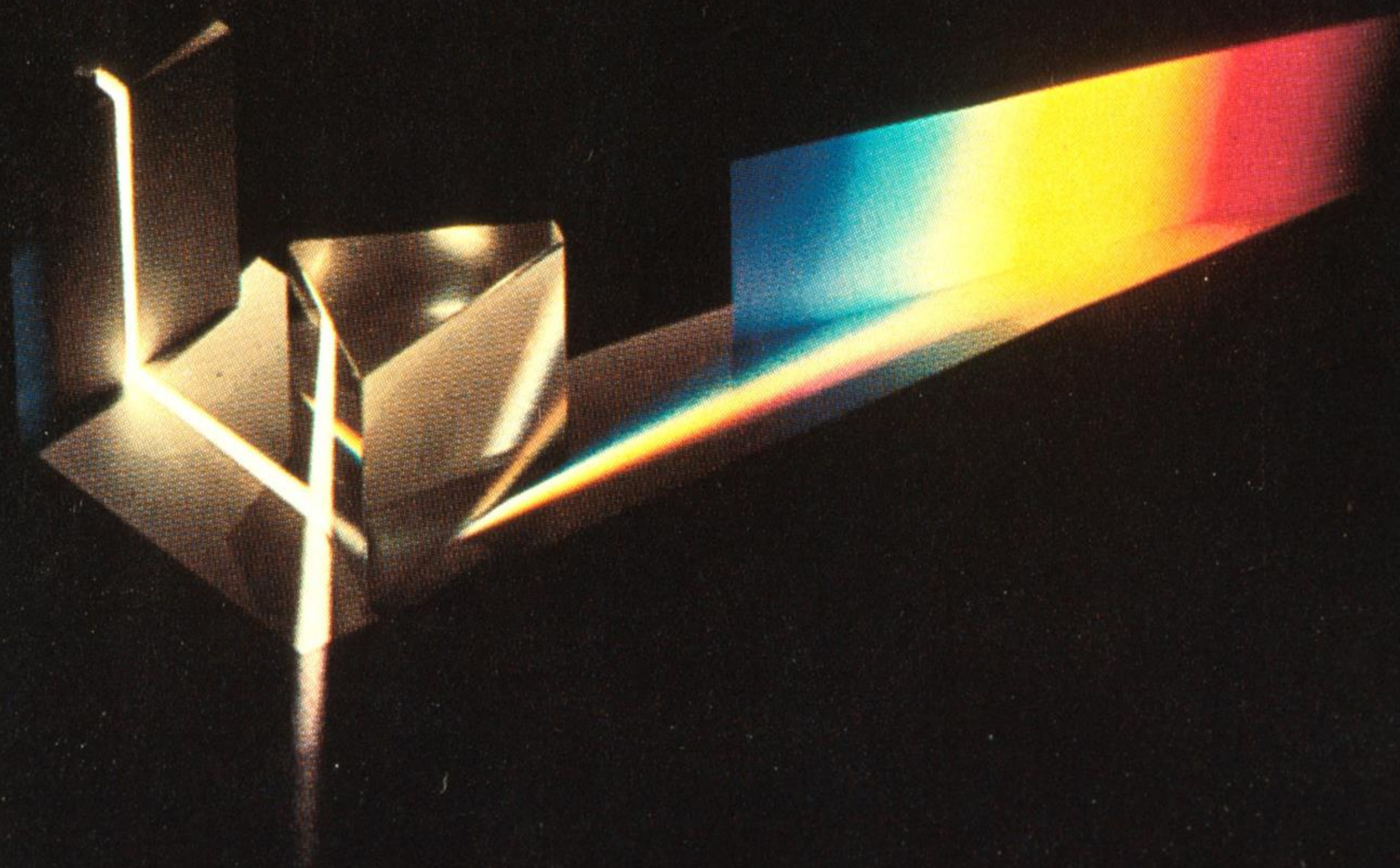
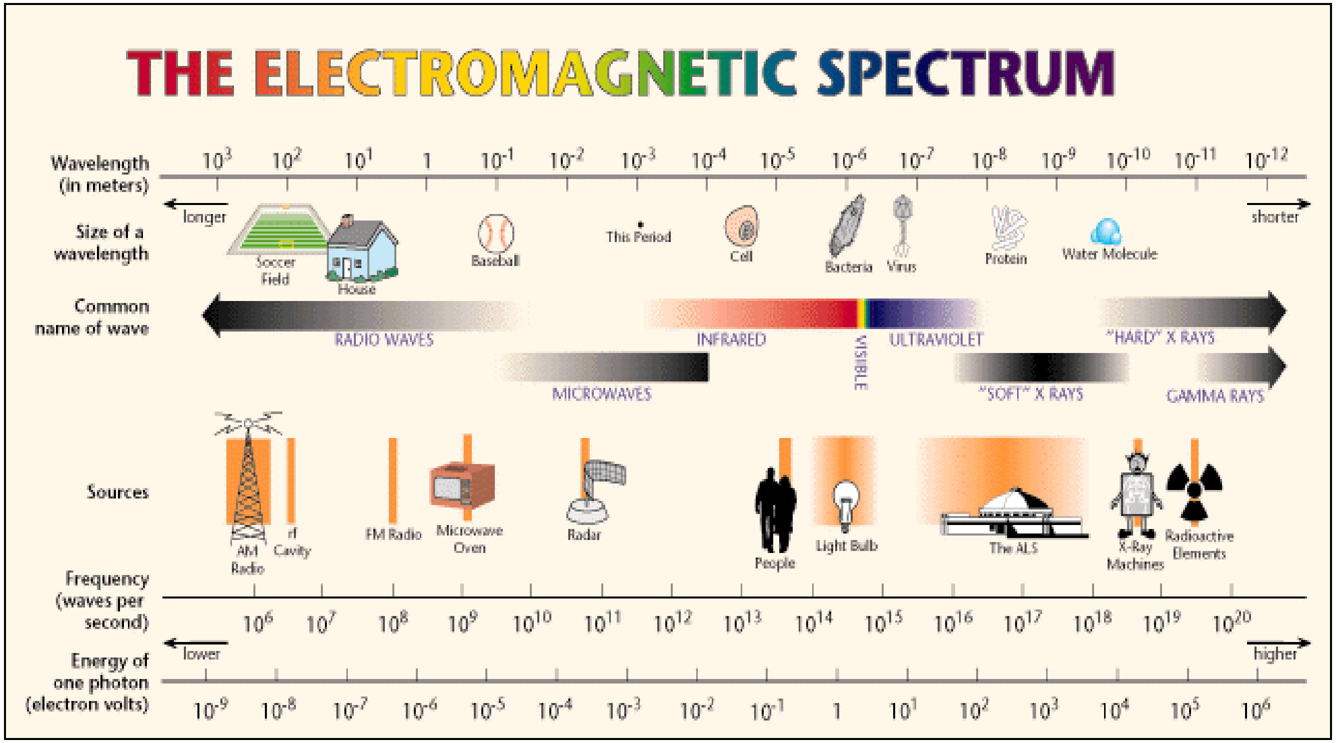
Colour Science



[source unknown]

What is light?

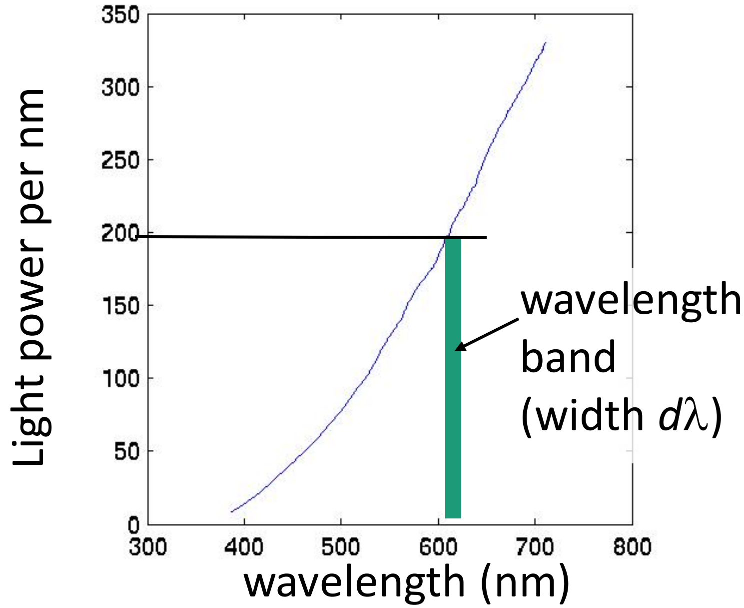
- Light is electromagnetic radiation, and exists as oscillations of different frequency (or, wavelength)



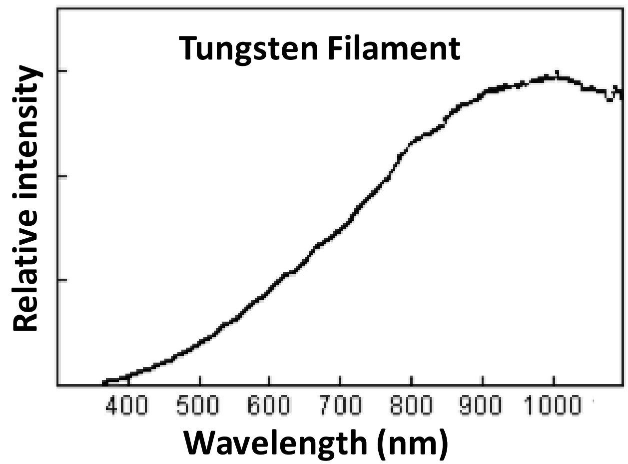
[Lawrence Berkeley Lab / MicroWorlds]

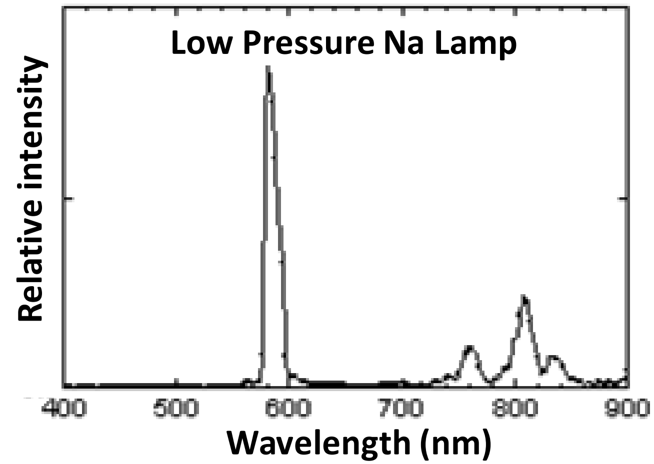
Measuring light

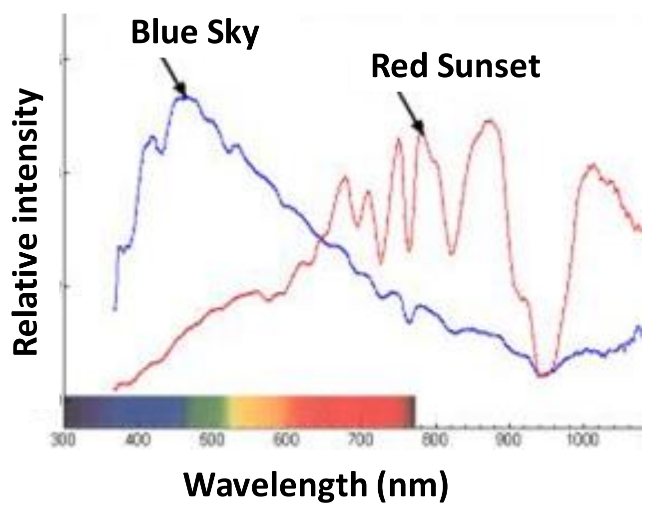
- Salient property is spectral power distribution (SPD)
  - The amount of light present at each wavelength
  - Units: Watts per nanometer (tells you how much power you'll find in a narrow range of wavelengths)
  - For colour, often use "relative units" when overall intensity is not important

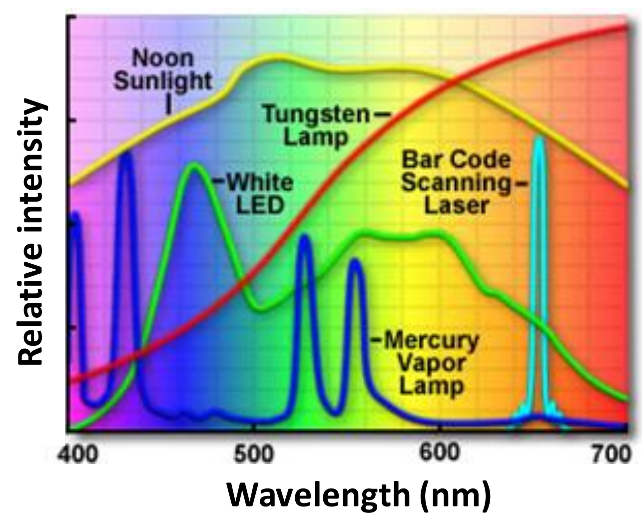


Spectral Distribution of Different Light Sources









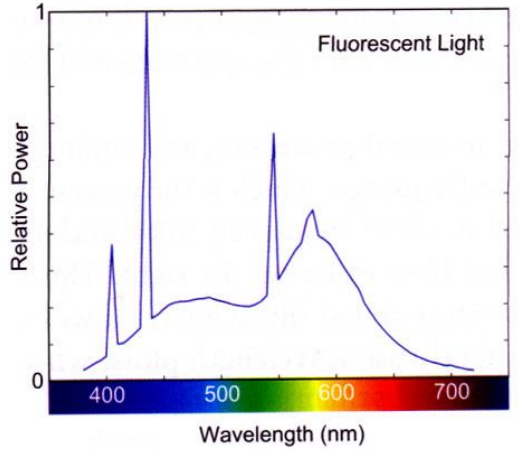
What is colour?

- Colours are the sensations that arise from light energy of different wavelengths
  - We are sensitive from about 380 to 760 nm
- Colour is a ***phenomenon of human perception***
  - It is **not** a universal property of light
- Roughly speaking, things appear “coloured” when they depend on wavelength and “gray” when they do not.

The problem of colour science

- Build a model for human colour perception
- That is, map a *Physical light description* to a *Perceptual colour sensation*

[Stone 2003]

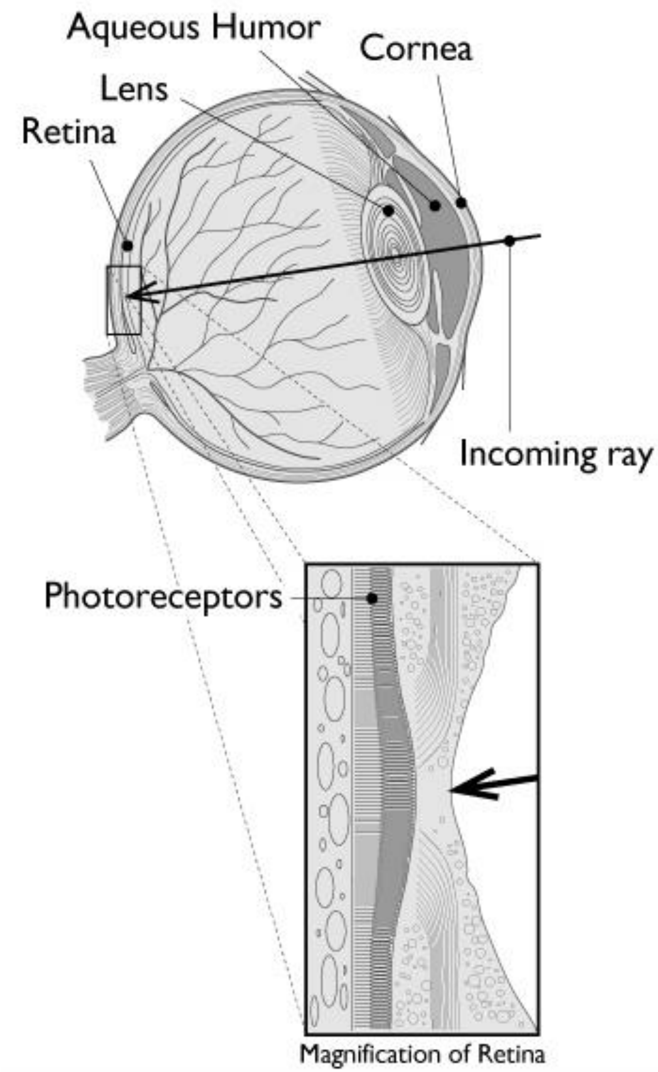


Physical

?

