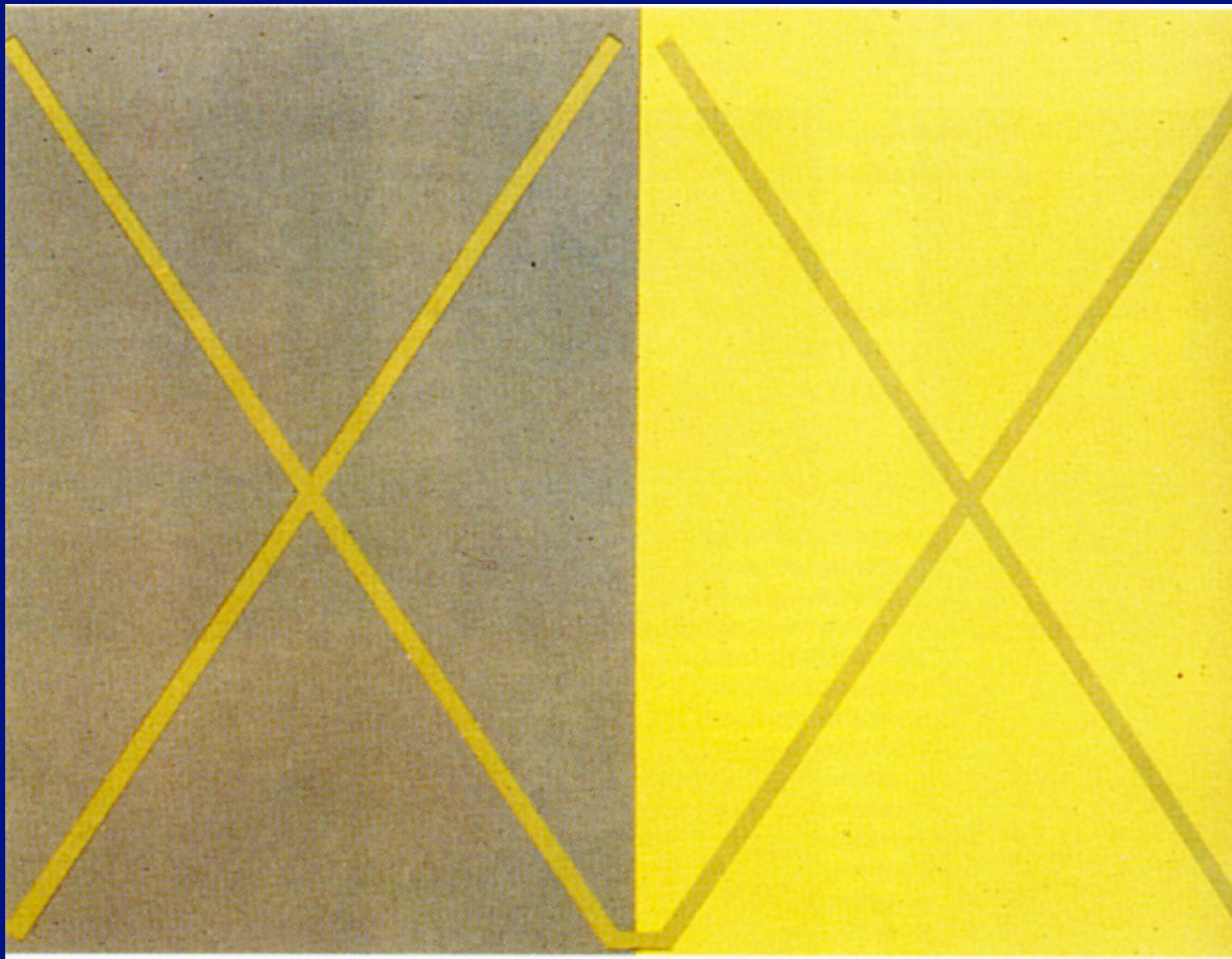
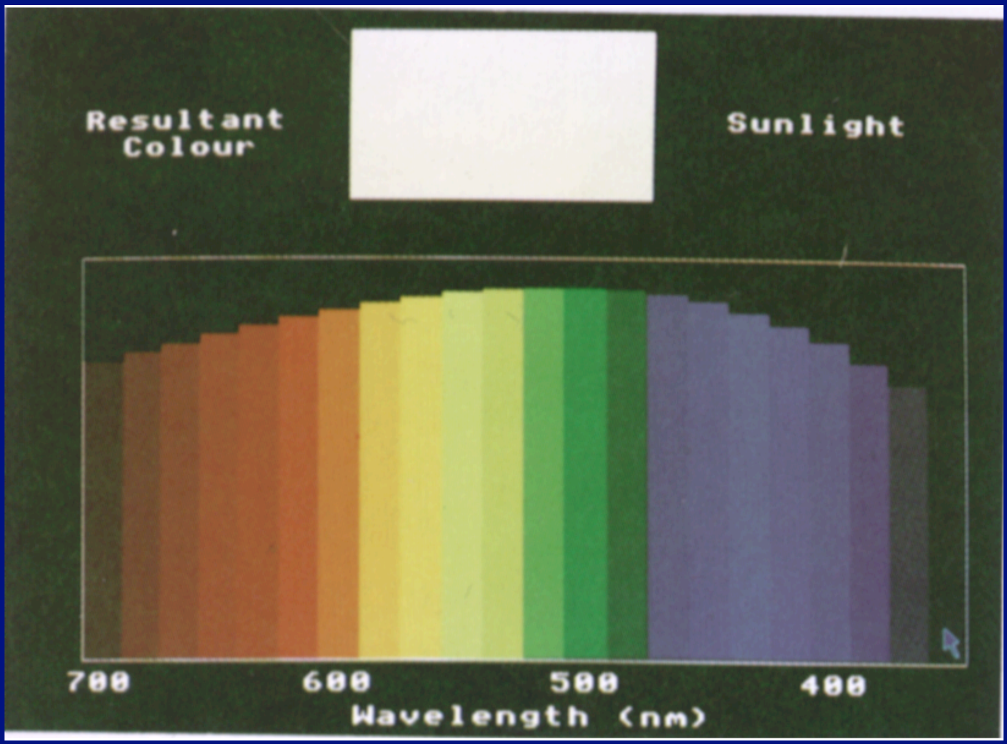
Causes of colour

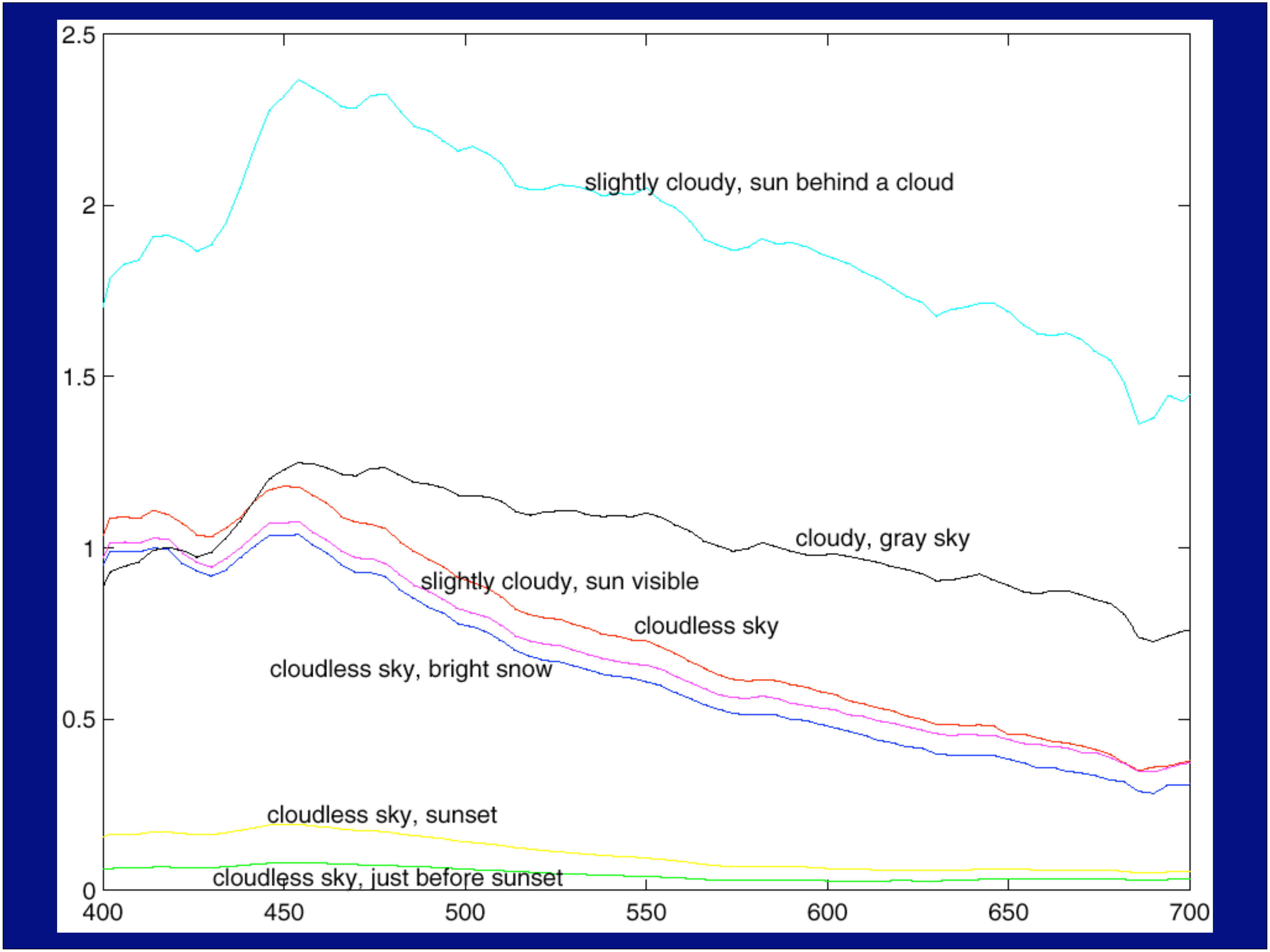
- The sensation of colour is caused by the brain.
- One way to get it is the response of the eye to the presence/absence of light at various wavelengths.
  - Dreaming, hallucination, etc.
  - Pressure on the eyelids
- Light could be
  - emitted with wavelengths absent (flourescent light vs. incandescent light)
  - differentially reflected - e.g. paint on a surface
  - differentially refracted - e.g. Newton's prism
  - subject to wavelength dependent specular reflection (most metals).
  - Flourescence -
    - invisible wavelengths absorbed and reemitted at visible wavelengths.
  - Phosphorescence (ditto, energy, longer timescale)

XXXXX	BLUE	YELLOW
XXXXX	GREEN	BLUE
XXXXX	RED	GREEN
XXXXX	YELLOW	RED
XXXXX	BLUE	YELLOW
XXXXX	RED	GREEN
XXXXX	GREEN	BLUE
XXXXX	BLUE	YELLOW
XXXXX	YELLOW	RED
XXXXX	RED	GREEN

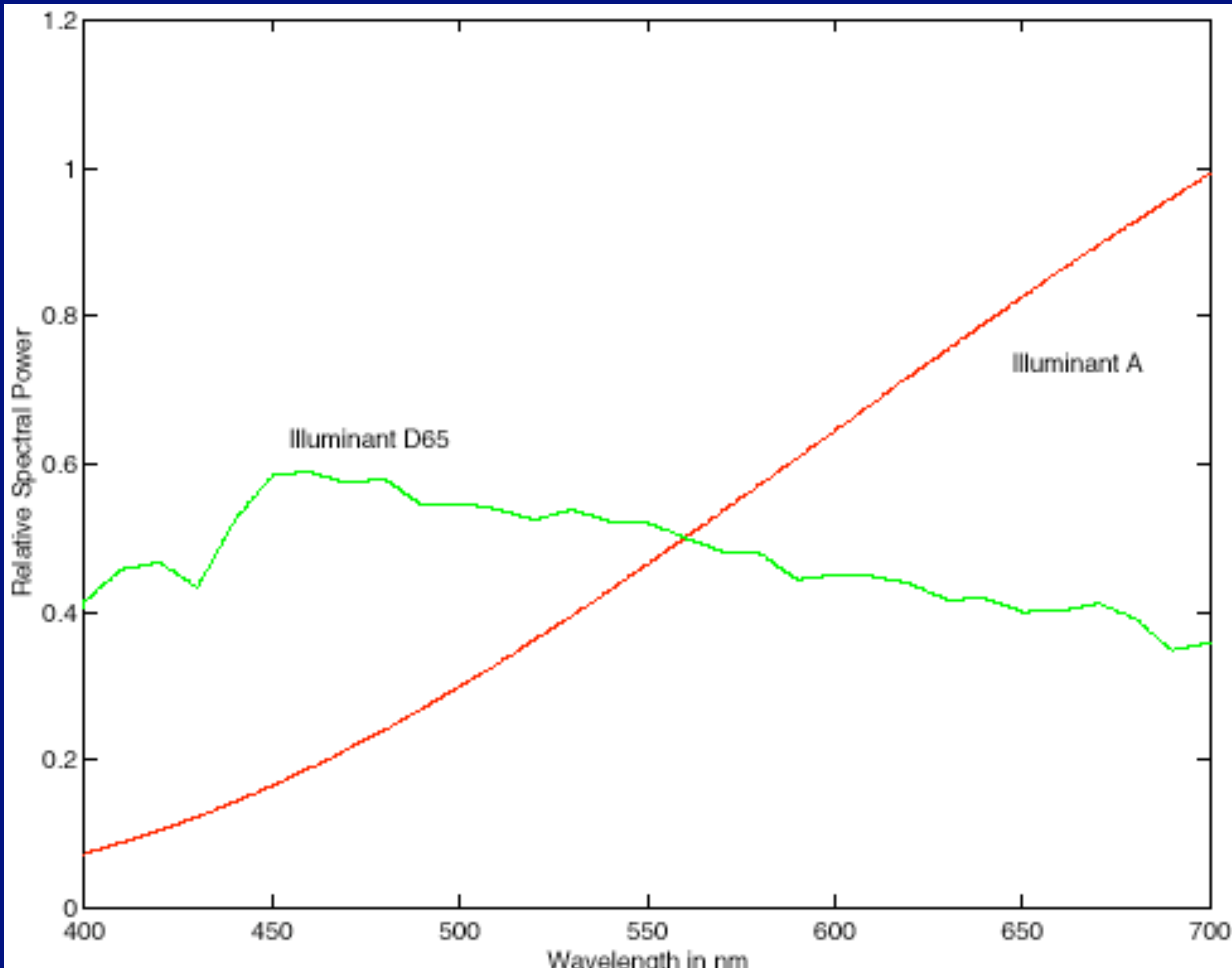


Sunlight

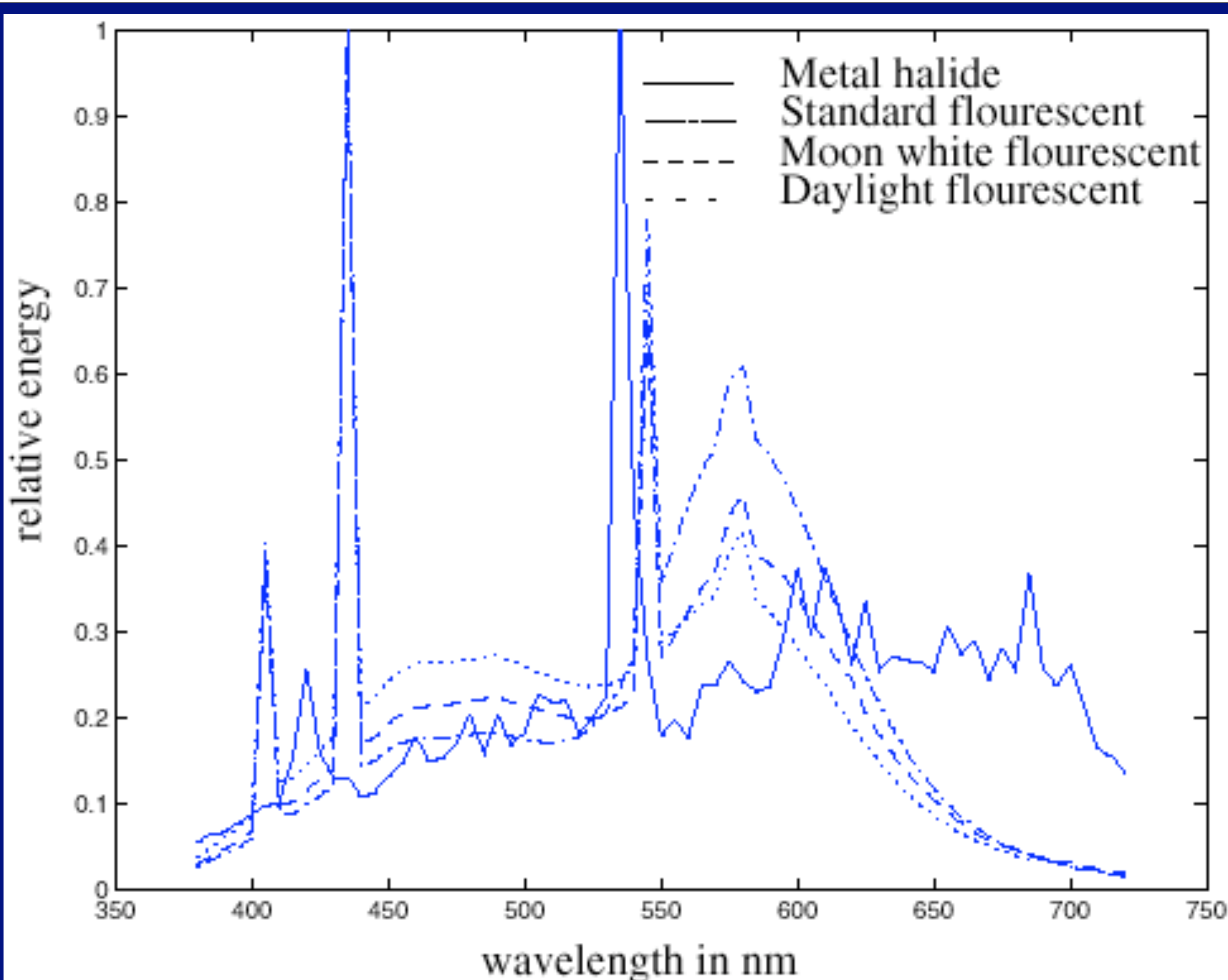


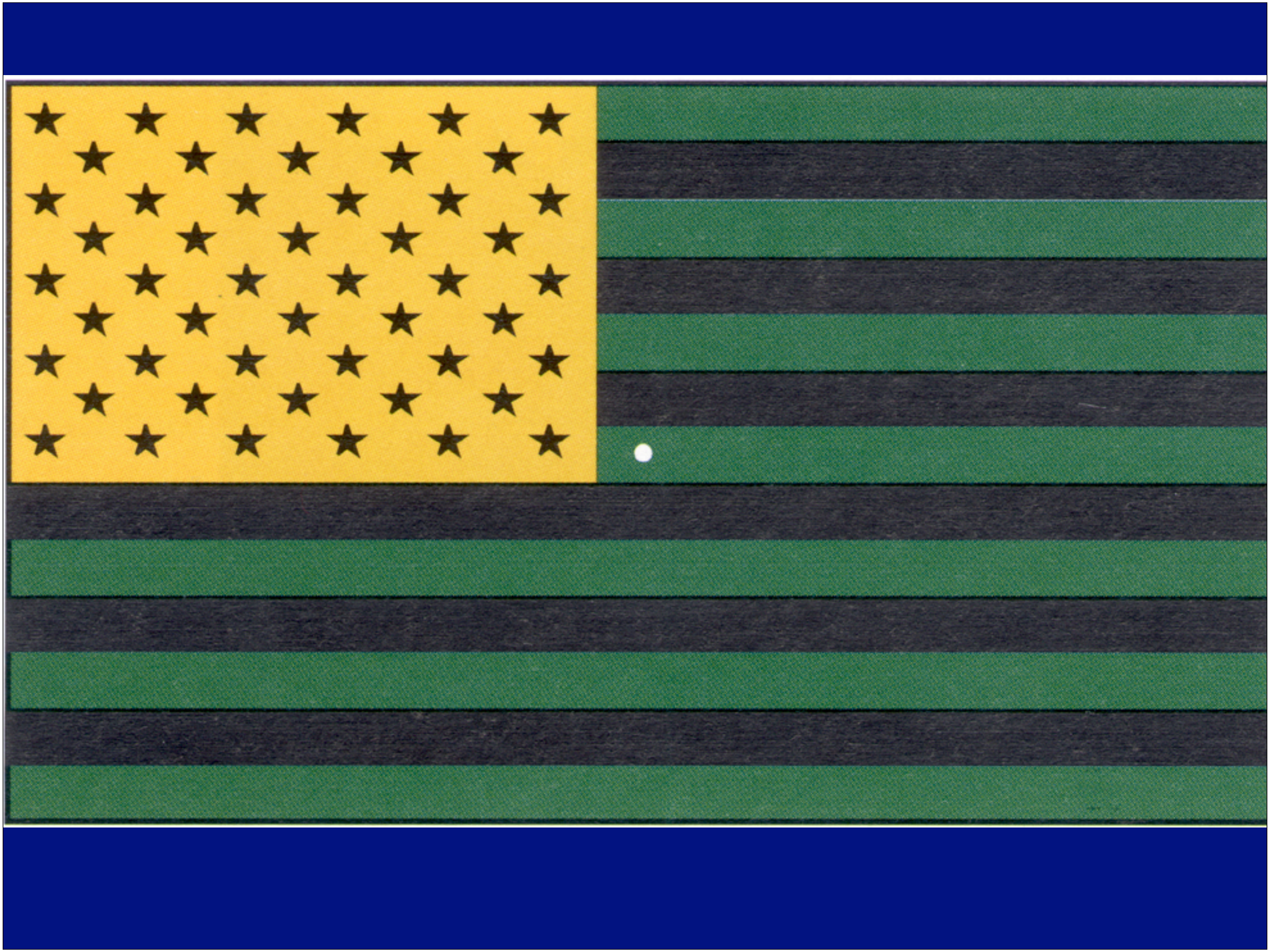


2.5
2
1.5
1
0.5
0
400
450
500
550
600
650
700
slightly cloudy, sun behind a cloud
cloudy, gray sky
slightly cloudy, sun visible
cloudless sky
cloudless sky, bright snow
cloudless sky, sunset
cloudless sky, just before sunset



