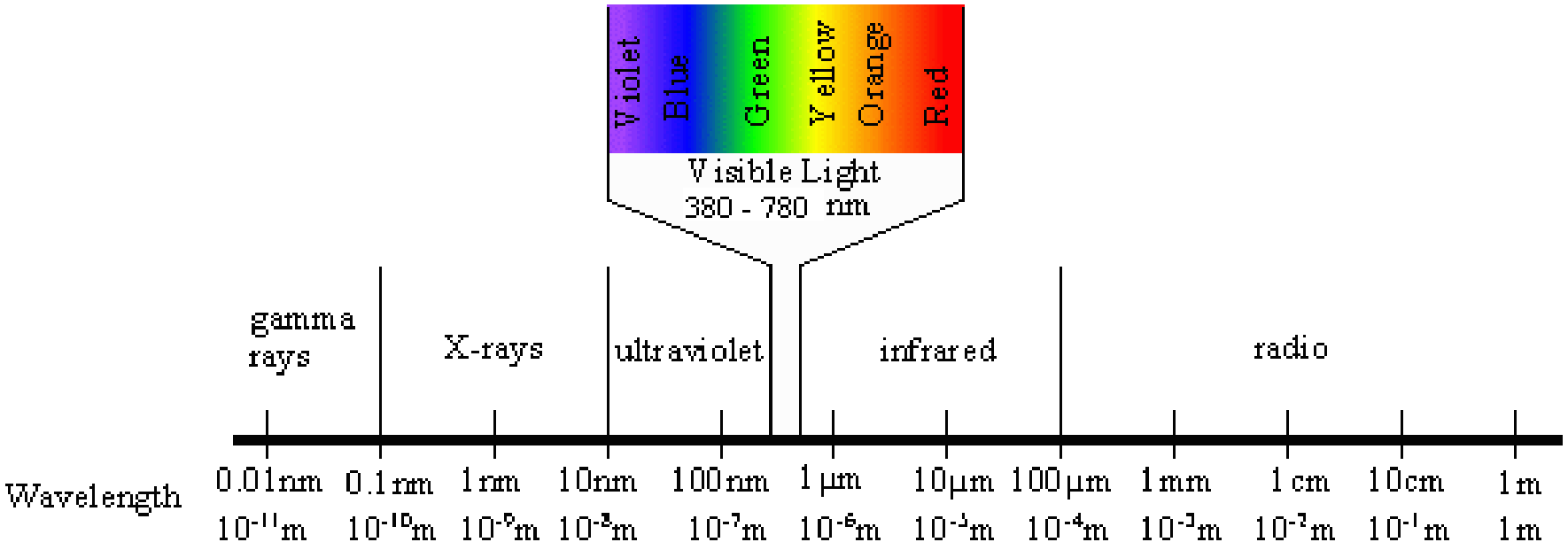
Digital Color

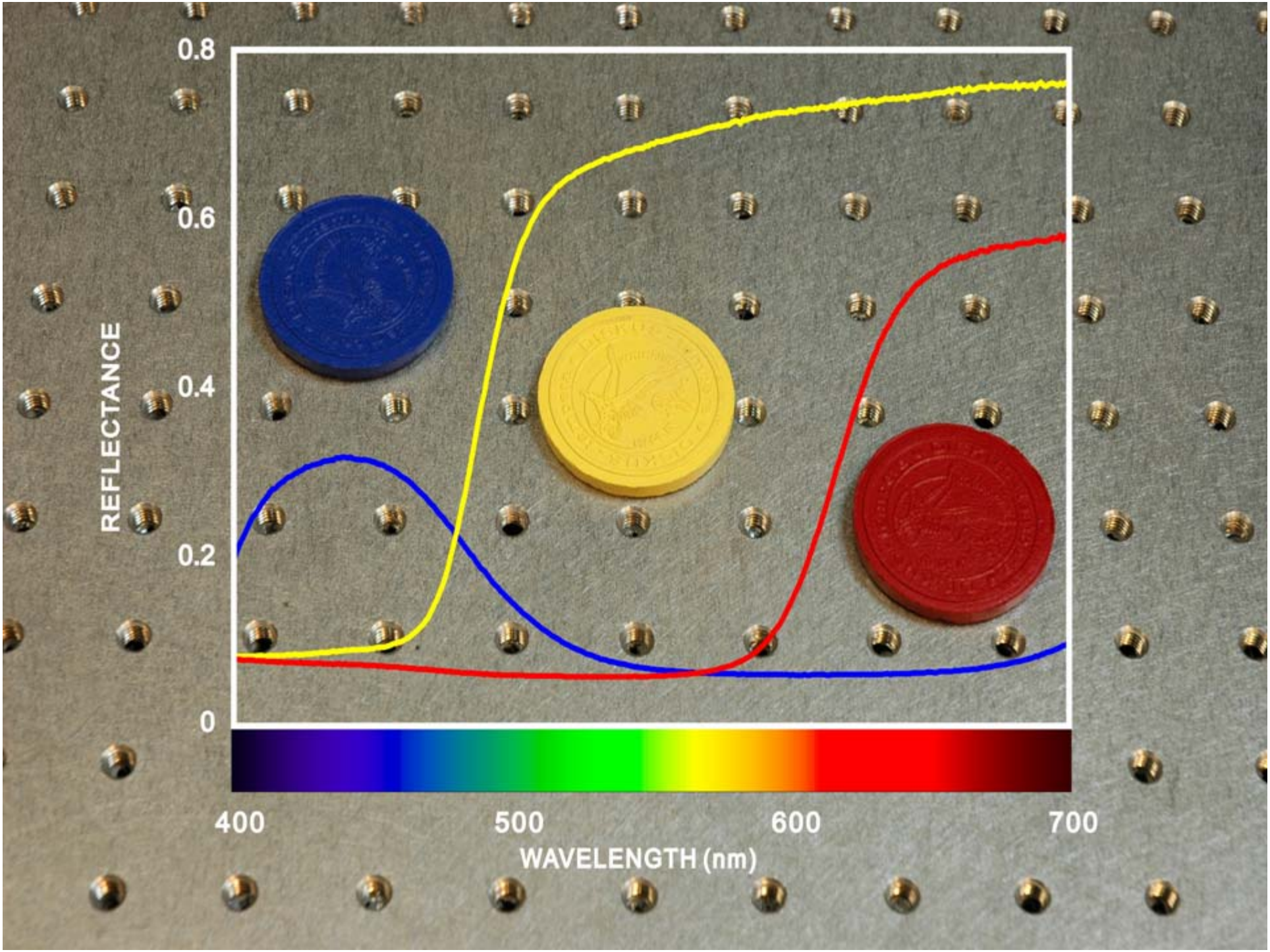
Lecture 2

Human color vision and

spectral color measurement

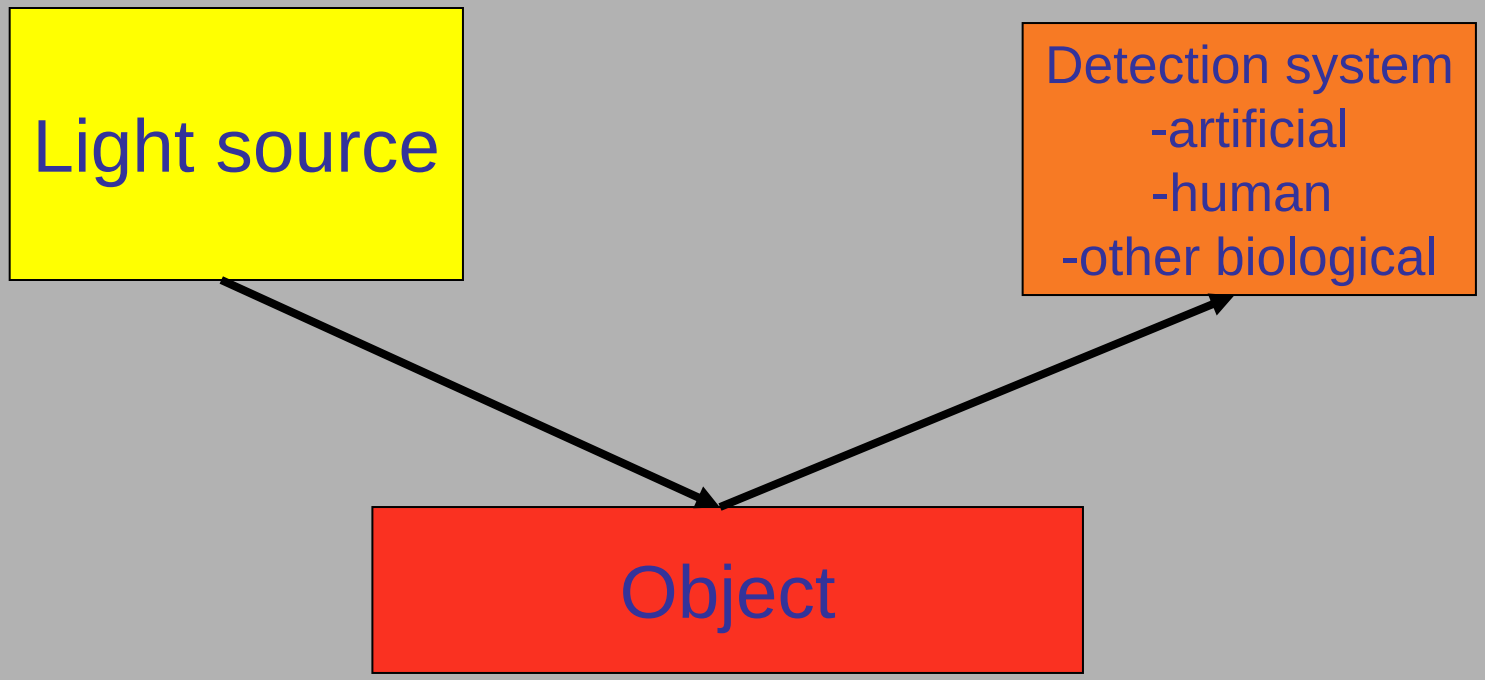
Visible spectrum

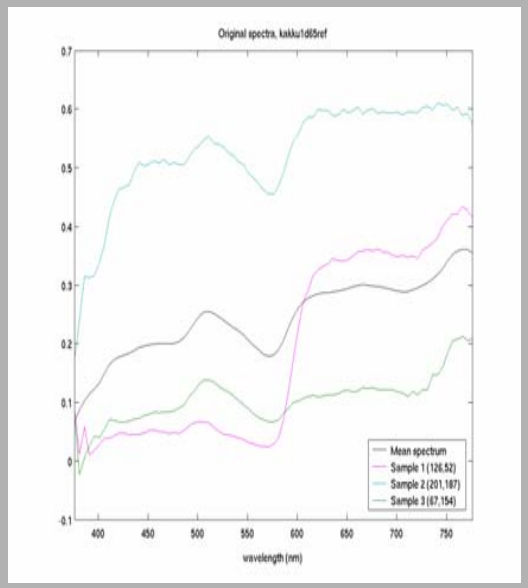


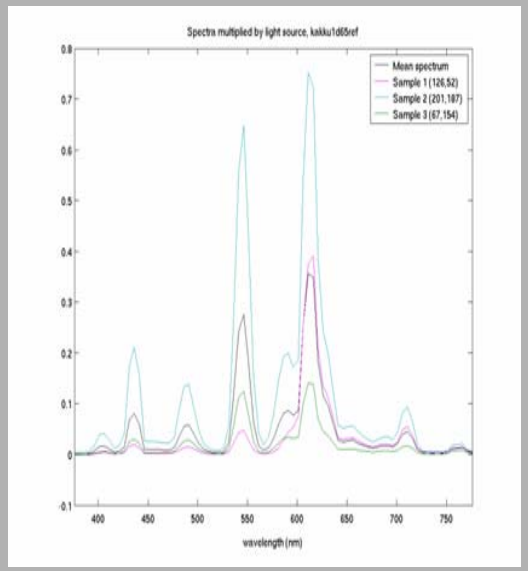

0.8
0.6
0.4
0.2
0
REFLECTANCE
400
500
600
700
WAVELENGTH (nm)

