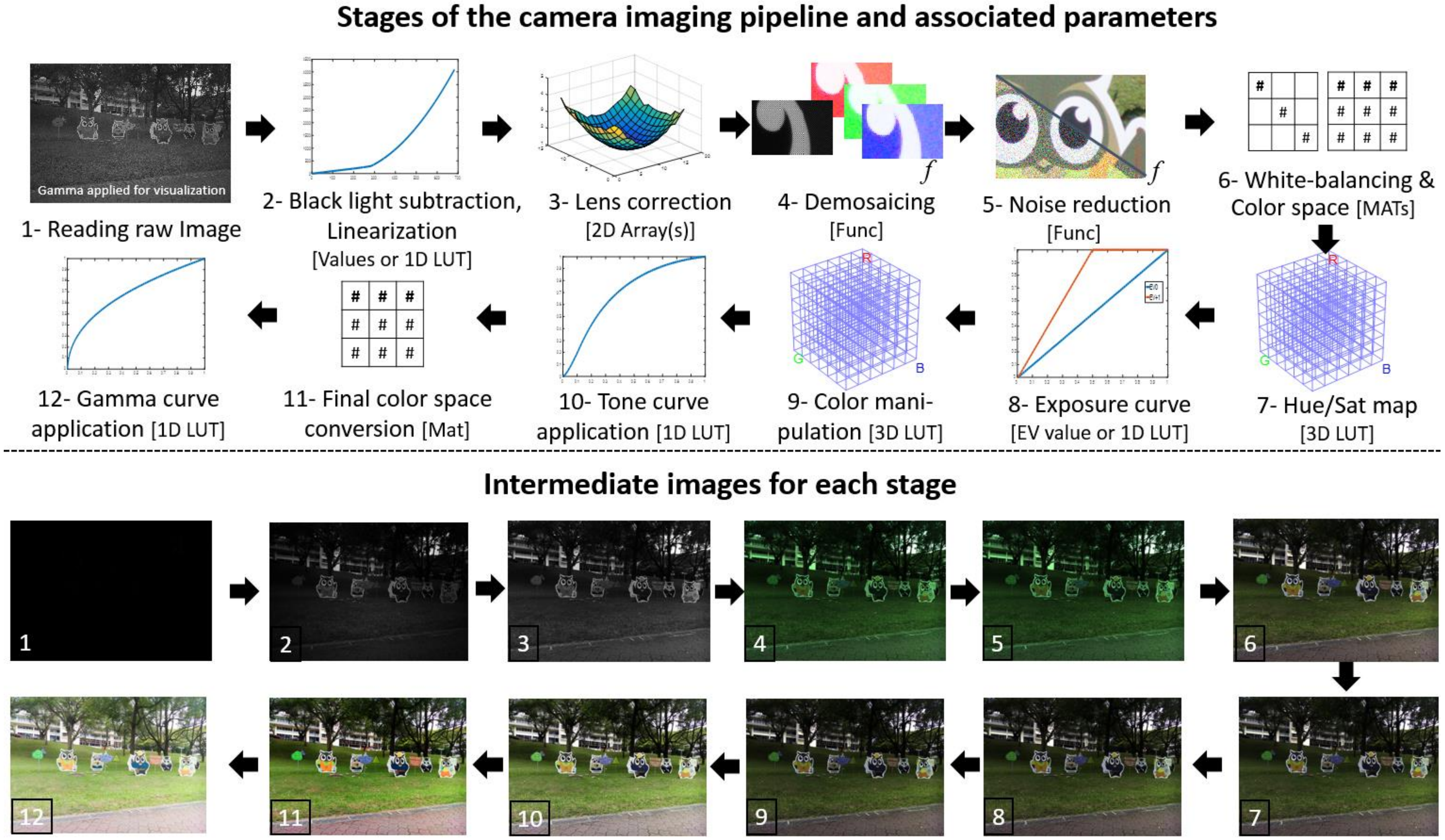
Save to file

ISP hardware will often divide these operations into two components – (1) Bayer-Processing and (2) Image Processing.