1.2
1
0.8
0.6
0.4
0.2
0
Relative Spectral Power
400
450
500
550
600
650
700
Wavelength in nm
Illuminant A
Illuminant D65


Metal halide
Standard flourescent
Moon white flourescent
Daylight flourescent
relative energy
wavelength in nm
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
350
400
450
500
550
600
650
700
750



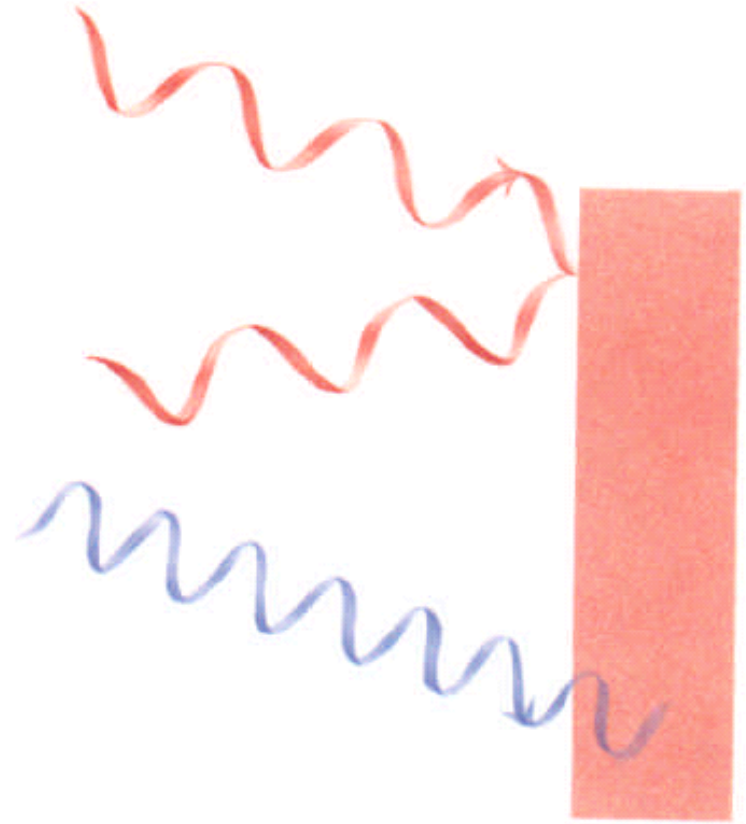


Fig. 1.18 Reflection: red light bounces off an opaque red object, while light of other colours is absorbed.

from "Colour in nature", P. Farrant

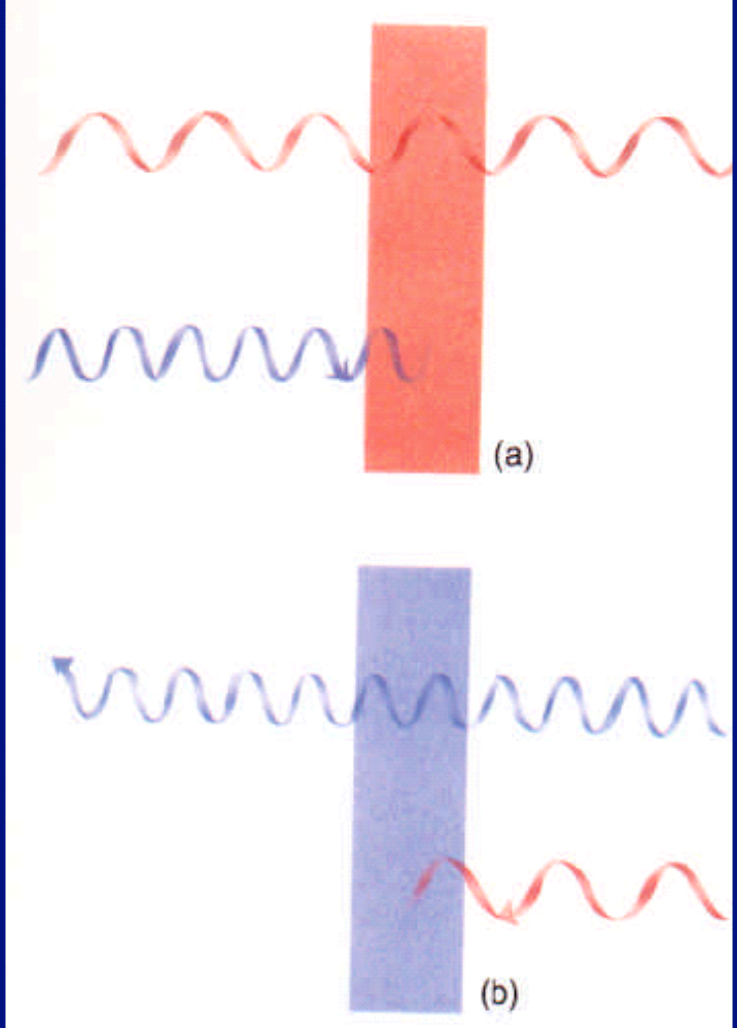


Fig. 1.17 Absorption: a red transparent medium absorbs all wavelengths of light except red (a); a blue transparent medium absorbs all wavelengths except blue (b)

from "Colour in nature", P. Farrant

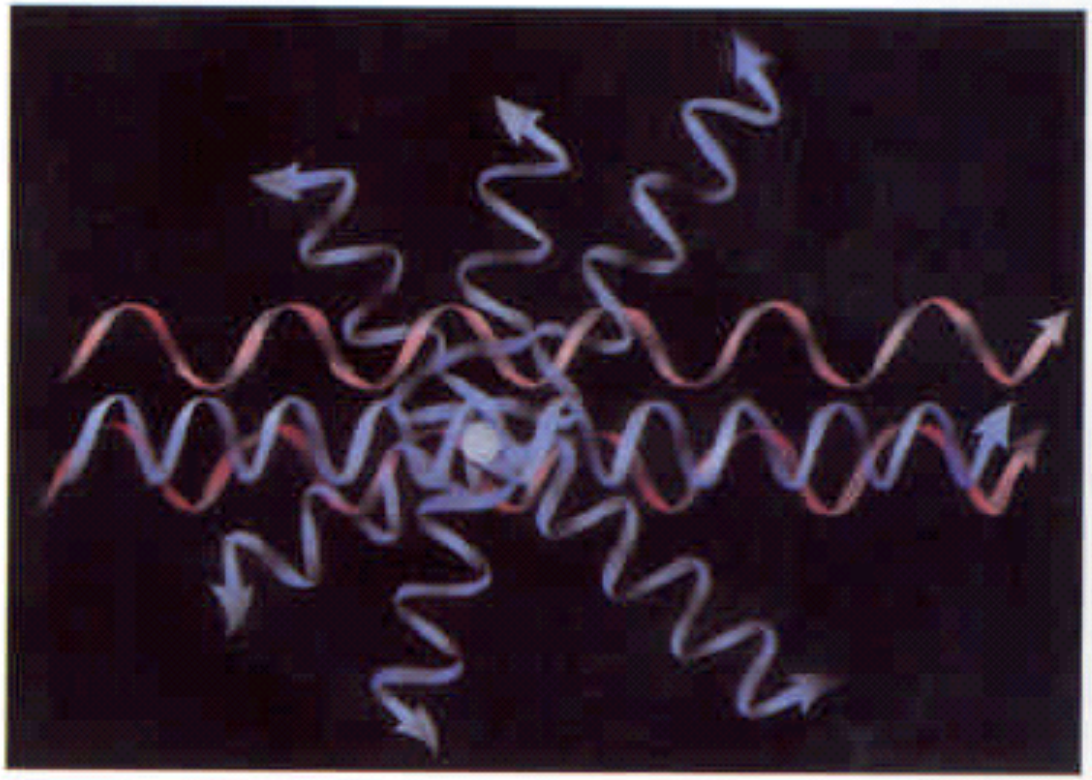


Fig. 1.25 Rayleigh scattering: when particles in air or water are small relative to light wavelength they scatter blue light preferentially.

from “Colour in nature”, P. Farrant

from “Colour in nature”, P. Farrant

from “Colour in nature”, P. Farrant

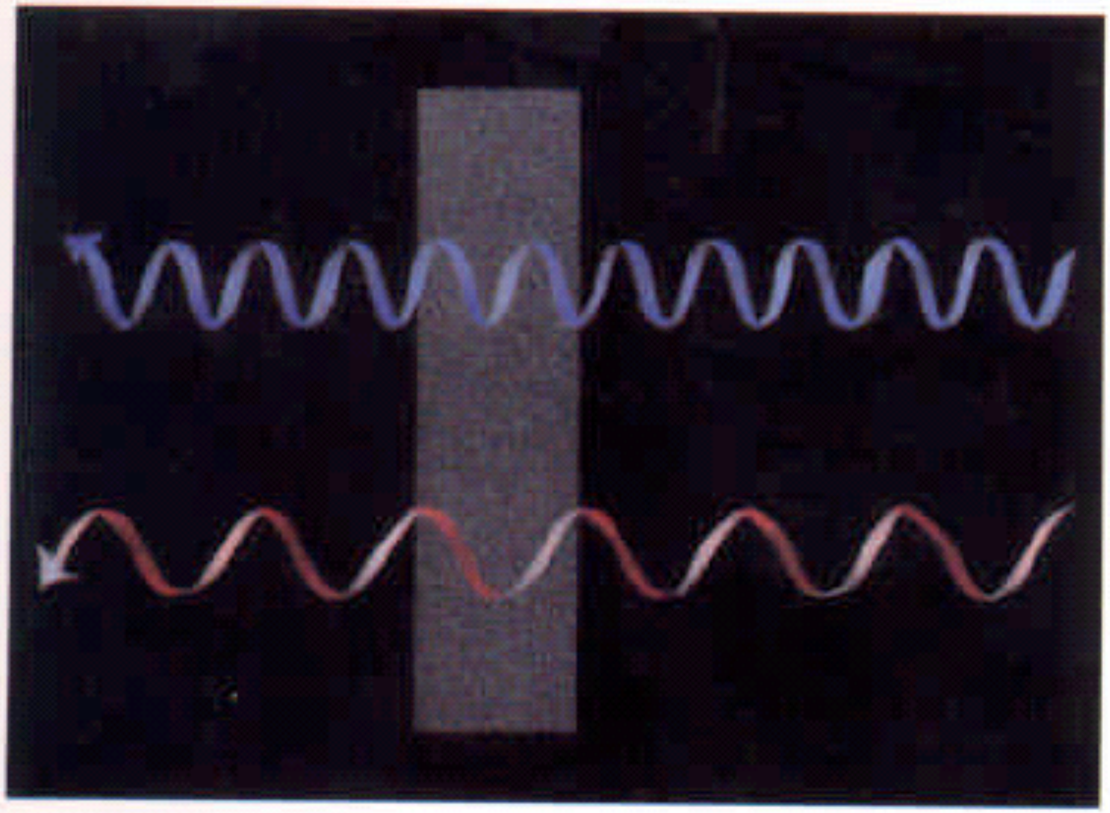


Fig. 1.16 Transmission: light waves of all colours pass through a colourless transparent medium.

from "Colour in nature", P. Farrant

from “Colour in nature”, P. Farrant

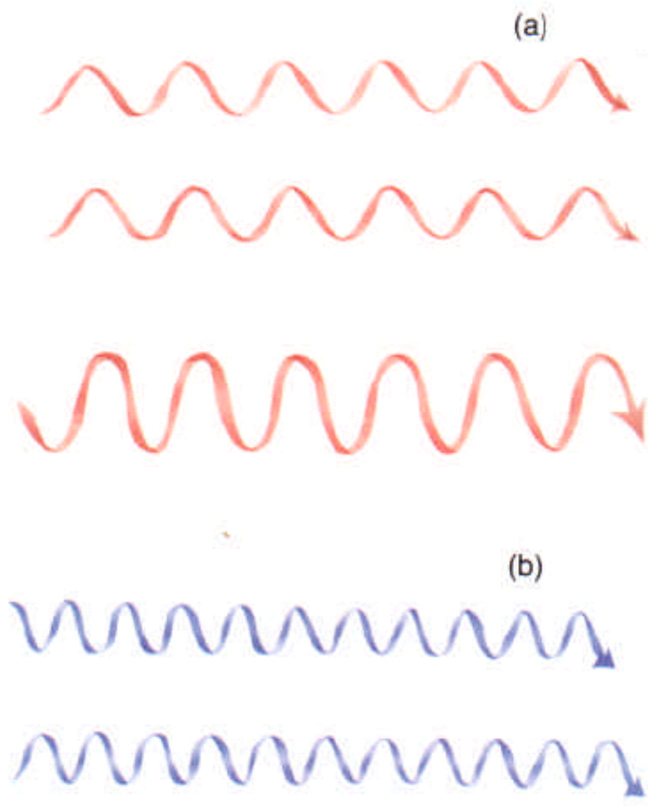


Fig. 1.20 Interference: when two light waves are in phase, they interfere positively to reinforce each other and produce a wave with double the intensity of colour (a). When two waves are out of phase they cancel each other and no colour is seen (b).

from "Colour in nature", P. Farrant

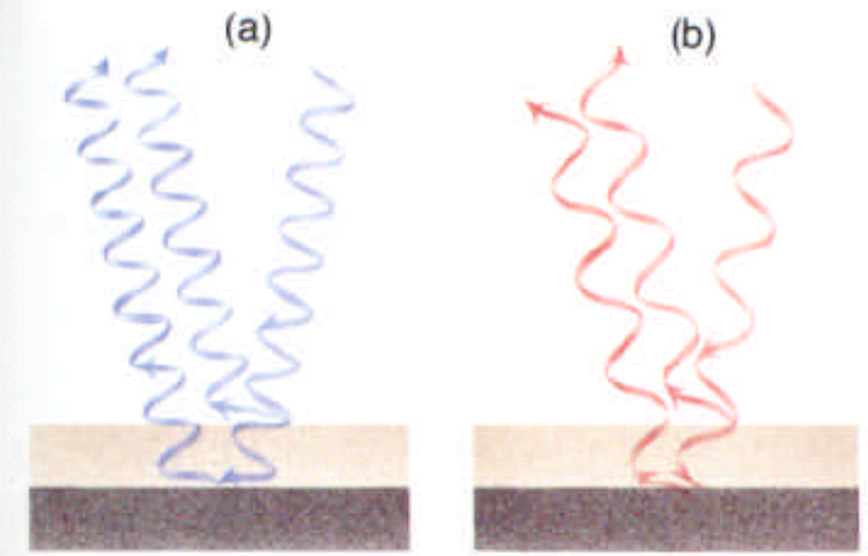
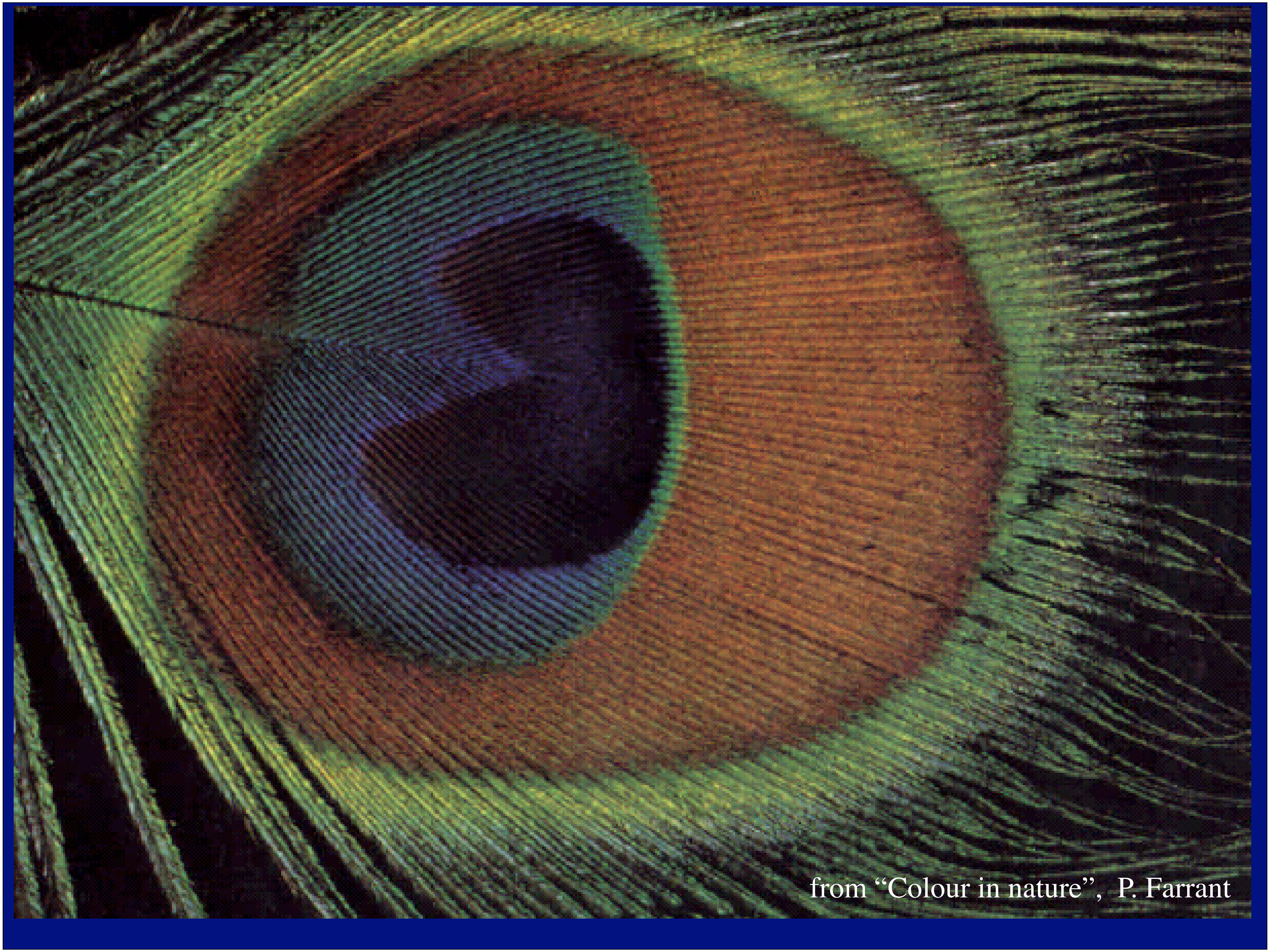


Fig. 1.22 Iridescence: when a light wave is partially reflected and partially transmitted at the surface of a thin layer of transparent material (e.g. a bubble), the two parts of the original wave may interfere with each other when the transmitted wave is reflected from a lower layer and re-emerges at the surface. In this case the blue waves are in phase and their colour is reinforced (a) but the red waves are out of phase and their colour is cancelled (b).

from “Colour in nature”, P. Farrant

from “Colour in nature”, P. Farrant


from “Colour in nature”, P. Farrant

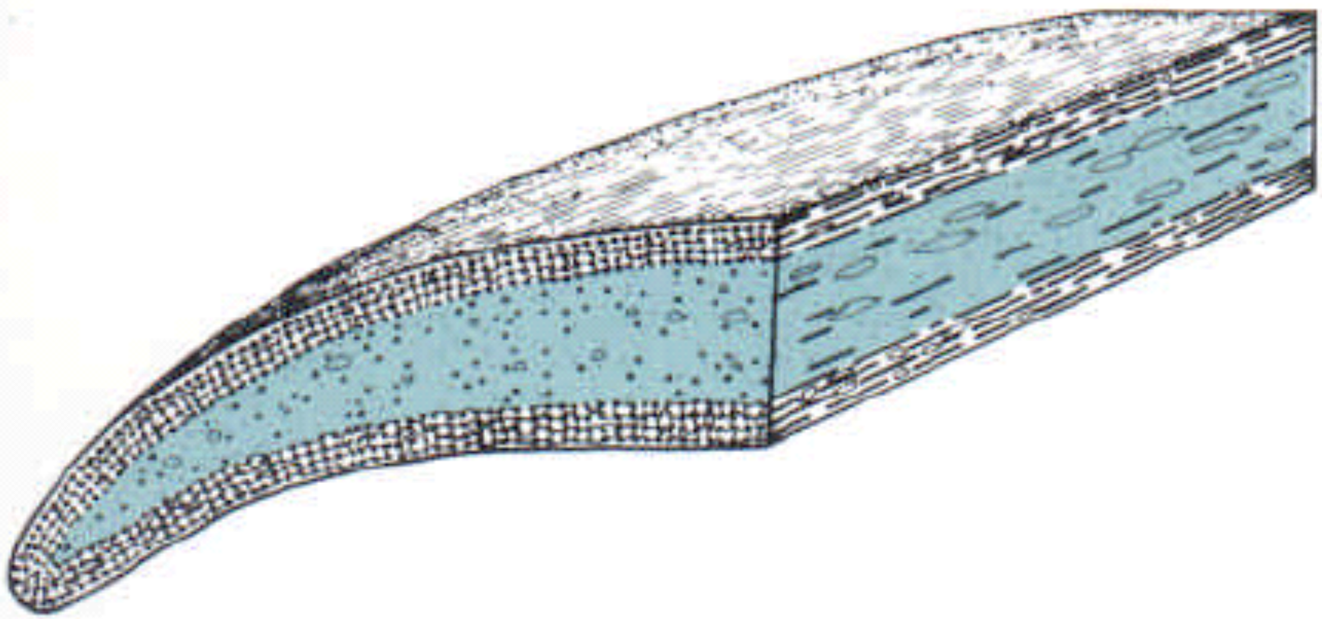


Fig. 10.1 The iridescence-producing structure of peacock feathers comprises evenly spaced melanin rods and air spaces, embedded in keratin.

from "Colour in nature", P. Farrant

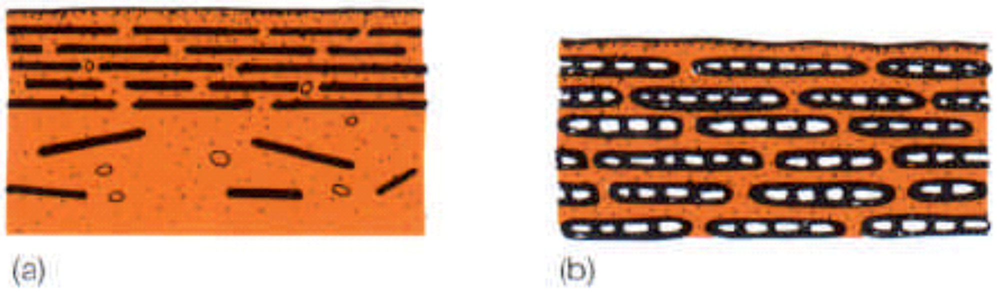


Fig. 10.2 The iridescence-producing structure of (a) sunbirds' feathers comprises layers of solid melanin platelet embedded in keratin, whereas that of (b) hummingbirds' consists of hollow melanin-line flat discs, also embedded in keratin.