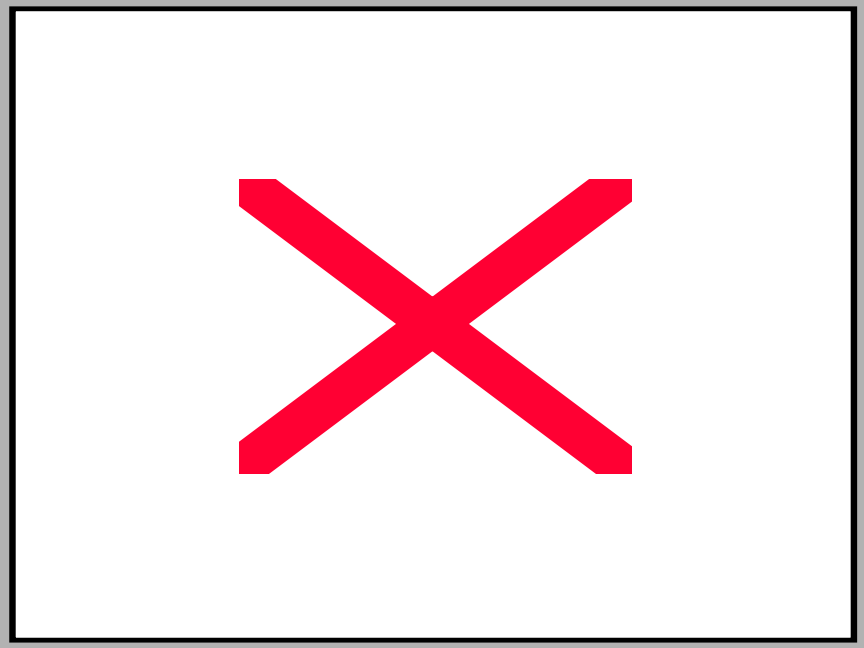
Our approach to color

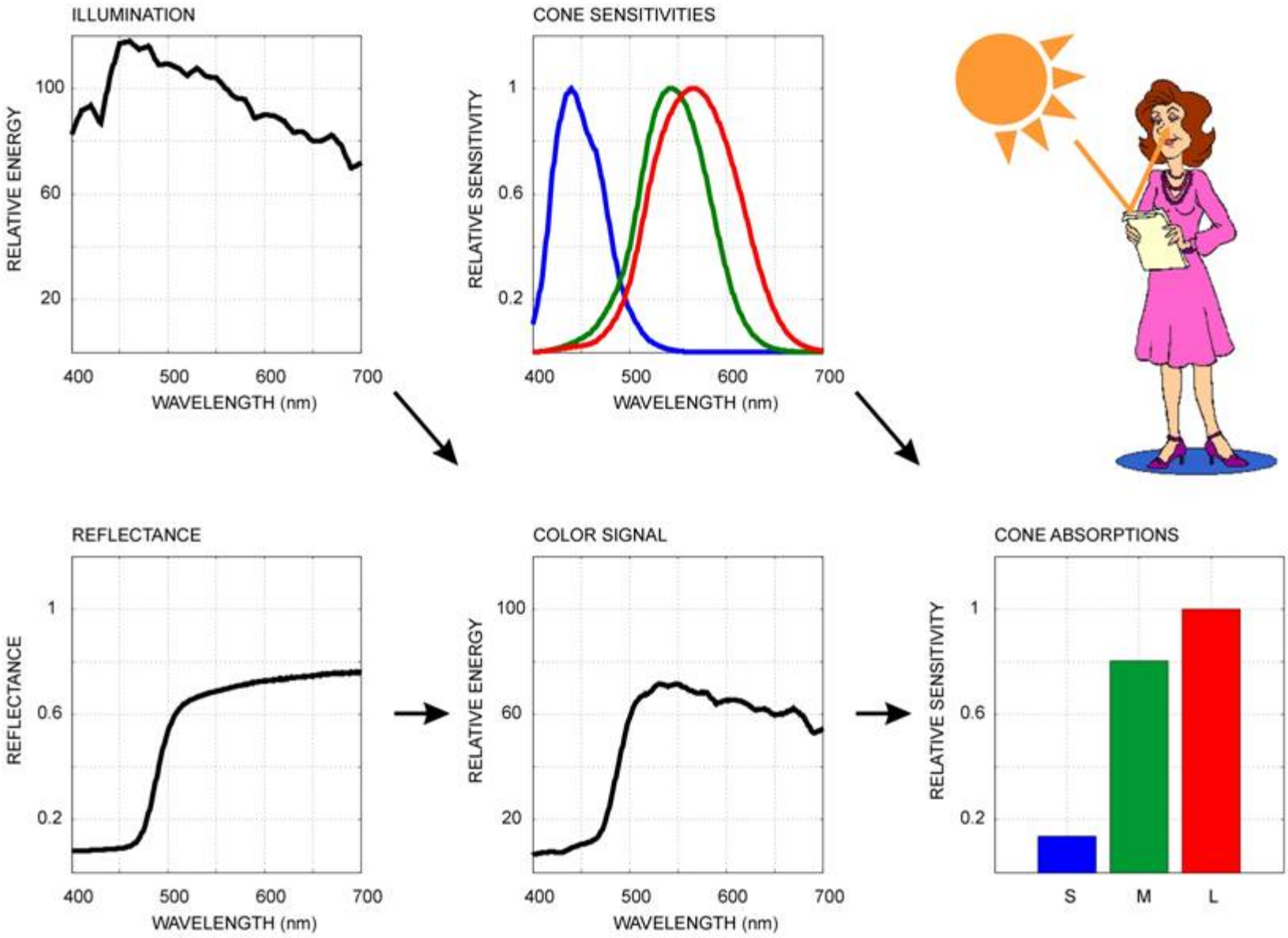
- Color information is carried by the light signal originated from the colored object
- This signal is measurable and unique




Original spectra, kakku1d65ref
Mean spectrum
Sample 1 (126,52)
Sample 2 (201,187)
Sample 3 (67,154)
wavelength (nm)

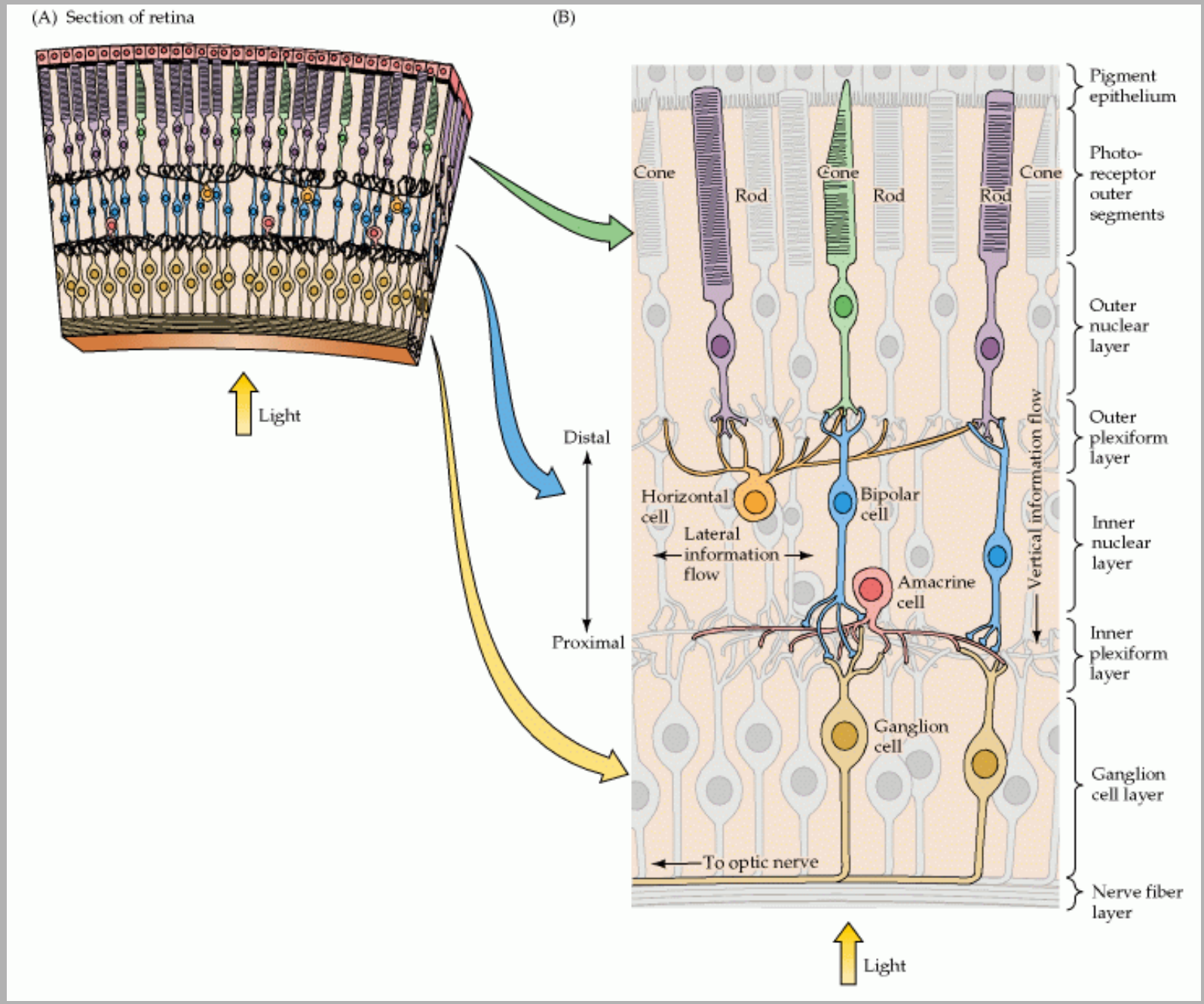

Spectra multiplied by light source, kakku1d65ref
Mean spectrum
Sample 1 (126,52)
Sample 2 (201,187)
Sample 3 (67,154)
wavelength (nm)




ILLUMINATION
RELATIVE ENERGY
100
60
20
400
500
600
700
WAVELENGTH (nm)
CONE SENSITIVITIES
RELATIVE SENSITIVITY
1
0.6
0.2
400
500
600
700
WAVELENGTH (nm)
REFLECTANCE
REFLECTANCE
1
0.6
0.2
400
500
600
700
WAVELENGTH (nm)
COLOR SIGNAL
RELATIVE ENERGY
100
60
20
400
500
600
700
WAVELENGTH (nm)
CONE ABSORPTIONS
RELATIVE SENSITIVITY
1
0.6
0.2
S
M
L

Human color vision

- First step: l, m, s cone responses
- Second step: opponent signal formation
  - $A = l + m + s$ achromatic channel
  - $R - G = l - m + s$ chromatic channel
  - $Y - B = l + m - s$ chromatic channel
- from retina to LGN "relay station"
- finally in visual cortex and complex network between different brain regions



Purves et al., Neuroscience, 2nd ed., Sinauer Associates (web-pages, 23.1.2007)

Multi-Stage Color Model

de Valois & de Valois, 1993

- 1st stage : cone pigments
  - L, M, S, assumed cone ratio 10:5:1
- 2nd stage: cone opponency
  - receptive fields of opponent cells
    - center vs. surround
    - in fovea: pure cone centers
      outside: L & M cones can be mixed in RF centers
      S cones don't mix with others
- 3rd stage (cortical): perceptual opponency
  - RG, BY, achromatic i.e. color and luminance channels separated

Multi-Stage Color Model

de Valois & de Valois, 1993

Matrix representation of the Multi-Stage Color Model (indiscriminate version)

$$\begin{bmatrix} L_O \\ M_O \\ S_O \end{bmatrix} = \begin{bmatrix} 6 & -5 & -1 \\ -10 & 11 & -1 \\ -10 & -5 & 15 \end{bmatrix} \begin{bmatrix} L \\ M \\ S \end{bmatrix}$$

$$\begin{bmatrix} RG \\ BY \\ A \end{bmatrix} = \begin{bmatrix} +1 & -1 & +1 \\ -1 & +1 & +1 \\ +1 & +1 & +1 \end{bmatrix} \begin{bmatrix} 10 & 0 & 0 \\ 0 & 5 & 0 \\ 0 & 0 & 2 \end{bmatrix} \begin{bmatrix} L_O \\ M_O \\ S_O \end{bmatrix} \left(= \begin{bmatrix} 90 & -115 & +25 \\ -130 & 95 & 35 \\ -10 & -5 & 15 \end{bmatrix} \begin{bmatrix} L \\ M \\ S \end{bmatrix} \right)$$

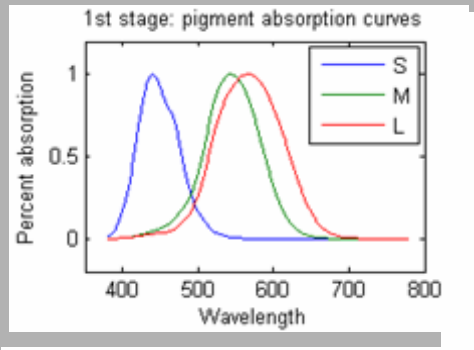
Multi-Stage Color Model in more general form:

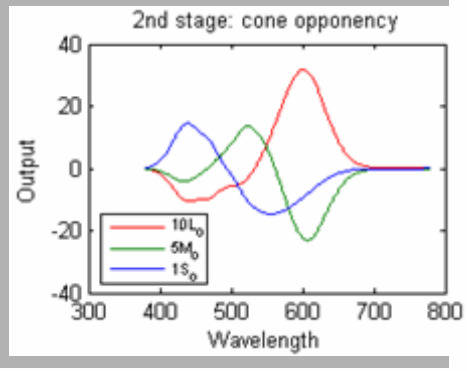
$$\begin{bmatrix} L_O \\ M_O \\ S_O \end{bmatrix} = \begin{bmatrix} W_M + W_S & -W_M & -W_S \\ -W_L & W_L + W_S & -W_S \\ -W_L & -W_M & W_L + W_M \end{bmatrix} \begin{bmatrix} L \\ M \\ S \end{bmatrix}$$

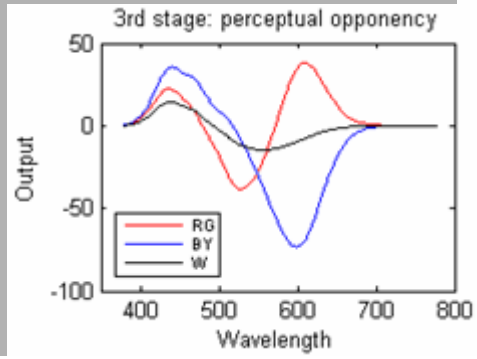
$$\begin{bmatrix} RG \\ BY \\ A \end{bmatrix} = \begin{bmatrix} +1 & -1 & +1 \\ -1 & +1 & +1 \\ +1 & +1 & +1 \end{bmatrix} \begin{bmatrix} W_L & 0 & 0 \\ 0 & W_M & 0 \\ 0 & 0 & 2 * W_S \end{bmatrix} \begin{bmatrix} L_O \\ M_O \\ S_O \end{bmatrix}$$

