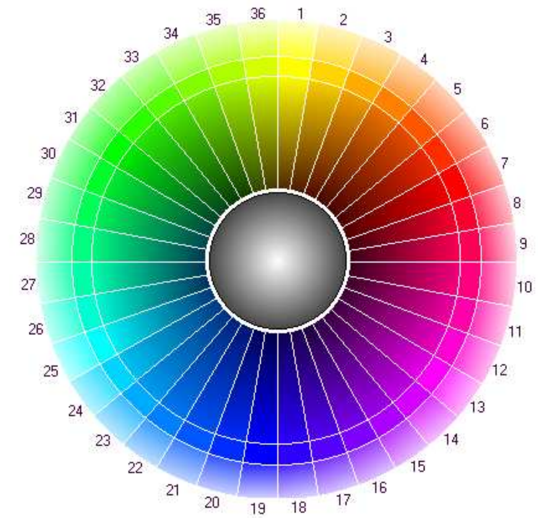
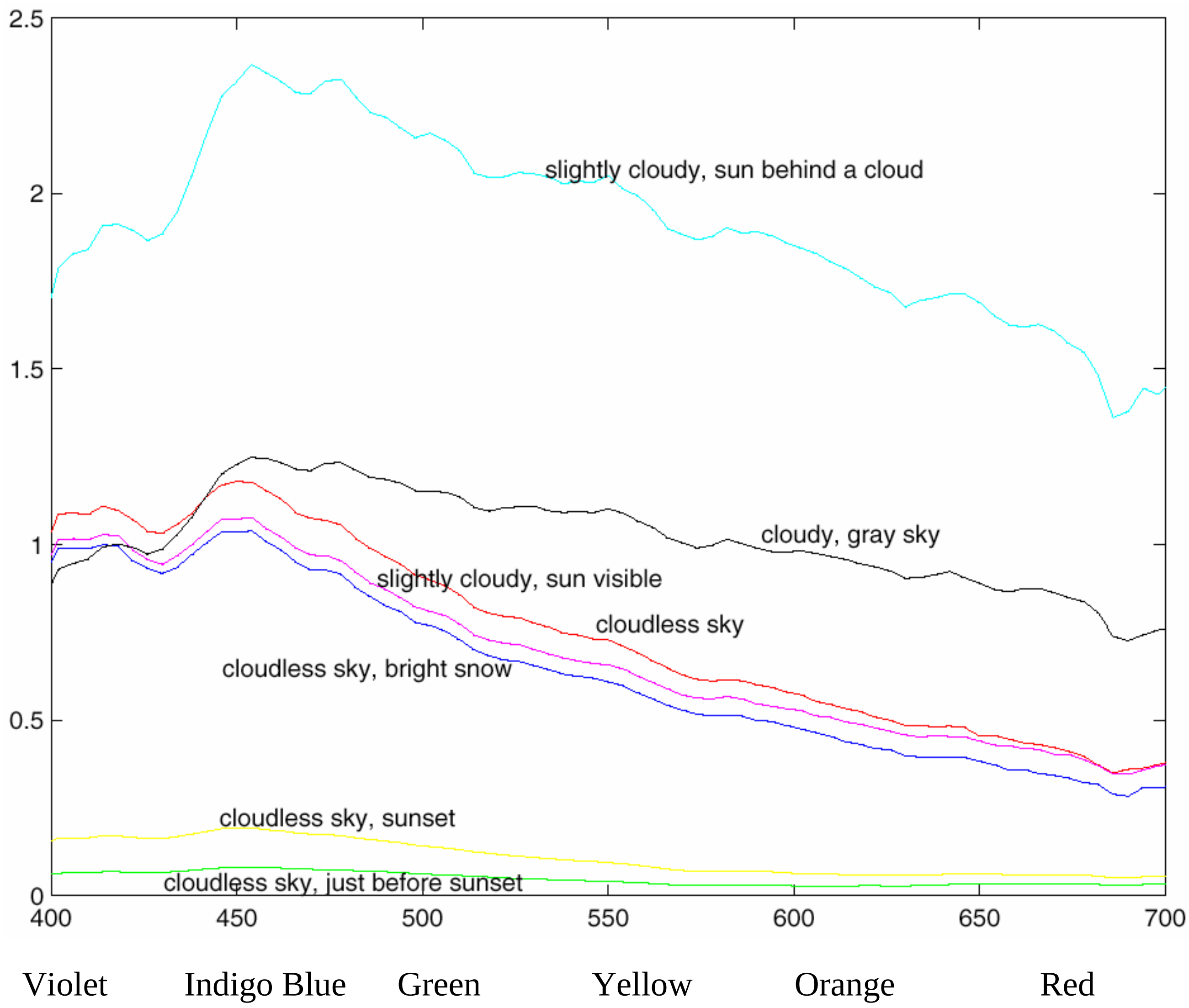
Colour

Reading: Chapter 6



- Light is produced in different amounts at different wavelengths by each light source
- Light is differentially reflected at each wavelength, which gives objects their natural colours (surface albedoes)
- The sensation of colour is determined by the human visual system, based on the product of light and reflectance

Credits: Many slides in this section from Jim Rehg and Frank Dellaert

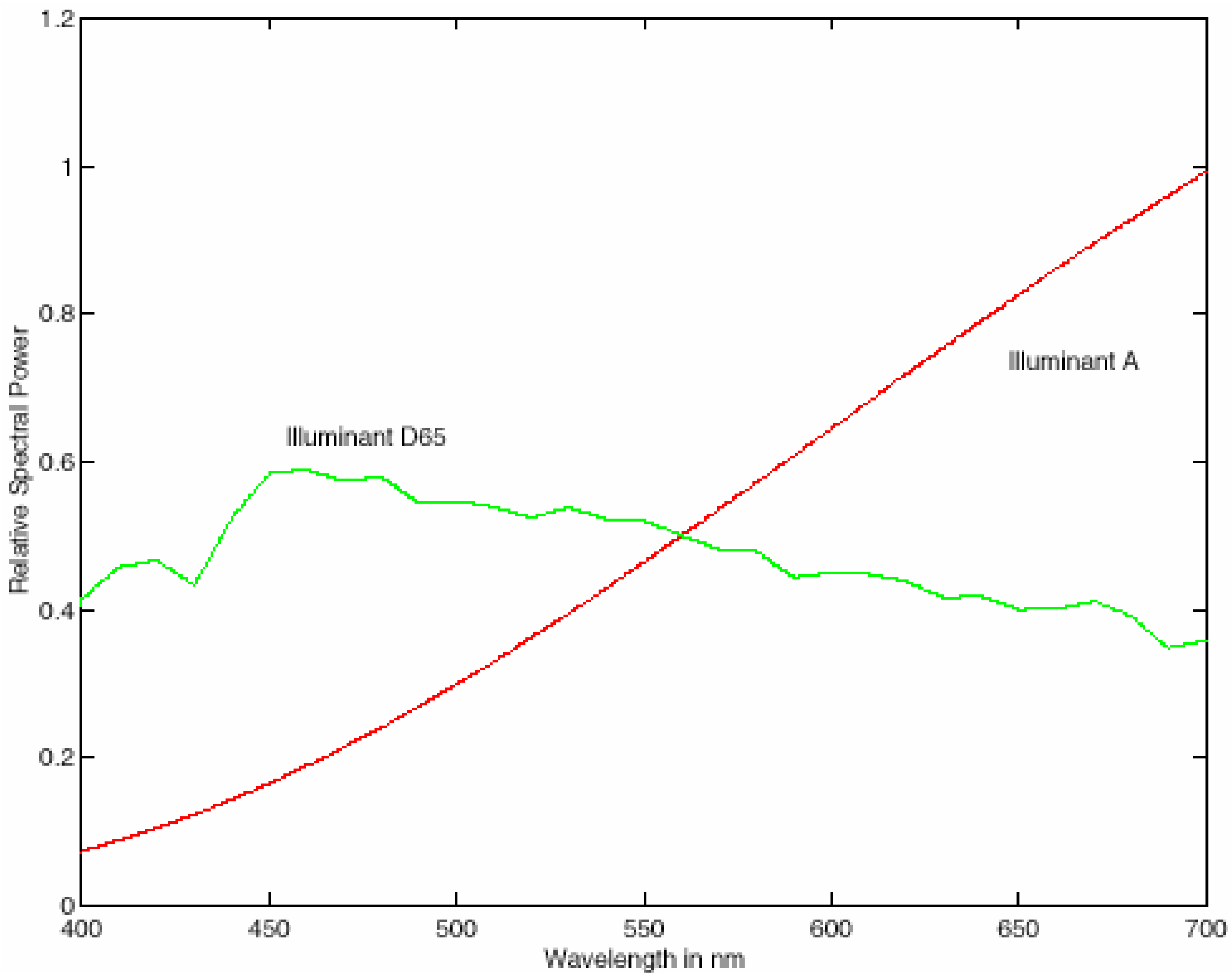


Measurements of relative spectral power of sunlight, made by J. Parkkinen and P. Silfsten. Relative spectral power is plotted against wavelength in nm. The visible range is about 400nm to 700nm. The colour names on the horizontal axis give the colour names used for monochromatic light of the corresponding wavelength.

Spectral power gives the amount of light emitted at each wavelength.

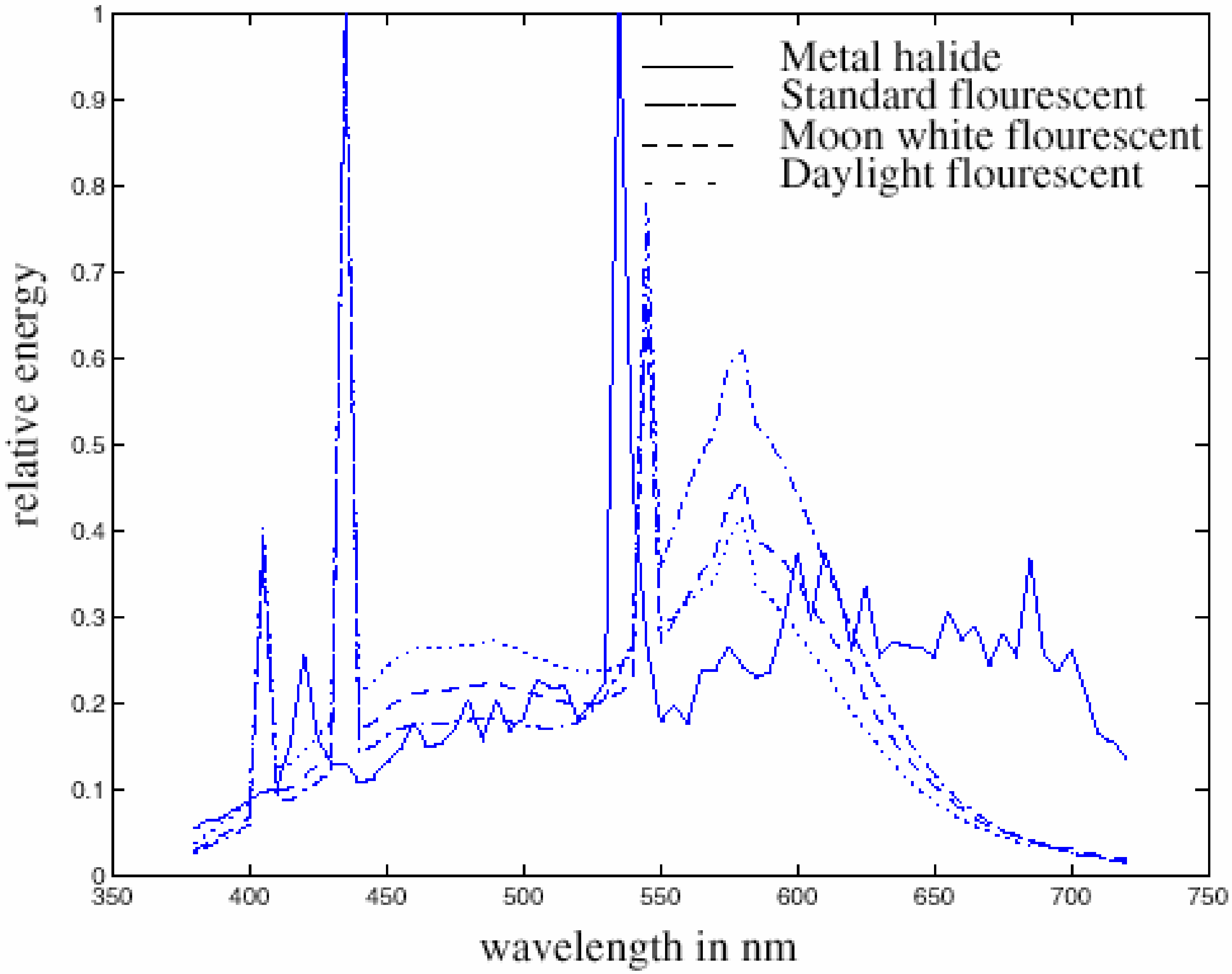
Black body radiators

- Construct a hot body with near-zero albedo (black body)
  - Easiest way to do this is to build a hollow metal object with a tiny hole in it, and look at the hole.
- The spectral power distribution of light leaving this object is a function of temperature (degrees Kelvin)
  - Surprisingly, the material does not make a difference!
- This leads to the notion of colour temperature --- the temperature of a black body that would create that colour
  - Candle flame or sunset: about 2000K
  - Incandescent light bulbs: 3000K
  - Daylight (sun): 5500K
  - Blue sky (shadowed from sun): 15,000K
- Colour camera film is rated by colour temperature

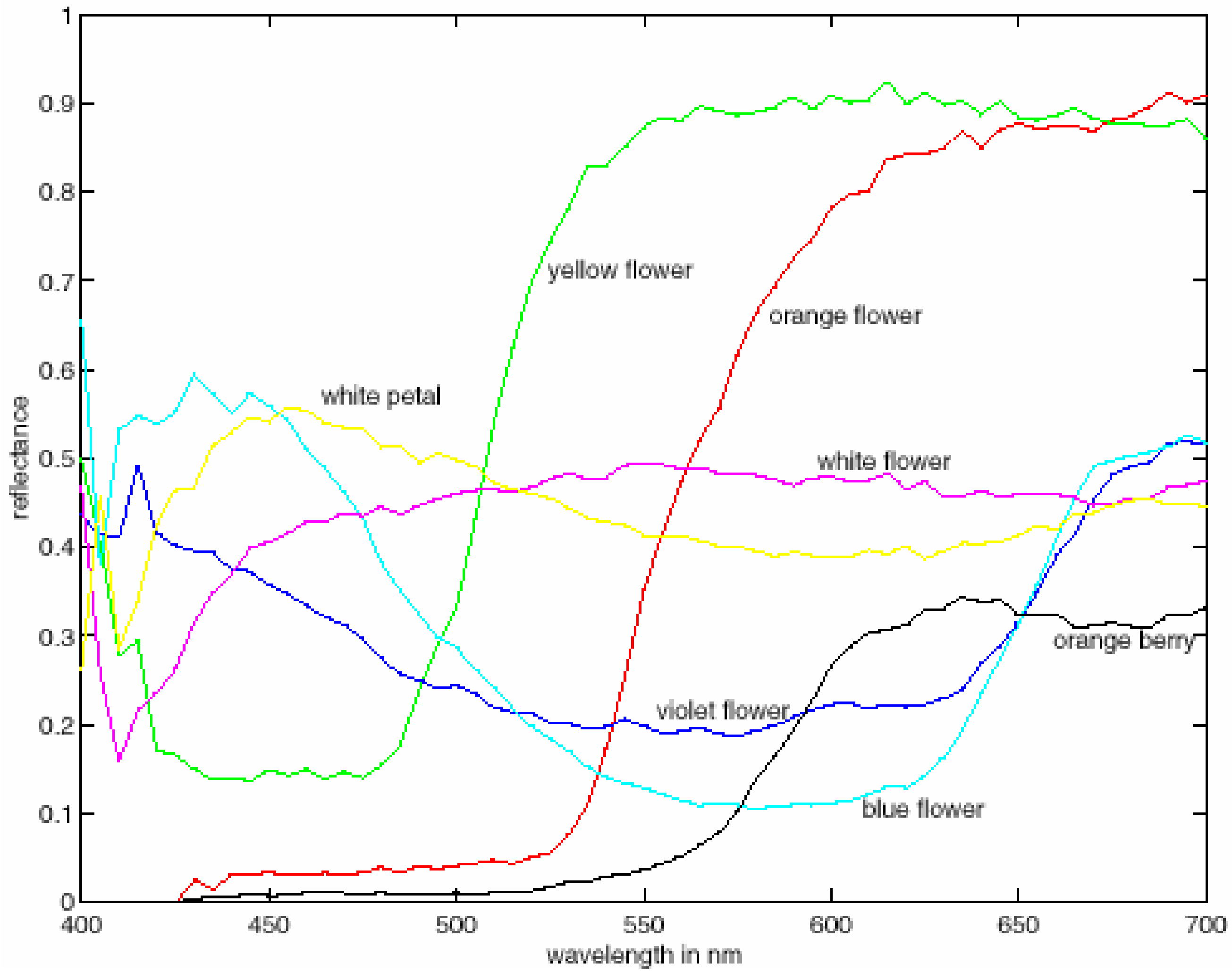


Violet Indigo Blue Green Yellow Orange Red

Relative spectral power of two standard illuminant models --- D65 models sunlight,and illuminant A models incandescent lamps. Relative spectral power is plotted against wavelength in nm.



