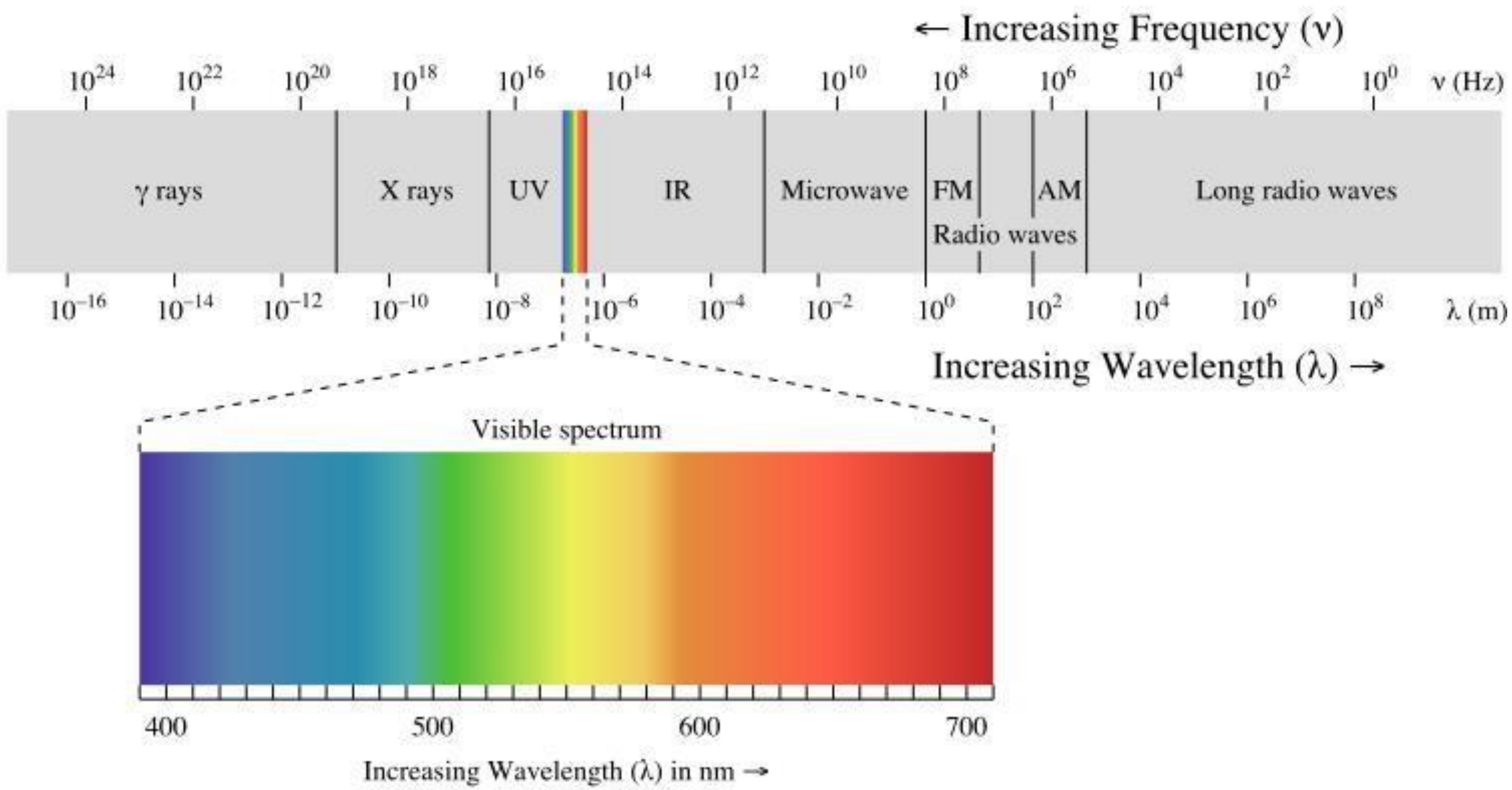
Lecture 10:

Color

Contents

Physics: No notion of "color"

- Light is simply a distribution of photons with different frequencies
- Specified as the "spectrum" of light
- No notion of "opposing color", "saturation", *etc*.

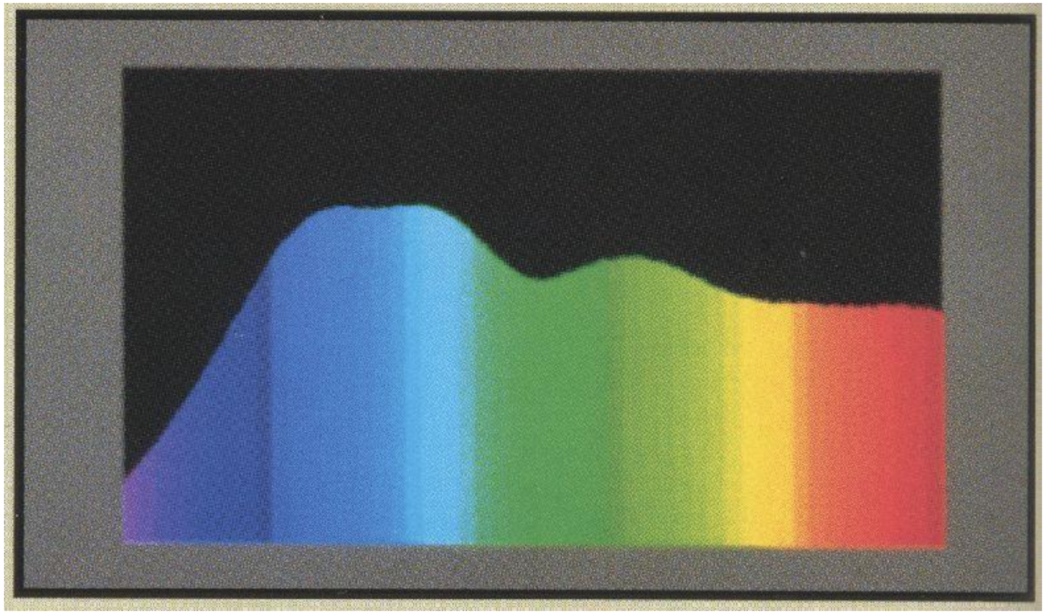


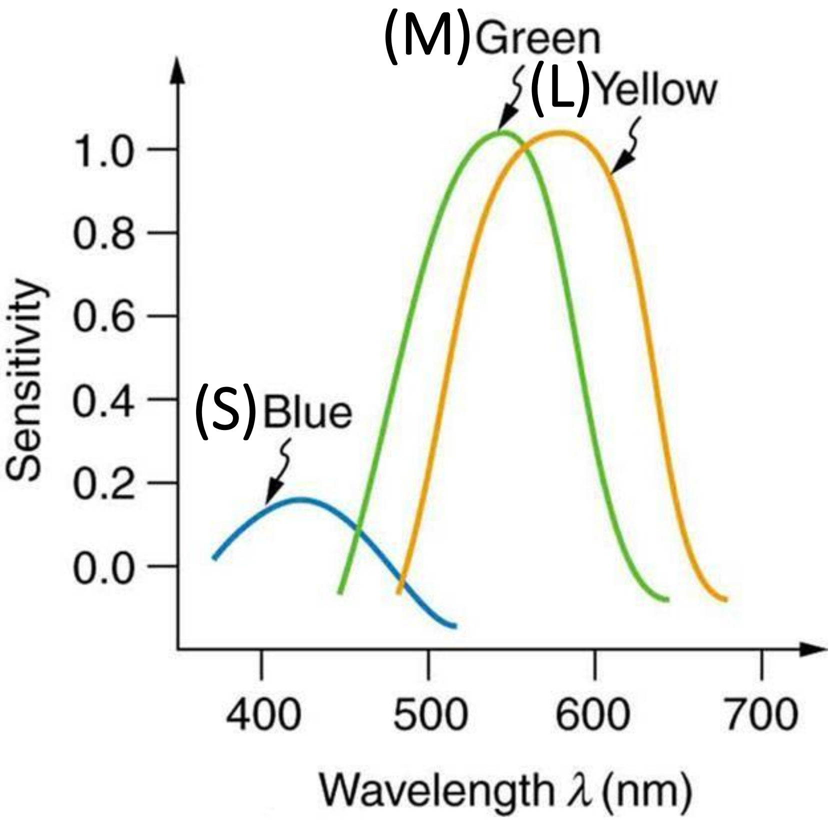
Human color perception

- Cones in retina: 3 different types
- Light spectrum is mapped to 3 different signal channels

Relative sensitivity of cones for different wavelengths

- Long (L, yellow / red), Medium (M, green), and Short (S, blue)



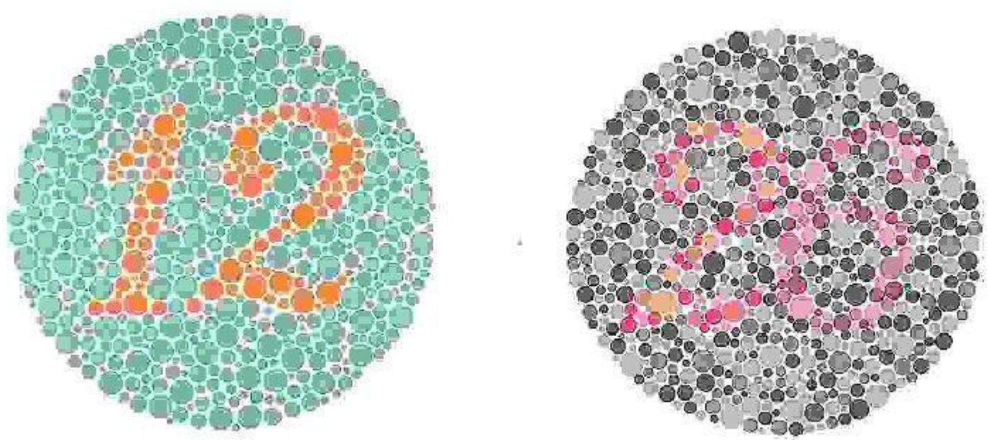


Di-chromaticity (dogs, cats)

- Yellow & blue-violet
- Green, orange, red indistinguishable

Tri-chromaticity (humans, monkeys)

- Red, green, blue
- Color-blindness (most often red-green)
    - Most often men



www.colorcube.com/illusions/clrblnd.html

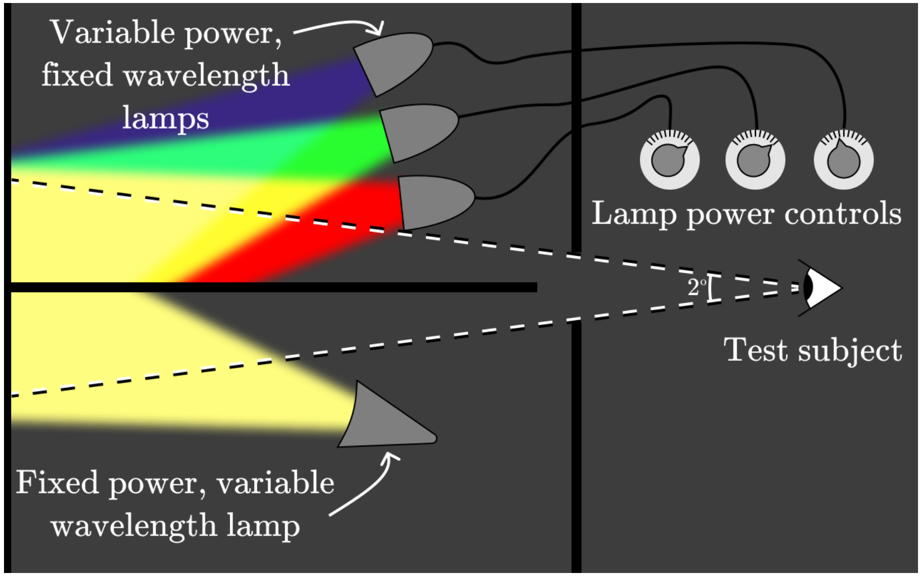
www.lam.mus.ca.us/cats/color/

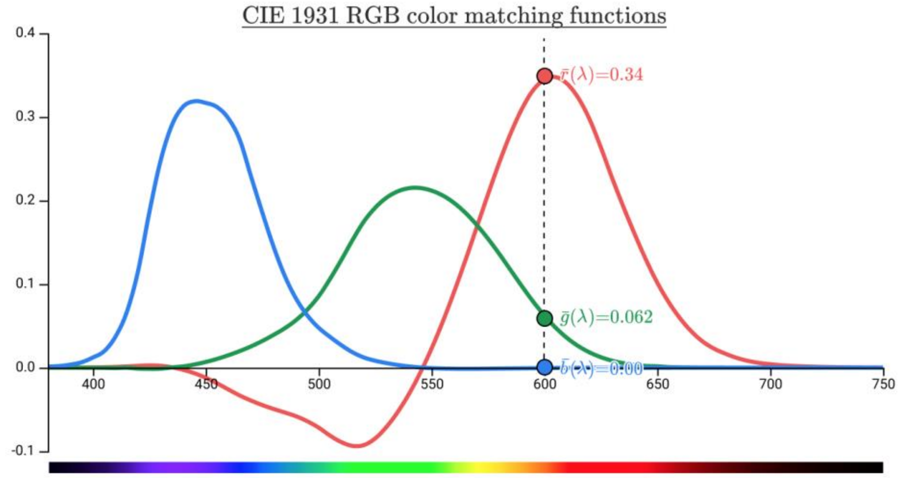
Observation

- Any color (left-hand side test source) can be matched using 3 linear independent reference primary colors (right-hand side)
- May require “negative” contribution of primary colors ⇔ positive contribution to test color
- “Matching curves” describe values for a certain set of primaries to match a mono-chromatic spectral test color of given intensity