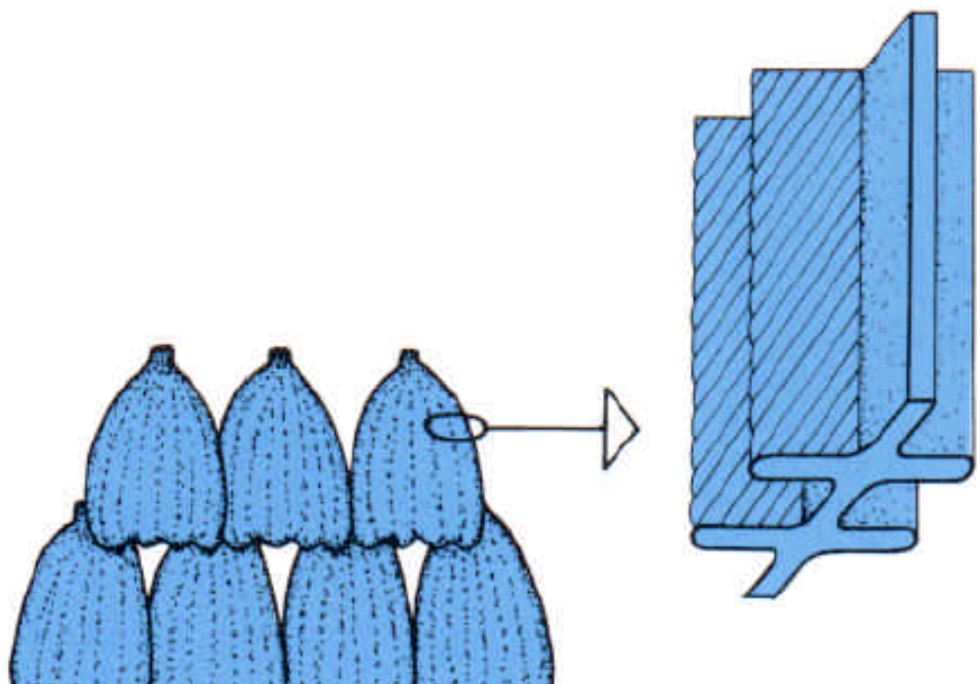
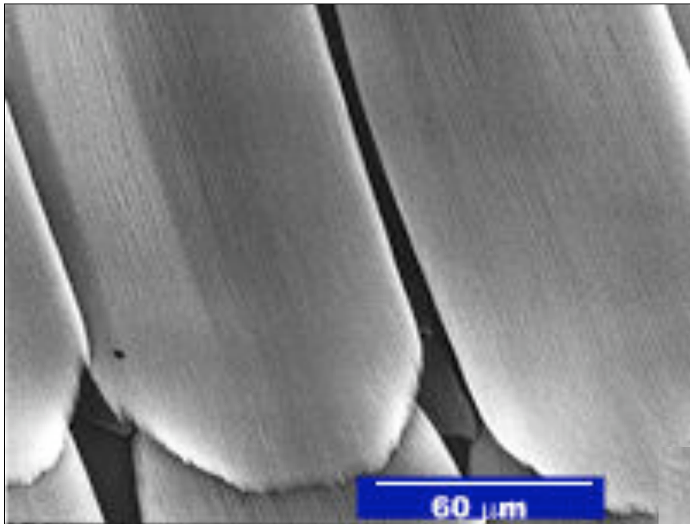
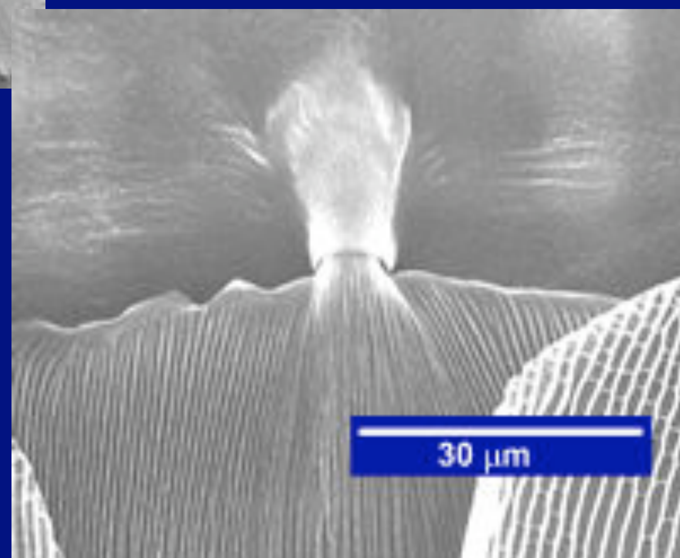
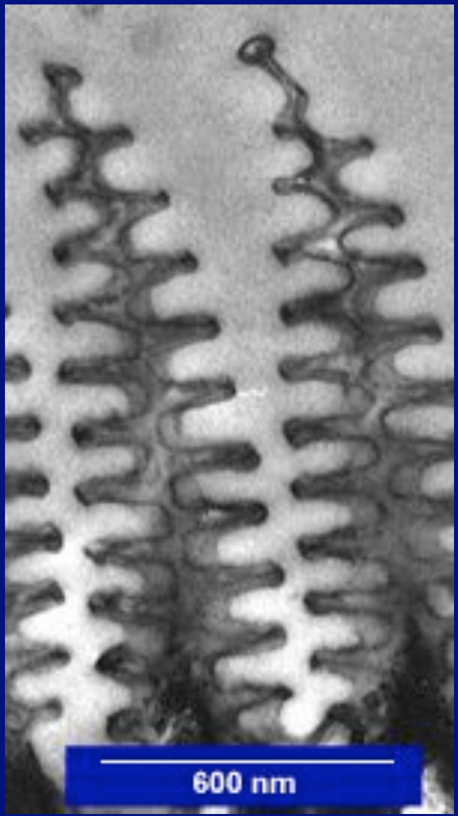


Fig. 10.3 Iridescence in morph butterflies is due to sloping layers within ridges on the win

from "Colour in nature", P. Farrant


60 µm


30 µm


600 nm

PL. 10.3 Melanin platelets between layers of keratin provide the structural basis of iridescence in sunbirds. *Photo W. Farrant*

from “Colour in nature”, P. Farrant

PL. 10.5 In pigeons, relatively large granules of melanin produce some interference colours.
Photo: P. Farrant.

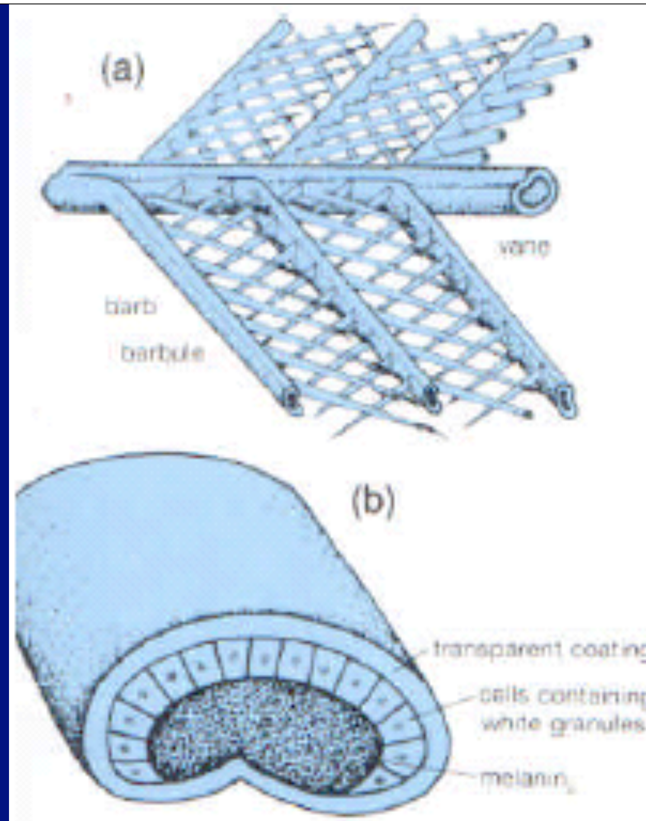
from "Colour in nature", P. Farrant

PL. 10.2 Goatfish with iridescent eyes; light is reflected from regular layers of guanine particles.

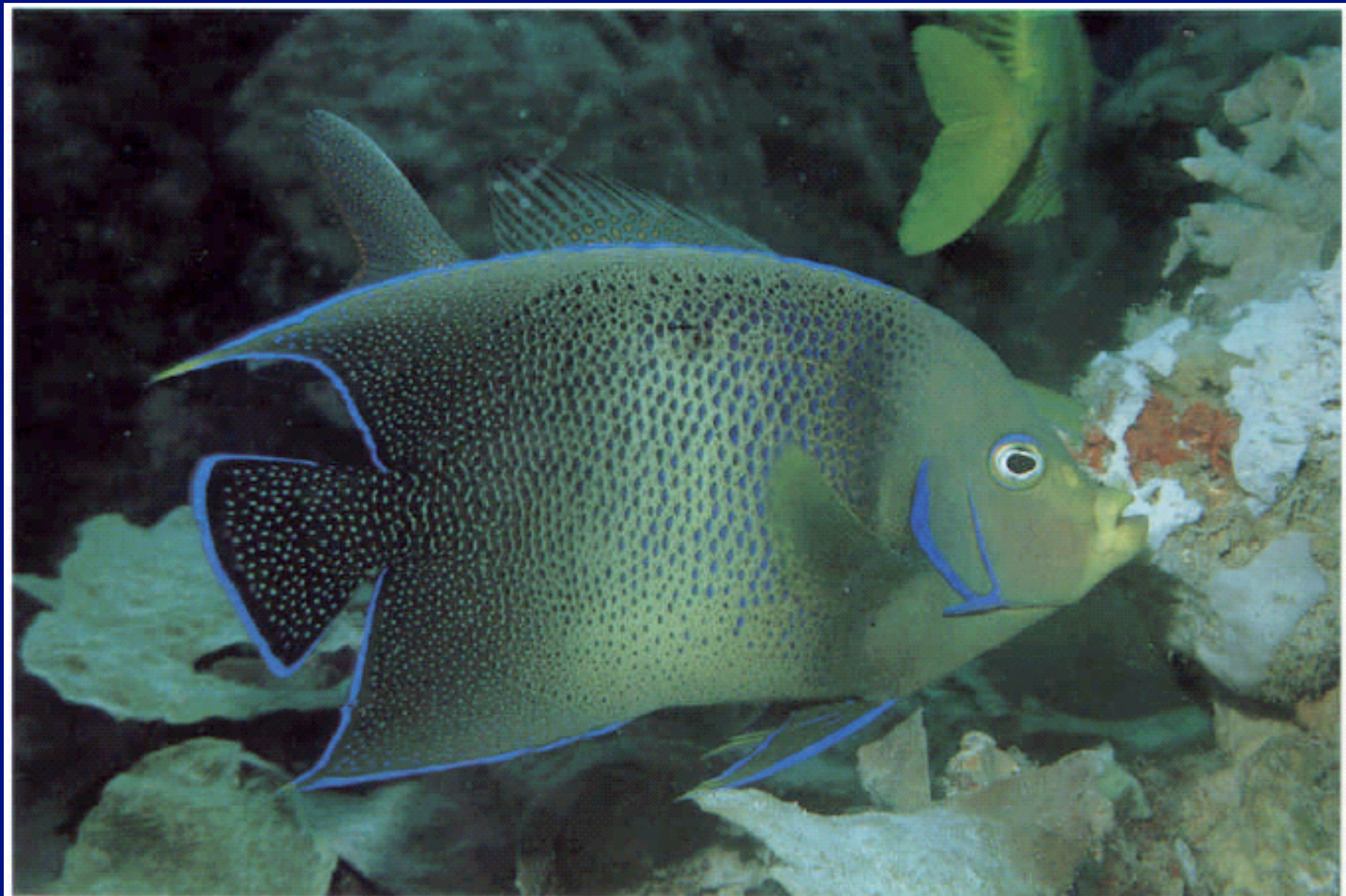
from “Colour in nature”, P. Farrant

Scattering (again)
causing Tyndall
Blue

(notice because scattering
occurs at an interface,
all media could be translucent
e.g. fresh snow)



ig. 10.4 (a) Feather structure of
blue bird.
b) Section through blue
arbule: Tyndall blue is a
tructural colour caused by
cattering of blue wavelengths
y microscopic particles in the
uter layer of cells. Inside the
ather there is a dark melanin
acking.



from “Colour in nature”, P. Farrant

from “Colour in nature”, P. Farrant

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
- Radiosity --- spectral radiosity

Color: film color mode

- 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 colour looks like a film in space; controls for nearby colors, and state of mind.
    - Other modes:
      - Surface colour
      - Volume colour
      - Mirror colour
      - Illuminant colour

Trichromacy

- 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.

Why specify color numerically?

- Accurate color reproduction is commercially valuable
  - e.g. Kodak yellow, painting a house.
- Of the order of 10 color names are widely recognized by English speakers - other languages have fewer/more, but not much more.
  - There's a great deal of structure to the way colour is spoken about (Berlin-Kay), but not much precision
- Color reproduction problems increased by prevalence of digital imaging - eg. digital libraries of art.
  - Choosing pixel values to reproduce/evoke experiences, e.g. an architectural model.
  - Consistency in user interfaces, monitor-printer consistency, monitor-lino consistency, etc.

Additive and subtractive matching

- Choose colors A, B, C such that no two can be mixed to match the third - Primaries.
  - Many colors can be represented as a mixture of A, B, C write M=a A + b B + c C
  - 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.
- • 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

Grassman's Laws

- For colour matches made in film colour mode:

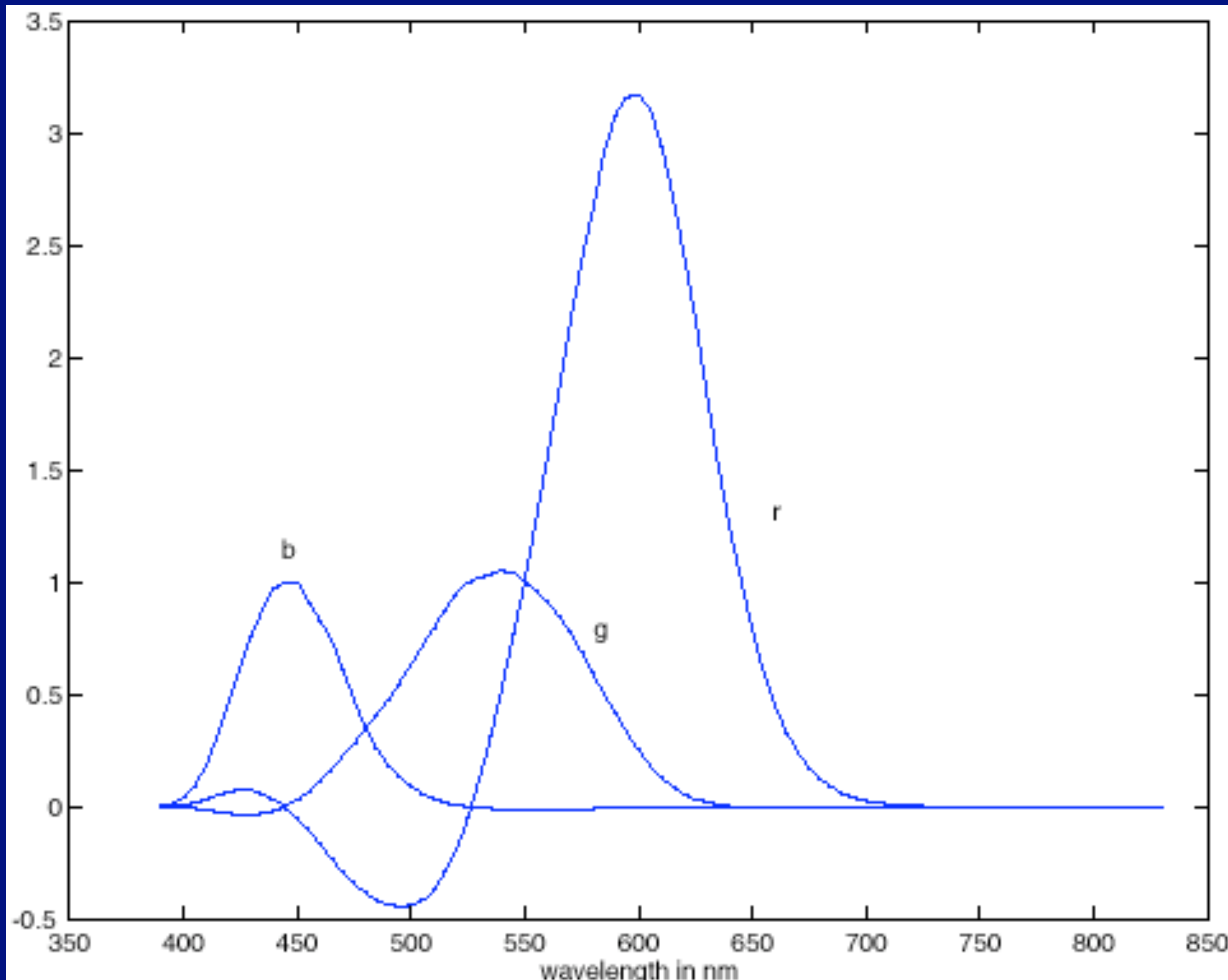
- symmetry: A=B <=>B=A
- transitivity: A=B and B=C => A=C
- proportionality: A=B <=> tA=tB
- additivity: if any two (or more) of the statements
  - A=B,
  - C=D,
  - (A+C)=(B+D) are true, then so is the third

Color matching functions

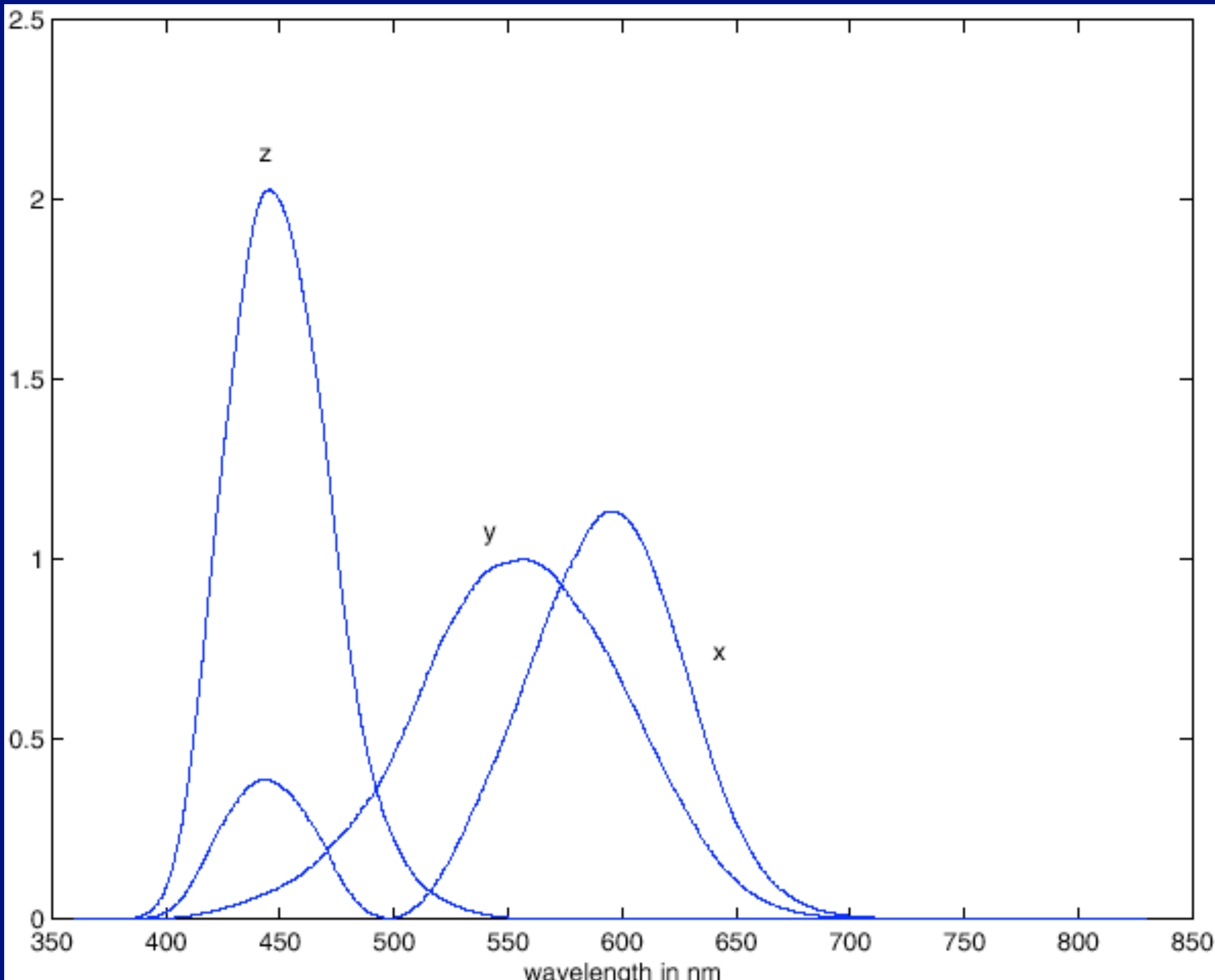
- Choose primaries, say A, B, C
- Given energy function, E
  - What amounts of primaries will match it?
  - For each wavelength, determine how much of A, of B, and of C is needed to match light of that wavelength alone.
  - Now match each wavelength in E, and sum