Perceptual

The eye as a measurement device



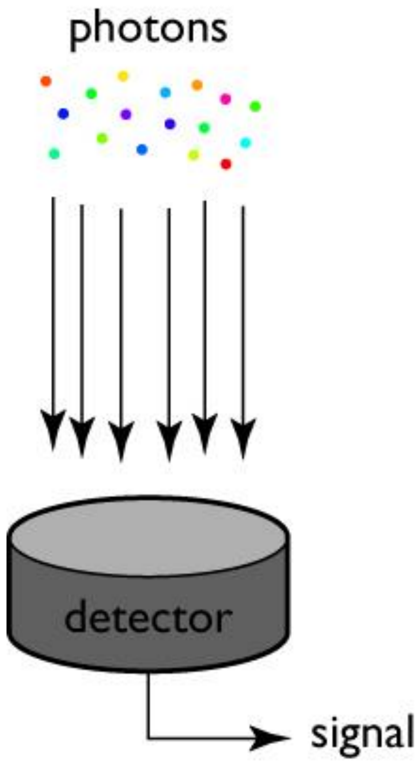
[Greger et al. 1995]

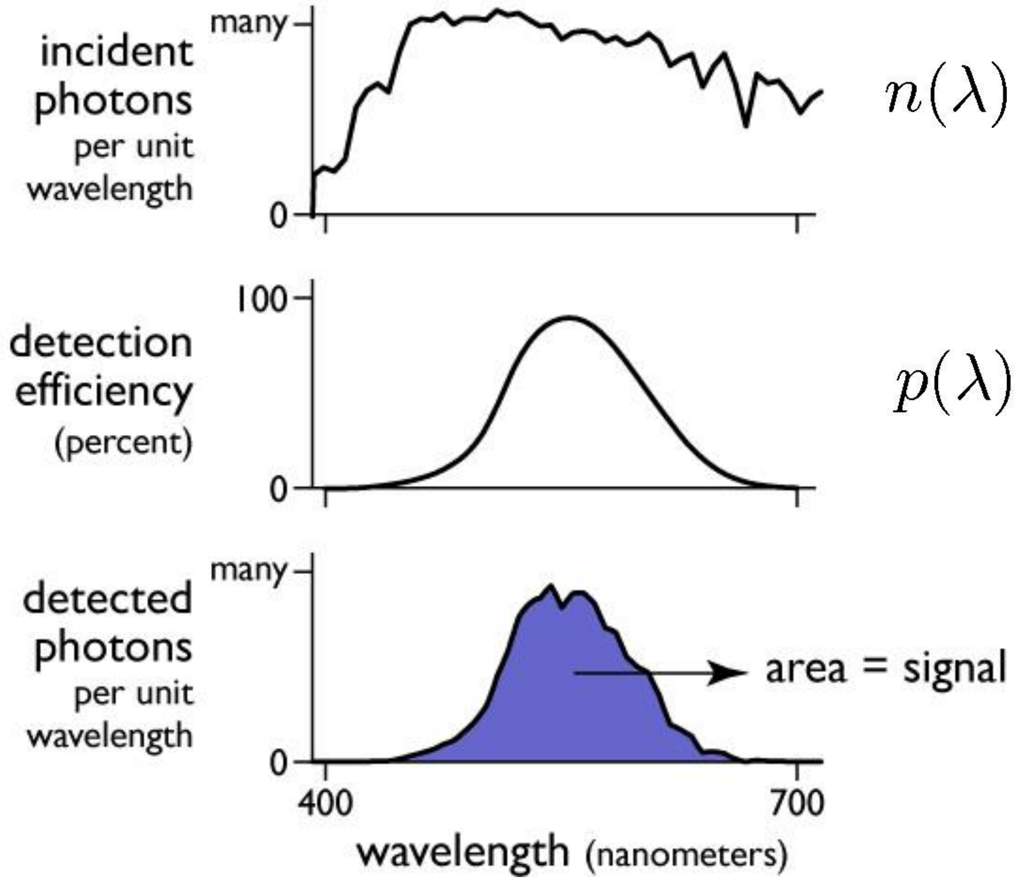
- We can model the low-level behavior of the eye by thinking of it as a light-measuring machine
  - Its optics are much like a camera
  - Its detection mechanism is also much like a camera
- Light is measured by the *photoreceptors* in the retina
  - They respond to visible light
  - Different types respond to different wavelengths

A simple light detector

- Produces a scalar value when photons land on it
  - Value depends strictly on number of photons detected
  - Each photon has a probability of being detected that depends on the wavelength
  - There is no way to tell the difference between signals caused by light of different wavelengths: there is just a number
- This model works for many detectors
  - Semiconductor based (such as in a digital camera)
  - Visual photo-pigment based (such as in human eyes)

A simple light detector





$$X = \int n(\lambda)p(\lambda)\, d\lambda$$

Light detection math

- Same math carries over to power distributions
  - Spectrum entering the detector has spectral power distribution (SPD), $s(\lambda)$
  - Detector has spectral sensitivity, or spectral response, $r(\lambda)$

$$X = \int s(\lambda) r(\lambda) d\lambda$$

measured signal

detector's sensitivity

input spectrum

Light detection math

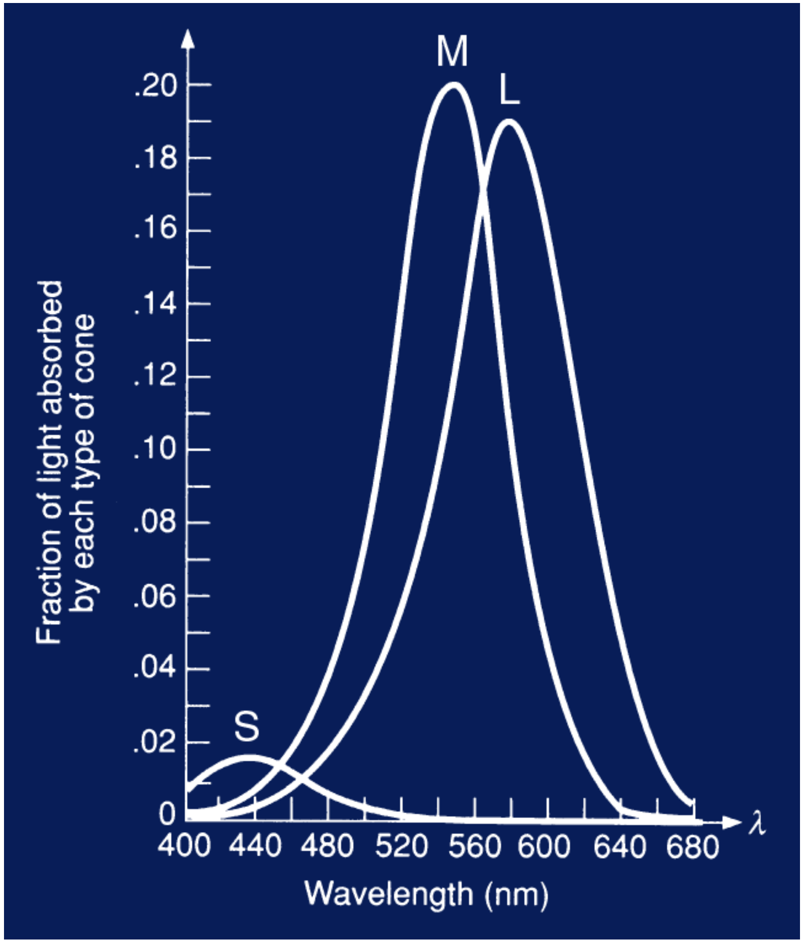
- Integral is like a dot product when we discretize the spectral power distribution and response as vectors
- Computation typically done exactly this way, using sampled representations of the spectra
- Let λ_i be regularly spaced sample points $\Delta\lambda$ apart,

$$X = \int s(\lambda) r(\lambda) d\lambda \approx \sum_i s_i r_i \Delta\lambda = \boldsymbol{s} \cdot \boldsymbol{r}$$

where $s_i = s(\lambda_i)$, $r_i = r(\lambda_i)$

- See this sum as a dot product (provided we include the $\Delta\lambda$ factor in the response vector $\boldsymbol{r}$)

Cone Responses (Short, Medium, Long)



[source unknown]

- S,M,L cones have broadband spectral sensitivity
- S,M,L neural response is integrated w.r.t. λ
  - we'll call the response functions r_S, r_M, r_L
- Results in a trichromatic visual system
- S, M, and L are ***tristimulus values***

Cone responses to a spectrum *s*

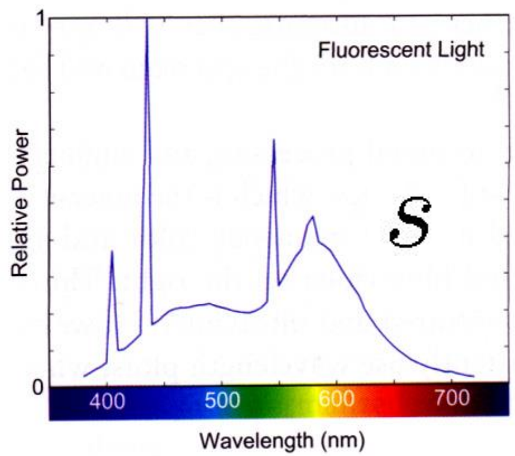
$$S = \int r_S(\lambda) s(\lambda)\, d\lambda = r_S \cdot s$$

$$M = \int r_M(\lambda) s(\lambda)\, d\lambda = r_M \cdot s$$

$$L = \int r_L(\lambda) s(\lambda)\, d\lambda = r_L \cdot s$$

Colourimetry answers the problem

- Wanted to map a ***Physical light description*** to a ***Perceptual colour sensation***
  - Basic solution was known and standardized by 1930
  - Though not quite in this form — *more on that in a bit*



Physical

$$S = r_S \cdot s$$
$$M = r_M \cdot s$$
$$L = r_L \cdot s$$

Perceptual

[Stone 2003]

Basic fact of colourimetry

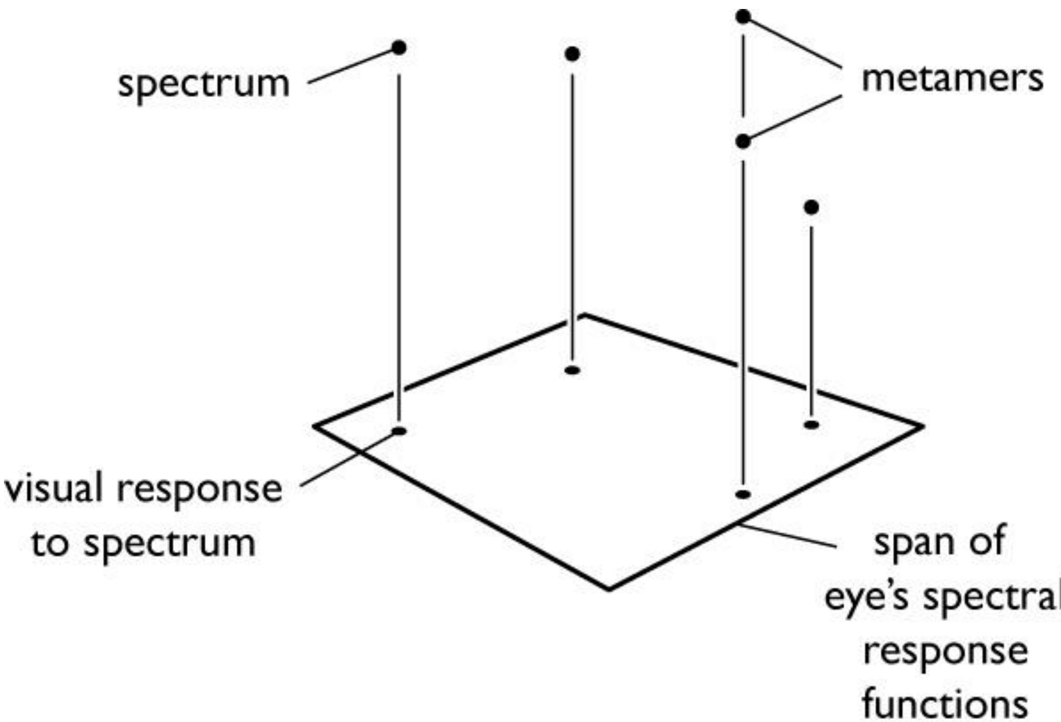
- Take a spectrum (i.e., a function of wavelength)
- Eye produces three numbers
- This throws away a lot of information!
    - Quite possible to have two different spectra that have the same S, M, L tristimulus values
    - Two such spectra are ***metamers***

Pseudo-geometric interpretation

- A dot product is a projection
- Projecting a high dimensional vector (a spectrum) onto three vectors
  - Differences perpendicular to all 3 vectors are undetectable
- For intuition, we can imagine a 3D analog
  - 3D stands in for high dimensional vectors
  - 2D stands in for 3D
  - Then vision is just projection onto a plane

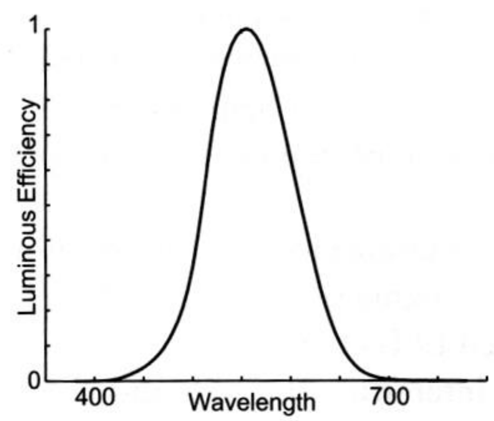
Pseudo-geometric interpretation

- The information available to the visual system about a spectrum is three values
  - This amounts to a loss of information analogous to projection on a plane
- Two spectra that produce the same response are ***metamers***



Luminance

- The overall magnitude of the visual response to a spectrum, independent of its "colour" (*chromaticity*)
  - Corresponds to the everyday concept "brightness"
- Determined by product of SPD with the luminous efficiency function V_λ that describes the eye's overall ability to detect light at each wavelength
- Lamps typically optimized to improve their luminous efficiency (tungsten vs. fluorescent vs. sodium vapor)



[Stone 2003]

