What is color?

- What do we mean by:
  - Color of an object
  - Color of a light
  - Subjective color impression.
  - Are all these notions the same?

- Wavelengths of light striking the eye are not sufficient or necessary for unique color impression.
- Surface color of an object is usually defined via its reflection function independent of any particular light's spectral distribution
- Color of a light is usually defined in terms of its spectral distribution.

- Sources of variations in the amount of light at different wavelengths:
  - Light could be produced in different amounts at different wavelengths (compare the sun and a fluorescent light bulb).
  - Light could be differentially reflected (e.g. some pigments).
  - It could be differentially refracted - (e.g. Newton's prism)
  - Wavelength dependent specular reflection - e.g. shiny copper penny (actually most metals).
  - Florescence - light at invisible wavelengths is absorbed and reemitted at visible wavelengths.

Radiometry for colour

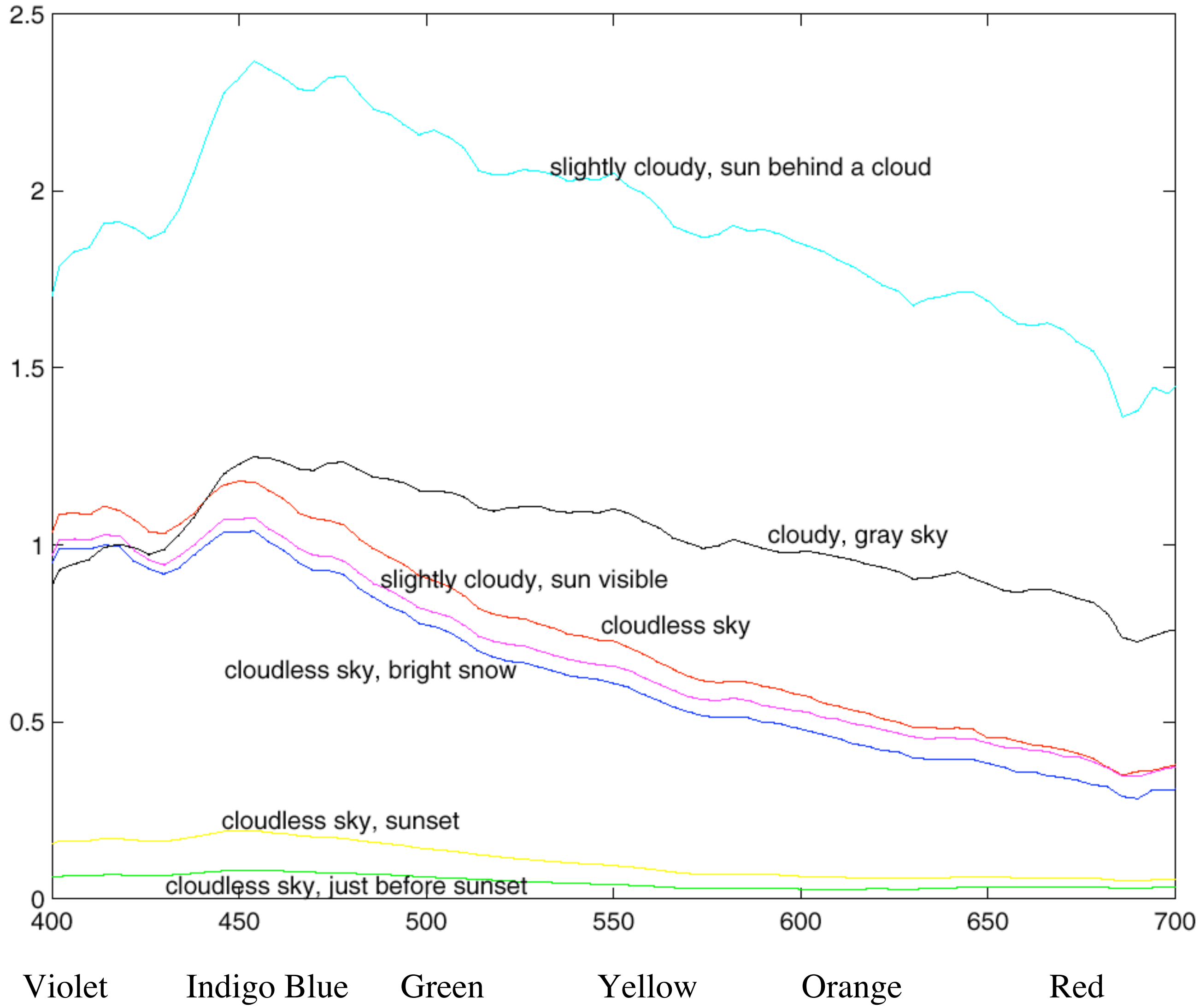
- All definitions are now “per unit wavelength”
- All units are now “per unit wavelength”
- All terms are now “spectral”
- Radiance becomes spectral radiance
  - watts per square meter per steradian per unit wavelength

Defining Source Color: Black body radiators

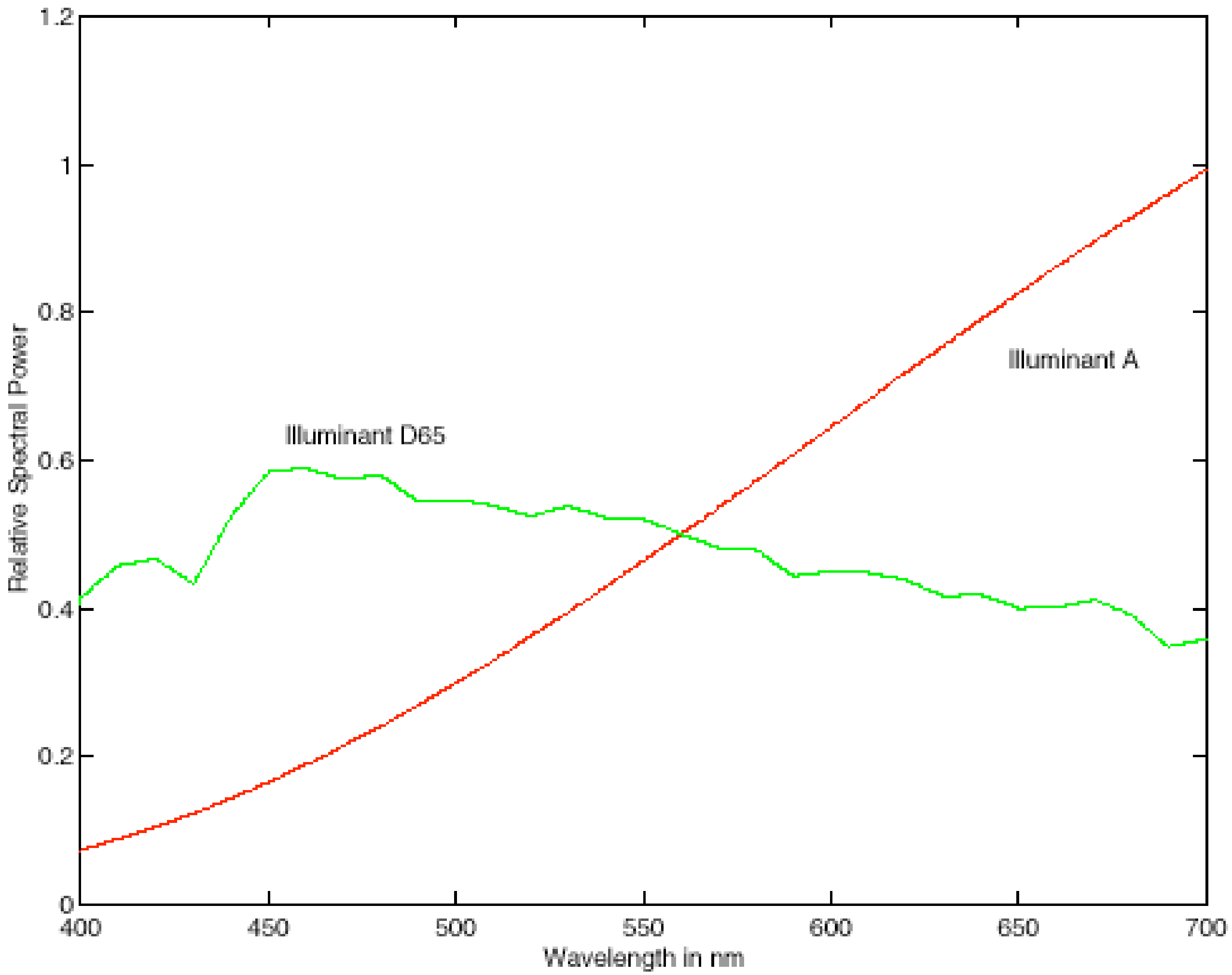
- Construct a hot body with near-zero albedo (black body)
  - Easiest way to do this is to build a hollow metal object with a tiny hole in it, and look at the hole.
- The spectral power distribution of light leaving this object is a simple function of temperature

$$E(\lambda) \propto \left(\frac{1}{\lambda^5}\right)\left(\frac{1}{\exp\left(hc/k\lambda T\right)-1}\right)$$

- This leads to the notion of color temperature --- the temperature of a black body that would look the same

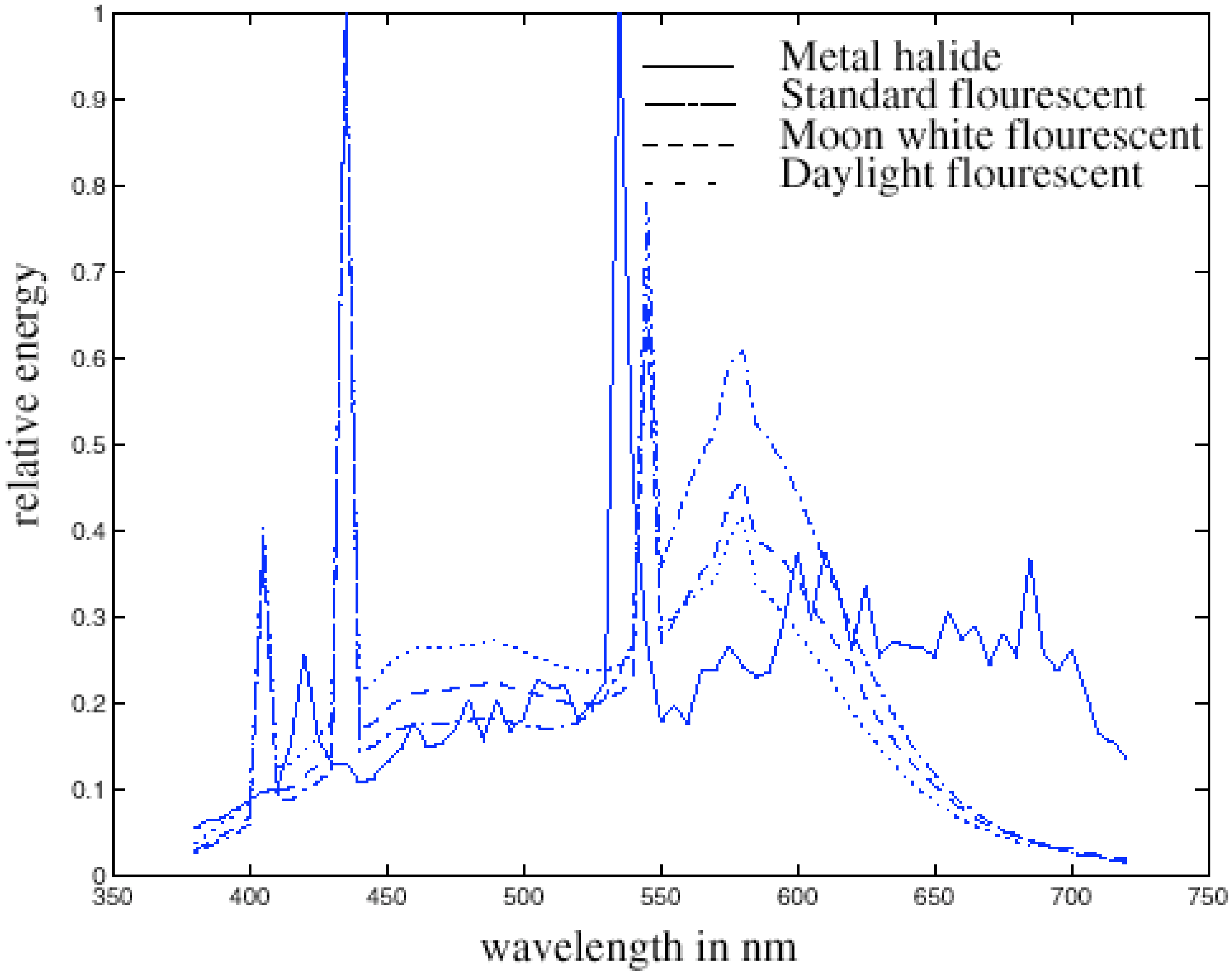


Measurements of relative spectral power of sunlight, made by J. Parkkinen and P. Silfsten. Relative spectral power is plotted against wavelength in nm. The visible range is about 400nm to 700nm. The color names on the horizontal axis give the color names used for monochromatic light of the corresponding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

