The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific and
Cultural Organization

IAEA
International Atomic Energy Agency

2018-16

Winter College on Optics in Environmental Science

2 - 18 February 2009

Multi-spectral Imaging: Overview and do-it-yourself experiments

Brydegaard M.

Lund Institute of Technology
Sweden

Multi-spectral Imaging: Overview and do-it-yourself experiments

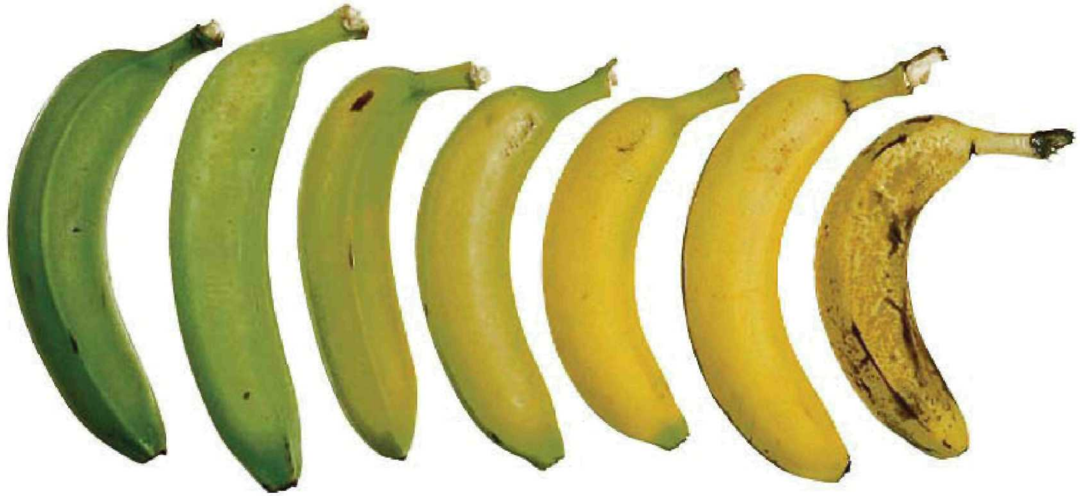
Abdus Salam International Center for Theoretical Physics, 2009

Mikkel Brydegaard

Division of Atomic Physics

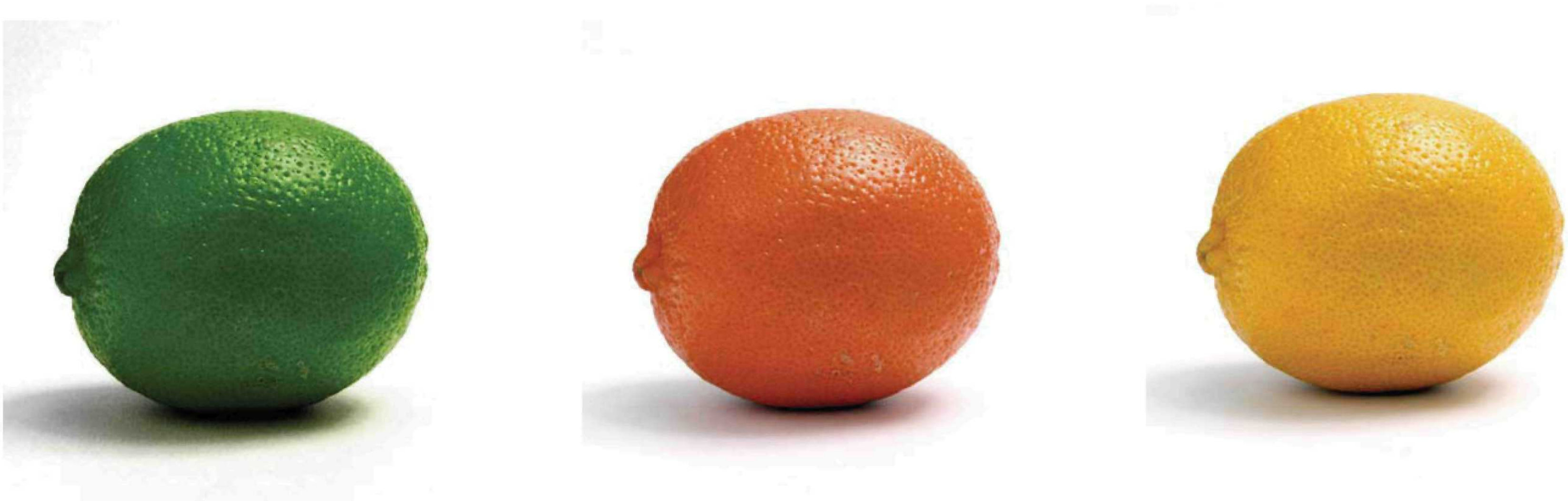
Lund University, Sweden

Spectroscopy for quality control



Which banana is the most tasty?

Spectroscopy for object identification

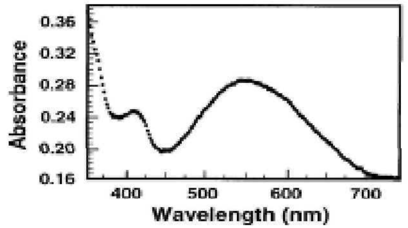


Lime, Orange and Lemon. Which is which?

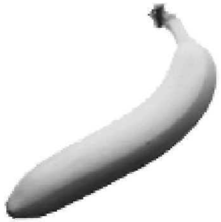
Spatial signatures and spectral signatures

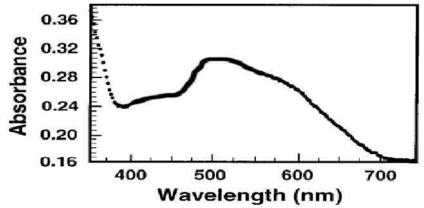
Spatial identification

Spectral identification

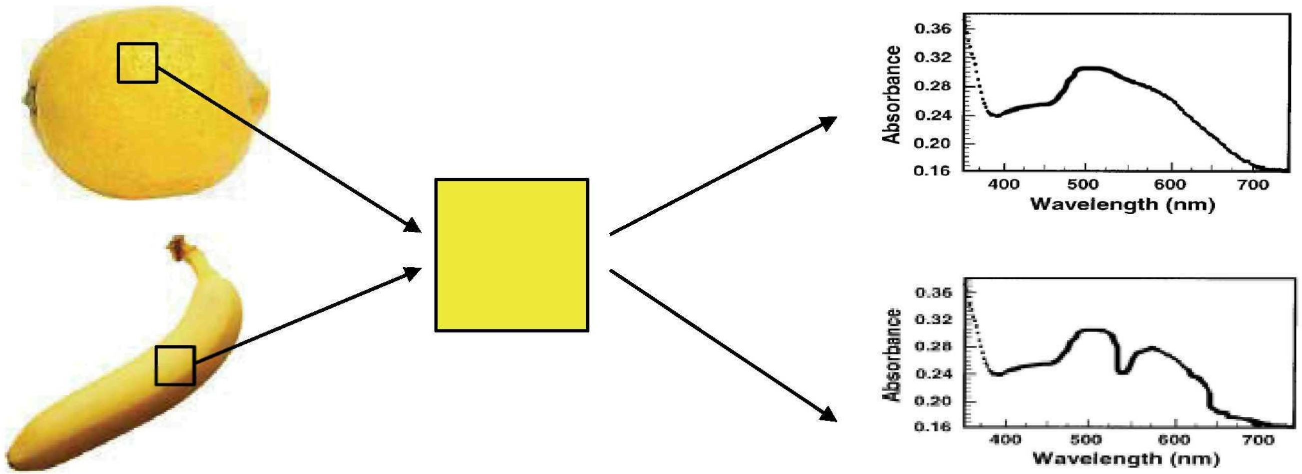


Tomato





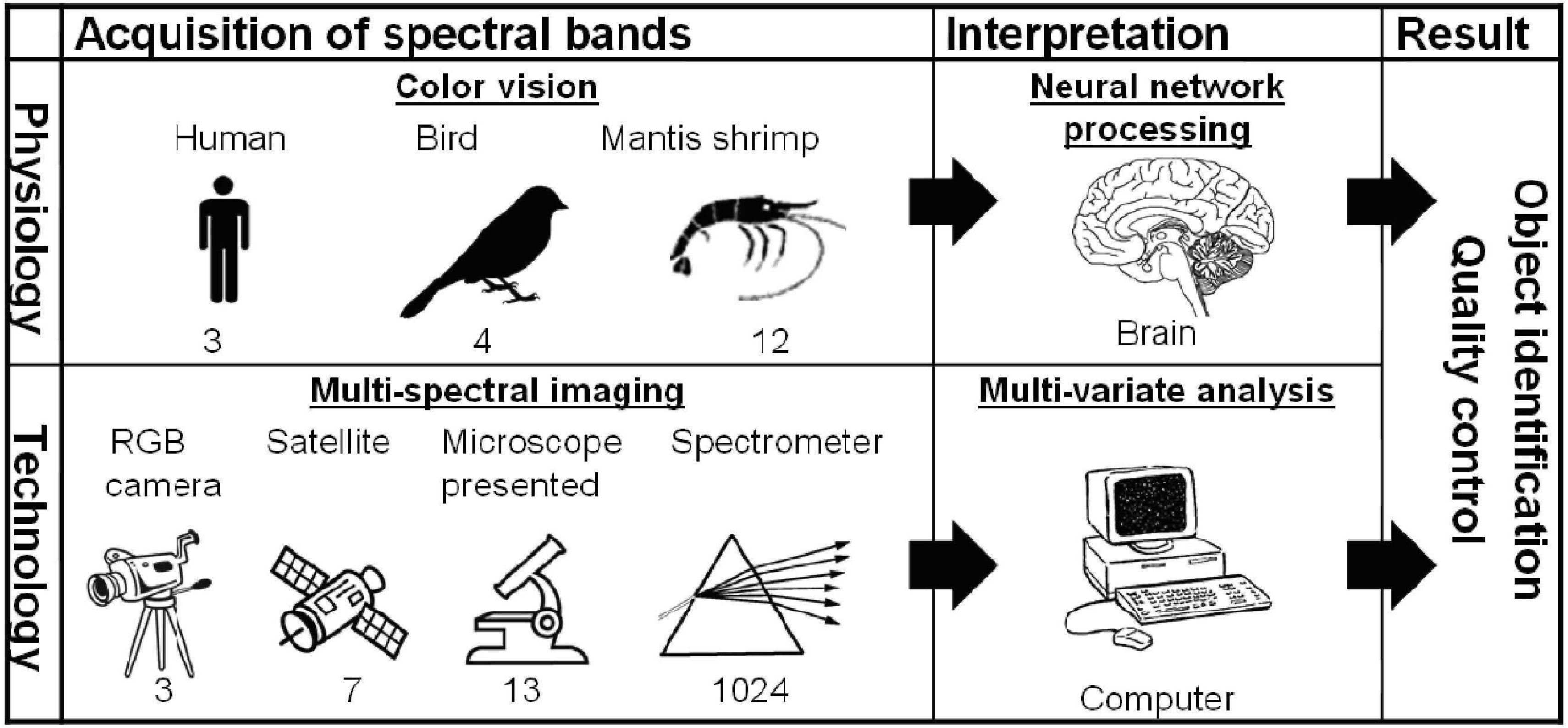
Banana



Banana

Lemon

What to do with spectroscopy?



M. Brydegaard, AJP, 2009

Light environment and evolution of senses

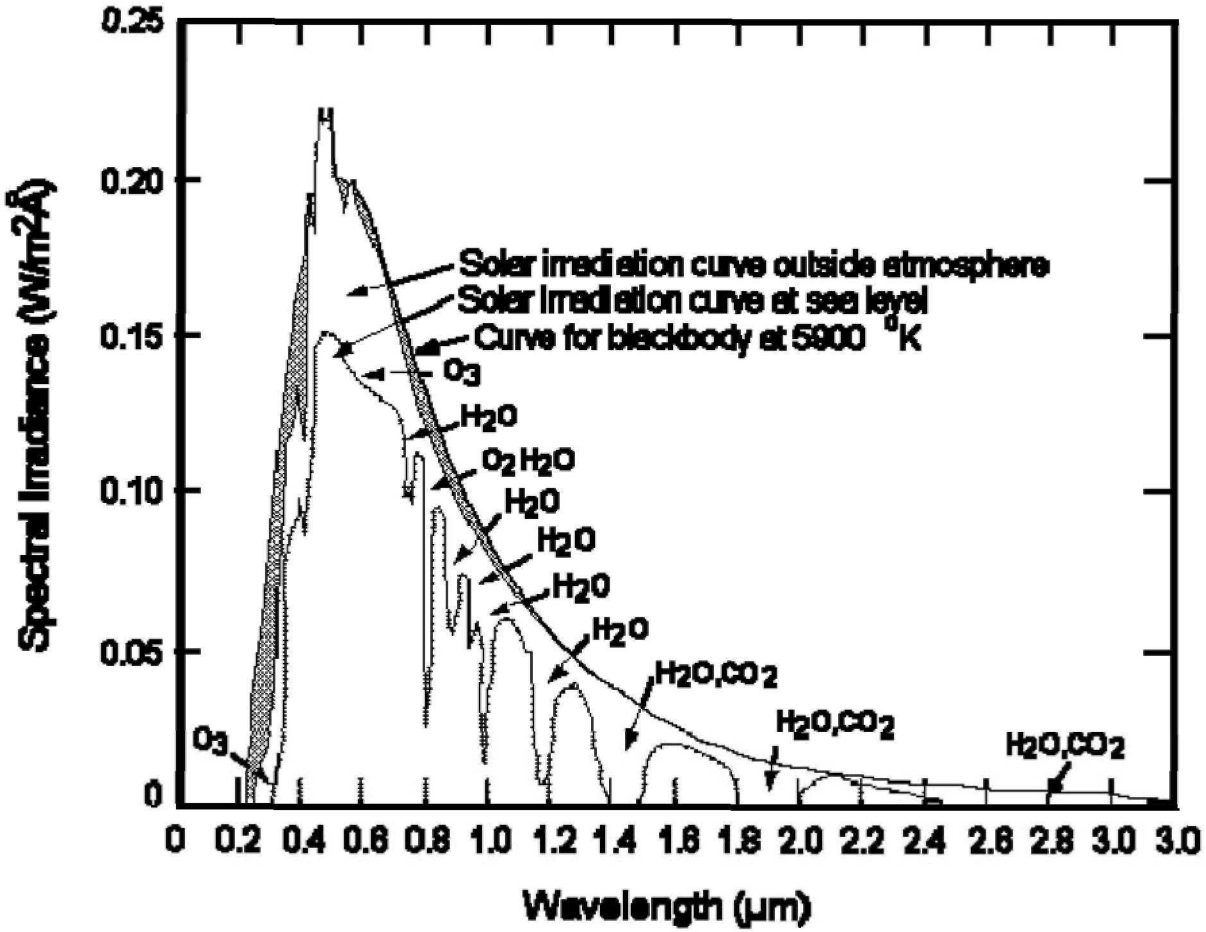
- **Black body radiation**
- **Planck's law of radiation**

$$I(\nu) = \frac{2h\nu^3}{c^2}\frac{1}{e^{\frac{h\nu}{kT}} - 1}$$

- **Differentiation leads to Wien's displacement law**

$$\lambda_{max} = \frac{b}{T}$$

- **The sun and black body radiation**
- **The solar radiation peaks around 550nm**