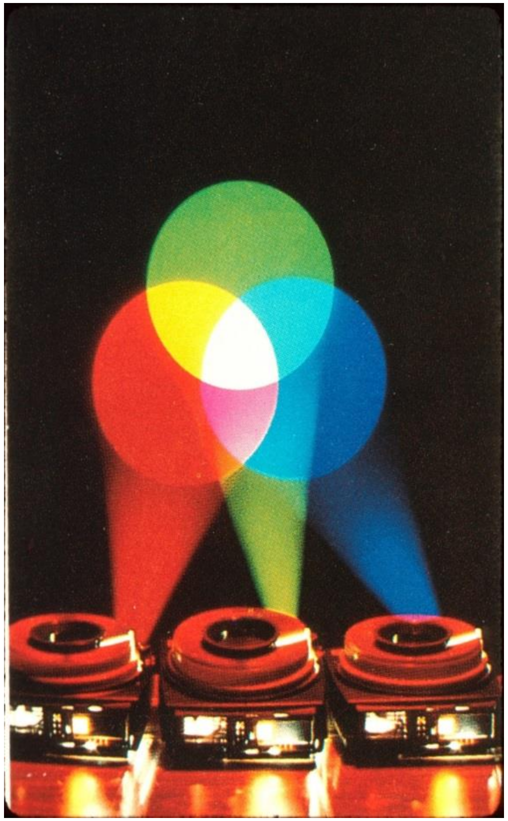
Luminance, mathematically

- Y just has another response curve (like S, M, and L)

$$Y = \mathrm{V}_\lambda \cdot s$$

- V_λ is a linear combination of S, M, and L responses
  - It must be since it is derived from cone outputs
- Factoring out luminance…
  - ***Chromaticity*** is a specification of a colour regardless of its luminance
  - Two dimensional (hue, saturation)
  - More on this soon…

Additive colour



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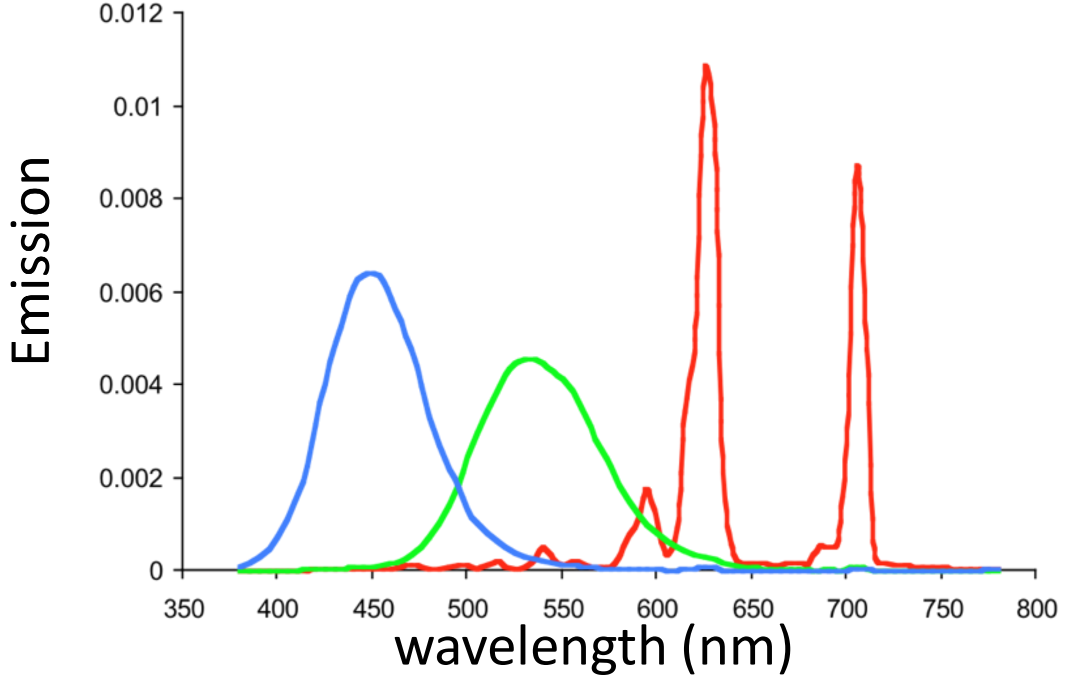
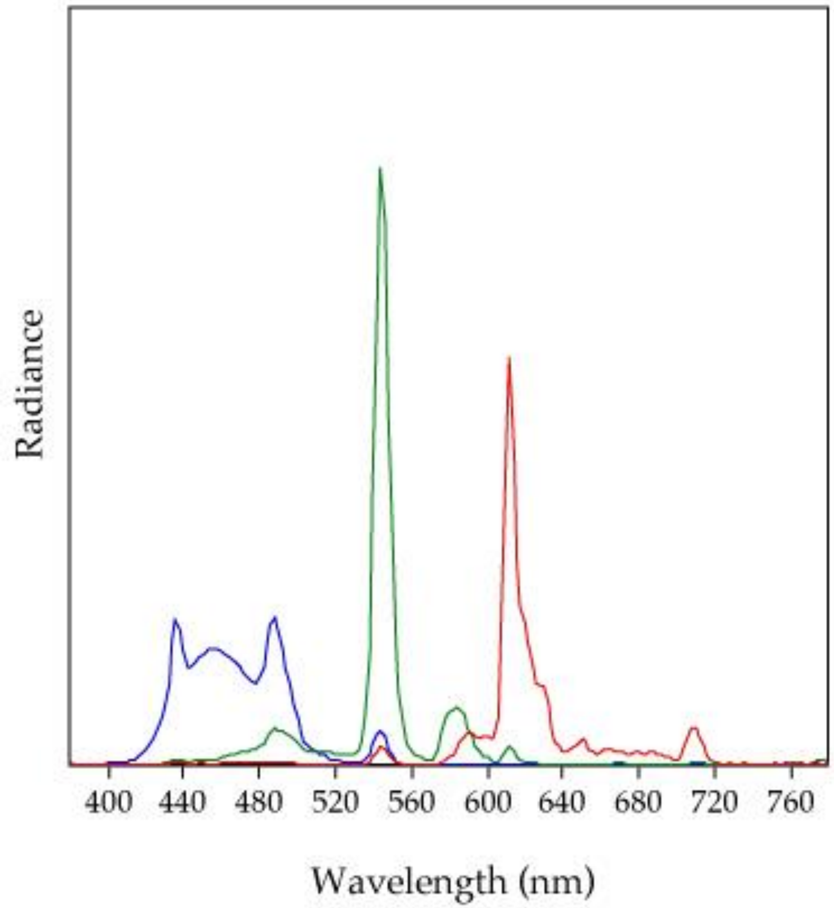
CRT display primaries

- **Primary colors** are sets of colors that can be combined to make a useful range of colors



LCD display primaries

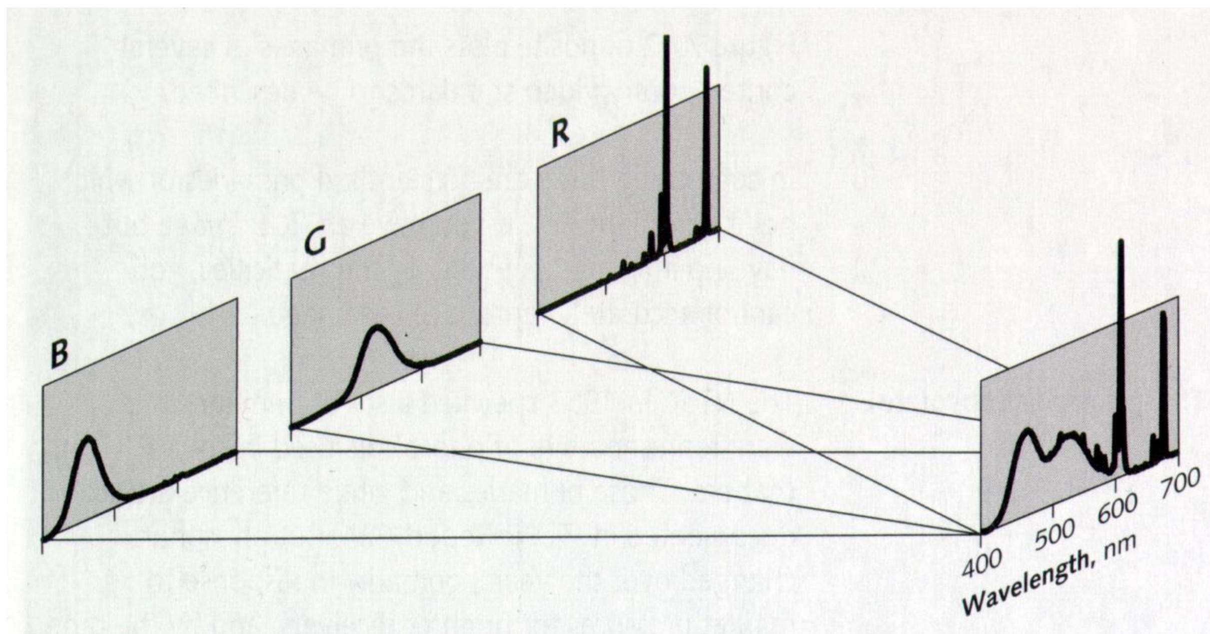
- Curves determined by (fluorescent) backlight and filters



[Fairchild 97]

Combining Monitor Primaries with Spatial Integration

- Phosphors in a CRT or filters in LCD provide primaries



[source unknown]

Subtractive colour

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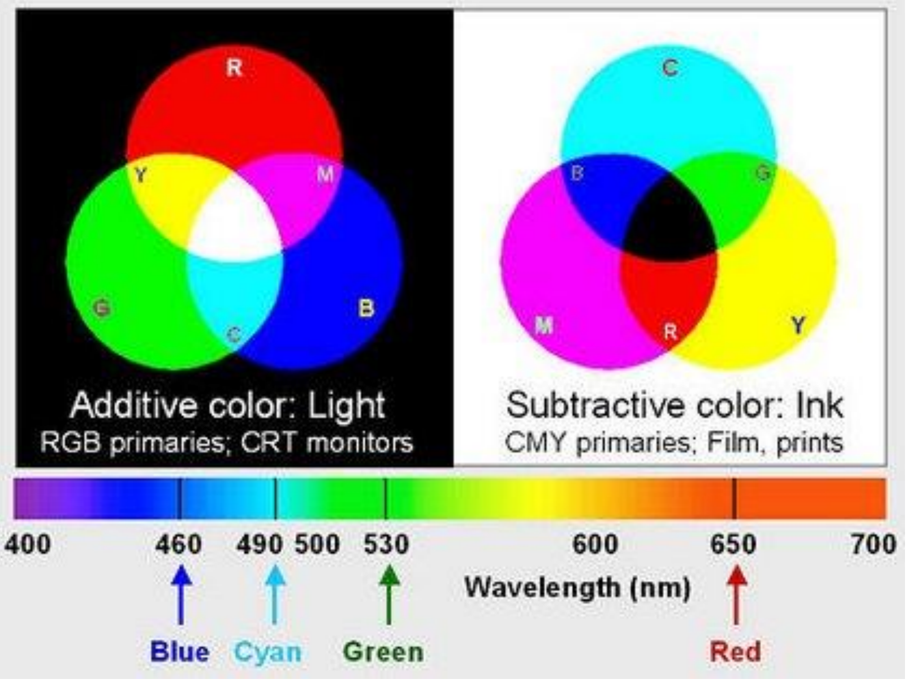
Subtractive colour

- Produce desired spectrum by *subtracting* from white light (usually via ***absorption*** by pigments)
- Photographic media (slides, prints) work this way
- Leads to C, M, Y as primaries
- Approximately, 1 – R, 1 – G, 1 – B

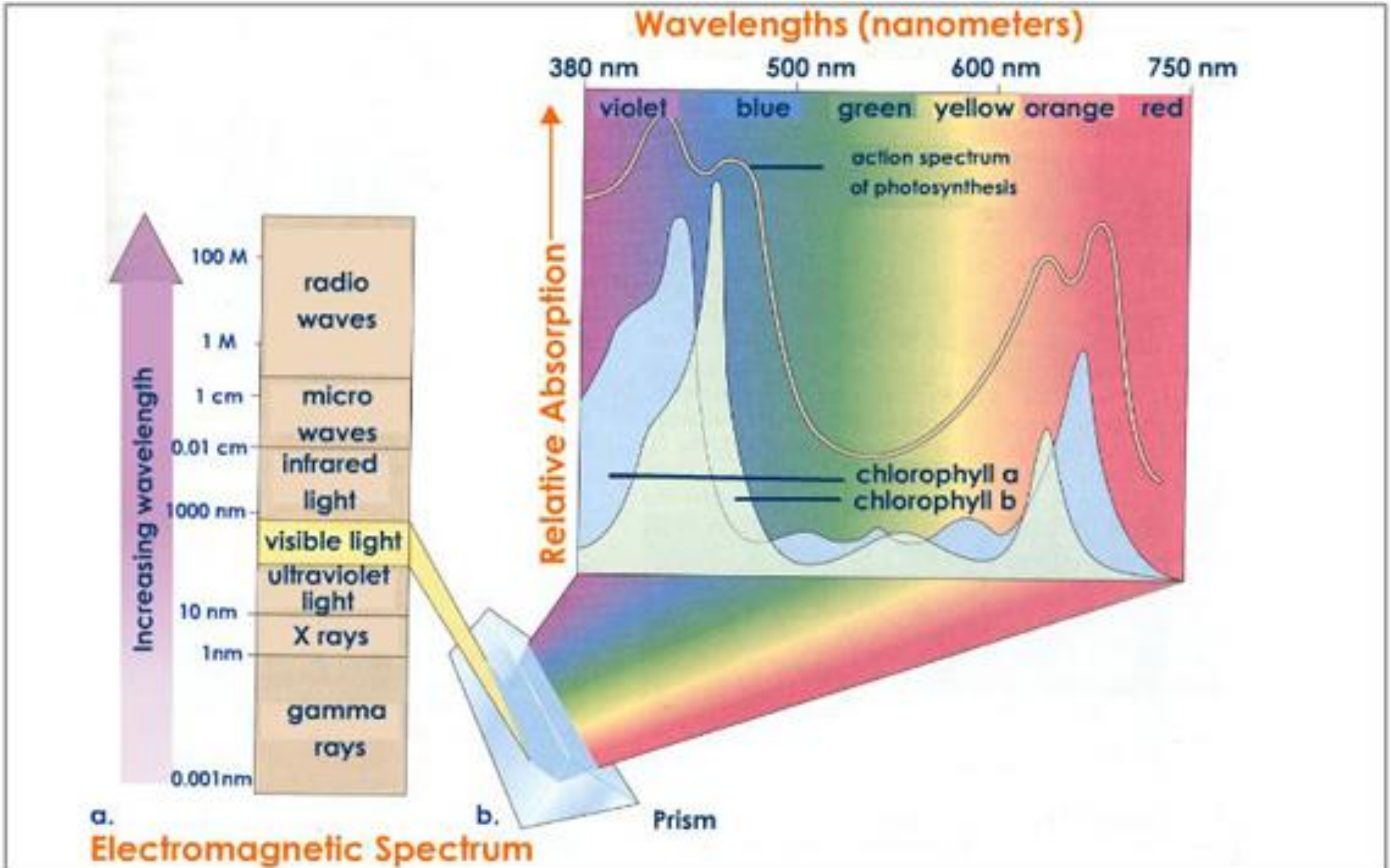
CMYK: Black also used in printing

- Cyan magenta and yellow do not do a good job of absorbing all light of the spectrum, and it tends to be a dark muddy brown, so black is added to the mix. Less ink too, so cheaper prints!