Measurements of relative spectral power of four different artificial illuminants, made by H.Sugiura. Relative spectral power is plotted against wavelength in nm. The visible range is about 400nm to 700nm.



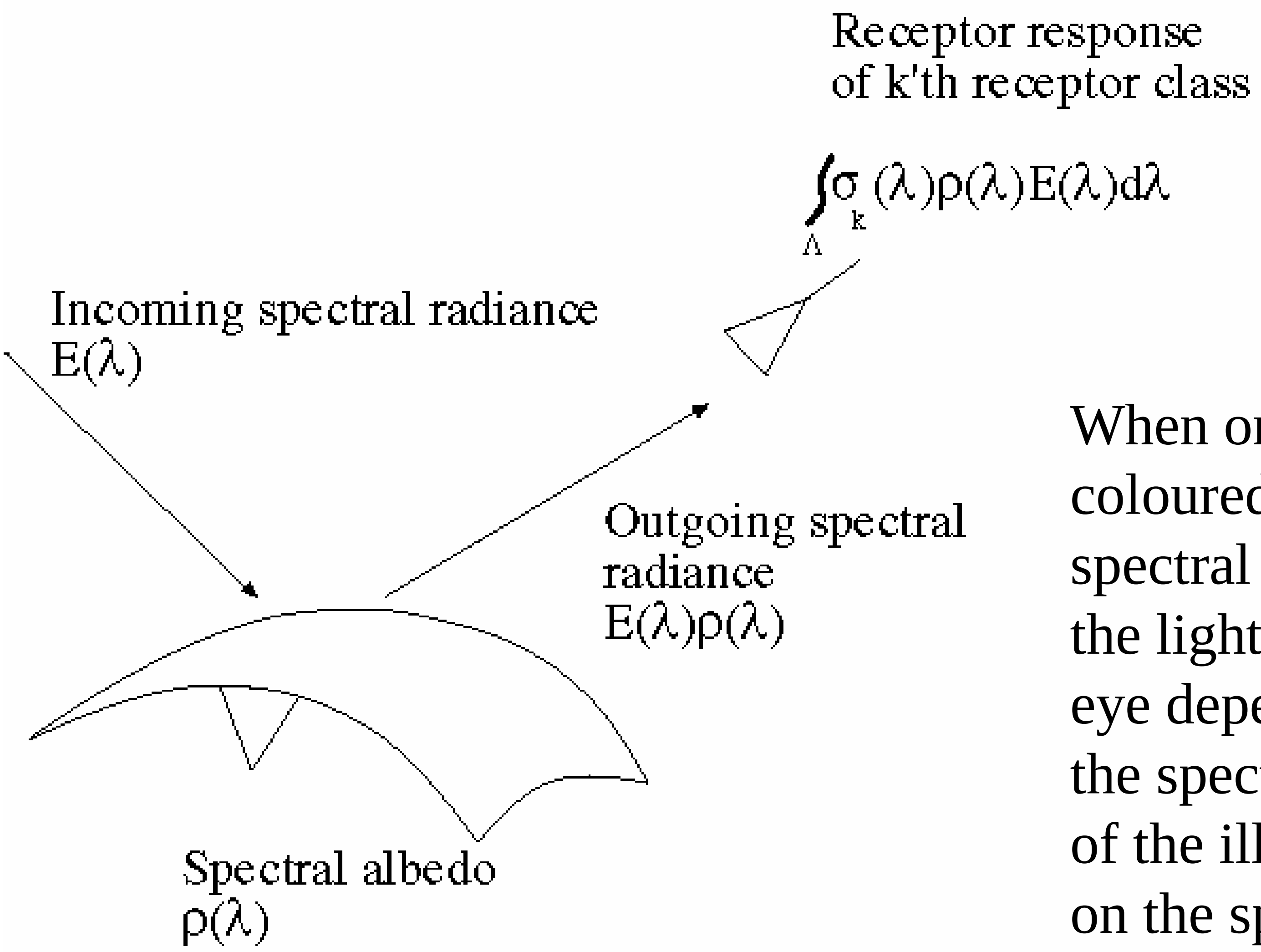
Spectral albedoes for several different flowers, with colour names attached. Notice that different colours typically have different spectral albedo, but that different spectral albedoes may result in the same perceived colour (compare the two whites). Spectral albedoes are typically quite smooth functions. Measurements by E.Koivisto.

Spectral reflectance (or *spectral albedo*) gives the proportion of light that is reflected at each wavelength

The appearance of colours

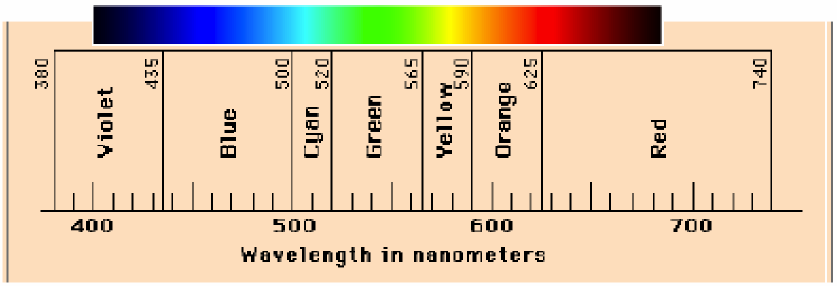
- Reflected light at *each wavelength* is the product of illumination and surface reflectance

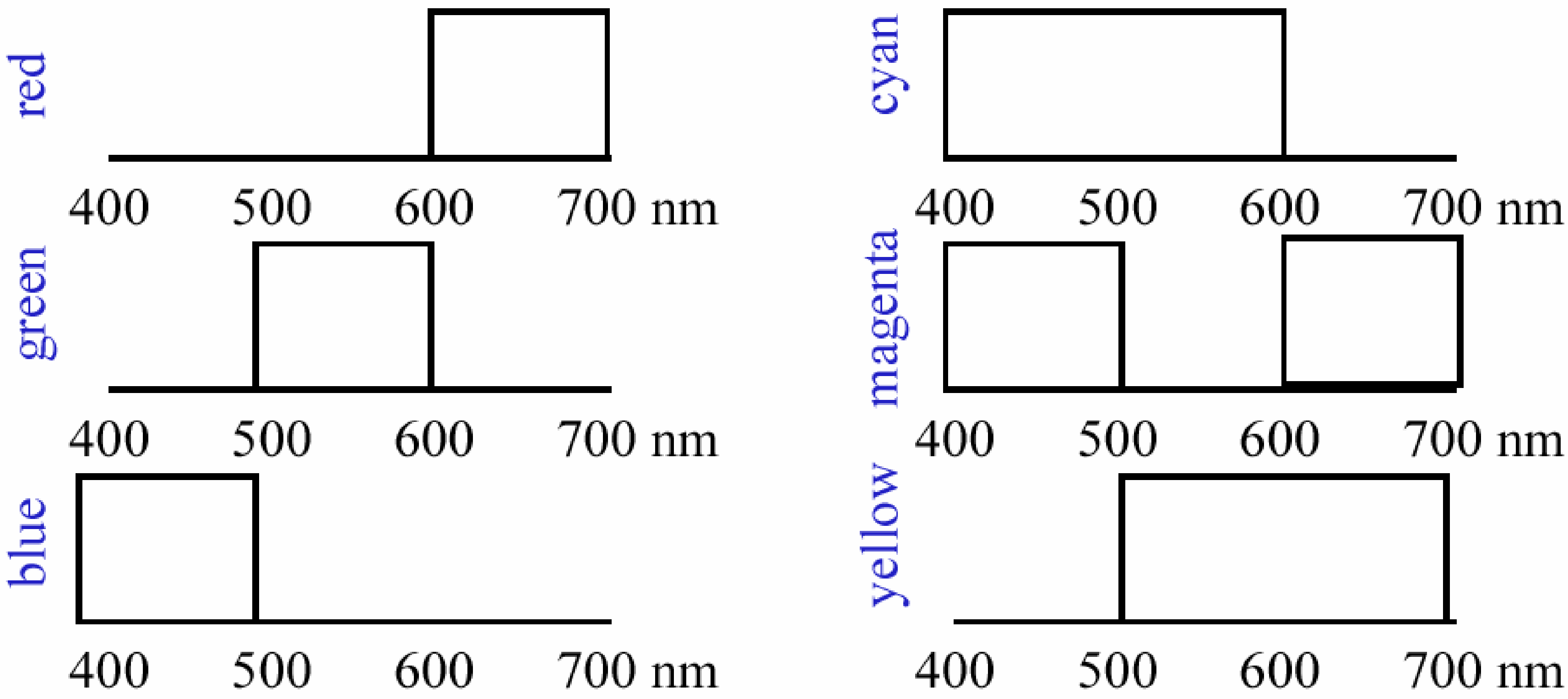
- Surface reflectance is typically modeled as having two components:
  - Lambertian reflectance: equal in all directions (diffuse)
  - Specular reflectance: mirror reflectance (shiny spots)



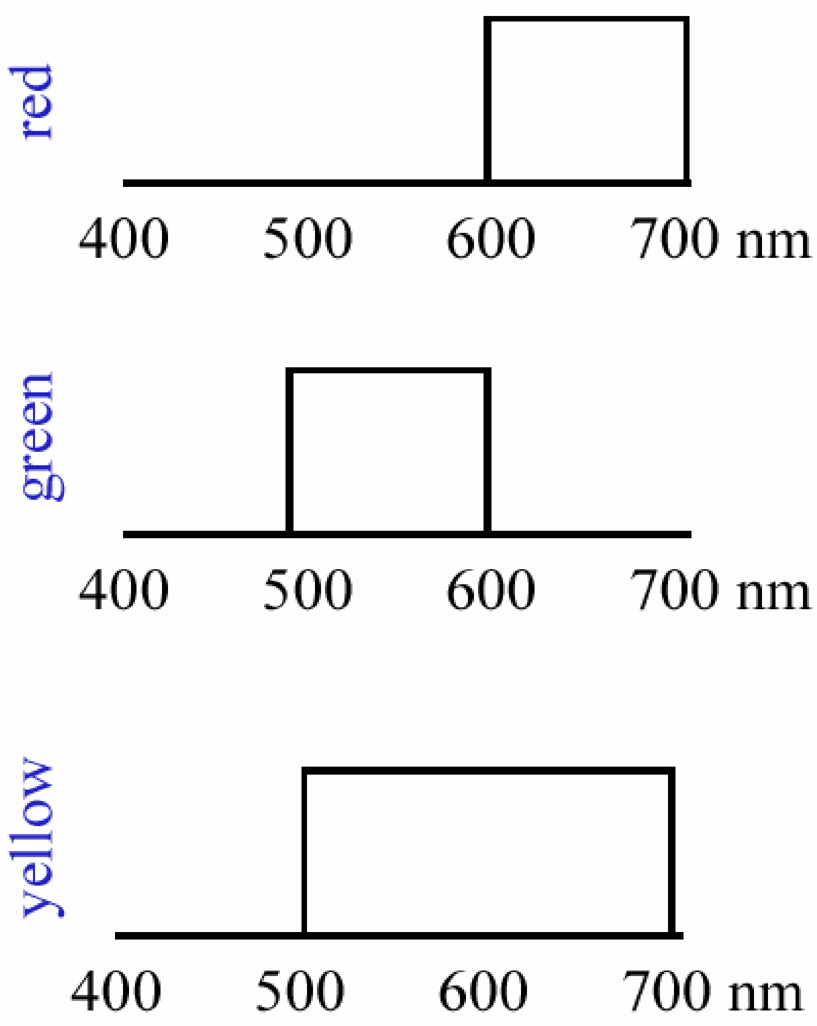
When one views a coloured surface, the spectral radiance of the light reaching the eye depends on both the spectral radiance of the illuminant, and on the spectral albedo of the surface.

colour Names for Cartoon Spectra





Additive colour Mixing

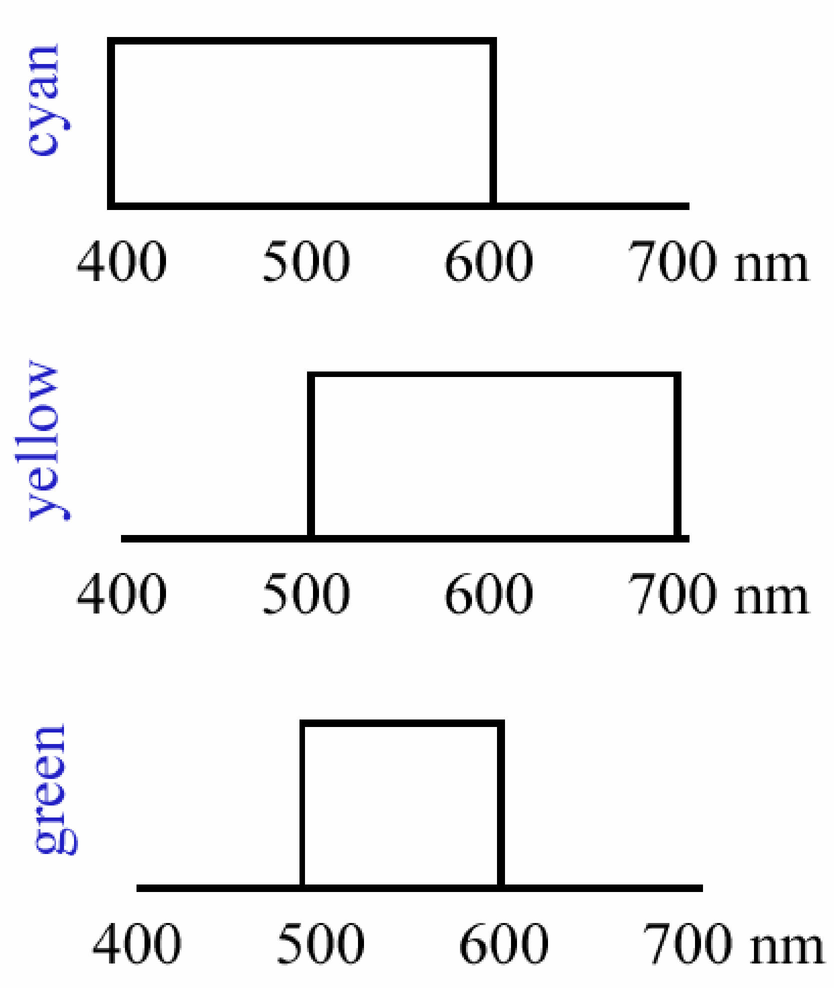


When colors combine by *adding* the color spectra. Examples that follow this mixing rule: CRT phosphors, multiple projectors aimed at a screen, Polachrome slide film.

Red and green make…

Yellow!

Subtractive colour Mixing

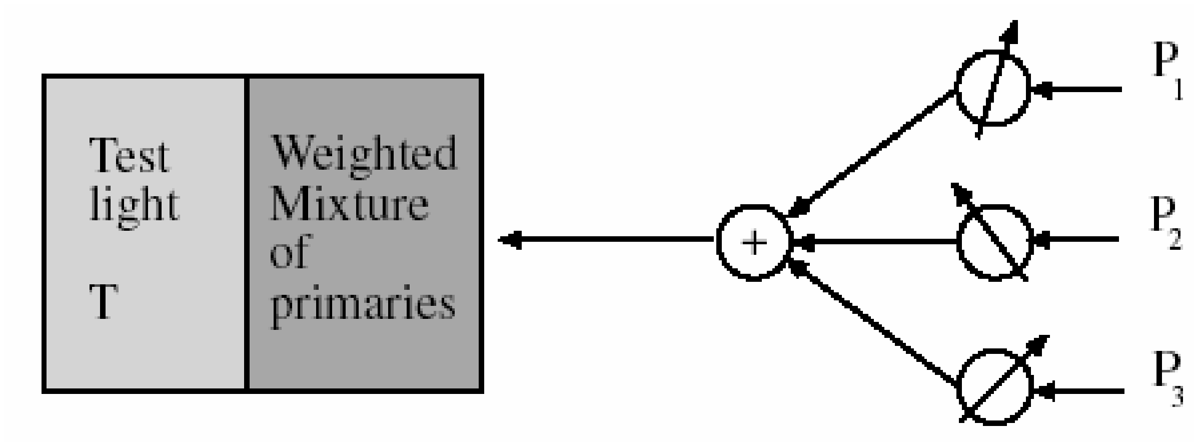


When colors combine by *multiplying* the color spectra. Examples that follow this mixing rule: most photographic films, paint, cascaded optical filters, crayons.