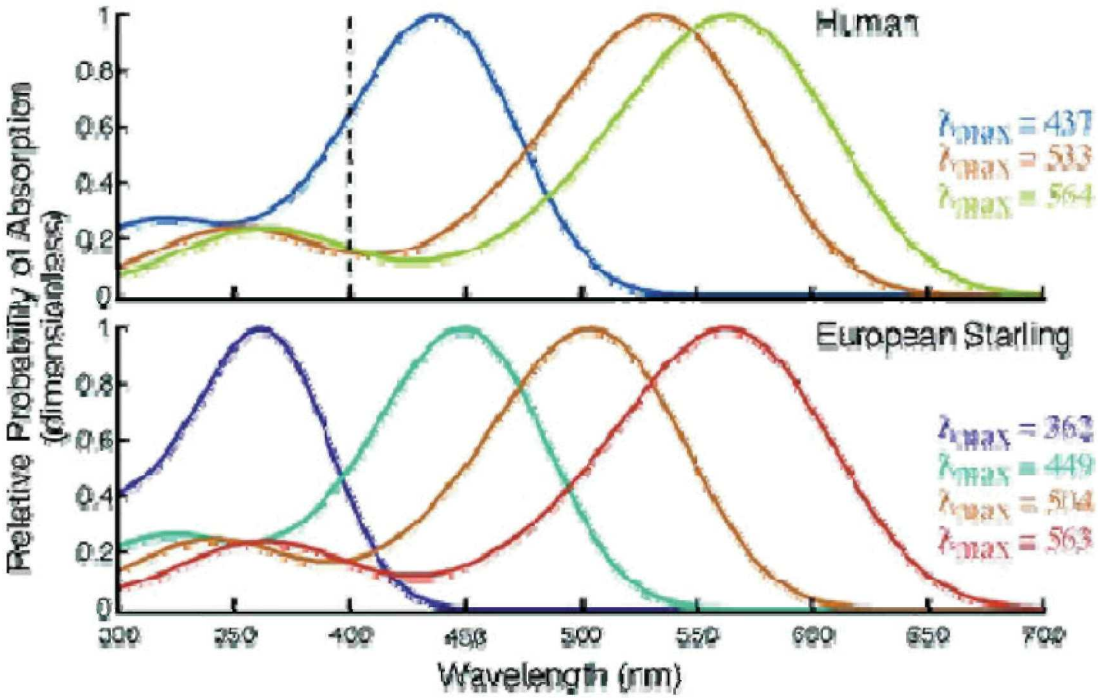


http://www.csr.utexas.edu/projects/rs/hrs/pics/irradiance.gif

Light environment and evolution of senses

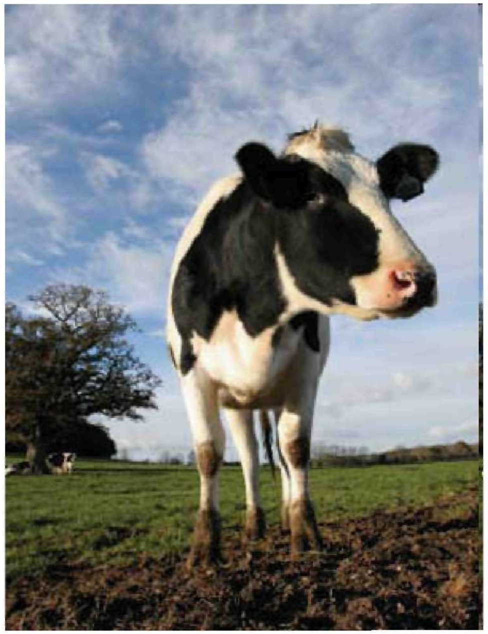
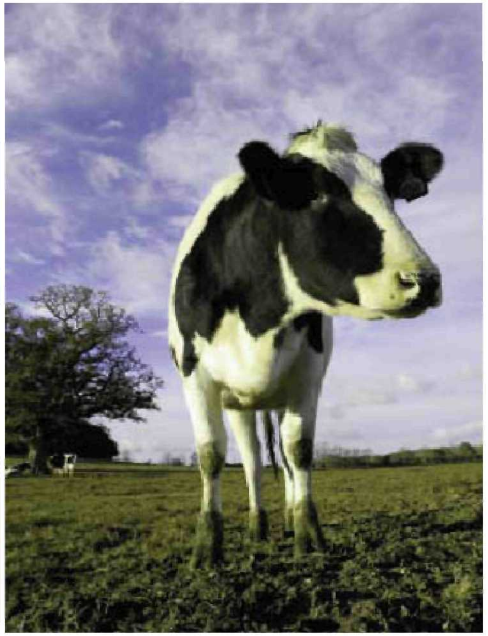
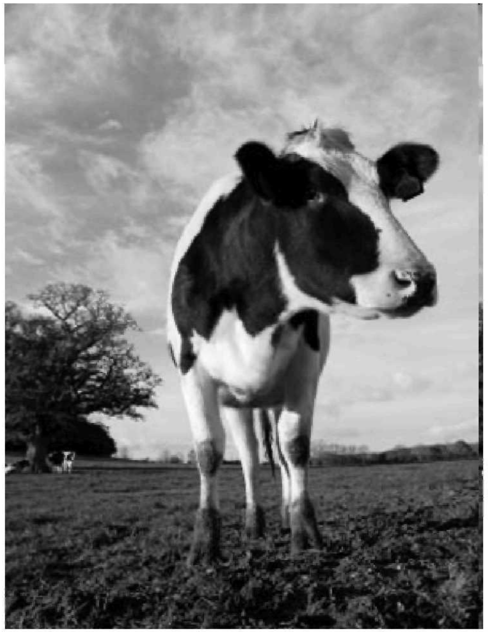
- Evolution of the human eye
- Other species
- Co evolution
- Contribution I_w to a color channel w given the emission spectra E(λ) and the sensibility spectra for the colour channel $S_w(\lambda)$

$$I_w = \int_0^{\infty} S_w(\lambda) * E(\lambda)\, d\lambda$$



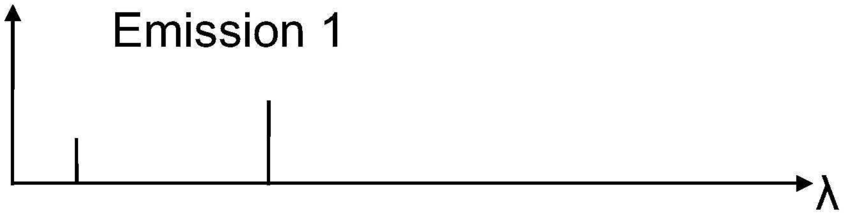
Spectral world perception

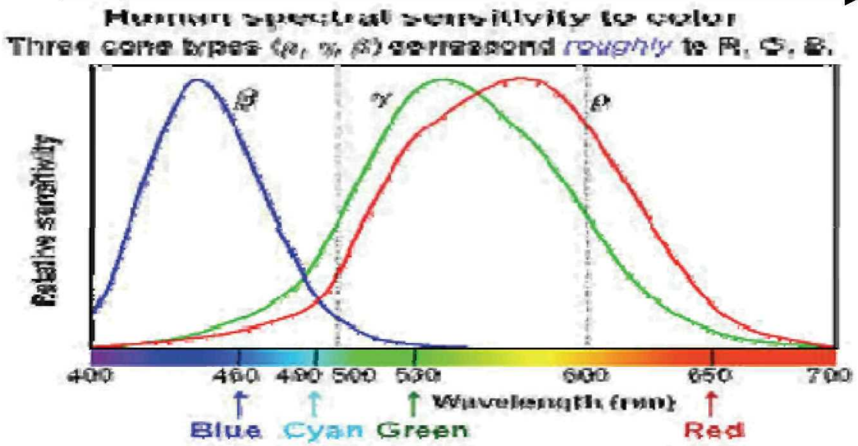
Spectral bands:

3	2	1	4
			? **Cannot be communicated to humans* :-(**
Human looking at cow	Cow looking at cow	BW observation of cow	Bird looking at cow

Limitation of human spectral resolution

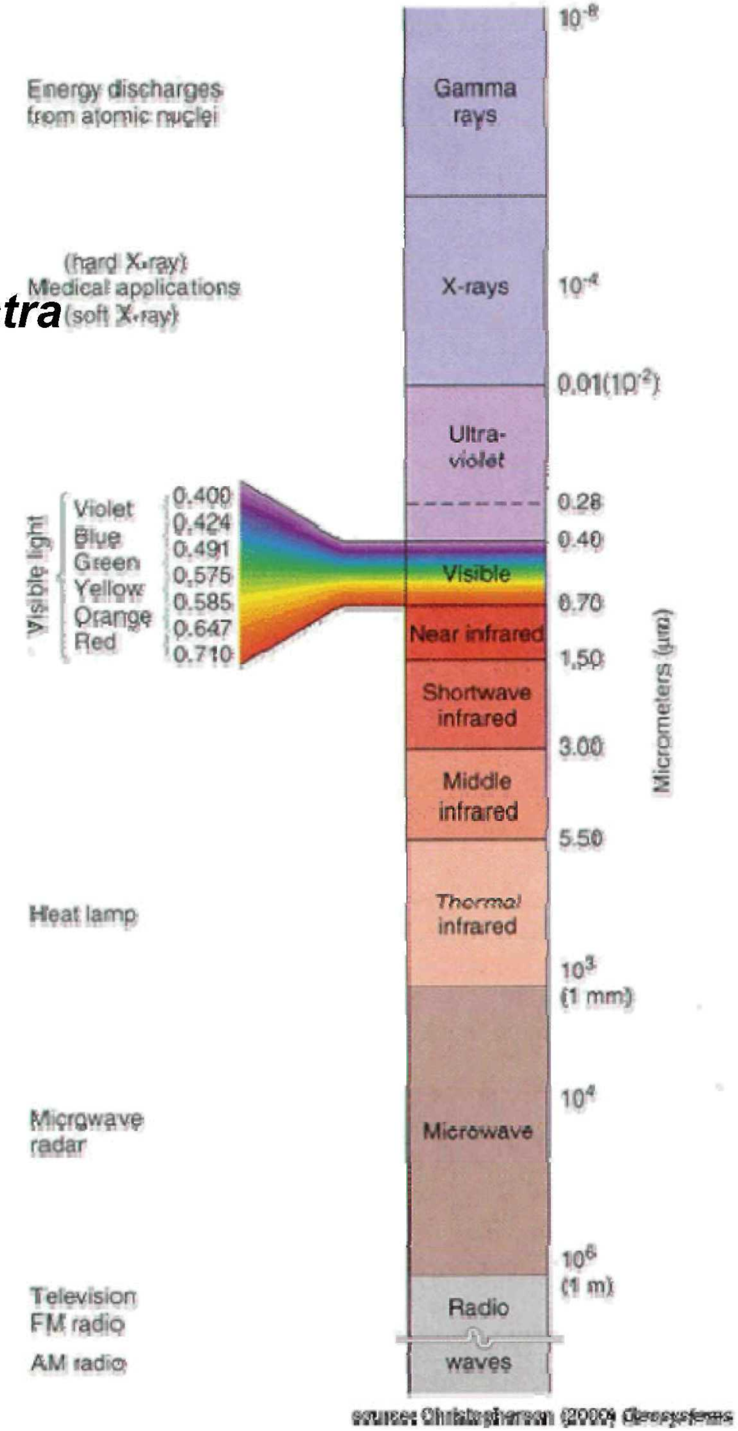
Consider two object with different emission spectra





RGB $_{\text{emission 1}}$ **= [1*0+1*1 , 1*0+1*1 , 1*1+1*1] = [1 , 1 , 2]**

RGB $_{\text{emission 2}}$ **= [0*2+2*1 , 0*2+2*1 , 1*2+1*1] = [1 , 1 , 2]**

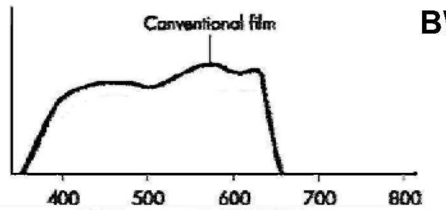


#1

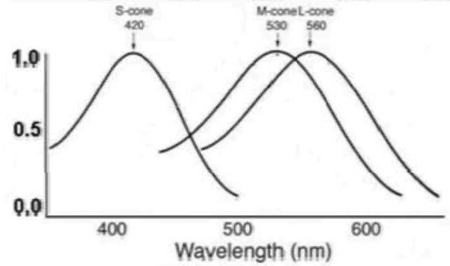
Comparison of spectral bands of various imaging systems

- Spectral content is discretized by a number spectral bands.
- Bands can vary in center position, shape and width
- Paradigm can be applied to all spectroscopic methods, including laser spectroscopy
- Contribution to a band is the integral of the product of sensitivity, reflectance and illumination spectrum.

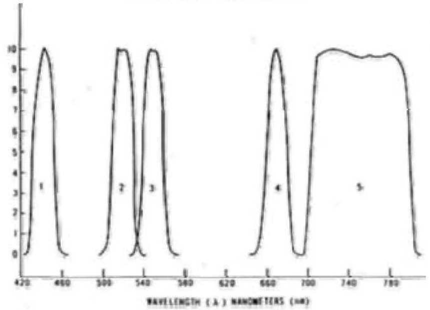
$$U_{channel(k)} = \int_0^{\infty} E_{(\lambda)} R_{(\lambda)} S_{k(\lambda)} d\lambda$$



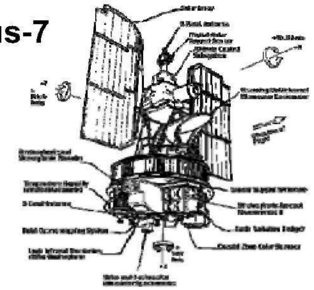
BW Camera

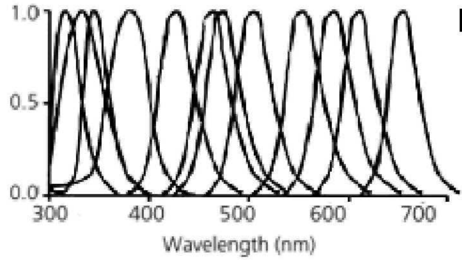


Human

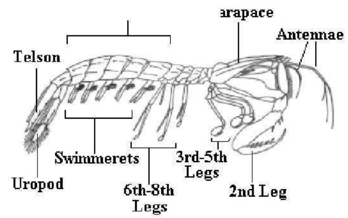


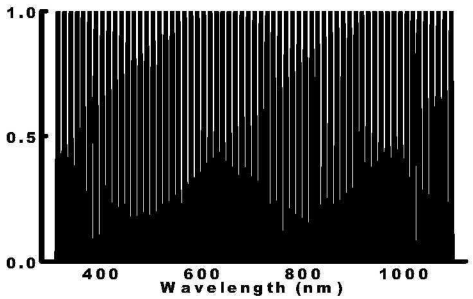
Nimbus-7



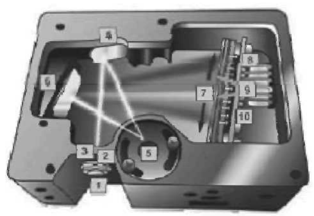


Mantis Shrimp

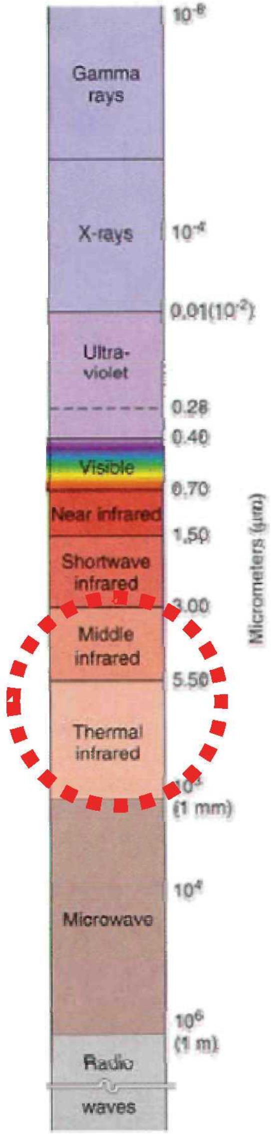




Spectrometer



Examples of what the human eye cannot see, IR



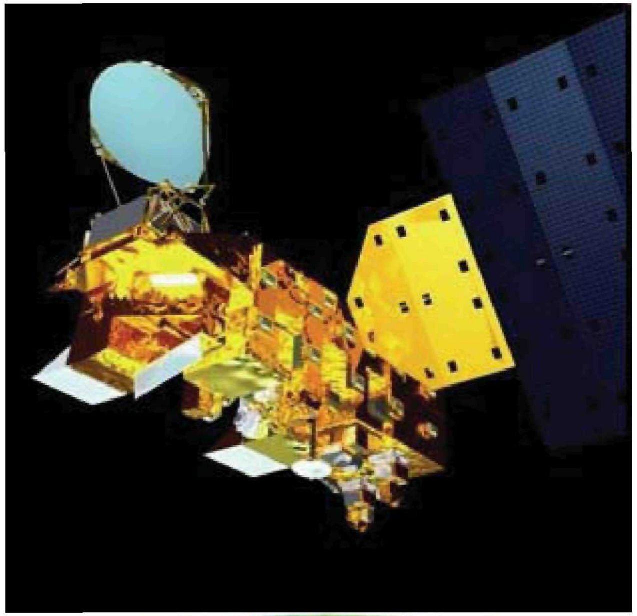
Leaking gas from a burnt out vehicle is made visible!