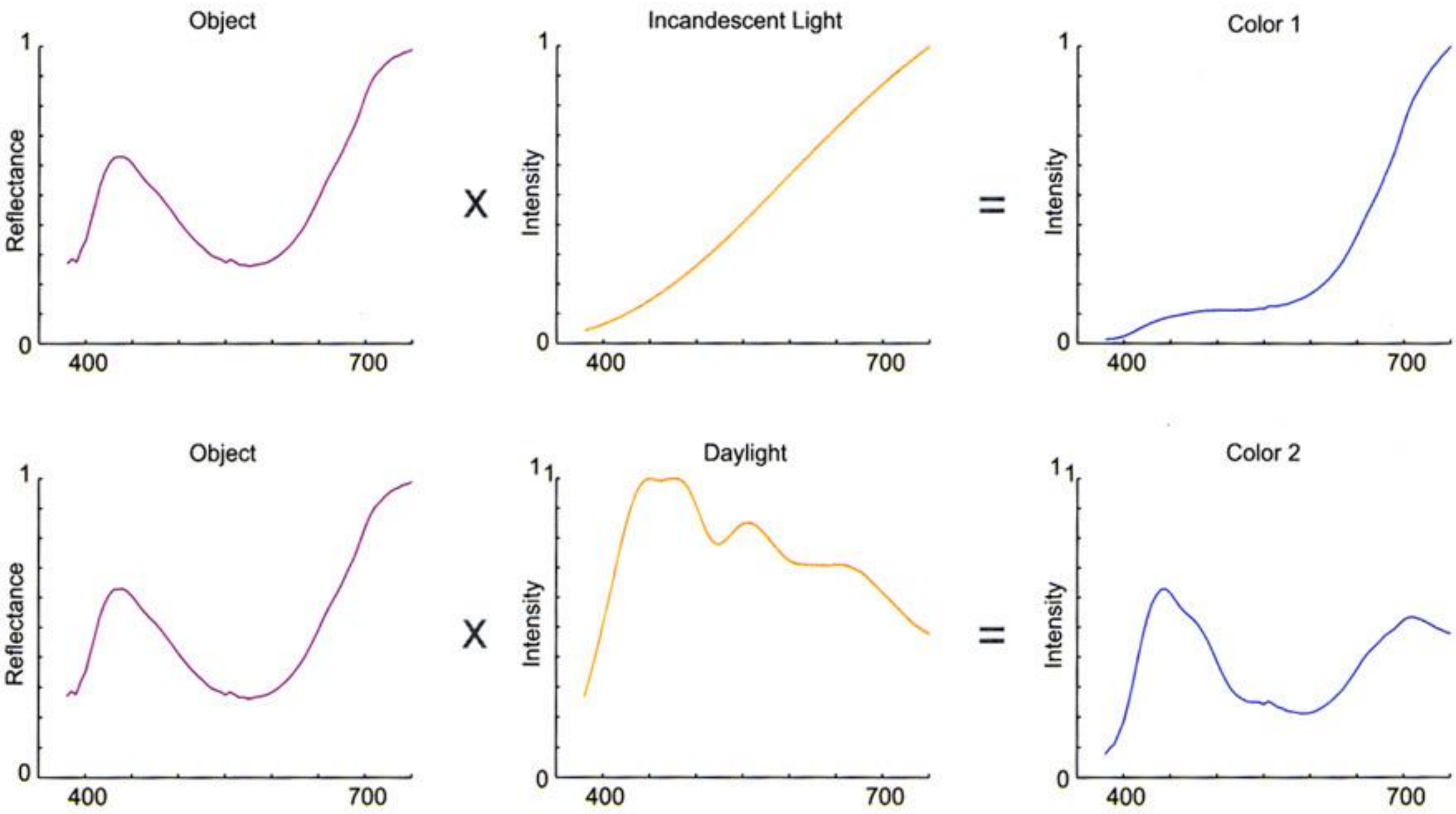


Why plants look green

Illuination and reflectance spectra



Observed colour depends on illumination



[Stone 2003]

Metamers only for a given illumination

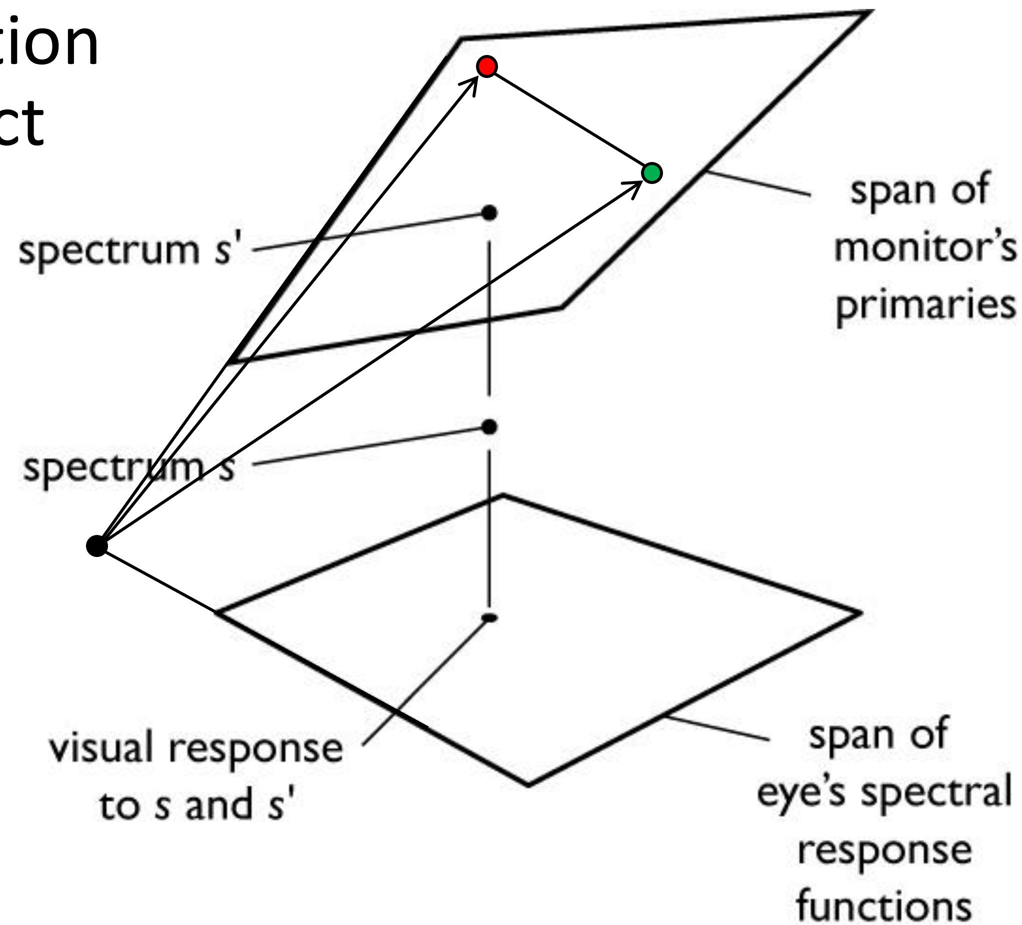
Colour reproduction

Colour reproduction

- How can spectrum ***s*** be matched on an RGB monitor?
  - "match" means it looks the same
  - any spectrum that projects to the same point in the visual colour space is a good reproduction
- Problem: Find a spectrum that the monitor can produce that matches ***s***
  - We want to display a metamer of ***s*** on the screen

Colour reproduction

Compute the combination of r, g, b that will project to the same visual response as ***s***.



Colour reproduction, linear algebra

- The projection onto the three response functions can be written in matrix form as

$$\begin{bmatrix} S \\ M \\ L \end{bmatrix} = \begin{bmatrix} - r_S - \\ - r_M - \\ - r_L - \end{bmatrix} \begin{bmatrix} | \\ s \\ | \end{bmatrix}$$

or,

$$V = M_{SML}\, s.$$

Colour reproduction, linear algebra

- The spectrum that is produced by the monitor for the colour signals R, G, and B is

$$s_a(\lambda) = Rs_r(\lambda) + Gs_g(\lambda) + Bs_b(\lambda).$$

- Again the discrete form can be written as a matrix:

$$\begin{bmatrix} | \\ s_a \\ | \end{bmatrix} = \begin{bmatrix} | & | & | \\ s_R & s_G & s_B \\ | & | & | \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

or,

$$s_a = M_{RGB}\,C.$$

Colour reproduction, linear algebra

- What colour do we see when we look at the display?
  - Feed C to display
  - Display produces sa
  - Eye looks at sa and produces visual response V

$$V = M_{SML} M_{RGB} C$$

$$\begin{bmatrix} S \\ M \\ L \end{bmatrix} = \begin{bmatrix} r_S \cdot s_R & r_S \cdot s_G & r_S \cdot s_B \\ r_M \cdot s_R & r_M \cdot s_G & r_M \cdot s_B \\ r_L \cdot s_R & r_L \cdot s_G & r_L \cdot s_B \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

Colour reproduction, linear algebra

$$M_{SML}\,\tilde{s} = M_{SML}\,\tilde{s_a}.$$

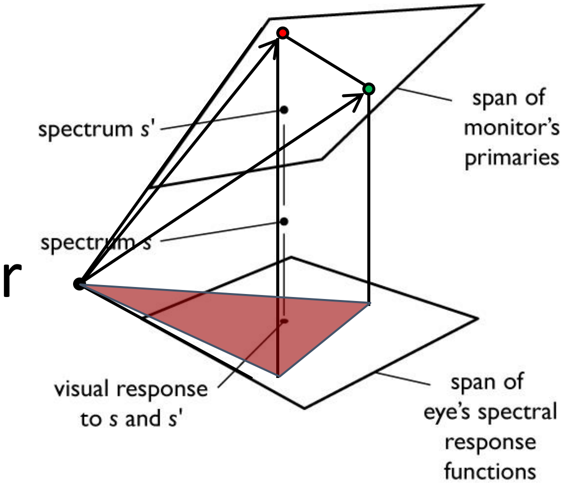
$$M_{SML}\,\tilde{s} = M_{SML} M_{RGB}\,C$$

$$C = \underbrace{(M_{SML} M_{RGB})^{-1} M_{SML}}_{\textit{colour matching matrix} \text{ for RGB}}\,\tilde{s}$$

What can go wrong?

- Could there be no matrix inverse?
  - RGB certainly selected to produce visual response vectors which are linearly independent!
  - Colour blindness? We're not modelling that!
- Does anything prevent C from being negative?

Colour spaces



- Need three numbers to specify a colour
  - But what three numbers?
  - A ***colour space*** is an answer to this question
- Common example: monitor RGB
  - Define colours by what *R, G, B* signals will produce them on your monitor (s = $R\mathbf{R} + G\mathbf{G} + B\mathbf{B}$ for some spectra **R**, **G**, **B**)
  - Device dependent (depends on gamma, phosphors, gains, …)
    - Therefore if I choose RGB by looking at my monitor and send it to you, you may not see the same colour ☹
  - Also leaves out some colours (limited *gamut*), e.g., vivid yellow (more on this later…)
  - The ***gamut*** is the subset of colours which can be represented within a given colour space or by a given output device.

Standard colour spaces

- We need to describe colours precisely for industry and science (paint, lighting, physics, chemistry)
- We want to describe all visible colours in terms of three variables (to get 3D coordinate space) vs. infinite number of spectral wavelengths or special reference swatches.

- One option: Standardized RGB (sRGB)
  - Makes a particular monitor RGB standard
  - Other colour devices simulate that monitor by calibration
  - sRGB is usable as an interchange colour space and is widely adopted today
  - Gamut is still limited

A universal colour space: *XYZ*

- Standardized by CIE (*Commission Internationale de l'Eclairage)*, standards organization for colour science
- Based on three "***imaginary***" primaries **X**, **Y**, and **Z**

$$\boldsymbol{s} = X\mathbf{X} + Y\mathbf{Y} + Z\mathbf{Z}$$

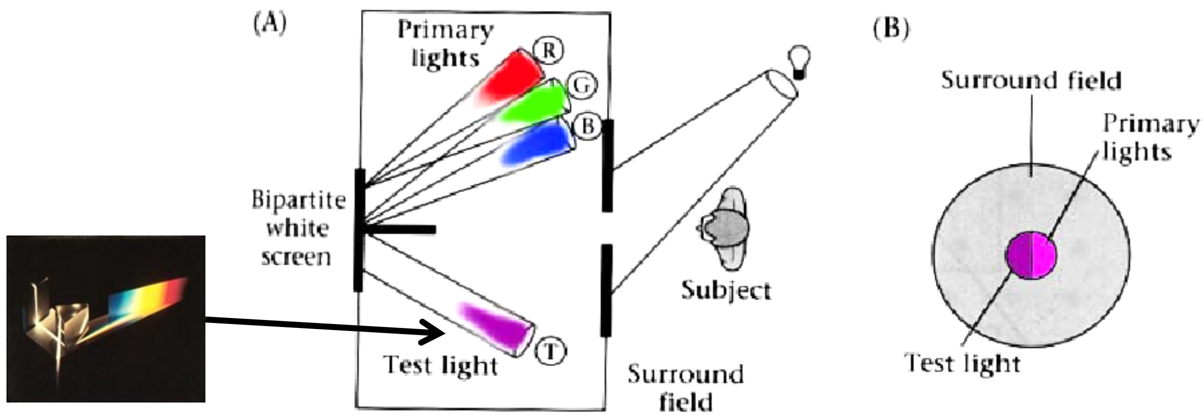
  - Imaginary because they are only realizable by spectra that are negative at some wavelengths!
  - Key properties
    - Any stimulus can be matched with ***positive*** scalars *X*, *Y*, and *Z*
    - Separates out luminance: **X**, **Z** have ***zero luminance***, so positive scalar *Y* tells you the luminance by itself

Colour matching experiment

Tristimulus theory leads to notion of matching all visible colours with combinations of red, green, and blue mono-spectral ***primaries***; it almost works!

The Colour Matching Experiment

- Choose three well-defined light colours to be the three variables (R = 700 nm G = 546.1 nm and B = 435.8 nm)
- Observers sit in a dark room matching colours
  - Observer views a divided screen and adjusts the intensities of 3 primary lights to match the appearance of a test light of pure wavelength



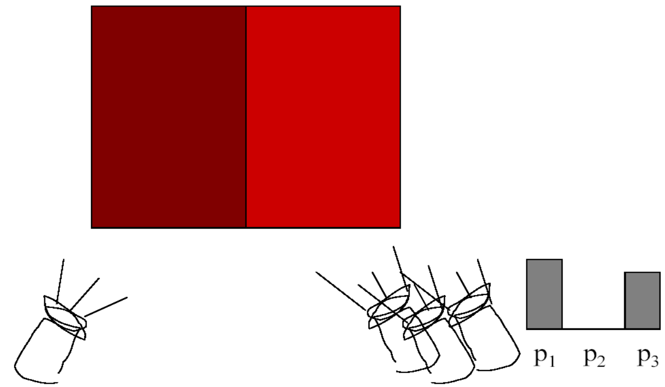
[Judd and Wyszecki 1975]

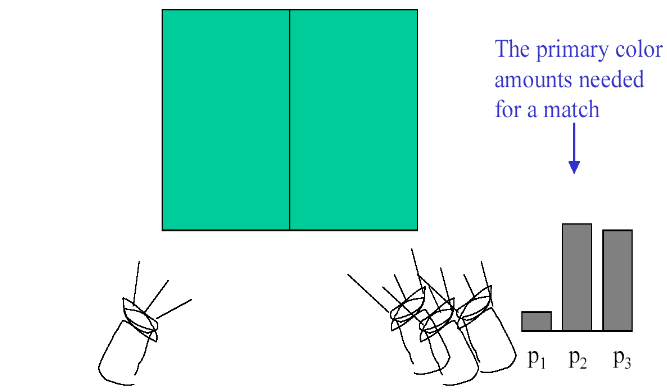
Top view of the experimental apparatus

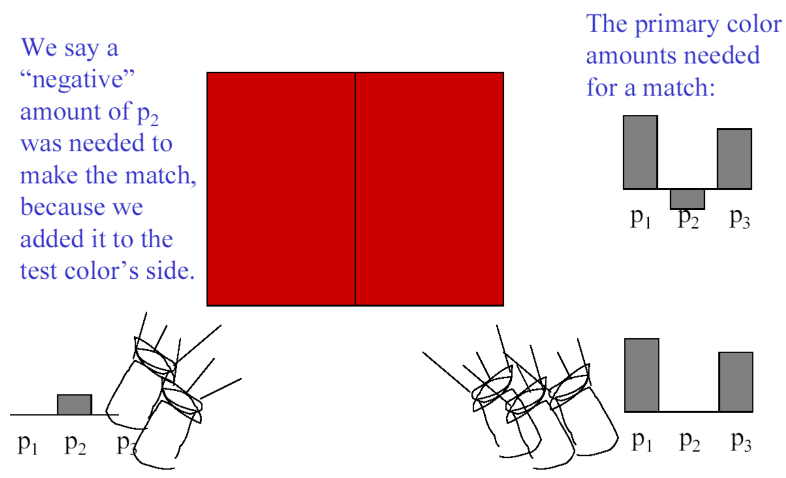
The appearance of the stimuli to the observer

The Experiment, Continued

- R, G and B can't match all colours...
- Sometimes need to add some R to the sample you are trying to match. Expressed mathematically as "-R".