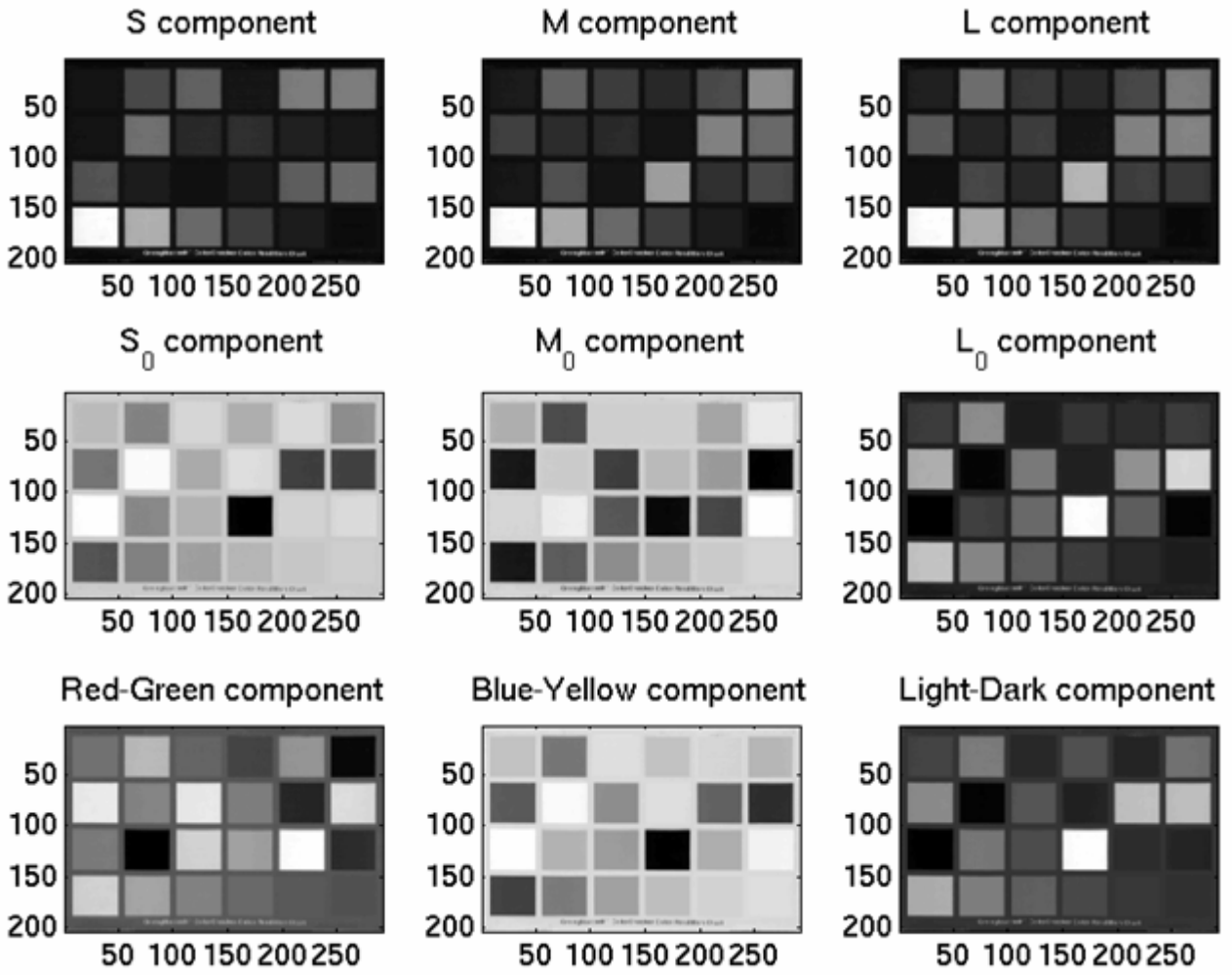
W_L, W_M and W_S are the weightings of cones L, M and S.

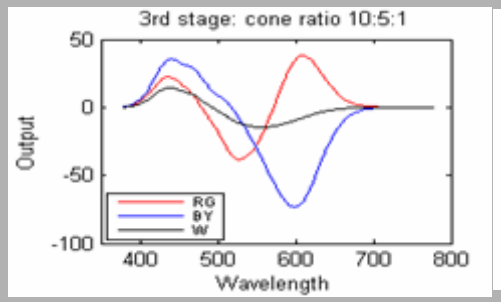
Multi-Stage Color Model: an Example

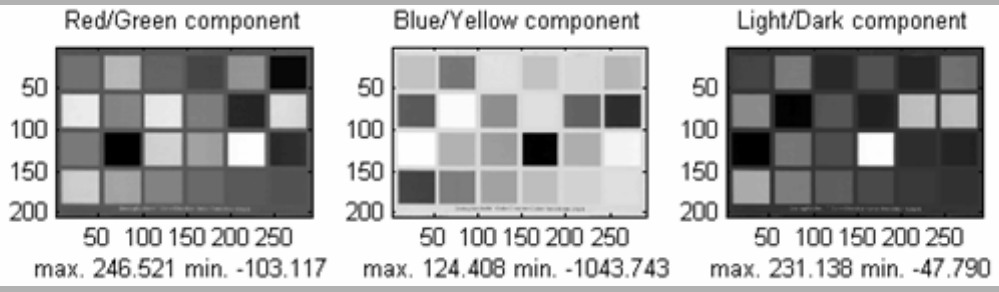


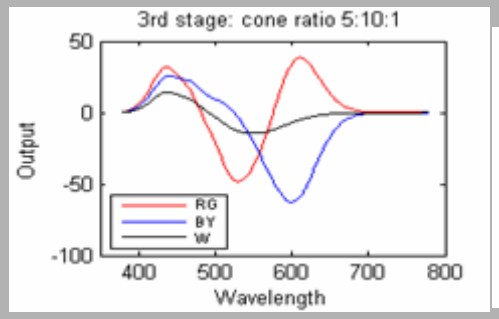


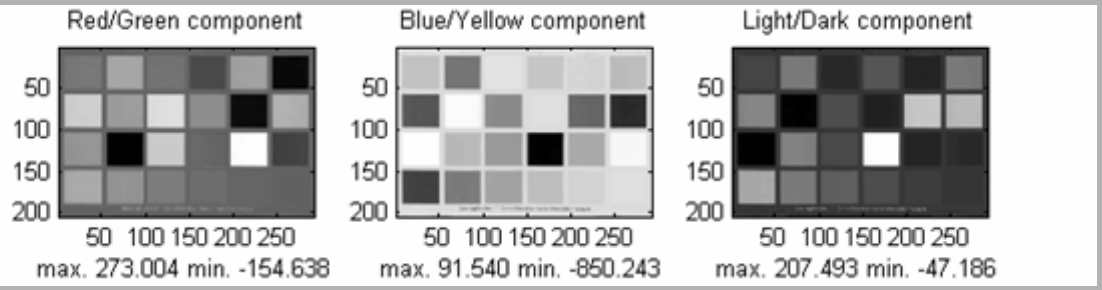


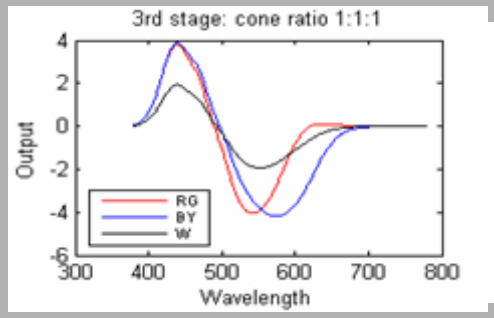


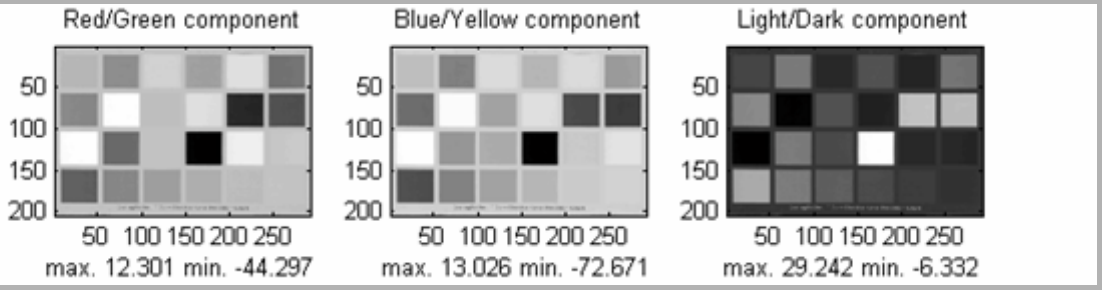

3rd stage: cone ratio 10:5:1
Output
Wavelength
RG
BY
W

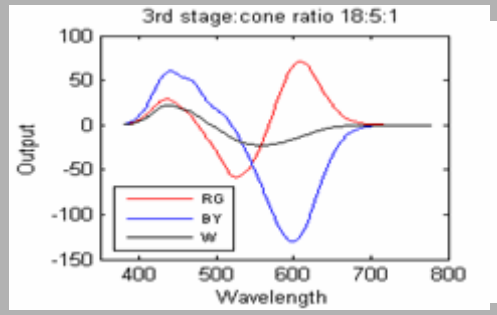

Red/Green component
Blue/Yellow component
Light/Dark component
max. 246.521 min. -103.117
max. 124.408 min. -1043.743
max. 231.138 min. -47.790

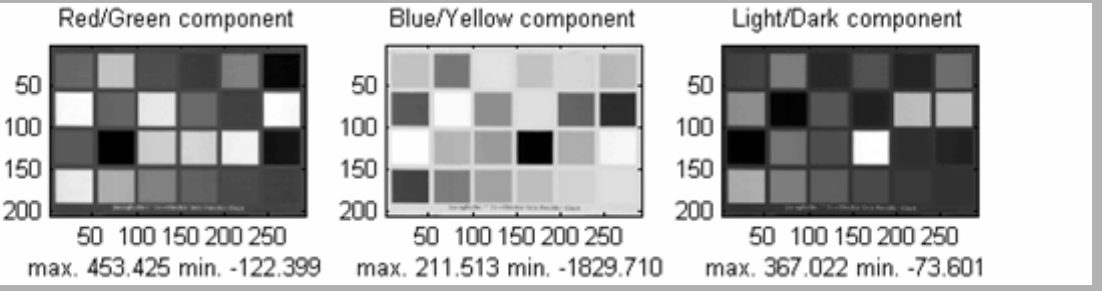

3rd stage: cone ratio 5:10:1
Output
Wavelength
RG
BY
W

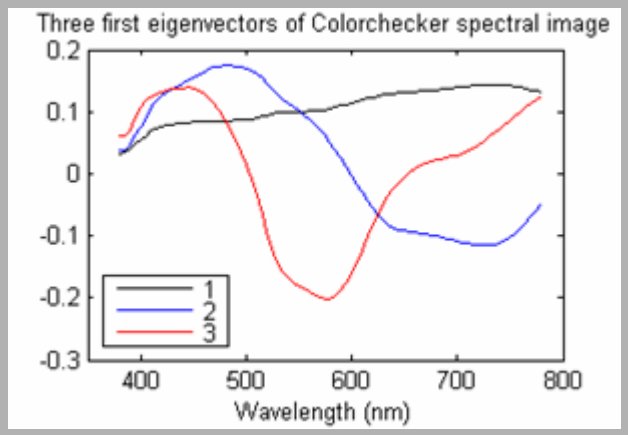

Red/Green component
Blue/Yellow component
Light/Dark component
max. 273.004 min. -154.638
max. 91.540 min. -850.243
max. 207.493 min. -47.186

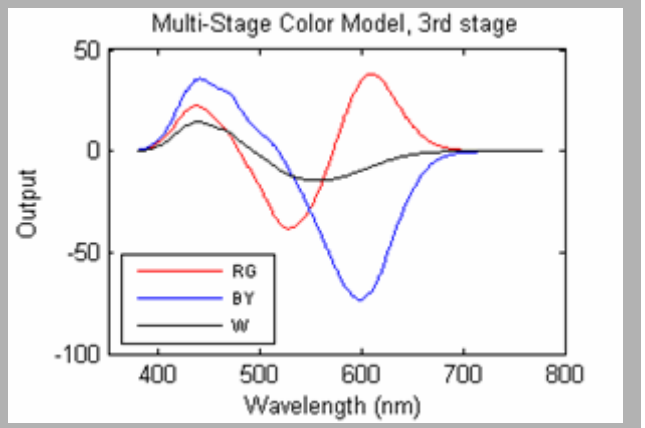

3rd stage: cone ratio 1:1:1
Output
Wavelength
RG
BY
W

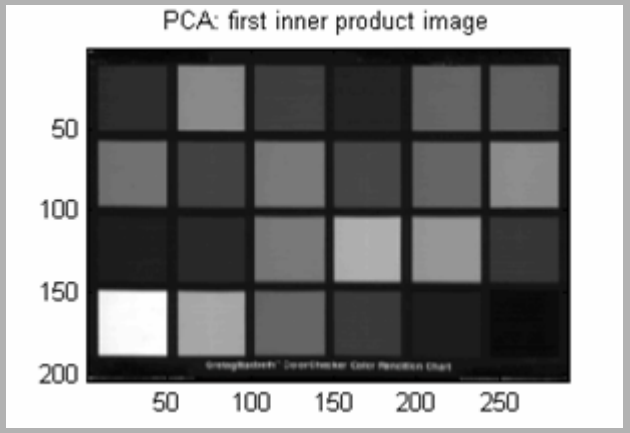

Red/Green component
Blue/Yellow component
Light/Dark component
max. 12.301 min. -44.297
max. 13.026 min. -72.671
max. 29.242 min. -6.332