Cyan and yellow (in crayons, called "blue" and yellow) make…

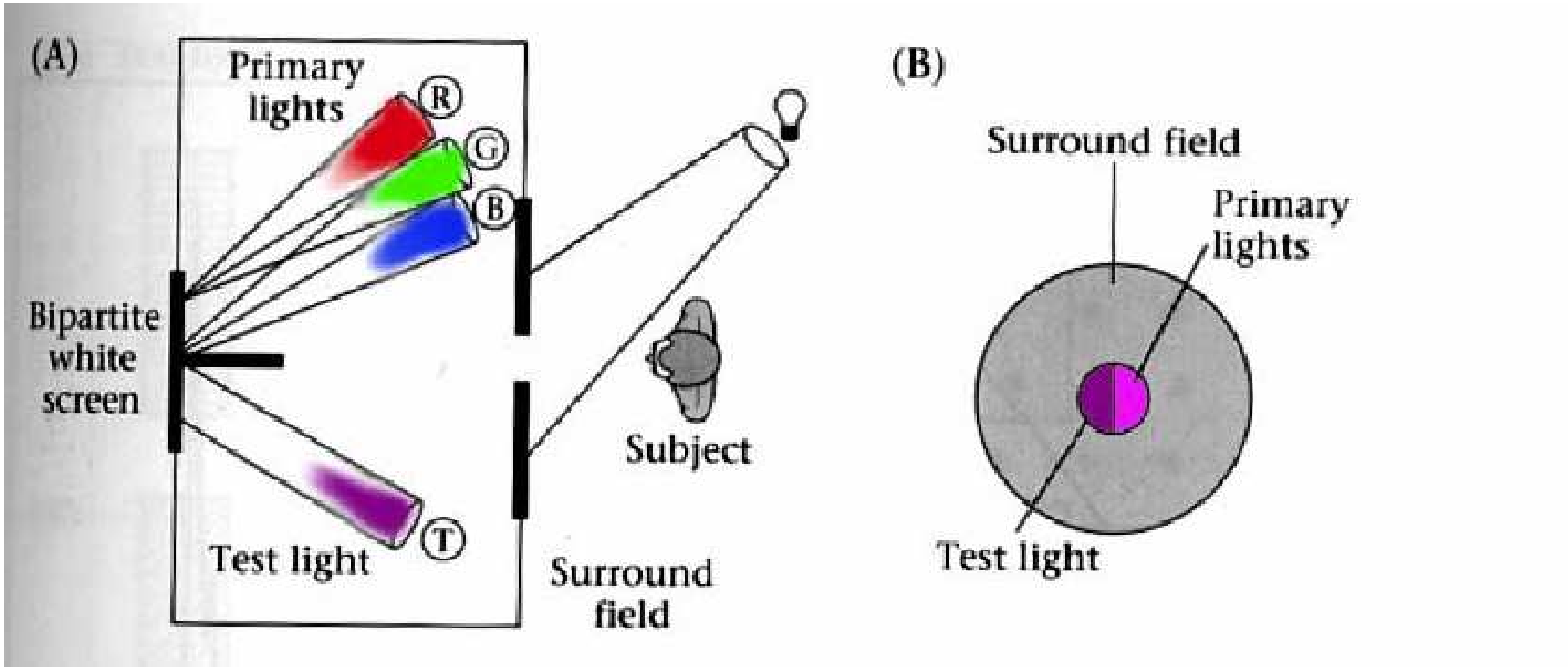
Green!

Colour matching experiments - I



- Show a split field to subjects; one side shows the light whose colour one wants to measure, the other a weighted mixture of primaries (fixed lights).