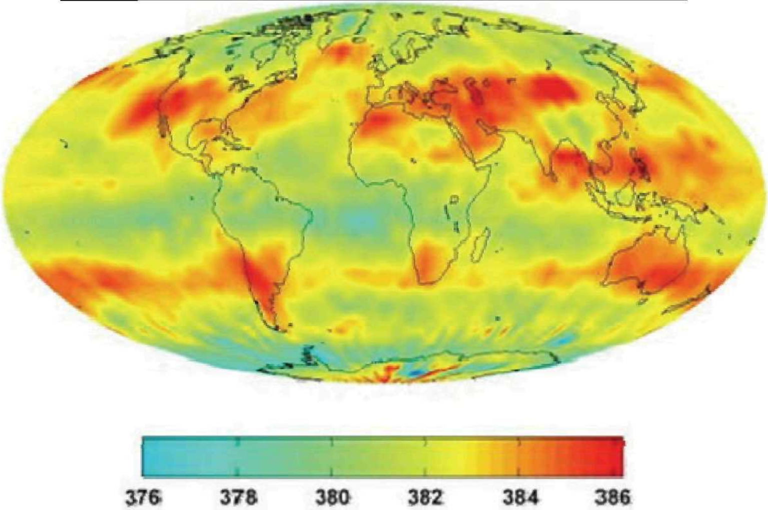
J. Sandsten, Opt. Expr. 2004

Blackbody, transmission and absorbance.

NASA

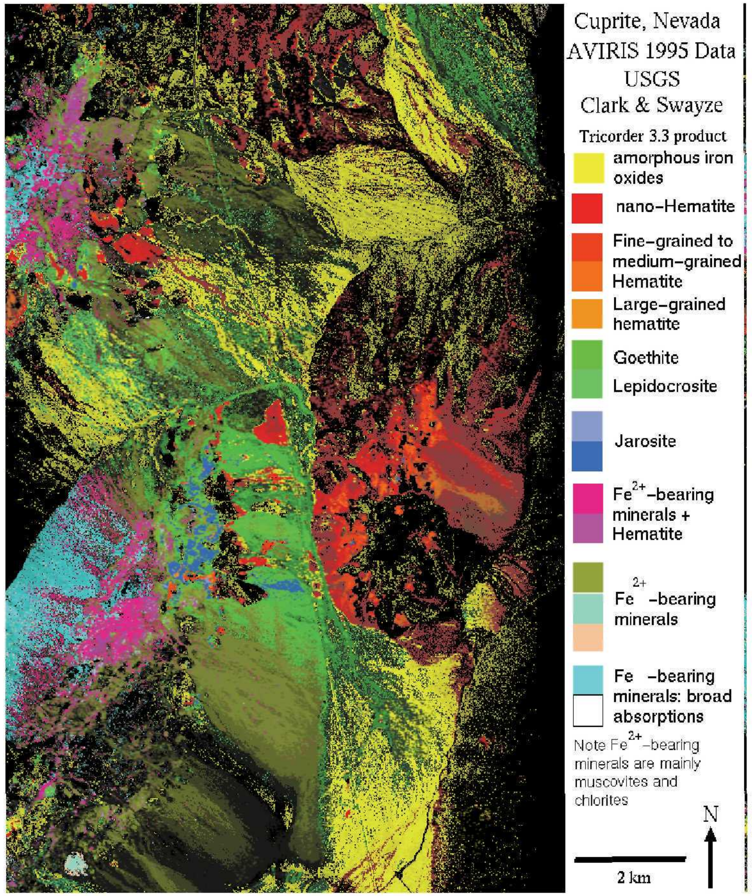
Examples of what the human eye cannot see, IR



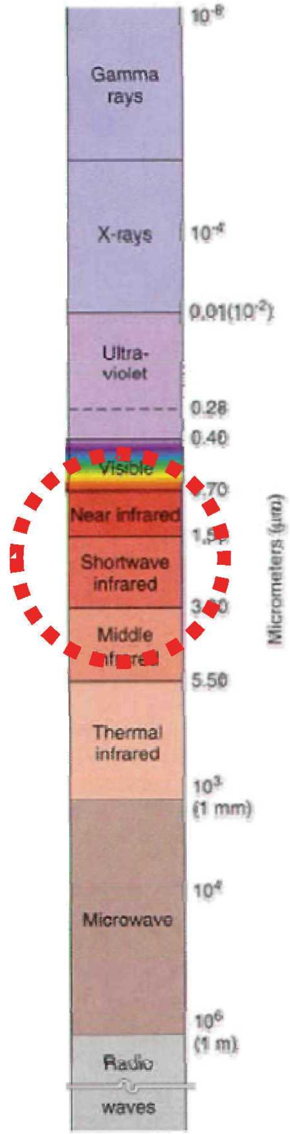


AIRS July 2008 CO_2 (ppmv)

Global concentration of CO_2 measured in the IR!



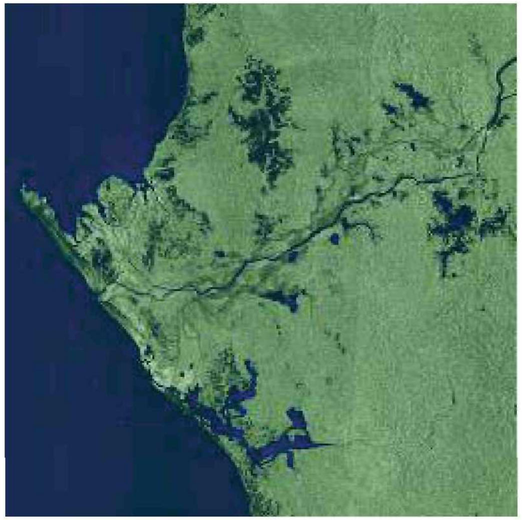
Mineral mapping from satellite covering 430nm-3µm wavelength



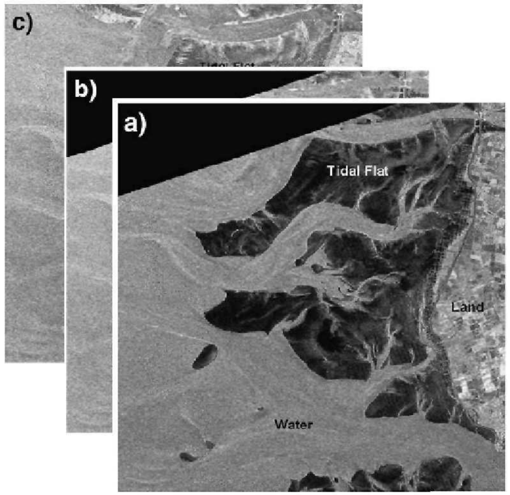
http://airs.jpl.nasa.gov/
http://m3.jpl.nasa.gov/

Examples of what the human eye cannot see, micro waves

Gabon at visible wavelength



Gabon at radar wavelength



L, C & X band SIR/SAR radar images of Wade Sea. M. Gade et Al.

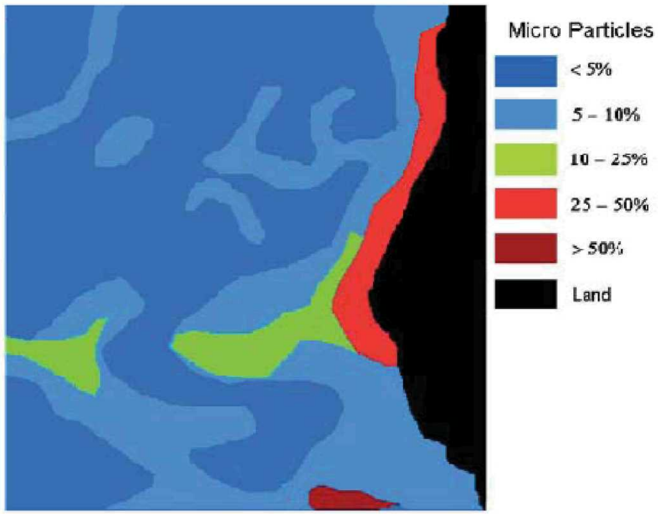
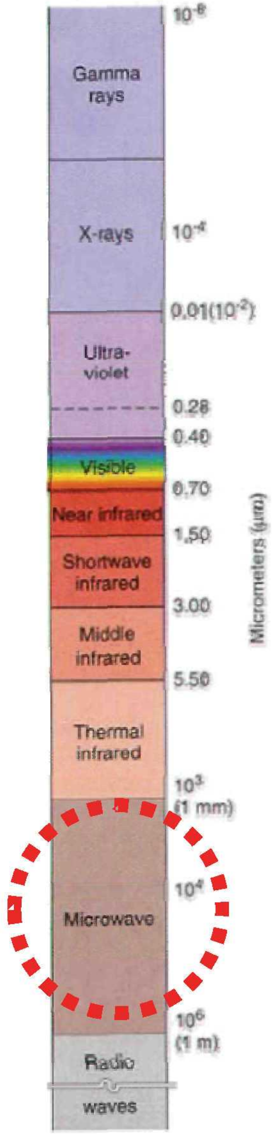


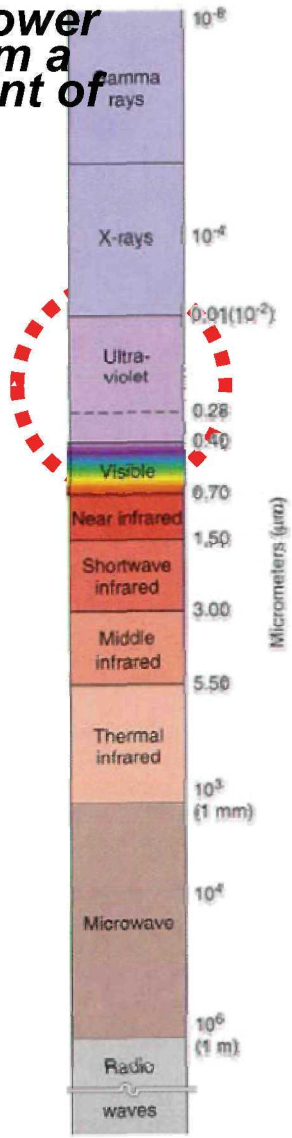
Fig. 10. Sediment classification provided by the Schleswig Holstein Wadden Sea National Park Office. The color coding denotes the percentage of micro particles (i.e., particles with diameters less than 63 μm).



Examples of what the human eye cannot see, UV

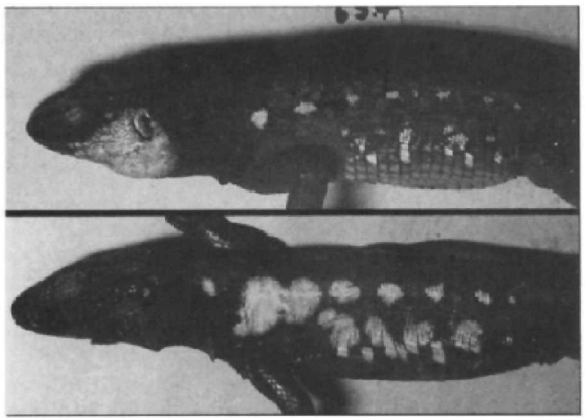
Visible Appearance | Spurious/false color | Recorded by digital camera through 18A UV filter | Greyscale, UV, record

Butter flower seen from a bees point of view

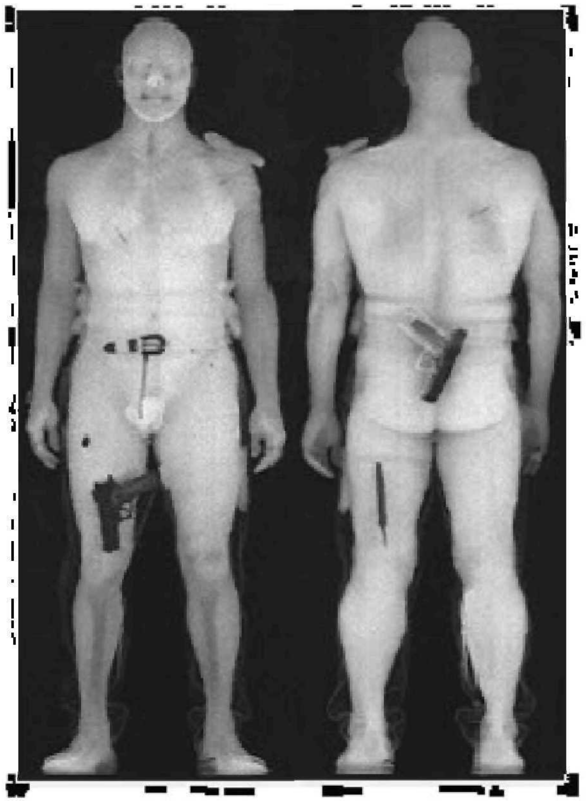


UV, Changing appearance in the visible

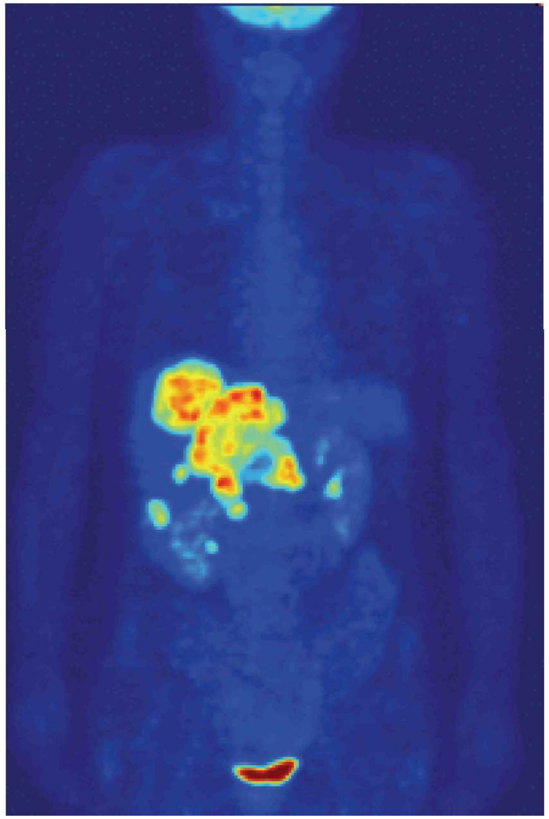
Invisible UV markings on Tenerife lizards



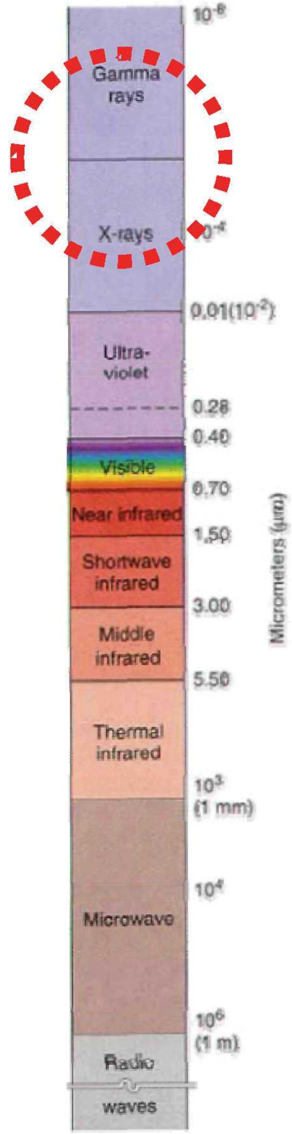
Examples of what the human eye can not see, gamma ray