Main results of key Color Matching Experiments

- Color perception forms a linear 3-D vector space
- Superposition holds





CIE color matching experiments

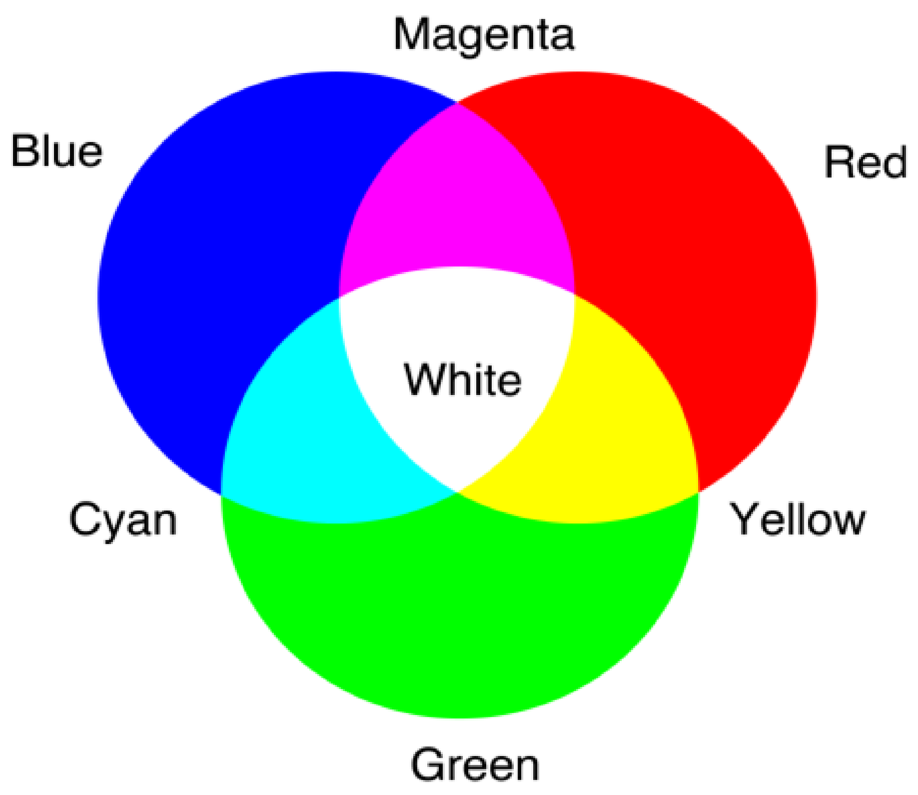
- First experiment [Guild and Wright, 1931]
  - Group of ~12 people with "normal" color vision (from London area)
  - 2-degree visual field (fovea only)
- Other experiment in 1964
  - Group of ~50 people (from different countries)
  - 10-degree visual field
  - More appropriate for larger field of view, but rarely used since similar

CIE-XYZ color space

- Transformation to a set of *virtual primaries*
  - Simple basis transform in 3D color space
- Goals:
  - Abstract from concrete primaries used in experiment
  - All matching functions should be positive
  - One primary should be roughly proportionally to light intensity (luminosity function $V(\lambda)$)

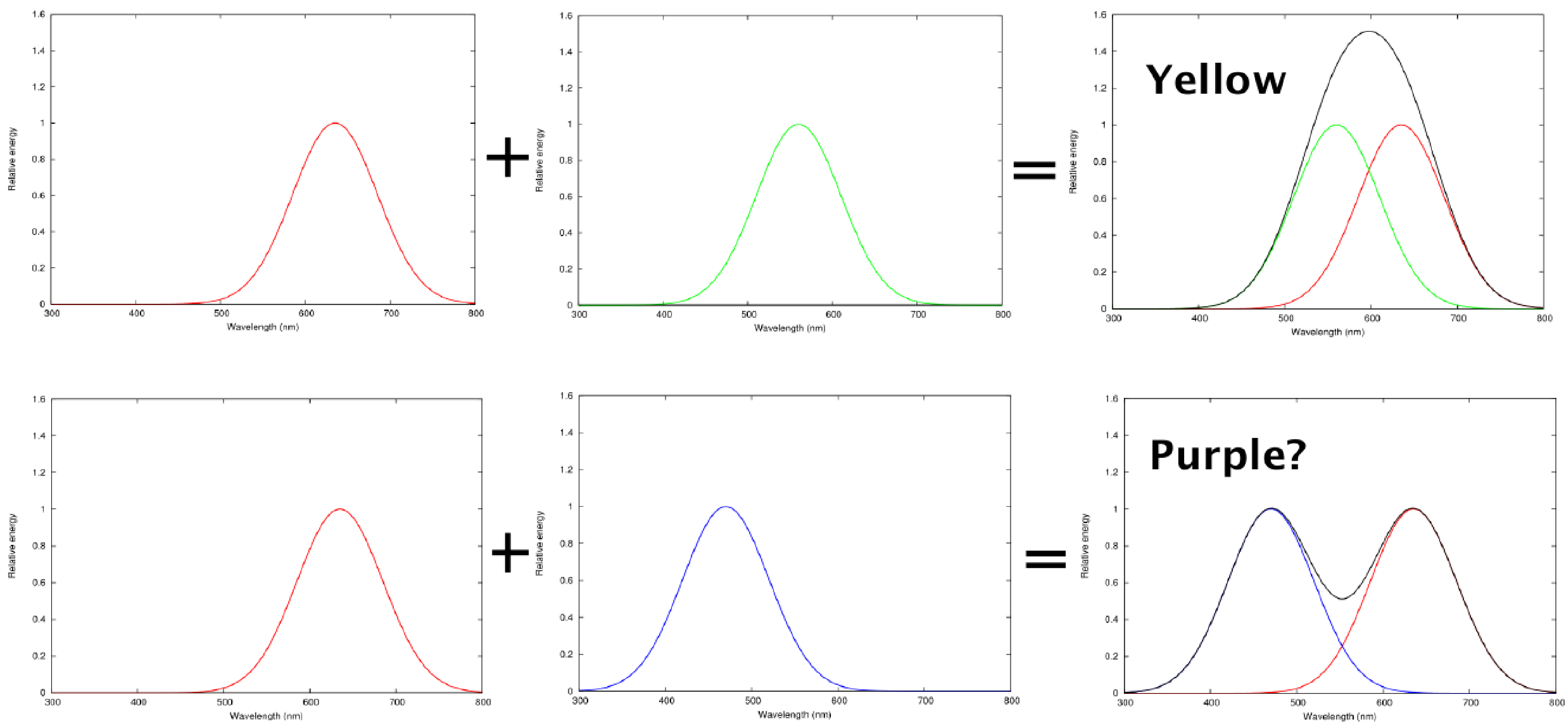
Light mixing

- The color of light coming from a particular source is constituted through an **additive color scheme**



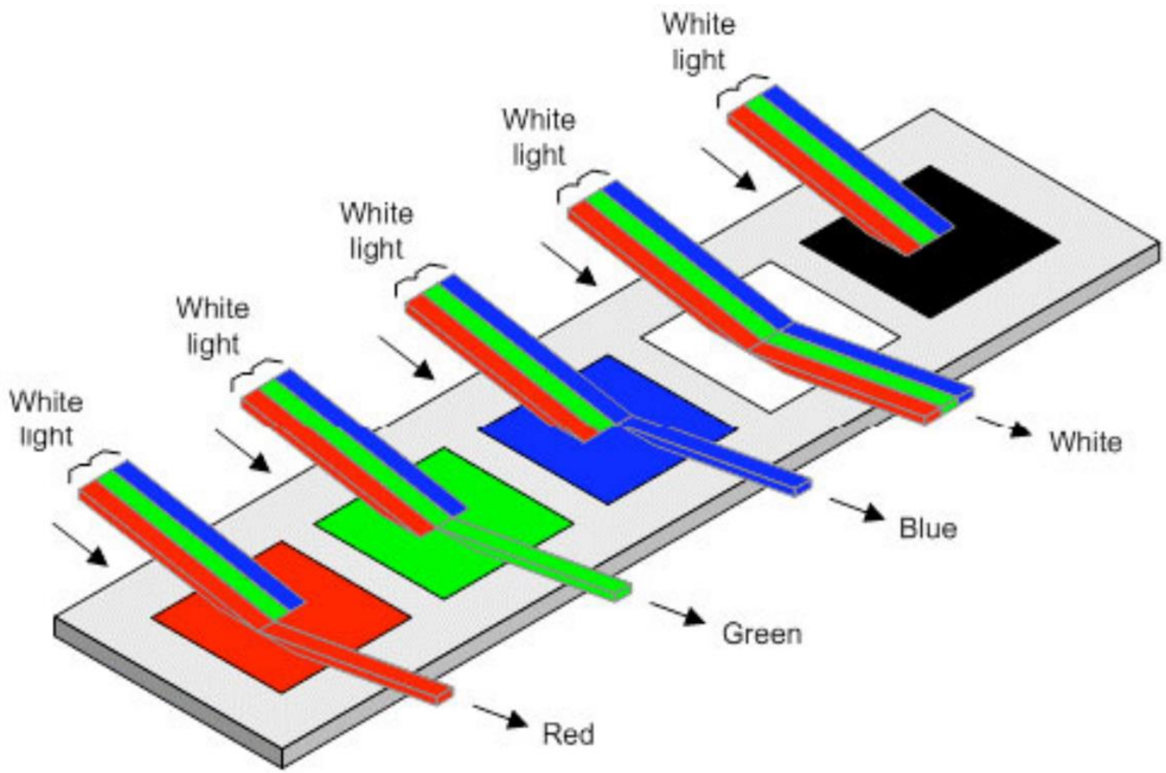
Adding energy

- The energy of light sources contributing particular frequency are simply combined into one spectrum



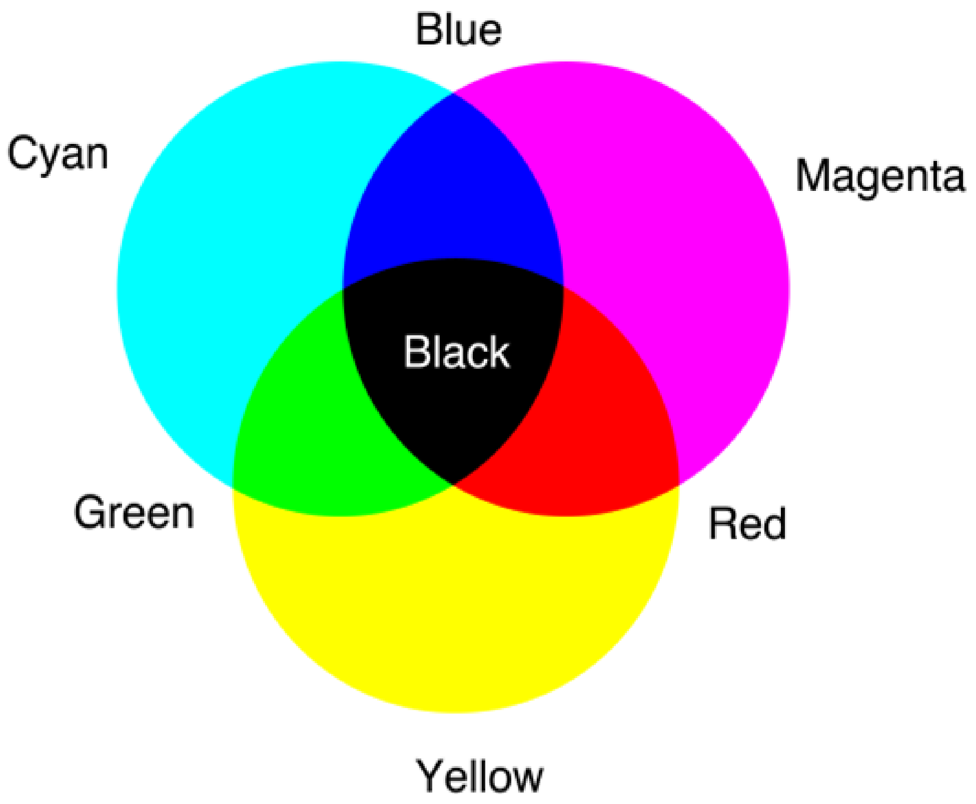
Why objects have colors?