Colour Matching Process



Basis for industrial colour standards

Colour Matching Experiment 1

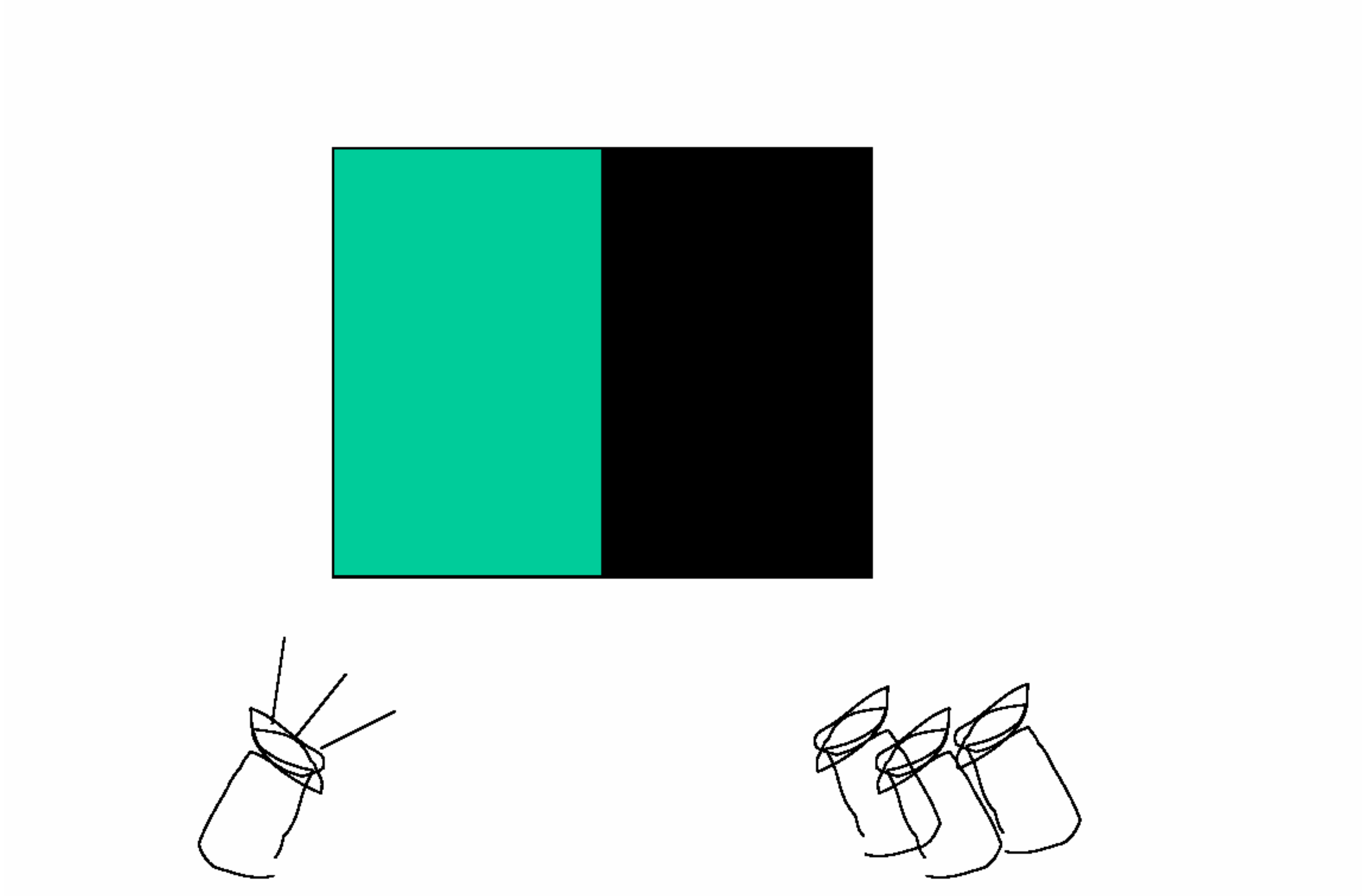


Image courtesy Bill Freeman

Colour Matching Experiment 1

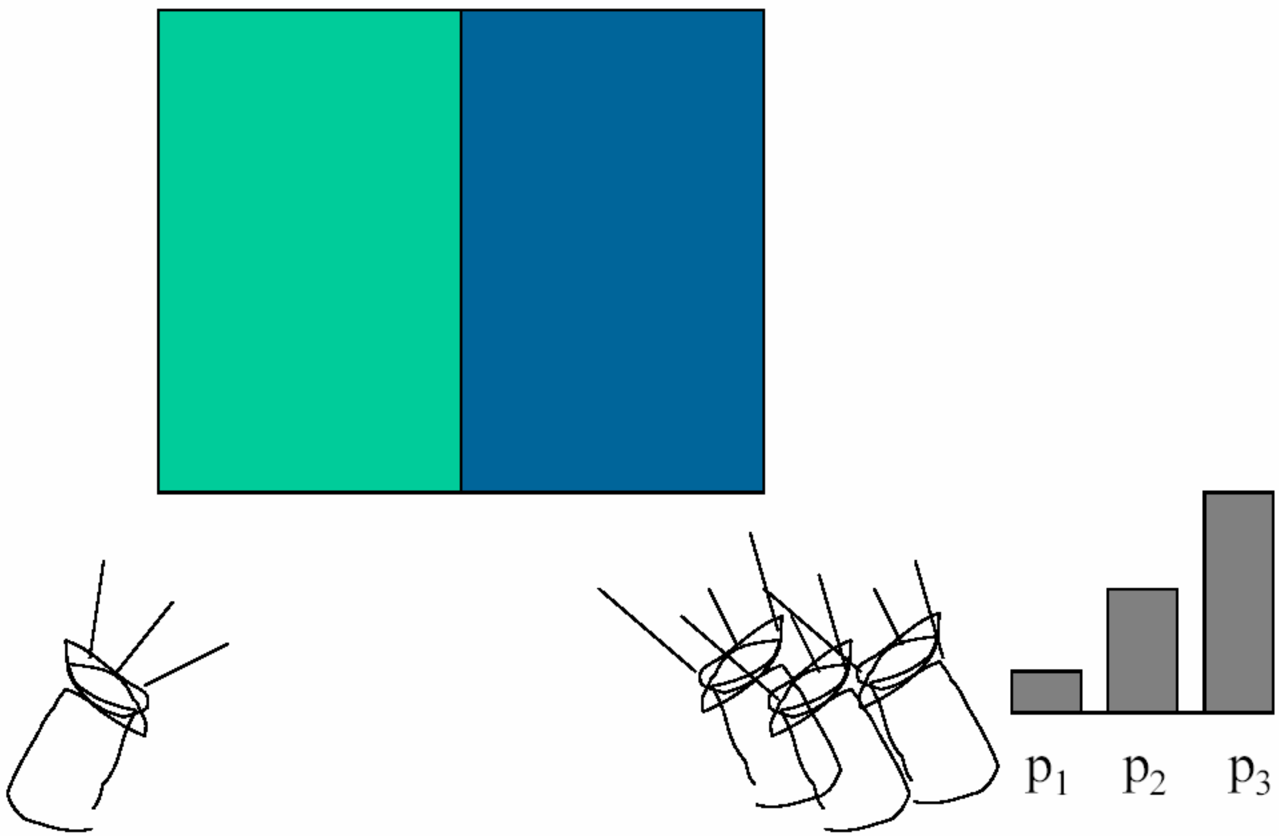


Image courtesy Bill Freeman

Colour Matching Experiment 1

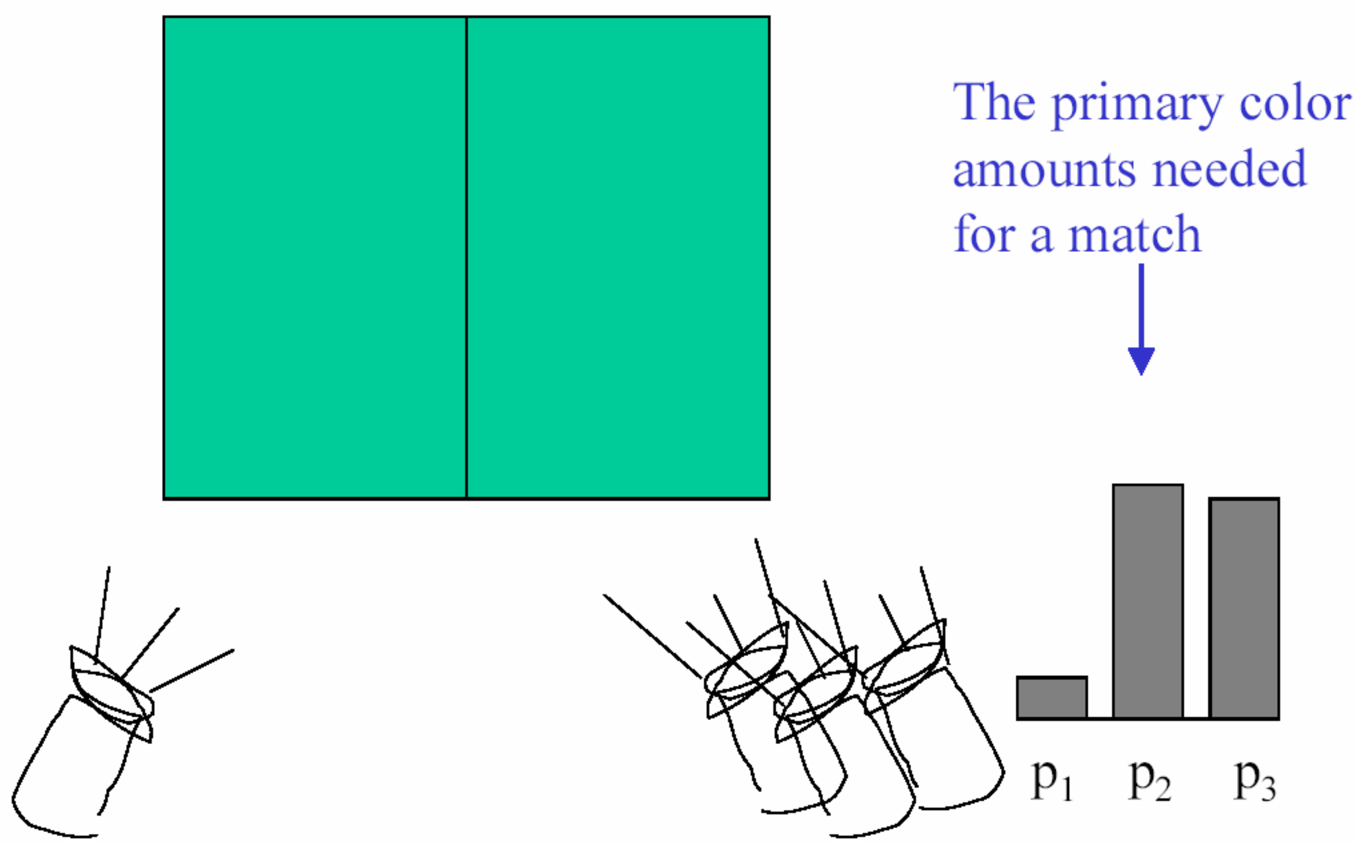


Image courtesy Bill Freeman

Colour Matching Experiment 2

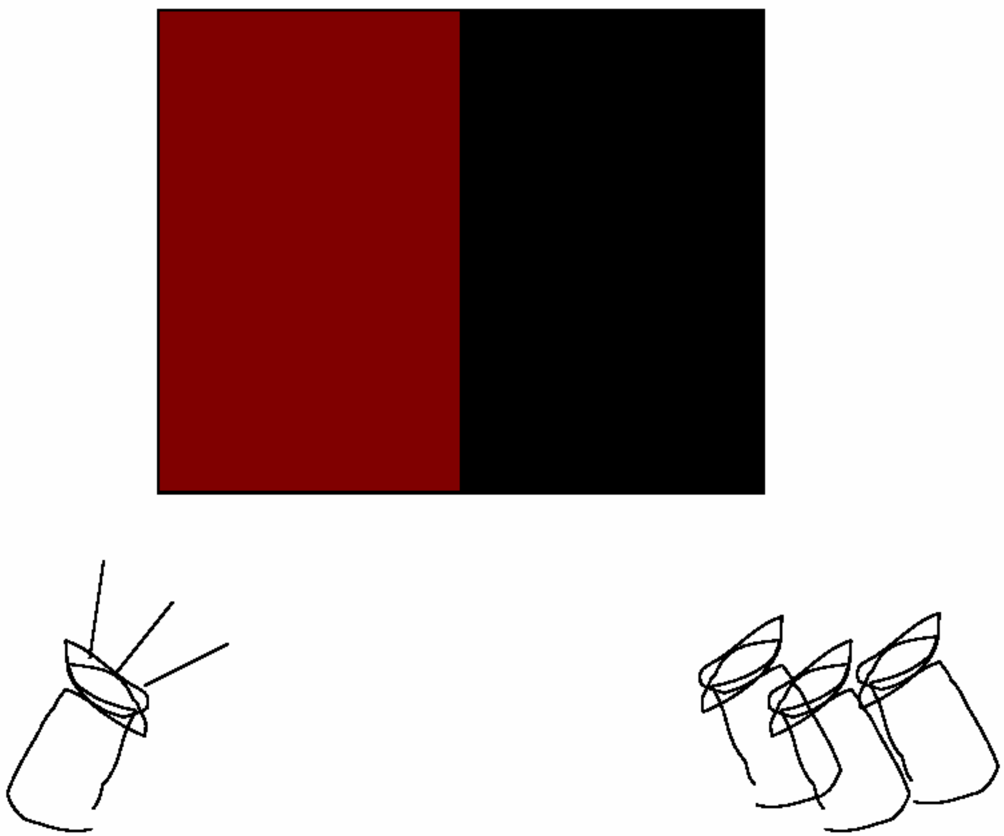


Image courtesy Bill Freeman

Colour Matching Experiment 2

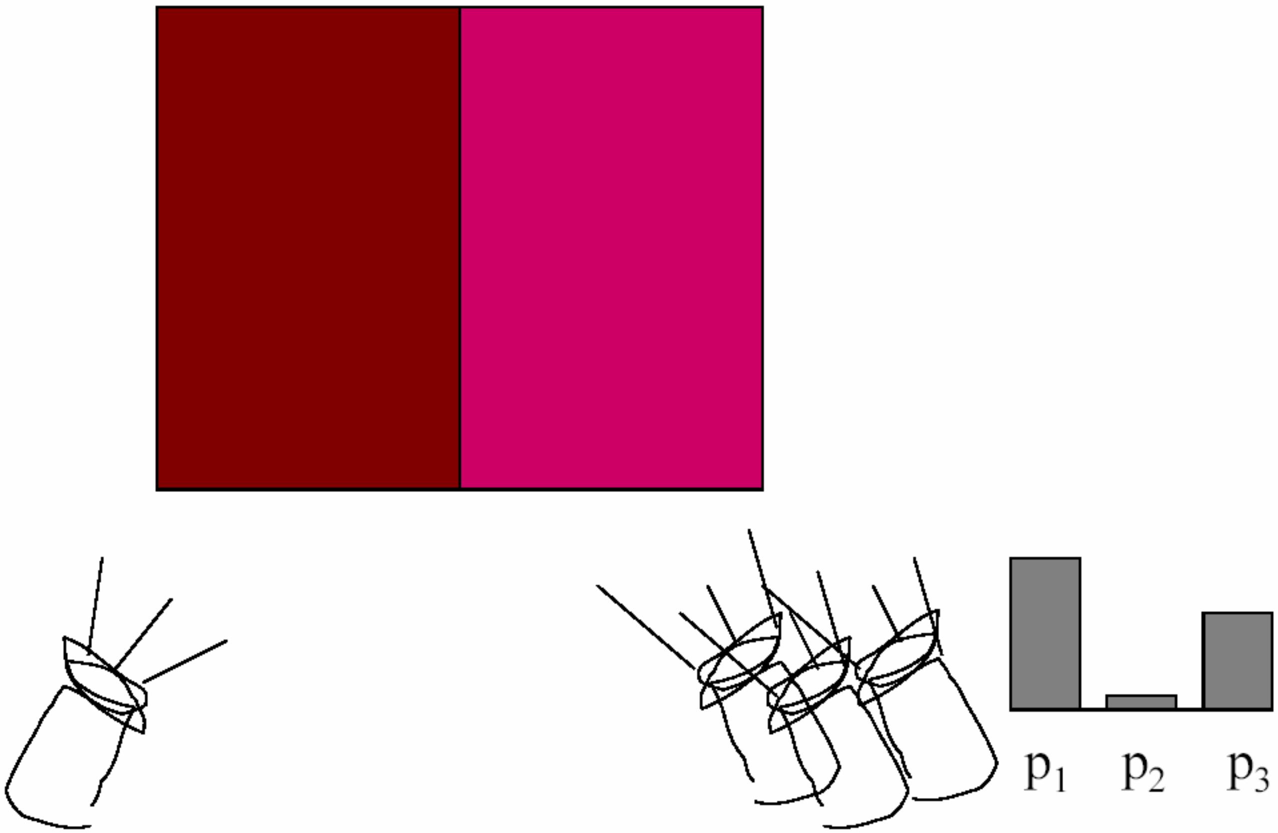


Image courtesy Bill Freeman

Colour Matching Experiment 2

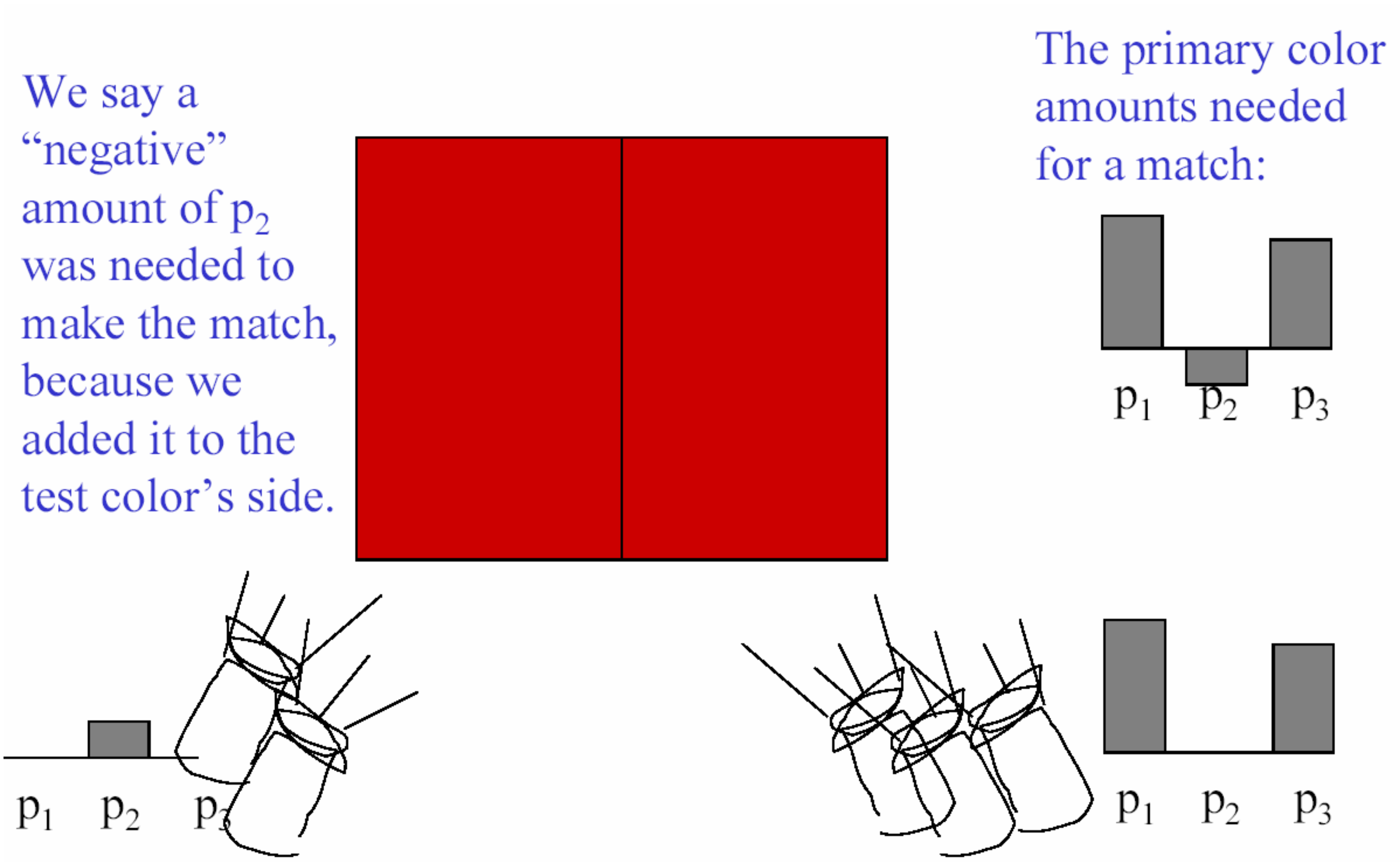


Image courtesy Bill Freeman

Colour matching experiments - II

- Many colours can be represented as a positive weighted sum of A, B, C
- write

$$M=a\ A + b\ B + c\ C$$

  where the = sign should be read as “matches”

- This is **additive** matching.
- Gives a colour description system - two people who agree on A, B, C need only supply (a, b, c) to describe a colour.

Subtractive matching

- Some colours can't be matched like this:
  instead, must write

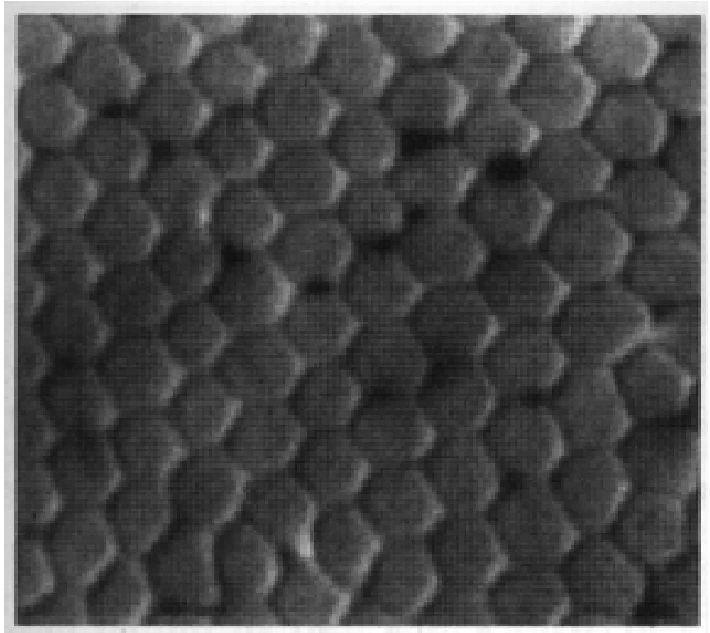
$$M + a\,A = b\,B + c\,C$$

- This is **subtractive** matching.
- Interpret this as (-a, b, c)
- Problem for building monitors: Choose R, G, B such that positive linear combinations match a large set of colours

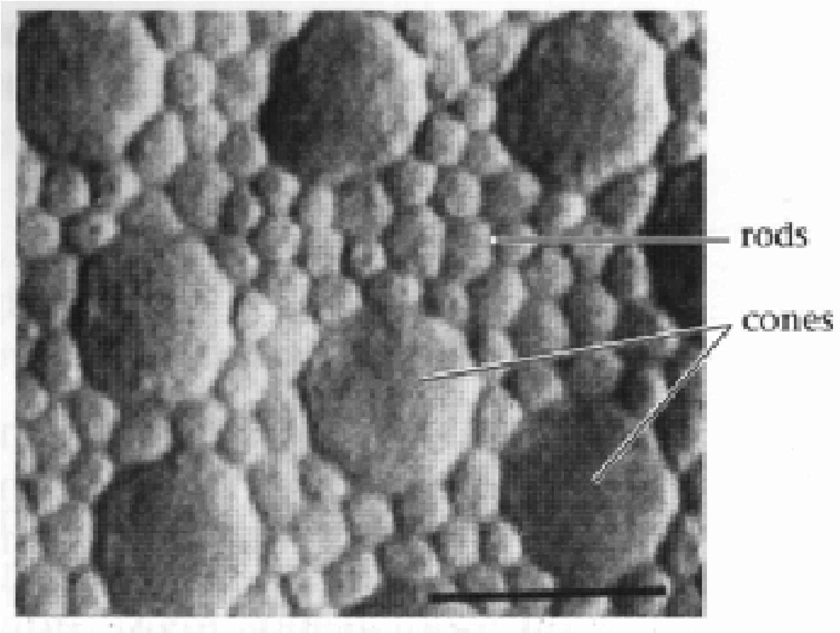
The principle of trichromacy

- Experimental facts:
  - Three primaries will work for most people if we allow subtractive matching
    - Exceptional people can match with two or only one primary (colour blindness)
    - This could be caused by a variety of deficiencies.
  - Most people make the same matches.
    - There are some anomalous trichromats, who use three primaries but make different combinations to match.