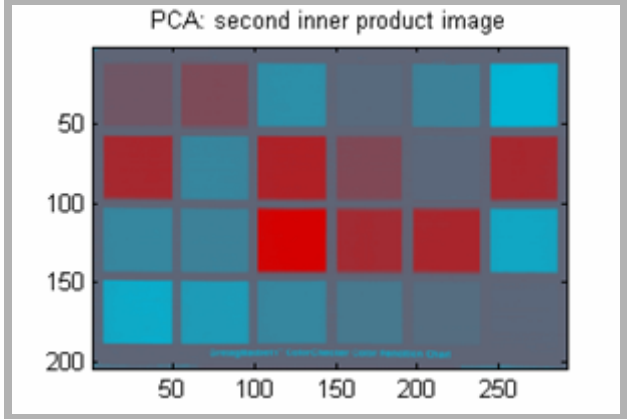

3rd stage:cone ratio 18:5:1
Output
Wavelength
RG
BY
W

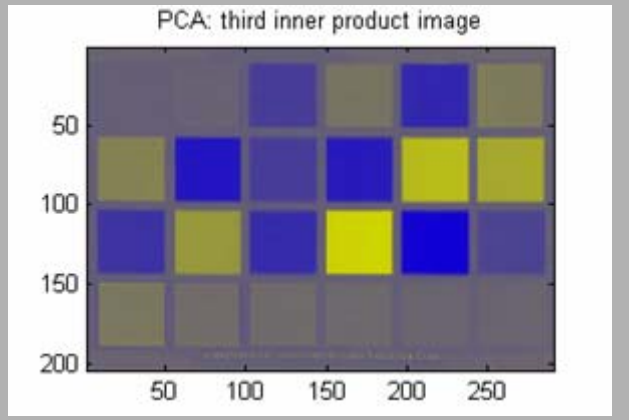

Red/Green component
Blue/Yellow component
Light/Dark component
max. 453.425 min. -122.399
max. 211.513 min. -1829.710
max. 367.022 min. -73.601

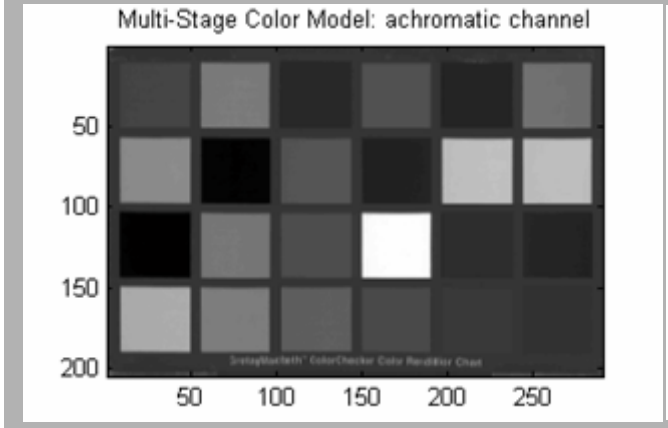

Three first eigenvectors of Colorchecker spectral image
0.2
0.1
0
-0.1
-0.2
-0.3
400
500
600
700
800
Wavelength (nm)
1
2
3

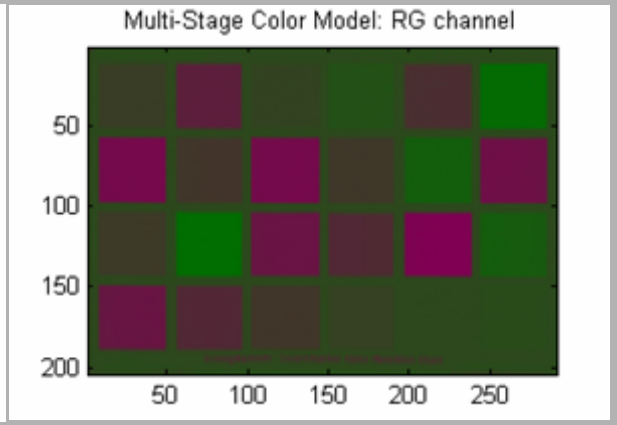

Multi-Stage Color Model, 3rd stage
50
0
-50
-100
Output
400
500
600
700
800
Wavelength (nm)
RG
BY
W

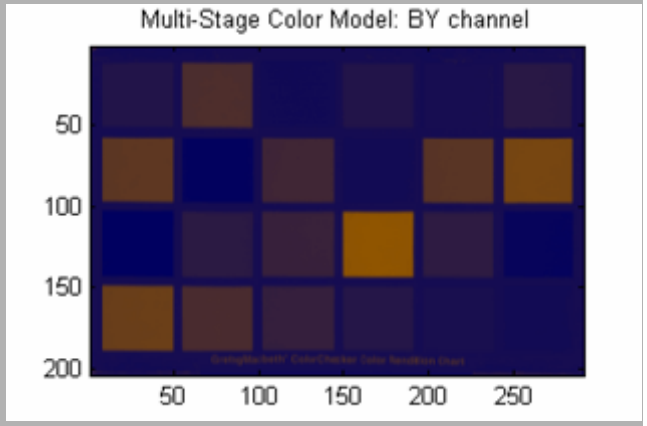

PCA: first inner product image
50
100
150
200
50
100
150
200
250


PCA: second inner product image
50
100
150
200
50
100
150
200
250


PCA: third inner product image
50
100
150
200
50
100
150
200
250


Multi-Stage Color Model: achromatic channel
50
100
150
200
50
100
150
200
250

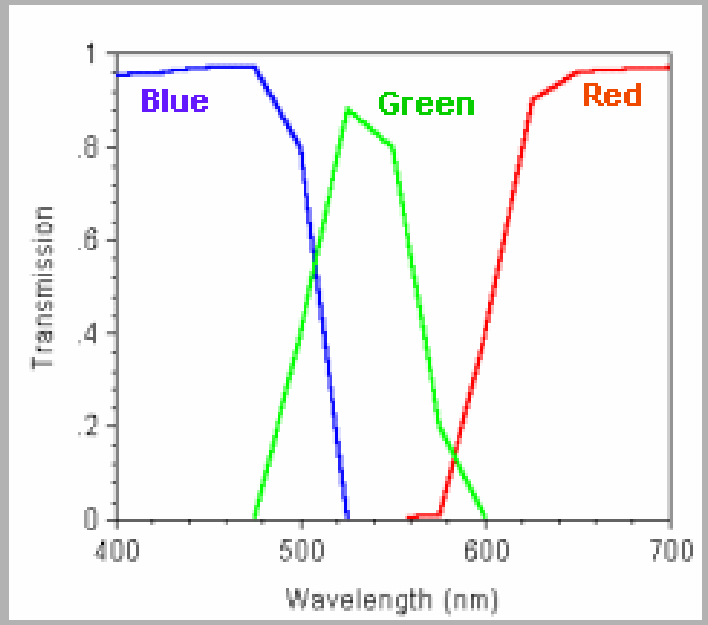

Multi-Stage Color Model: RG channel
50
100
150
200
50
100
150
200
250


Multi-Stage Color Model: BY channel
50
100
150
200
50
100
150
200
250

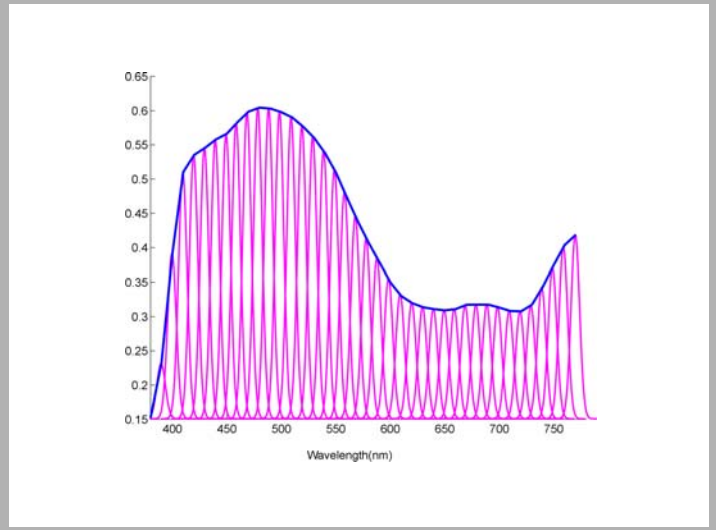
Color measuring and imaging

Principle in color imaging

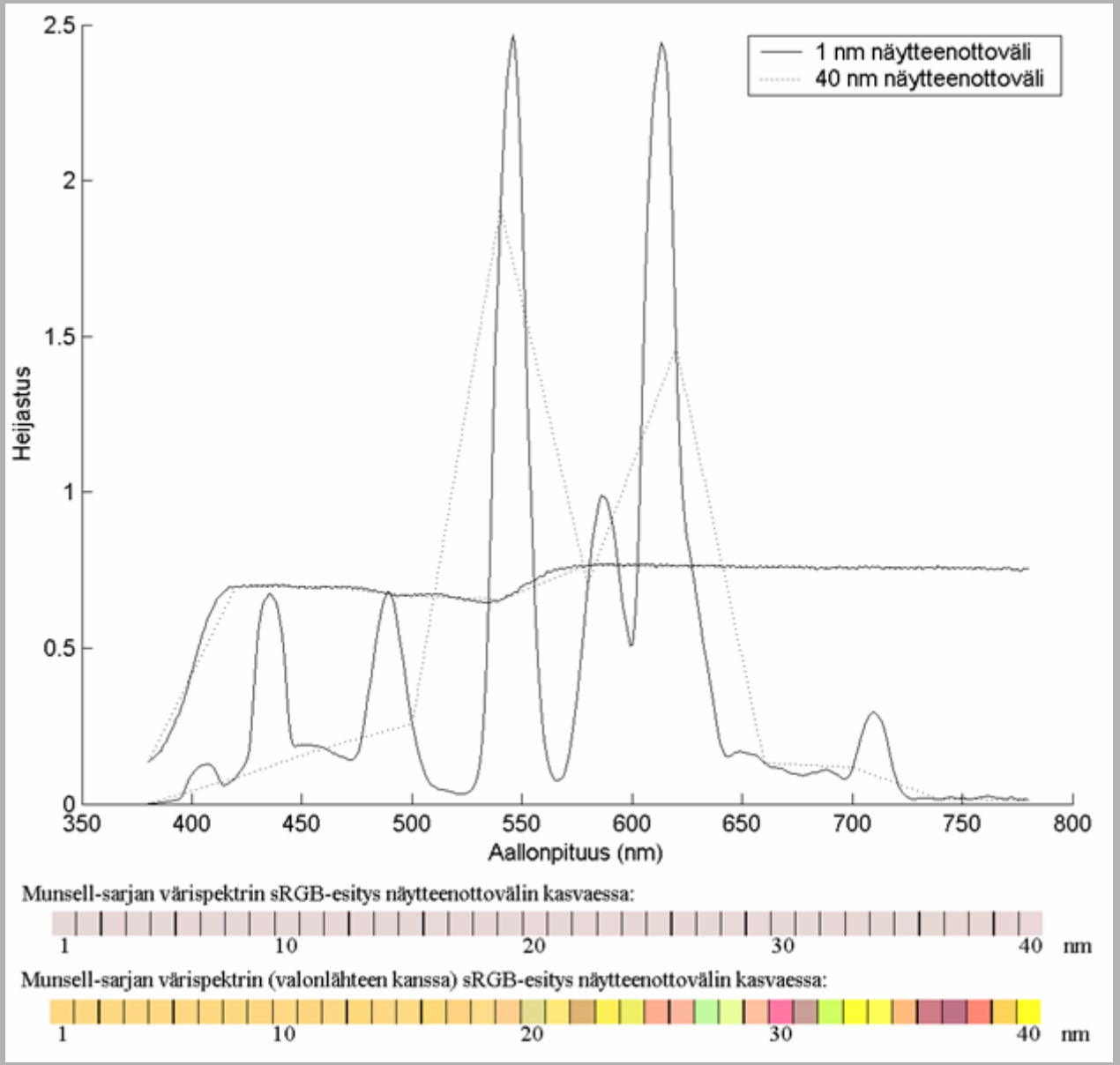
- Color spectrum is measured
- Wide band (like RGB) sampling