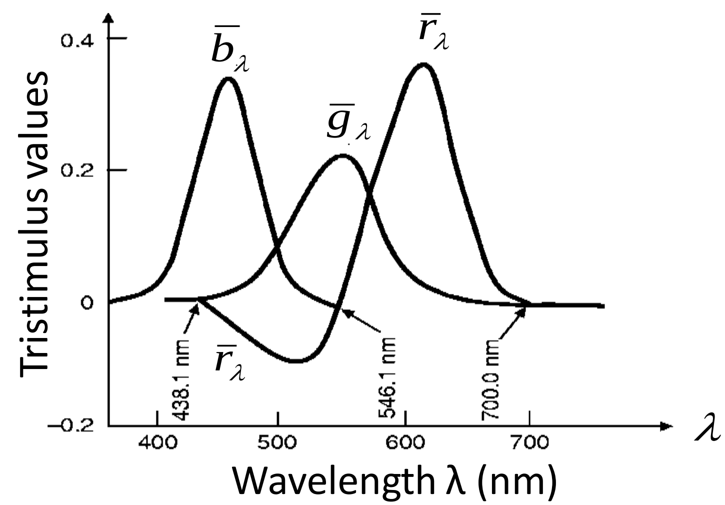






Colour Matching

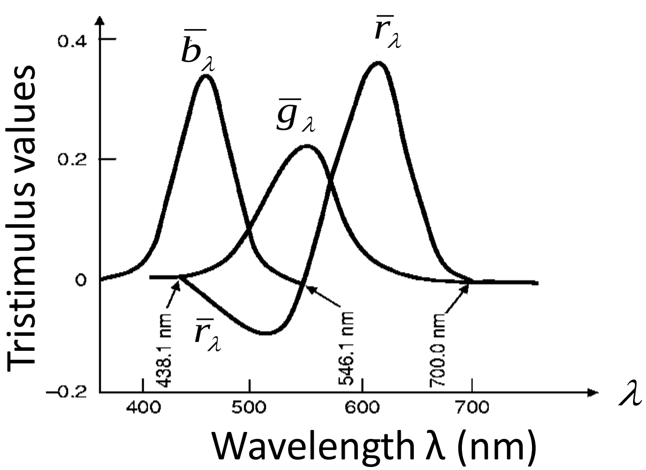
- The graph shows does *NOT* show response functions! It shows ***mixing weights***
- Negative value of $\bar{r}(\lambda)$ implies cannot match, must "subtract," i.e., add that amount to unknown
- Mixing positive amounts of arbitrary R, G, B primaries provides large colour gamut, but no device based on a finite # of primaries can show all colours!

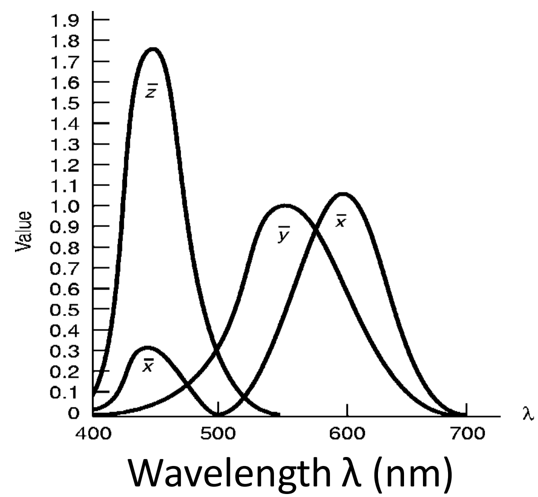


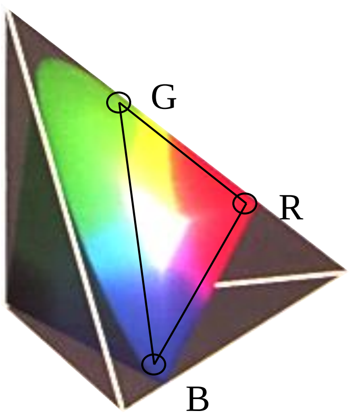
Colour-matching functions, showing amounts of three primaries needed by average observer to match a colour of constant luminance, for all values of dominant wavelength in visible spectrum.

Make CIE Space for colour Matching Curves

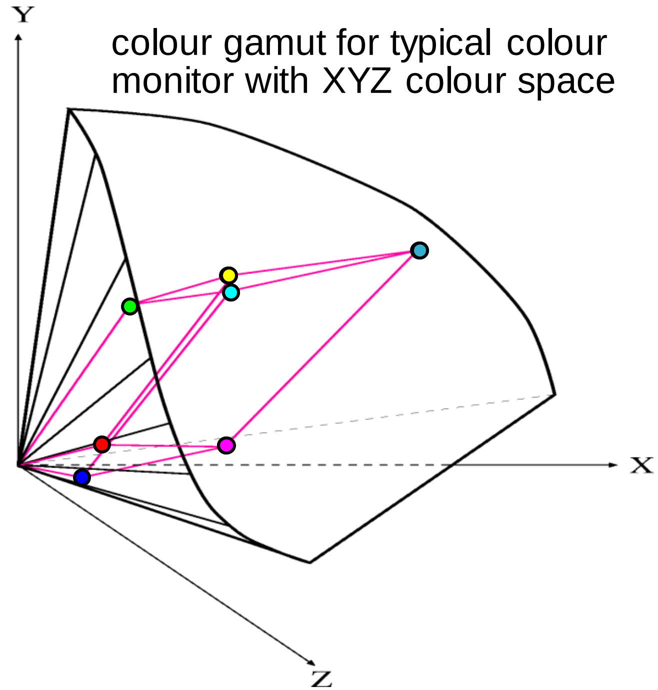
- Fit curves to tristimulus functions $\bar{r}_\lambda$, $\bar{g}_\lambda$, and $\bar{b}_\lambda$
- Transform response functions to produce three new primaries (imaginary) **X**, **Y**, **Z**, and matching curves $\bar{x}_\lambda$, $\bar{y}_\lambda$, $\bar{z}_\lambda$
  - ***Negative colours are not a practical concept***
  - $\bar{y}$ designed to correspond to ***luminance response of human eye***
  - $\bar{x}_\lambda$, $\bar{y}_\lambda$, $\bar{z}_\lambda$ are linear combinations of $\bar{r}_\lambda$, $\bar{g}_\lambda$, $\bar{b}_\lambda$
  - RGB maps to XYZ via a matrix

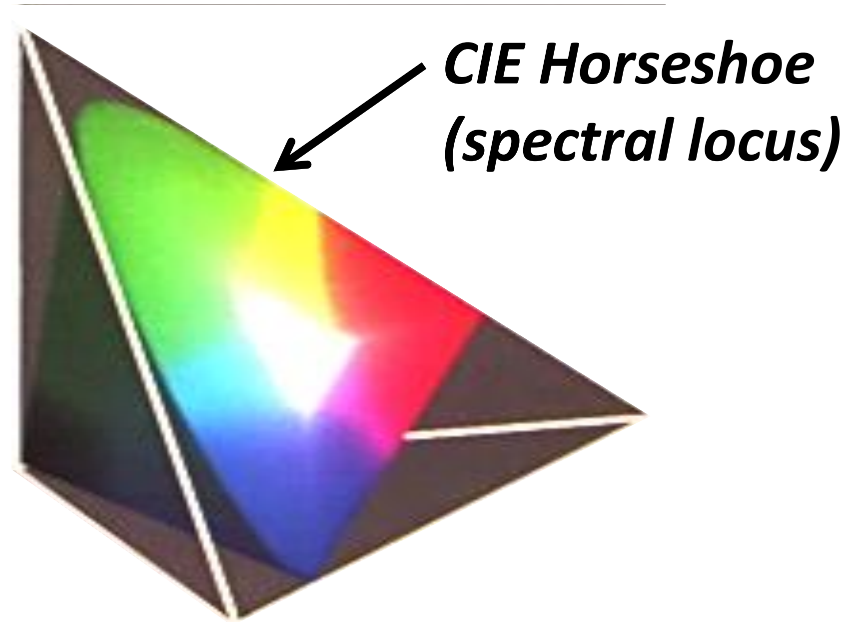






CIE Space Showing an RGB Gamut

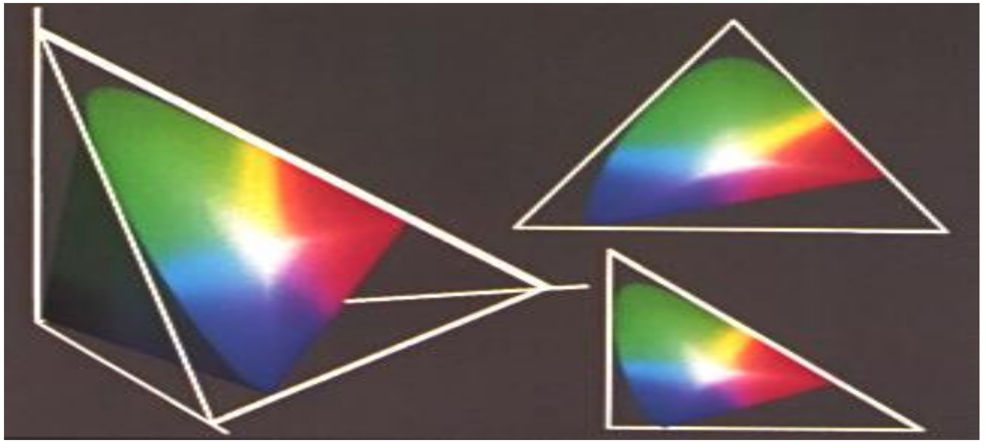




- Note irregular shape of visible gamut in CIE space;
  - Due to eye's response to pure frequencies as measured by response curves
  - Range of displayable colours clearly smaller than all colours visible in XYZ space.

CIE Space Projection to Chromaticity Diagram

- ***Chromaticity*** – Everything that deals with colour (Hue and Saturation, not luminance / brightness)
  - Left: plane embedded in CIE space.
  - Top right: view perpendicular to plane.
  - Bottom right: projection onto (X, Y) plane (Z = 0 plane). This is called the chromaticity diagram

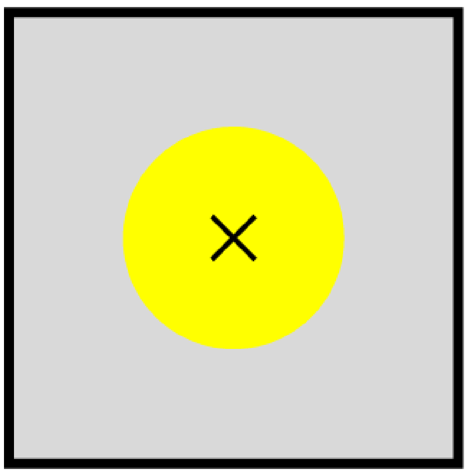


Several views of
X + Y + Z = 1
plane of CIE space

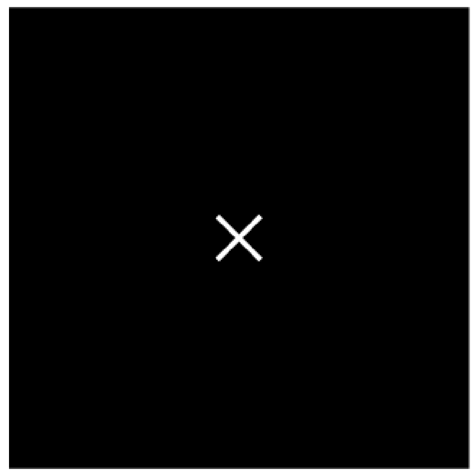
Visualizing the *XYZ* Color Space

Chimerical colour demo

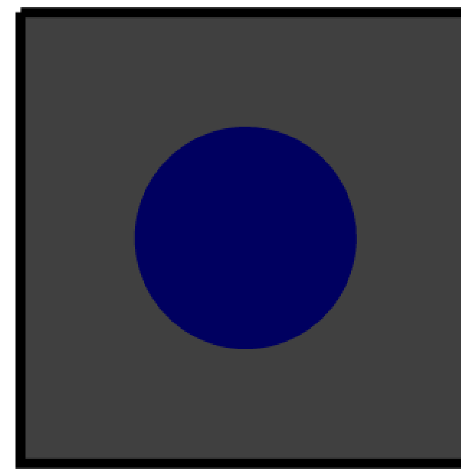
- Stygian Blue
  (simultaneously deep blue and black)



Fatigue Template
(stare at “x”)



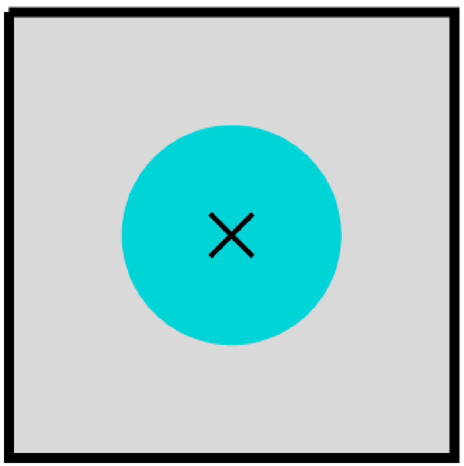
Target field
(glance at “x”)



Approximate
rendering

Chimerical colour demo

- Hyperbolic Orange
  (more than 100% color saturation)



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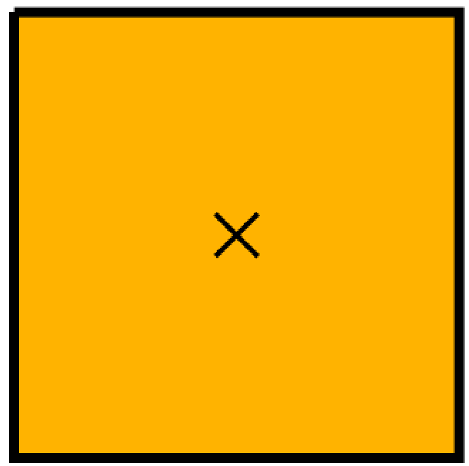