Human Photoreceptors

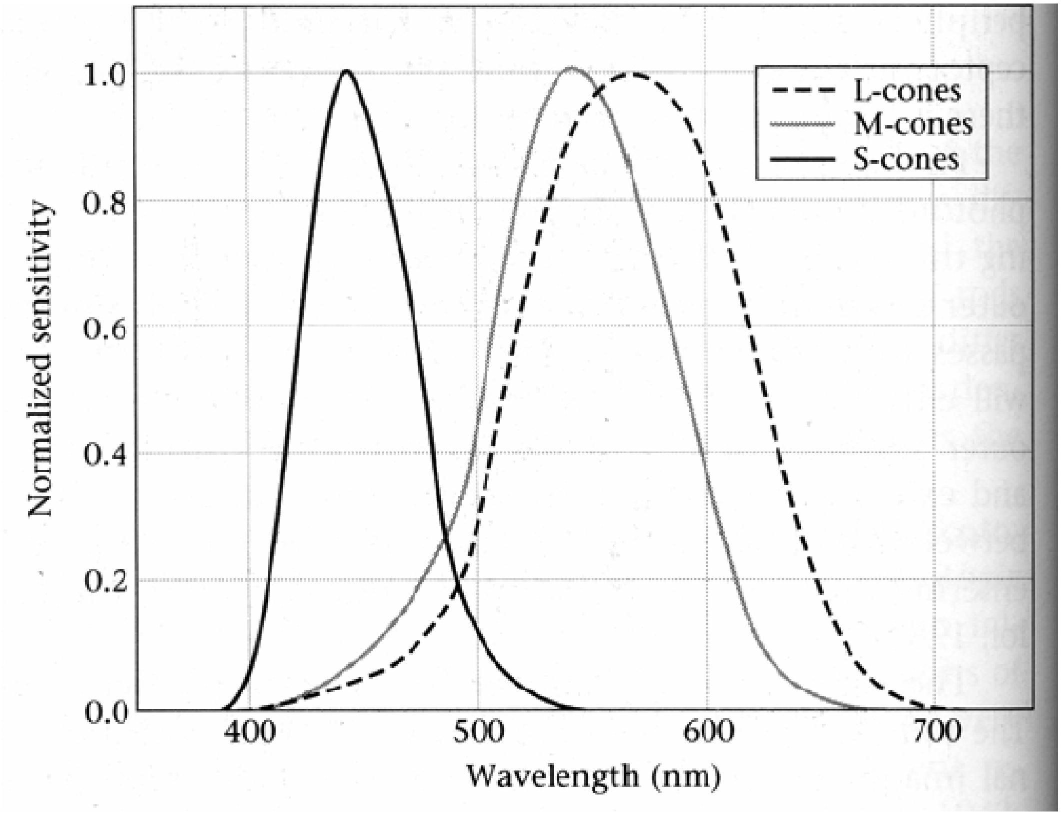


Fovea



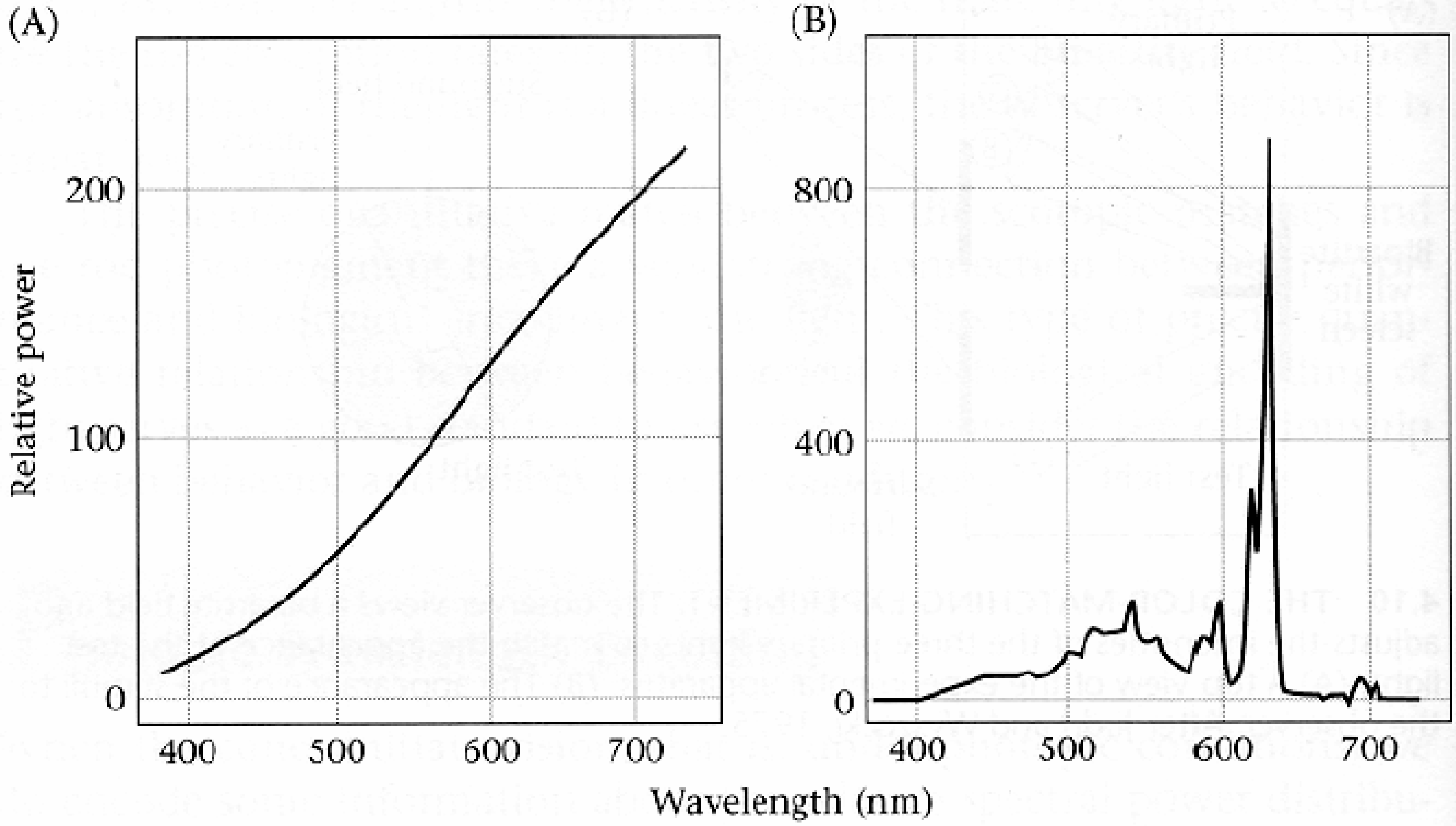
Periphery

Human Cone Sensitivities



- Spectral sensitivity of L, M, S (red, green, blue) cones in human eye

Metameric lights



4.11 METAMERIC LIGHTS. Two lights with these spectral power distributions appear identical to most observers and are called metamers. (A) An approximation to the spectral power distribution of a tungsten bulb. (B) The spectral power distribution of light emitted from a conventional television monitor whose three phosphor intensities were set to match the light in panel A in appearance.

Foundations of Vision, by Brian Wandell, Sinauer Assoc., 1995

Grassman's Laws

For color matches:

- symmetry: U=V <=>V=U
- transitivity: U=V and V=W => U=W
- proportionality: U=V <=> tU=tV
- additivity: if any two (or more) of the statements

  U=V,

  W=X,

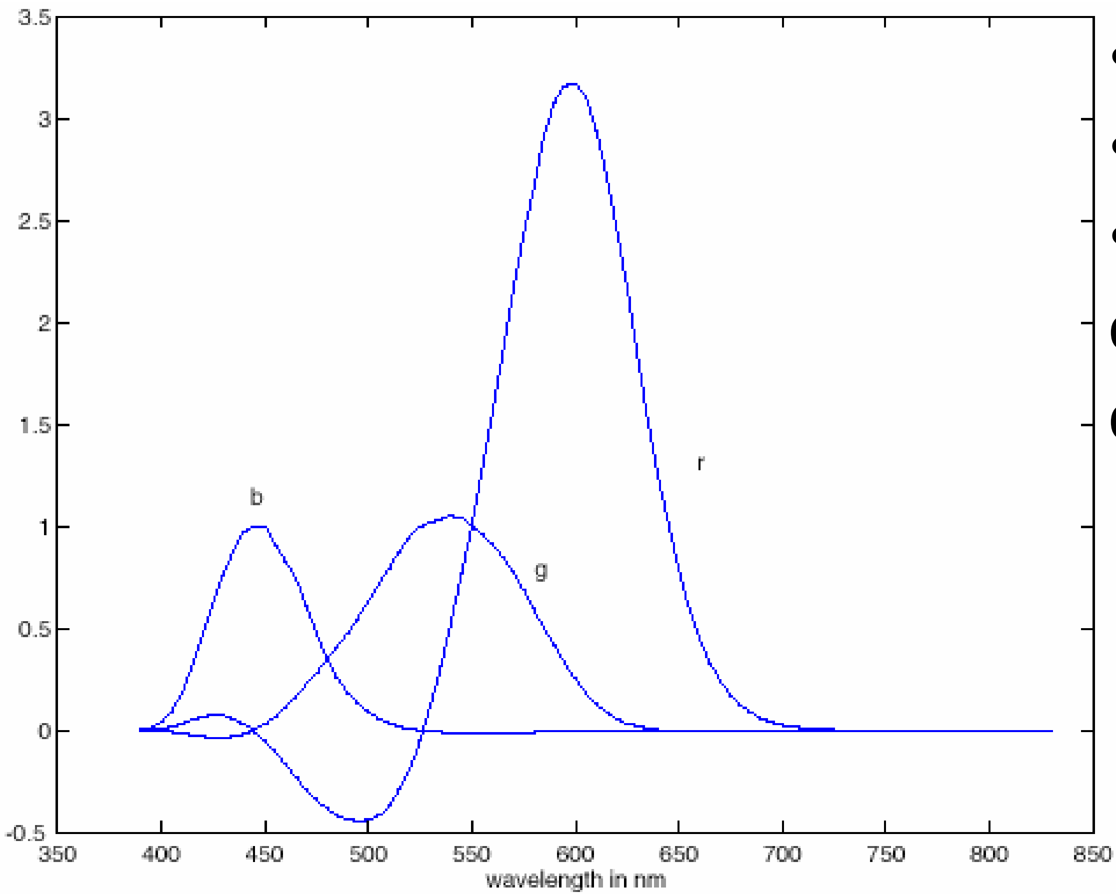
  (U+W)=(V+X) are true, then so is the third

These statements are as true as any biological law. They mean that color matching in film color mode is linear.

Linear colour spaces

- A choice of primaries yields a linear colour space --- the coordinates of a colour are given by the weights of the primaries used to match it.
- Choice of primaries is equivalent to choice of colour space.
- **RGB:** primaries are monochromatic. Energies are 645.2nm, 526.3nm, 444.4nm.
- **CIE XYZ:** Primaries are imaginary, but have other convenient properties. Colour coordinates are (X,Y,Z), where X is the amount of the X primary, etc.

RBG colour Matching



- monochromatic
- 645.2, 526.3, 444.4 nm.
- negative parts -> some colours can be matched only subtractively.

Figure courtesy of
D. Forsyth

CIE XYZ colour Matching

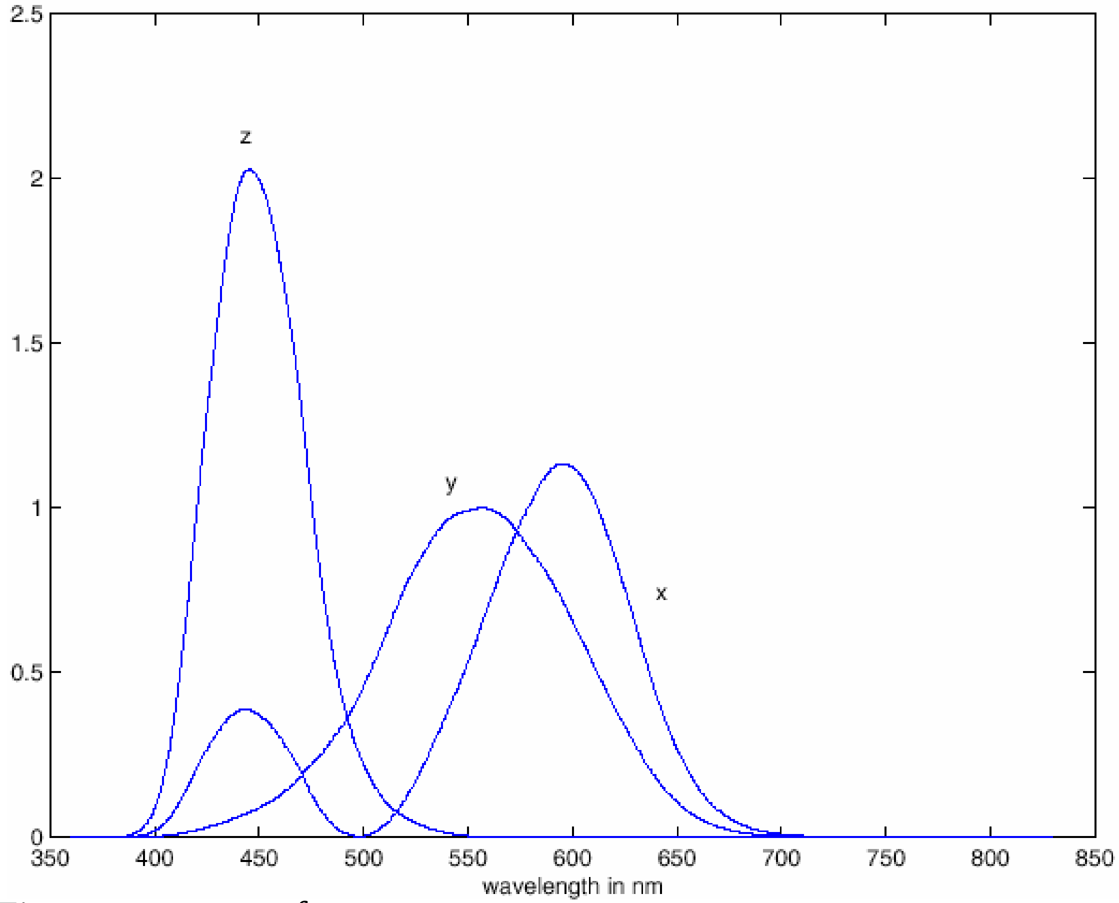
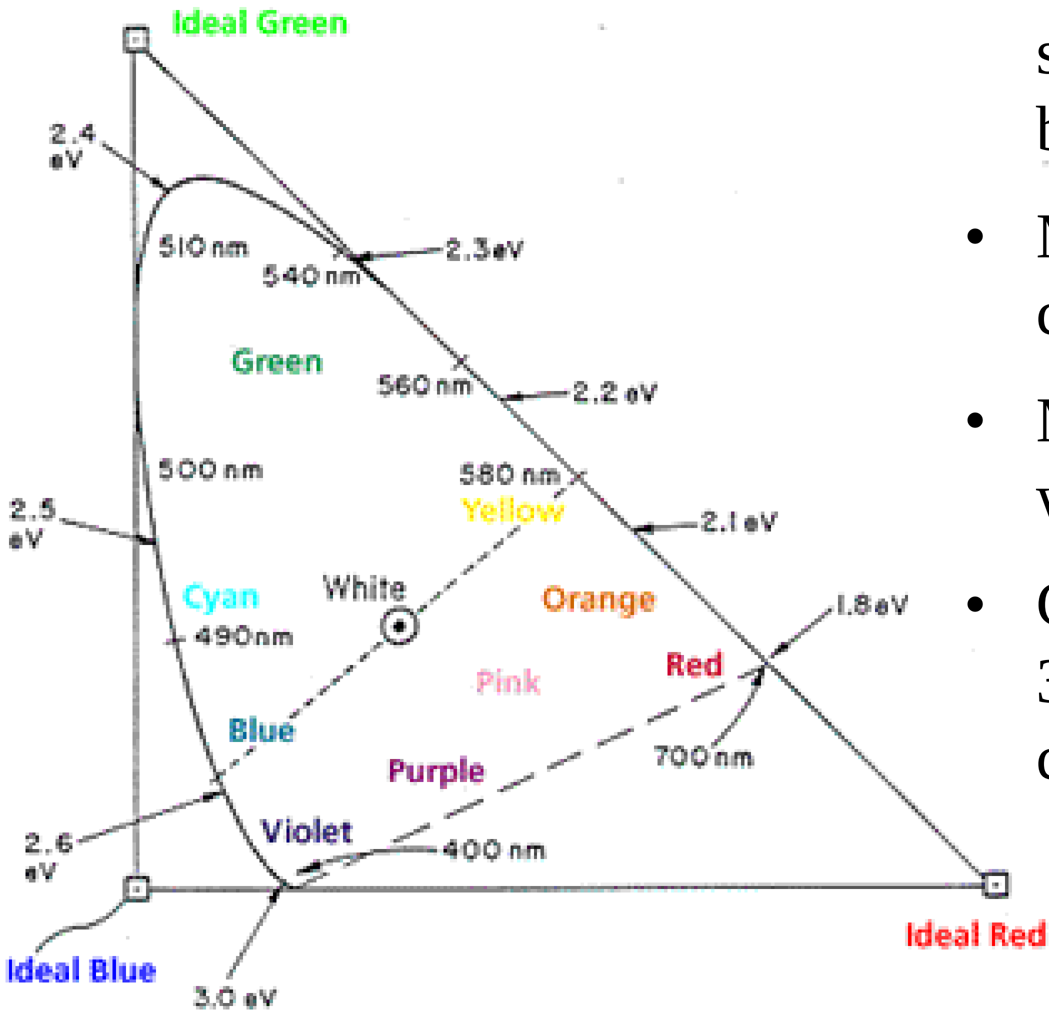


Figure courtesy of
D. Forsyth

CIE XYZ: colour matching functions are positive everywhere, but primaries are imaginary.

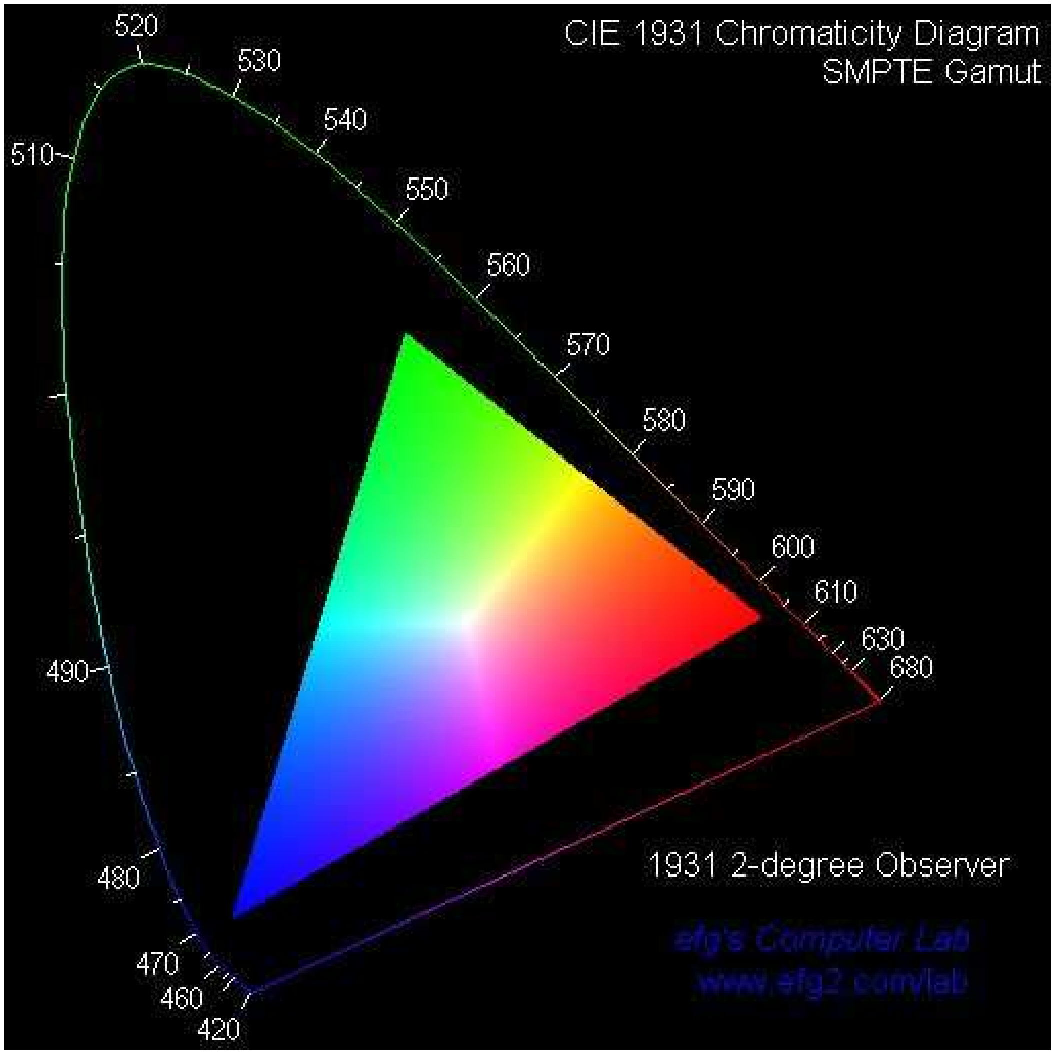
Usually draw x, y, where x=X/(X+Y+Z)
y=Y/(X+Y+Z)
So overall brightness is ignored.