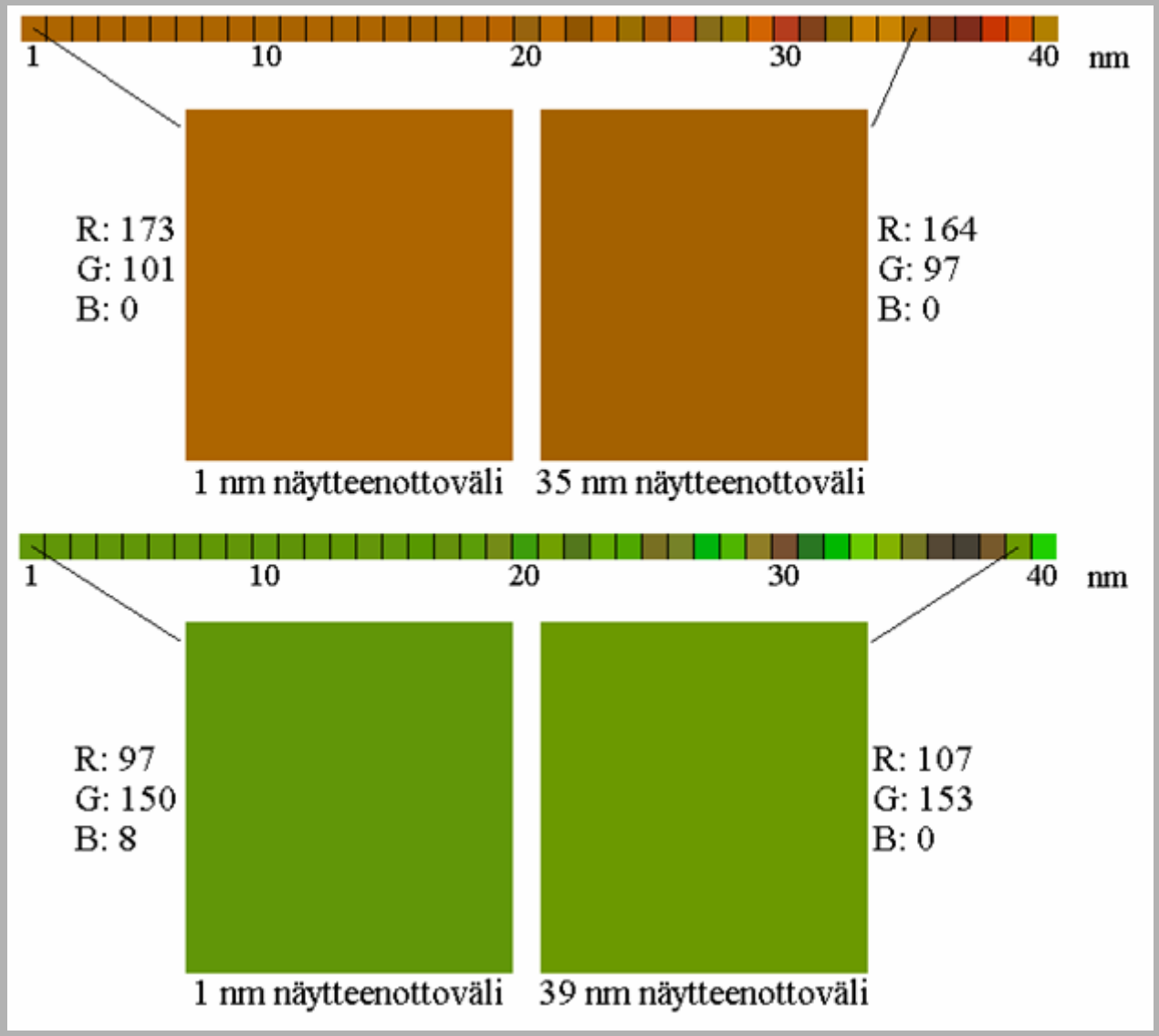
narrow band (color spectrum) sampling



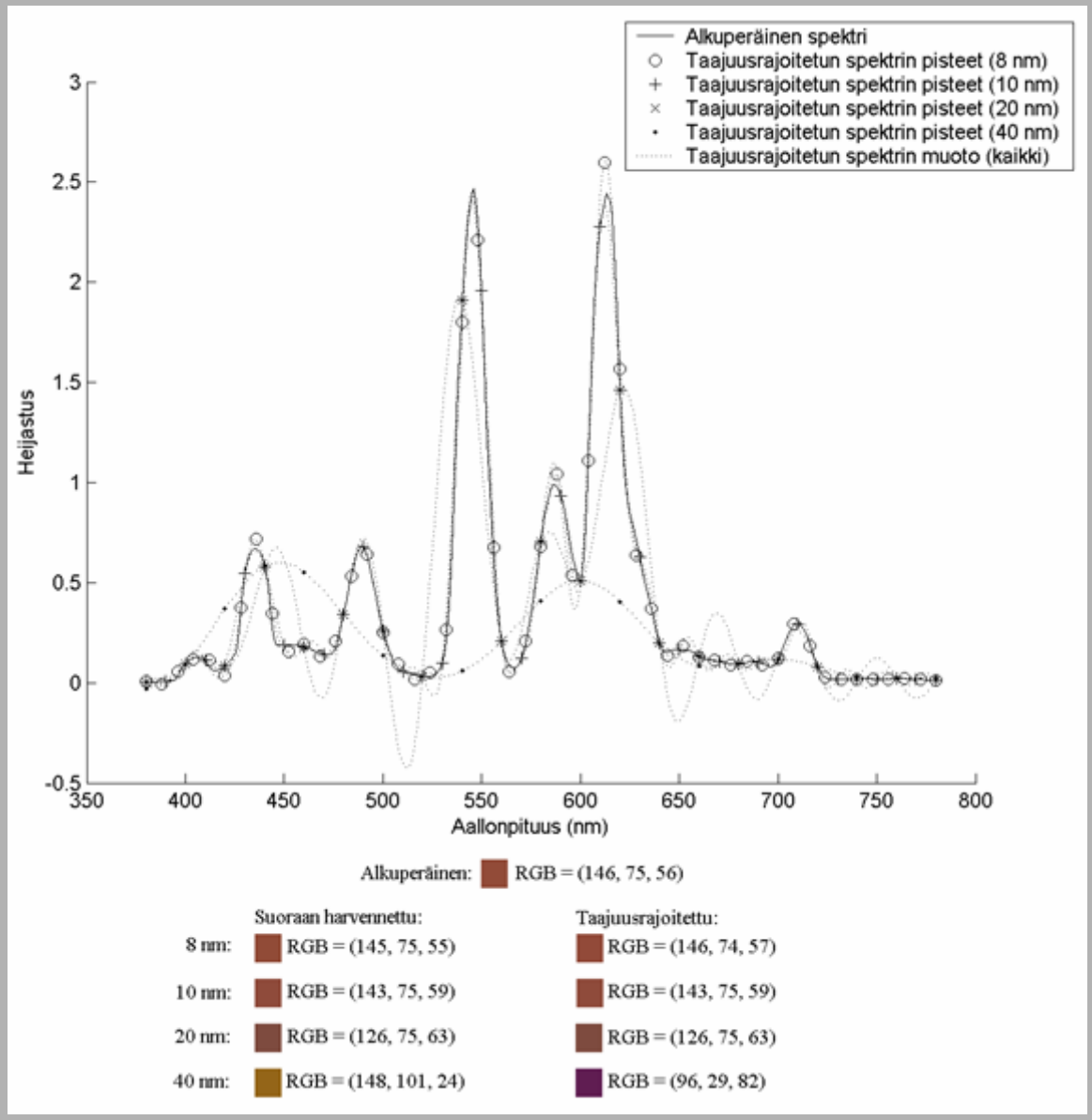
Spectral dependence on sampling

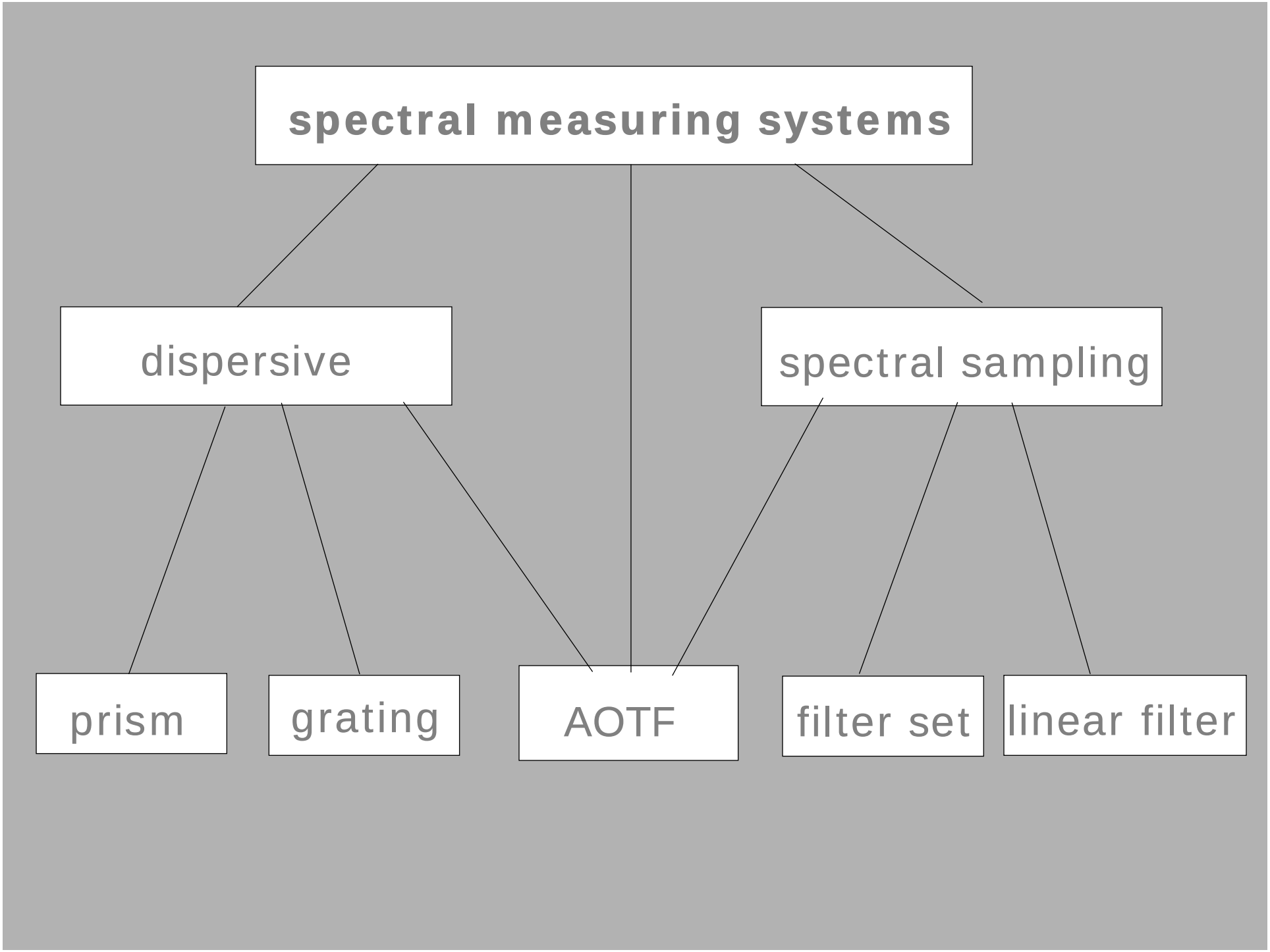


Color dependence on sampling



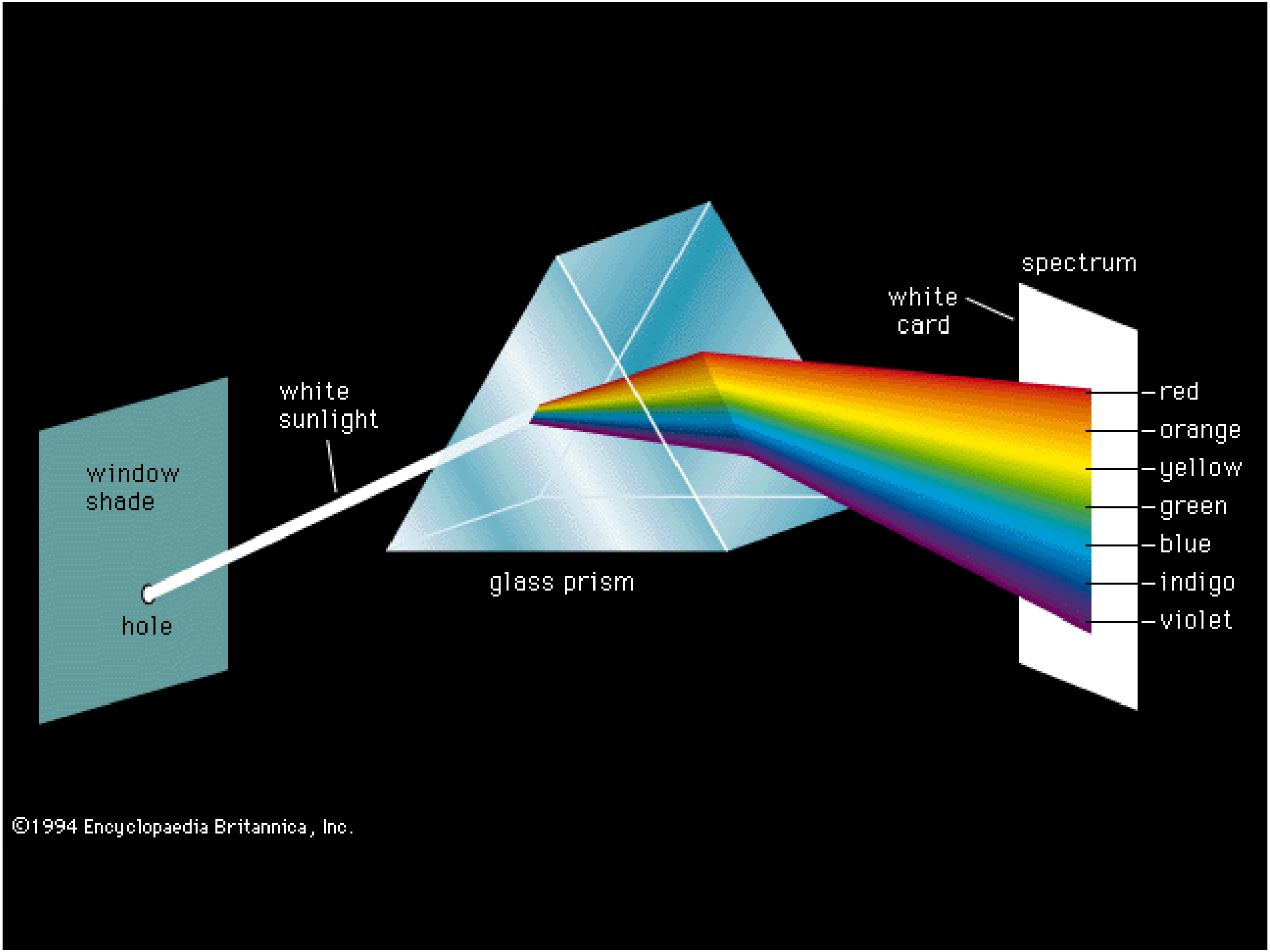
Change of RGB-values due to sampling



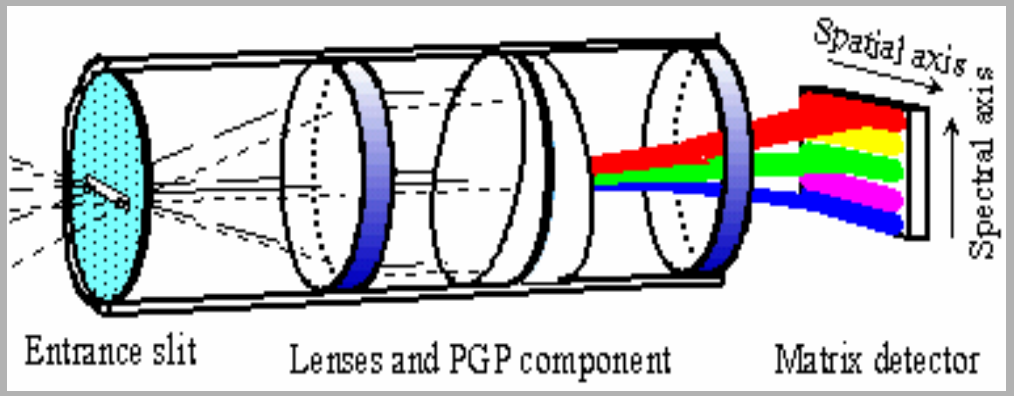

spectral measuring systems
dispersive
spectral sampling
prism
grating
AOTF
filter set
linear filter

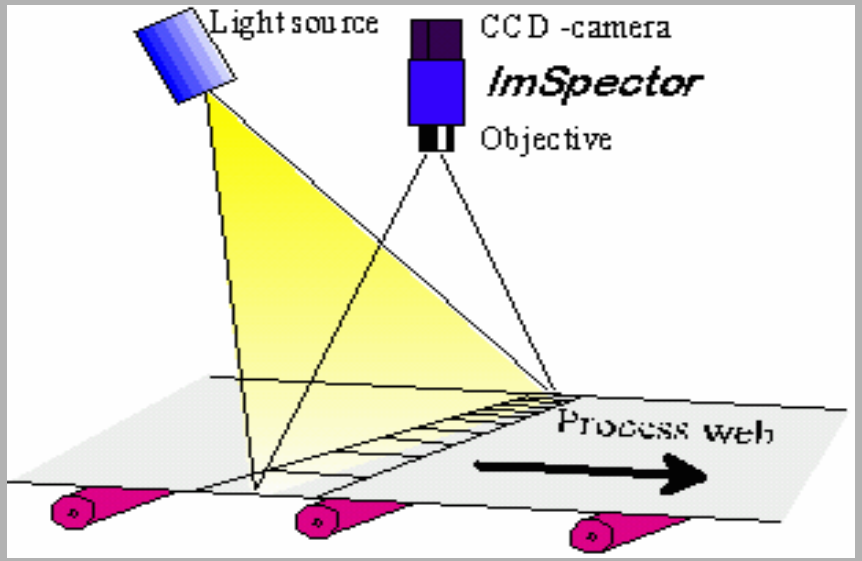
Multispectral cameras

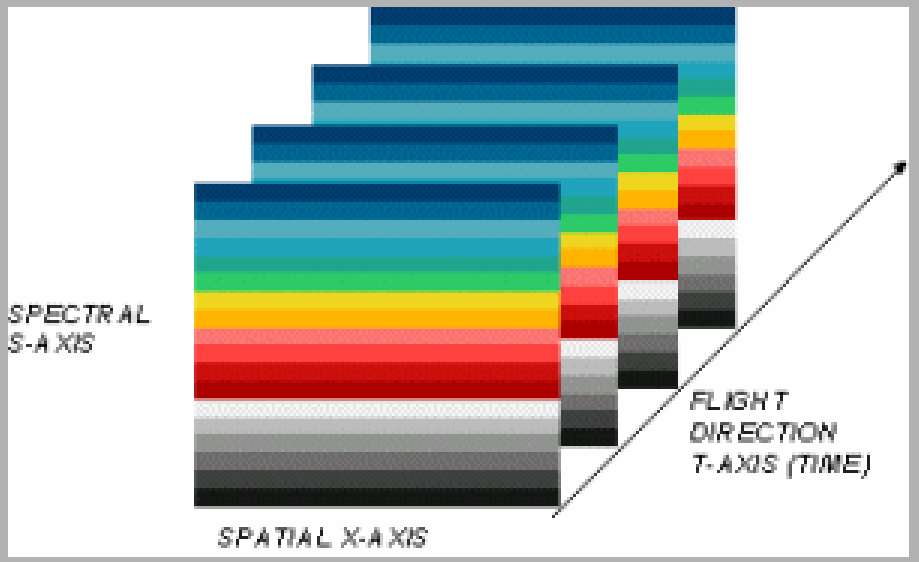
16-band multispectral camera for still image


spectrum
white
card
white
sunlight
window
shade
hole
glass prism
red
orange
yellow
green
blue
indigo
violet
©1994 Encyclopaedia Britannica, Inc.

Spectral Line Camera