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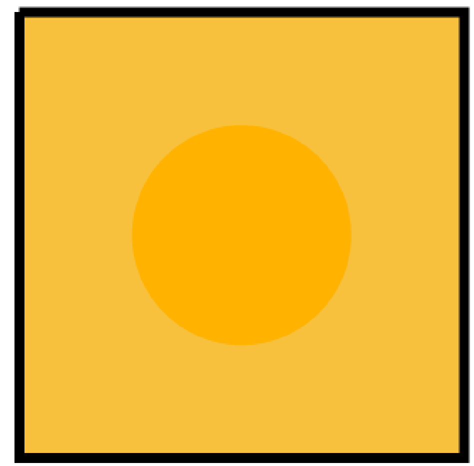
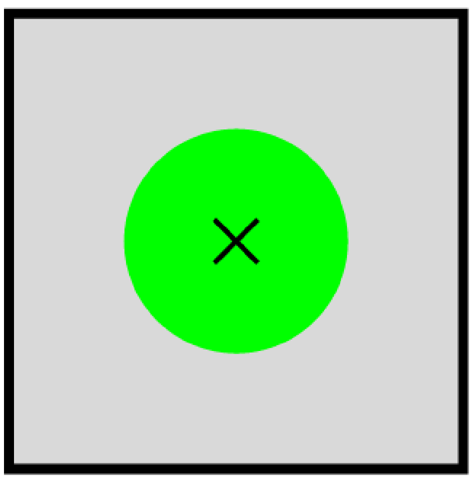


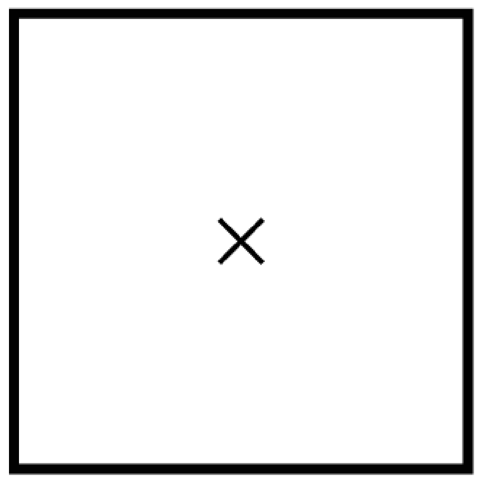
Approximate
rendering

Chimerical colour demo

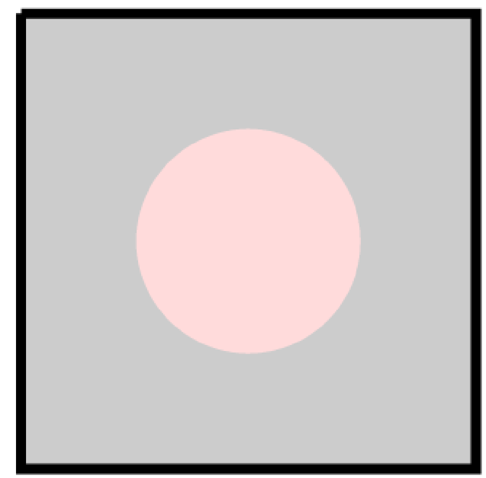
- Self-Luminous Red
  (simultaneously red and brighter than white)



Fatigue Template
(stare at “x”)



Target field
(glance at “x”)



Approximate
rendering

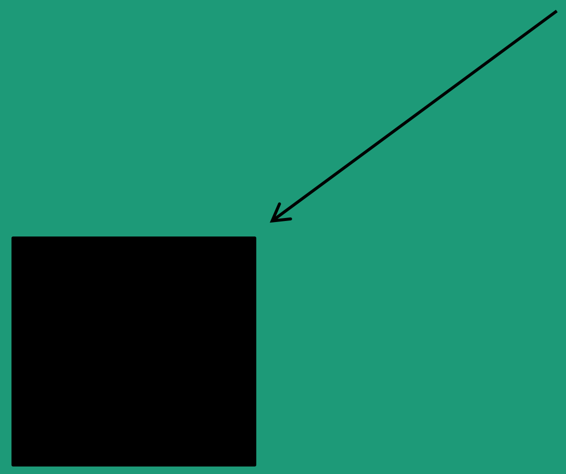
Questions

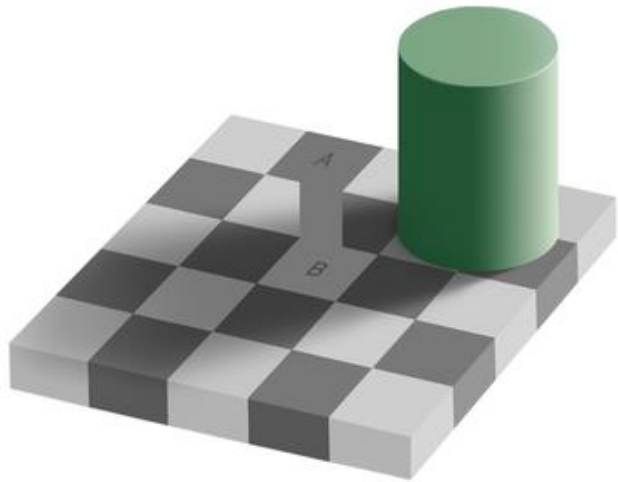
- What colour is the moon?
  http://goo.gl/rNF3Fr
- What colour is the sun?
  http://goo.gl/FLSciH
- What colour are the stars?
  http://goo.gl/h2FlNx
  http://goo.gl/kPYME3

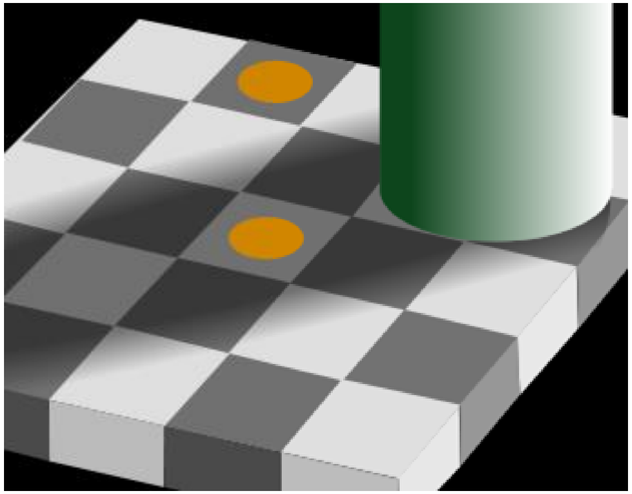
Questions

- Is the projection screen white?

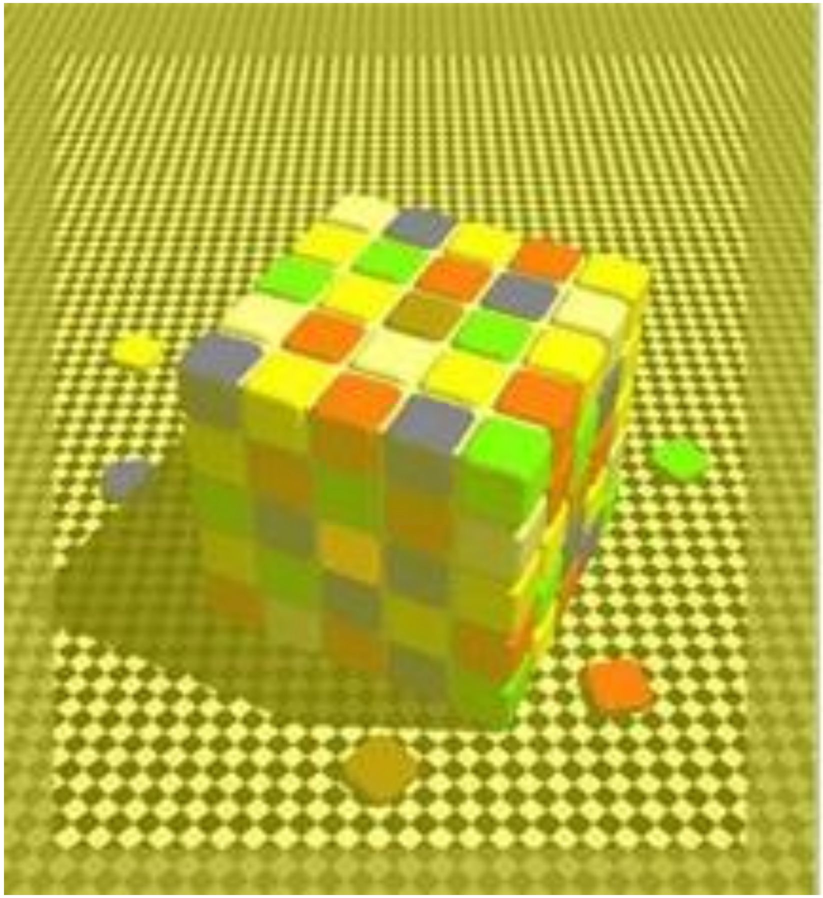
Is this square black?