- When light of a particular make-up of frequencies strikes a surface
- (a part of) some frequencies are eliminated (absorbed by the surface)
- (a part of) some frequencies are reflected



Color creation

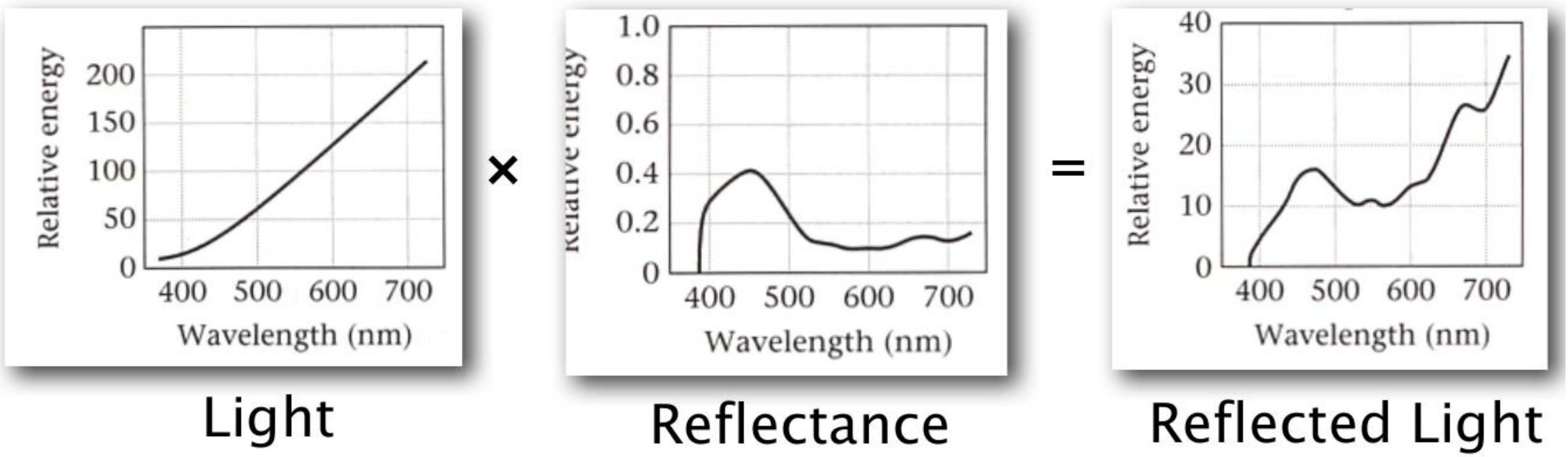
- The color that we perceive on the surface of an object or after light goes through a filter is described by the **subtractive color scheme**



Result

- The light reflected from an object is a function of incident light and the **reflectance** properties of the object (the opposite of absorbance)

$$R(\lambda) = r(\lambda)E(\lambda) = (1 - a(\lambda))E(\lambda)$$



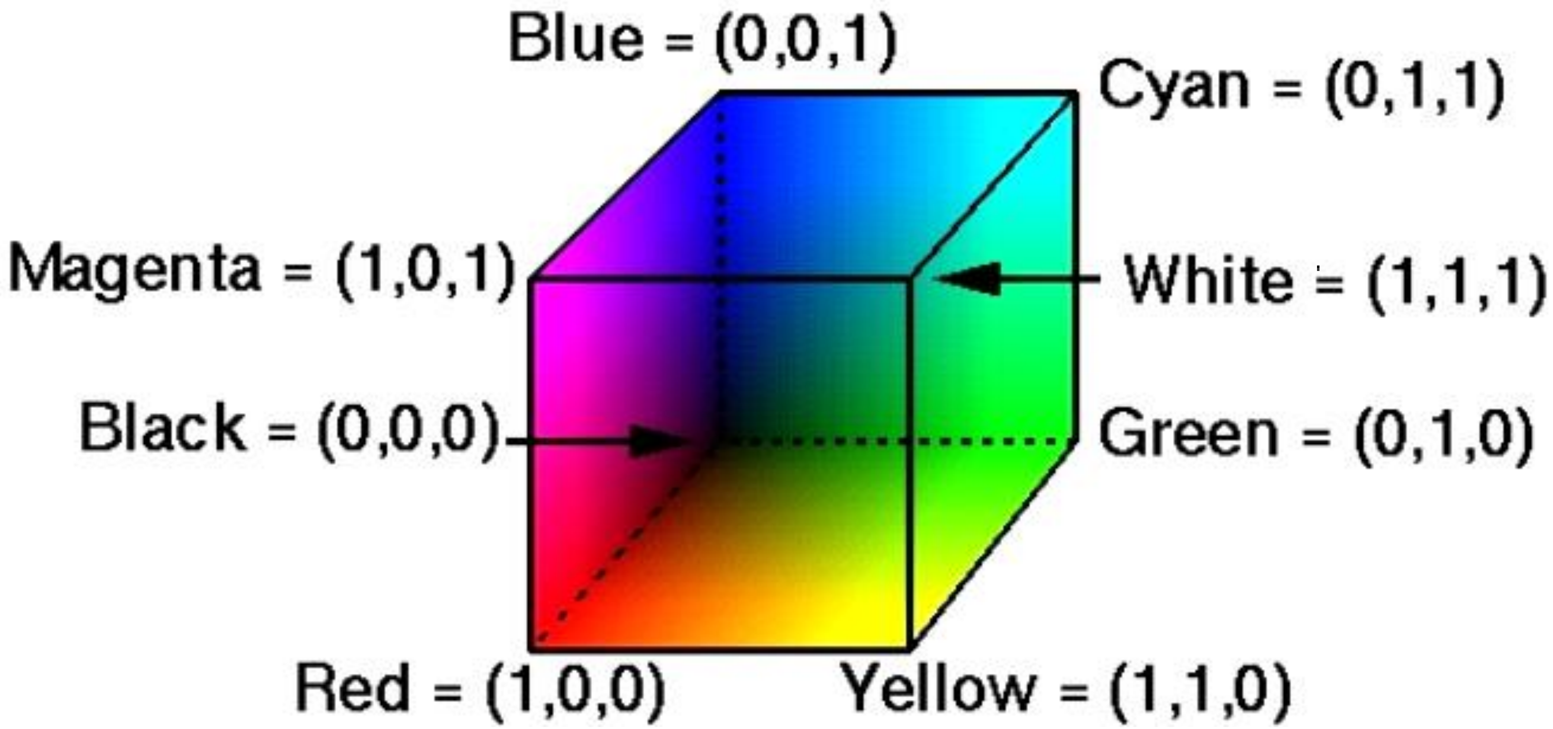
- **Radiometry** is the science of quantifying these and other phenomena concerning the behavior of light and its perception

Color model

- Since the human eye works with only 3 signals (ignoring rods), we work with 3 signals for
  - Images
  - Displays
  - Printers
  - ...
- Image formats store values in the R, G, and B channels
- The values stored are typically between 0 and 255 (unless its HDR)
  - How many colors can we represent?
- The relative values give the color, and the overall values give the intensity
- The computer monitor / display can be used to further increase or decrease the overall global image intensity (brightness / darkness)

RGB color cube

- A symbolic representation of our color spectrum (**gamut**)
- Map each primary color in the RGB color space to the unit distance along the x, y, z axes
  - (0,0,0) → (1,1,1)
  - The color cube represents all possible colors
    ...in our very limited perception of them!!

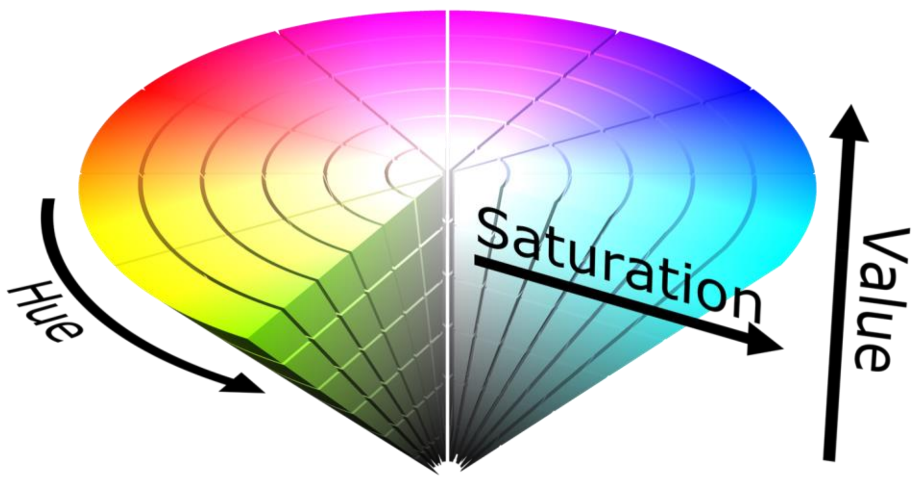


RGB is not the only possible representation!

HSV: Hue, Saturation and Value

- **Hue**: rainbow of colors (“wavelength”)
- **Saturation**: distribution of intensity for a particular color
- **Value**: relative lightness or darkness of a particular color

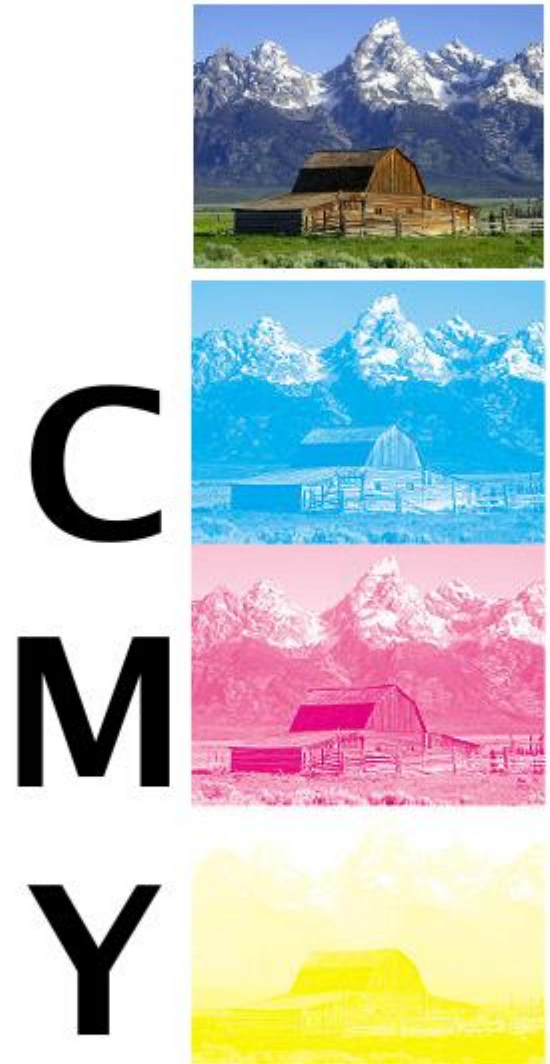
great for user interfaces, “color picker”



RGB is not the only possible representation!

CMY: Cyan, Magenta, Yellow

- The three primary colors of the subtractive color model
- Partially or entirely masking / filtering (=absorbing colors) a white background
- The ink reduces the light that would otherwise be reflected
- Equal mixtures of C, M, Y should (ideally) produce all shades of gray



CMY(K) color model

Advantages of using black ink:

- Most fine details are in printed with the Key color (K=black in most cases)
- Less dependency on (perfectly) accurate color alignment
- Mixtures of 100% C, 100% M and 100% Y do not give perfect black in practice