Geometry of colour (CIE)

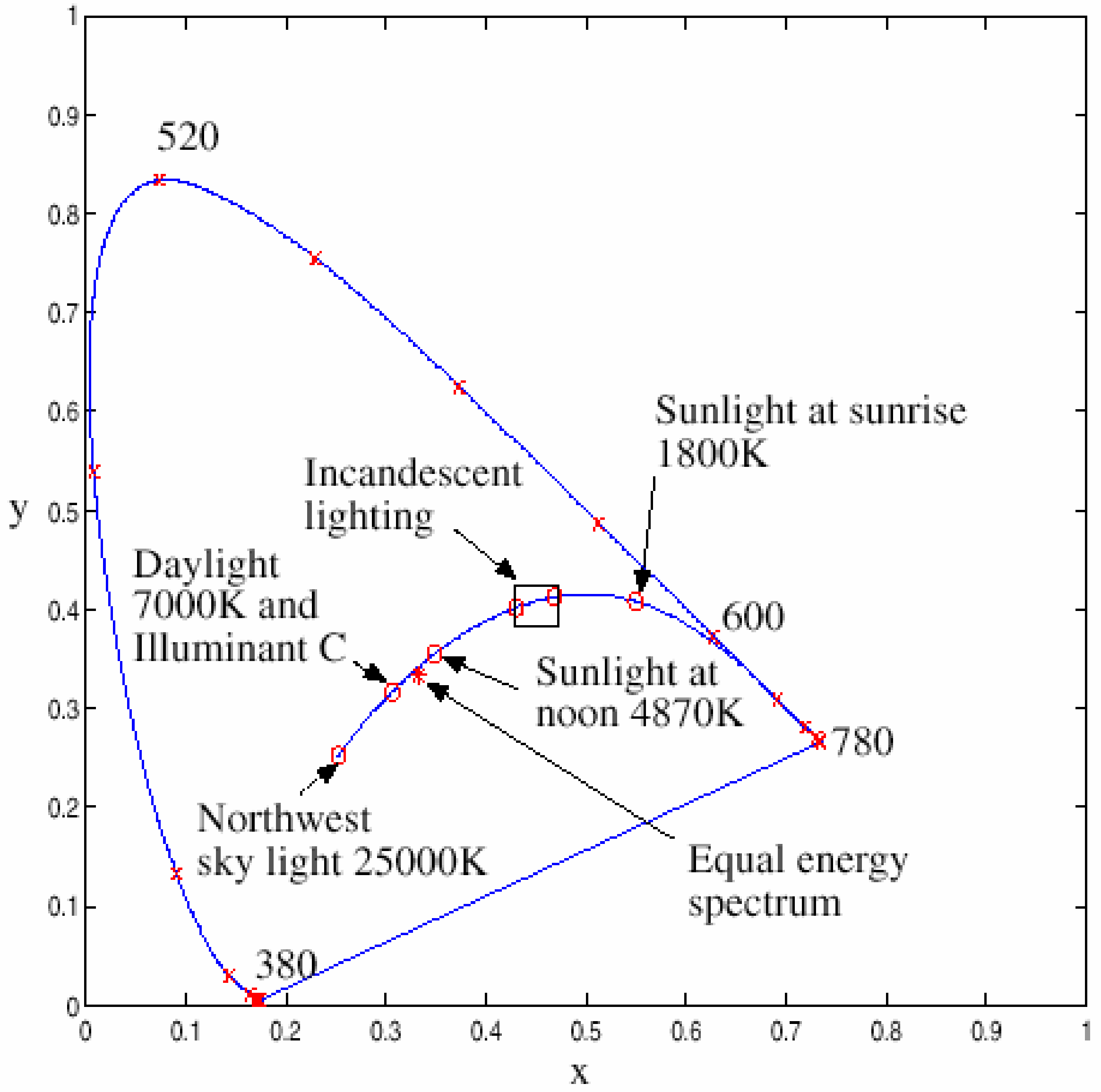


- White is in the center, with saturation increasing towards the boundary
- Mixing two coloured lights creates colours on a straight line
- Mixing 3 colours creates colours within a triangle
- Curved edge means there are no 3 actual lights that can create all colours that humans perceive!

RGB colour Space



The colours that can be displayed on a typical computer monitor (phosphor limitations keep the space quite small)



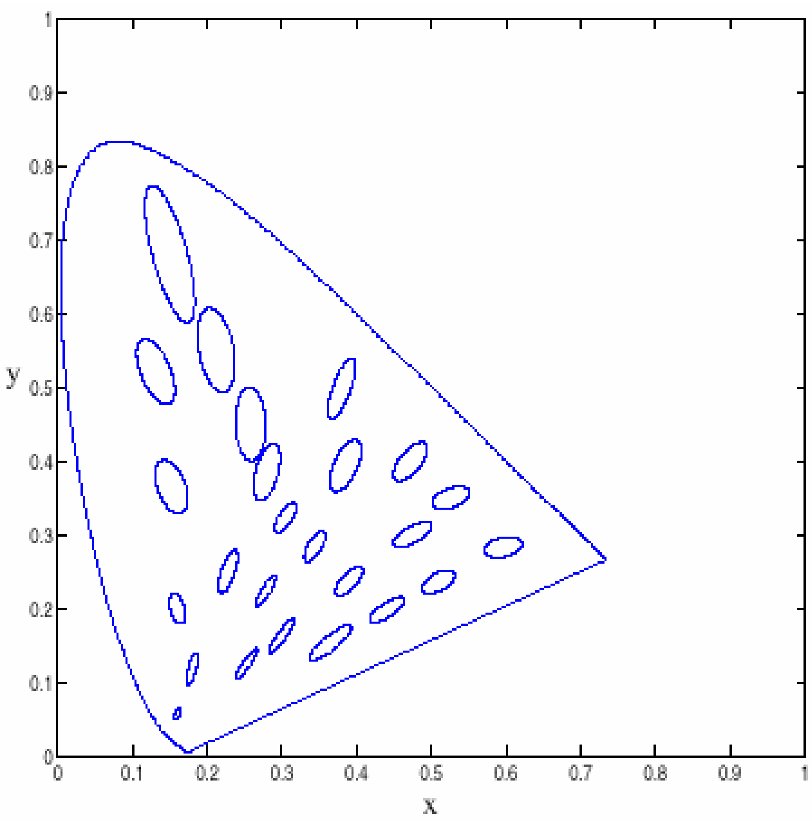
The black-body locus (the colours of heated black-bodies).

Uniform colour spaces

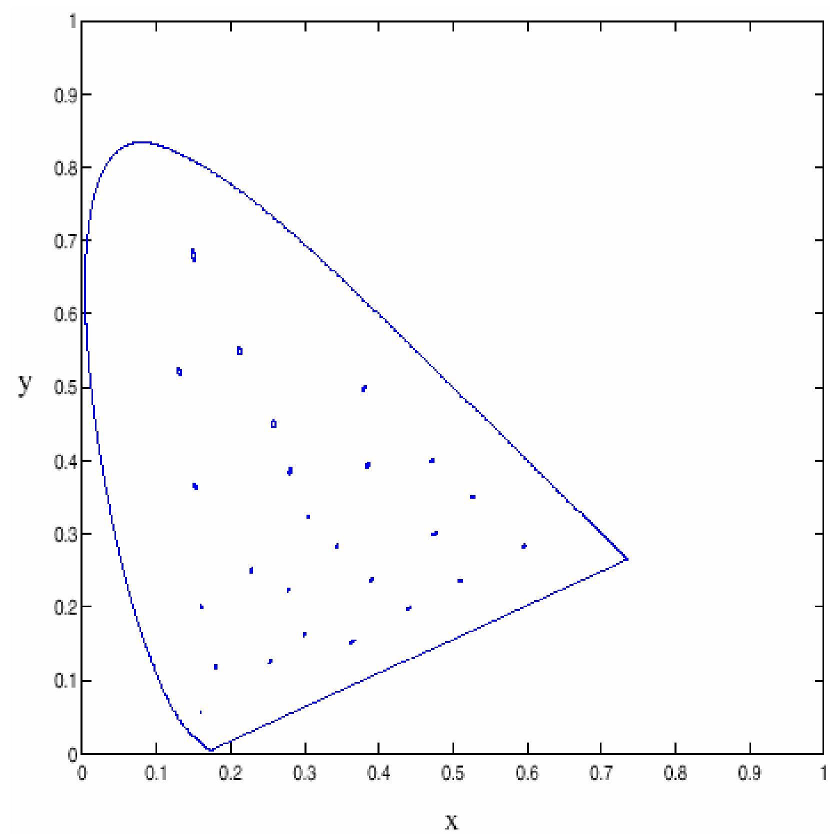
- McAdam ellipses (next slide) demonstrate that differences in x,y are a poor guide to differences in colour
  - Each ellipse shows colours that are perceived to be the same
- Construct colour spaces so that differences in coordinates are a good guide to differences in colour.

McAdam ellipses

Figures courtesy of
D. Forsyth



10 times actual size



Actual size

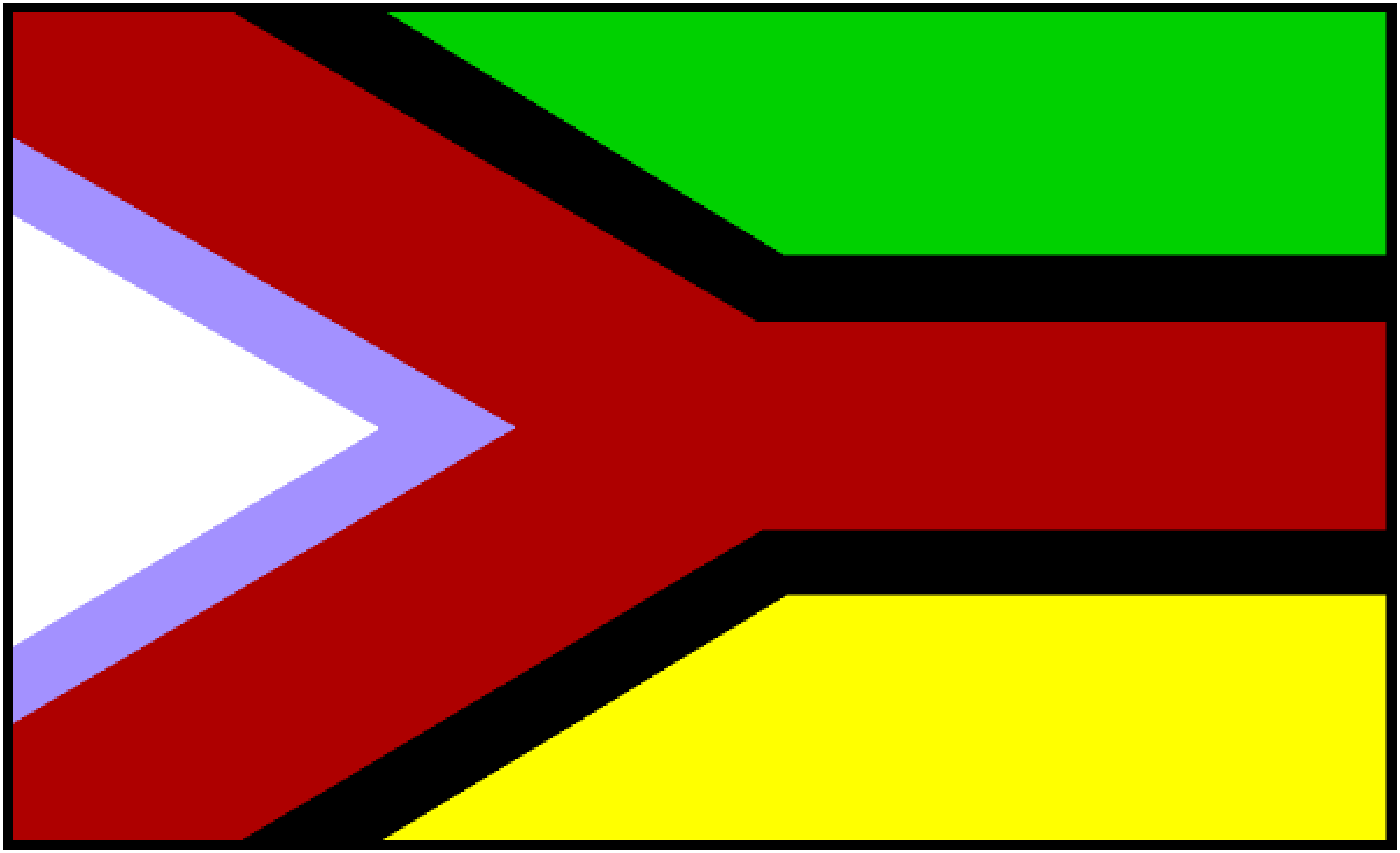
Non-linear colour spaces

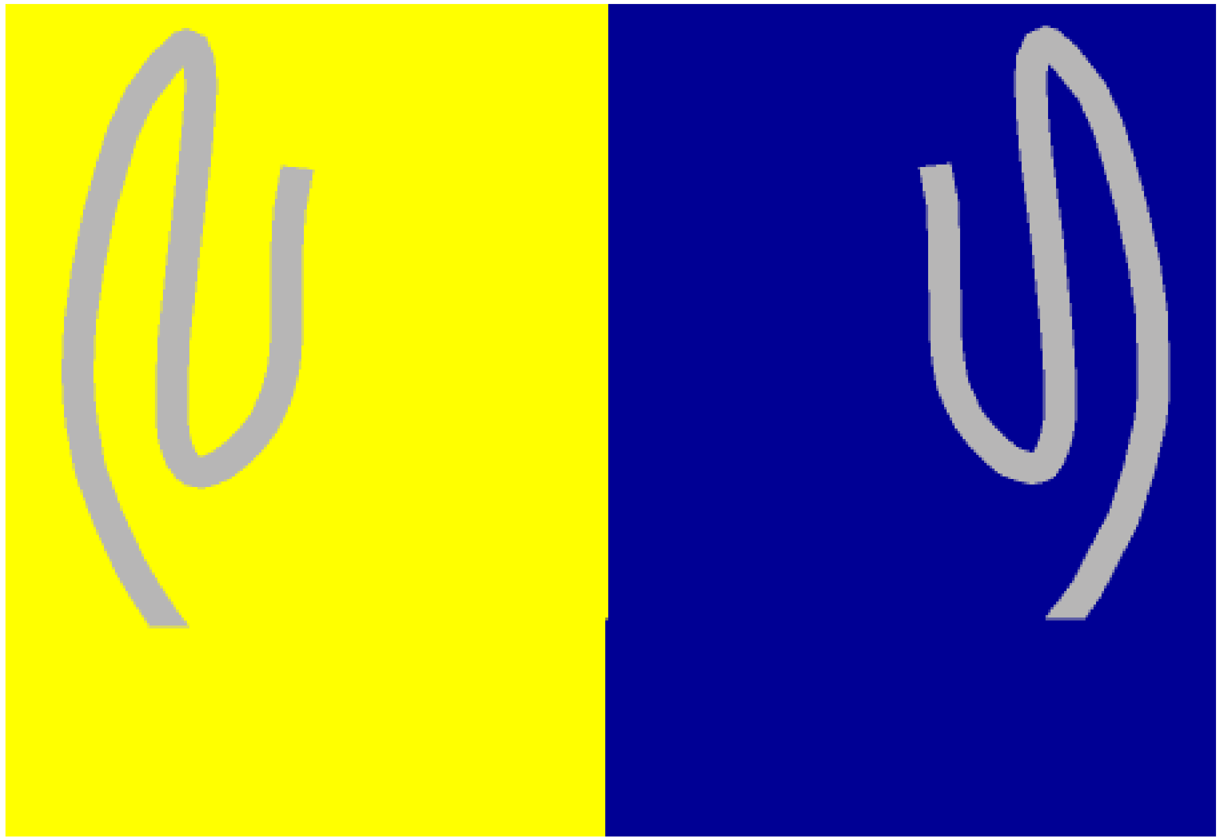
- **HSV:** (Hue, Saturation, Value) are non-linear functions of XYZ.
  - because hue relations are naturally expressed in a circle