Color spaces

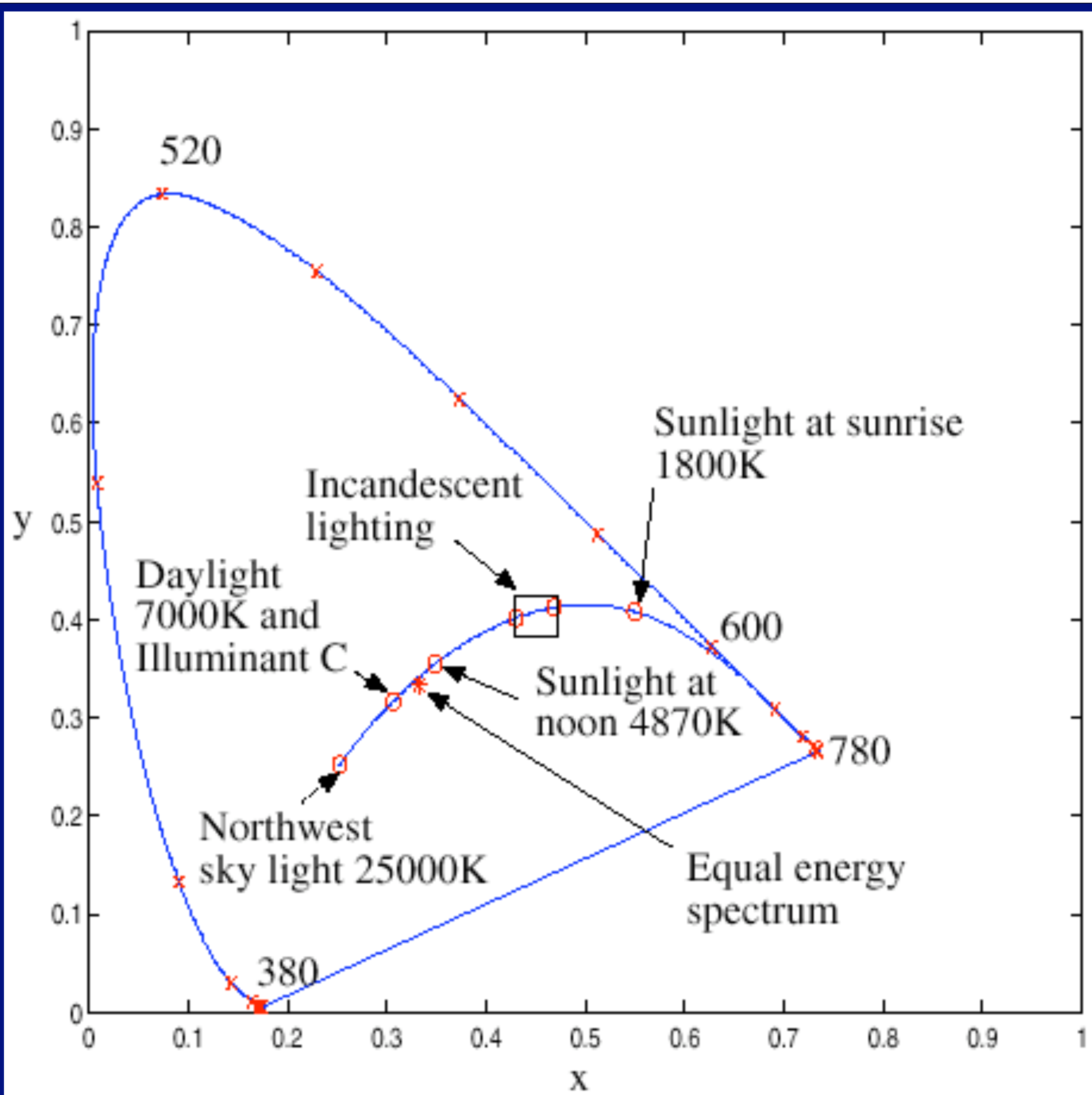
- Linear color spaces
  - describe colors as linear combinations of primaries
  - Choice of primaries=choice of color matching functions=choice of color space
  - Color matching functions all within linear transformations
- RGB:
  - primaries are monochromatic,645.2nm, 526.3nm, 444.4nm.
  - Color matching 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 $x=X/(X+Y+Z)$, $y=Y/(X+Y+Z)$



3.5
3
2.5
2
1.5
1
0.5
0
-0.5
350
400
450
500
550
600
650
700
750
800
850
wavelength in nm
b
g
r

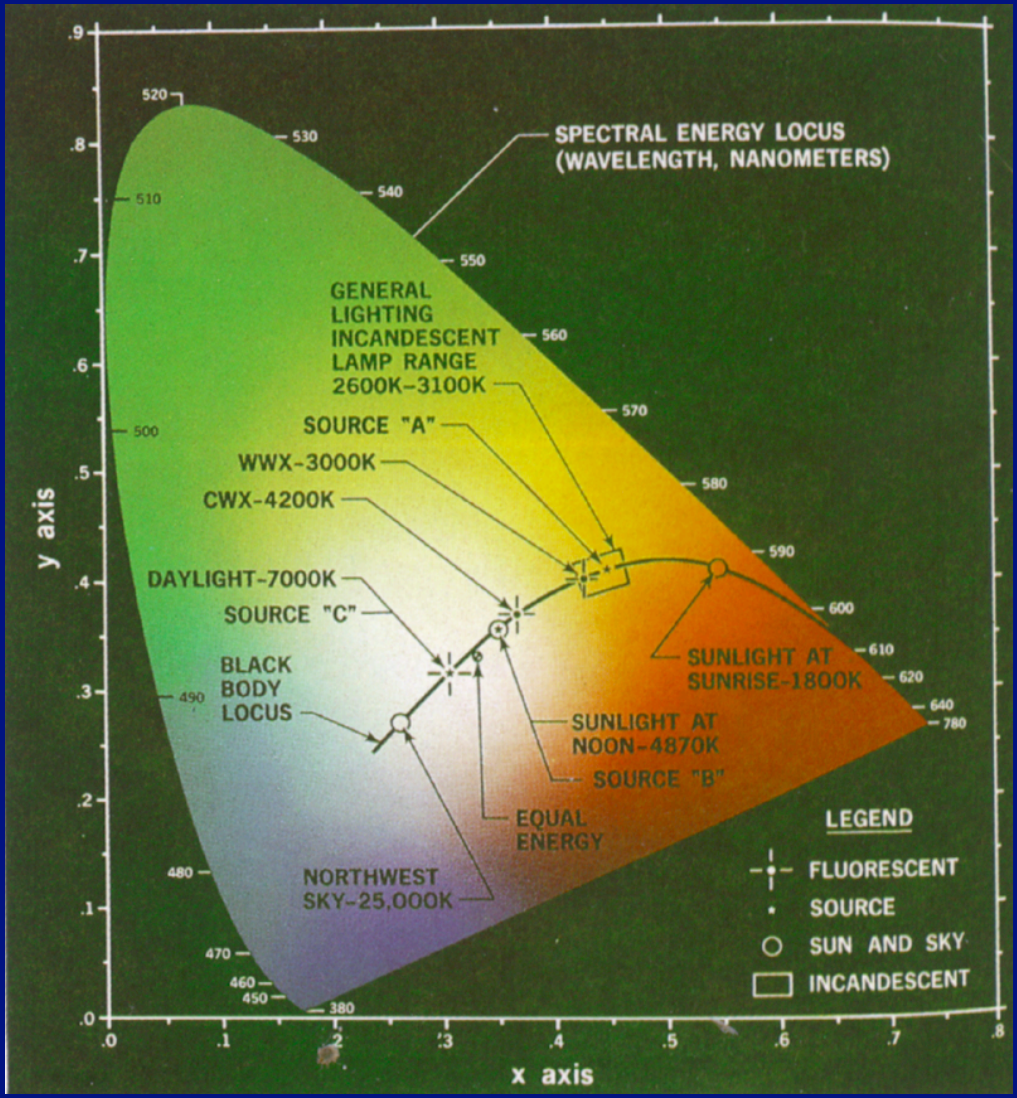


2.5
2
1.5
1
0.5
0
350
400
450
500
550
600
650
700
750
800
850
wavelength in nm
z
y
x



520
600
780
380
Sunlight at sunrise 1800K
Incandescent lighting
Daylight 7000K and Illuminant C
Sunlight at noon 4870K
Northwest sky light 25000K
Equal energy spectrum
y
x
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

CIE x, y

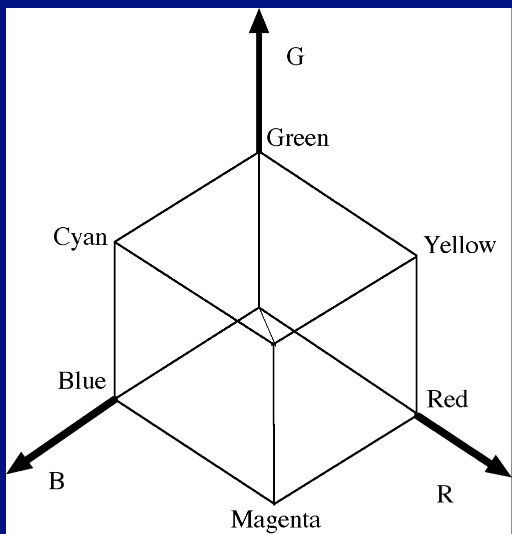


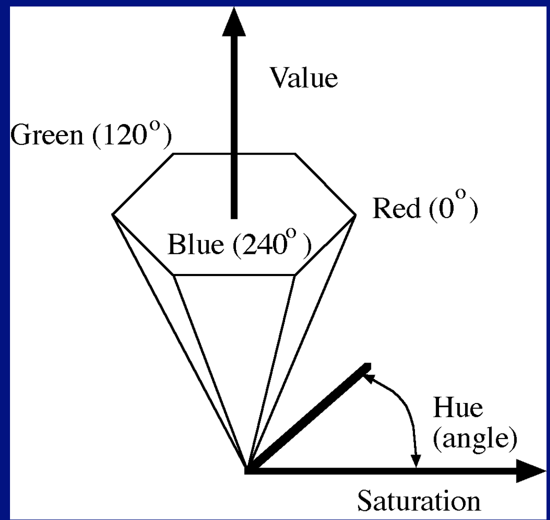
SPECTRAL ENERGY LOCUS
(WAVELENGTH, NANOMETERS)
GENERAL
LIGHTING
INCANDESCENT
LAMP RANGE
2600K-3100K
SOURCE "A"
WWX-3000K
CWX-4200K
DAYLIGHT-7000K
SOURCE "C"
BLACK
BODY
LOCUS
SUNLIGHT AT
SUNRISE-1800K
SUNLIGHT AT
NOON-4870K
SOURCE "B"
EQUAL
ENERGY
NORTHWEST
SKY-25,000K
LEGEND
FLUORESCENT
SOURCE
SUN AND SKY
INCANDESCENT
520
530
510
540
550
560
570
500
580
590
600
610
620
640
780
490
480
470
460
450
380
y axis
x axis
.9
.8
.7
.6
.5
.4
.3
.2
.1
.0
.0
.1
.2
.3
.4
.5
.6
.7
.8

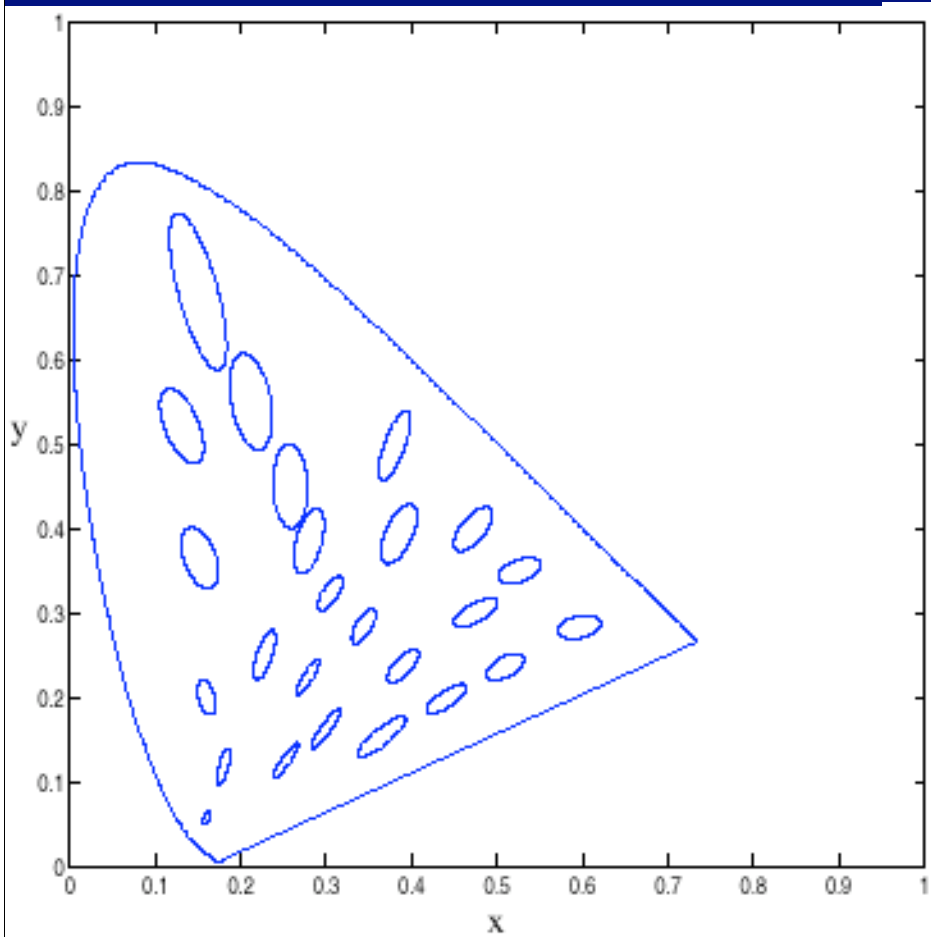
Non-linear colour spaces

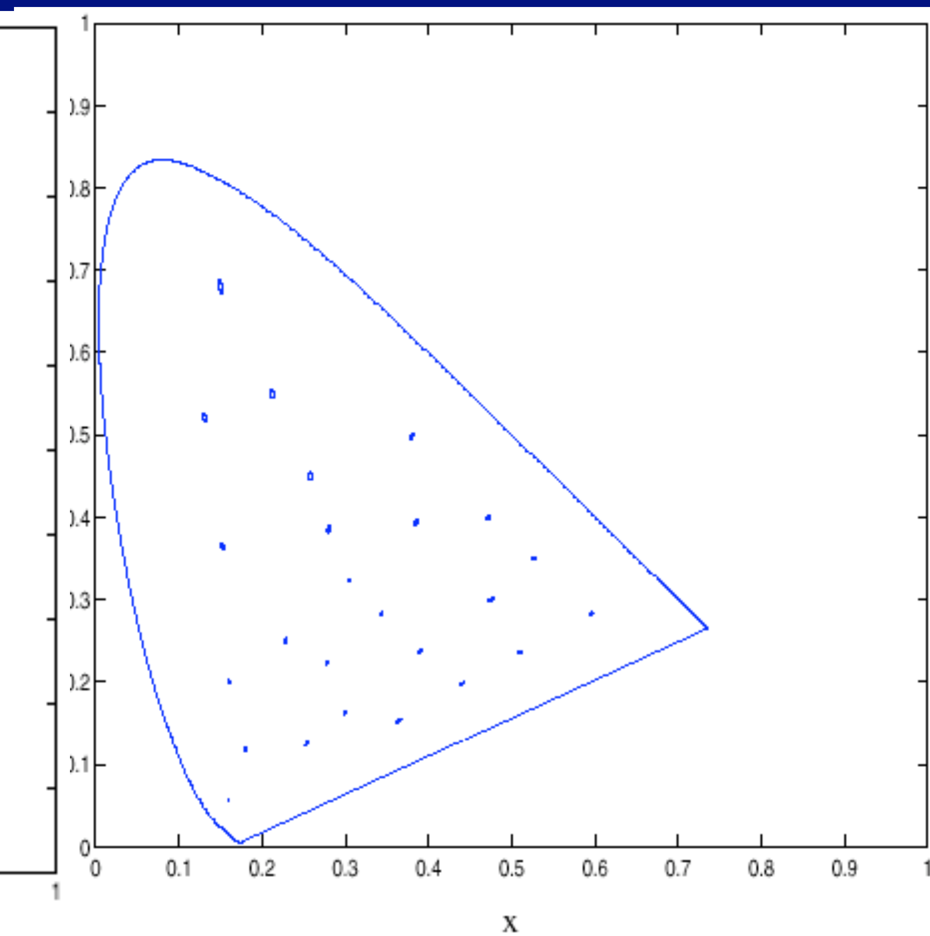
- HSV: Hue, Saturation, Value are non-linear functions of XYZ.
  - because hue relations are naturally expressed in a circle
- Uniform: equal (small!) steps give the same perceived color changes.
- Munsell: describes surfaces, rather than lights - less relevant for graphics. Surfaces must be viewed under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

HSV hexcone

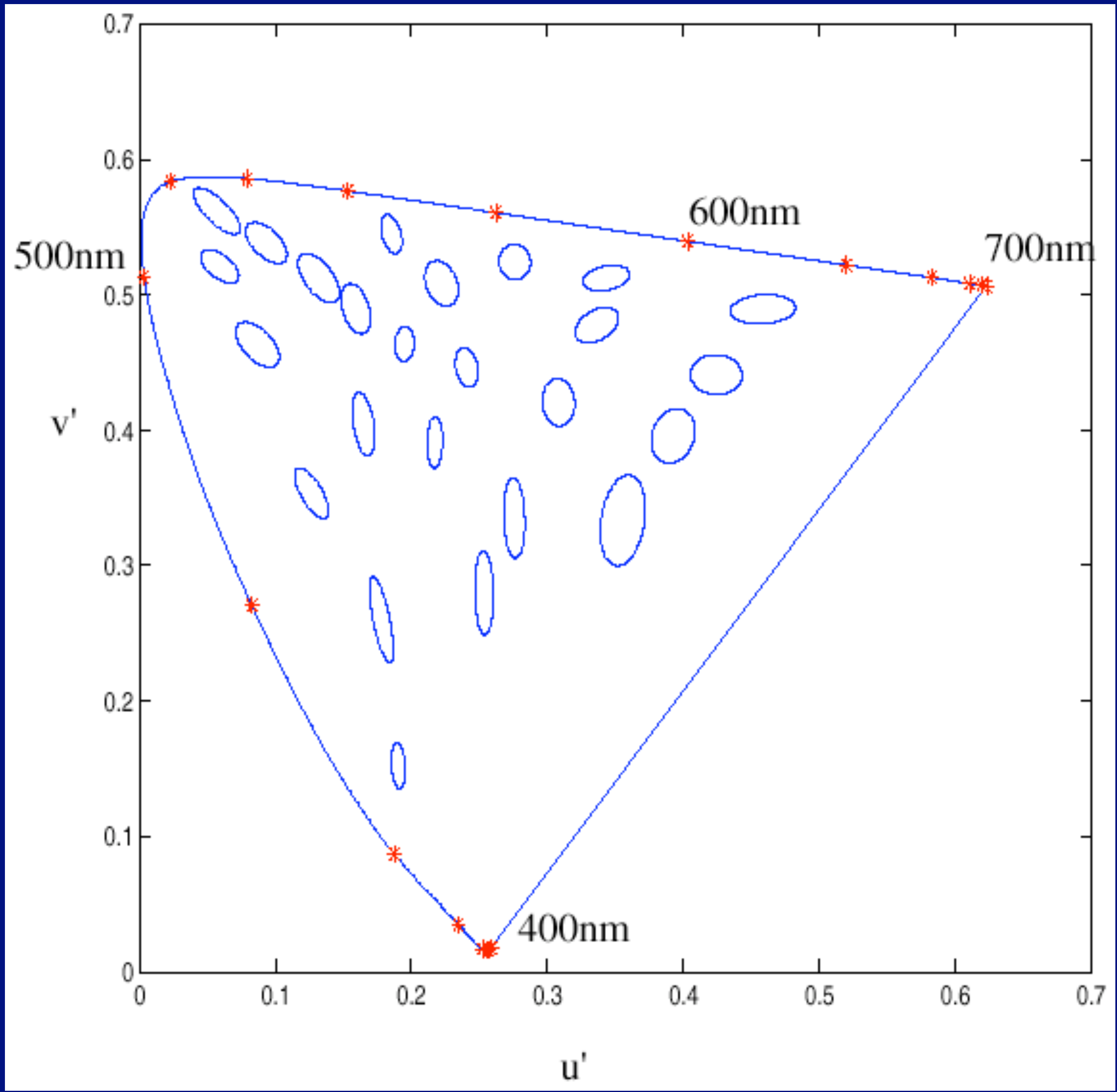

G
Green
Cyan
Yellow
Blue
Red
B
R
Magenta


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

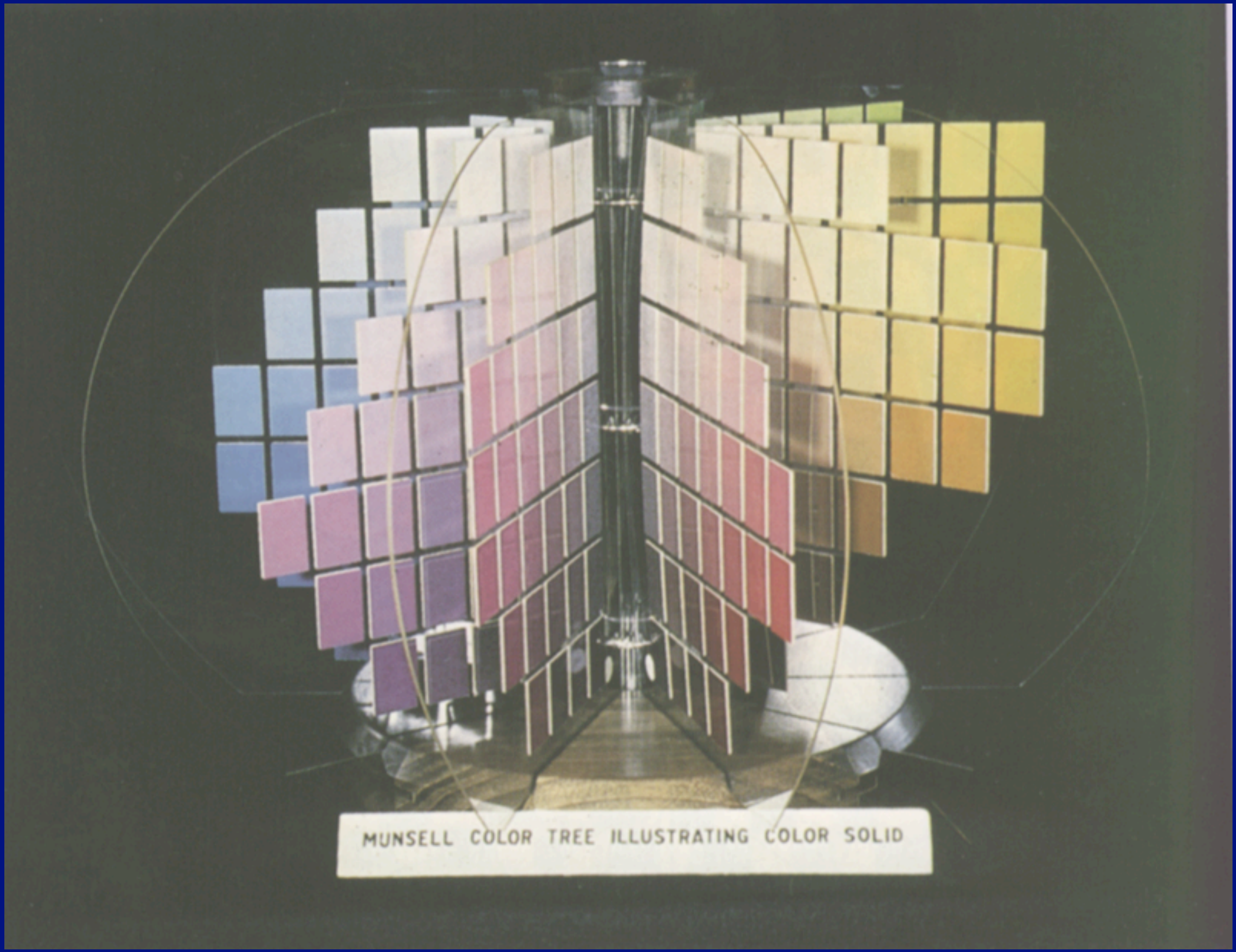

y
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
x
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1