Backscatter X-ray in use in Amsterdam airport



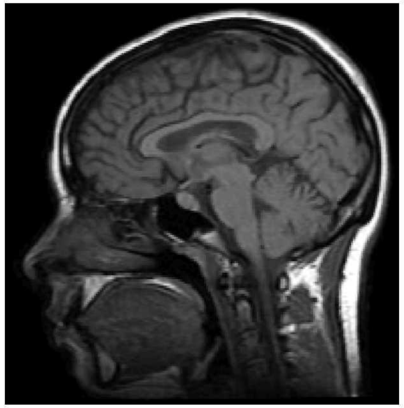
Positron Emission Tomography (PET) for drug tracing



http://en.wikipedia.org/wiki/Backscatter_X-ray

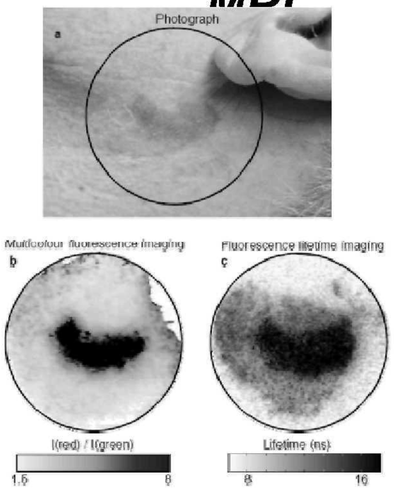
http://en.wikipedia.org/wiki/Positron_emission_tomography

Examples of what the human eye cannot see in medicine

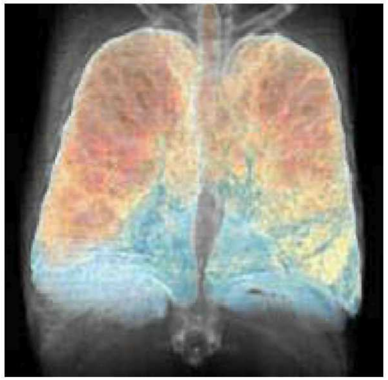


MRI

Thermography

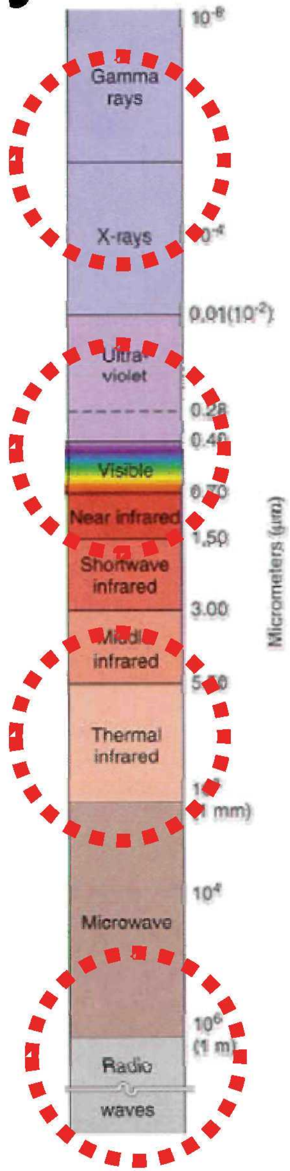


Photosensitizers

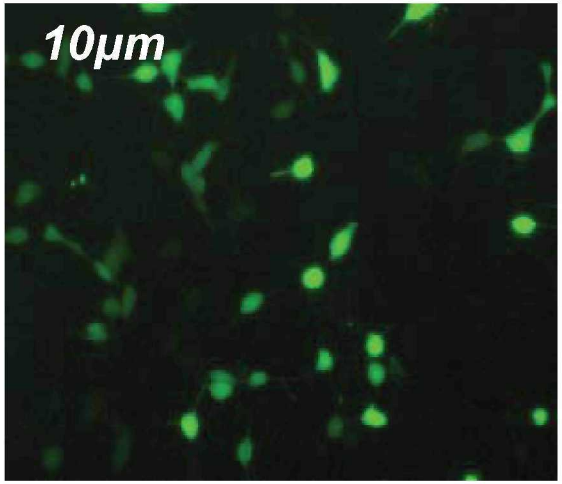


Multi-spectral X-ray

RGB Pill cameras

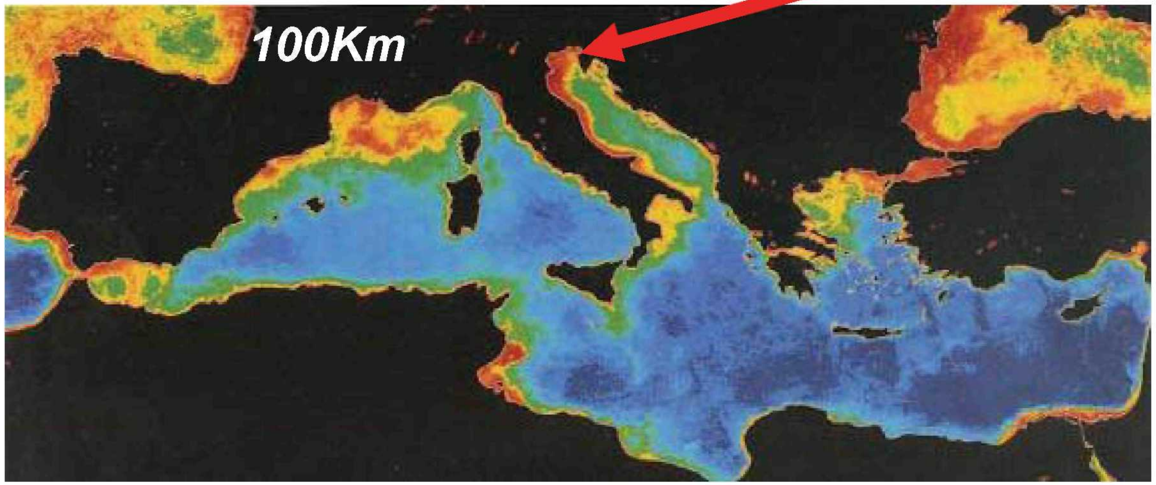


Examples of spatial scales

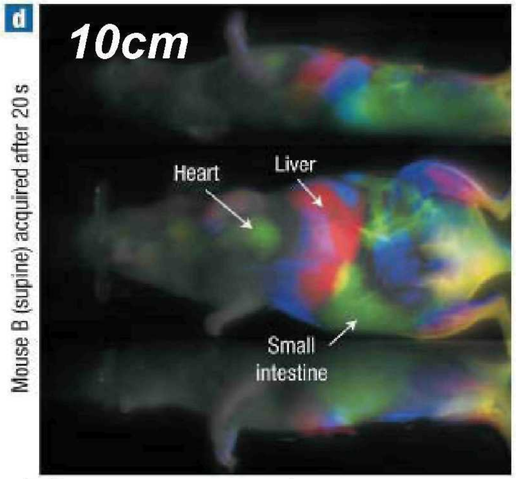


Nerve pulses observed with Ca++ fluorescence imaging

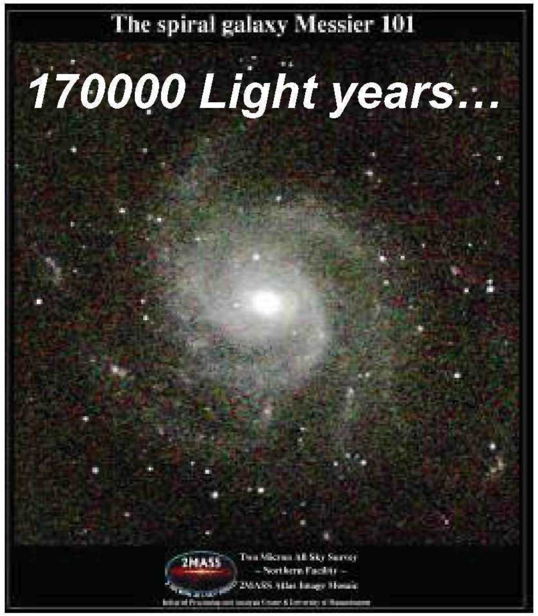
Trieste



Environmental monitoring of the Mediterranean sea



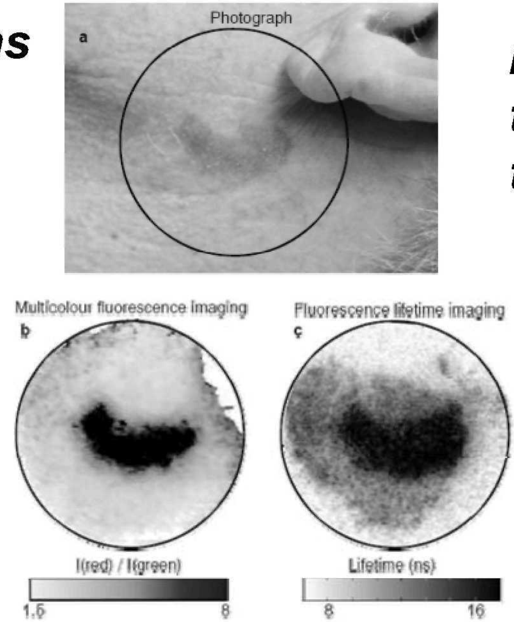
Fluorescent mouse organs, Hillman Et al. 2008



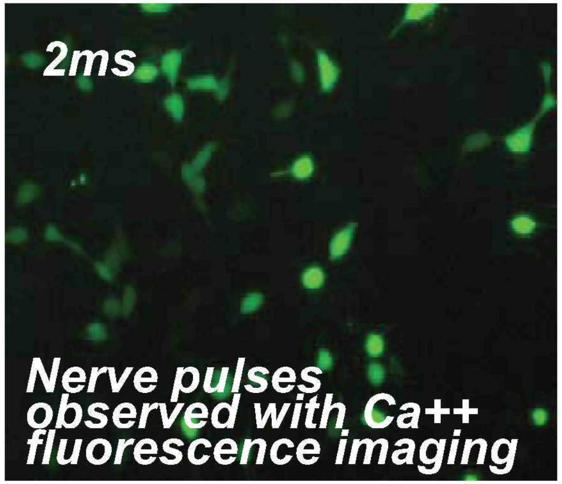
NIR image of Messier 101 spiral galaxy

Examples of temporal scales

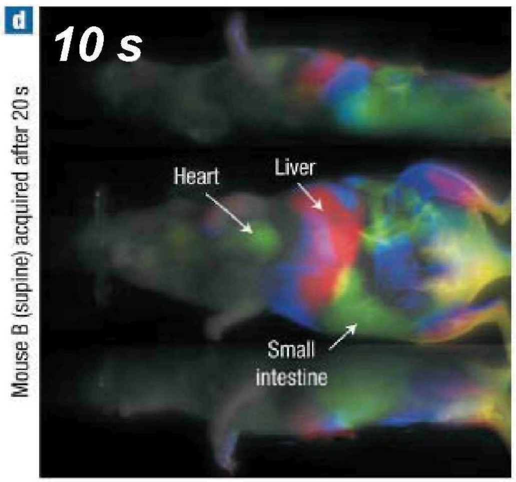
2ns



Fluorescence life time imaging for tumor detection

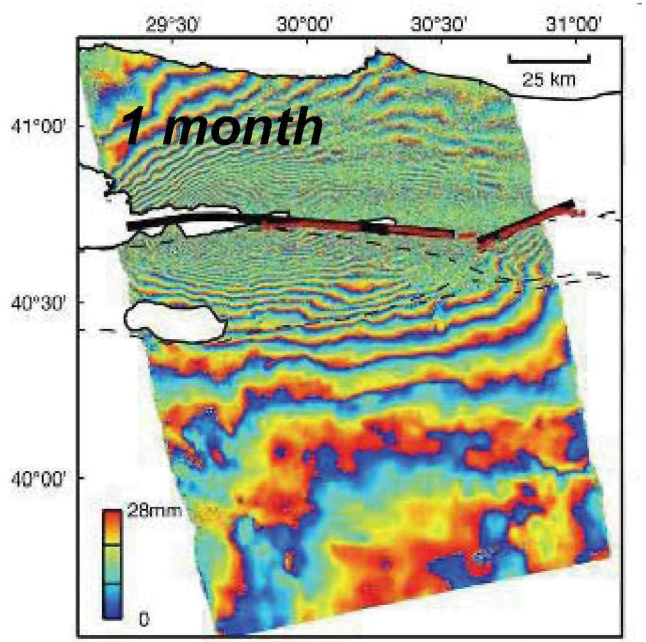


S. Andersson-Engels



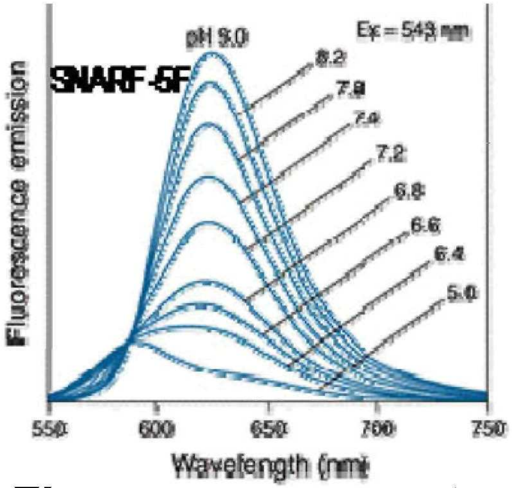
Fluorescent mouse organs, Hillman Et. al.

Turkish earth quake, Izmit 1999

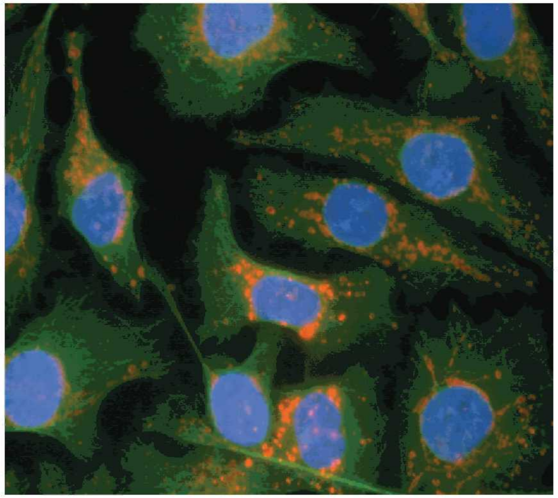


http://en.wikipedia.org/wiki/Interferometric_synthetic_aperture_radar

Indirect photosensitizers and bio-markers



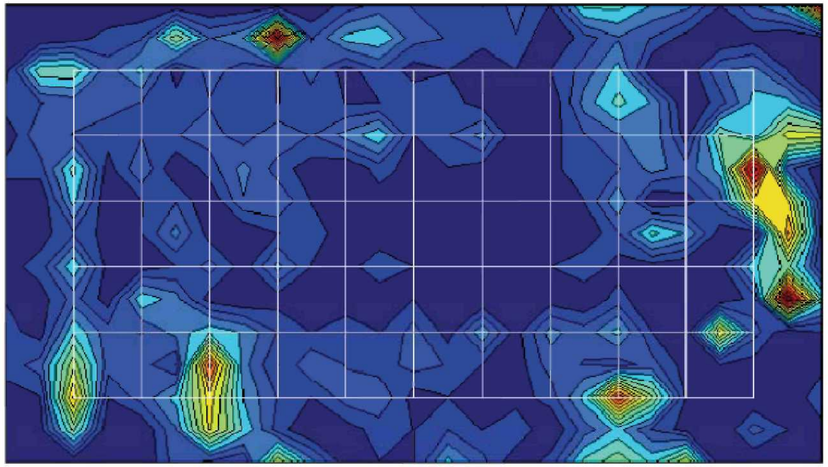
Fluorescence spectra depending on the pH