Reduce bleeding and time to dry

Save colored ink

RGB color cube

- A symbolic representation of our color spectrum (**gamut**)
- Map each primary color in the RGB color space to the unit distance along the x, y, z axes
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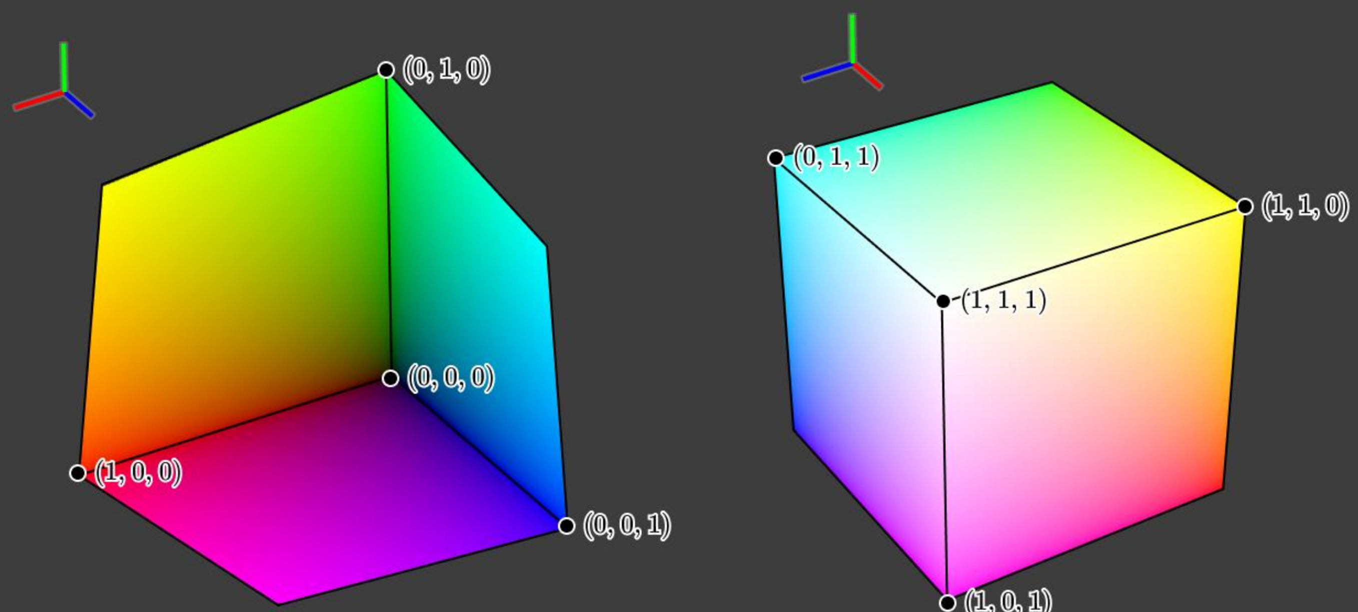
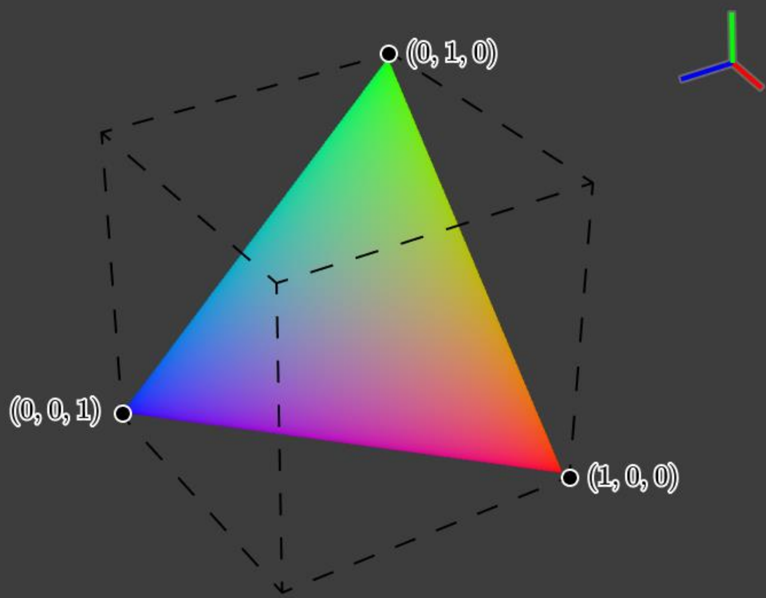
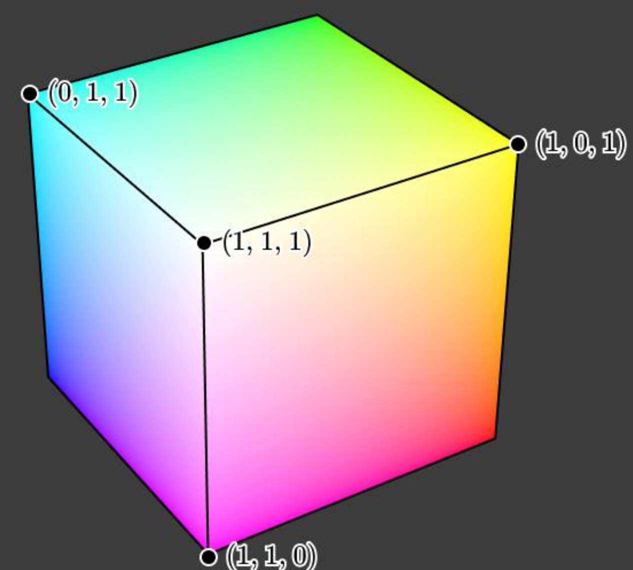


RGB color cube

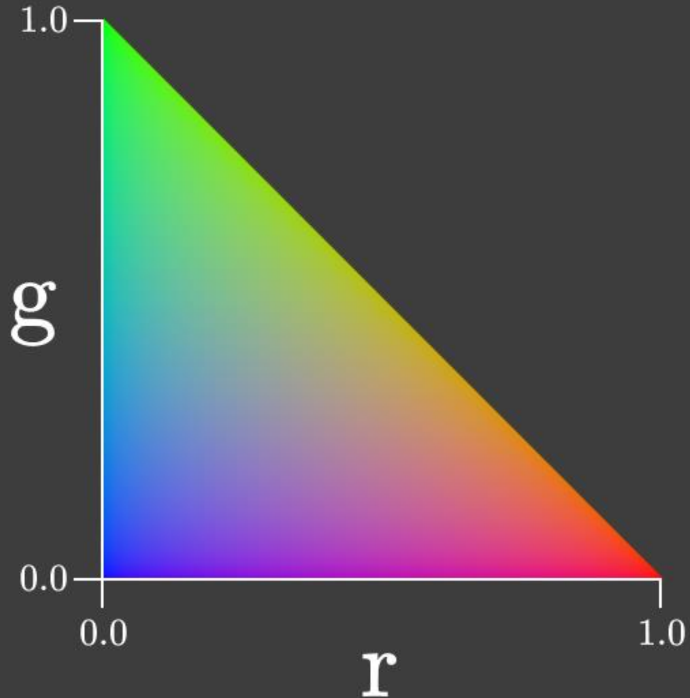
- Slice the cube diagonally across the plane containing (1, 0, 0), (0, 1, 0) and (0, 0, 1)
- This triangle slice of the cube has the property that R + G + B = 1, and we can use R + G + B as an approximation of lightness





Chromaticity

- If we take a top-down view of the triangular slice, then we get a two - dimensional representation of color called **chromaticity**
- This particular kind is called **rg-chromaticity**
- Chromaticity gives us information about the ratio of the primary colors independent of the lightness.



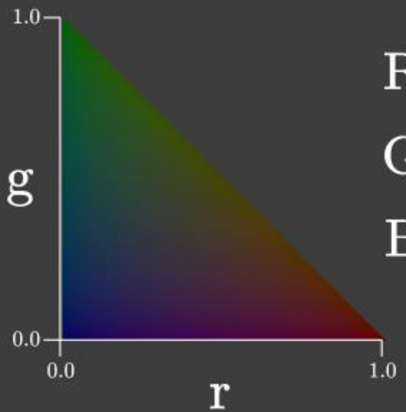
$$R = r$$

$$G = g$$

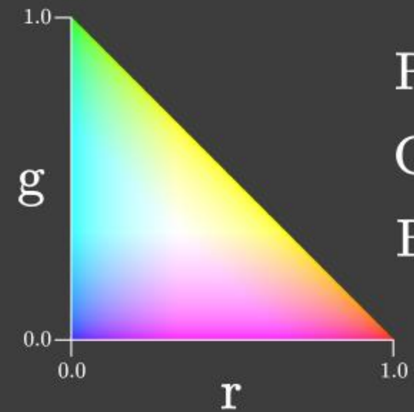
$$B = 1 - g - r$$

Chromaticity

- We can have the same chromaticity at many different intensities



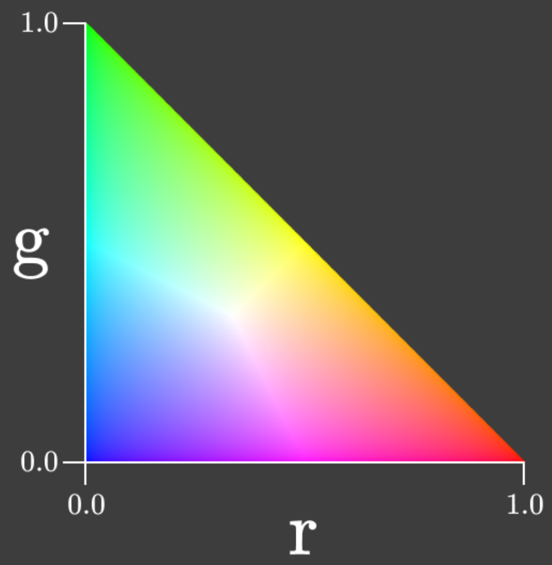
$$R = 0.125\, r$$
$$G = 0.125\, g$$
$$B = 0.125\, (1 - g - r)$$



$$R = 3r$$
$$G = 3g$$
$$B = 3(1 - g - r)$$

Chromaticity

- We can have the same chromaticity at many different intensities
- We can even make a chromaticity graph where the intensity varies with r & g in order to maximize intensity while preserving the ratio between R, G, and B
- Chromaticity is a useful property of a color to consider because it stays constant as the intensity of a light source changes, so long as the light source retains the same spectral distribution. As you change the brightness of your screen, chromaticity is the thing that stays constant!



$$k = \max(r, g, 1 - g - r)$$

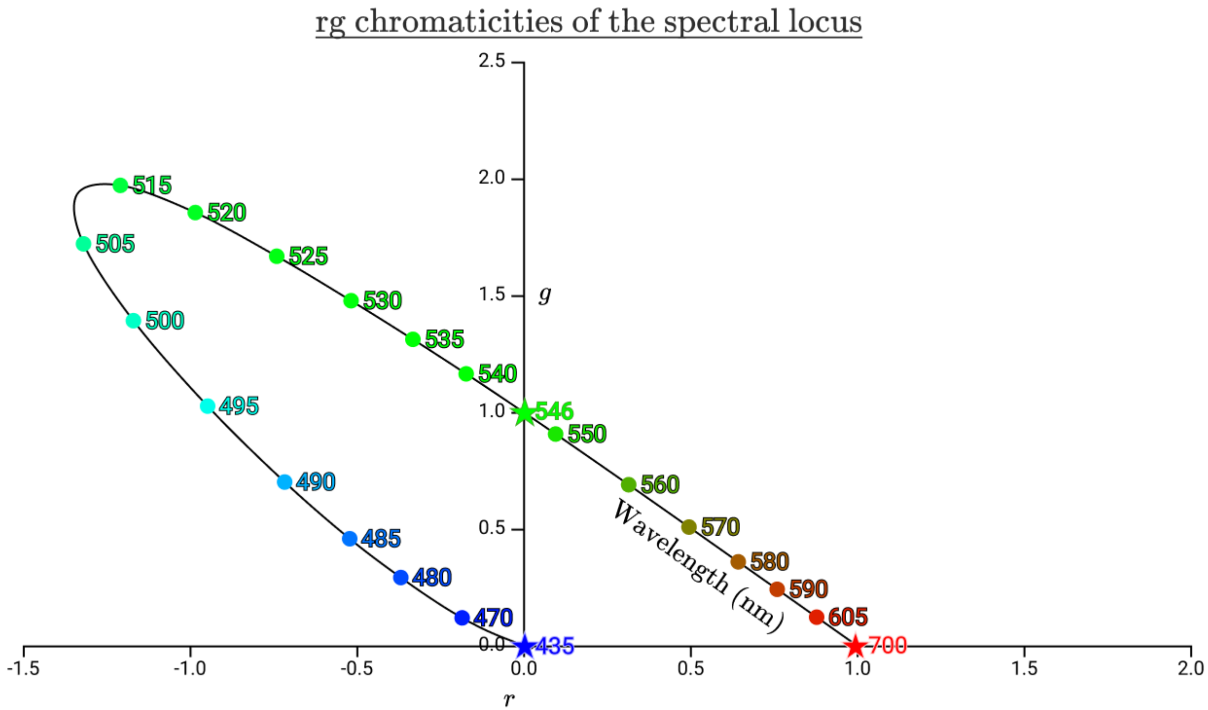
$$R = r/k$$

$$G = g/k$$

$$B = (1 - g - r)/k$$

Gamuts and the spectral locus

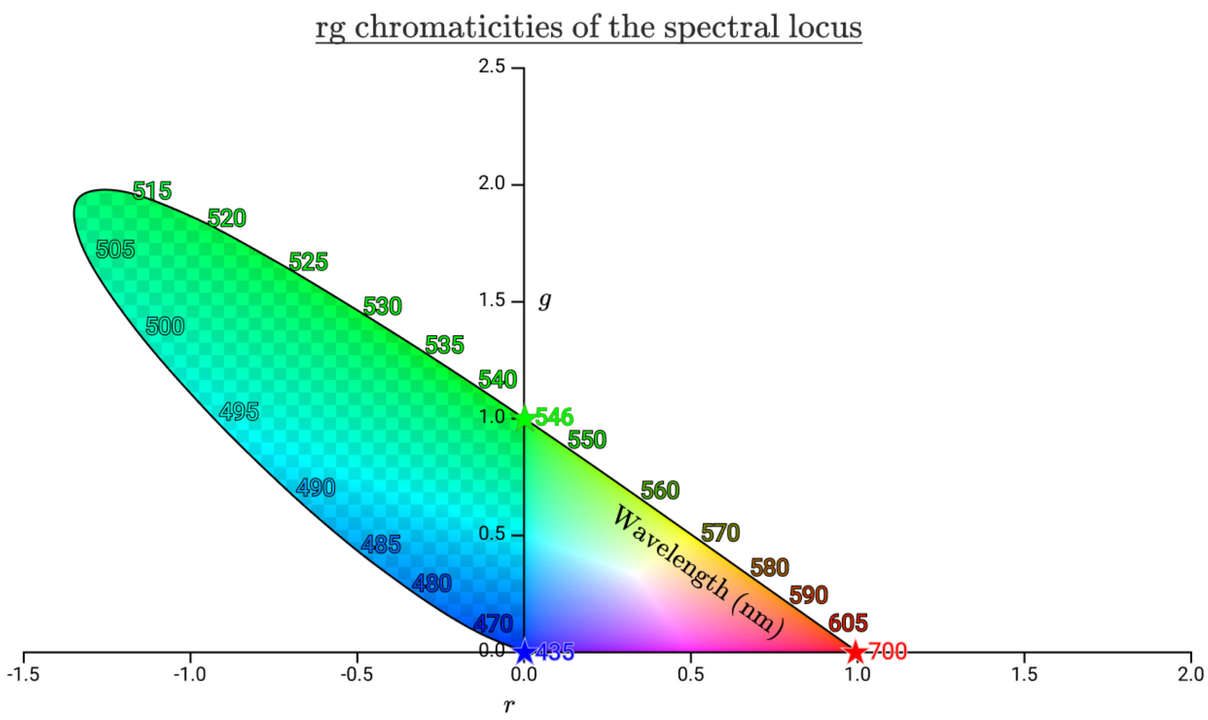
- If we take our color matching functions $r(\lambda)$, $g(\lambda)$ and $b(\lambda)$ and use them to plot the rg-chromaticities of the spectral colors, we end up with a plot like this:



- The black curve with the colorful dots on it shows the chromaticities of all the pure spectral colors. The curve is called the **spectral locus**. The stars mark the wavelengths of the variable power test lamps used in the color matching experiments.