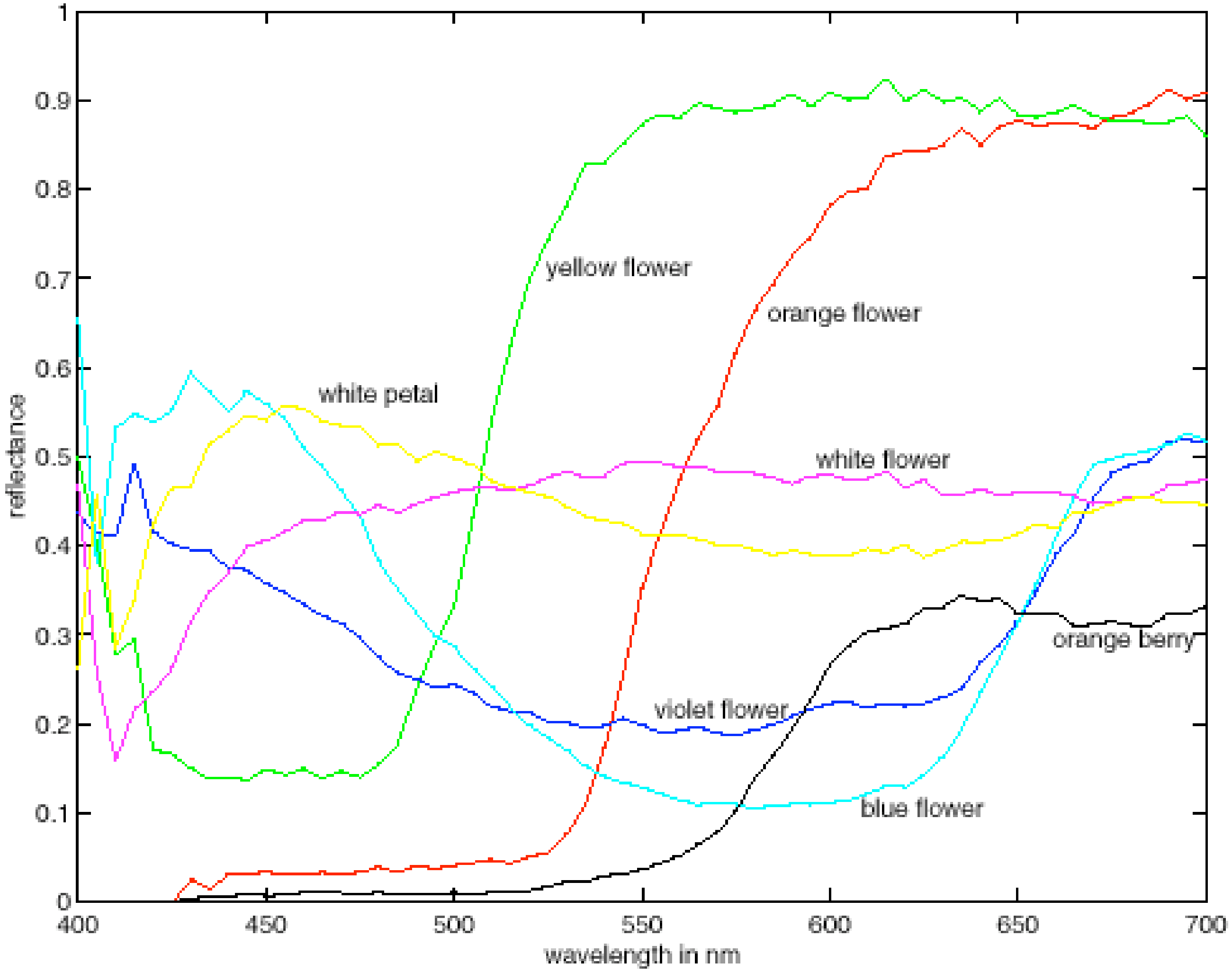


Violet Indigo Blue Green Yellow Orange Red

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. The visible range is about 400nm to 700nm. The color names on the horizontal axis give the color names used for monochromatic light of the corresponding wavelength --- the "colors of the rainbow".



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

The appearance of colors

- Color appearance is strongly affected by (at least):
  - other nearby colors,
  - adaptation to previous views
  - “state of mind”
- We show several demonstrations in what follows.
- **Film color mode**:
  View a colored surface through a hole in a sheet, so that the color looks like a film in space; controls for nearby colors, and state of mind.
- Other modes:
  - Surface color
  - Volume color
  - Mirror color
  - Illuminant color

The appearance of colors

- Hering, Helmholtz: Color appearance is strongly affected by other nearby colors, by adaptation to previous views, and by "state of mind"
- Film color mode: View a colored surface through a hole in a sheet, so that the color looks like a film in space; controls for nearby colors, and state of mind.
  - Other modes:
    - Surface colour
    - Volume colour
    - Mirror colour
    - Illuminant colour
- By experience, it is possible to match almost all colors, viewed in film mode using only three primary sources - the principle of **trichromacy**.
  - Other modes may have more dimensions
    - Glossy-matte
    - Rough-smooth
- Most of what follows discusses film mode.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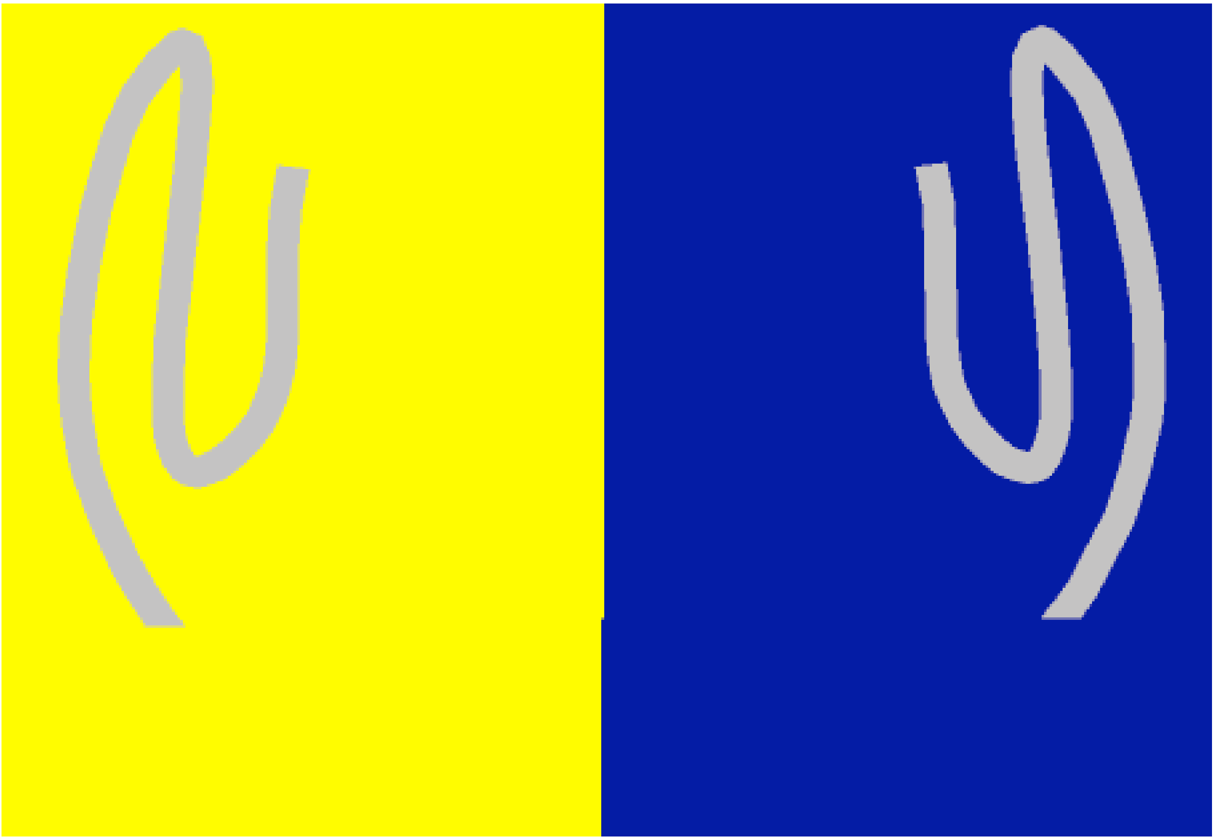
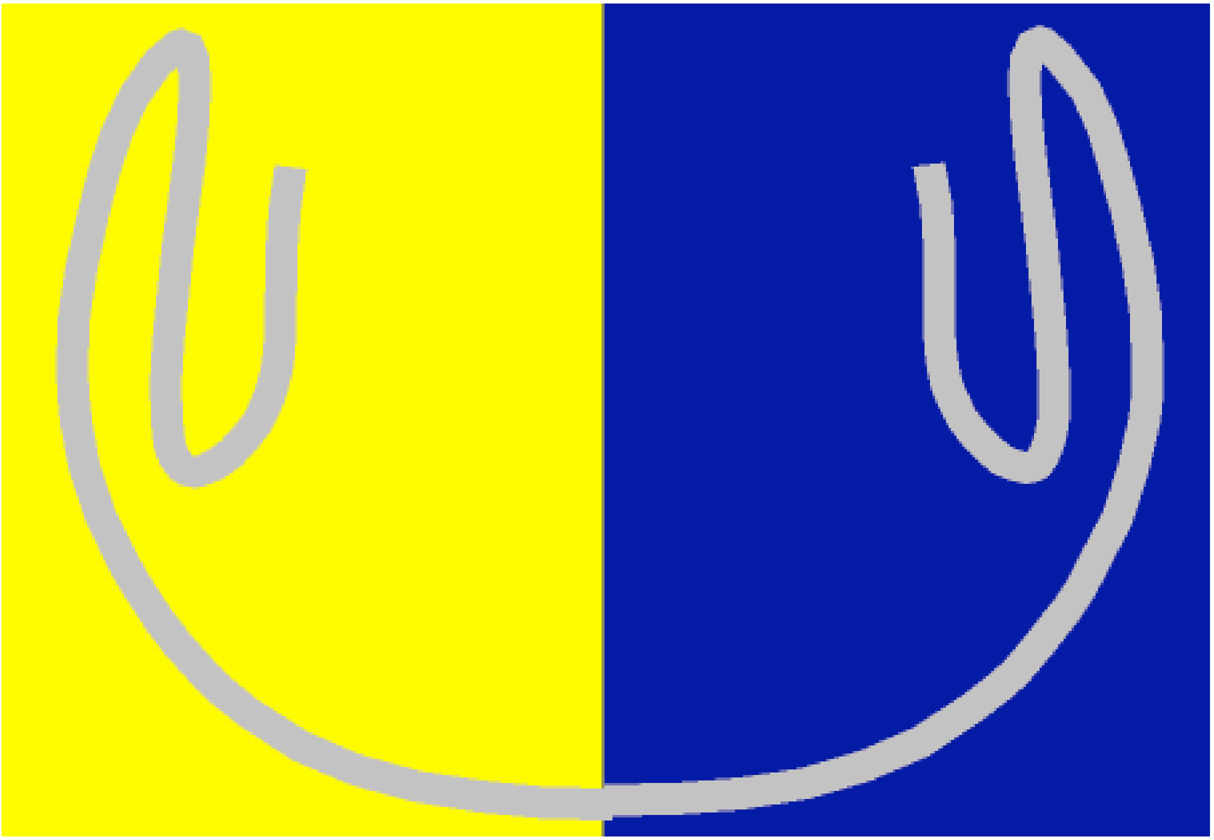
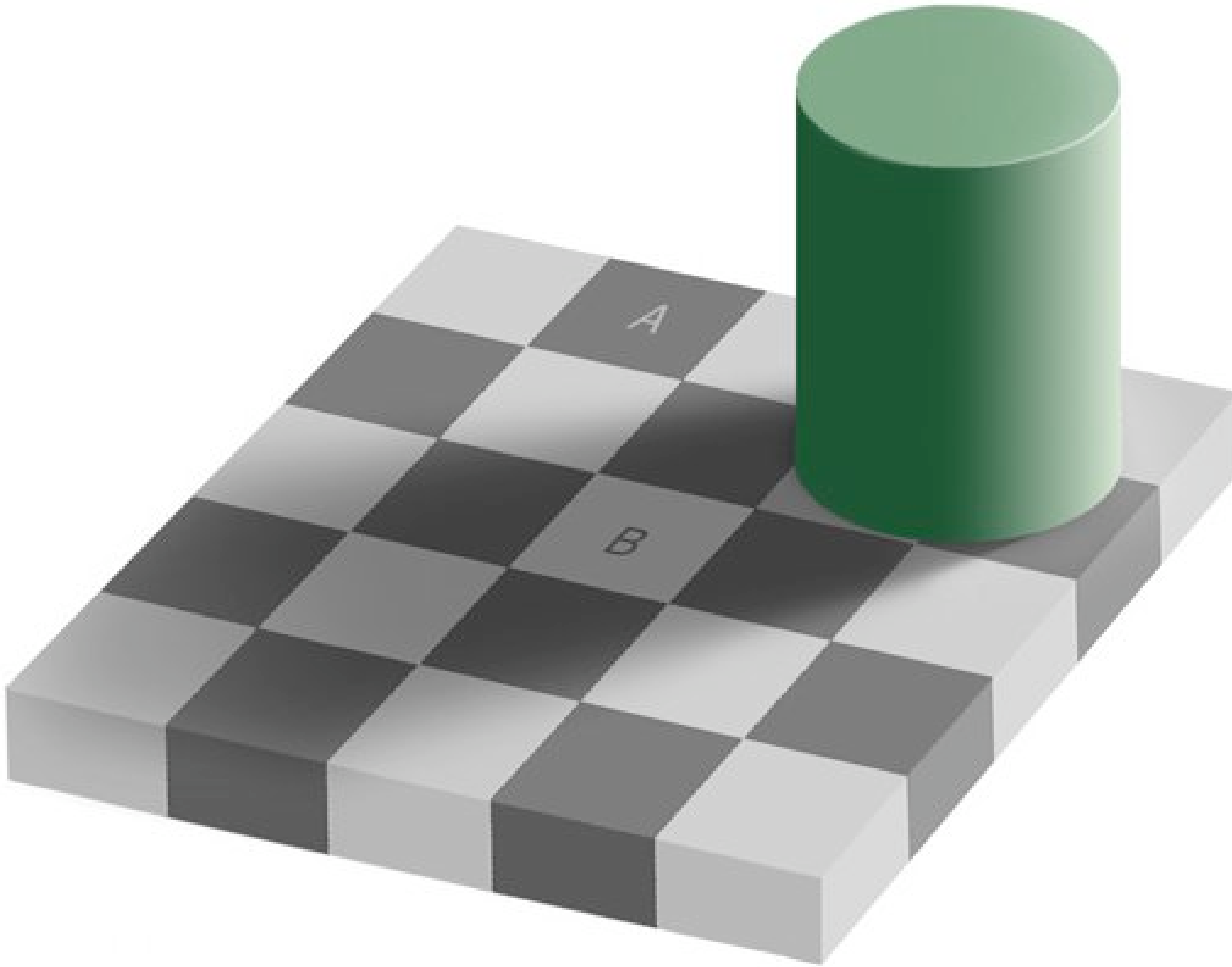
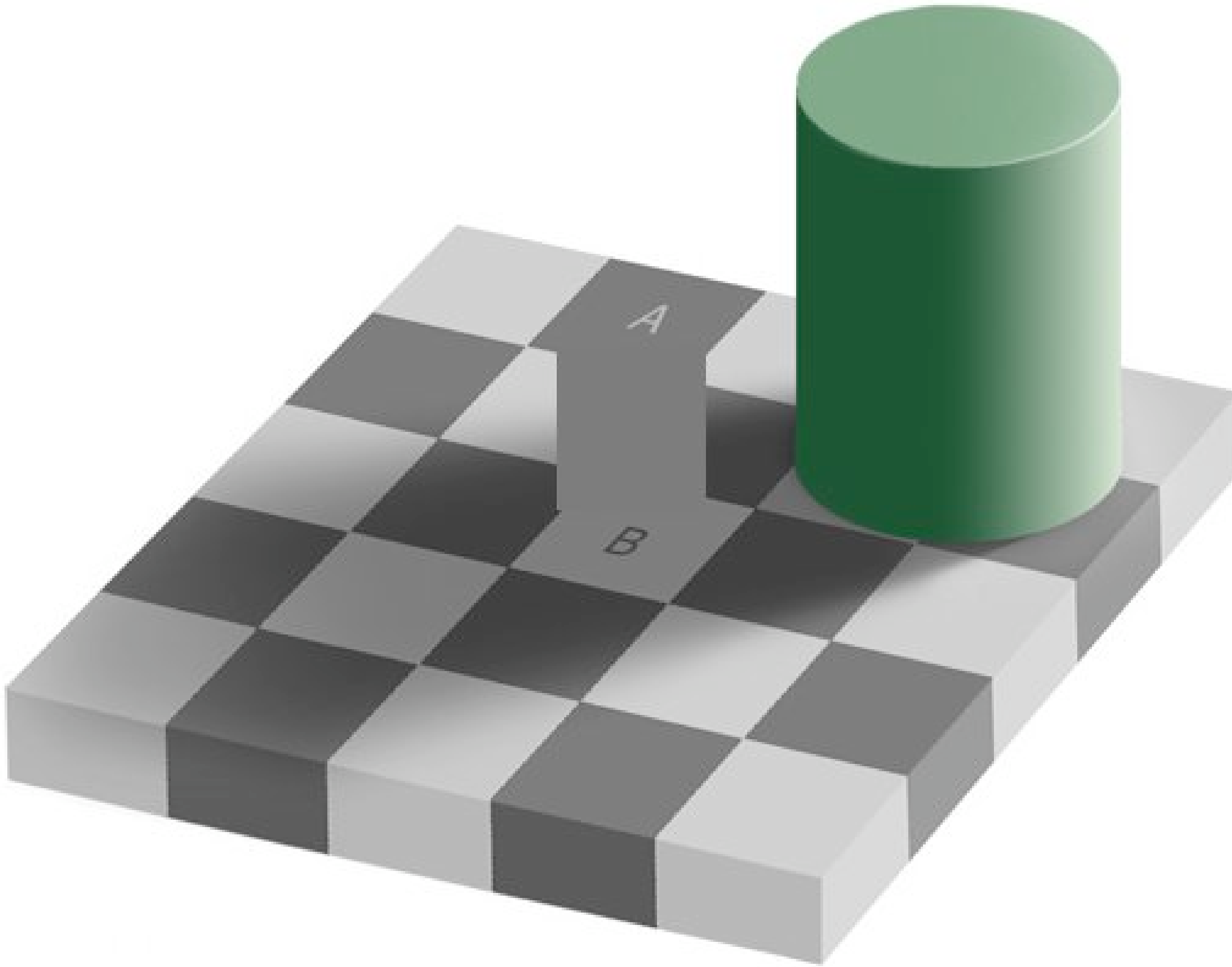
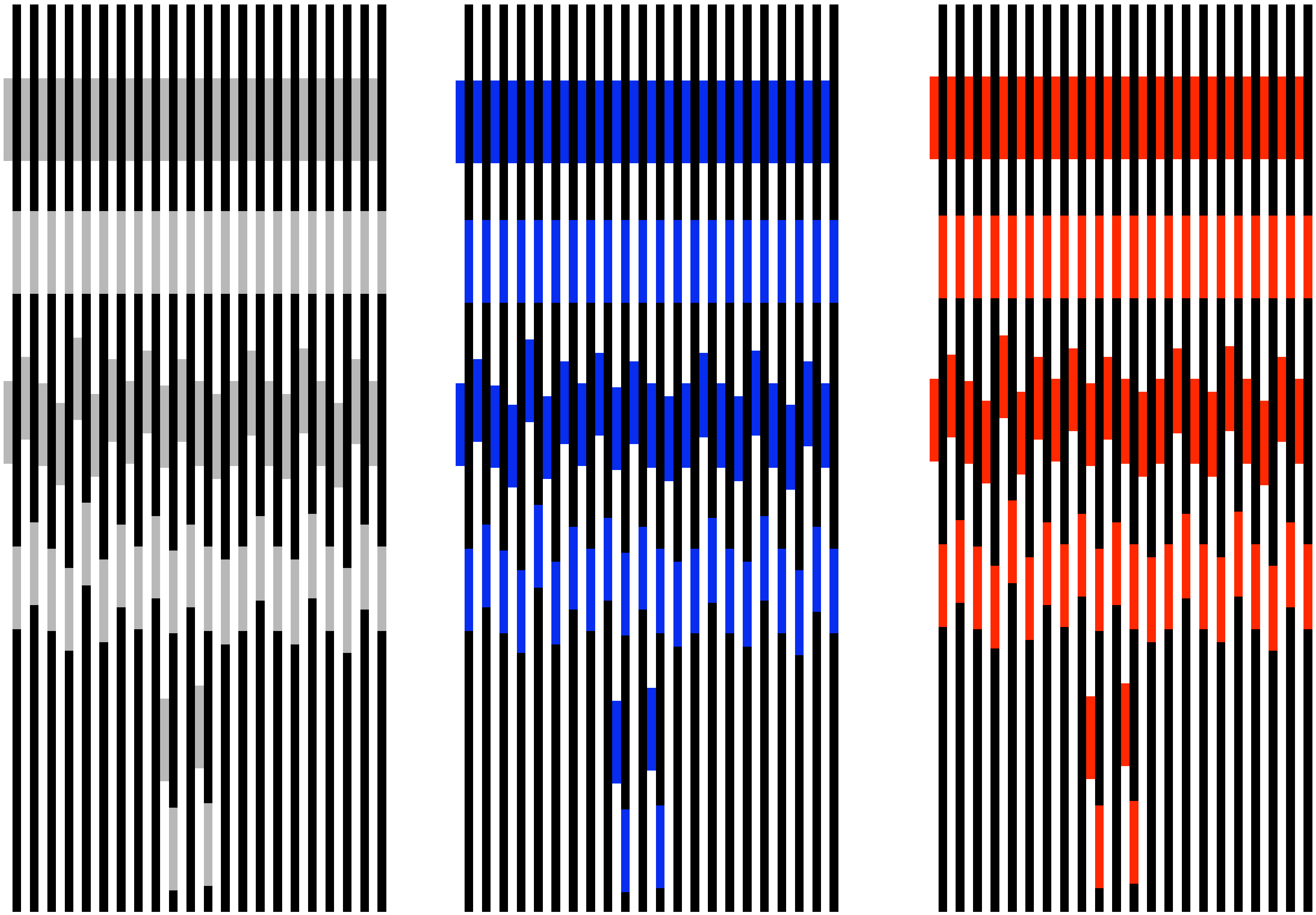