ImSpector V8

- spectral range: 380 – 780 nm
- spectral resolution: 4 nm
- spectral interval: avg. 0.46 nm
- slit width: 50 μm
- numerical aperture: F/2.8
- camera:
  - PCO PixelFly (12-bit)
  - CCD: 1280 x 1024

ImSpector V10E

- spectral range: 400 – 1000 nm
- spectral resolution: 2.8 nm
- spectral interval: avg. 0.74 nm
- slit width: 30 μm
- numerical aperture: F/2.4
- camera:
  - Adimec-1600m/D (12-bit)
  - CCD: 1600 x 1200

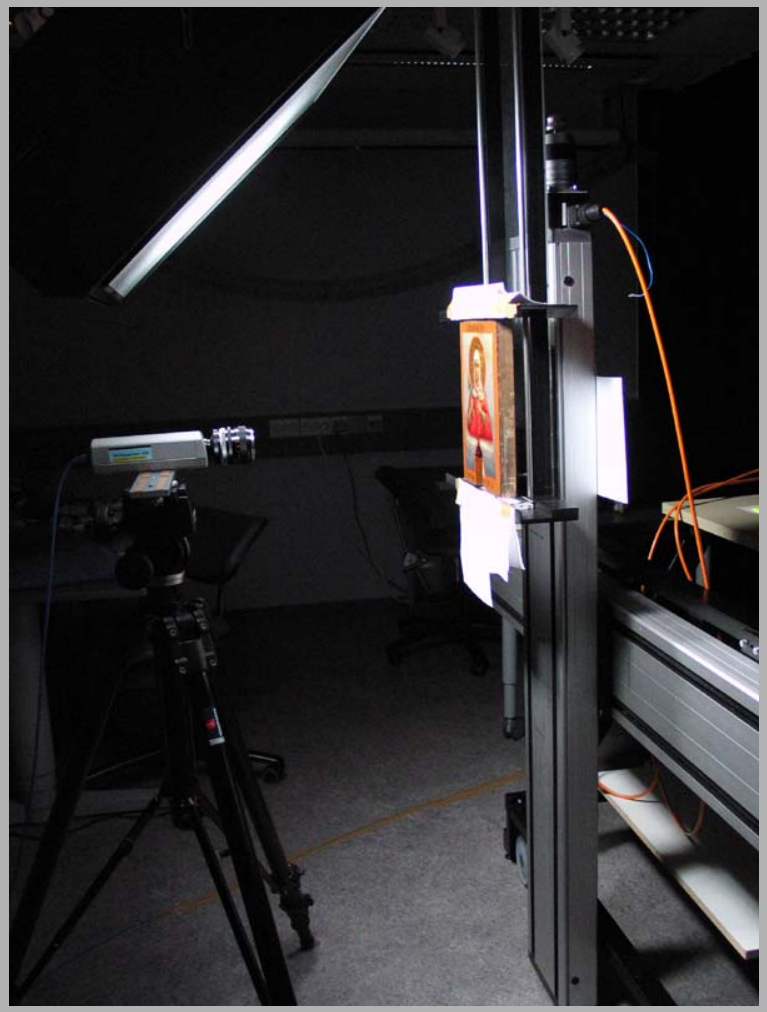
ImSpector N17E

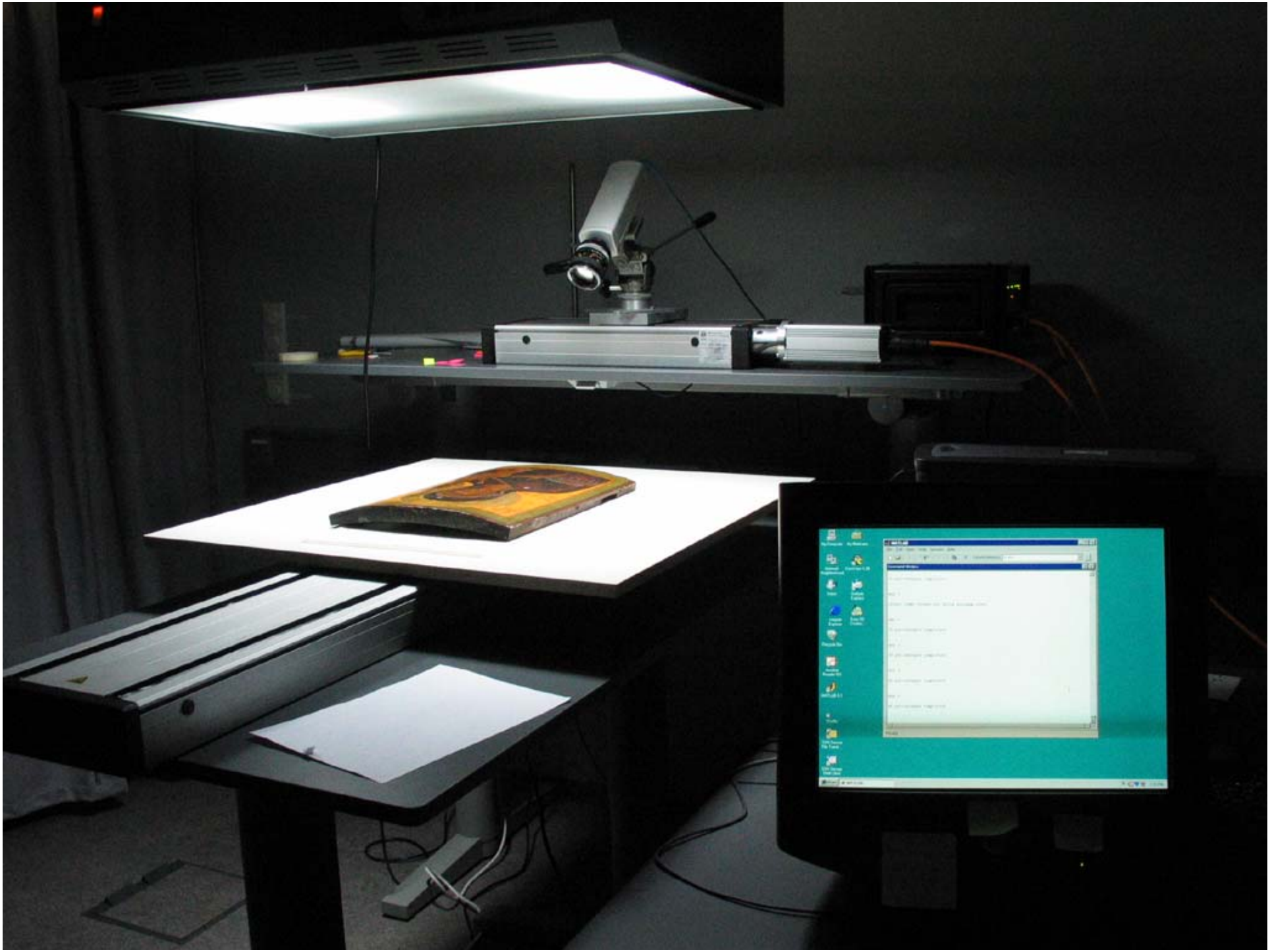
- spectral range: 950 – 1700 nm
- spectral resolution: 5 nm
- spectral interval: avg. 3.3 nm
- slit width: 30 μm
- numerical aperture: F/2.8
- camera:
  - Xenics InGaAs
    XEVA-USB-FPA (12-bit)
  - CCD: 320 x 256

Nuance LCTF (by CRi)