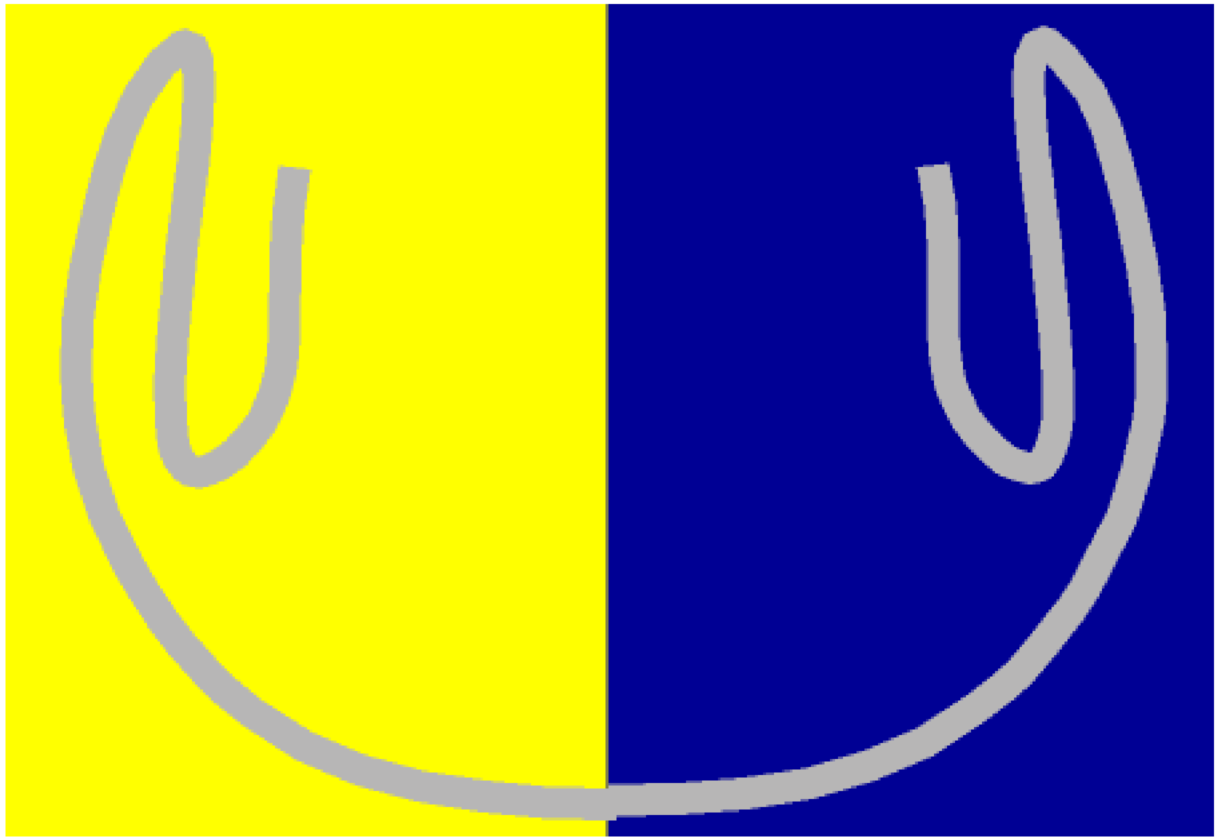
- **Munsell:** describes surfaces, rather than lights - less relevant for graphics. Surfaces must be viewed under fixed comparison light

Adaptation phenomena

- The response of your colour system depends both on spatial contrast and what it has seen before (adaptation)
- This seems to be a result of coding constraints -- receptors appear to have an operating point that varies slowly over time, and to signal some sort of offset. One form of adaptation involves changing this operating point.
- Common example: walk inside from a bright day; everything looks dark for a bit, then takes its conventional brightness.







Viewing coloured objects

- Assume diffuse (Lambertian) plus specular model
- **Specular component**
  - specularities on dielectric (non-metalic) objects take the colour of the light
  - specularities on metals have colour of the metal
- **Diffuse component**
  - colour of reflected light depends on both illuminant and surface

Finding Specularities

- Assume we are dealing with dielectrics
  - specularly reflected light is the same colour as the source
- Reflected light has two components
  - diffuse
  - specular
  - and we see a weighted sum of these two
- Specularities produce a characteristic dogleg in the histogram of receptor responses
  - in a patch of diffuse surface, we see a colour multiplied by different scaling constants (surface orientation)
  - in the specular patch, a new colour is added; a “dog-leg” results

Skewed-T in Histogram

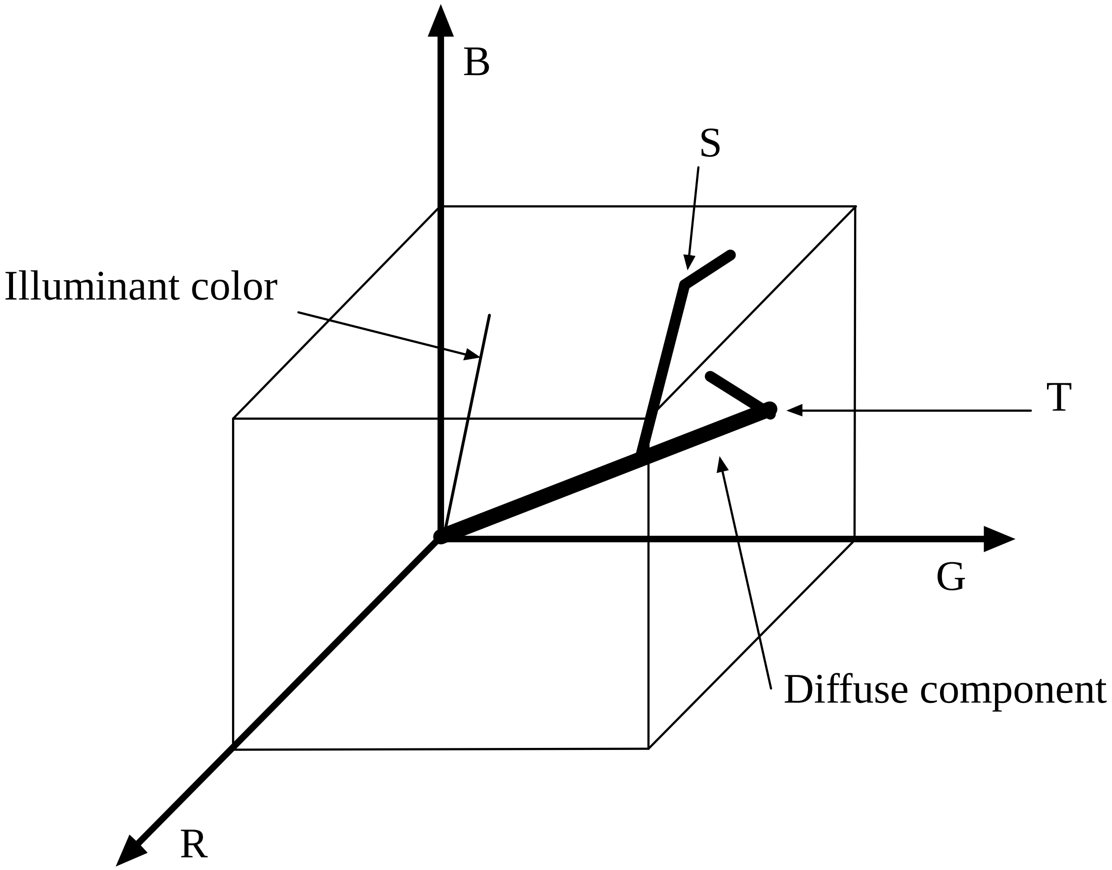


Figure courtesy of
D. Forsyth

A Physical Approach to colour Image Understanding – Klinker, Shafer, and Kanade. IJCV 1990

Skewed-T in Histogram

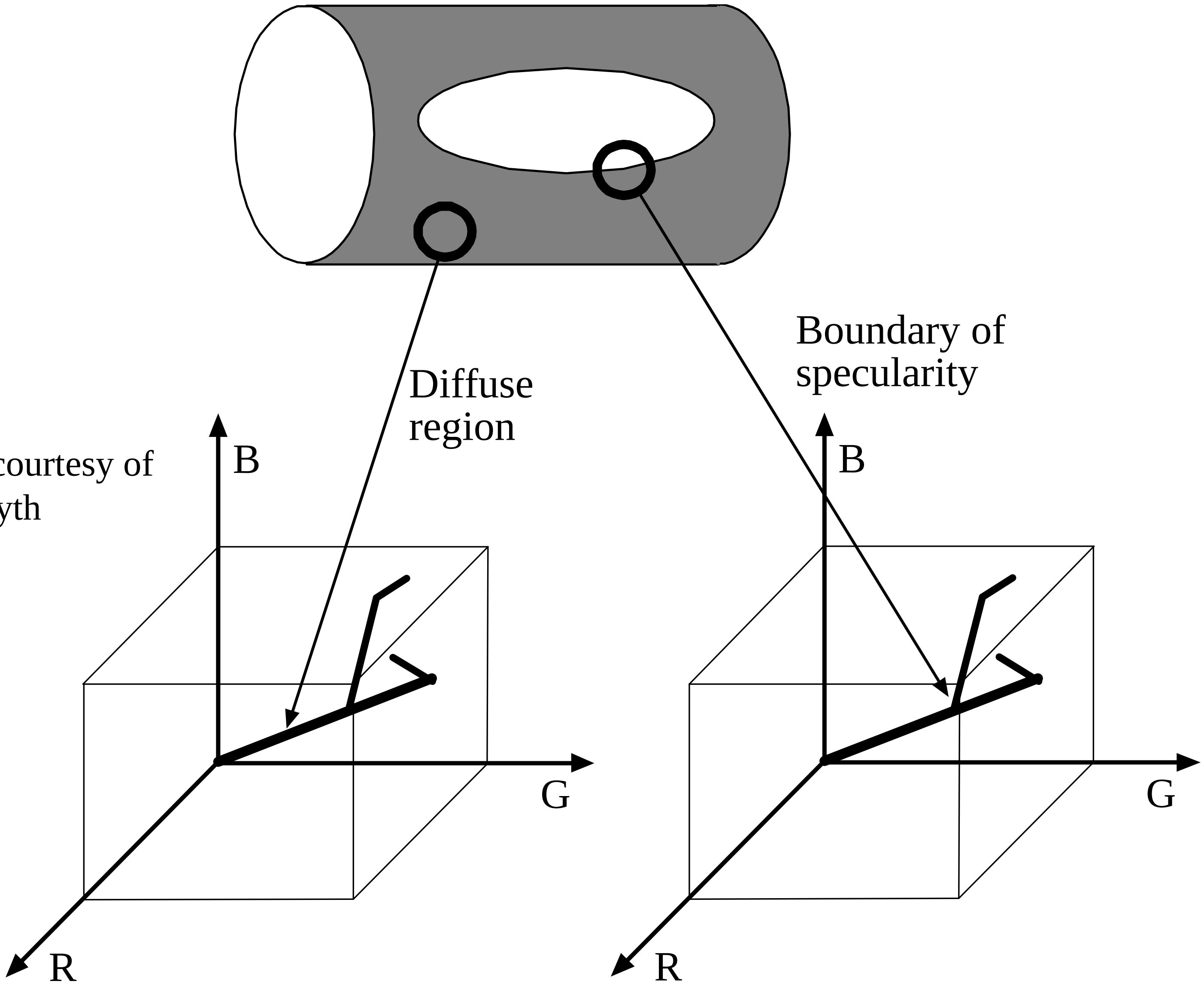
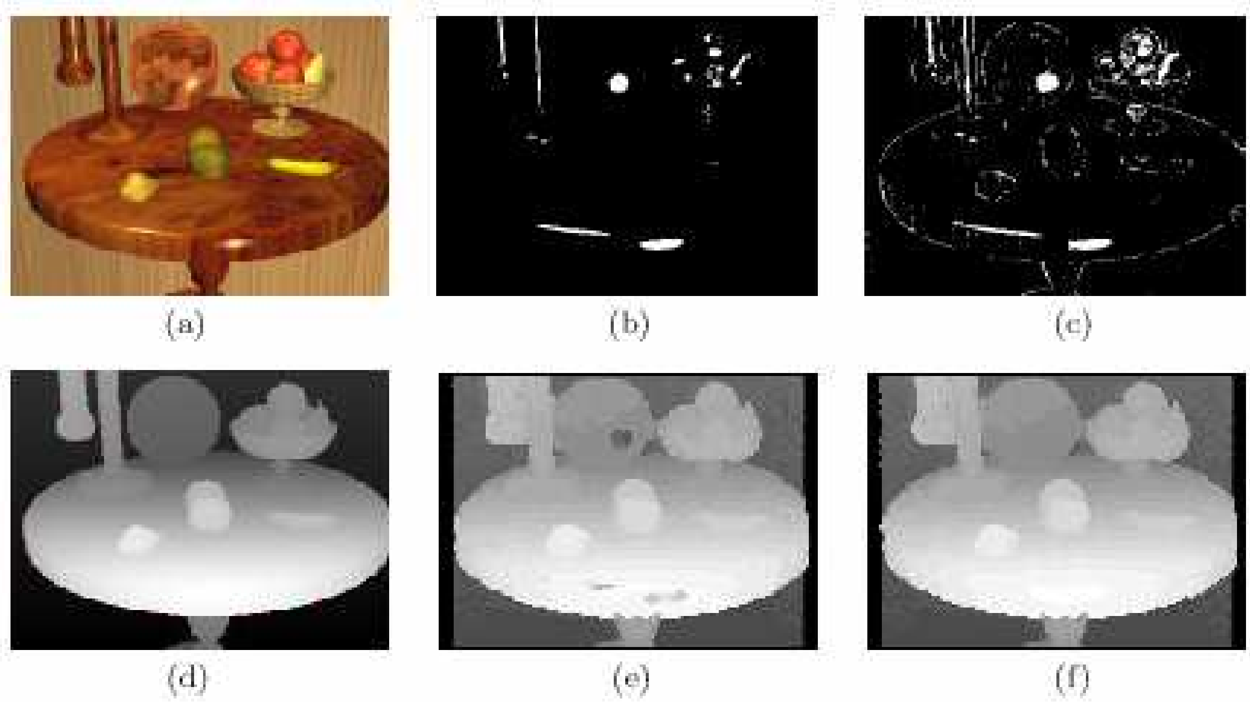


Figure courtesy of
D. Forsyth

Recent Application to Stereo

Synthetic scene:



Motion of camera causes highlight location to change. This cue can be combined with histogram analysis.