pH distribution in cells

Trained honey bee

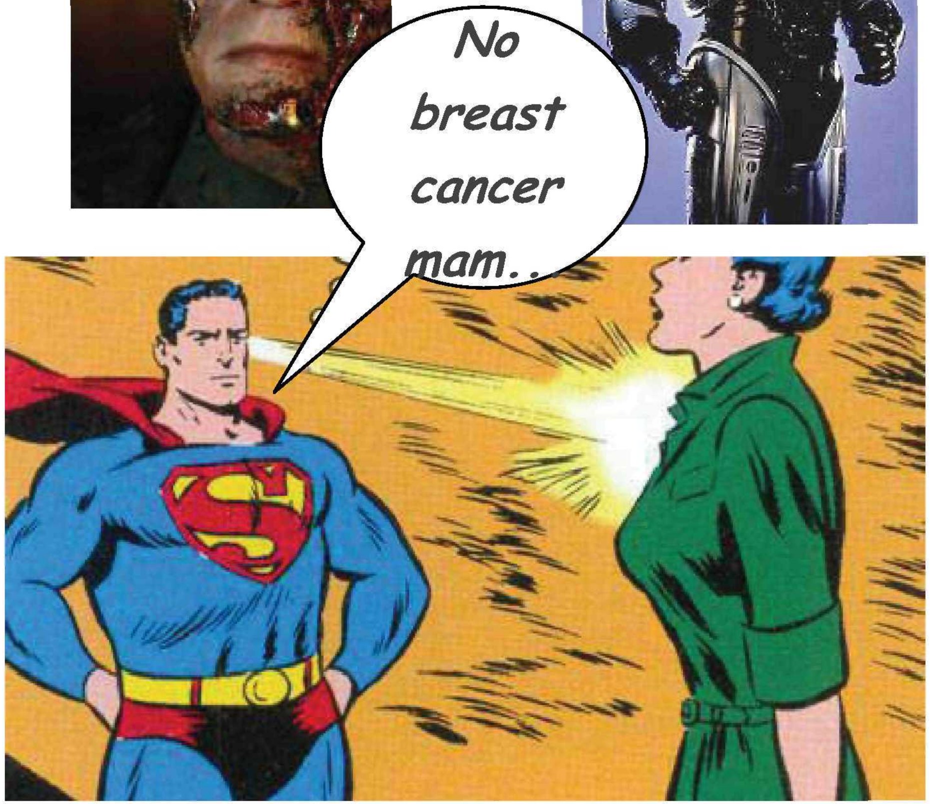
J. Shaw, Opt. Expr. 2005



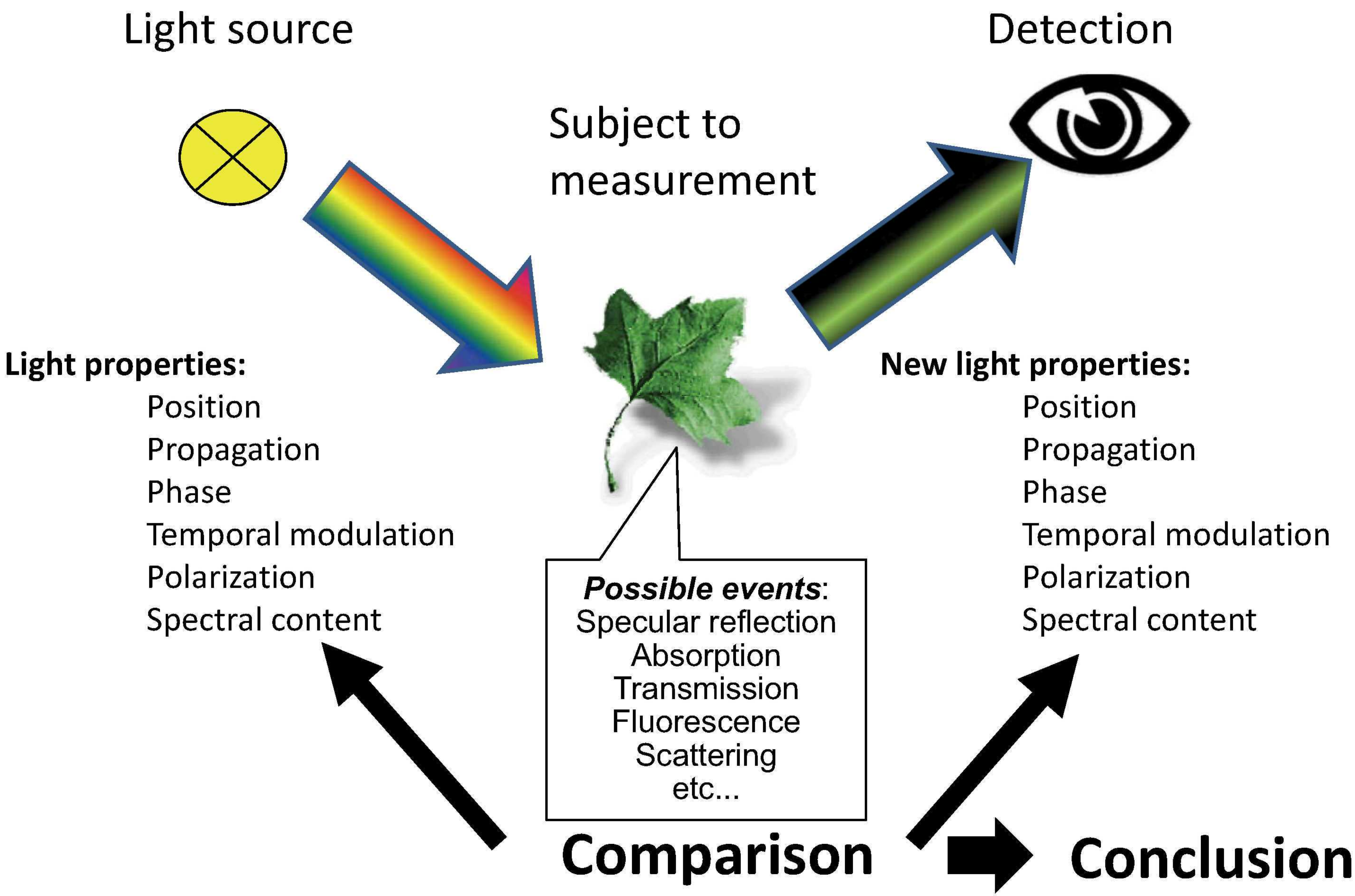
Bee concentration and landmine distribution

The ultimate multi spectral imaging conditions

- All super heroes uses multispectral imaging
- Infinitive spatial resolution
- Complete spatial dimension coverage, 3D
- Infinitive spectral resolution
- Infinitive temporal resolution
- Complete spectral region coverage

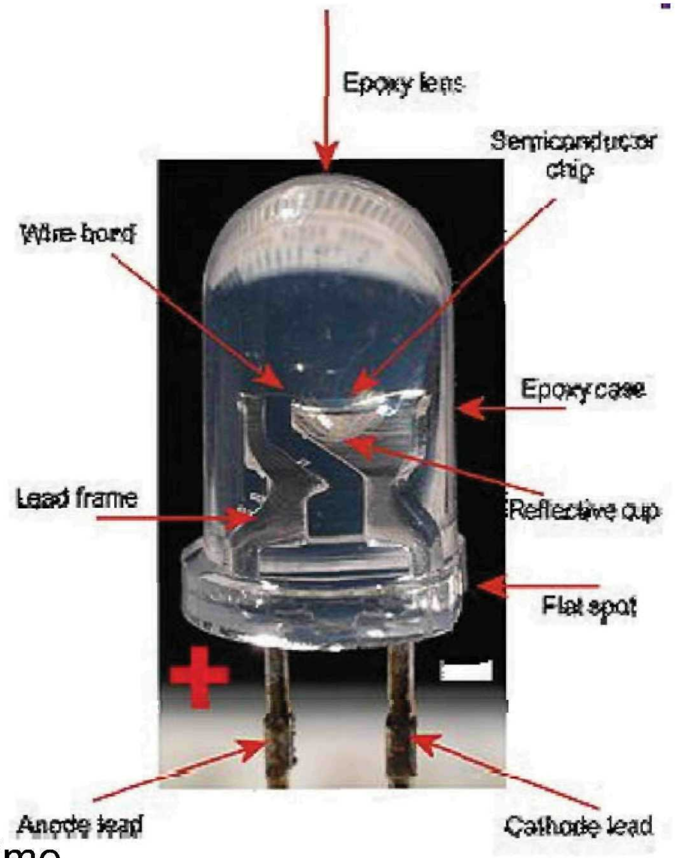


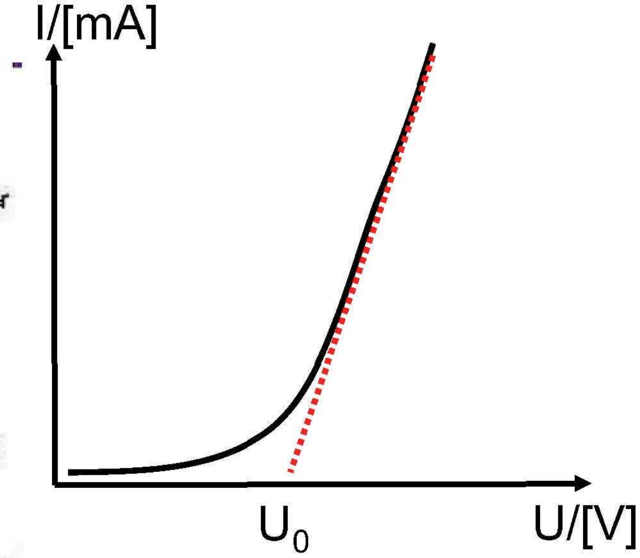
Measuring with light

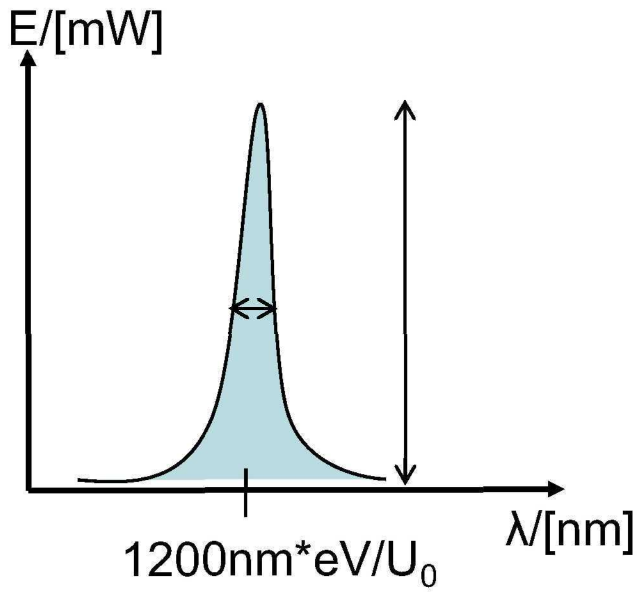


The Light Emitting Diode, 255nm-7µm

- IU characteristic
- Band gap, peak emission, U_0
- FWHM
- Divergence
- Current, intensity
- Pulsed operation
- Temperature
- Emissive yield
- Modulation, rise time and capacitances
- Still evolving

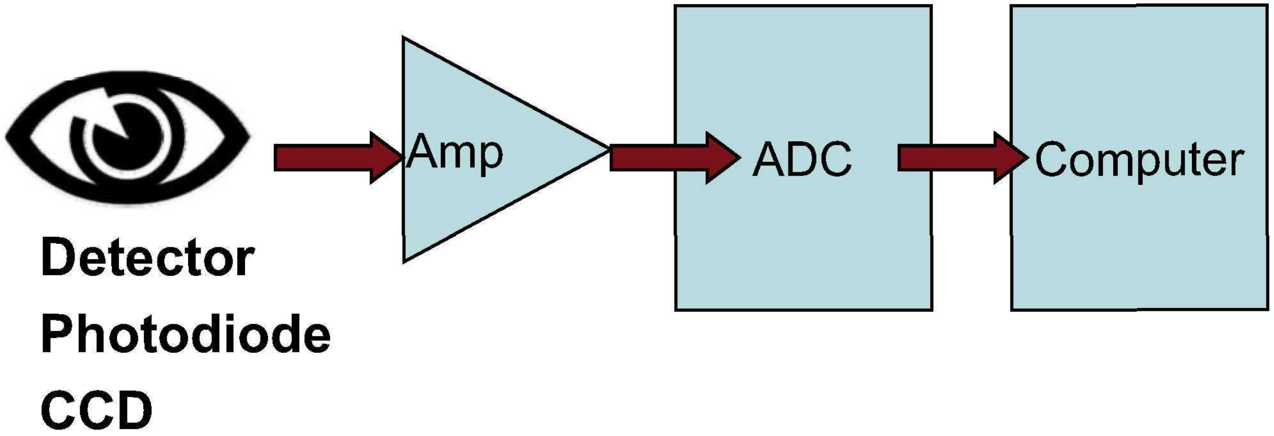


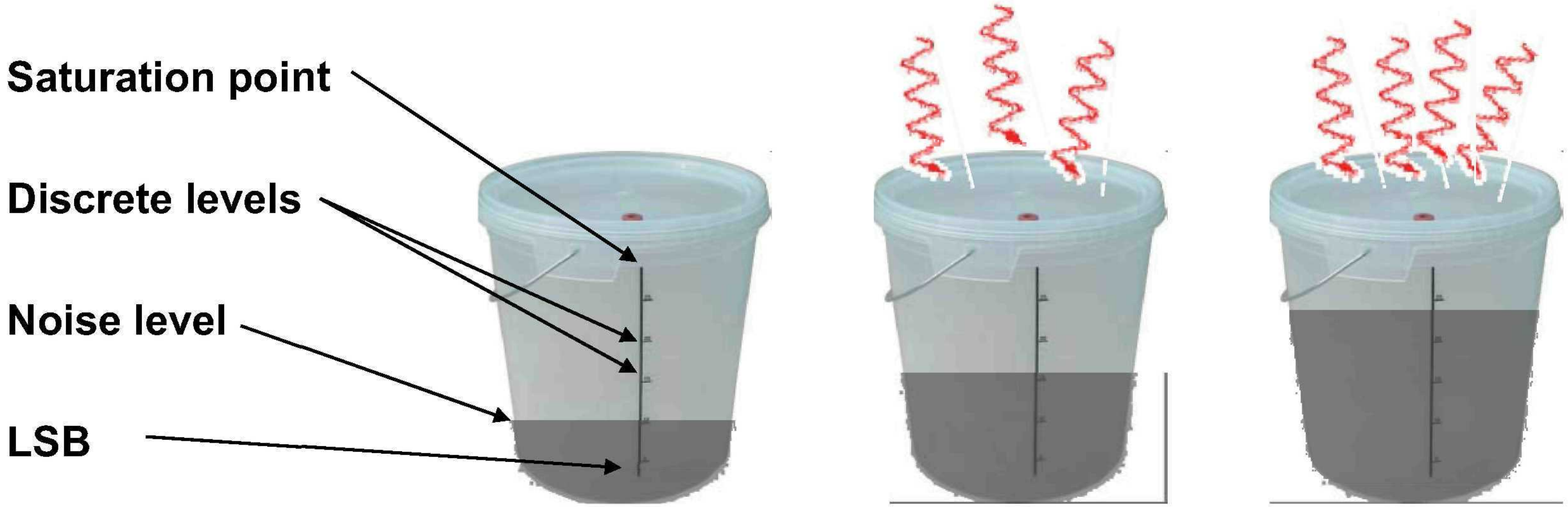




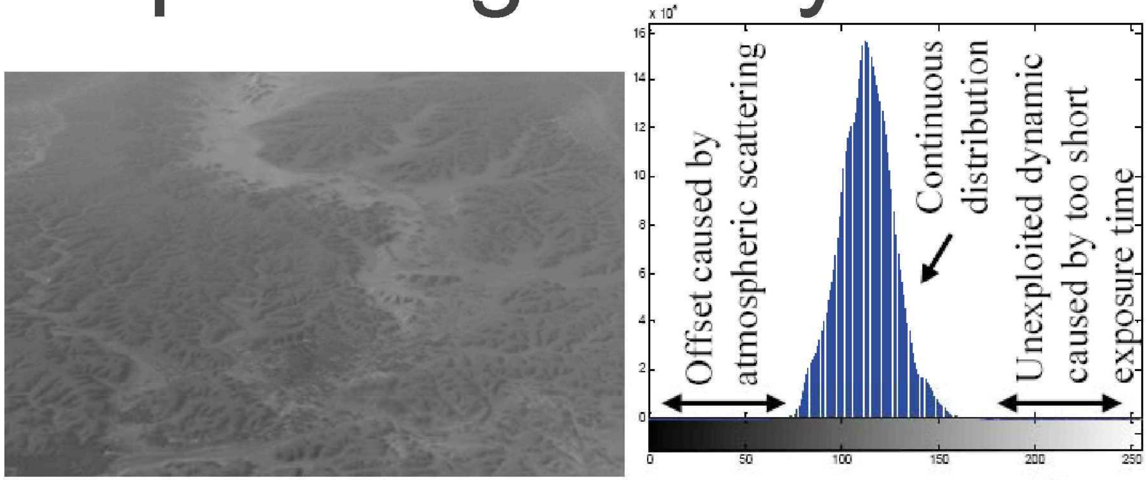
Detectors and dynamic range

- Light intensity measurements
- Light descretized by photons and bits
- Upper and lower limits
- Noise and uncertainty





Intensity histograms, spanning the dynamics.