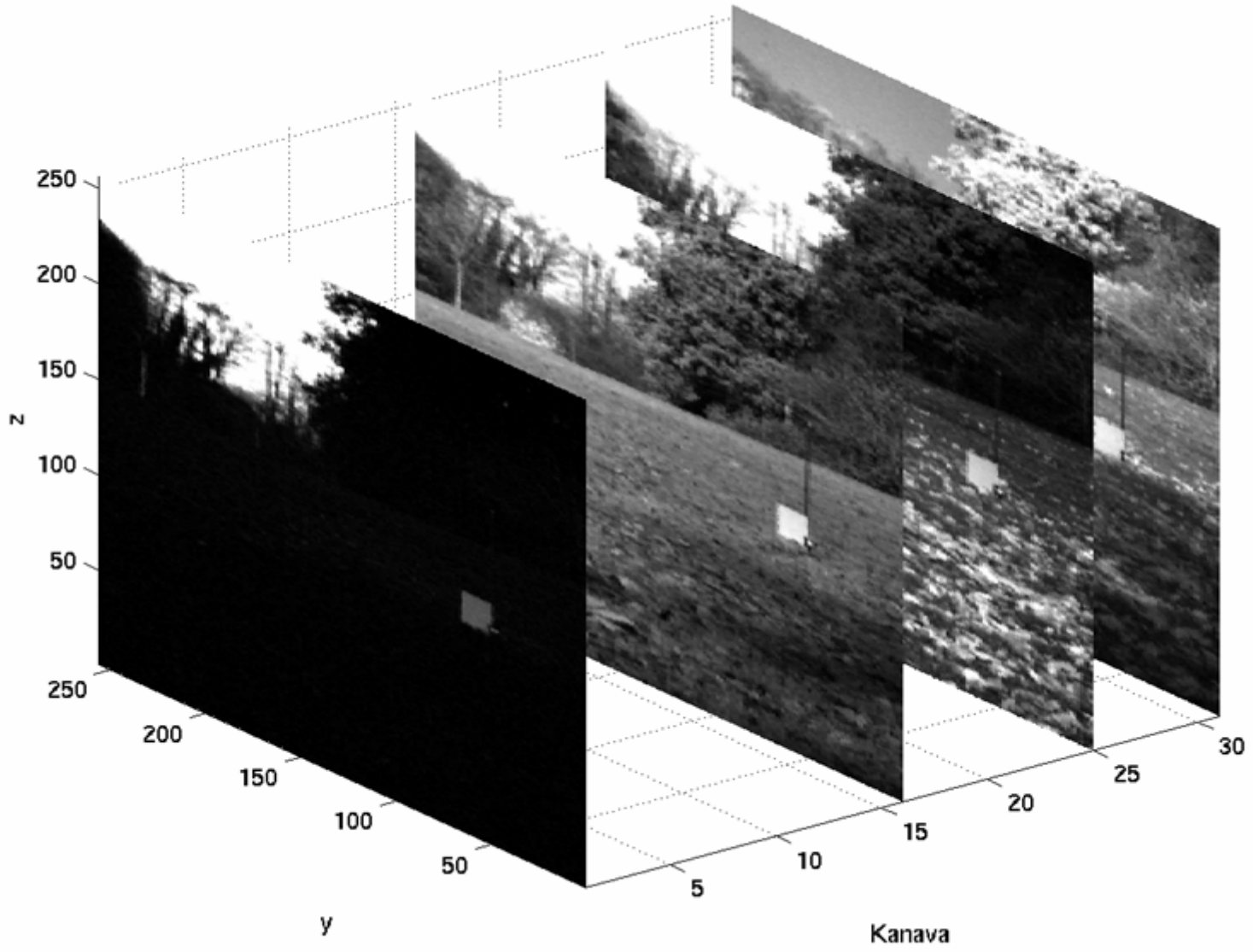
- spectral range: 420 – 720 nm
- spectral bandwidth: 10 nm
- wavelength accuracy: 1.25 nm
- camera:
  - 1.3 M pixels (12-bit)