A
B


A
B

Munker-White Illusion



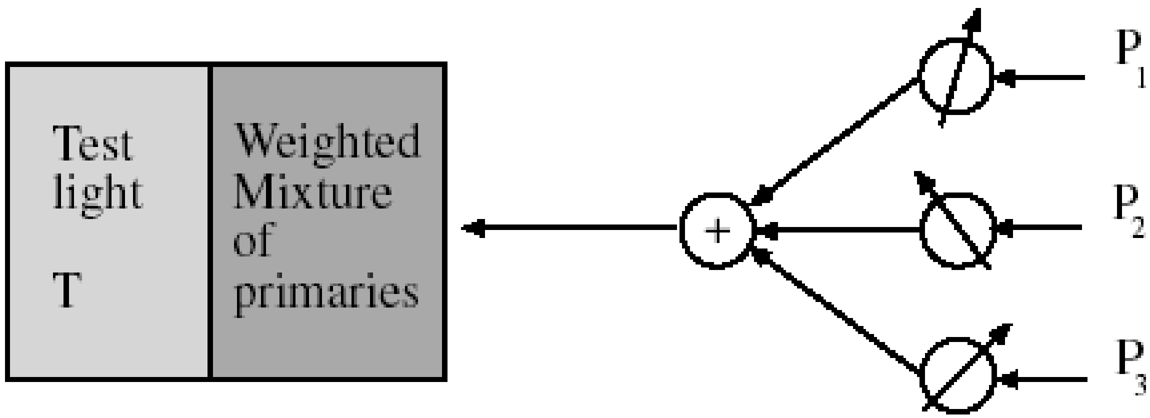
Simutaneous Contrast Illusion

Paint or Shading?

Why specify color numerically?

- Accurate color reproduction is commercially valuable
  - Many products are identified by color (“golden” arches;
- Few color names are widely recognized by English speakers -
  - About 10; other languages have fewer/more, but not many more.
  - It’s common to disagree on appropriate color names.
- Color reproduction problems increased by prevalence of digital imaging - eg. digital libraries of art.
  - How do we ensure that everyone sees the same color?

Color matching experiments - I



- Show a split field to subjects; one side shows the light whose color one wants to measure, the other a weighted mixture of primaries (fixed lights).
- Each light is seen in film color mode.

Color matching experiments - II

- Many colors can be represented as a mixture 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 color description system - two people who agree on A, B, C need only supply (a, b, c) to describe a color.

Subtractive matching

- Some colors 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 colors

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.
    - 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
    - These matches can be used to determine the genetics of their photopigments.

Grassman's Laws

- For colour matches made in film colour mode:
  - 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 color spaces

- A choice of primaries yields a linear color space --- the coordinates of a color are given by the weights of the primaries used to match it.
- Choice of primaries is equivalent to choice of color space.
- **RGB:** primaries are monochromatic energies are 645.2nm, 526.3nm, 444.4nm.
- **CIE XYZ:** Primaries are imaginary, but have other convenient properties. Color coordinates are (X,Y,Z), where X is the amount of the X primary, etc.
  – Usually draw x, y, where
    $x=X/(X+Y+Z)$
    $y=Y/(X+Y+Z)$

Color matching functions

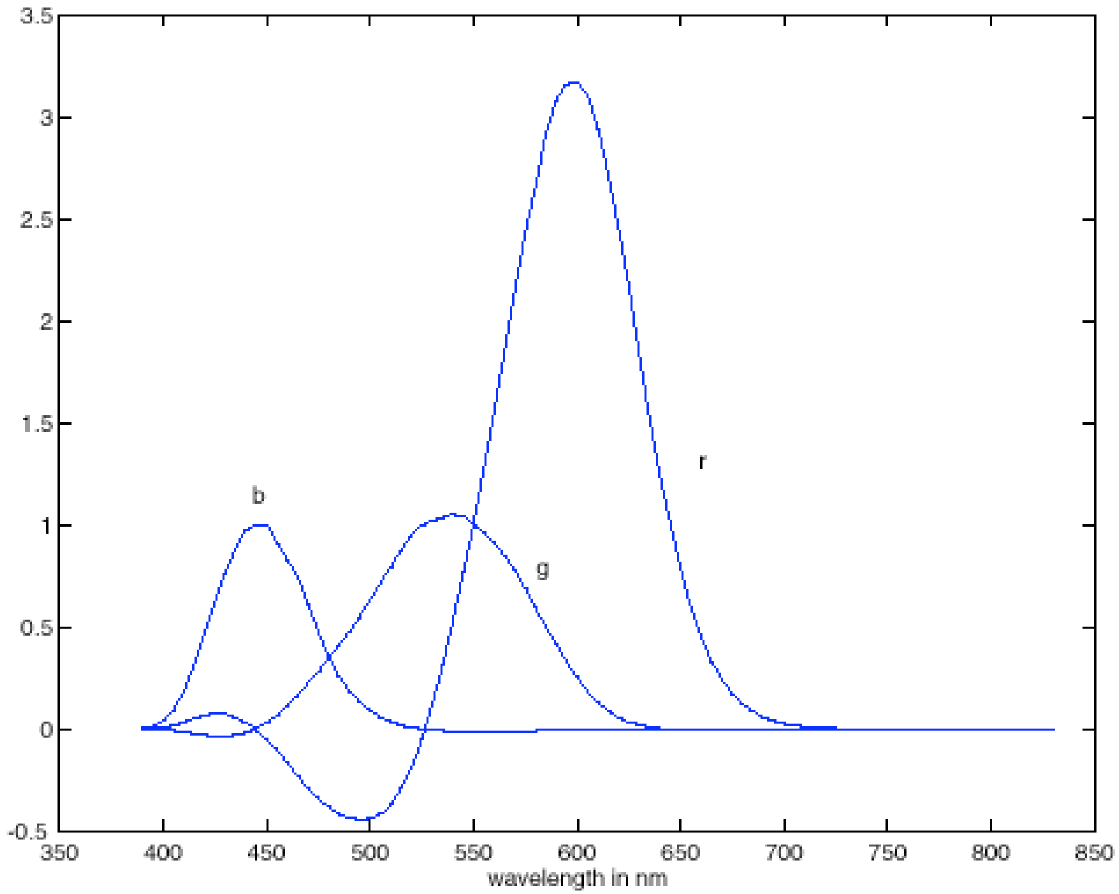
- Choose primaries, say A, B, C
- Given energy function, $E(\lambda)$ what amounts of primaries will match it?
- For each wavelength, determine how much of A, of B, and of C is needed to match light of that wavelength alone.