Gamuts and the spectral locus

- If we overlay our previous chromaticity triangles onto this chart, we're left with this:



- The area inside the spectral locus represents all of the chromaticities that are visible to humans. The checkerboard area represents chromaticities that humans can recognize, but that *cannot* be reproduced by any positive combination of 435nm, 546nm, and 700nm lights. From this diagram, we can see that we're unable to reproduce any of the spectral colors between 435nm and 546 nm, which includes pure cyan.

Standardized imaginary primaries CIE XYZ (1931)

- In 1931, the International Comission on Illumination convened and created two color spaces
  1. The RGB color space we've already discussed, which was created based on the results of Wright & Guild's color matching experiments
  2. The XYZ color space

- The goals of the XYZ color space was to have positive values for all human visible colors
  - Make all chromaticities fit in the range [0, 1] on both axes

- To achieve this, a linear transformation of RGB space was carefully selected

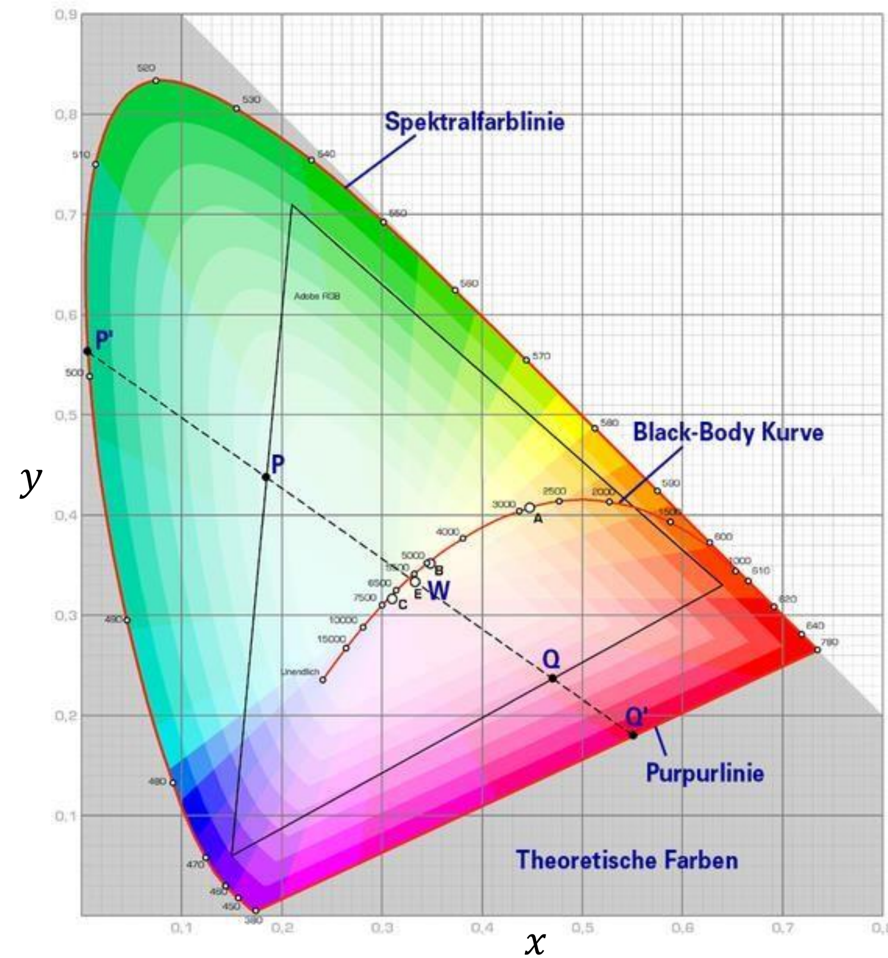
$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \frac{1}{b_{21}} \begin{bmatrix} b_{11} & b_{12} & b_{13} \\ b_{21} & b_{22} & b_{23} \\ b_{31} & b_{32} & b_{33} \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix} = \frac{1}{0.17697} \begin{bmatrix} 0.49 & 0.31 & 0.2 \\ 0.177 & 0.812 & 0.011 \\ 0 & 0.01 & 0.99 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

xy Chromaticity Diagram

- The analog of rg-chromaticity for XYZ space is **xy-chromaticity** and is the more standard coordinate system used for chromaticities diagrams
  - 2D plot over x and y
  - Points called *“color locations”*

Locations of interest

- Pure spectral colors (red line)
- Purple line: interpolate red & violet
- White point: ~(1/3, 1/3)
  - Device dependent / eye adaptation
- Black-body curve



Gamut

- Gamuts are typically represented by a triangle placed into an xy-chromaticity diagram
- Device-independent

Device color gamut

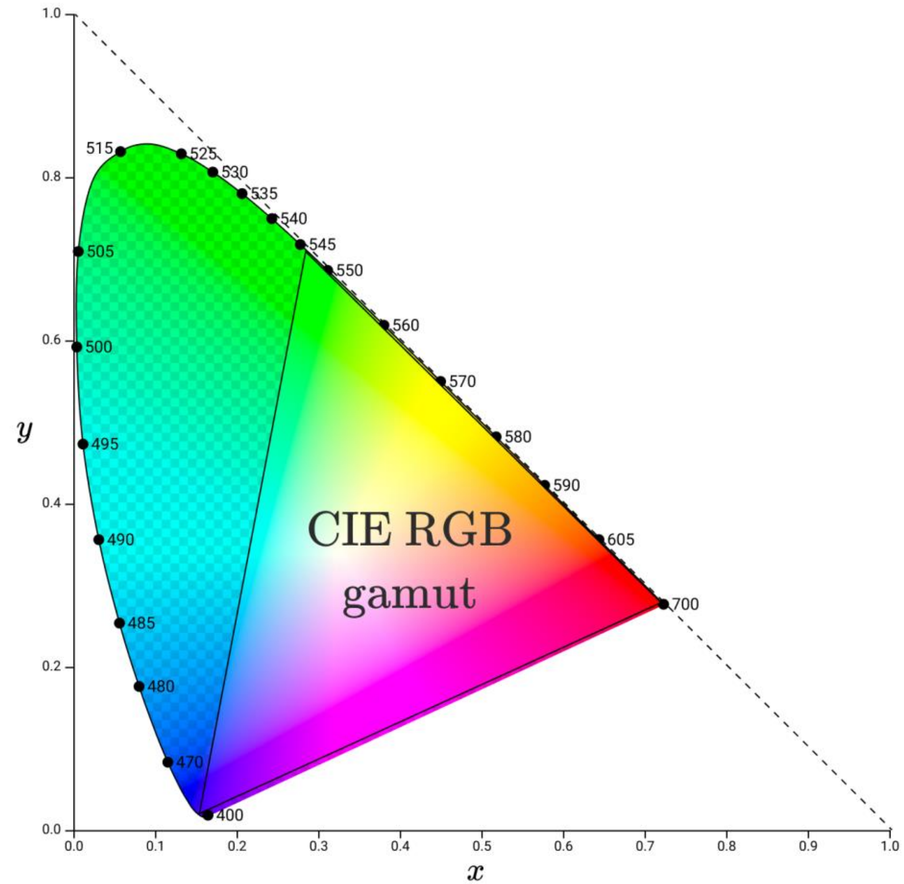
- Triangle inside color space defined by additive color blending

RGB colors

- Colors defined as linear combinations of primary colors of the device

RGB space gamut

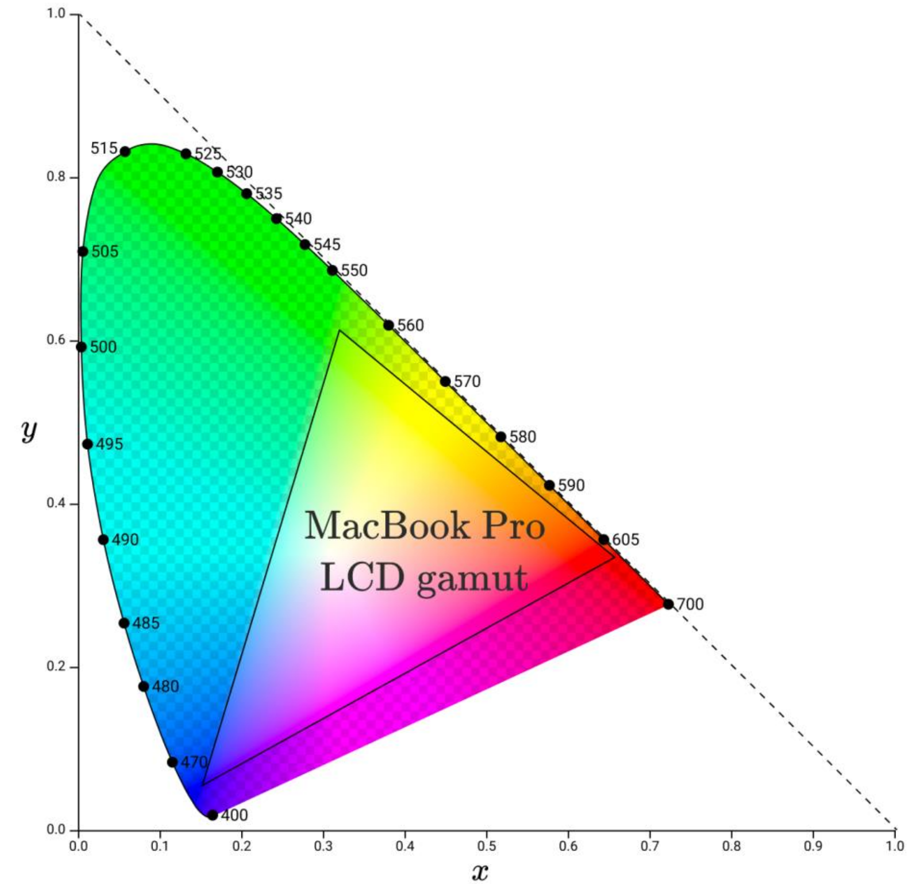
- Device (monitor/projector) dependent (!!!)
    - Choice of primaries used (lamps, LEDs)
    - Weighting of primaries (filters)
- White-point / temperature adjustment
    - Virtually moves colors within the gamut



The gamut of CIE RGB in xy-space

Gamut compression / mapping

- What to do if colors lay outside of the printable area?
  - Scaling, clamping, other non-linear mappings
- Each device should replace its out-of-gamut colors with the nearest approximate achievable colors
- Possible significant color distortions in a printed → scanned →displayed image