(a) (b)

Figure 20 (a) Original image of Saharan city from an airplane (b) its histogram

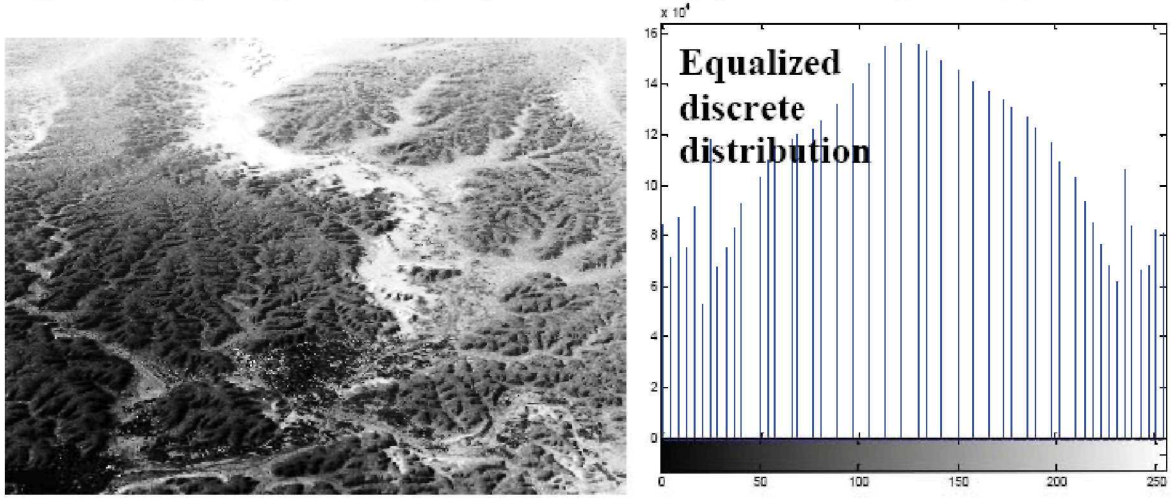
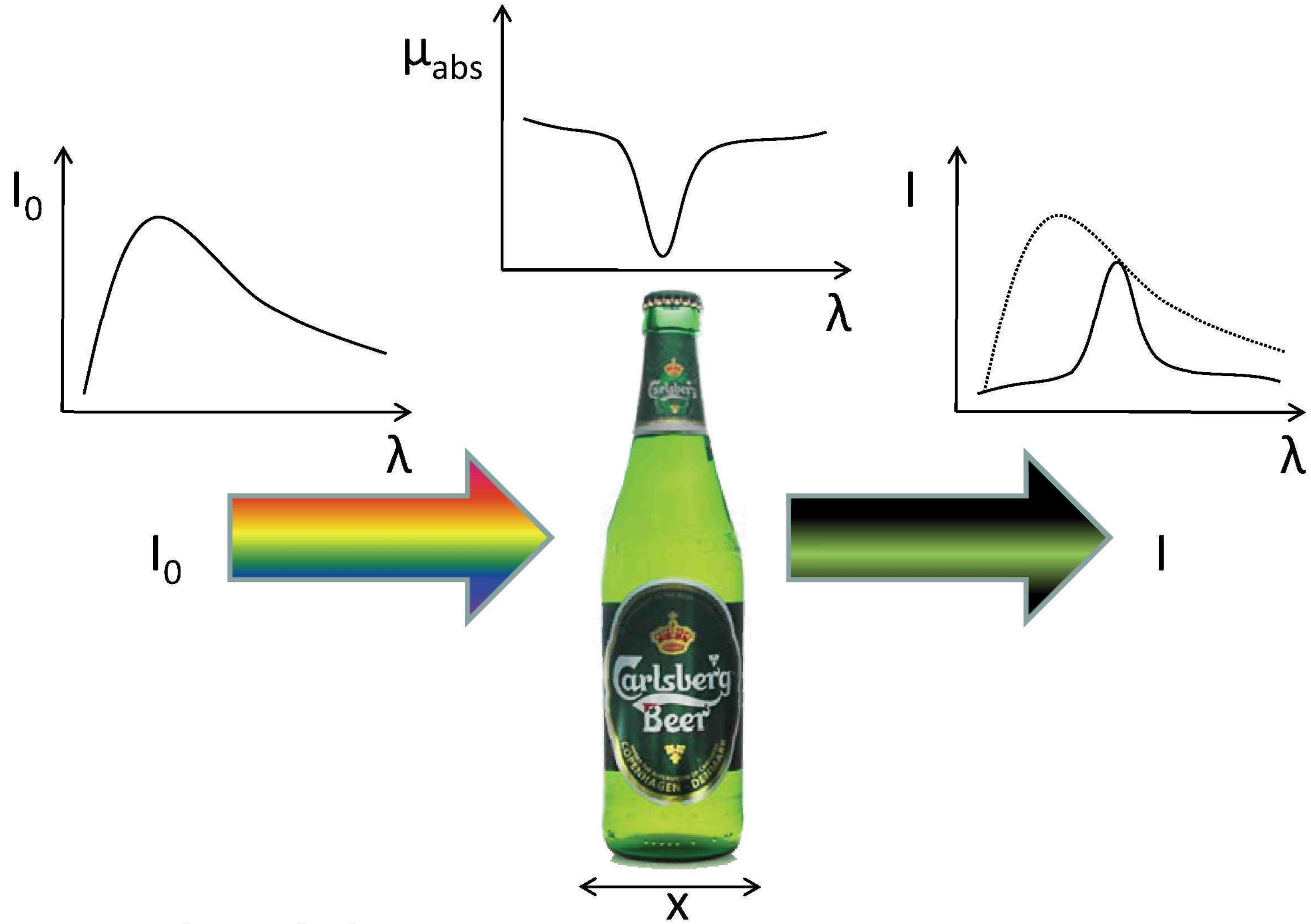


Figure 21 (a) Image subjected to histogram equalisation and (b) its histogram.

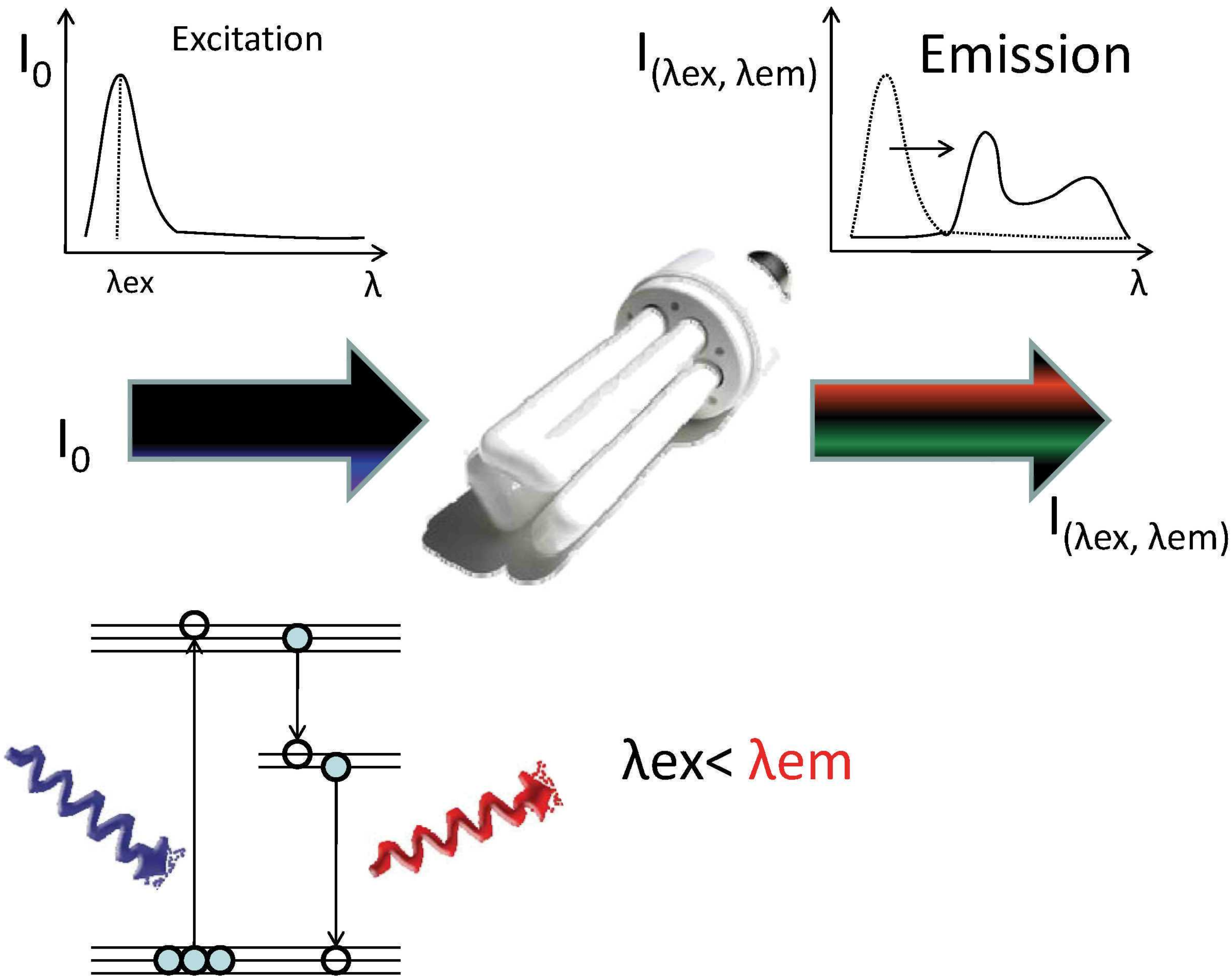
Absorbing volume



Beer-Lambert's law:

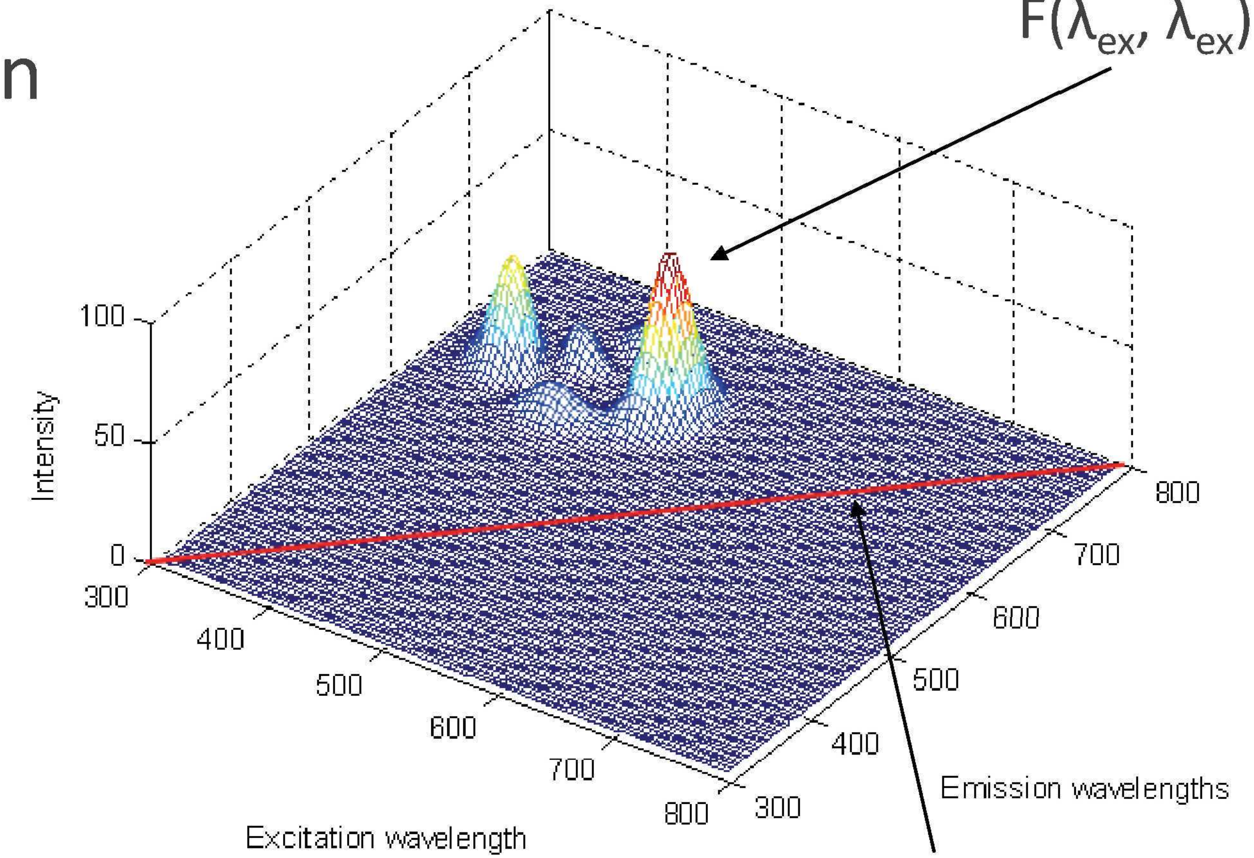
$dI_{(\lambda)}/dx = -\mu_{abs(\lambda)} \rightarrow I_{(\lambda)}=I_{0(\lambda)}e^{-\mu abs(\lambda)x}$

Fluorescence

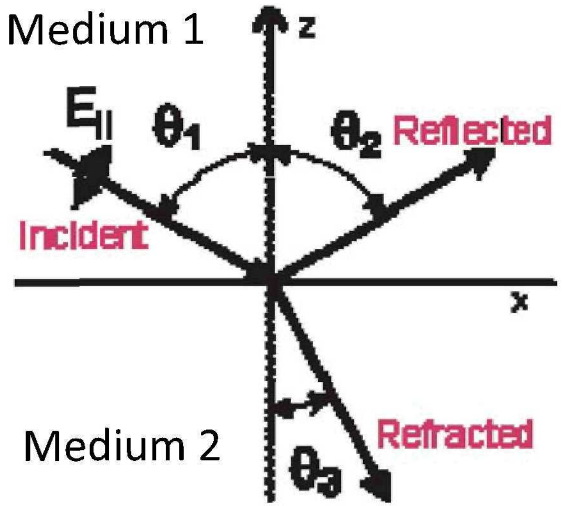


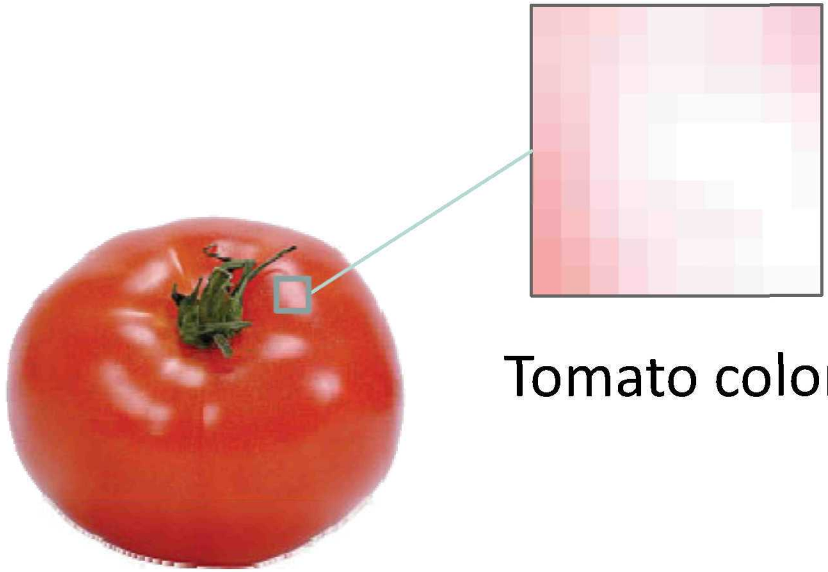
Fluorescence spectra

Emmission
Excitation
Matrix



Reflecting surface





Tomato color?