$$a(\lambda)$$
$$b(\lambda)$$
$$c(\lambda)$$

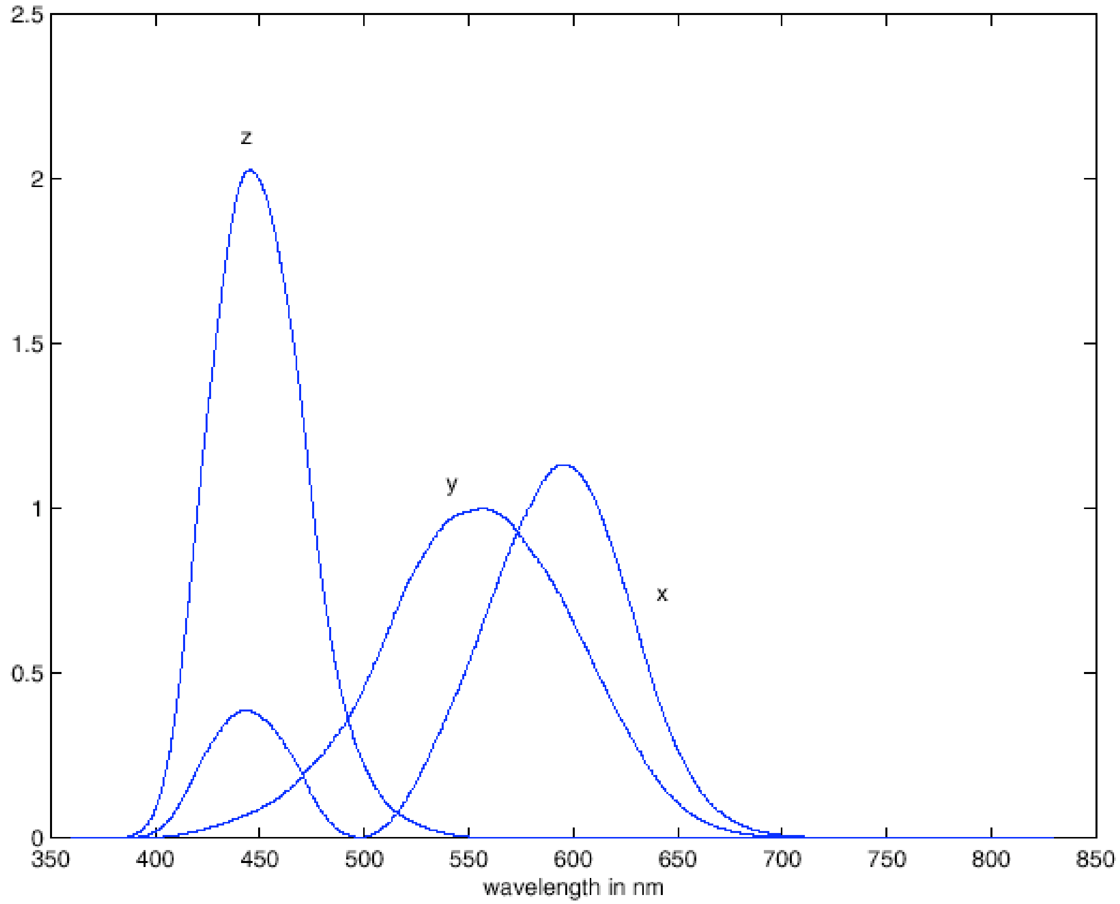
- These are colormatching functions

Then our match is:

$$\left\{\int a(\lambda)E(\lambda)d\lambda\right\}A +$$
$$\left\{\int b(\lambda)E(\lambda)d\lambda\right\}B +$$
$$\left\{\int c(\lambda)E(\lambda)d\lambda\right\}C$$



RGB: primaries are monochromatic, energies are 645.2nm, 526.3nm, 444.4nm. Color matching functions have negative parts -> some colors can be matched only subtractively.



CIE XYZ: Color matching functions are positive everywhere, but primaries are imaginary. Usually draw x, y, where

$x=X/(X+Y+Z)$

$y=Y/(X+Y+Z)$

Color receptors

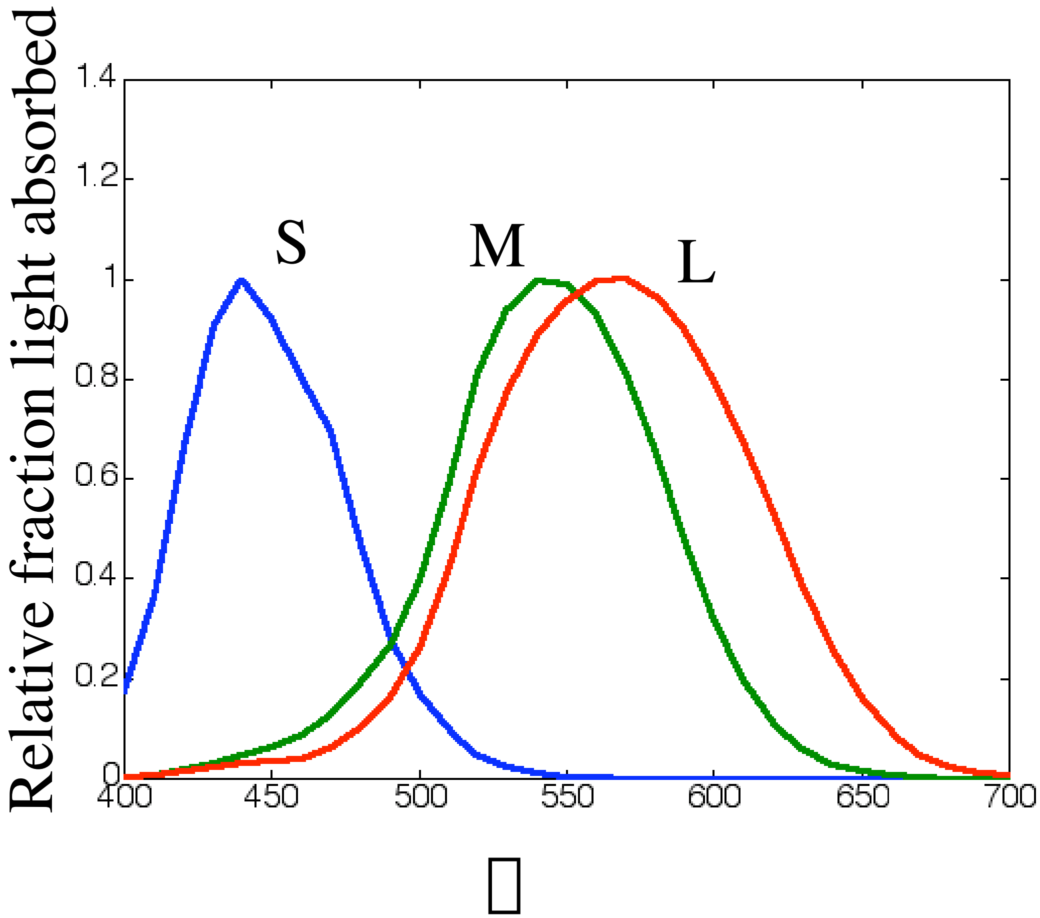
- **Principle of univariance**: cones give the same kind of response, in different *amounts*, to different wavelengths. The output of the cone is obtained by summing over wavelengths. Responses are measured in a variety of ways (comparing behaviour of color normal and color deficient subjects).

- All experimental evidence suggests that the response of the k'th type of cone can be written as

$$\int \sigma_k(\lambda) E(\lambda) d\lambda$$

where $\sigma_k(\lambda)$ is the sensitivity of the receptor and spectral energy density of the incoming light.

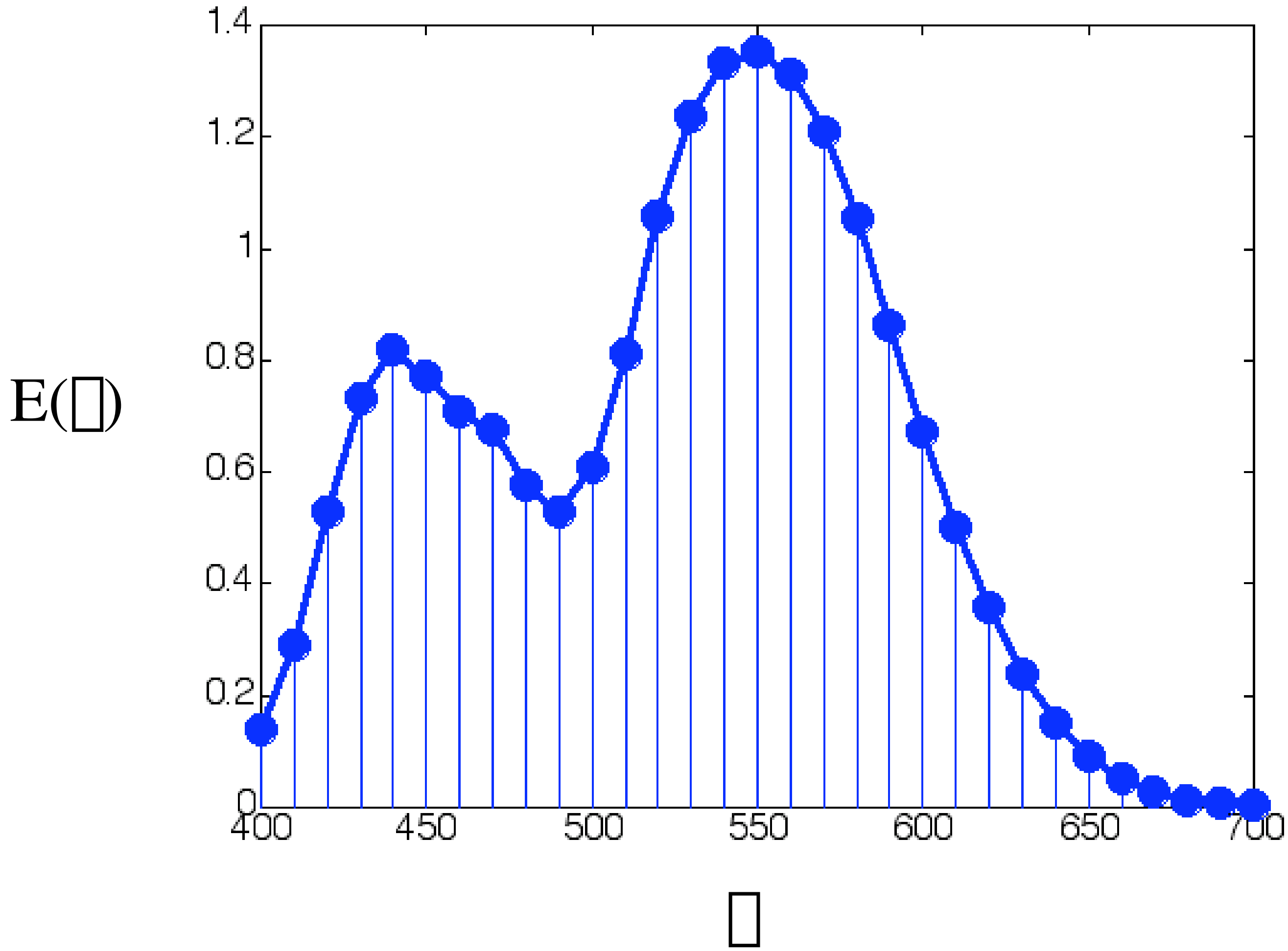
Color receptors



Plot shows relative sensitivity as a function of wavelength, for the three cones. The S (for short) cone responds most strongly at short wavelengths; the M (for medium) at medium wavelengths and the L (for long) at long wavelengths.

These are occasionally called B, G and R cones respectively, but that's misleading - you don't see red because your R cone is activated.