The gamut of P3 in xy-space

Gamut compression / mapping

- What to do if colors lay outside of the printable area?
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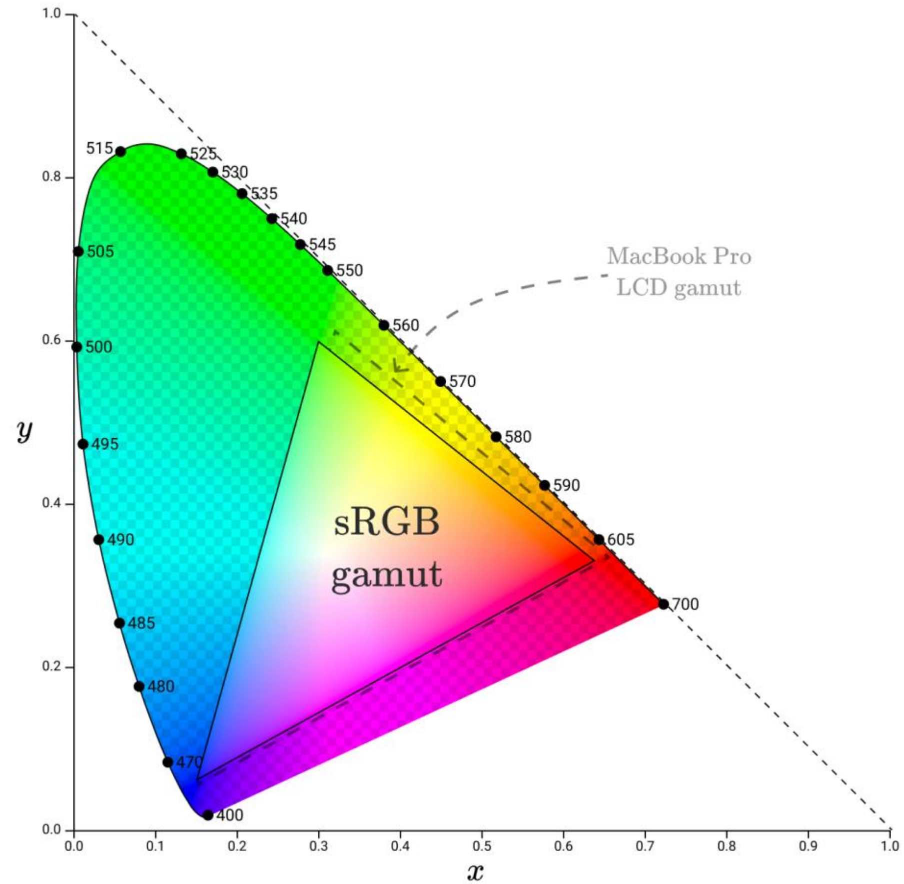
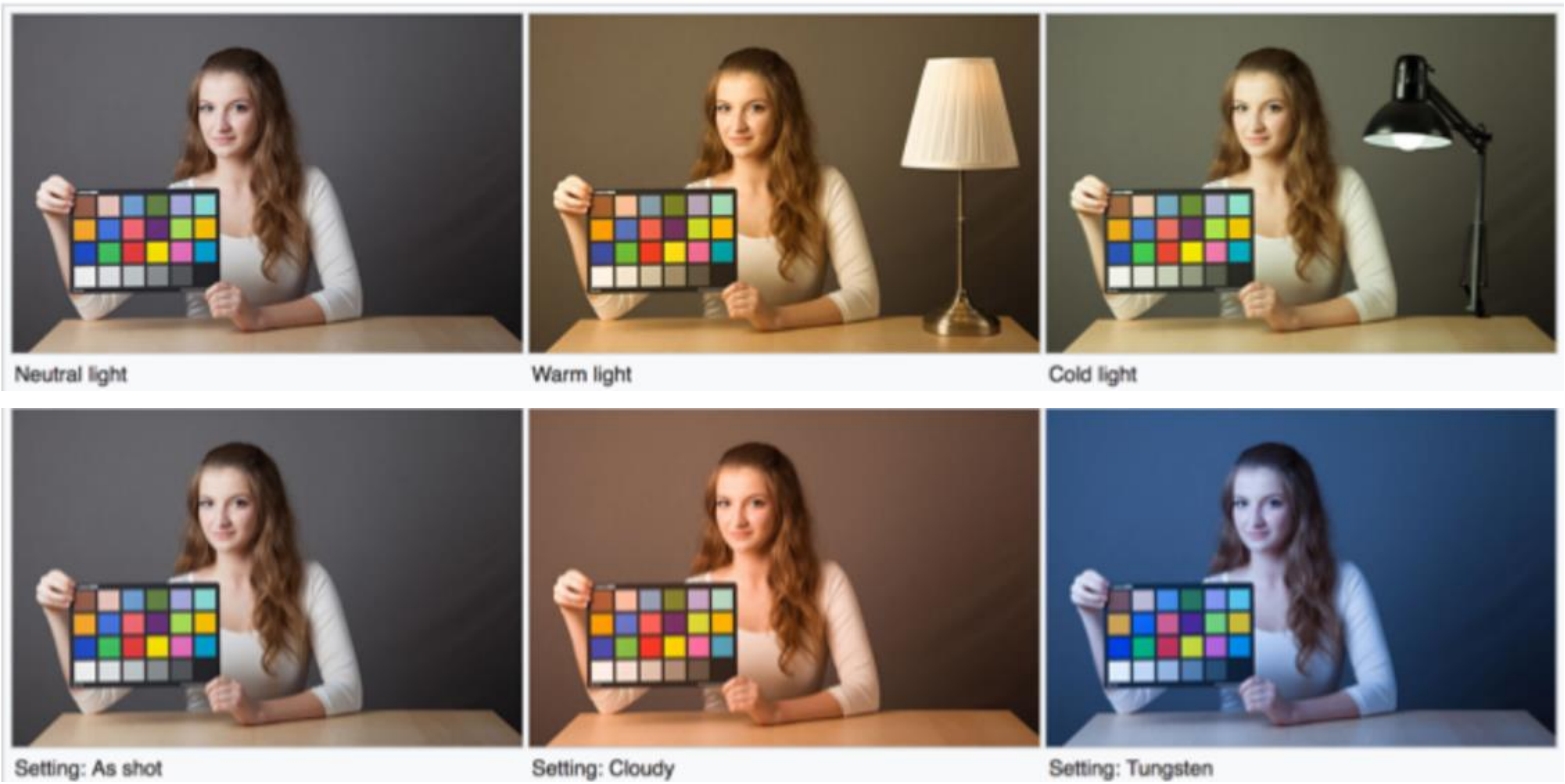


The gamut of sRGB in xy-space

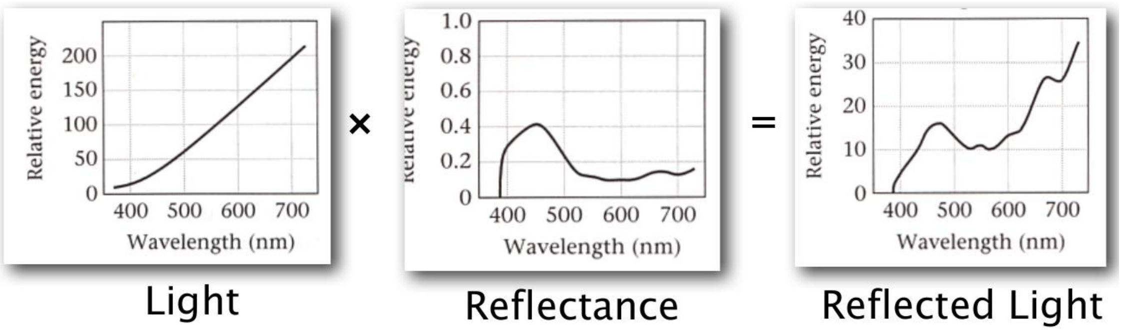
A point operation executed on color images

- Which one of the images below has the “right” colors?



White balance

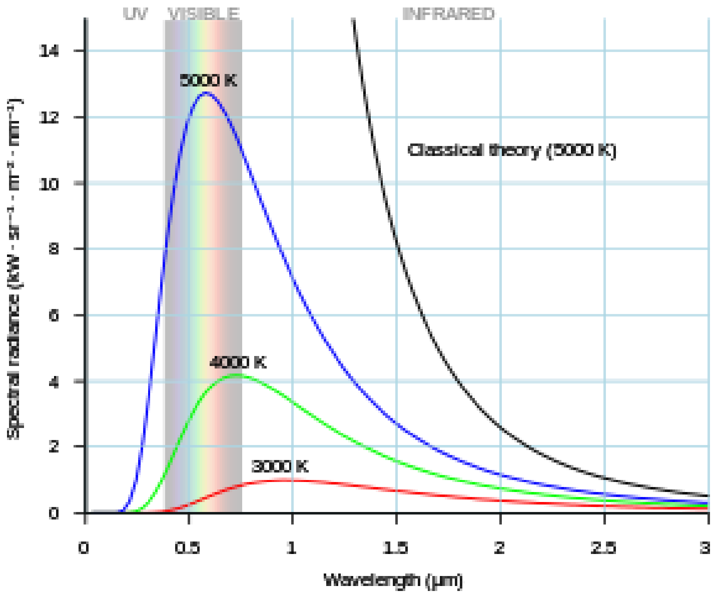
- The color of the light arriving in our eyes does not depend only on the color of the object!



- Our eyes automatically adapt to the prevailing light conditions in a given space – the "color constancy" mechanism in our cortex makes us fill in the missing color components so that familiar objects maintain color

White balance

- More systematic: estimate **color temperature** and **green-magenta shift**

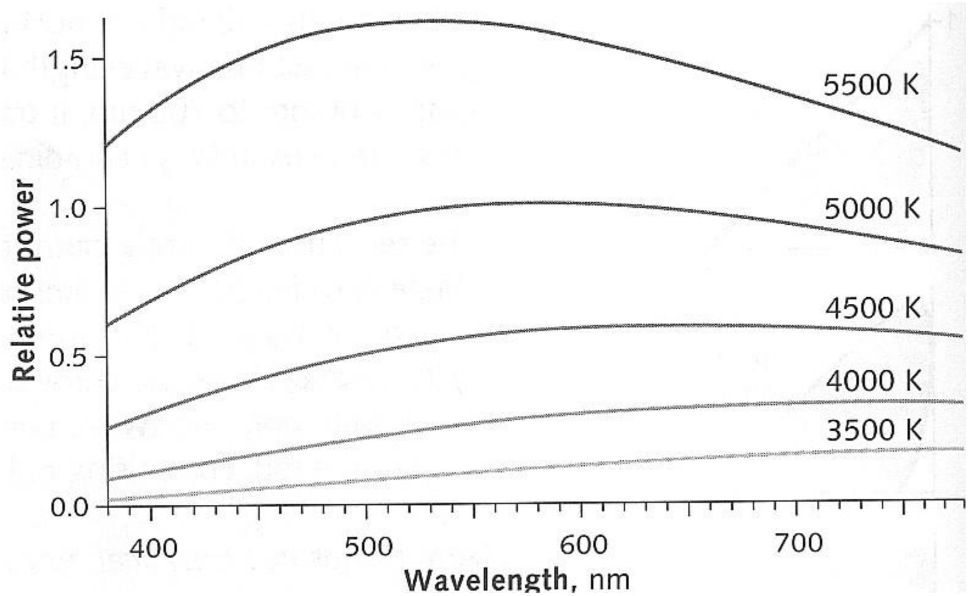


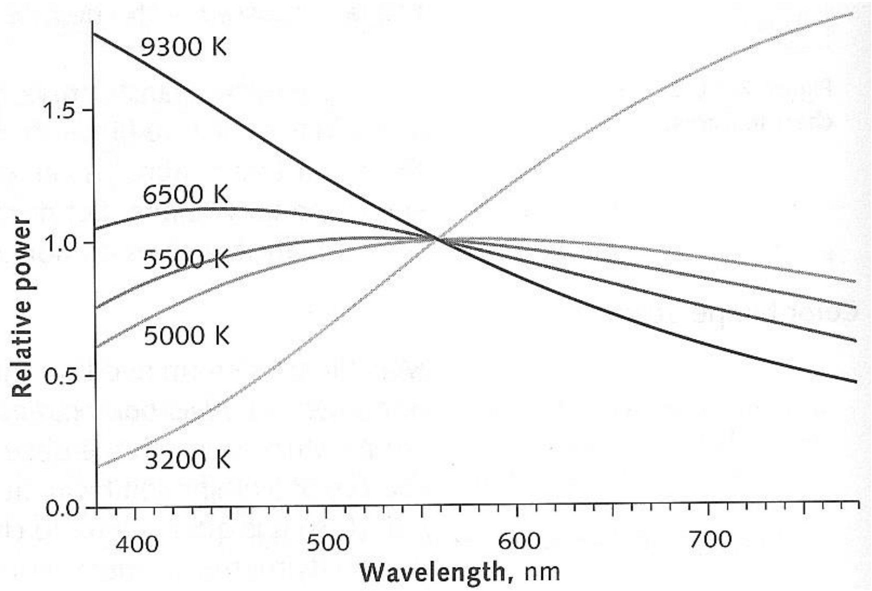
Black body radiation at different temperatures

- Color temperature – estimation of the global spectrum of the light source

Theoretical light source: A black body radiator

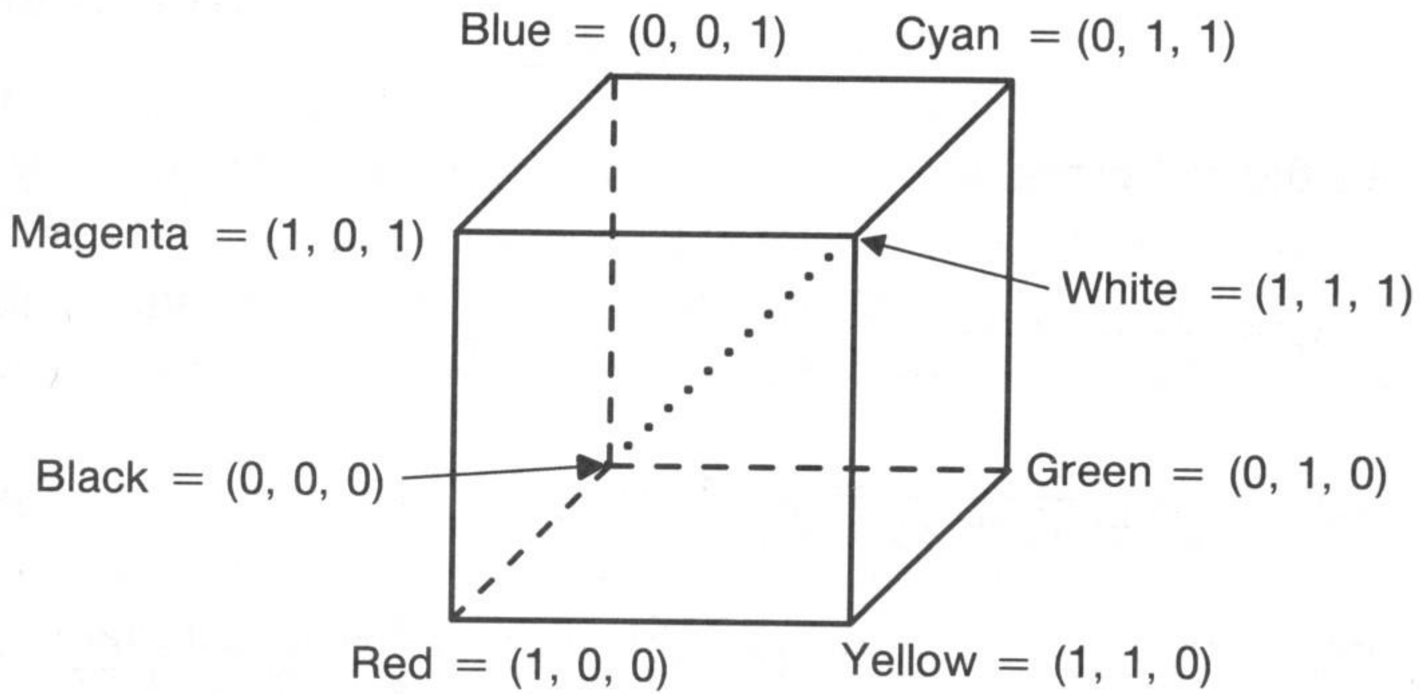
- Perfect emitter: whole energy emitted by thermal excitation only
- Has a fixed frequency spectrum $\rho = \rho(\lambda, T)$ (Planck's law)
- Spectrum can be converted into CIE-xy color location
  - Energy shifts toward shorter wavelengths as the temperature of the black body increases
  - Normalizing the spectrum (at 550 nm)
- Allows for white point specification through temperatures