Spectral camera measurements

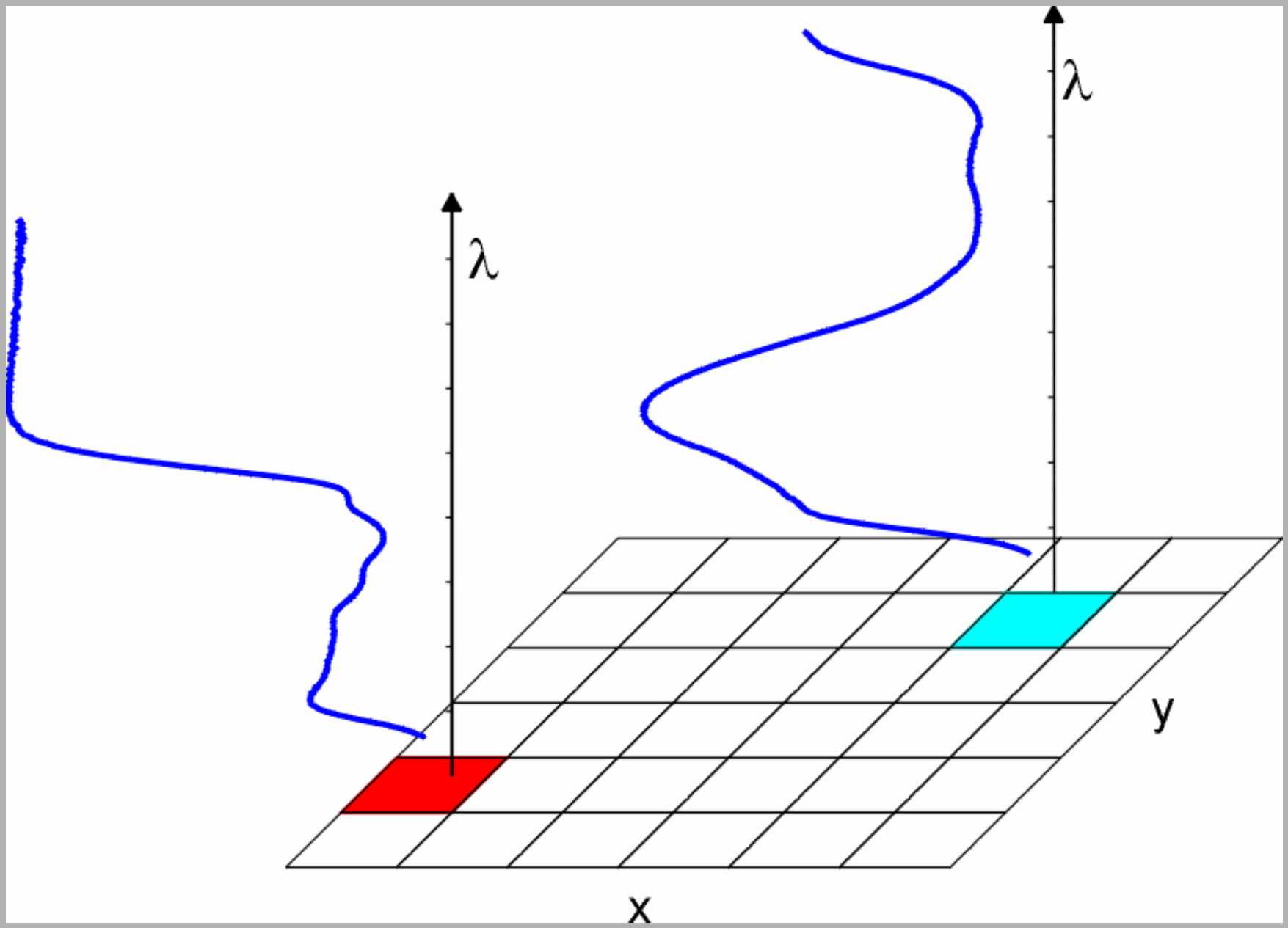




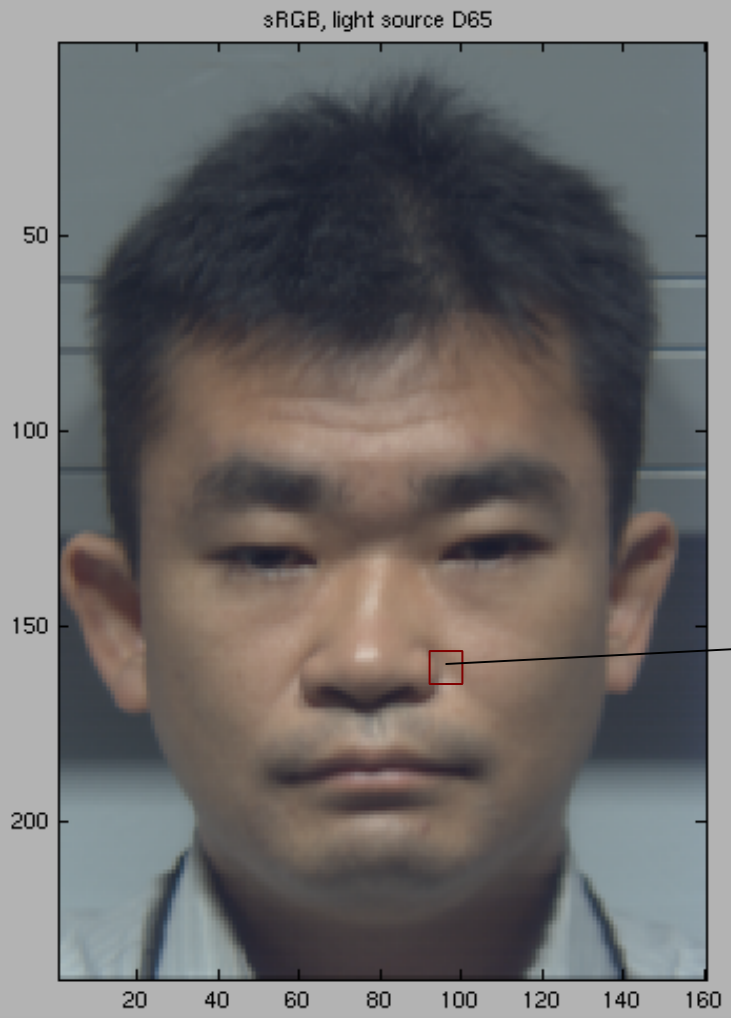
Components of a spectral image

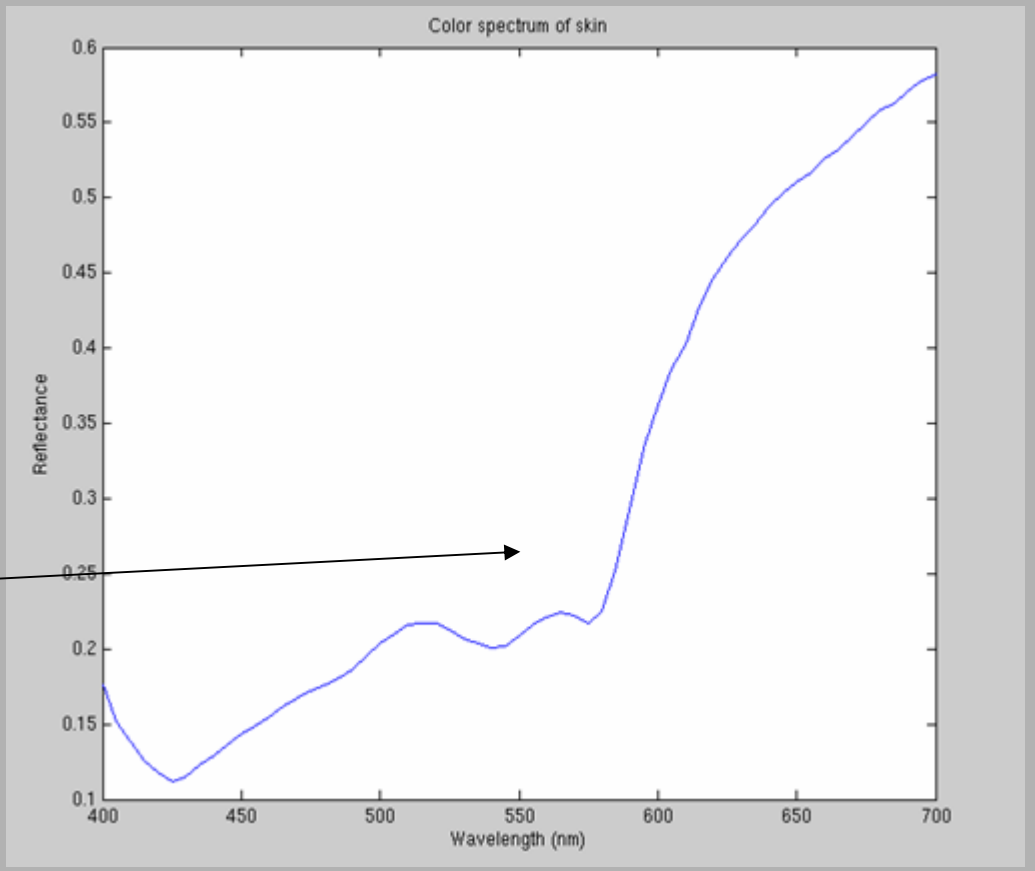


Pixels of a spectral image

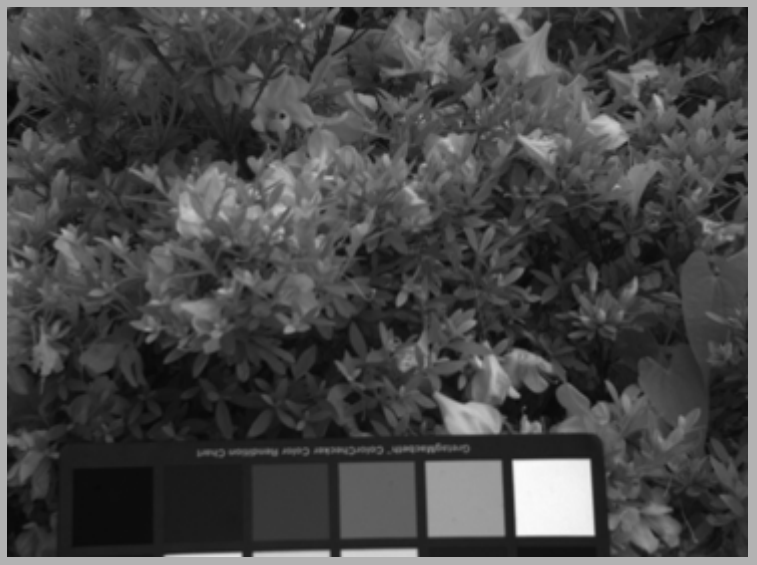


Spectral Face Image

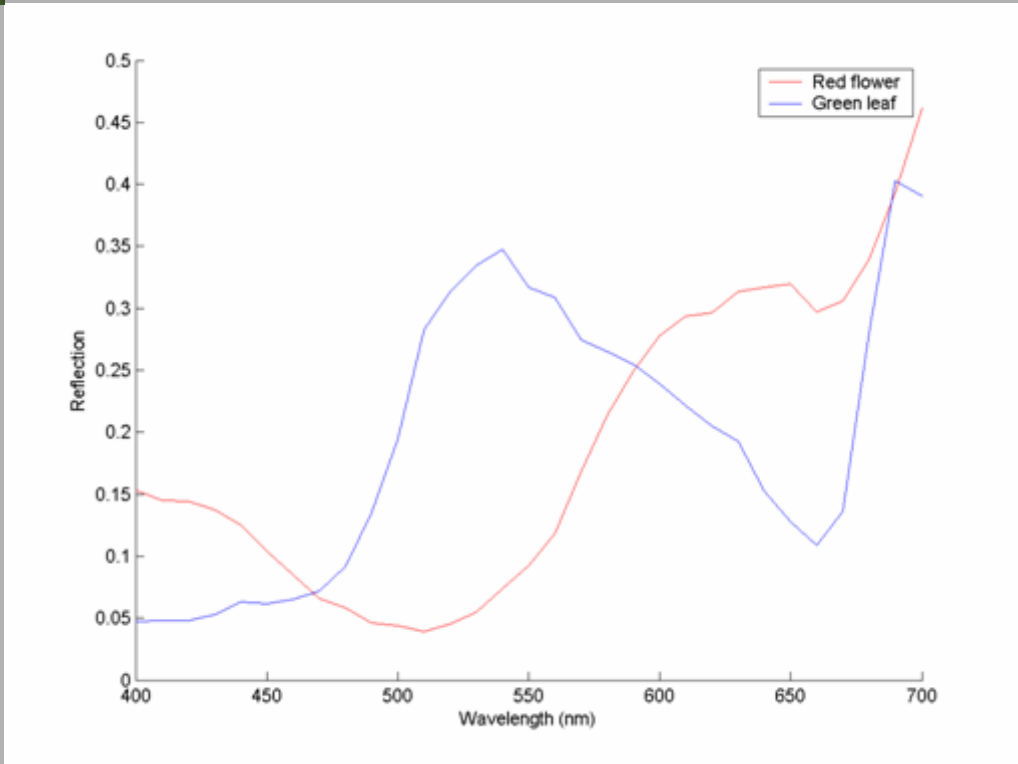


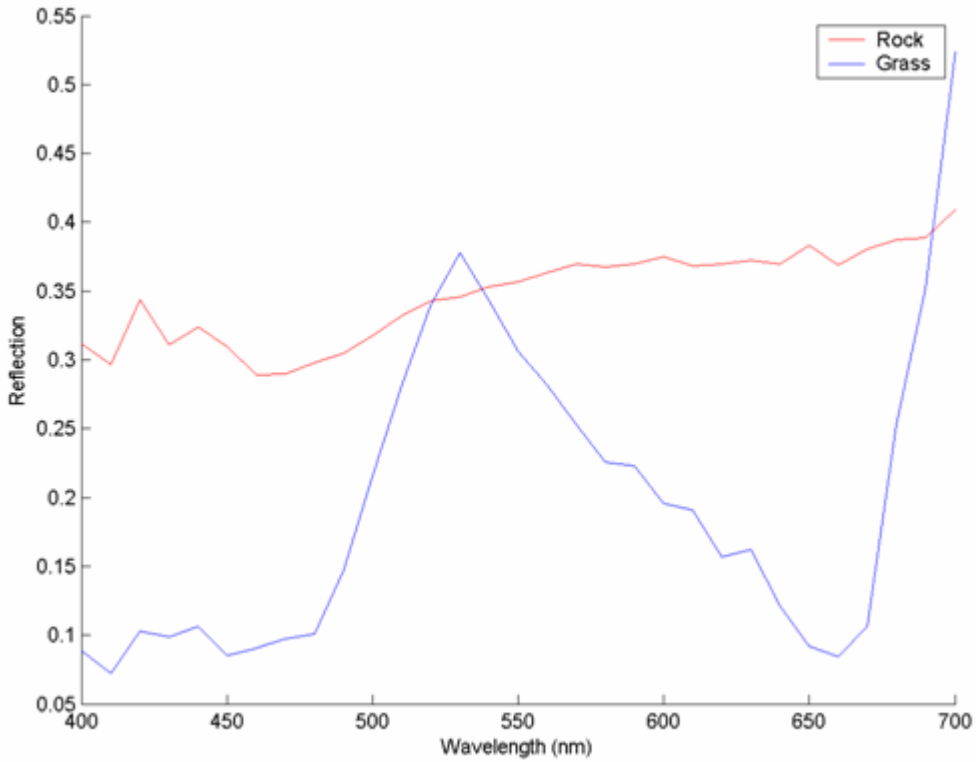


Spectral component images (400, 550, 700 nm)

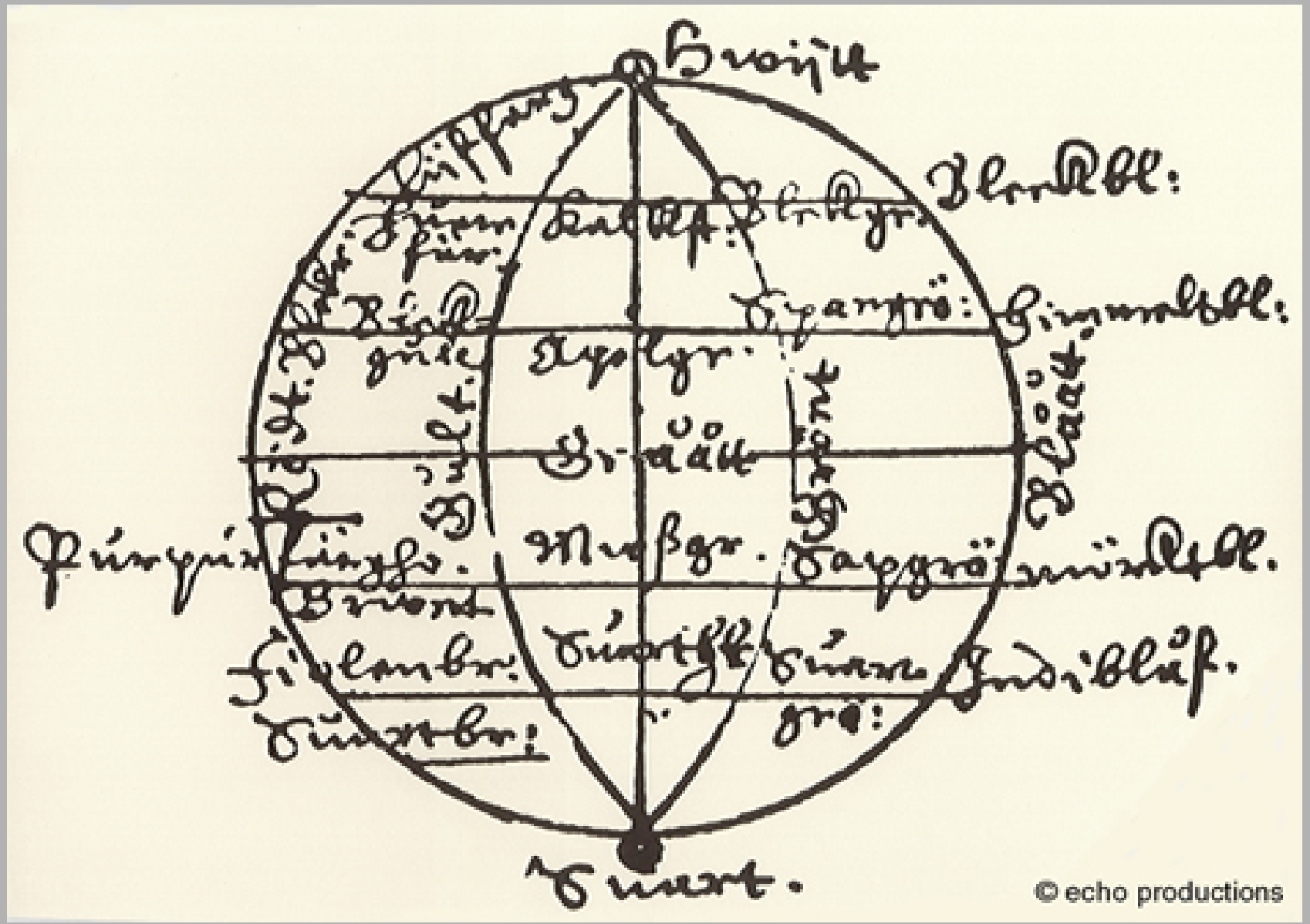


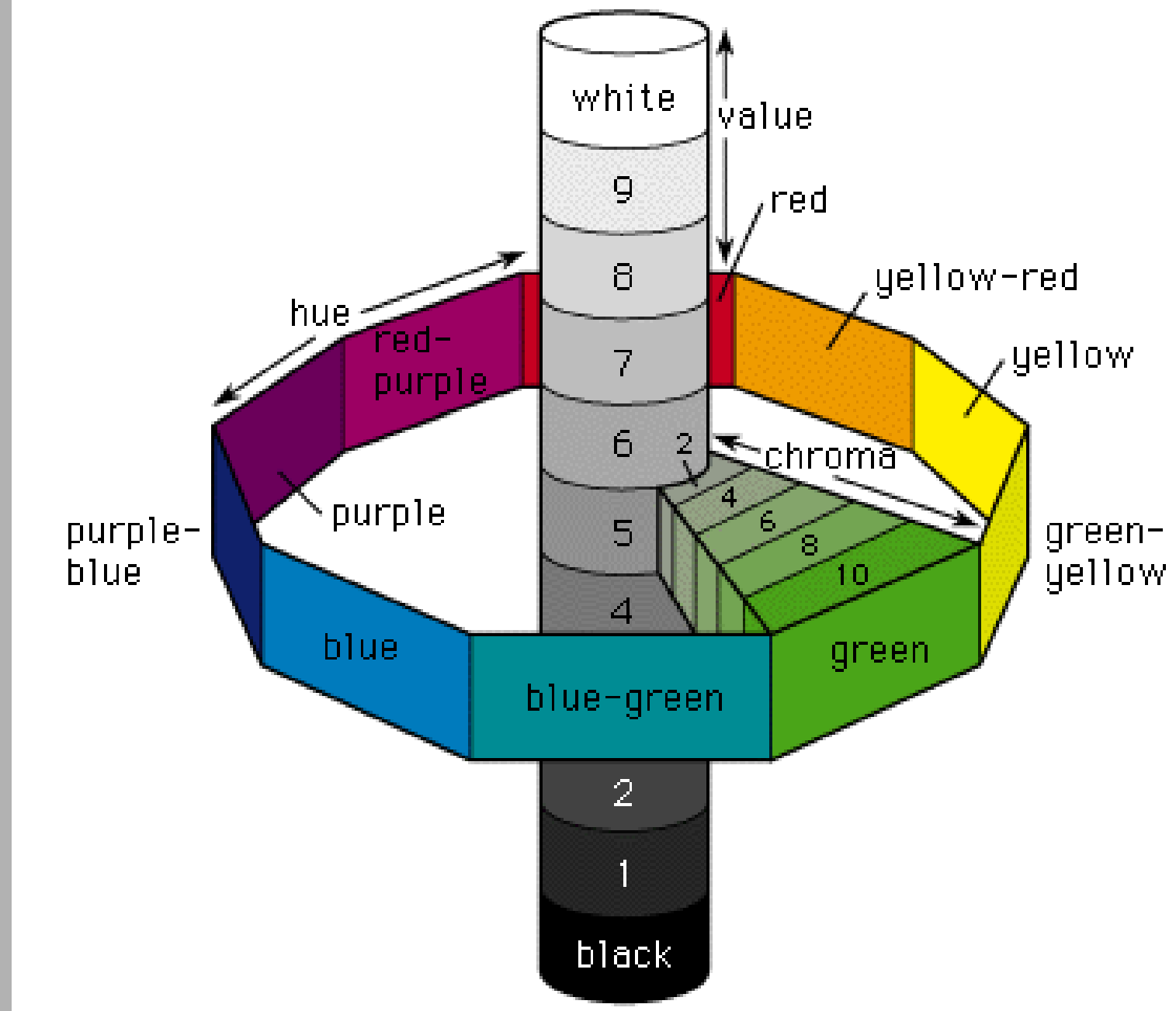

GretagMacbeth™ ColorChecker Color Rendition Chart


Red flower
Green leaf
Reflection
Wavelength (nm)
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
400
450
500
550
600
650
700


Rock
Grass
Reflection
Wavelength (nm)
0.55
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
400
450
500
550
600
650
700

Color ordering and coordinates





xy-chromaticity coordinates