Simpler if we discretize frequency

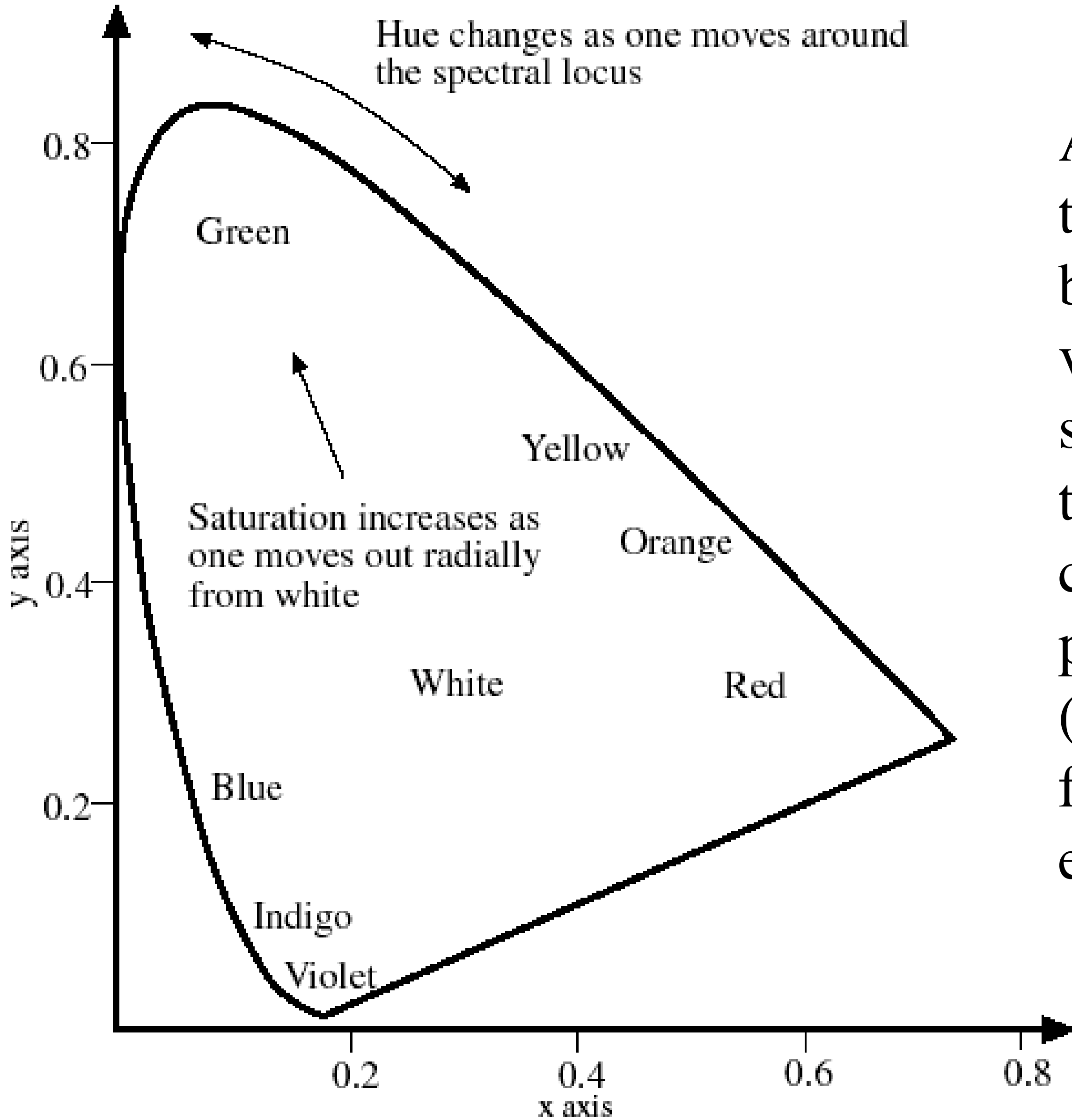


What does color matching do?

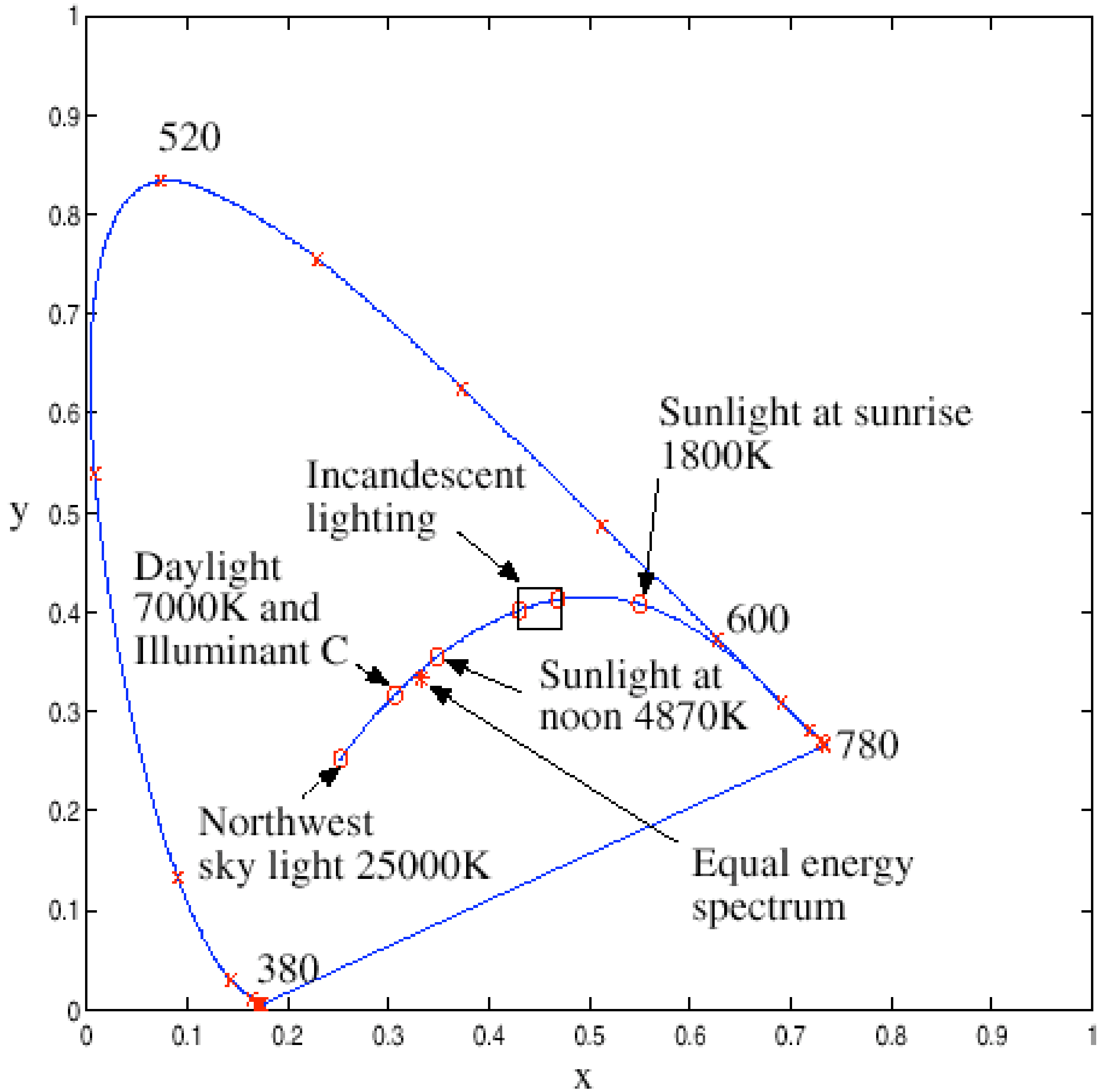
Choose
$$\begin{bmatrix} f_1 \\ f_2 \\ f_3 \end{bmatrix} = \begin{bmatrix} \vec{a}^T \\ \vec{b}^T \\ \vec{c}^T \end{bmatrix} \vec{E}$$

Such that when:
$$\begin{bmatrix} I_r \\ I_g \\ I_b \end{bmatrix} = \begin{bmatrix} \vec{\square}_r^T \\ \vec{\square}_g^T \\ \vec{\square}_b^T \end{bmatrix} \vec{E}$$

Then the combined primaries yields:
$$\begin{bmatrix} I_r \\ I_g \\ I_b \end{bmatrix} = \begin{bmatrix} \vec{\square}_r^T \\ \vec{\square}_g^T \\ \vec{\square}_b^T \end{bmatrix} \begin{bmatrix} \vec{A} & \vec{B} & \vec{C} \end{bmatrix} \begin{bmatrix} f_1 \\ f_2 \\ f_3 \end{bmatrix}$$



A qualitative rendering of the CIE (x,y) space. The blobby region represents visible colors. There are sets of (x, y) coordinates that don't represent real colors, because the primaries are not real lights (so that the color matching functions could be positive everywhere).

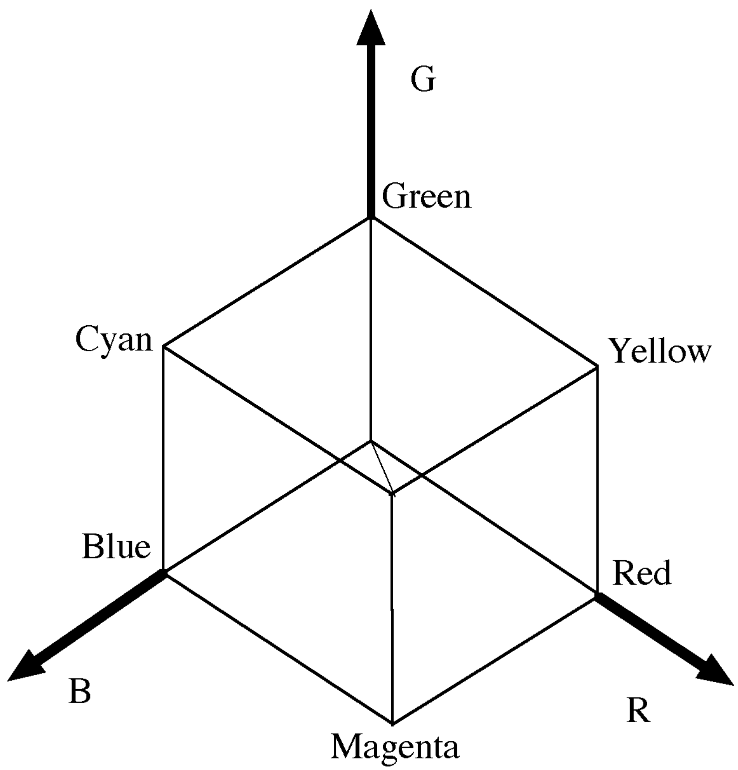


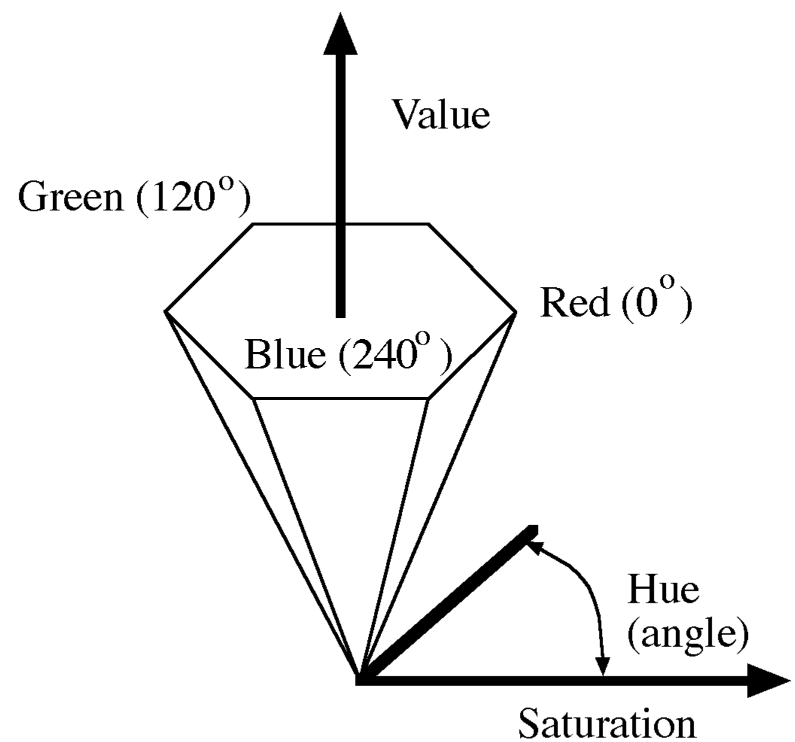
A plot of the CIE (x,y) space. We show the spectral locus (the colors of monochromatic lights) and the black-body locus (the colors of heated black-bodies). I have also plotted the range of typical incandescent lighting.

Non-linear colour spaces

- HSV: Hue, Saturation, Value are non-linear functions of XYZ.
  - because hue relations are naturally expressed in a circle
- Uniform: equal (small!) steps give the same perceived color changes.
- Munsell: describes surfaces, rather than lights - less relevant for graphics. Surfaces must be viewed under fixed comparison light