0
).1
).2
).3
).4
).5
).6
).7
).8
).9
1
x
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

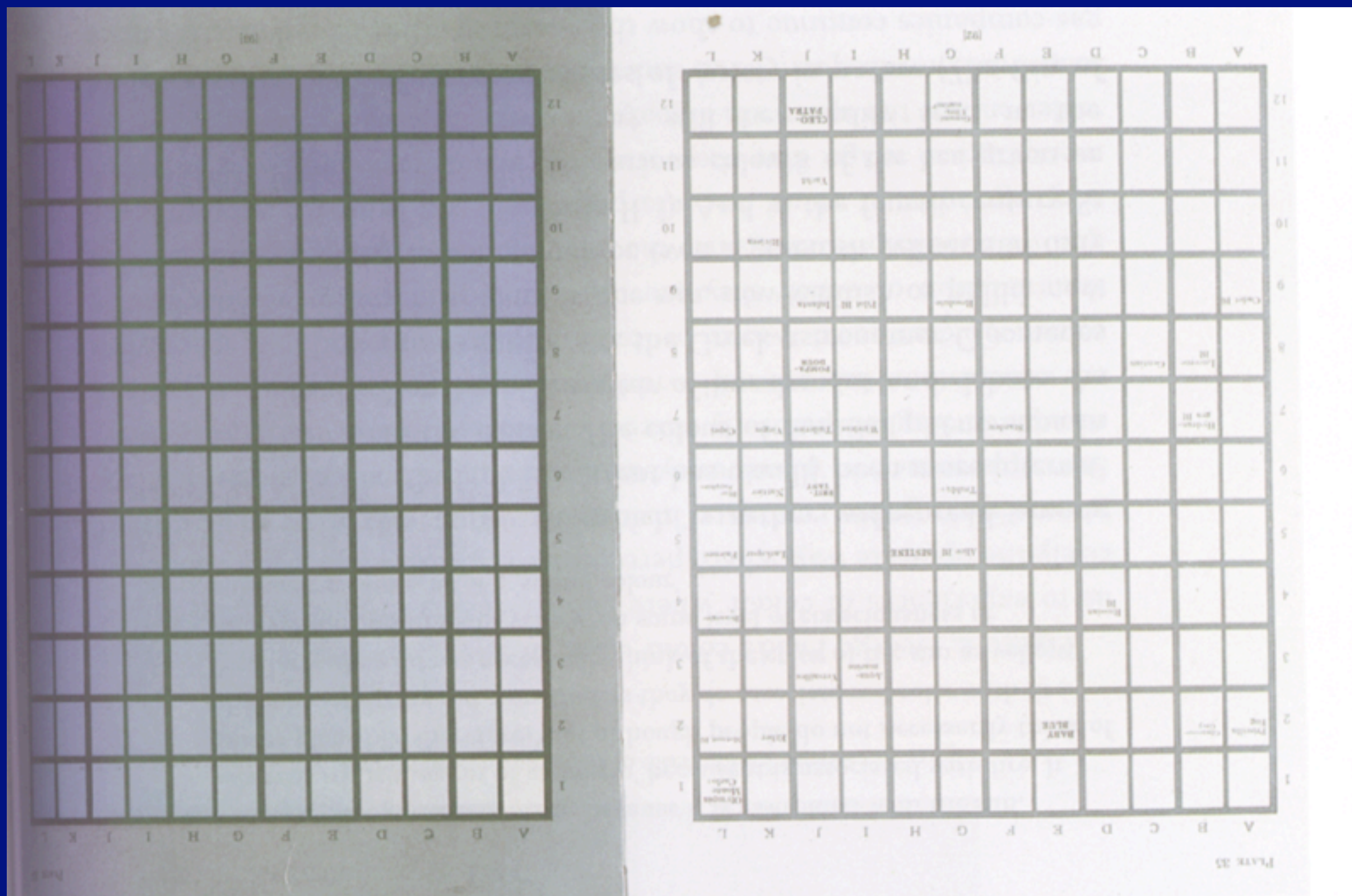
CIE u'v' which is a projective transform of x, y



Munsell color space



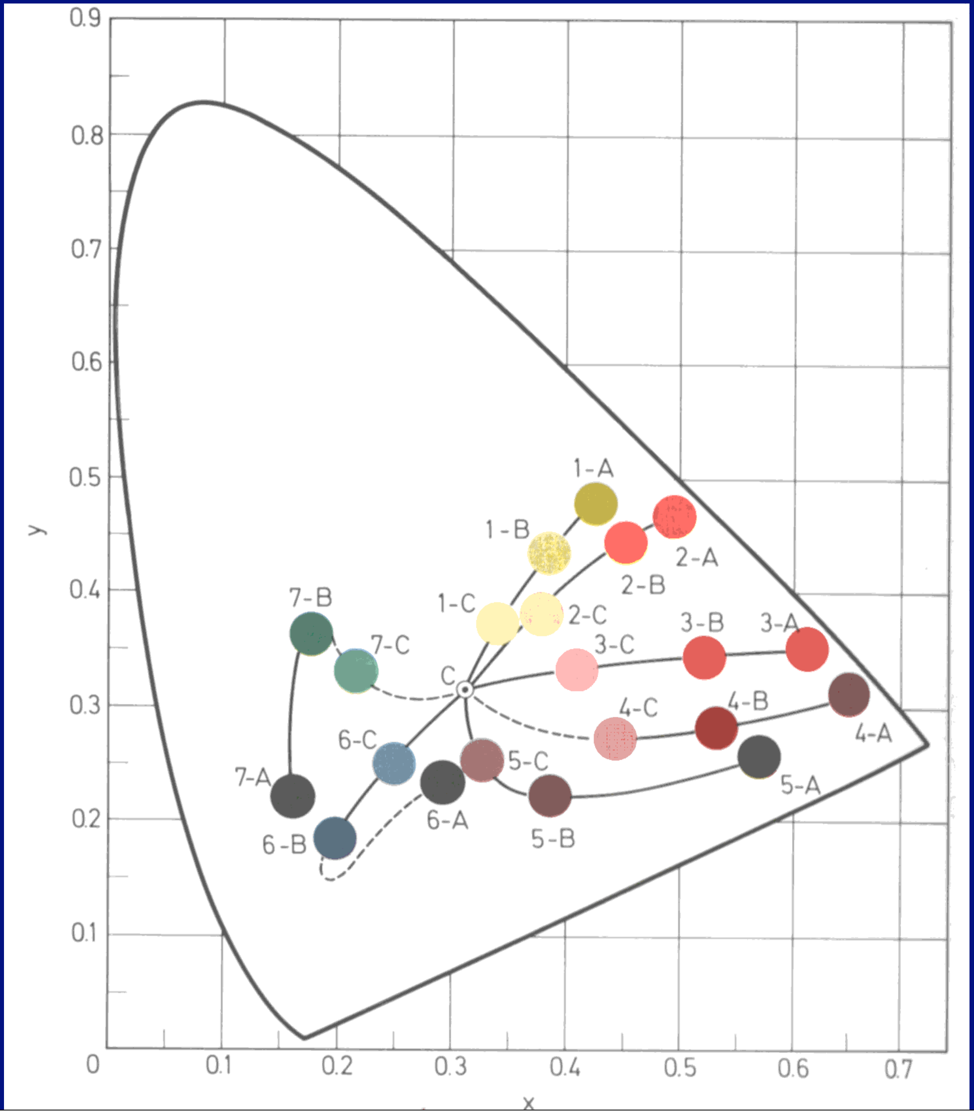
Color books



Subtractive mixing

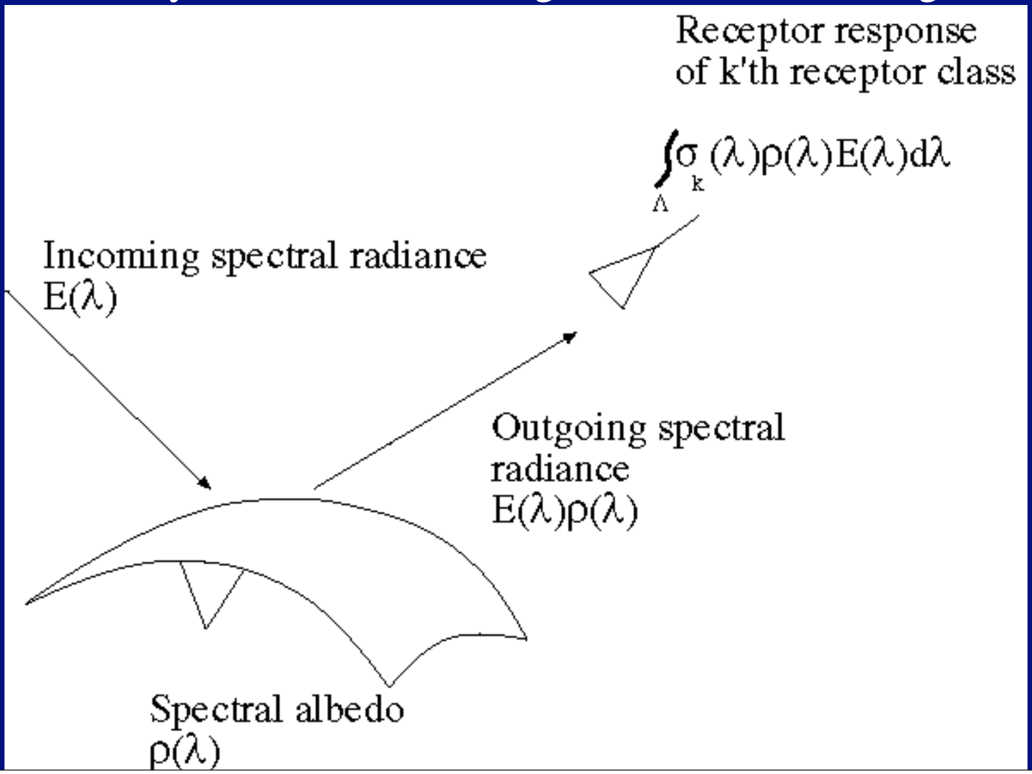
- Inks subtract light from white, whereas phosphors glow.
- Linearity depends on pigment properties - often hugely non-linear.
- Inks:
  - Cyan=White-Red,
  - Magenta=White-Green,
  - Yellow=White-Blue.
- For a good choice of inks, and good registration, matching is linear and easy
  - eg. C+M+Y=White-White=Black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

Mixing pigments in CIE with Titanium Dioxide

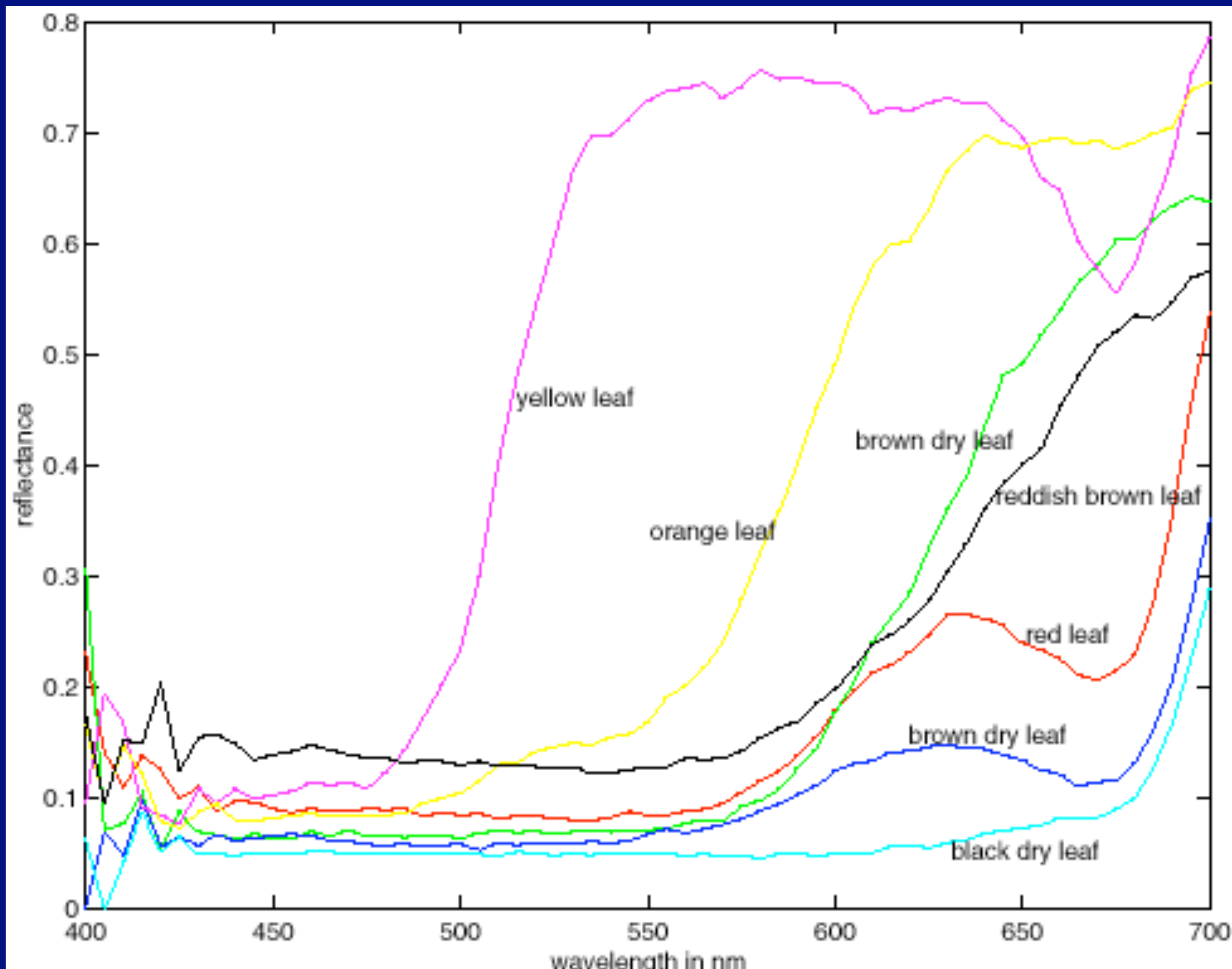


The color of objects

- Colored light arriving at the camera involves two effects
  - The color of the light source
  - The color of the surface
  - Changes caused by different colored light sources can be large