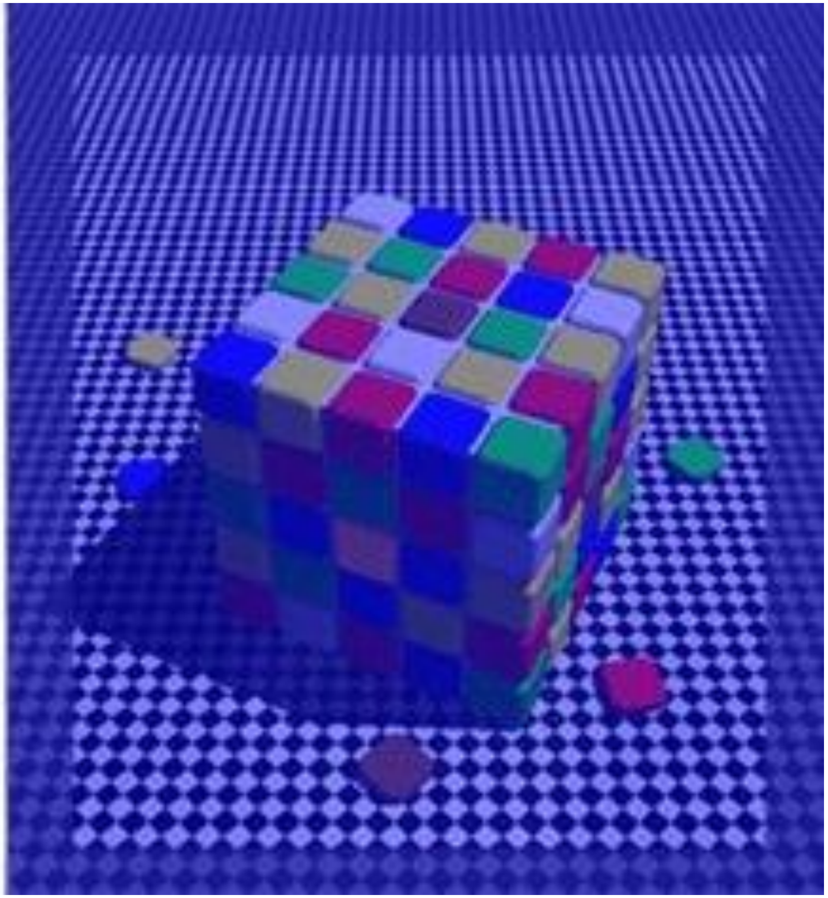



A
B



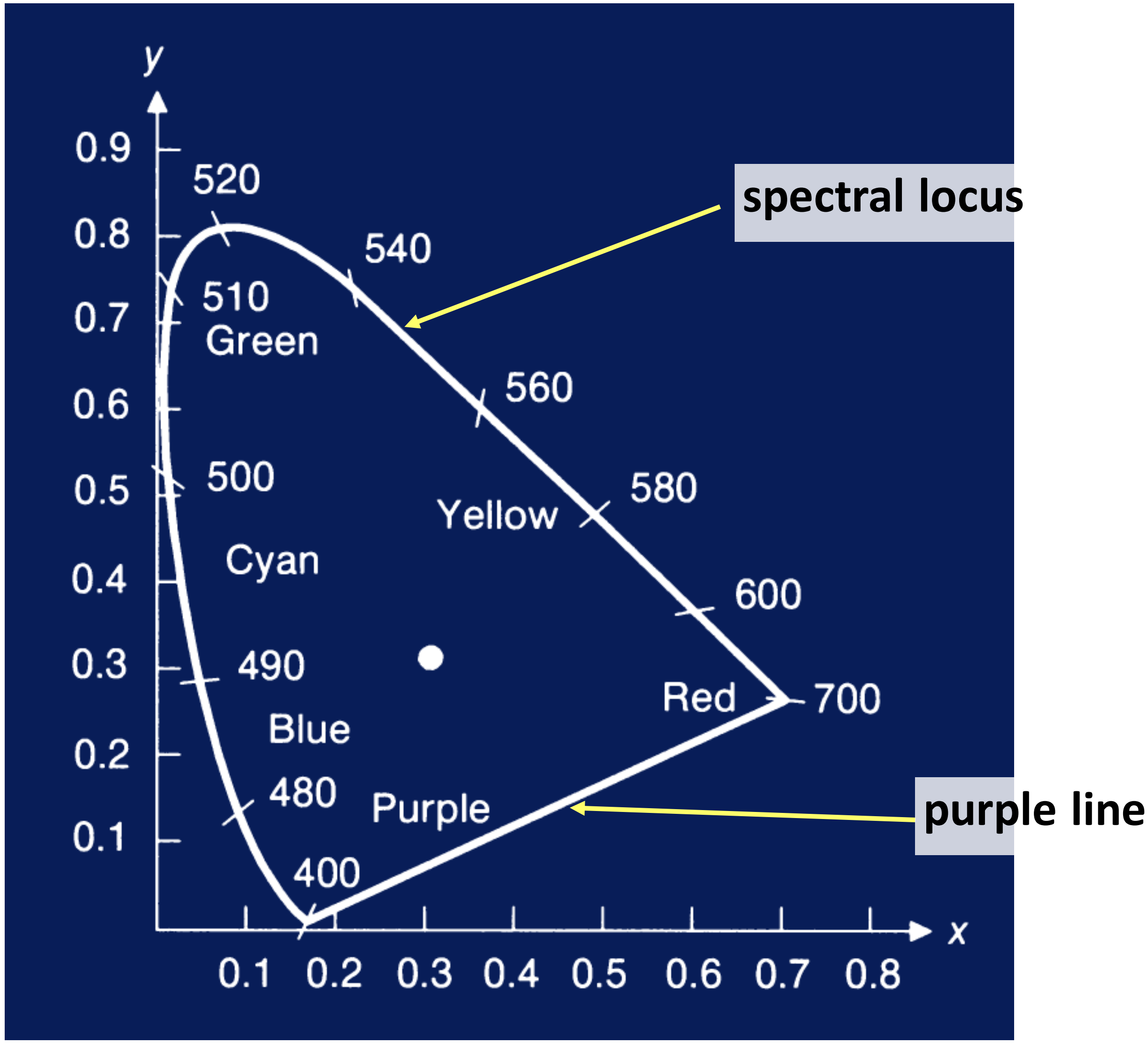
Lottolab





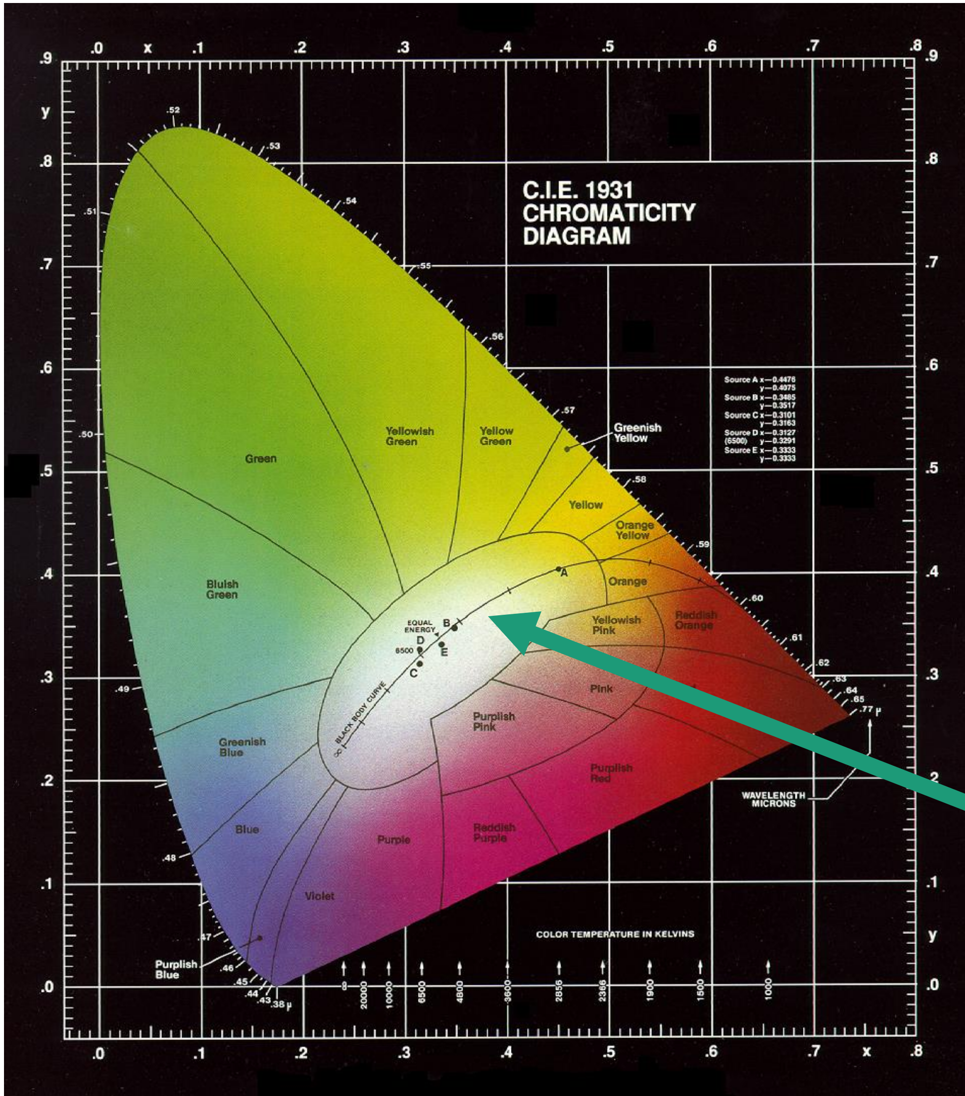
Gamut Gallery

Chromaticity Diagram



[source unknown]

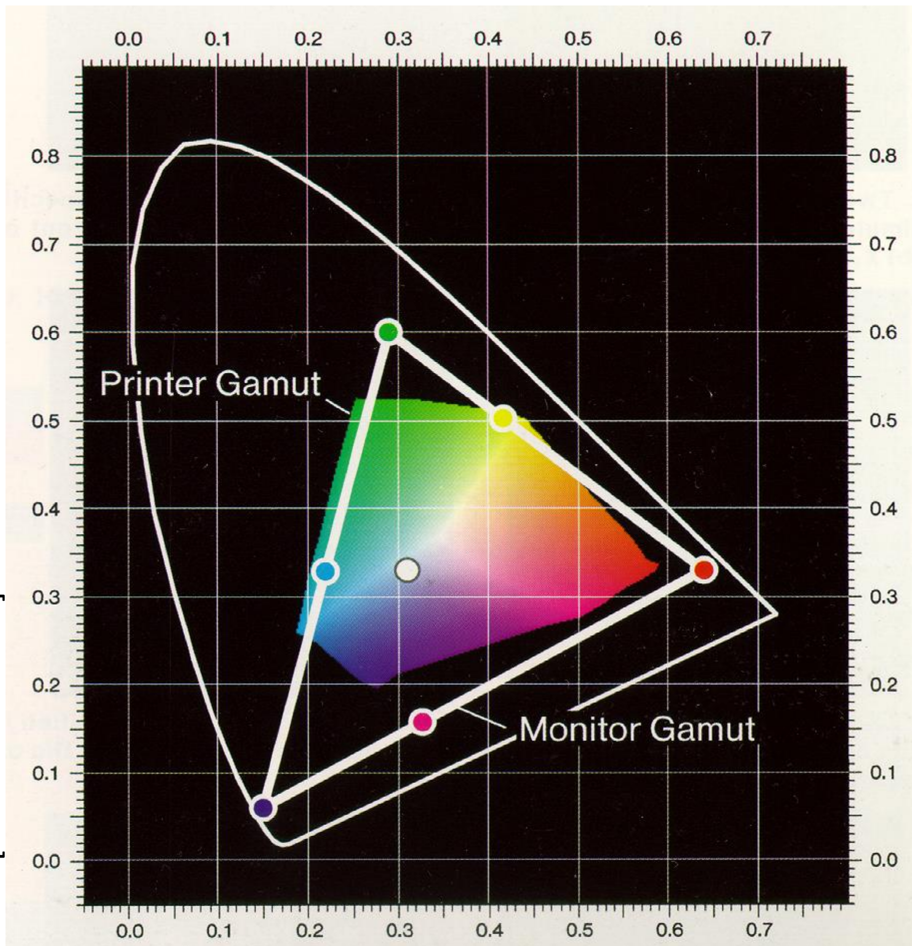
Chromaticity Diagram



Black body curve

[source unknown]

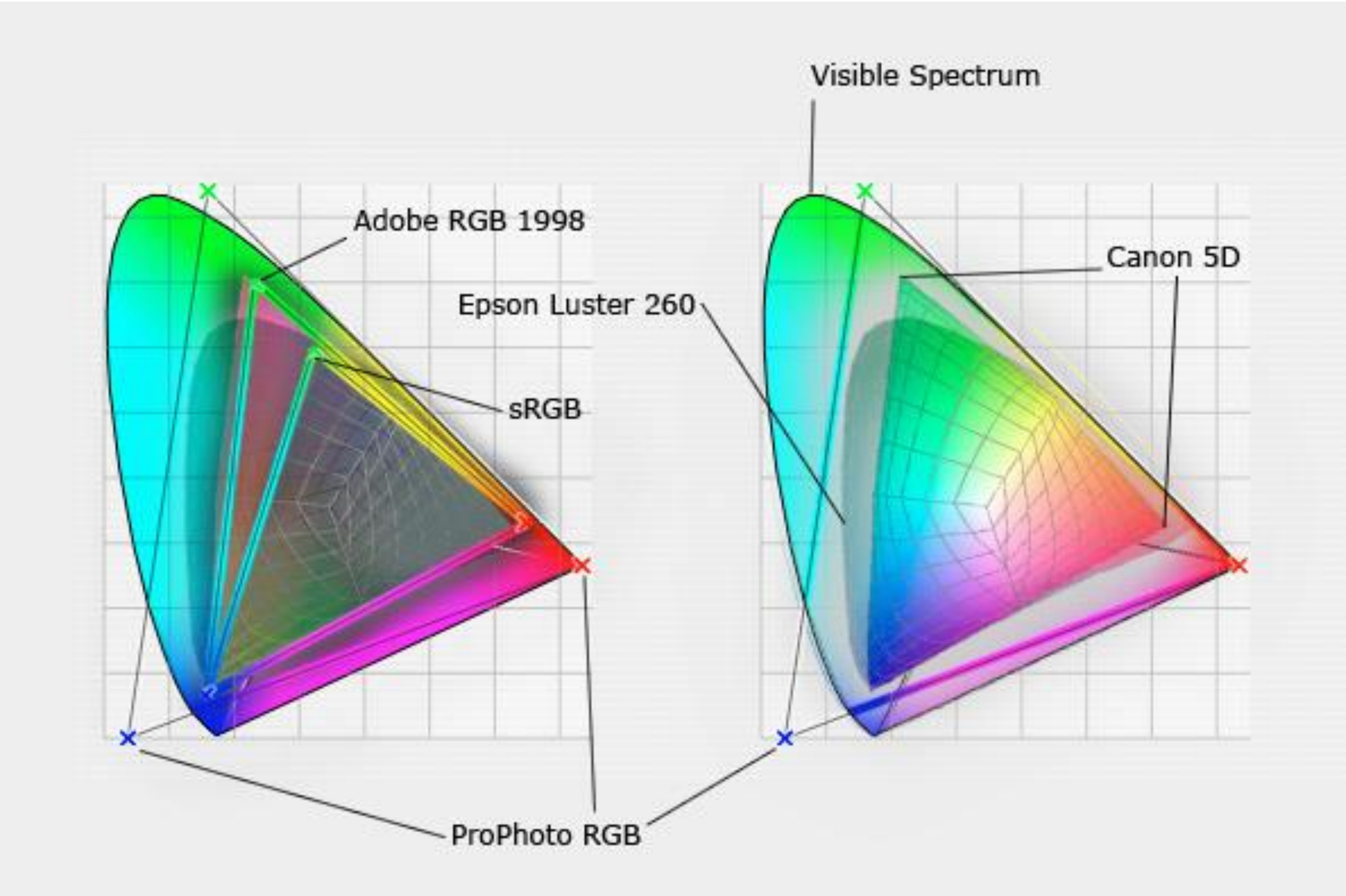
Colour Gamuts



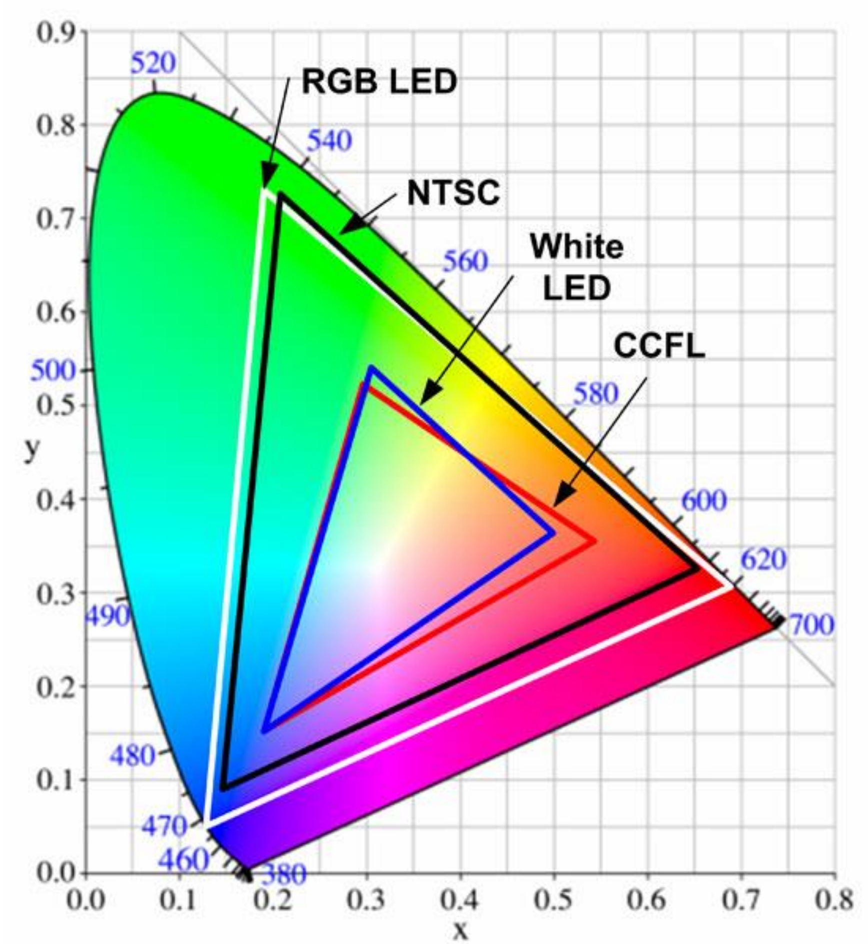
[source unknown]

- Monitors/printers can't produce all visible colours
- Reproduction is limited to a particular domain
- For additive colour (e.g. monitor) gamut is the triangle defined by the chromaticities of the three primaries.