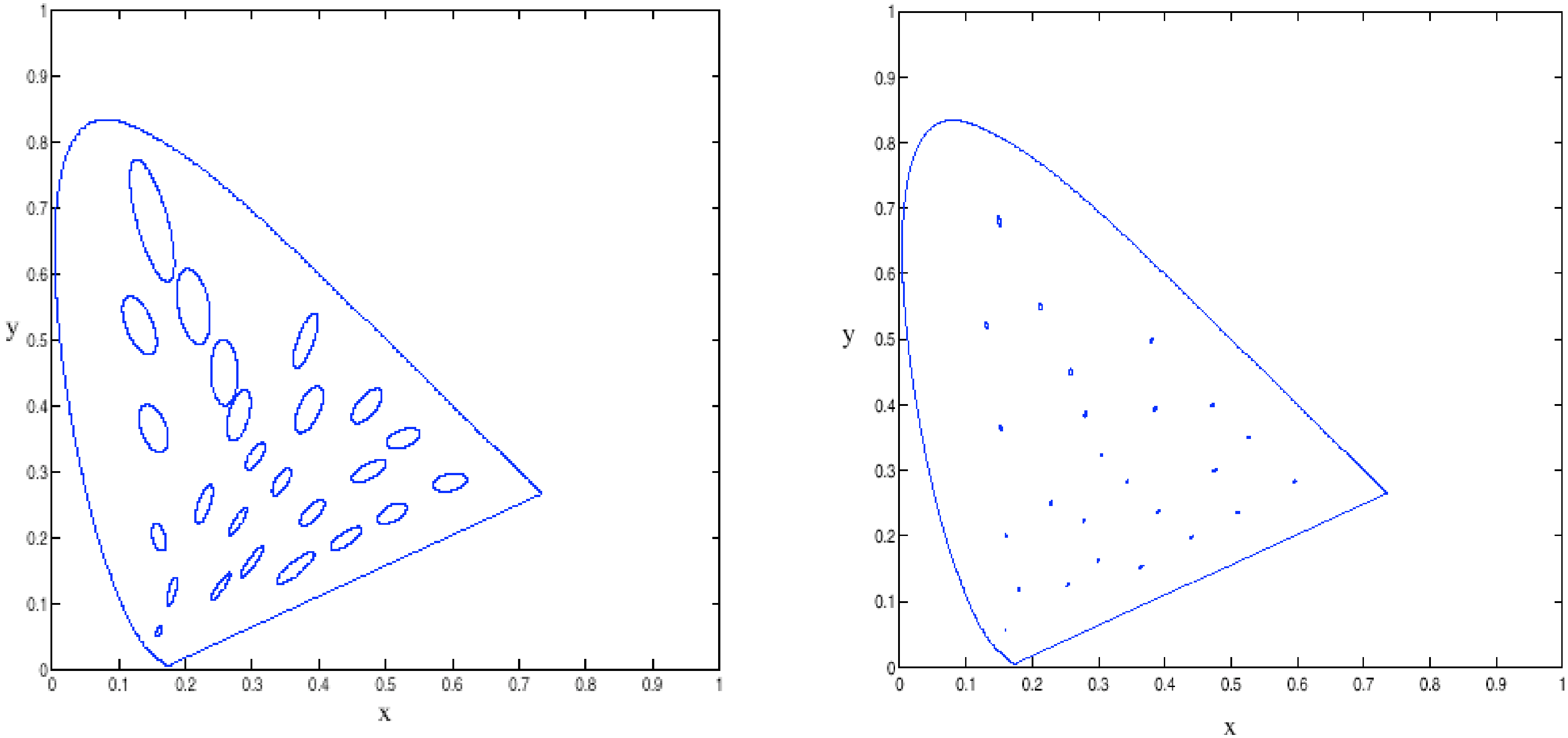
HSV hexcone


G
Green
Cyan
Yellow
Blue
Red
B
R
Magenta


Value
Green (120°)
Red (0°)
Blue (240°)
Hue
(angle)
Saturation

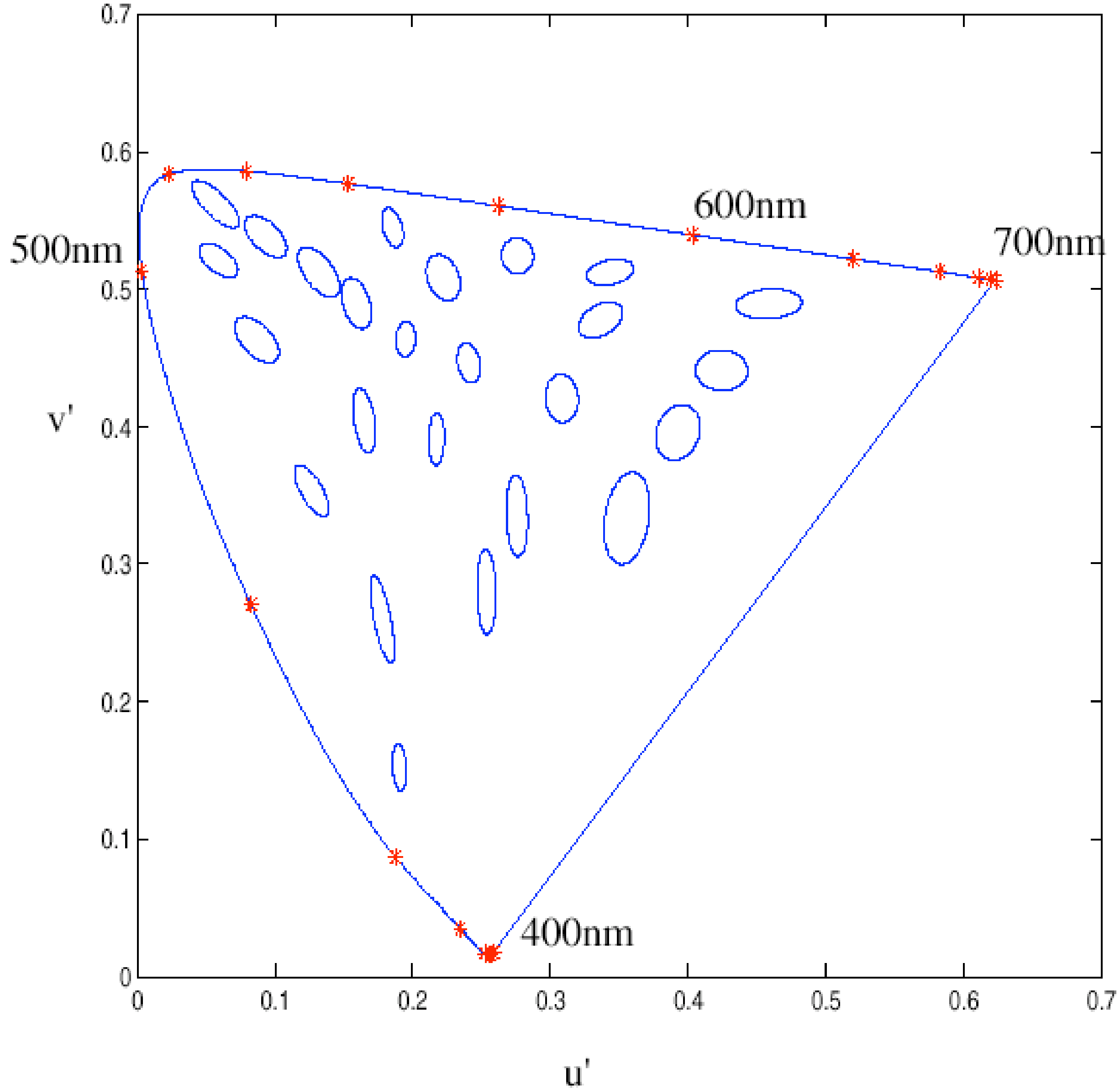
Uniform color spaces

- McAdam ellipses (next slide) demonstrate that differences in x,y are a poor guide to differences in color
- Construct color spaces so that differences in coordinates are a good guide to differences in color.



Variations in color matches on a CIE x, y space. At the center of the ellipse is the color of a test light; the size of the ellipse represents the scatter of lights that the human observers tested would match to the test color; the boundary shows where the just noticeable difference is. The ellipses on the left have been magnified 10x for clarity; on the right they are plotted to scale. The ellipses are known as MacAdam ellipses after their inventor. The ellipses at the top are larger than those at the bottom of the figure, and that they rotate as they move up. This means that the magnitude of the difference in x, y coordinates is a poor guide to the difference in color.

CIE u'v' which is a projective transform of x, y. We transform x,y so that ellipses are most like one another. Figure shows the transformed ellipses.