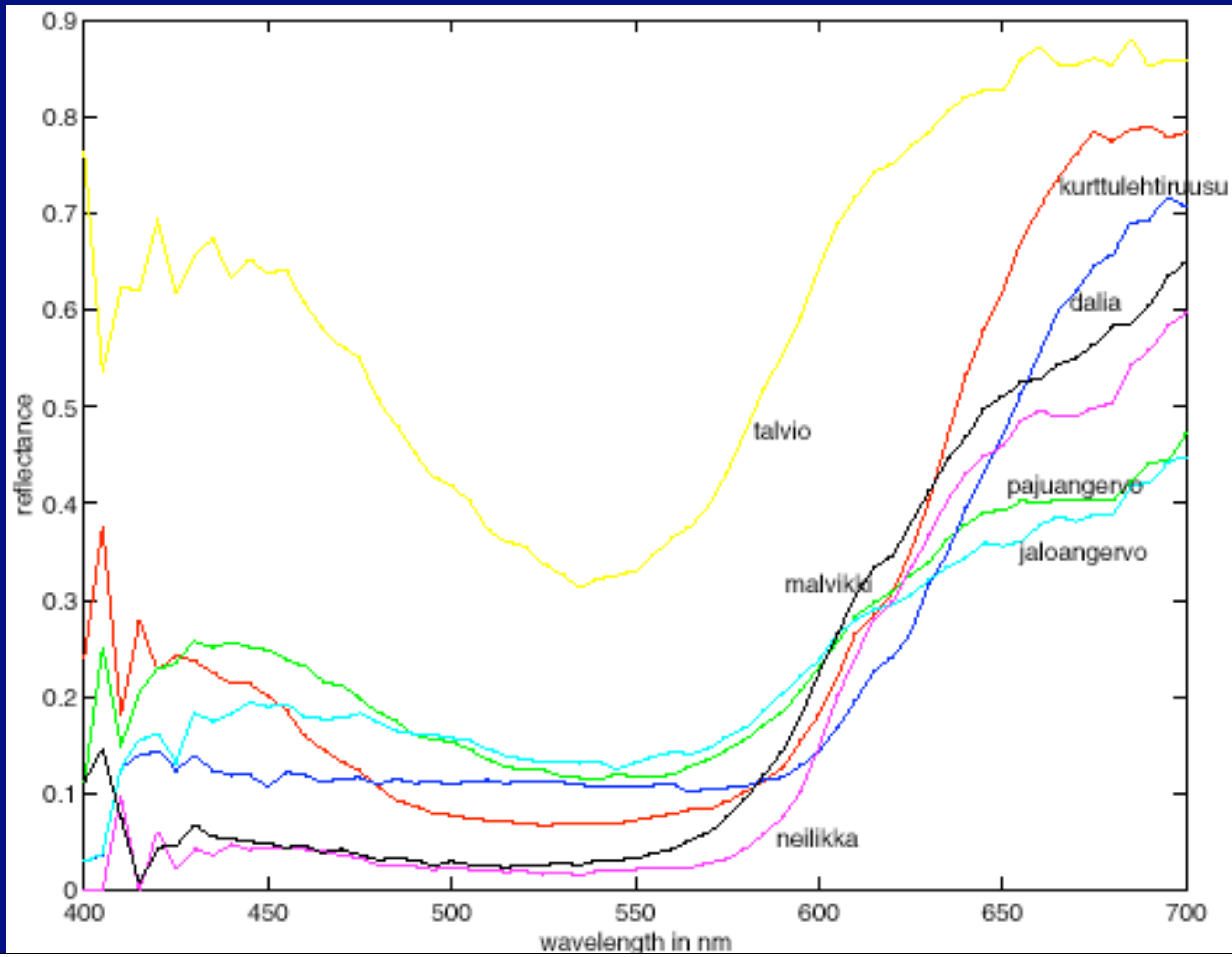


Leaf reflectances

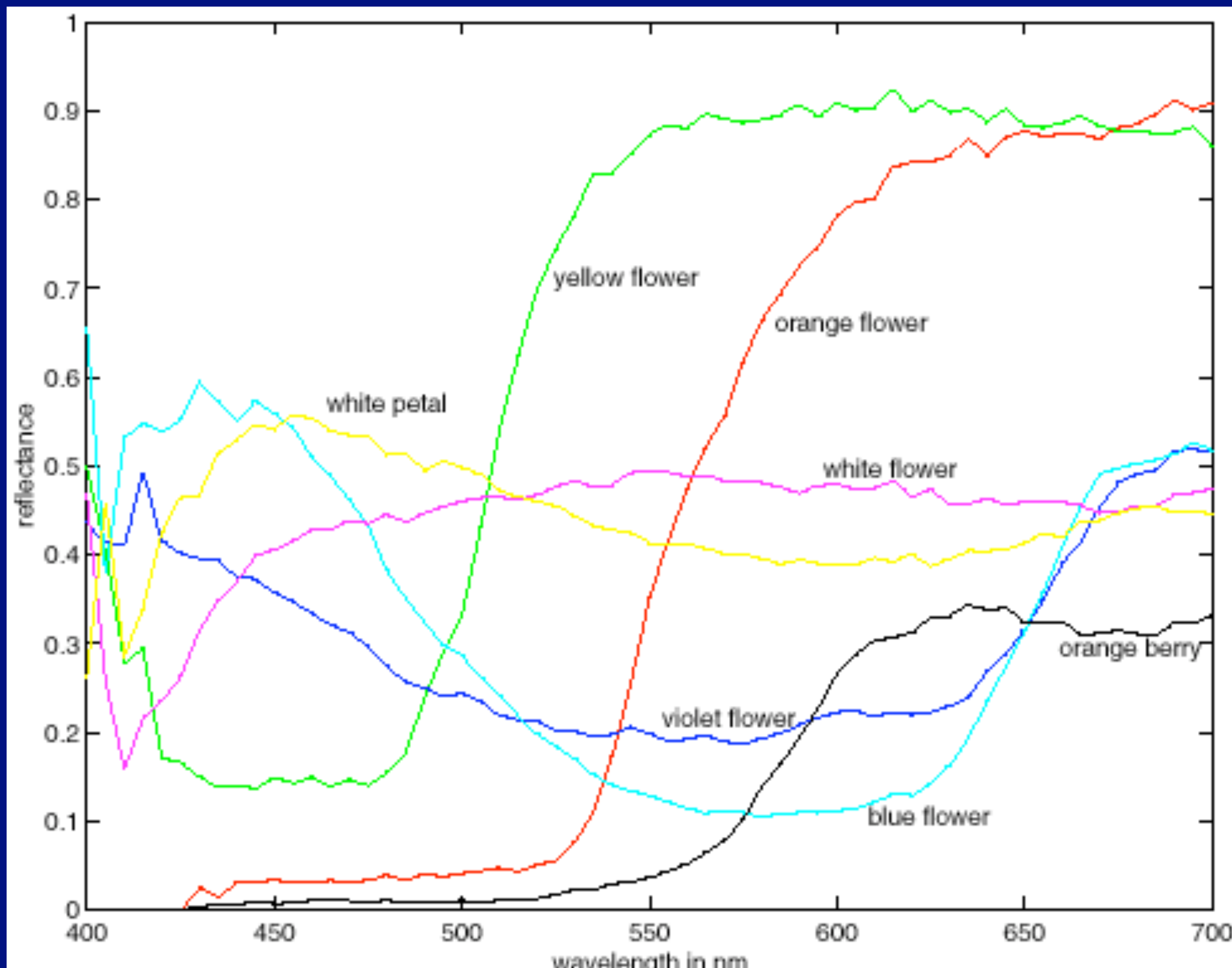


Petal reflectances

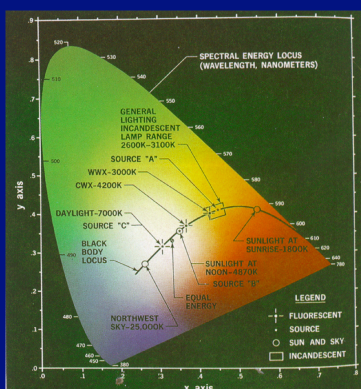
Different red flowers

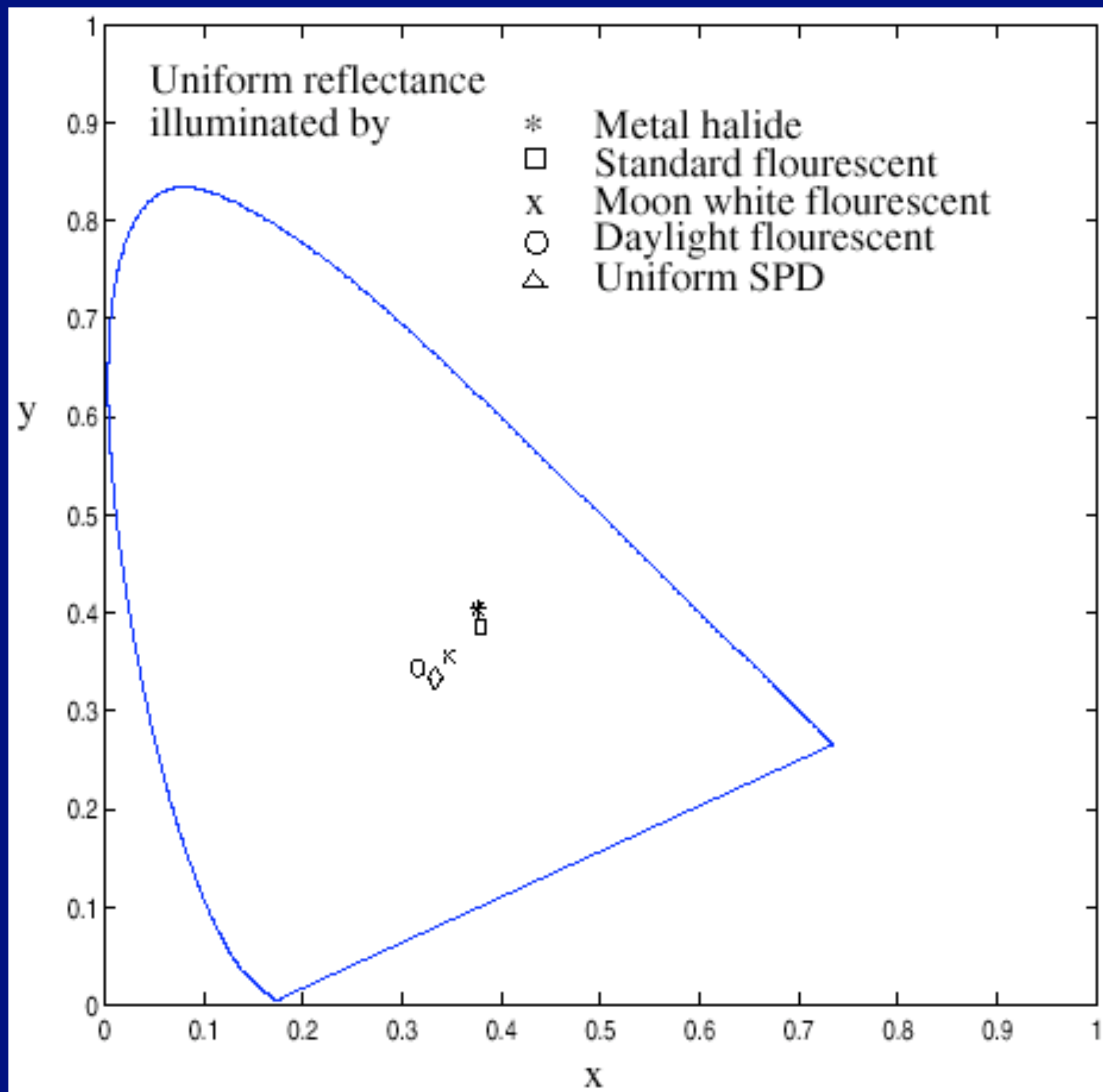


Petal reflectances

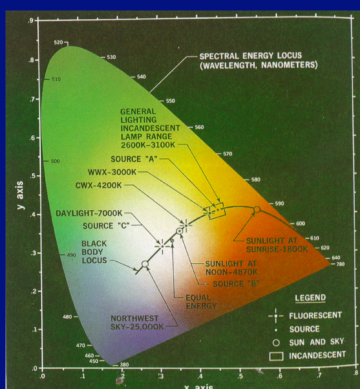


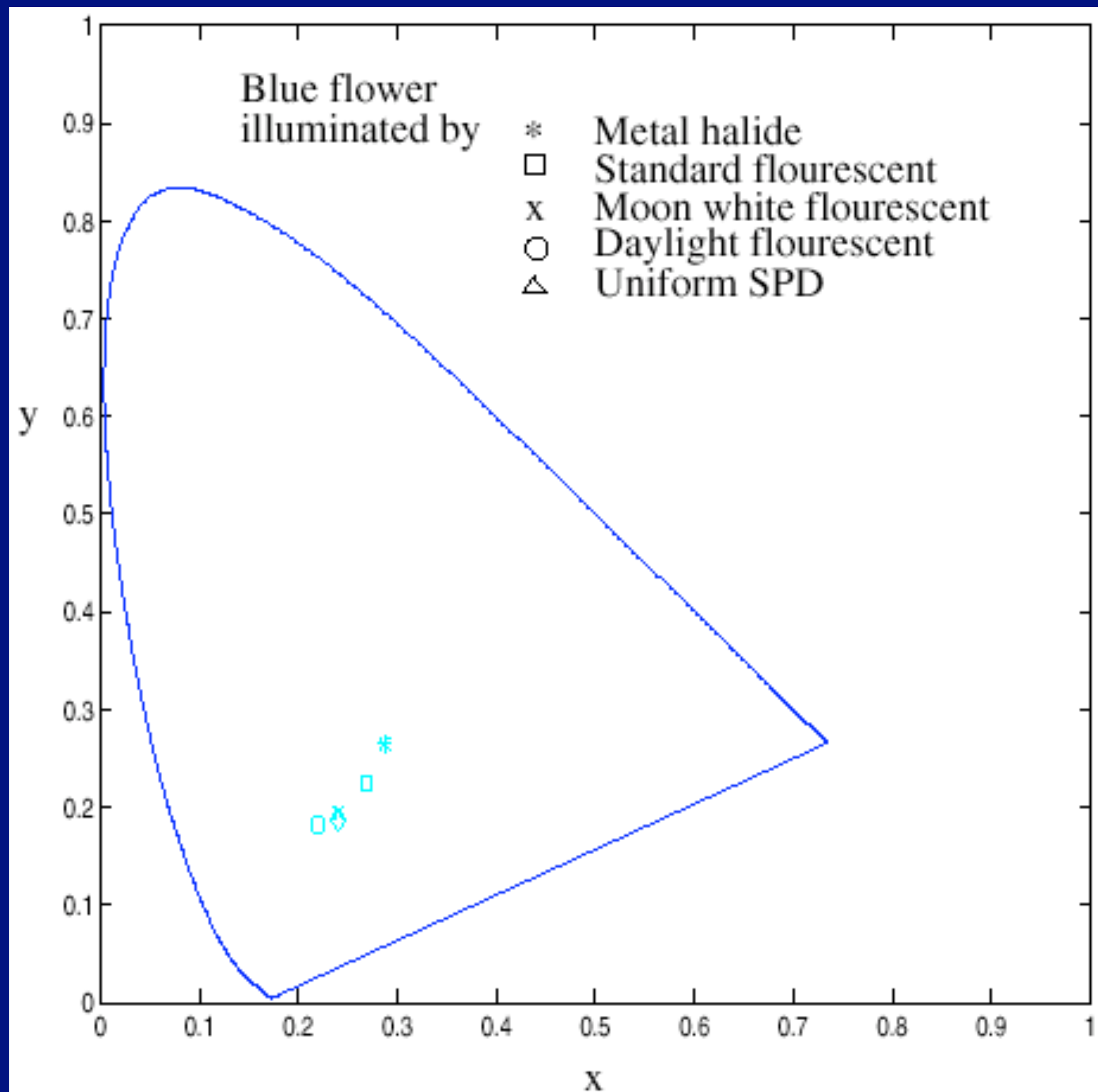
Different lights on uniform reflectances



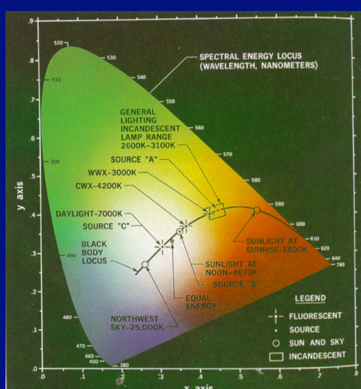


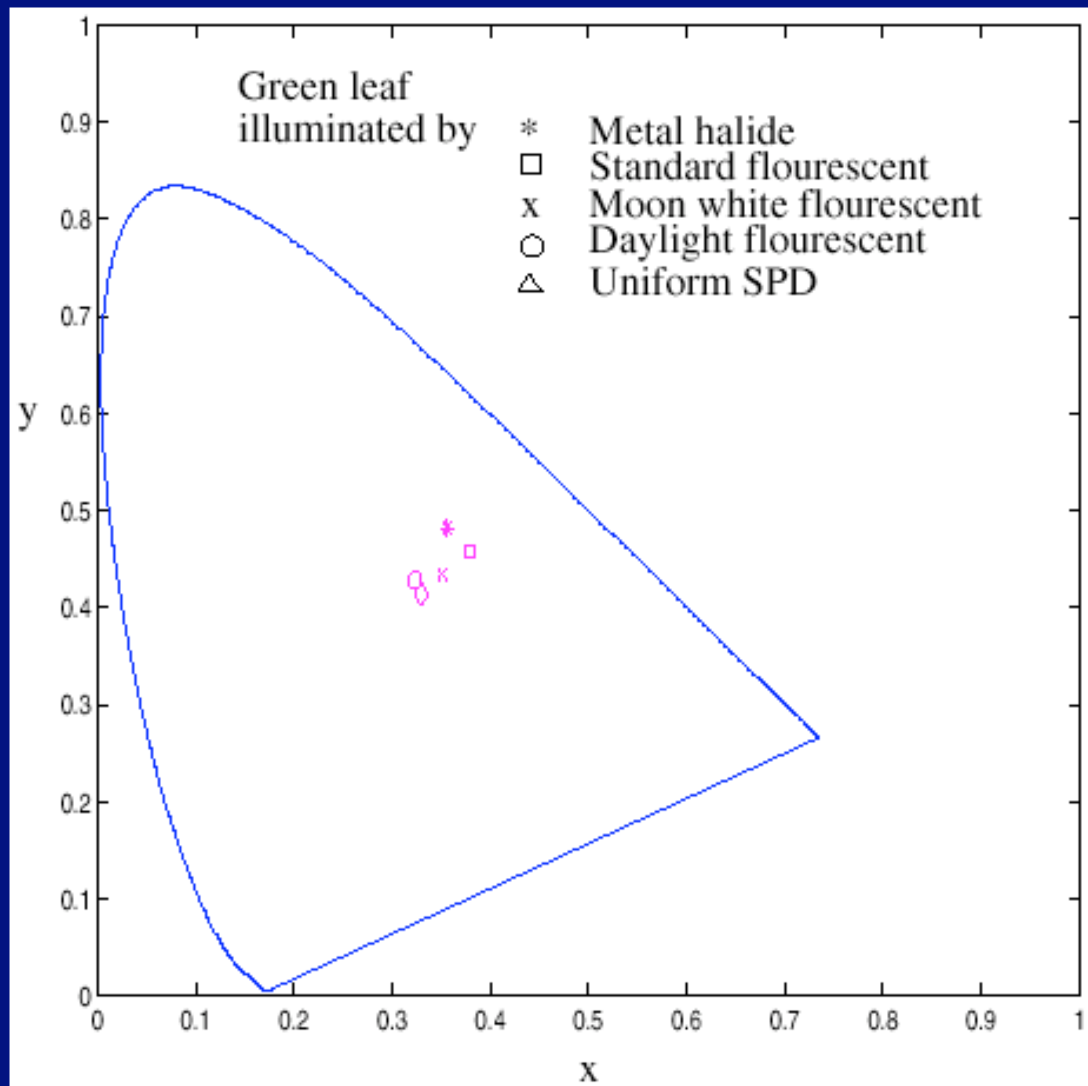
Different lights on blue flower





Different lights on green leaf

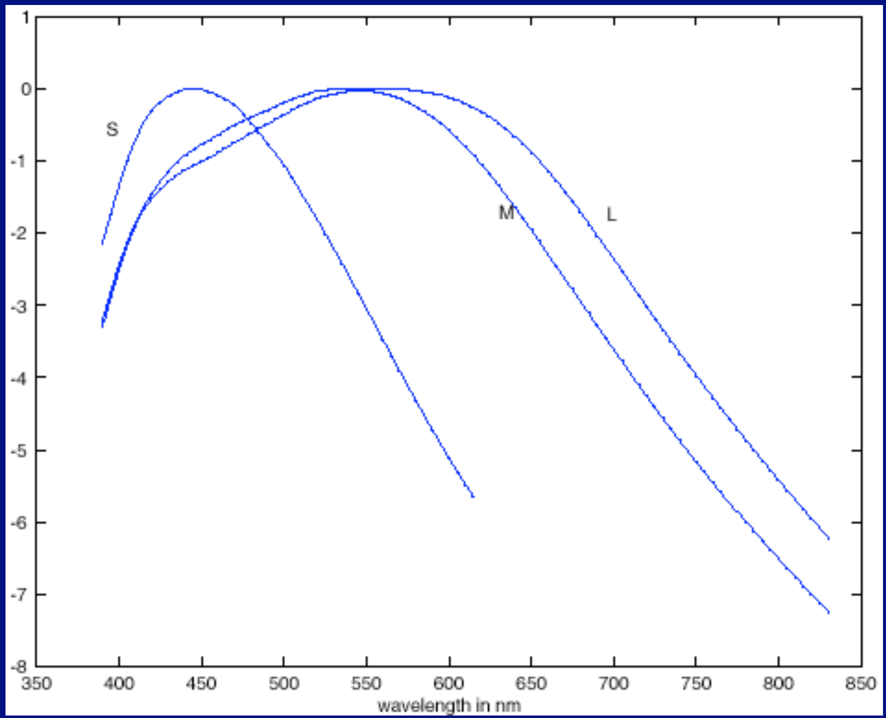




Color receptors and color deficiency

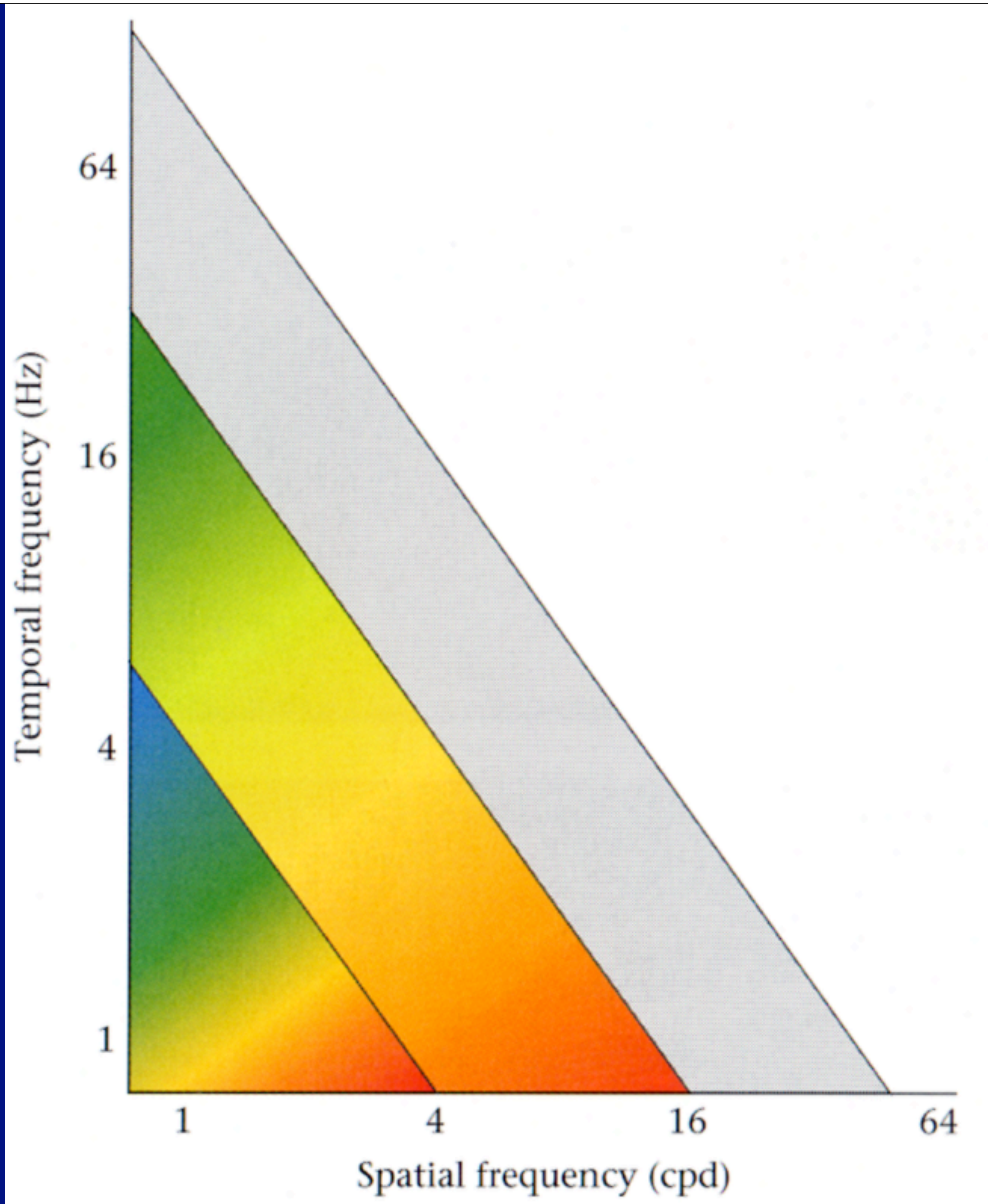
- Trichromacy is justified -
  - in color normal people, there are three types of color receptor (shown by molecular biologists).
- Some people have fewer;
  - most common deficiency is red-green color blindness in men. Red and green receptor genes are carried on the X chromosome. Most red-green color blind men have two red genes or two green genes. Yields an evolutionary story.
- Deficiency
  - can be caused by CNS, by optical problems in the eye, or by absent receptors
- Other color deficiencies:
  - Anomalous trichromacy
  - Achromatopsia
  - Macular degeneration