Colour spaces on CIE horse shoe

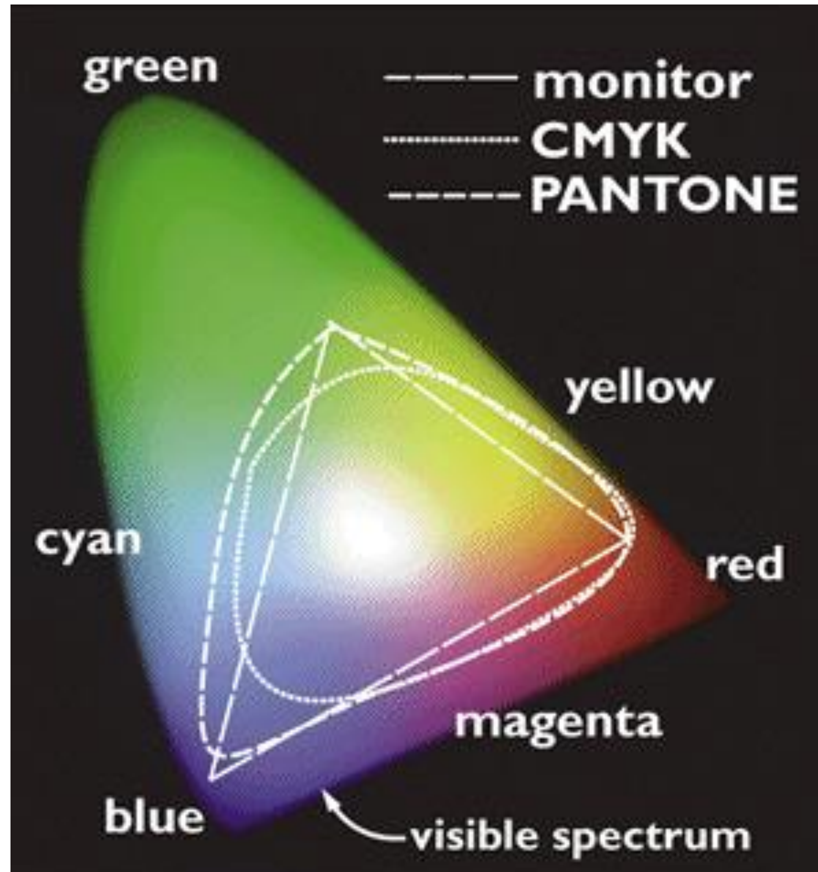


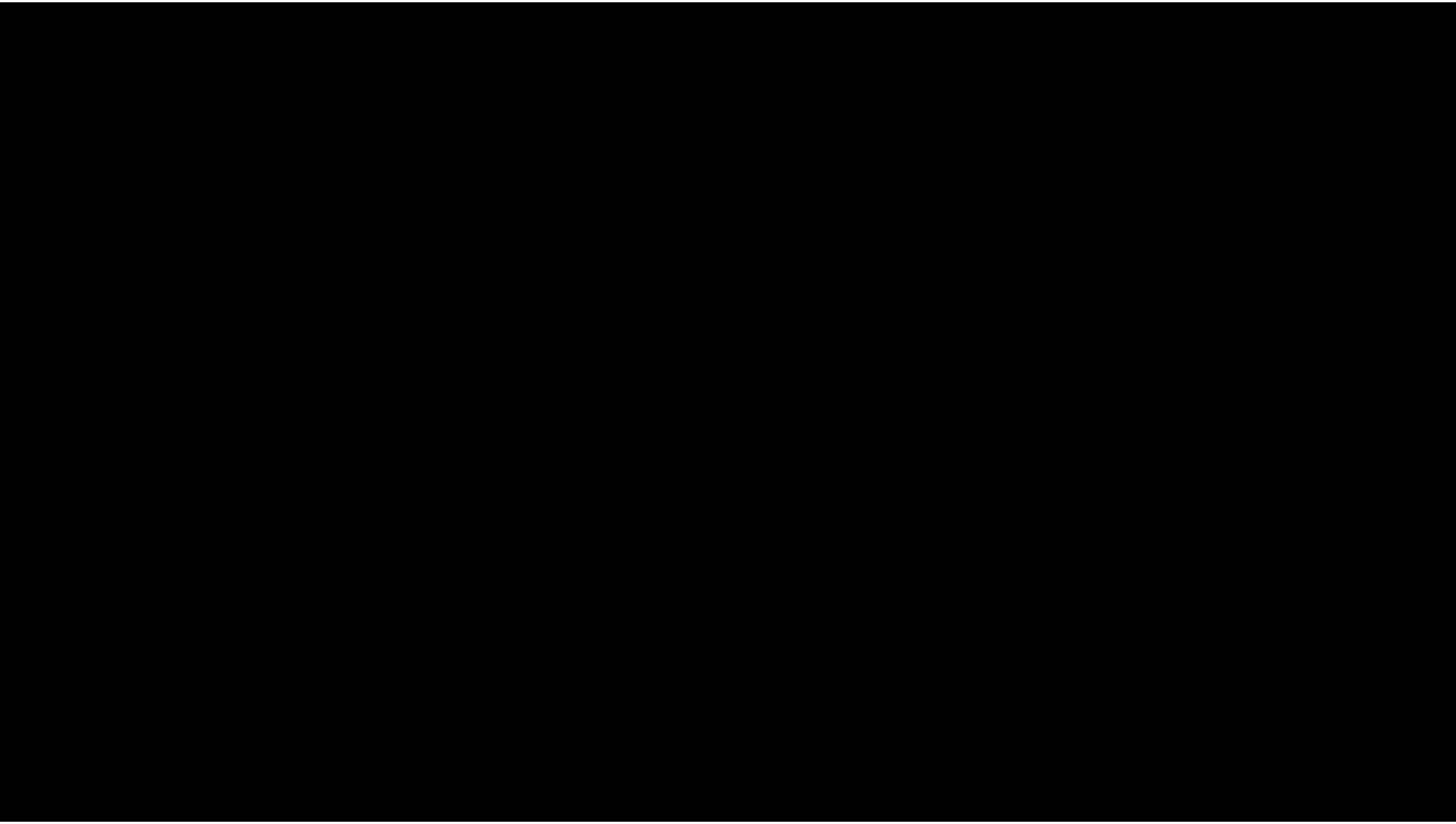
Additive display gamut comparison



Subtractive colour gamut comparison

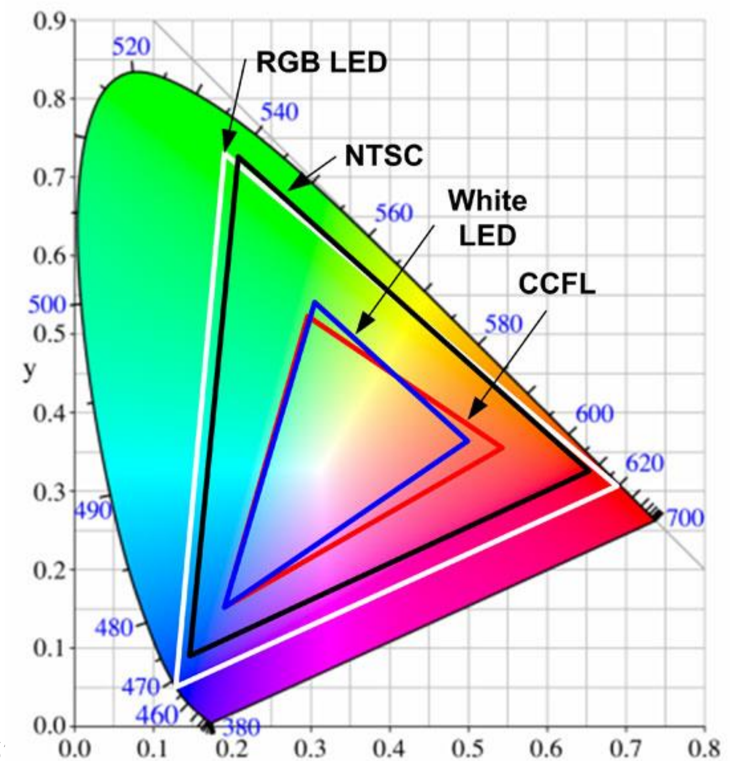
- Pantone has 13 base pigments
  (plus black and white)

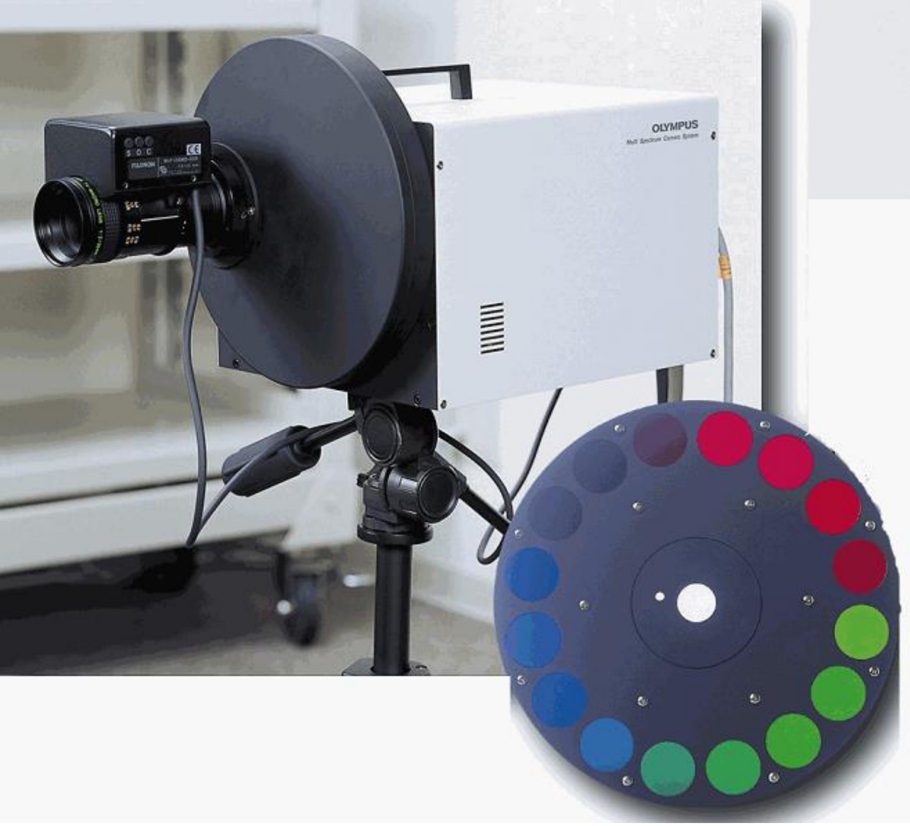




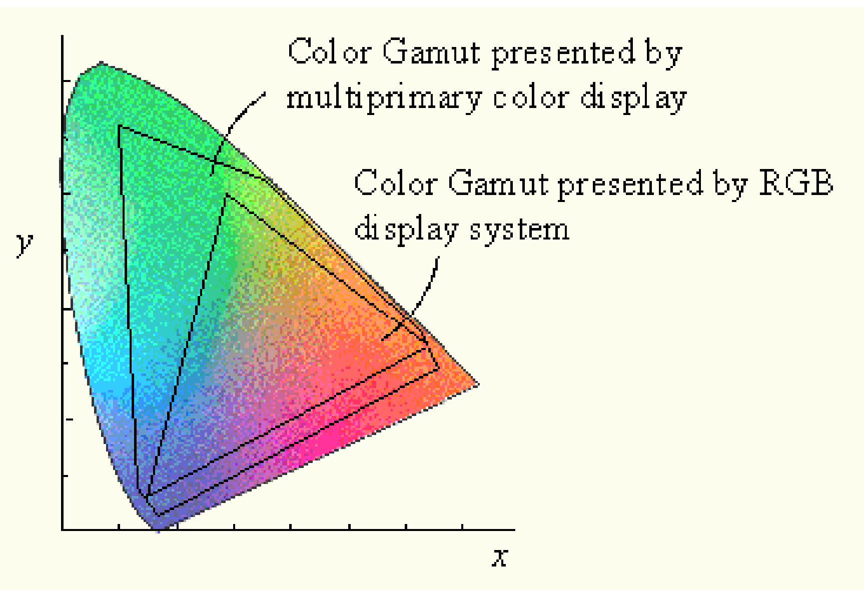
Questions

- Are other TVs not able to display yellow?
- What real benefits might this display technology have?




OLYMPUS

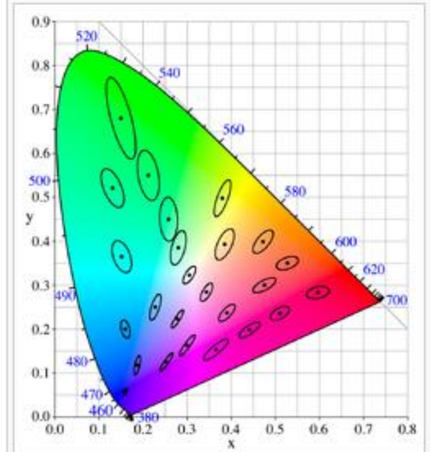

OLYMPUS


Color Gamut presented by multiprimary color display
Color Gamut presented by RGB display system
y
x

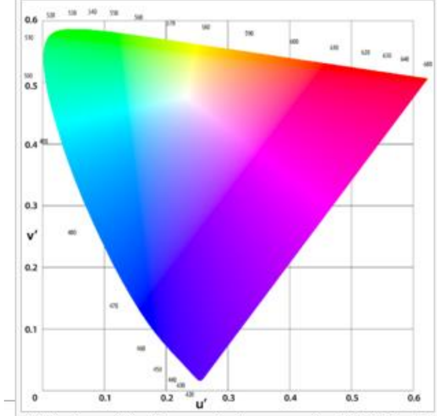
Perceptually uniform colour spaces

CIE 1976 L*a*b* and L*u*v*

- Perceptually uniform colour spaces
  - Nonlinear transformations from XYZ
  - Designed so that equal differences in coordinates produce equally visible differences in colour
  - LUV: slightly simpler transformation
  - LAB: more complex but more uniform
  - Both separate luminance from chromaticity
  - Including a gamma-like nonlinear component is important

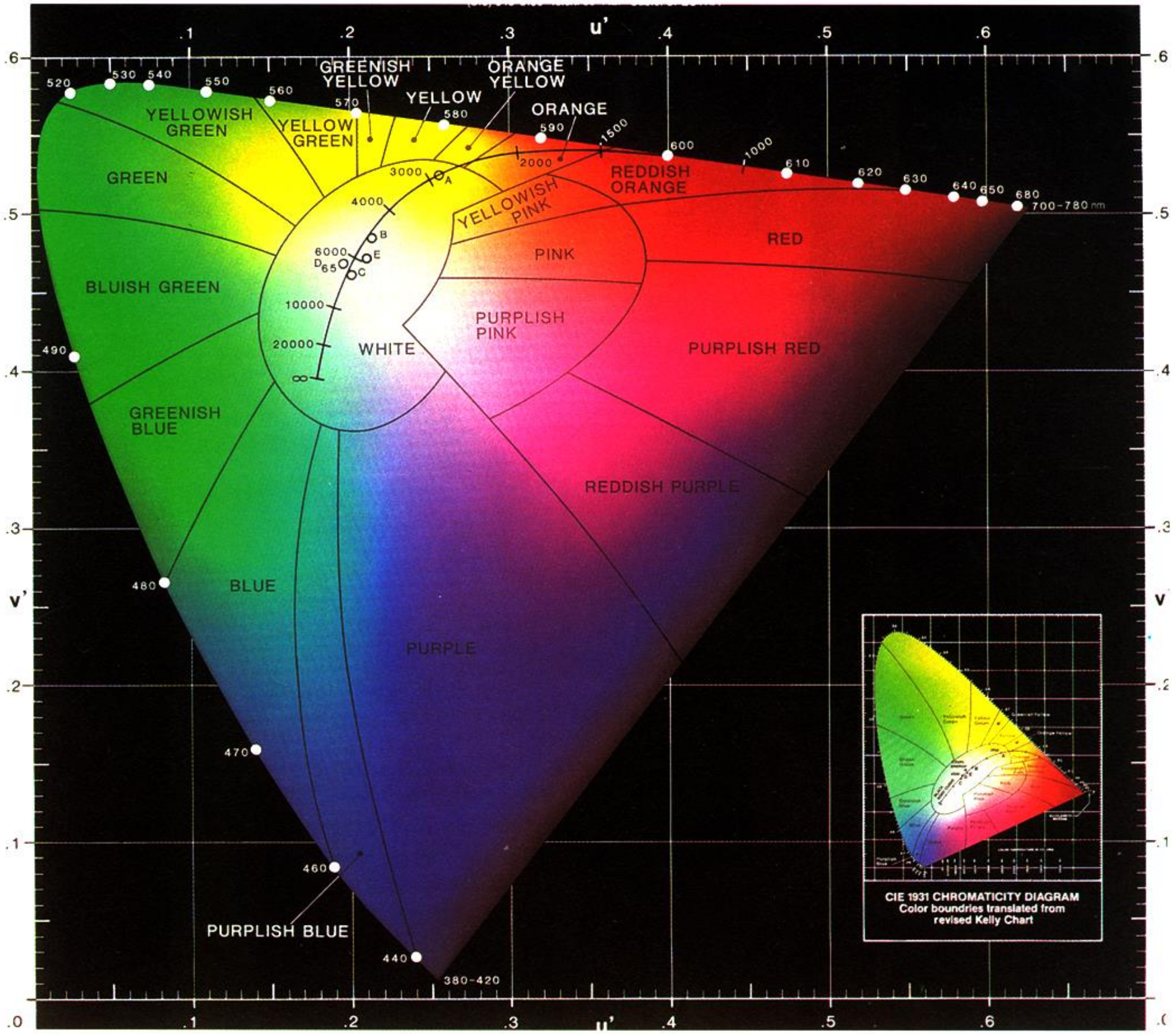


MacAdam diagram in the CIE 1931 color space



(u',v') chromaticity diagram, also known as the *CIE 1976 UCS* (uniform chromaticity scale) diagram

CIE Chromaticity Diagram



CIE 1976 UCS chromaticity diagram from *Electronic colour: The Art of colour Applied to Graphic Computing* by Richard B. Norman, 1990

Inset: CIE 1931 chromaticity diagram

Again note curve showing blackbody radiation for different temperatures!

Things to Remember…

- Metamer
- Gamut
- Luminance and chromaticity
- Colour matching experiment
- CIE colour space
- Perceptually uniform colour spaces

Review and More Information

- Textbook chapter 21
  - Colorimetry 21.1
    - Cone Responses 21.1.2
    - Colour Matching Experiments 21.1.3
    - Standard Observers and CIE 21.1.4
  - Colour Spaces 21.2
    - Matrix transform 21.2.1