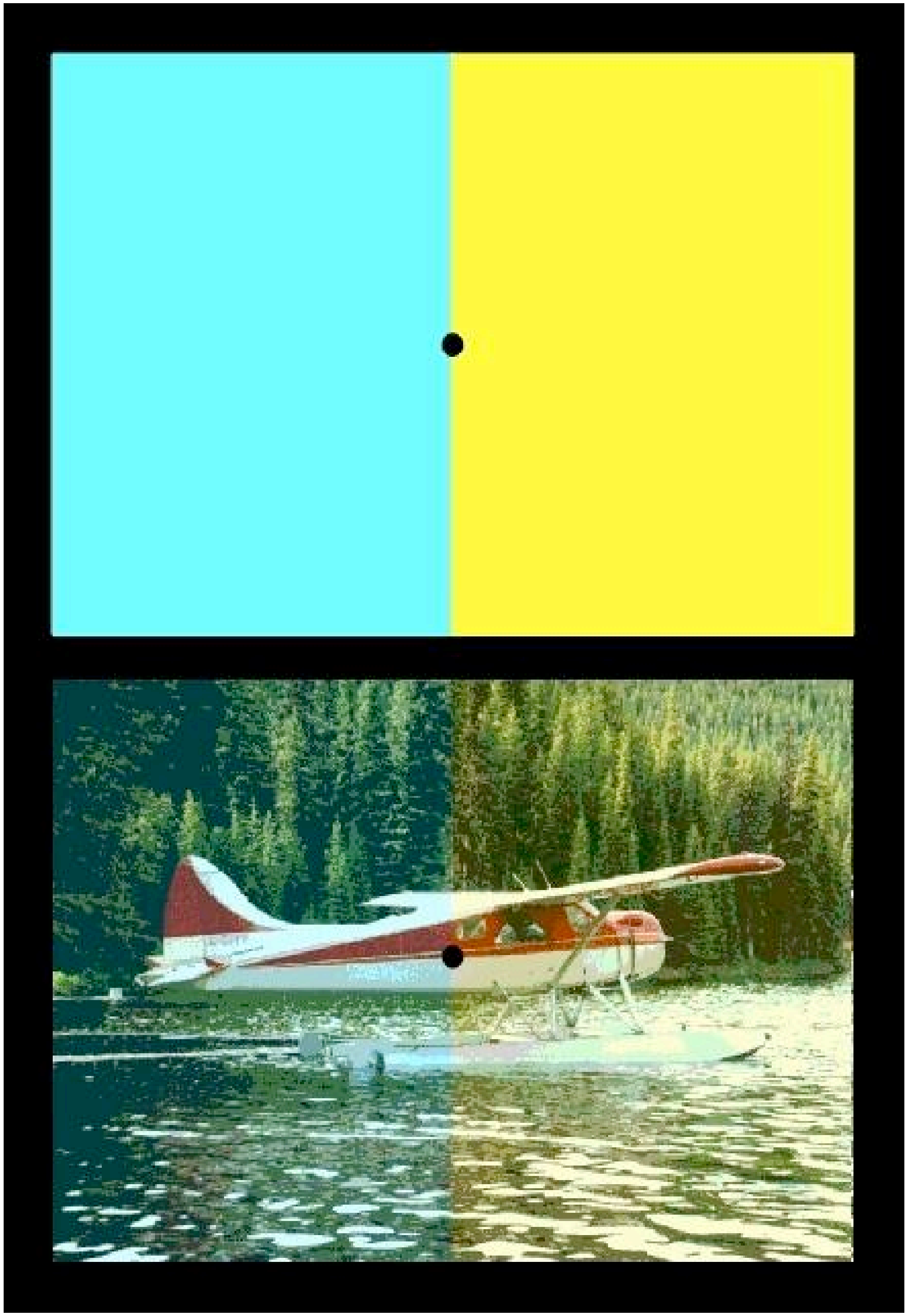


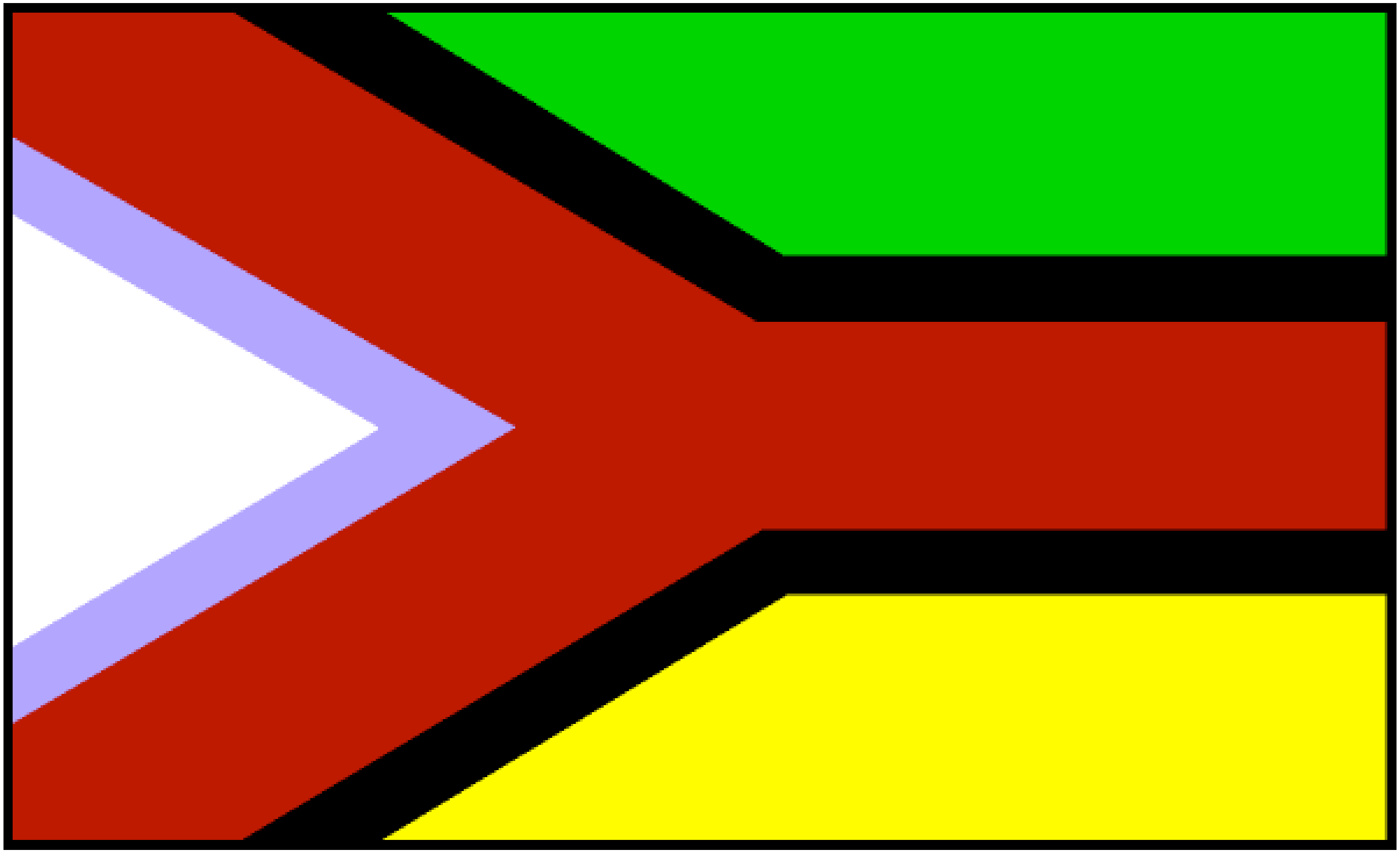
Color receptors and color deficiency

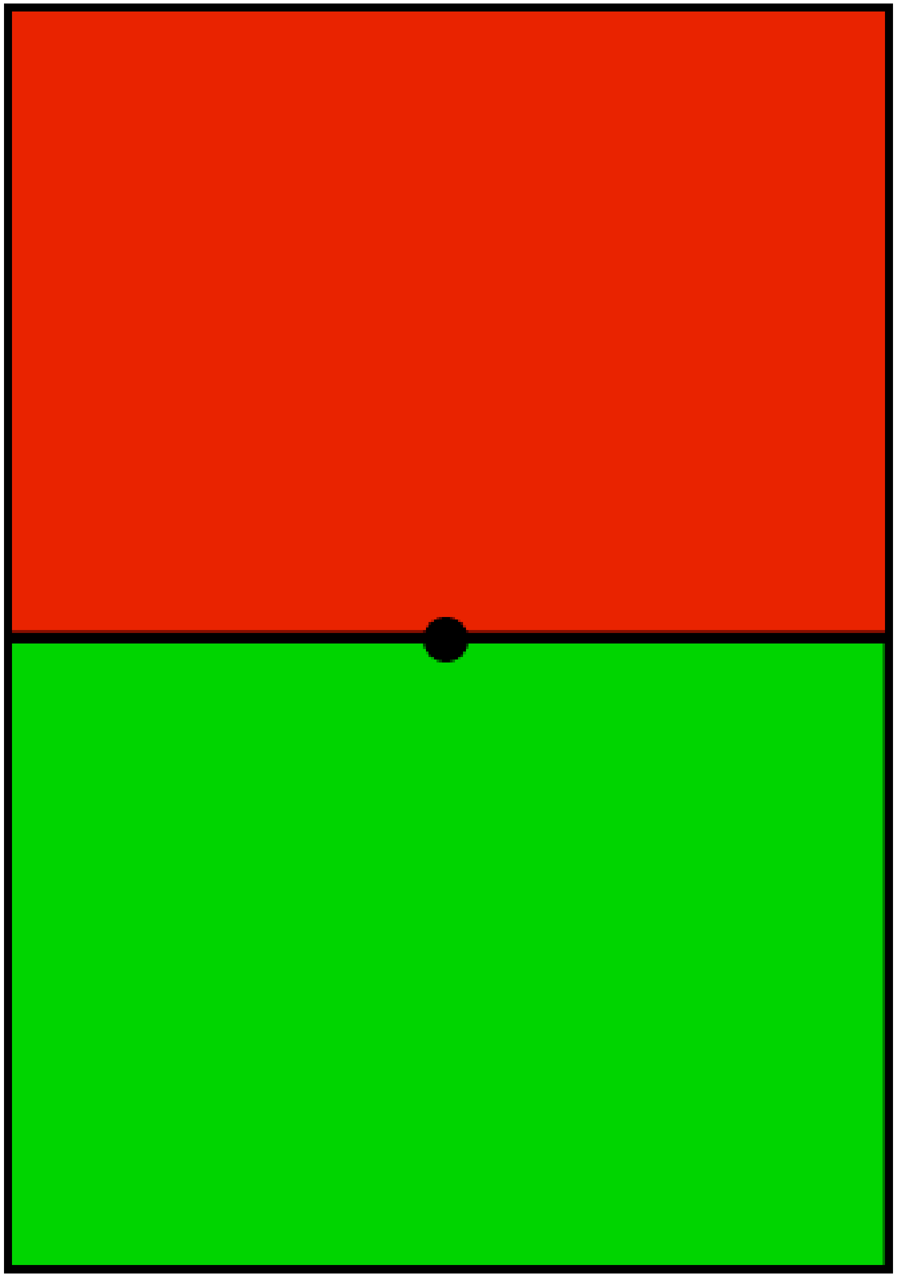
- Trichromacy is justified - in color normal people, there are three types of color receptor, called **cones**, which vary in their sensitivity to light at different wavelengths (shown by molecular biologists).
- Deficiency can be caused by CNS, by optical problems in the eye, or by absent receptor types
  - Usually a result of absent genes.
- Some people have fewer than three types of receptor; most common deficiency is red-green color blindness in men.
- Color deficiency is less common in women; red and green receptor genes are carried on the X chromosome, and these are the ones that typically go wrong. Women need two bad X chromosomes to have a deficiency, and this is less likely.

Adaptation phenomena

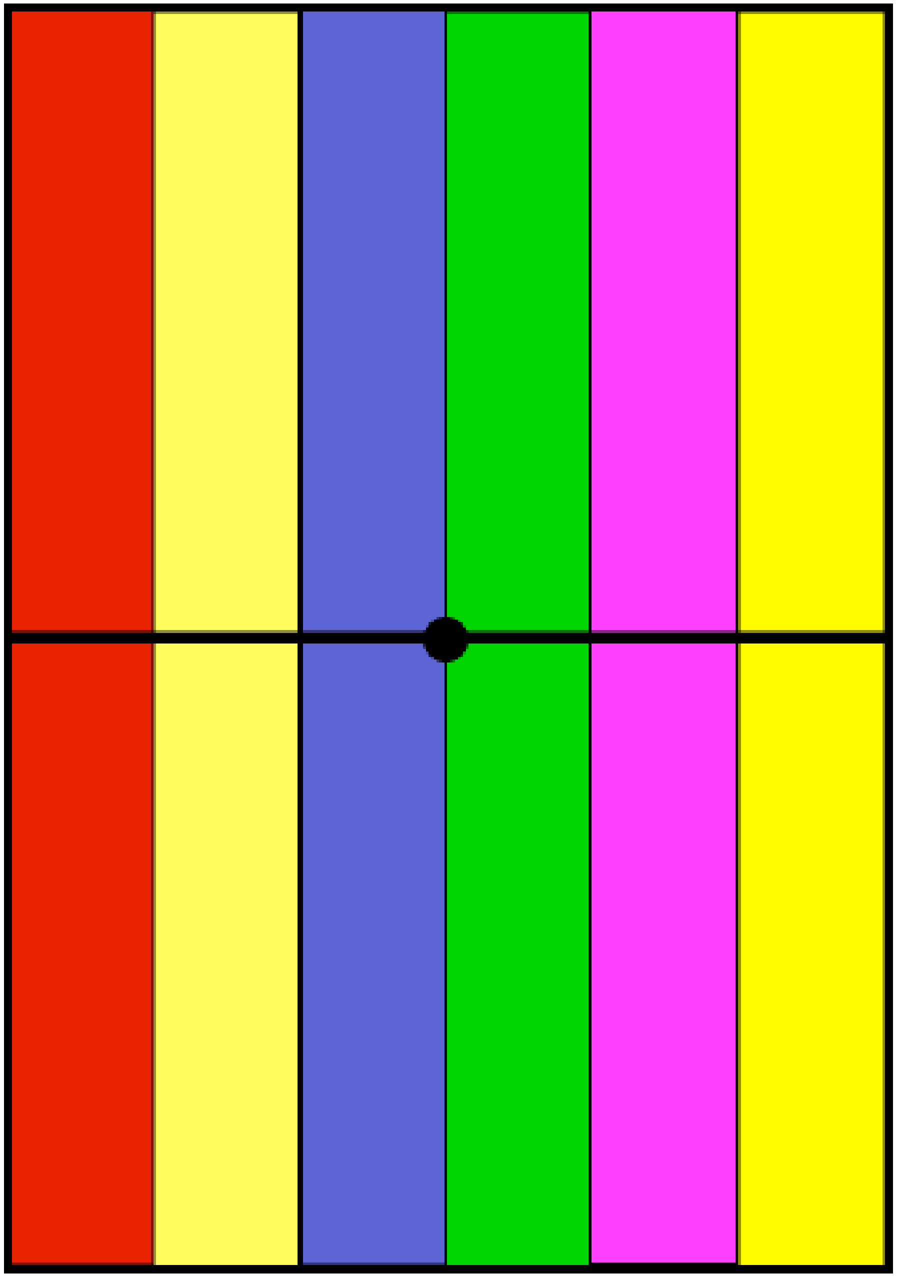
- The response of your color system depends both on spatial contrast and what it has seen before (adaptation)
- This seems to be a result of coding constraints --- receptors appear to have an operating point that varies slowly over time, and to signal some sort of offset. One form of adaptation involves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