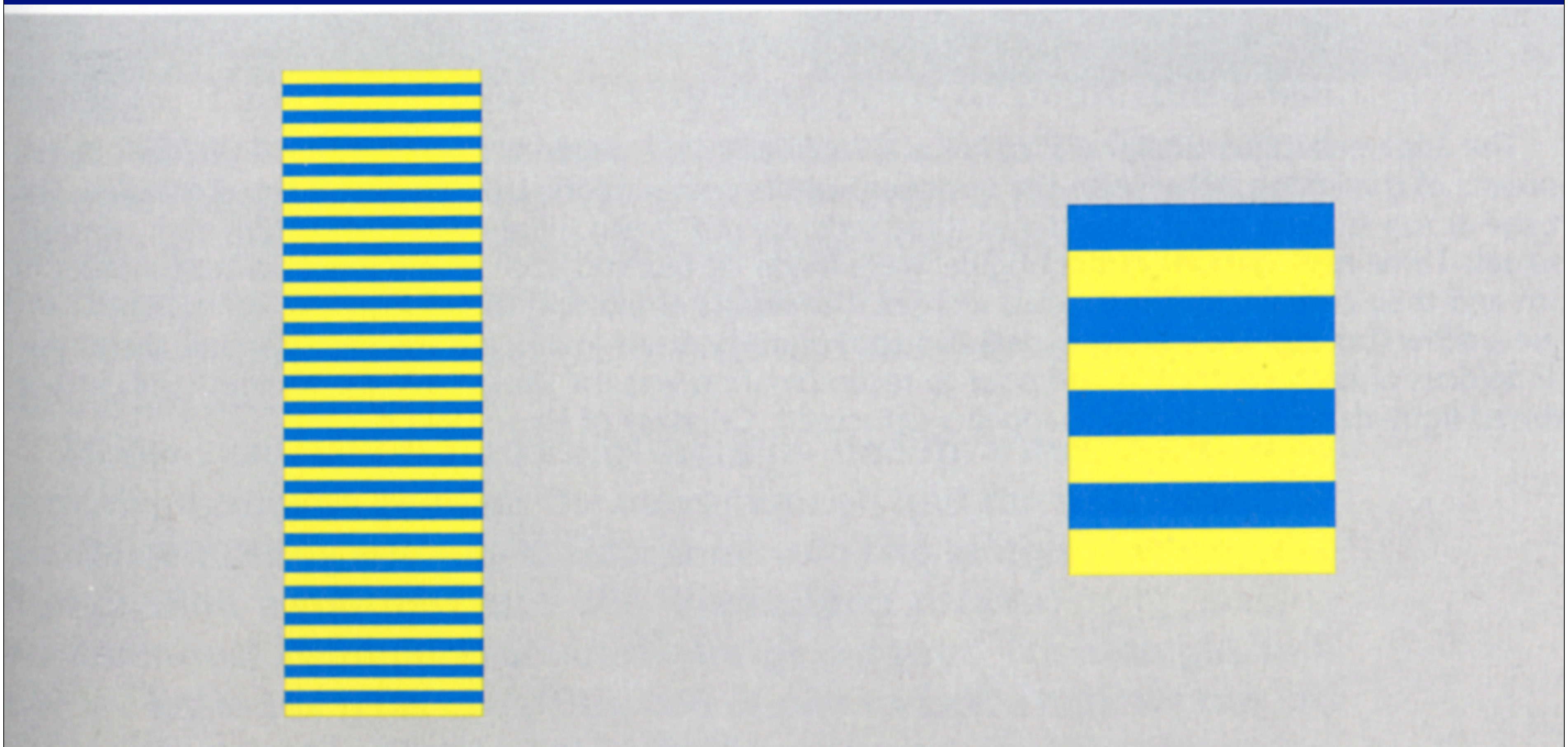
Color receptors

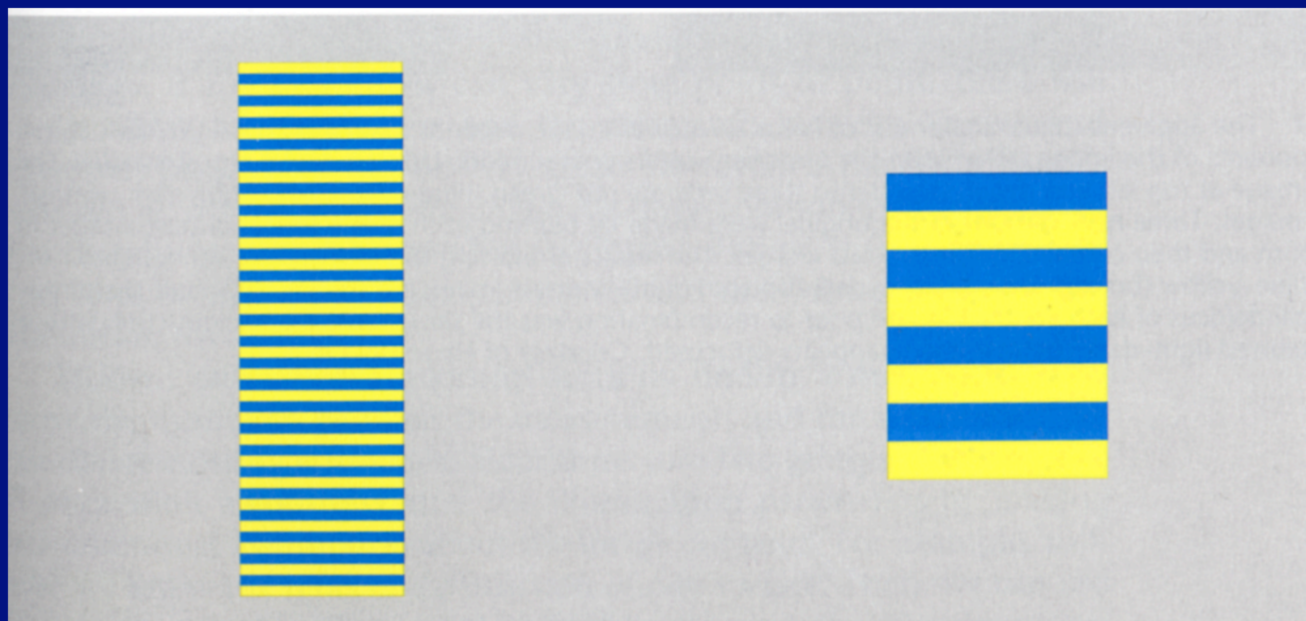


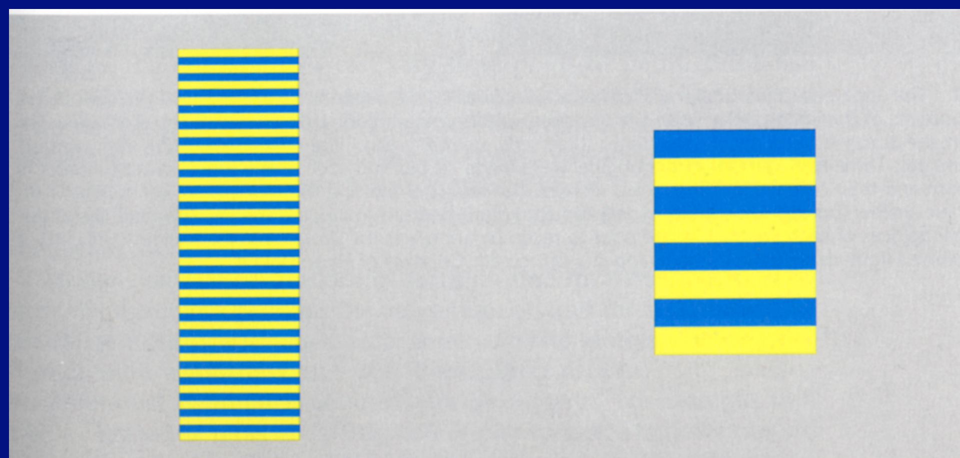
Principle of univariance: cones give the same kind of response, in different amounts, to different wavelengths. Output of cone is obtained by summing over wavelengths.

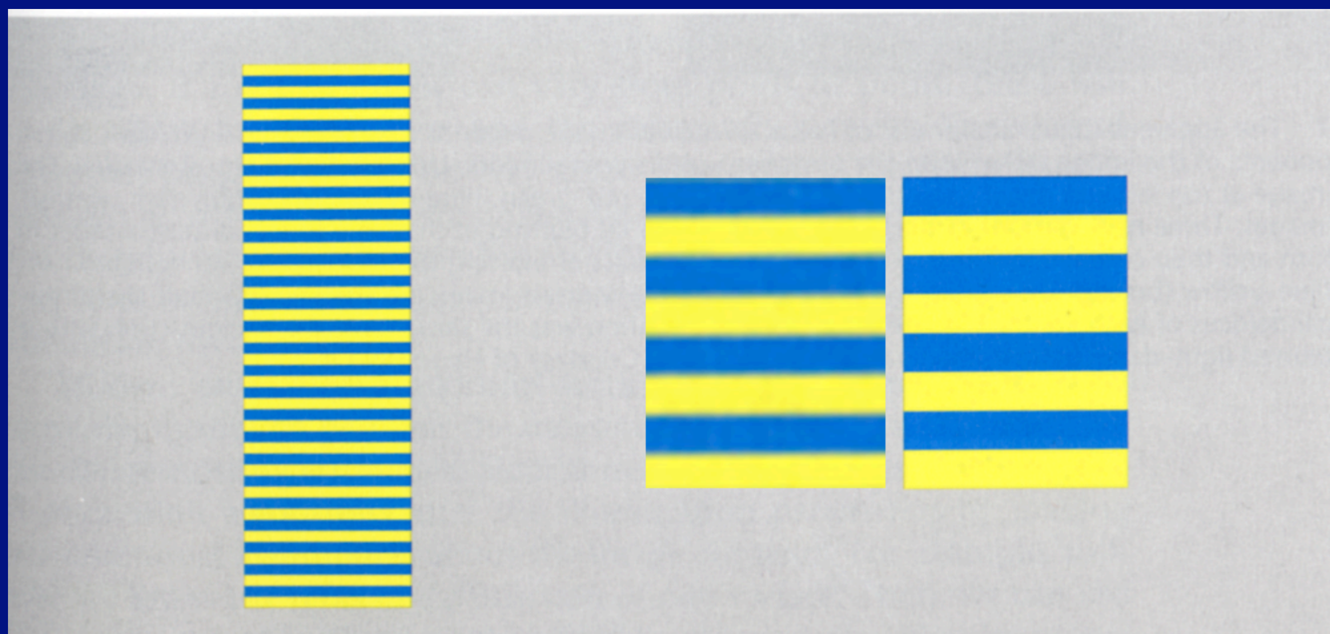
Responses measured in a variety of ways

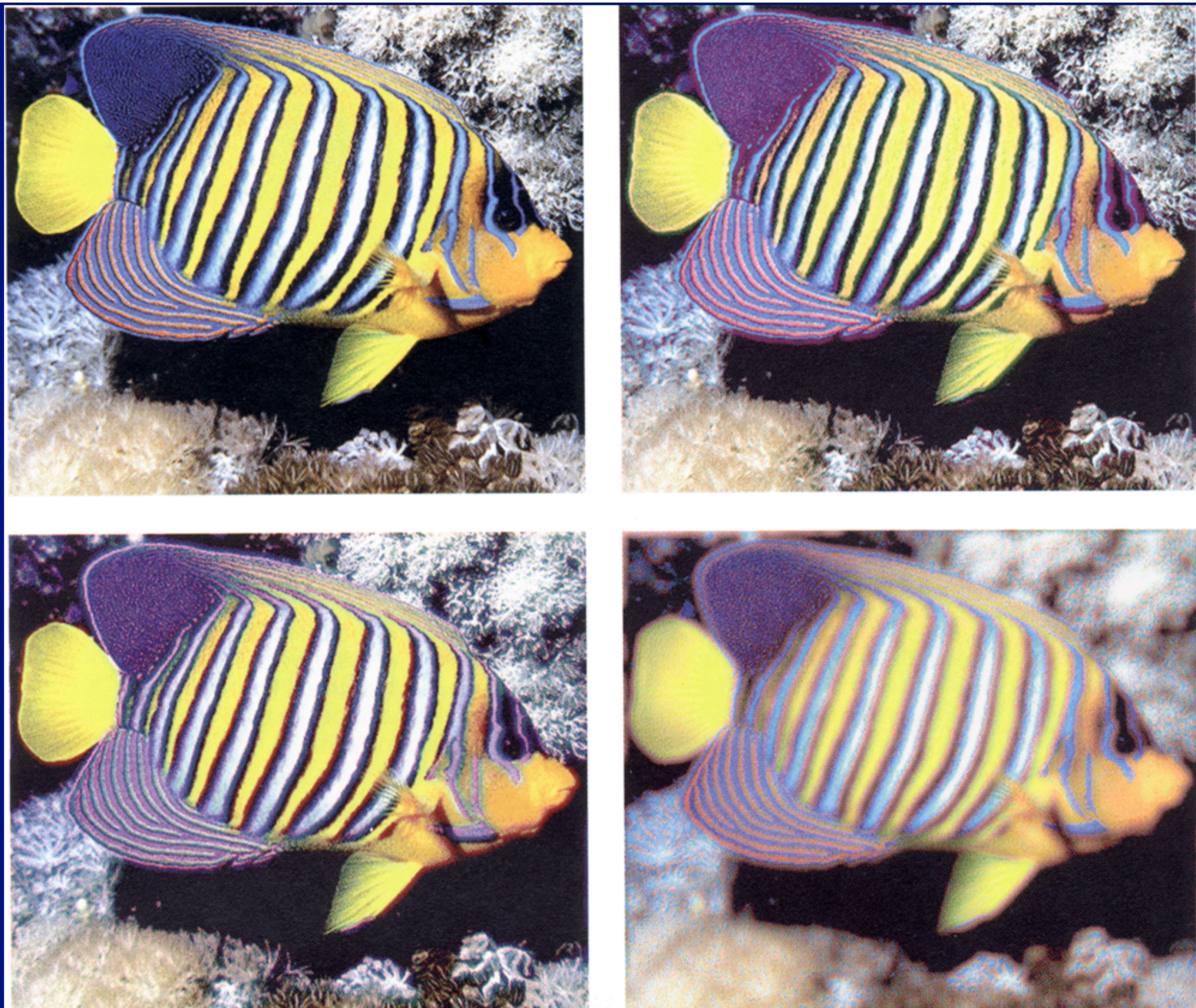

64
16
4
1
Temporal frequency (Hz)
1
4
16
64
Spatial frequency (cpd)