RGB:

- Simplest model for computer graphics
- Natural for additive devices (*e.g.* monitors)
- Device dependent (!!!)
    - **Most display applications do not correct for it!!!!**
- Many image formats don't allow primaries to be specified



Standardization of RGB

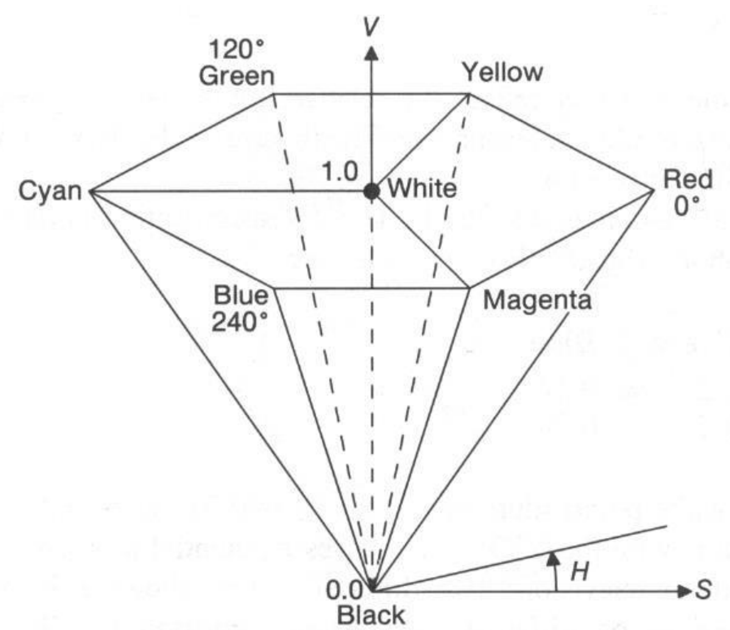
- RGB for standardized primaries and white point (and gamma)
- Specification of default CIE-XYZ values for monitors
  - Red: 0.6400, 0.3300
  - Green: 0.3000, 0.6000
  - Blue: 0.1500, 0.0600
  - White: 0.3127, 0.3290 (D65)
  - Gamma: 2.2
- Same values as HDTV and digital video (ITU-R 709)
- http://www.color.org

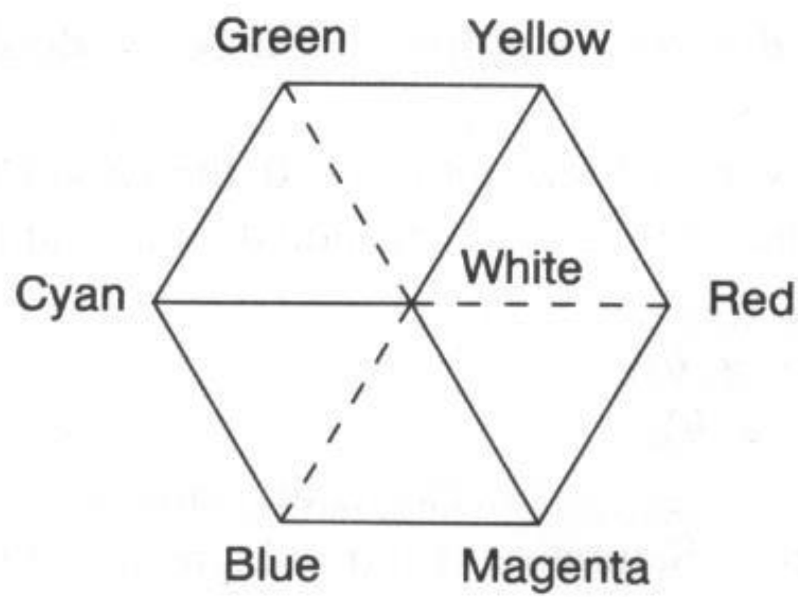
Utilization:

- sRGB is a standard replacement profile of International Color Consortium
- Assume all image data's without ICC profile implicitly lie in sRGB
  - Generating: ICC-Profile or writing sRGB
  - Reading/output: using ICC-Profile or assume sRGB

HSV / HSB (Hue, Saturation, Value / Brightness)

- Motivated from artistic use and intuitive color definition (vs. RGB)
  - H is equivalent to tone
  - S is equivalent to saturation (H undefined for S == 0)
  - V / B is equivalent to the gray value
- Pure tones for S == 1 and V == 1
- Intuitive model for color blending
- Builds on RGB



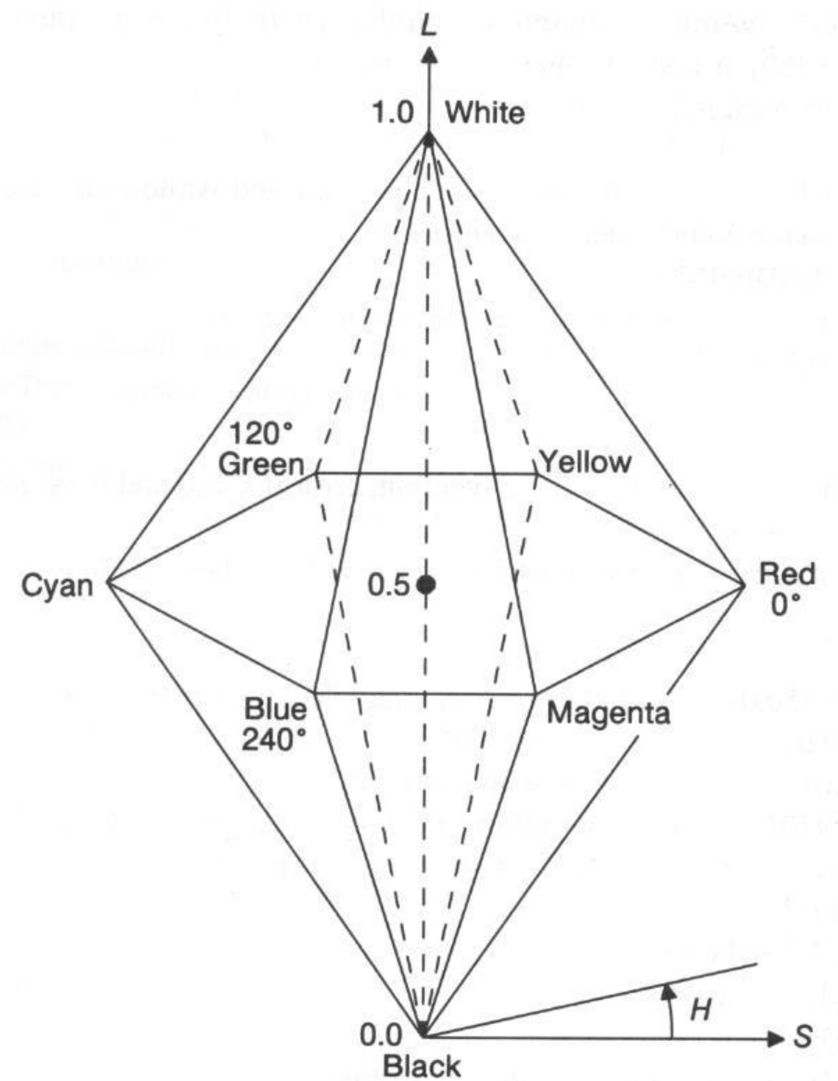


HLS (Hue, Lightness, Saturation)

- Similar to HSV / HSB
- Slightly less intuitive

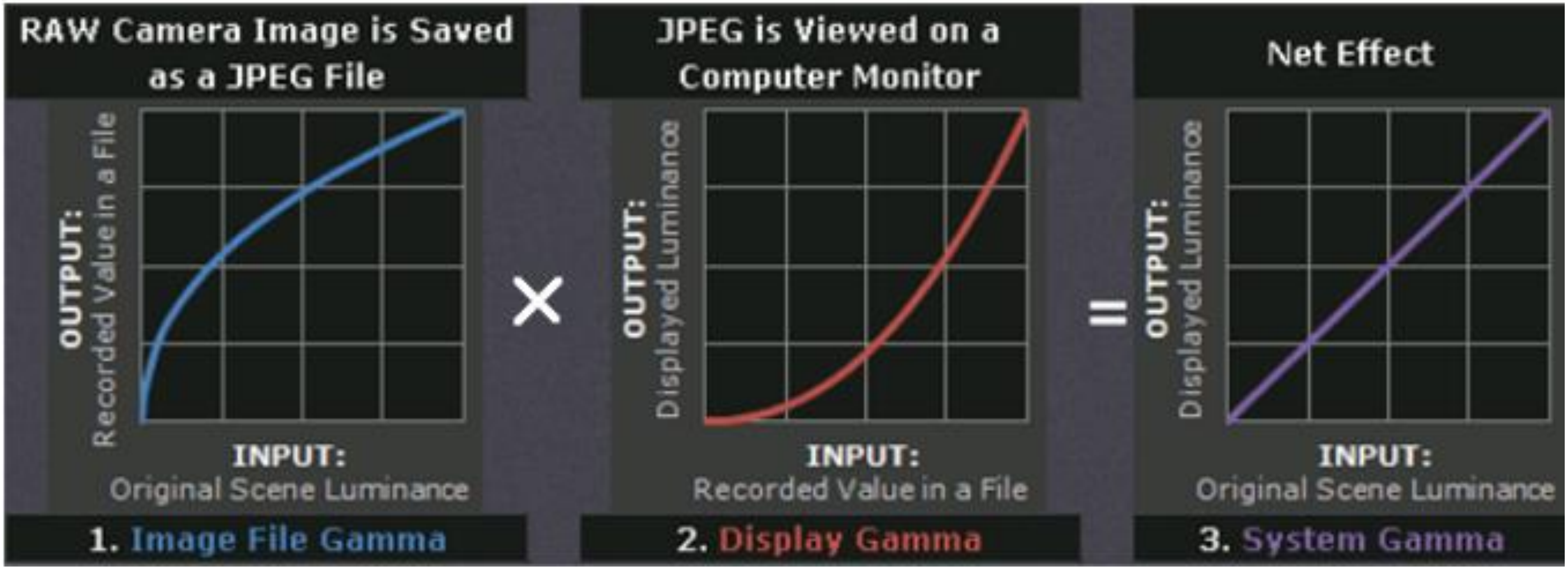
Many other color models

- TekHVC
  - Developed by Tektronix
  - Perceptually uniform color space
- Video-processing
  - Y´, B-Y, R-Y
  - Y´IQ
  - Y´PrPb
  - Y´CrCb
- Non-linear color spaces



Gamma Encoding and Correction

- Color model optimization: maximize the use of the bits relative to human perception
- More bits are allocated to the darker regions of the image than to the lighter regions
- Gamma correction is applied to the gamma encoded (compressed) images to convert them back to the original scene luminance