Congratulations!

Software camera pipeline

[ECCV'16]
Karaimer and Brown



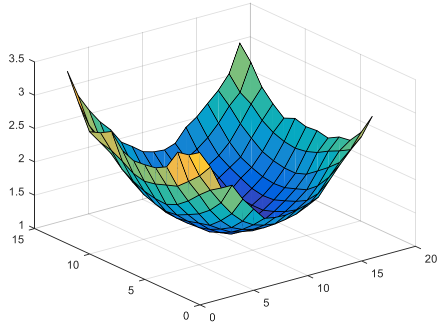
Walking through the pipeline (1)

Camera raw-RGB

Walking through the pipeline (2)

Black level subtraction and linearization + defective pixel mask

Walking through the pipeline (3)



Lens correction
(non-uniform gain)

Walking through the pipeline (4)

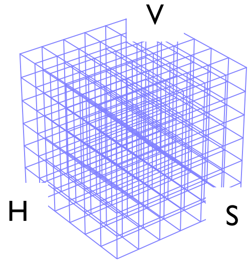
Demosaicing
+ Noise Reduction

Walking through the pipeline (5)

$$\begin{bmatrix} \# & & \\ & \# & \\ & & \# \end{bmatrix} \quad \begin{bmatrix} \# & \# & \# \\ \# & \# & \# \\ \# & \# & \# \end{bmatrix}$$

White balance
+ color space transform
(CIE XYZ/Pro-photo)

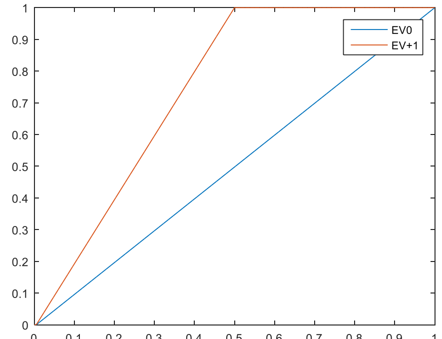
Walking through the pipeline (6)



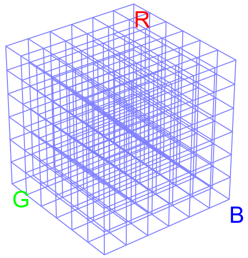
Hue-saturation adjustment

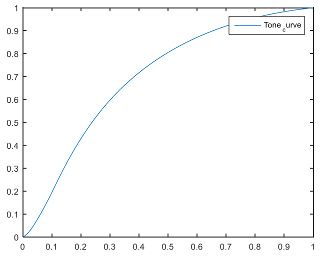
Walking through the pipeline (7)

Exposure Compensation



Walking through the pipeline (8)





Color rendering

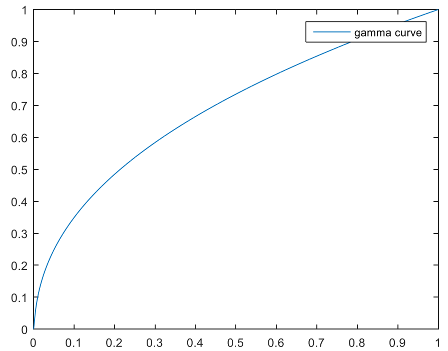
Walking through the pipeline (9)

#	**#**	**#**
#	#	#
#	#	#

sRGB conversion

Walking through the pipeline (10)

sRGB gamma



Lecture Summary

- Cameras mimic the human visual system by using a tri-stimulus color filter array (CFA)
- The camera specific raw-RGB values are converted to a perceptual color space (e.g., CIE XYZ)
  - To do this correctly, computational color constancy must be applied (white-balance)
- The image is then manipulated to make it look aesthetically pleasing
  - Photo-finishing enhances the images visual quality
- The image is then encoded in a display-referred color space for your device (sRGB, AdobeRGB, Display P3)