Figure courtesy of Sing Bing Kang

Recent Application to Stereo

"Real" scene:

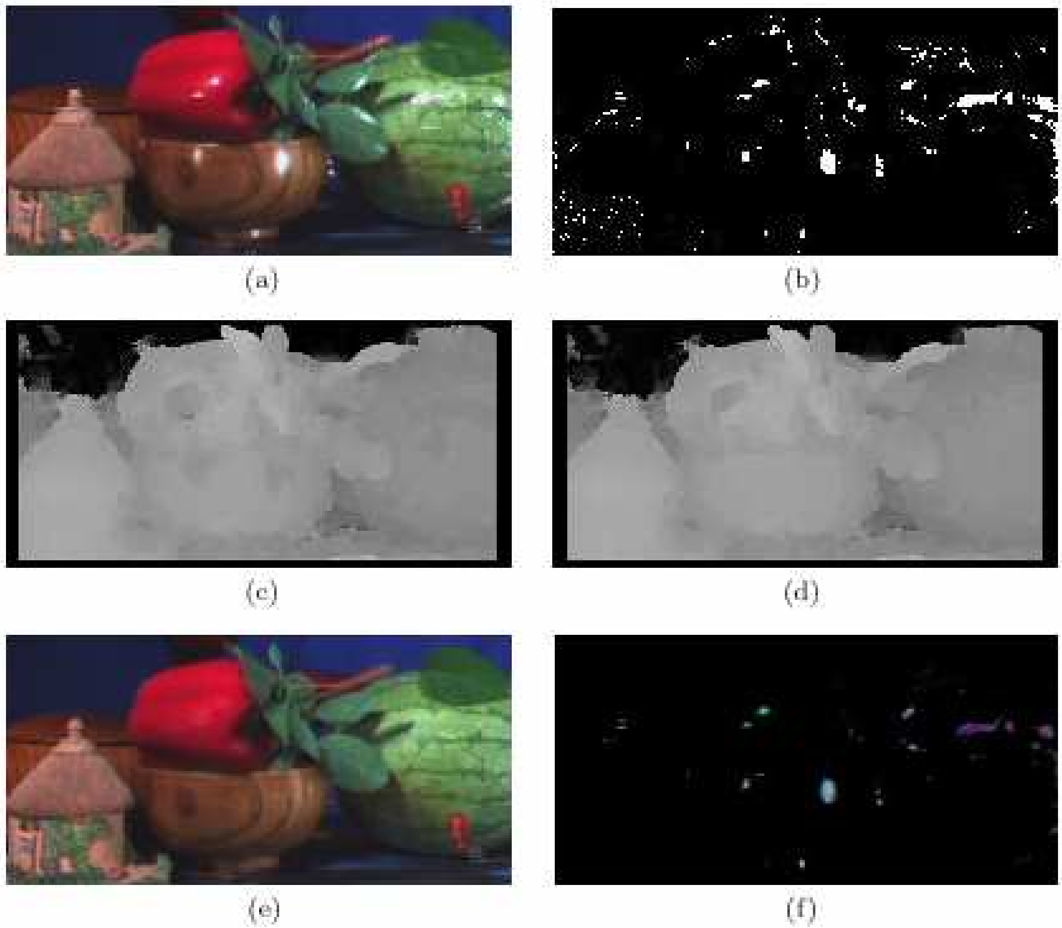


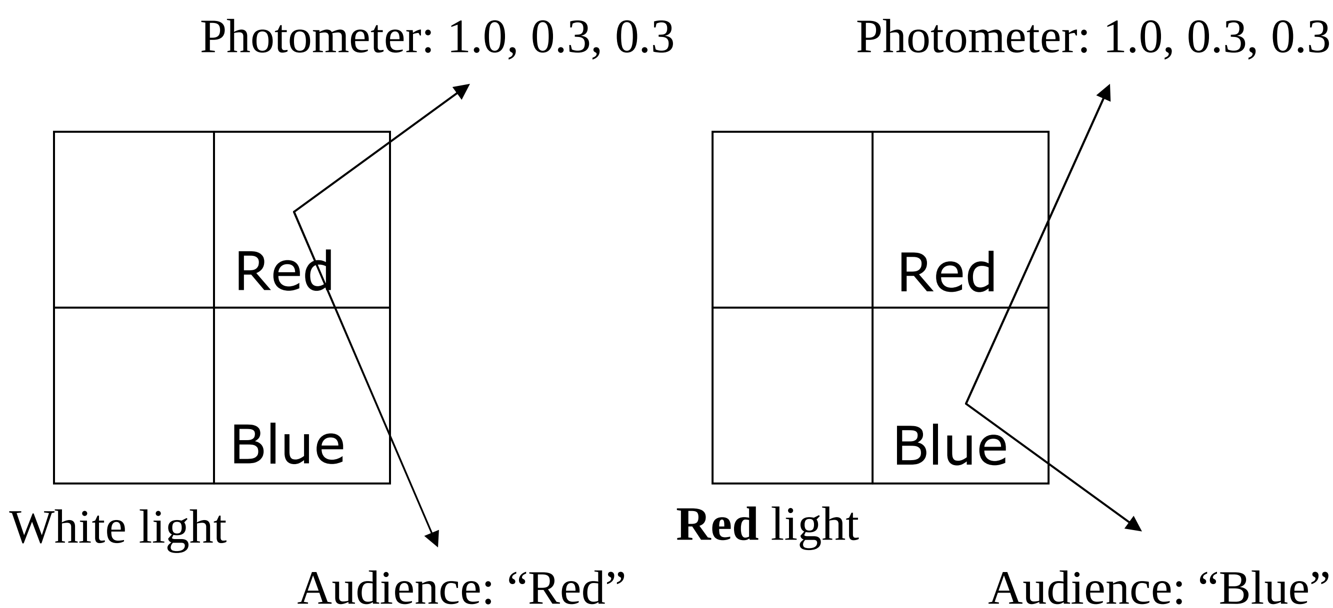
Figure courtesy of
Sing Bing Kang

Human colour Constancy

- **Colour constancy:** determine hue and saturation under different colours of lighting
- **Lightness constancy:** gray-level reflectance under differing intensity of lighting
- Humans can perceive
  - colour a surface would have under white light
  - colour of reflected light (separate surface colour from measured colour)
  - colour of illuminant (limited)

Land’s Mondrian Experiments

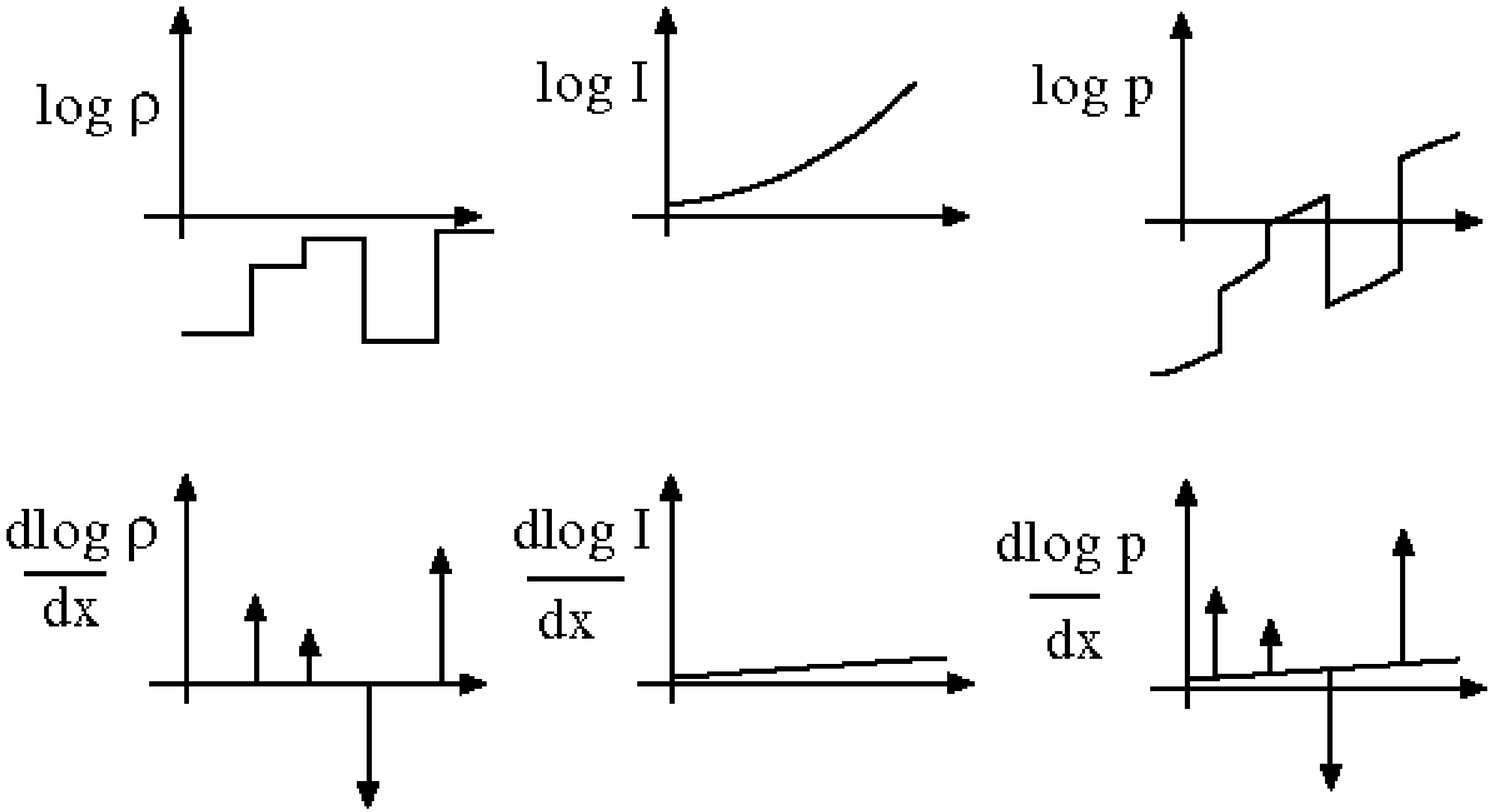
- Squares of colour with the same colour radiance yield very different colour perceptions



Basic Model for Lightness Constancy

- Assumptions:
  - Planar frontal scene
  - Lambertian reflectance
  - Linear camera response
- Modeling assumptions for scene
  - Piecewise constant surface reflectance
  - Slowly-varying Illumination

1-D Lightness "Retinex"



Threshold gradient image to find surface (patch) boundaries

Figure courtesy of
D. Forsyth

1-D Lightness "Retinex"

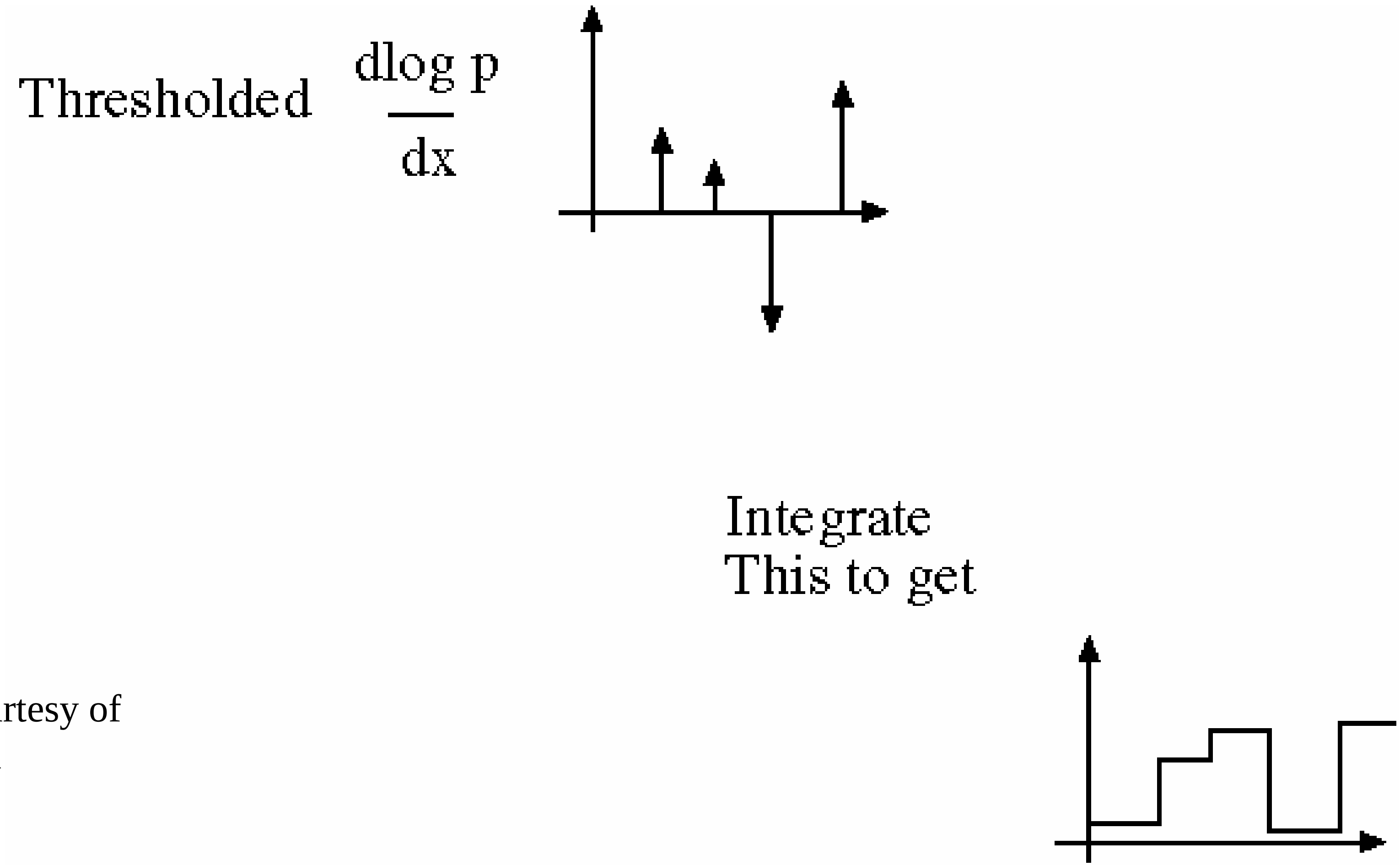


Figure courtesy of
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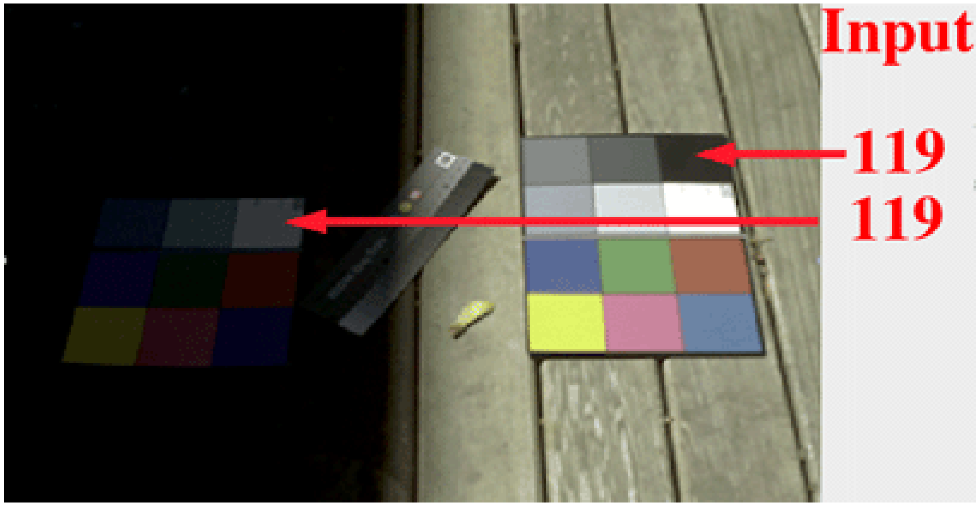
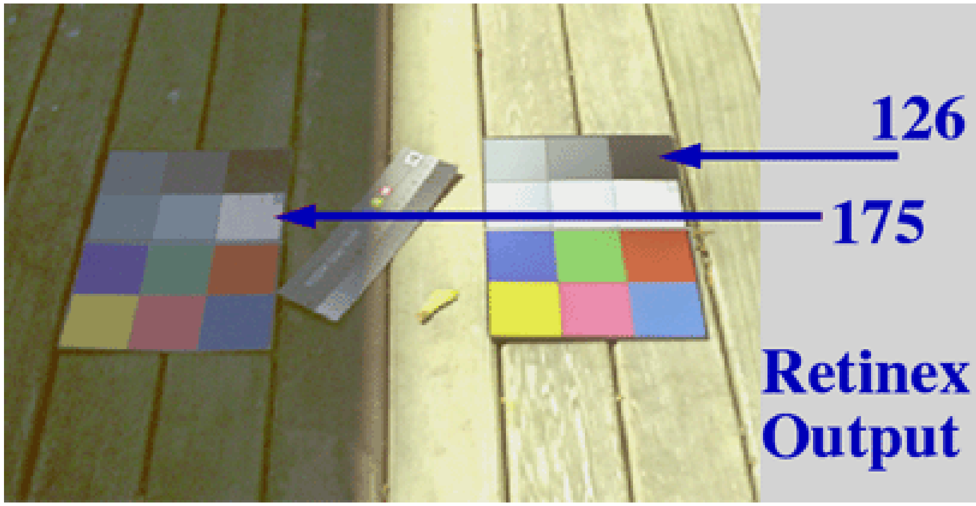
Integration to recover surface lightness (unknown constant)

colour Retinex





Images courtesy John McCann

Colour constancy

- Following methods have been used:
  - Average reflectance across scene is known (often fails)
  - Brightest patch is white
  - Gamut (collection of all colours) falls within known range
  - Known reference colour (colour chart, skin colour…)
- Gamut method works quite well for correcting photographs for human observers, but not well enough for recognition
- For object recognition, best approach is to use ratio of colours on the same object (Funt and Finlayson, 1995)