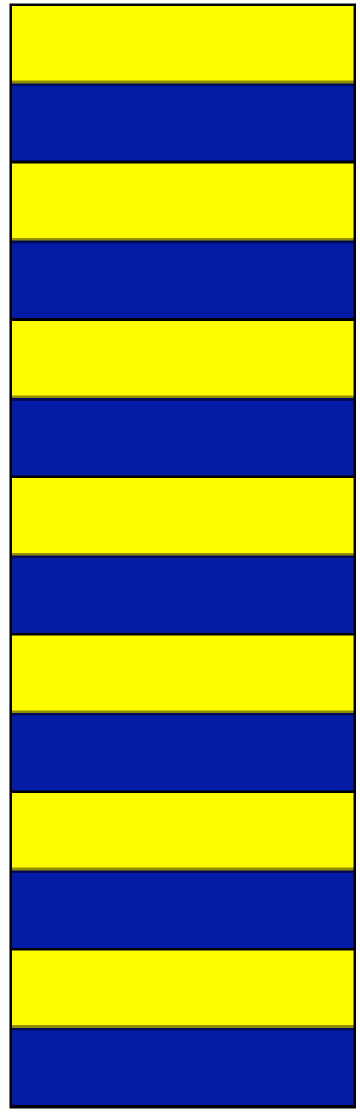


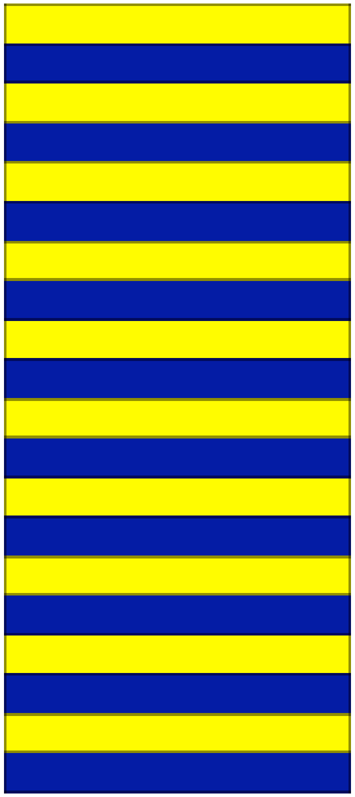


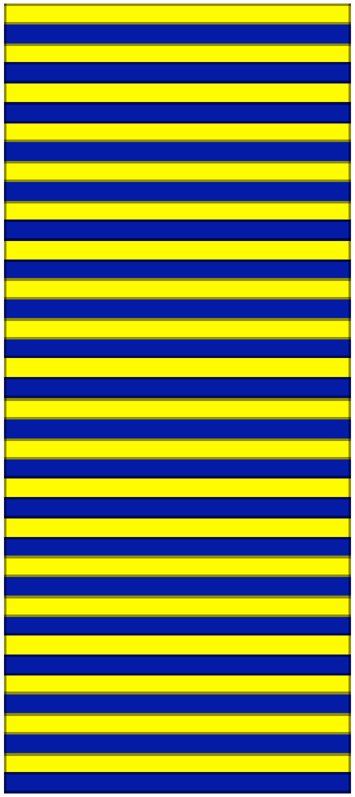
Set: Color
Slides by D.A. Forsyth

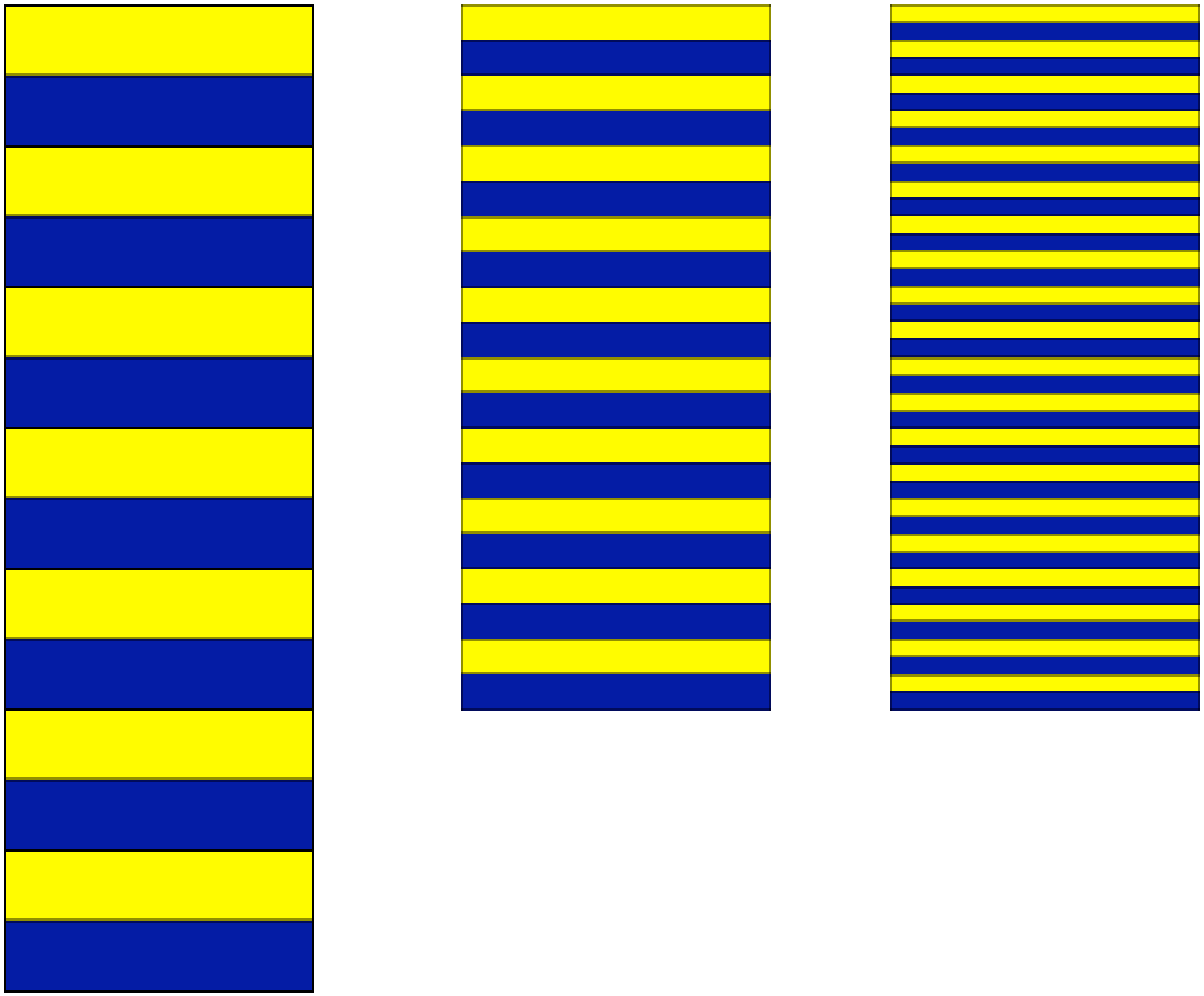


Set: Color
Slides by D.A. Forsyth







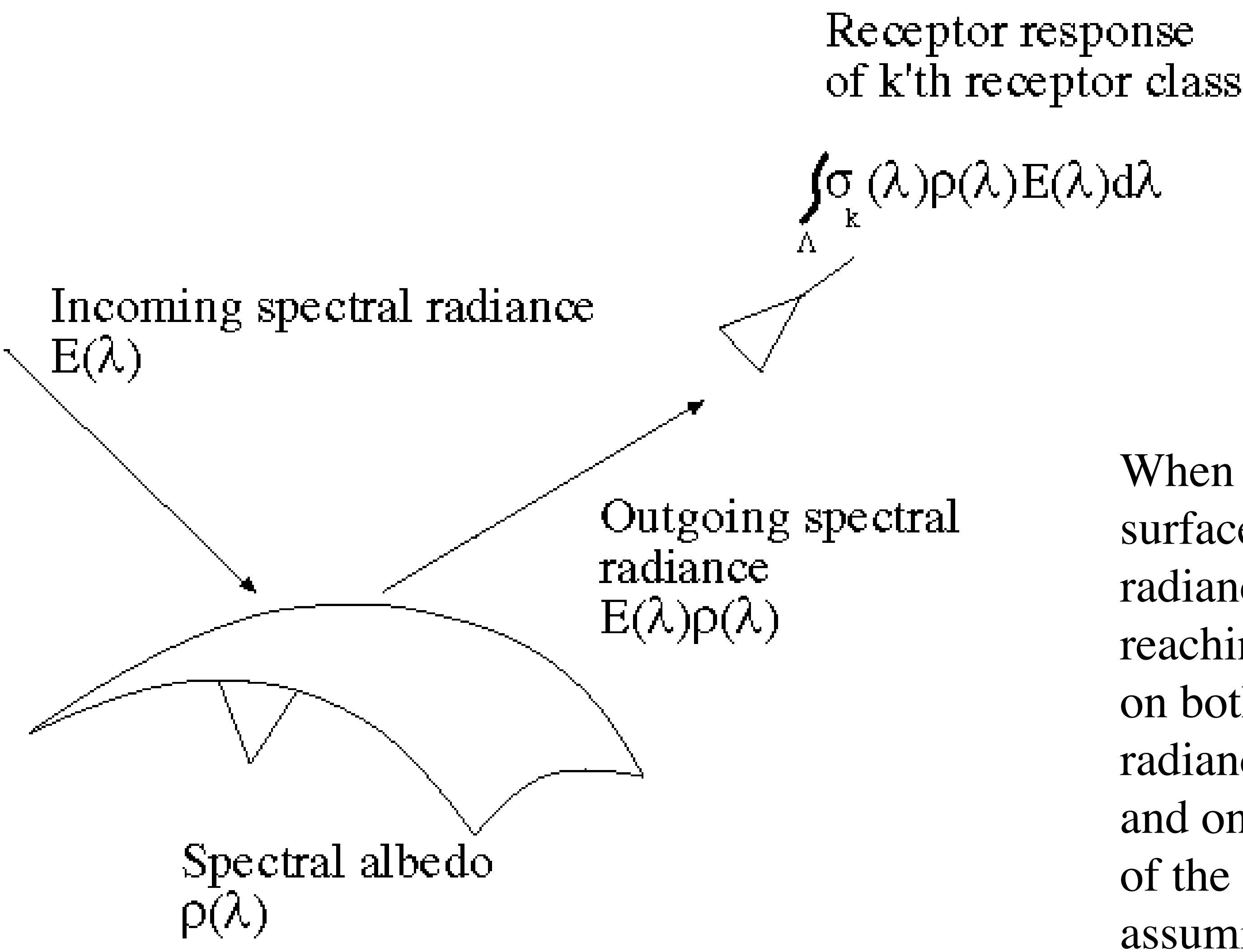


Viewing coloured objects

- Assume diffuse+specular model

- Specular
  - specularities on dielectric objects take the colour of the light
  - specularities on metals can be coloured

- Diffuse
  - colour of reflected light depends on both illuminant and surface
  - people are surprisingly good at disentangling these effects in practice (colour constancy)
  - this is probably where some of the spatial phenomena in colour perception come from



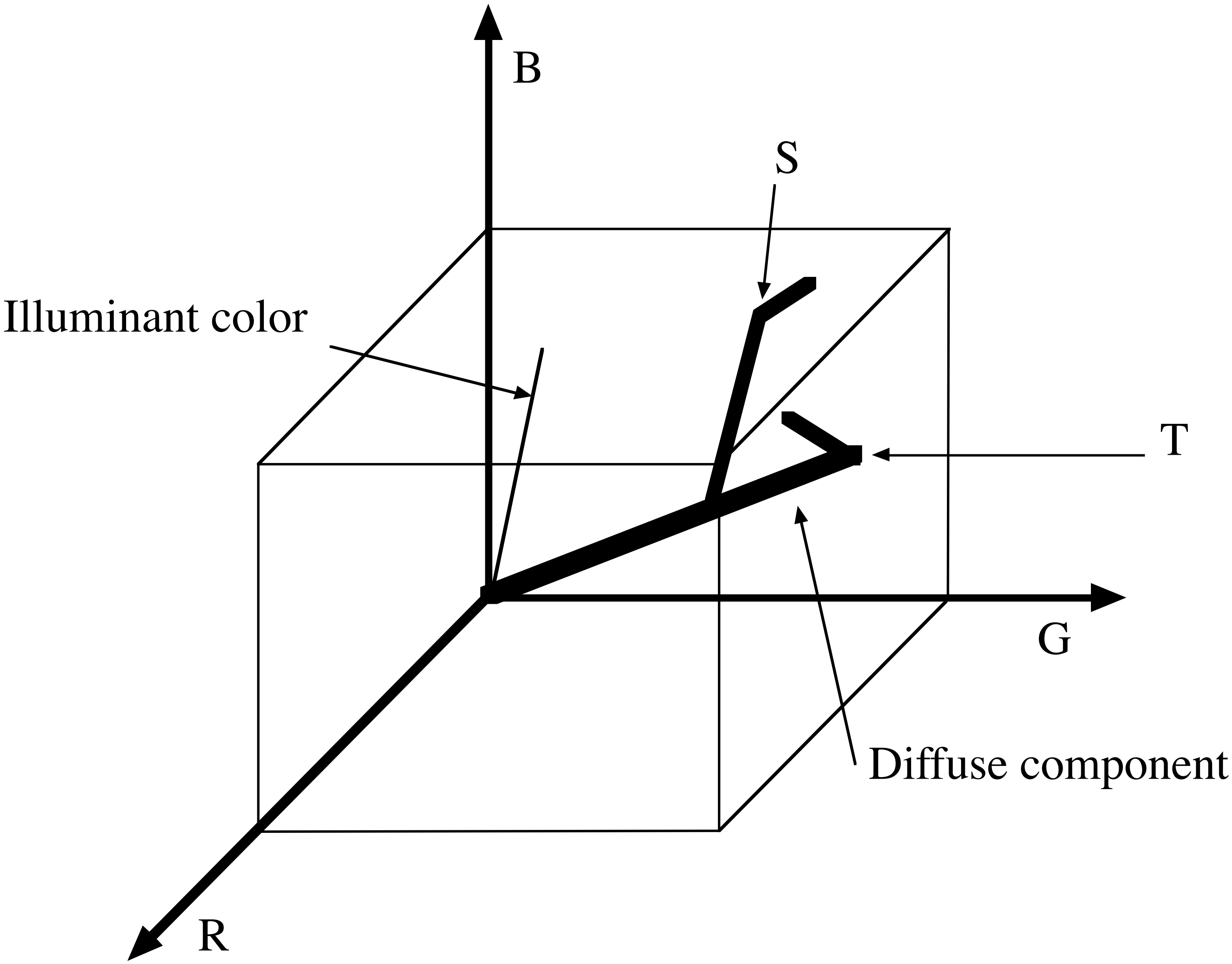
When one views a colored surface, the spectral radiance of the light reaching the eye depends on both the spectral radiance of the illuminant, and on the spectral albedo of the surface. We're assuming that camera receptors are linear, like the receptors in the eye. This is usually the case.

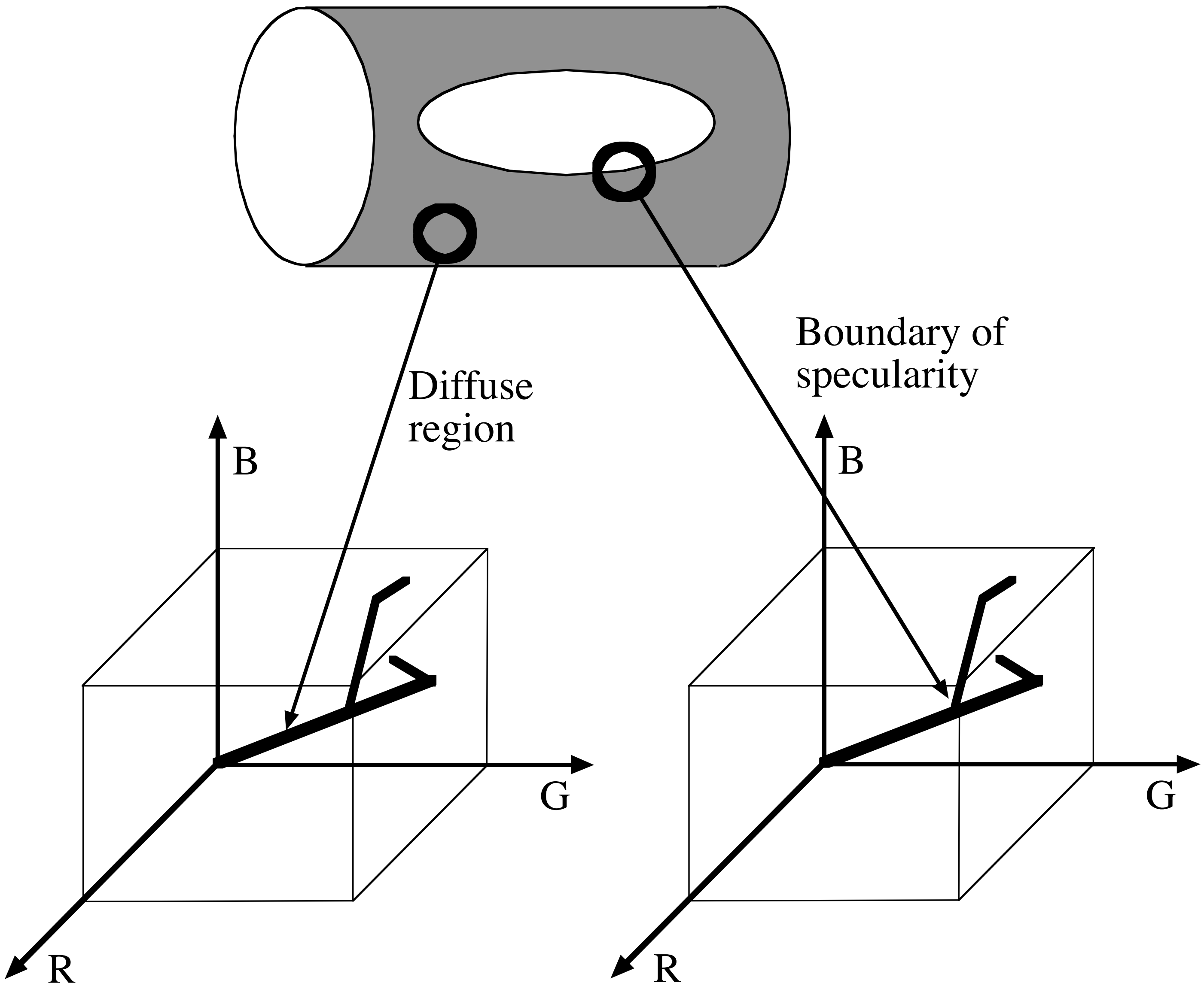
Subtractive mixing of inks

- Inks subtract light from white, whereas phosphors glow.
- Linearity depends on pigment properties
  - inks, paints, often hugely non-linear.
- Inks: Cyan=White-Red, Magenta=White-Green, Yellow=White-Blue.
- For a good choice of inks, and good registration, matching is linear and easy
- eg. C+M+Y=White-White=Black
  C+M=White-Yellow=Blue
- Usually require CMY and Black, because colored inks are more expensive, and registration is hard
- For good choice of inks, there is a linear transform between XYZ and CMY

Finding Specularities

- Assume we are dealing with dielectrics
  - specularly reflected light is the same color 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 color multiplied by different scaling constants (surface orientation)
  - in the specular patch, a new color is added; a “dog-leg” results


B
S
Illuminant color
T
G
Diffuse component
R


Boundary of
specularity
Diffuse
region
B
G
R
B
G
R