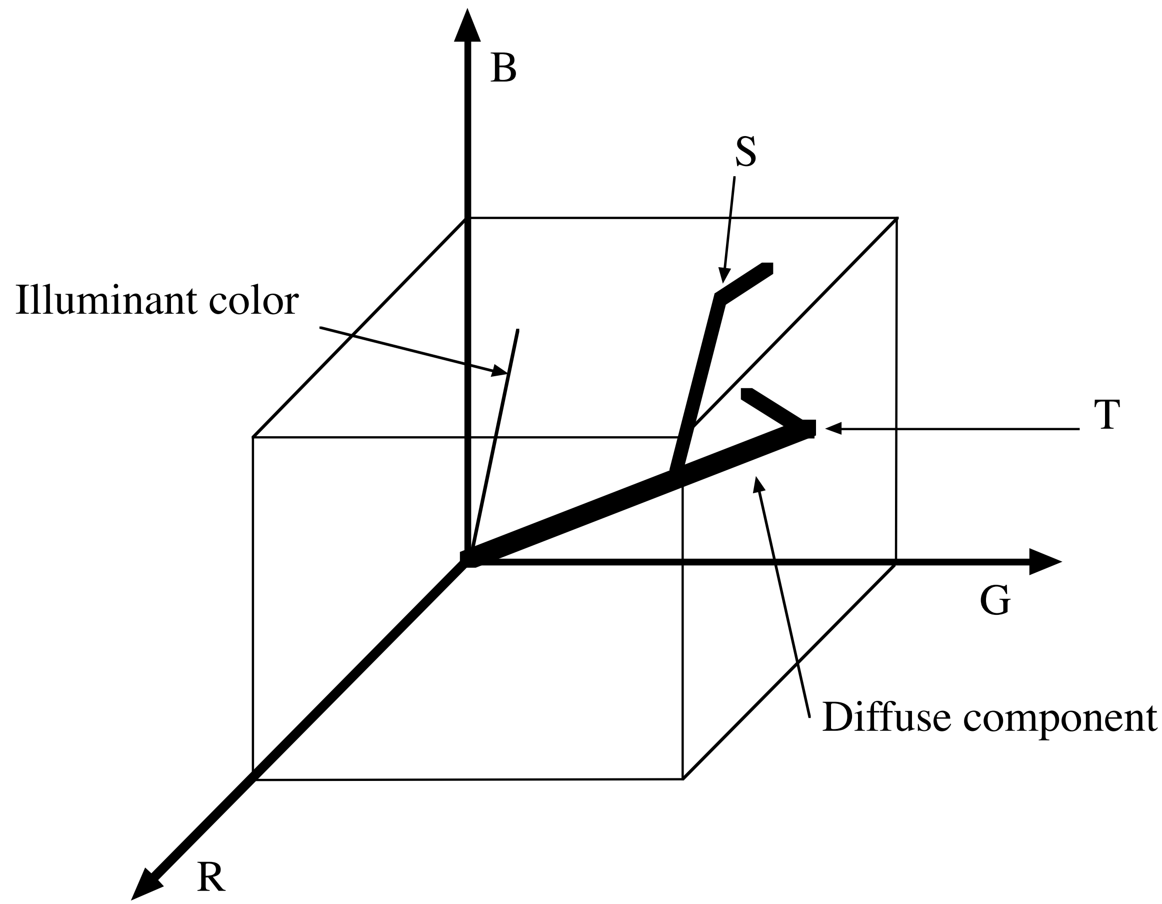


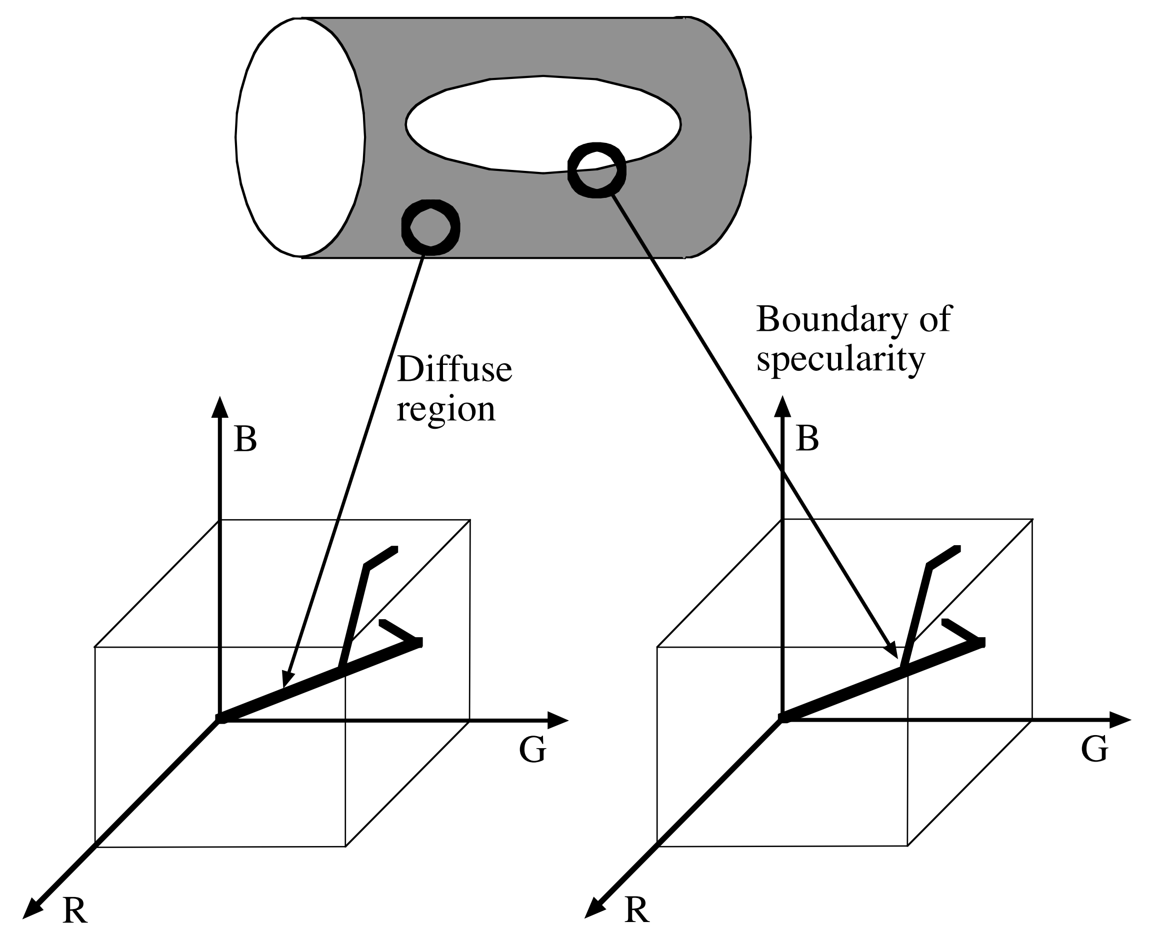




Finding Specularities

- 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

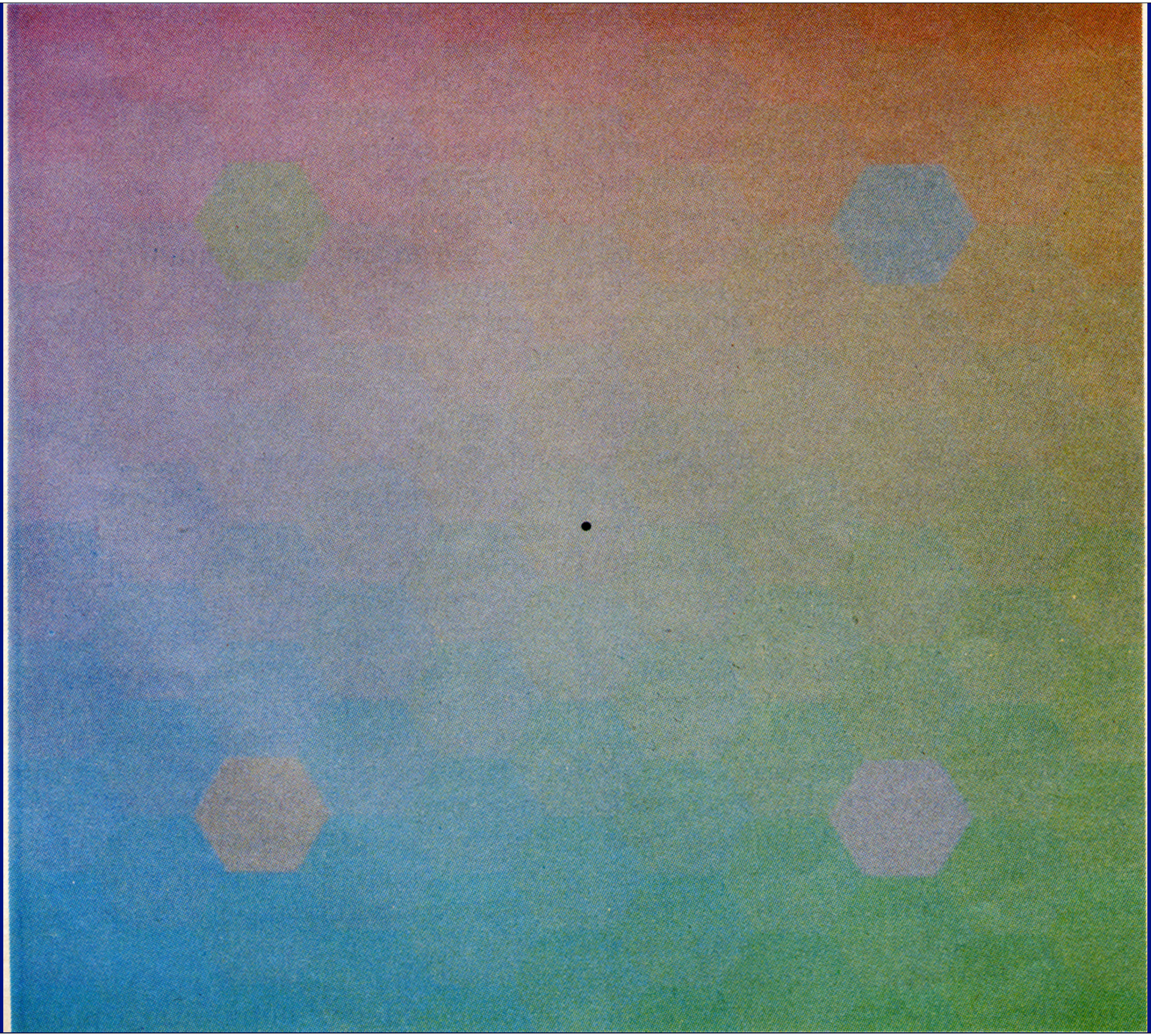

B
S
Illuminant color
T
G
Diffuse component
R

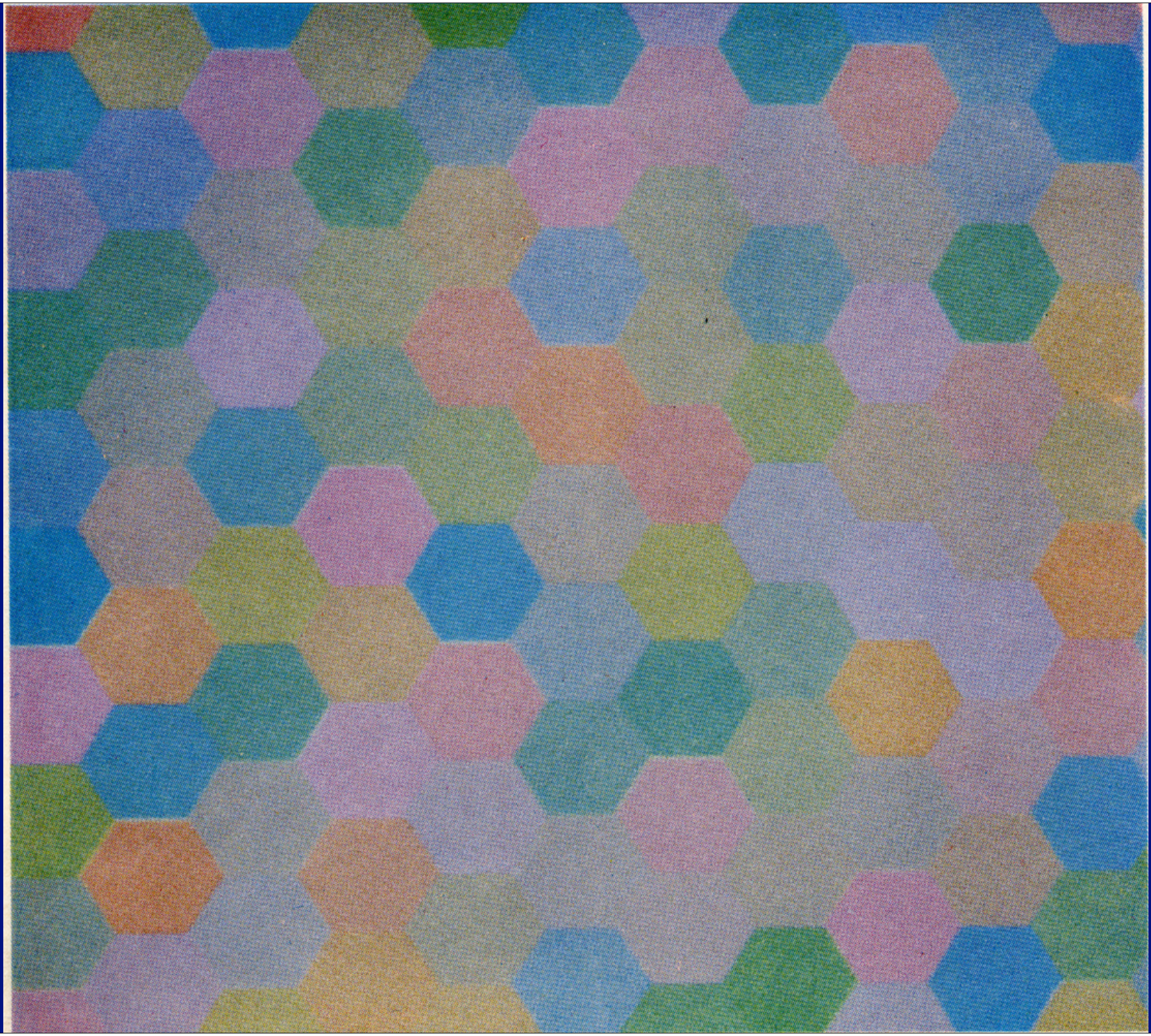


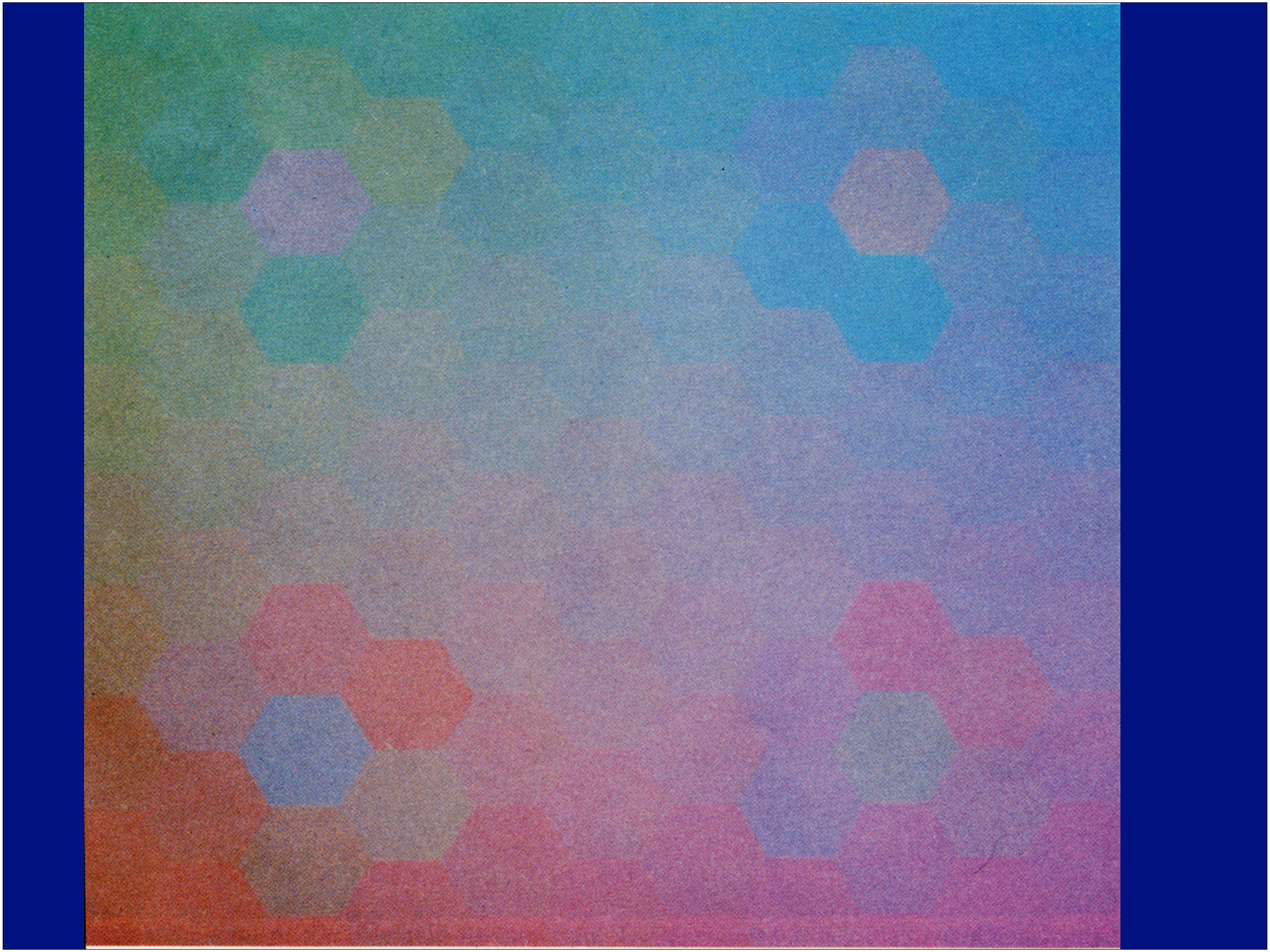
Diffuse region
Boundary of specularity
B
G
R
B
G
R

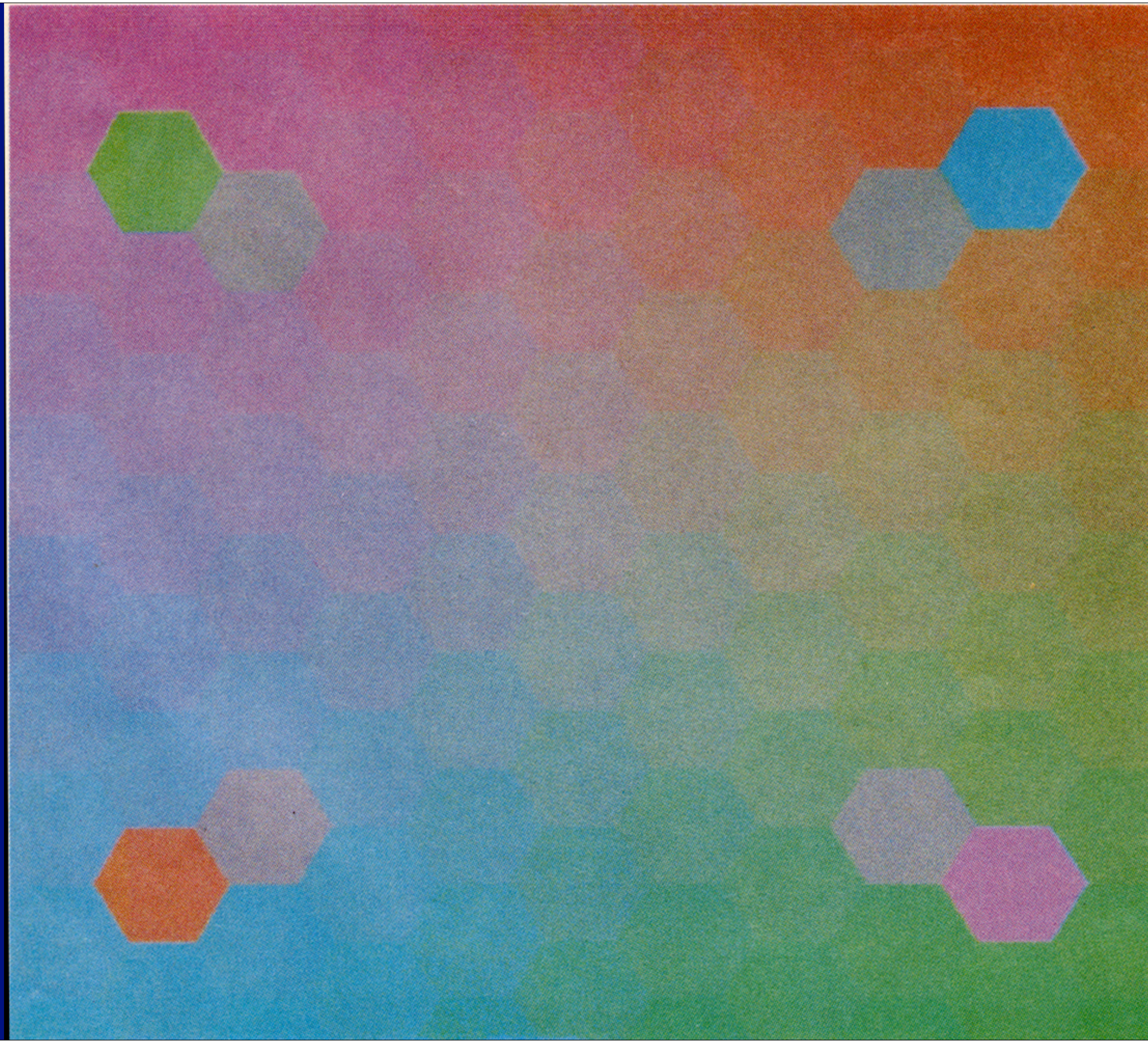
Constancy

- We observe the colour of the light reflected from surfaces
- But we want surface colour
  - problem is known as colour constancy
- Multiple types of report
  - The colour of paint I would use is
  - The colour of the surface is
  - The colour of the light is
- Problem is well understood, and largely solved
  - solutions not currently used very widely

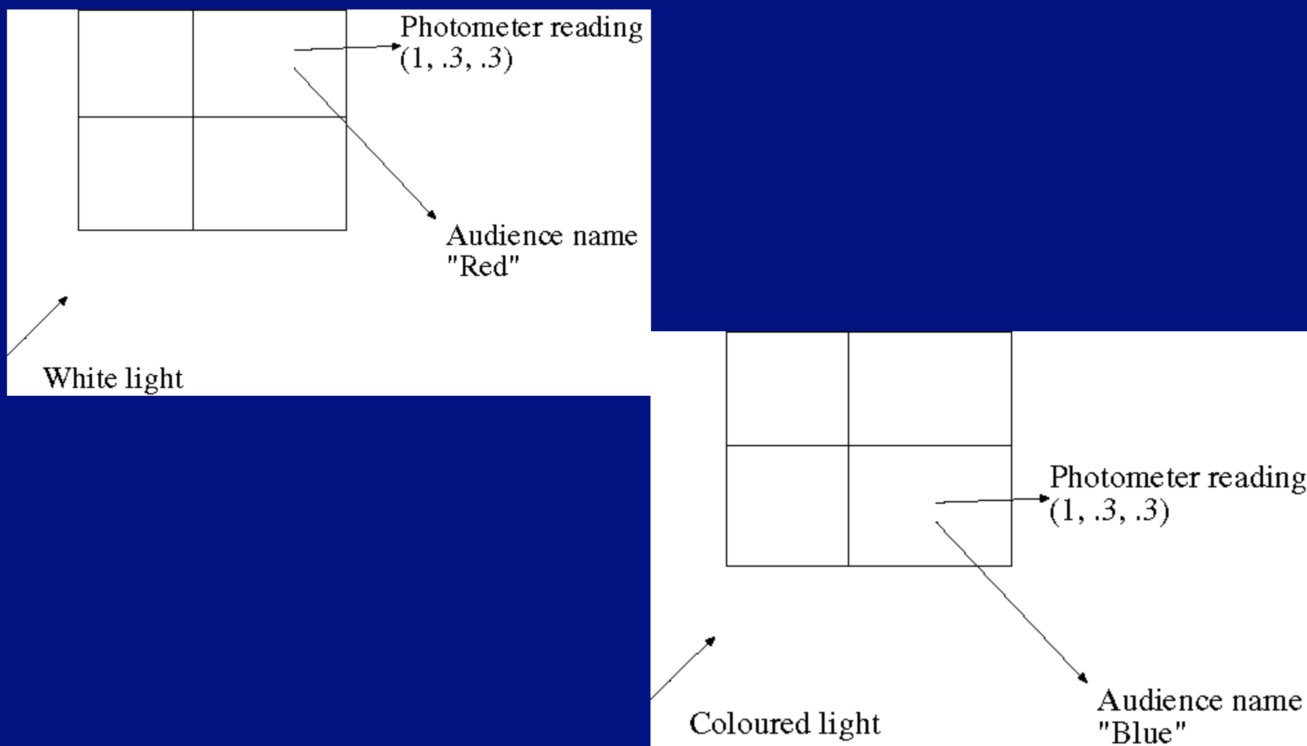






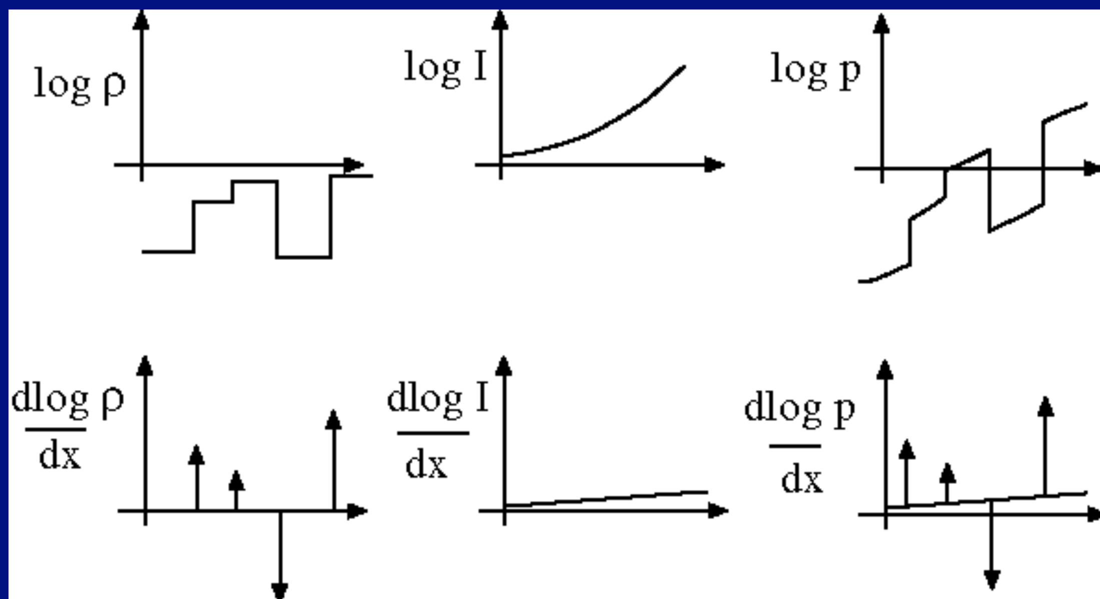


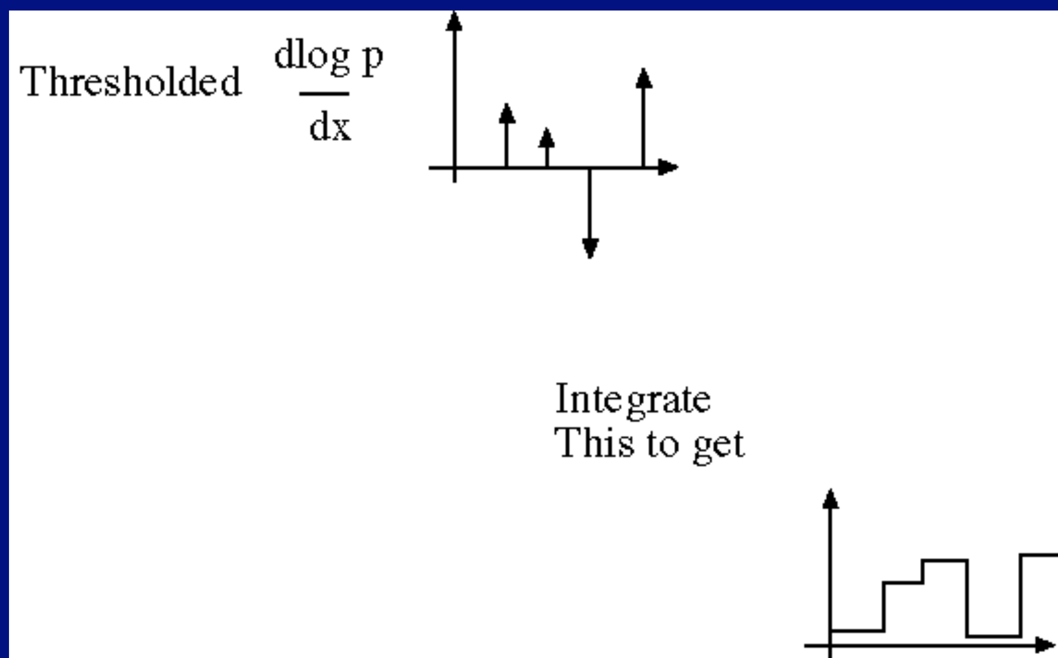
Land's Demonstration



Lightness Constancy

- Lightness constancy
  - how light is the surface, independent of the brightness of the illuminant
  - issues
    - spatial variation in illumination
    - absolute standard
  - Human lightness constancy is very good
- Assume
  - frontal 1D “Surface”
  - slowly varying illumination
  - quickly varying surface reflectance


log ρ
log I
log p
dlog ρ / dx
dlog I / dx
dlog p / dx


Thresholded
dlog p
dx
Integrate
This to get

Lightness Constancy in 2D

- Differentiation, thresholding are easy
  - integration isn’t
  - problem - gradient field may no longer be a gradient field
- One solution
  - Choose the function whose gradient is “most like” thresholded gradient
  - This yields a minimization problem
  - How do we choose the constant of integration?
    - average lightness is grey
    - lightest object is white

      ?

Simplest colour constancy

- Adjust three receptor channels independently
  - Von Kries
  - Where does the constant come from?
    - White patch
    - Averages
    - Some other known reference (faces, nose)

Colour Constancy - I

- We need a model of interaction between illumination and surface colour
  - finite dimensional linear model seems OK
  - FDLM
    - surface spectral albedo is a weighted sum of basis functions
    - illuminant spectral exitance is a weighted sum of basis functions
    - This gives a quite simple form to interaction between the two

General strategies

- Determine what image would look like under white light
- Assume
  - that we are dealing with flat frontal surfaces
  - We've removed specularities
  - no variation in illumination
- We need some form of reference
  - brightest patch is white
  - spatial average is known
  - gamut is known
  - specularities