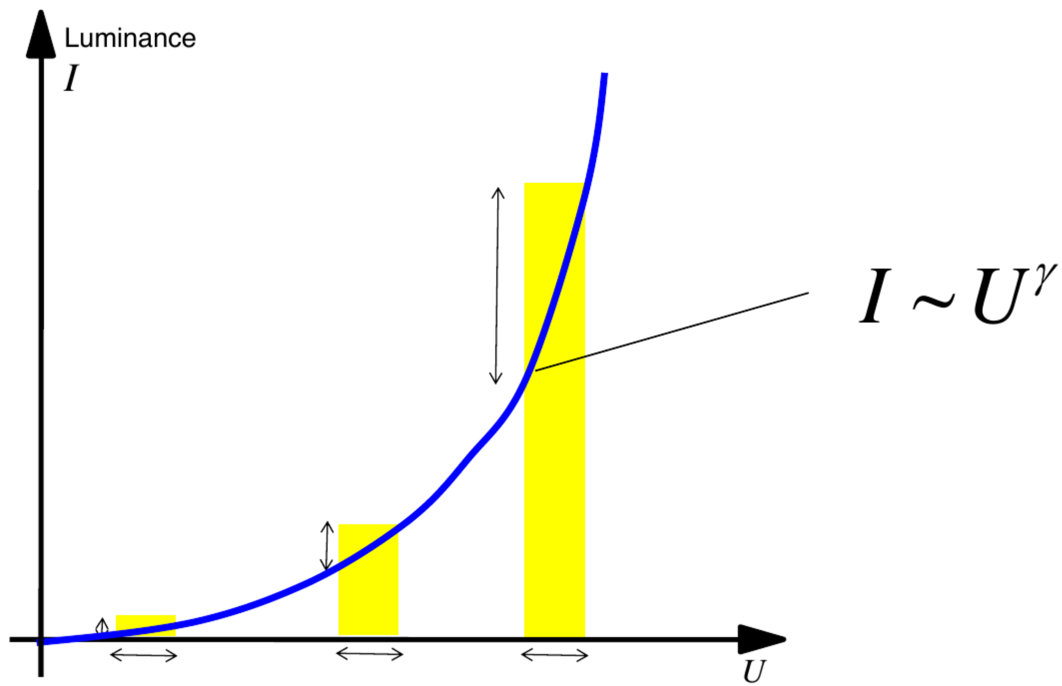


Quantization of the intensity

- We can briefly come back to the discussion of the gamma encoding / correction

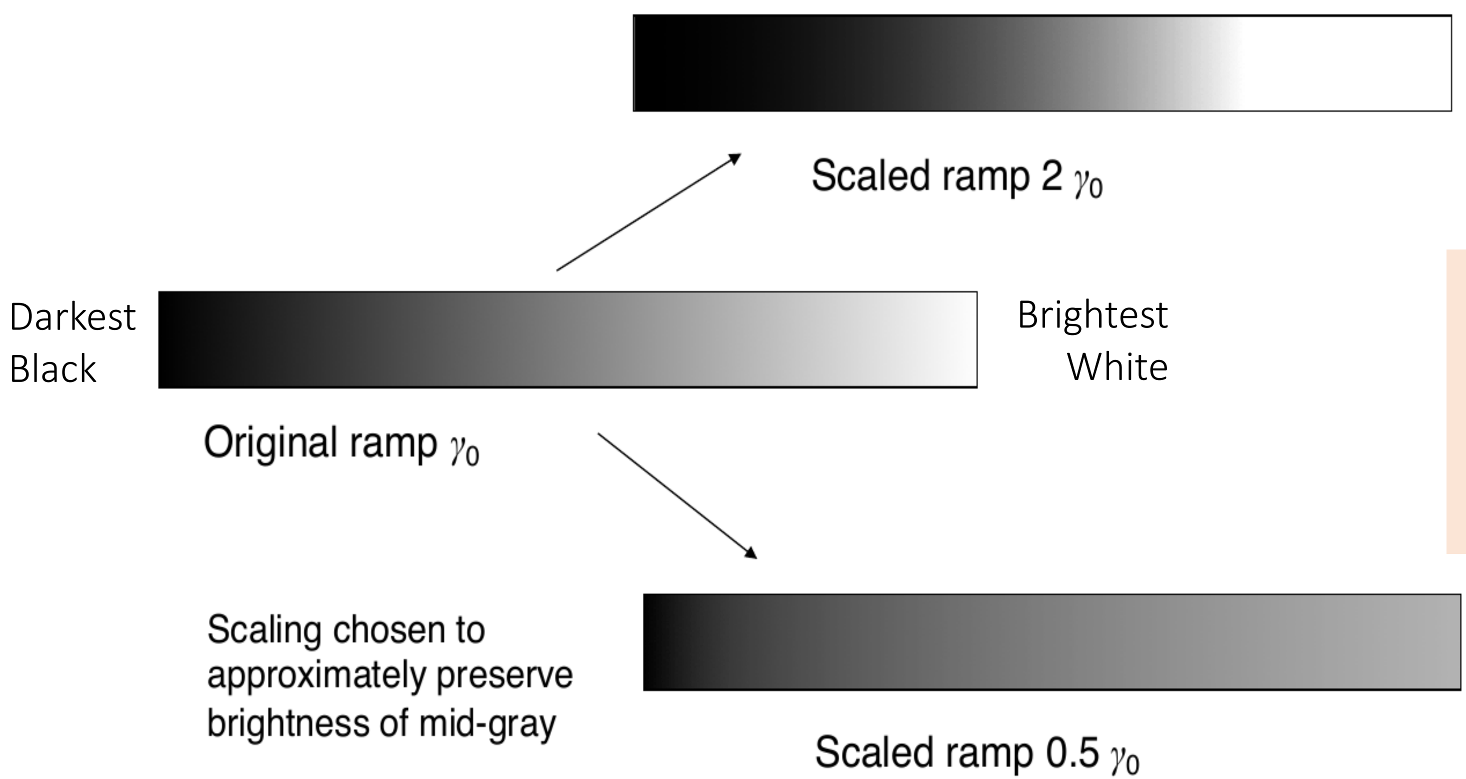
Darkest Black

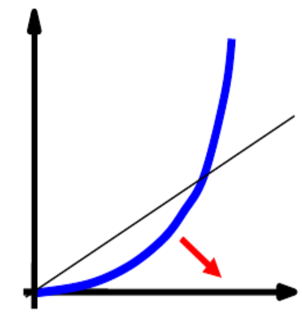
Brightest White



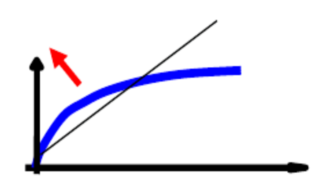
Quantization of the intensity

- Gamma adjustment is just one of the operations which we can conduct on the values of the pixels





Exponent γ larger than 1 “bends” the curve down for input values [0, 1] while lower than one bends it up.



Quantization of the intensity

- Simple operation, interesting result: contrast adjustment

Original image

$$f[x,y]$$

γ increased by 50%

$$a\cdot(f[x,y])^{\gamma}$$

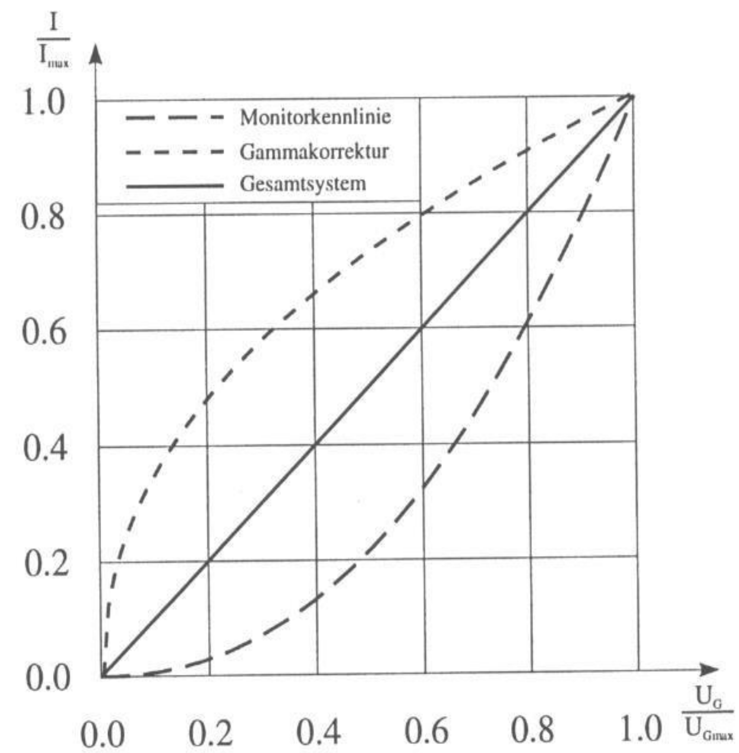
with $\gamma = 1.5$

Display-Gamma

- Intensity I of electron beam in CRT monitors is non-linear with respect to the applied voltage U
- Best described as power law: $L = U^{\gamma}$
- Gamma-Factor $\gamma = \sim 2.2$ due to physical reasons
- For compatibility also in other displays (LCD, OLED, *etc*.)

Gamma correction

- Pre-correct values with inverse to achieve linear curve overall
- Quantization loss if value represented with less than 12 bits
    - Hardly ever implemented this way in apps and HW



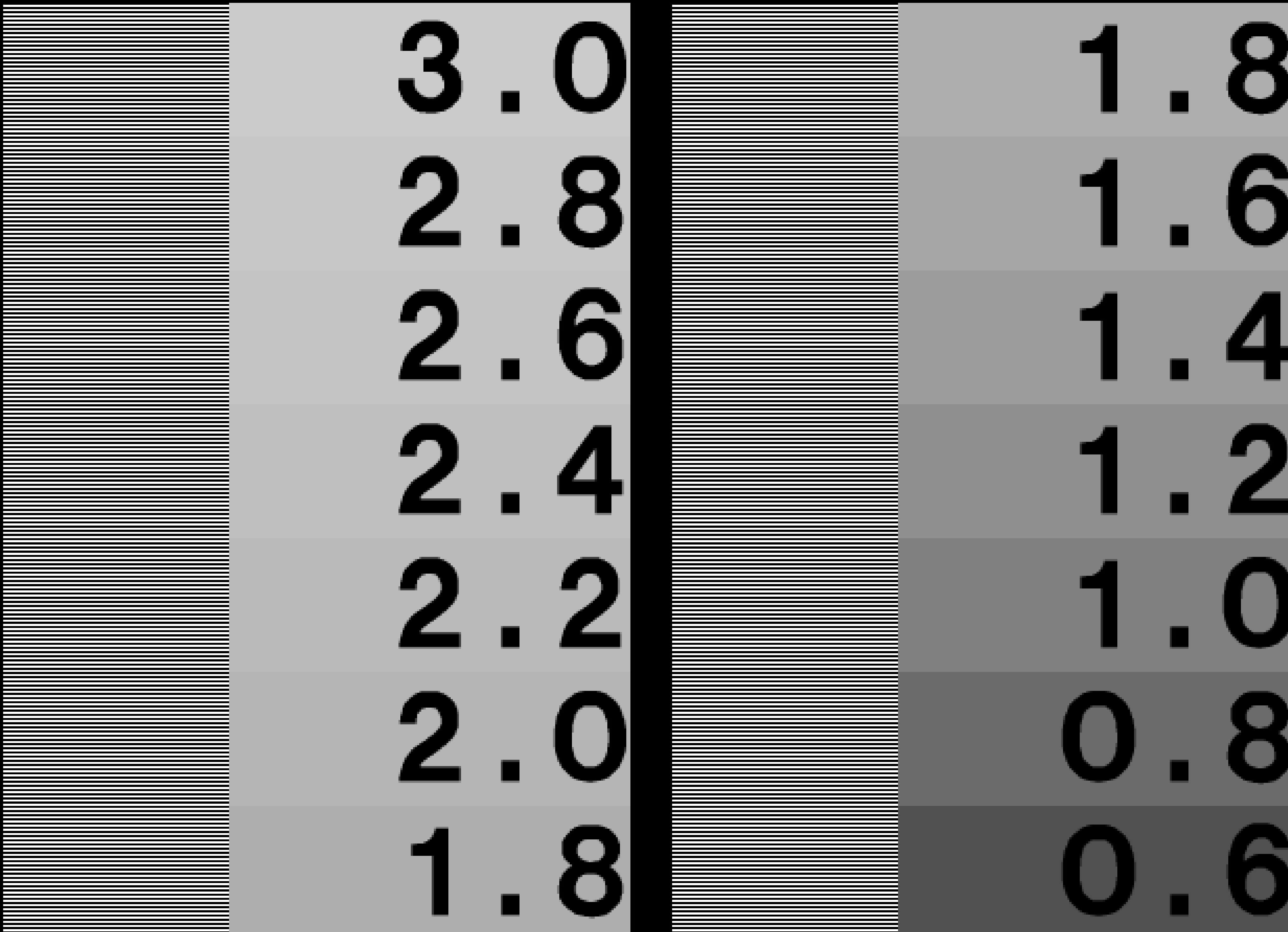
Gamma of monitor not always theoretical 2.2

Testing:

- 50% intensity should give 50% grey (half black-white)
- Match actual gray with true black / white average $\rightarrow \gamma$

Usage of the gamma testing chart:

- Take some distance from your monitor, such that you can no longer see the horizontal lines.
- Where brightness of the lines area is equal to brightness of the number area, read your gamma setting.


3.0
2.8
2.6
2.4
2.2
2.0
1.8
1.8
1.6
1.4
1.2
1.0
0.8
0.6

Camera-gamma

- Old cameras (electron tube) also had a gamma factor
- Essentially the inverse of the monitor gamma (due to physics)
  ⇒Display corrected the camera

"Human-gamma"

- Human brightness perception exhibits a log curve response
- Actually roughly follows a gamma curve with a value of 1/3
- Old cameras therefore encode light in a perceptually uniform way
  - Optimal for processing, compressing and transmitting values
- New cameras specifically generate the same output for compatibility reasons (!)

Additional Reading

- Jamie Wong: *Color: From Hexcodes to Eyeballs*, available online, April 3, 2018