Snell's law: $\theta_1 = \theta_2$

$$n_1 \sin\theta_1 = n_2 \sin\theta_3$$

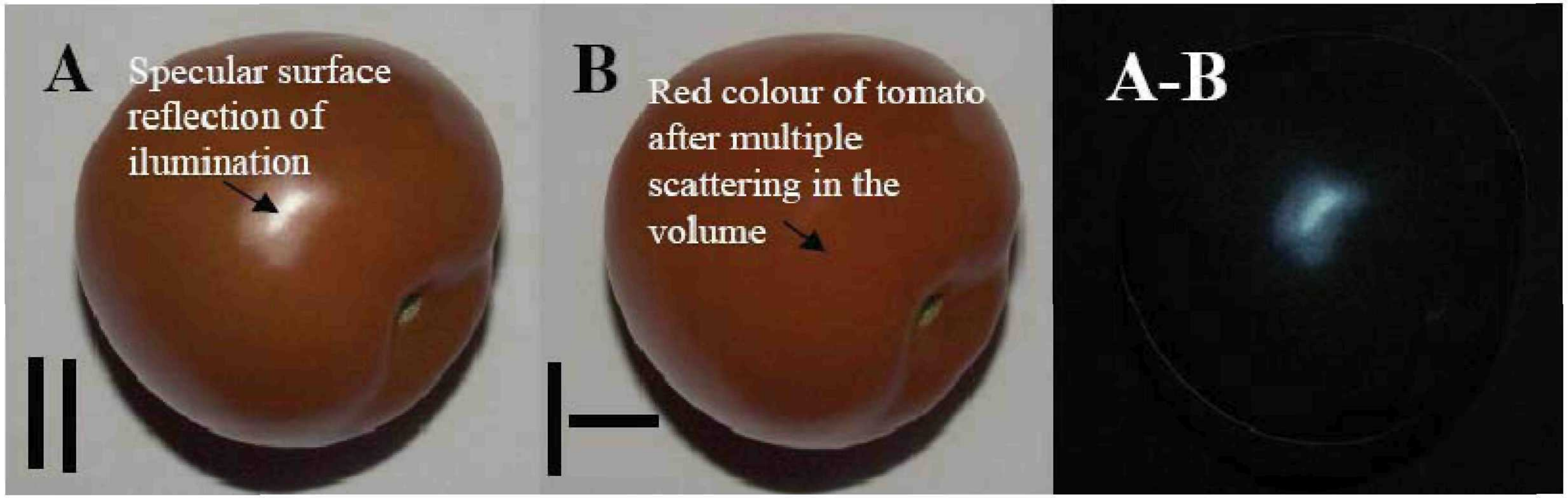
Fresnel equations:

$$R_{II} = \frac{\mathrm{tg}^2(\theta_1 - \theta_3)}{\mathrm{tg}^2(\theta_1 + \theta_3)}; \qquad T_{II} = \frac{\sin 2\theta_1 \sin 2\theta_3}{\sin^2(\theta_1 + \theta_3)\cos^2(\theta_1 - \theta_3)}$$

$$R_{\perp} = \frac{\sin^2(\theta_1 - \theta_3)}{\sin^2(\theta_1 + \theta_3)}; \qquad T_{\perp} = \frac{\sin 2\theta_1 \sin 2\theta_3}{\sin^2(\theta_1 + \theta_2)}$$

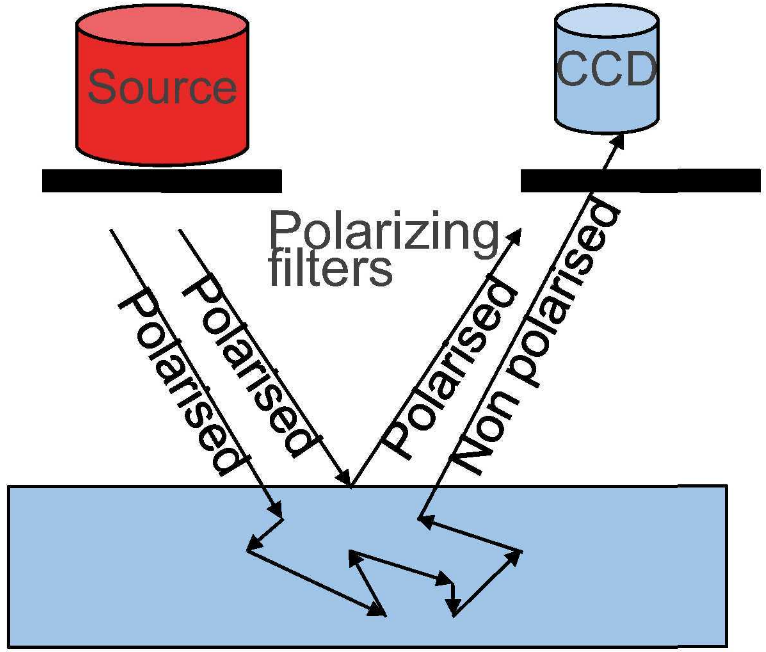
$$R_{II,\perp} = \left(\frac{n_2 - n_1}{n_2 + n_1}\right)^2; \qquad T_{II,\perp} = \frac{4 n_2 n_1}{(n_2 + n_1)^2}$$

Specular

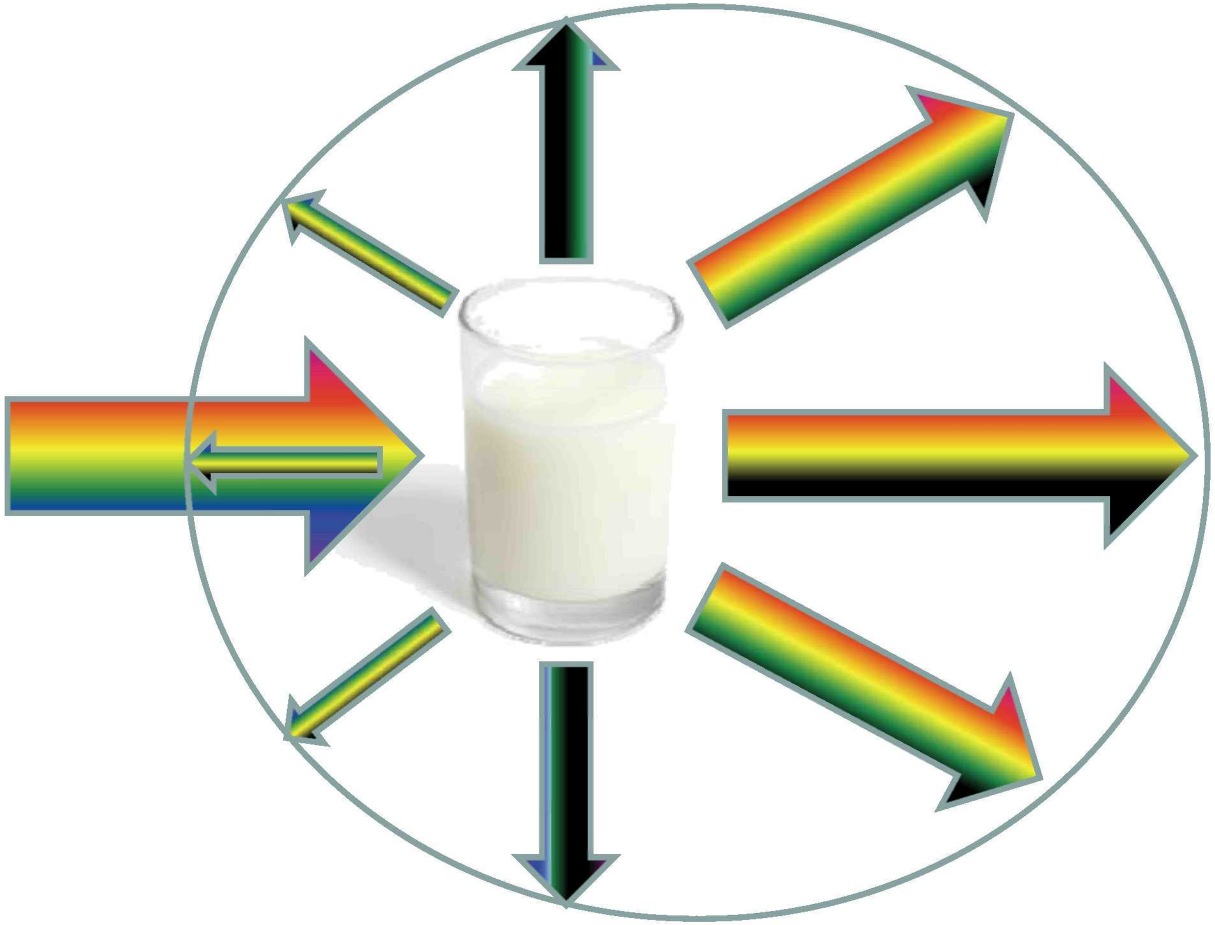


Probing of refractive index at surface

Probing of absorption and scattering in volume



Scattering volume



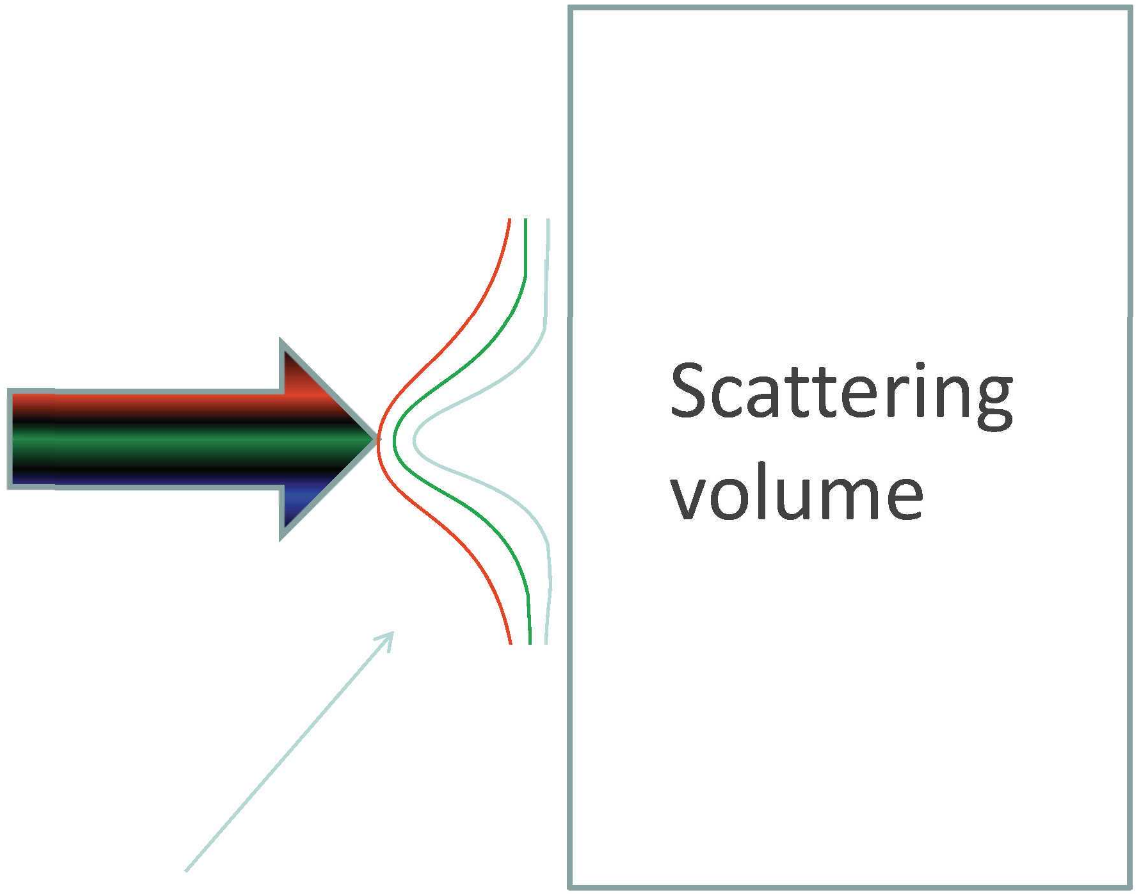
Probability of scattering:

$\mu_{sca(\lambda)}$

Dependence of incidence angle:

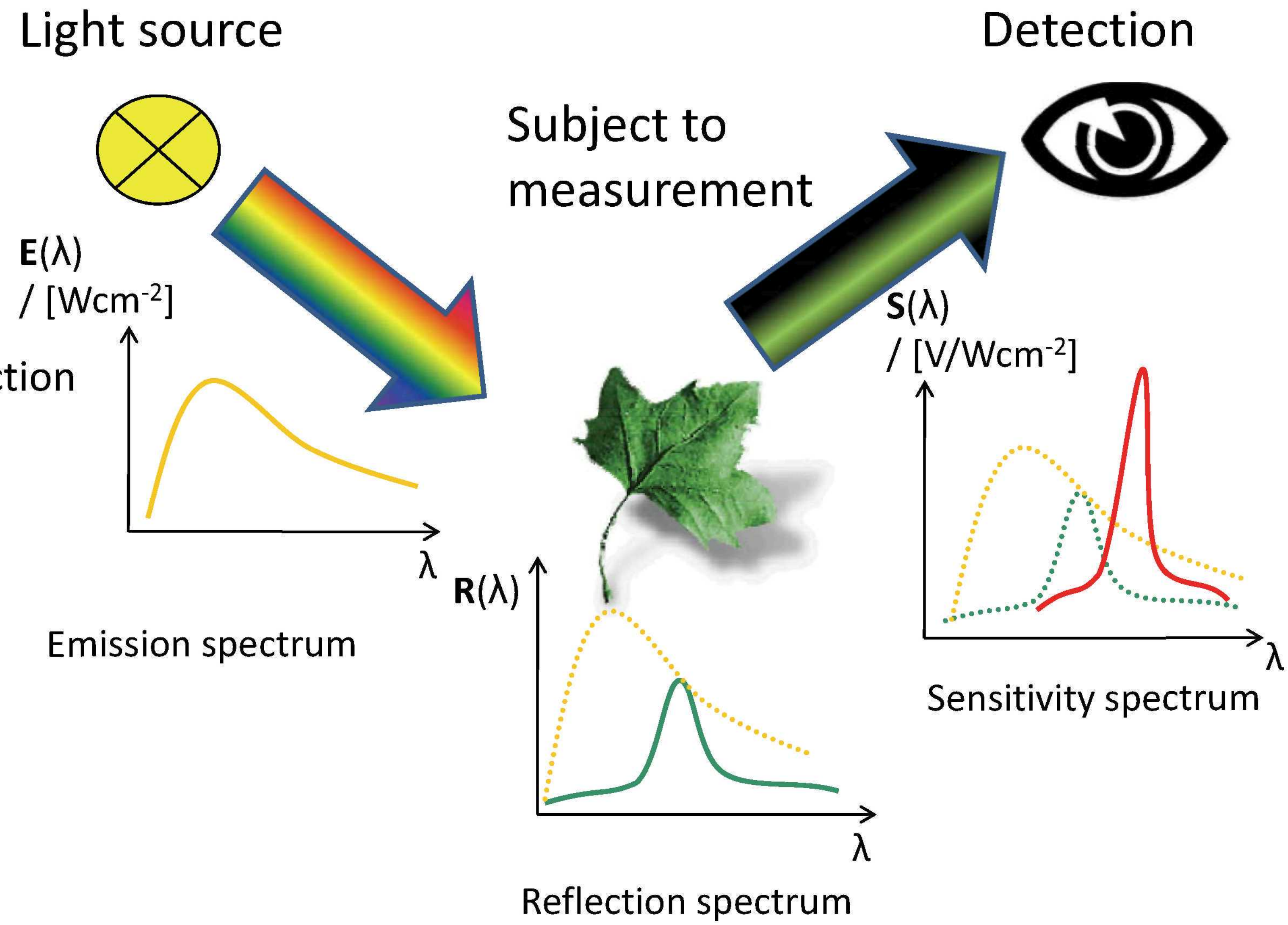
g-factor

Back-scattered light



Green's functions:
$G(\mu_{abs(\lambda)}, \mu_{sca(\lambda)}, g)$

Simplified spectroscopy



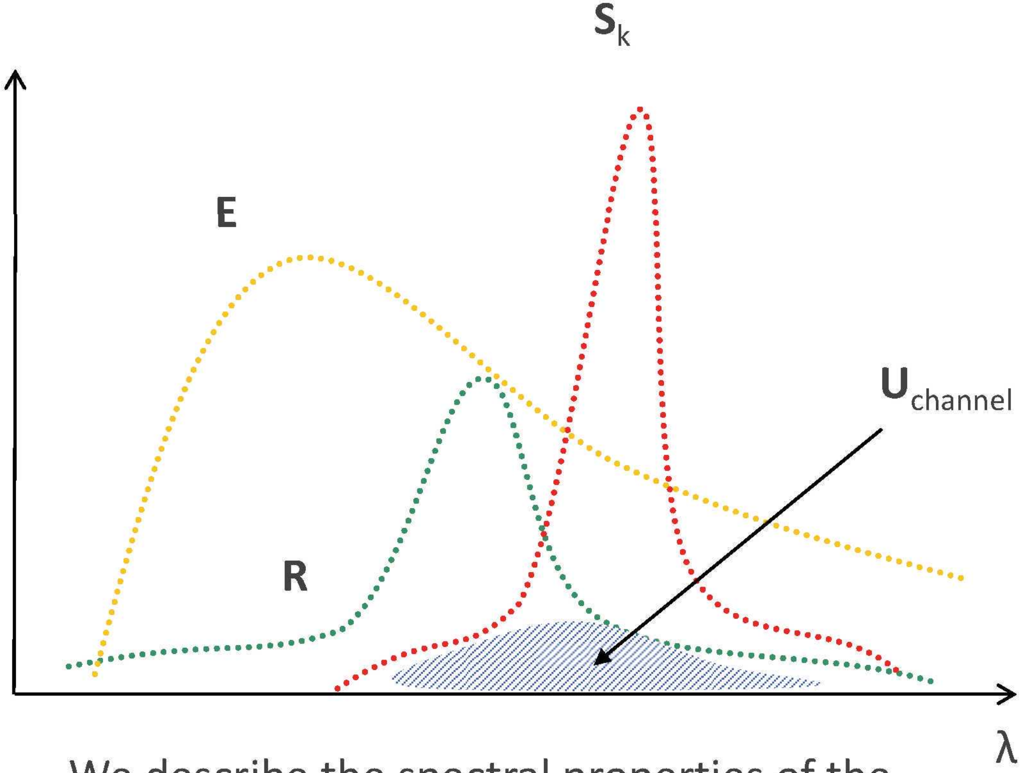
- Emission, reflection and sensitivity
- Reflectance $R(\lambda)=I(\lambda)/I_0(\lambda)$

Contribution to a spectral band

$$U_{channel(k)} = \int_0^{\infty} E_{(\lambda)} R_{(\lambda)} S_{k(\lambda)} d\lambda$$

- Emission, reflection and sensitivity

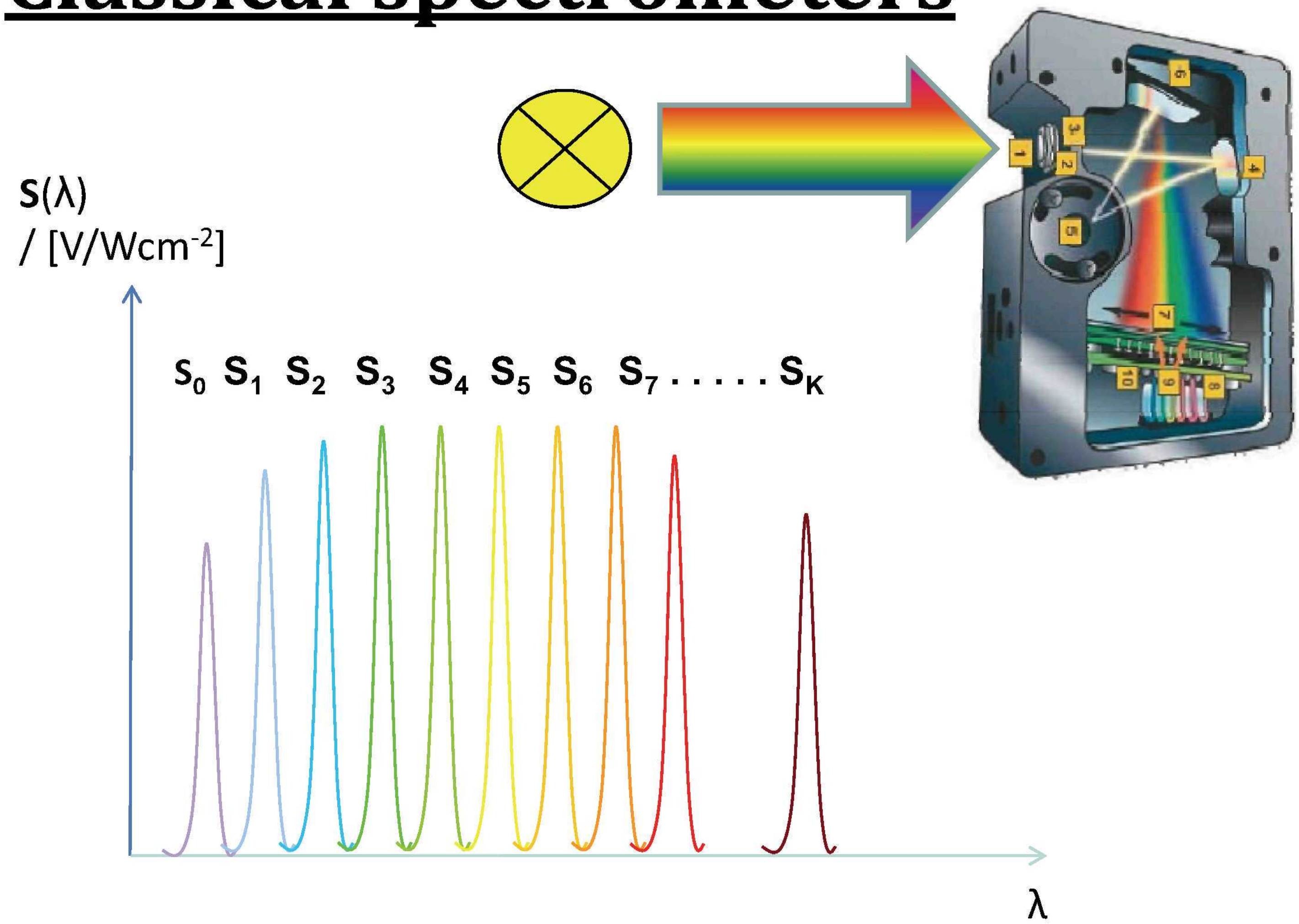
- Reflectance $R(\lambda)=I(\lambda)/I_0(\lambda)$



We describe the spectral properties of the object in terms of $\mathbf{U_{channel}}$. More channals can provide better describtion of **R**

Sources of spectral data

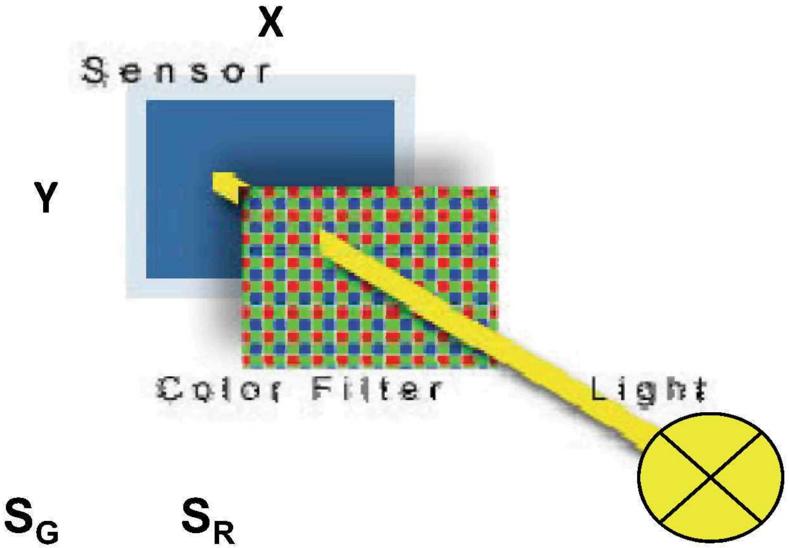
Classical spectrometers

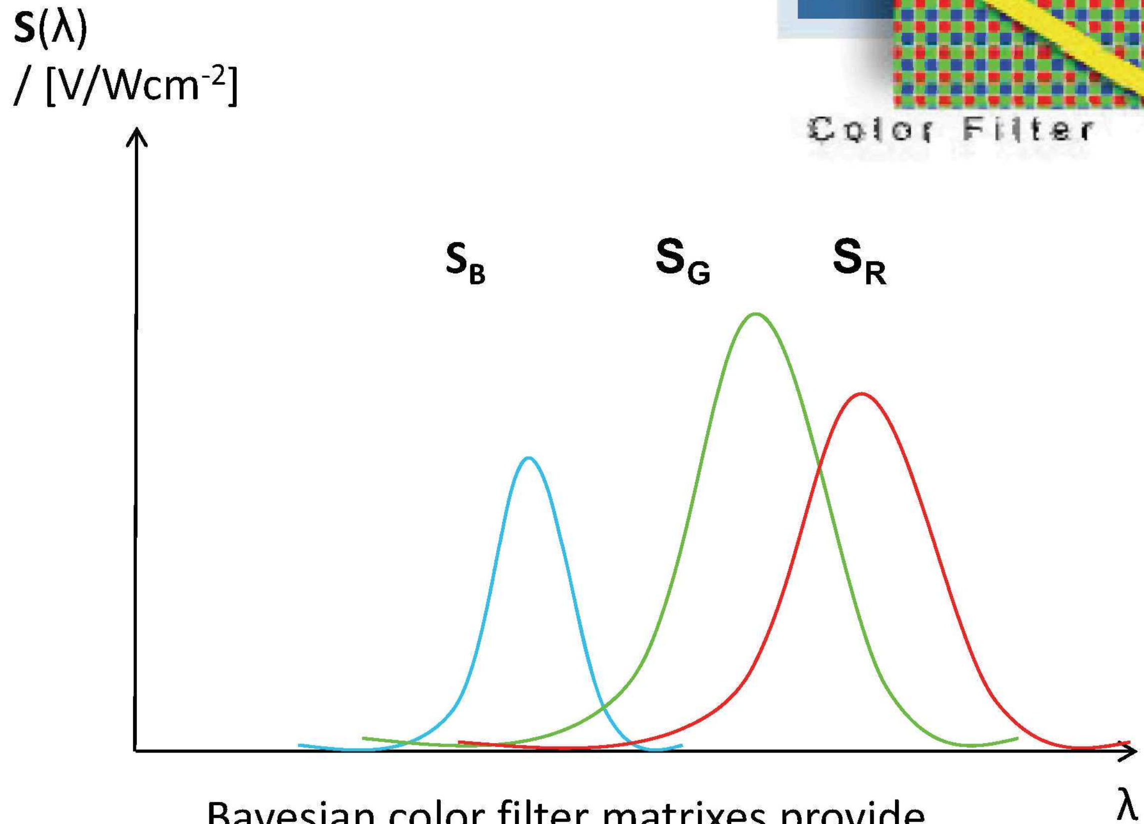


Filtering and/or dispersion of light provide thousands of spectral bands. We obtain a **1 times K** vector containing a spectrum from each measurement.

Sources of spectral data

Color cameras

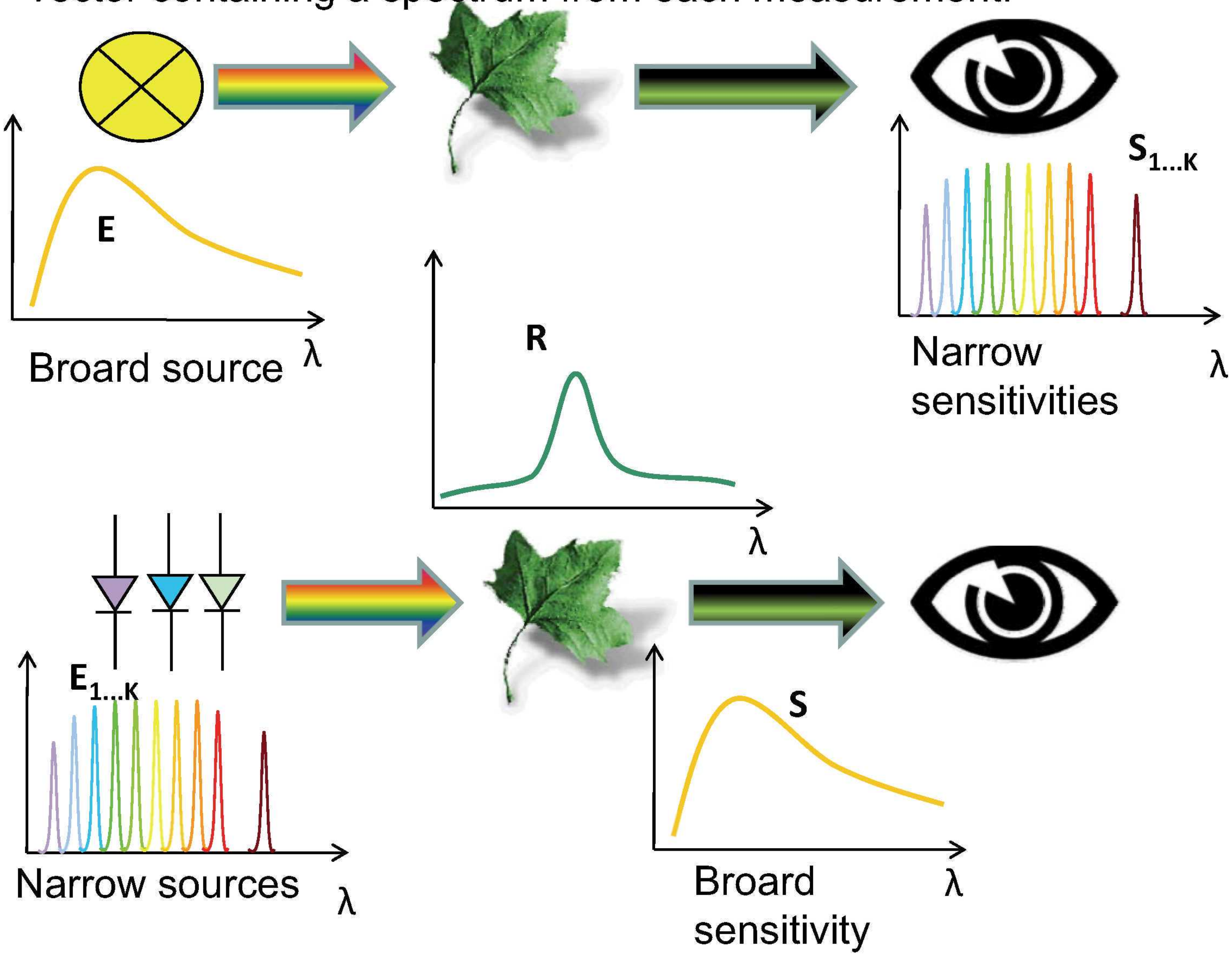




Bayesian color filter matrixes provide spectral bands in color pictures. We obtain **XY times 3** individual spectral measurements. Objects in the pictures is described spectroscopically in the **RGB** color space.

Assessment of spectral properties R

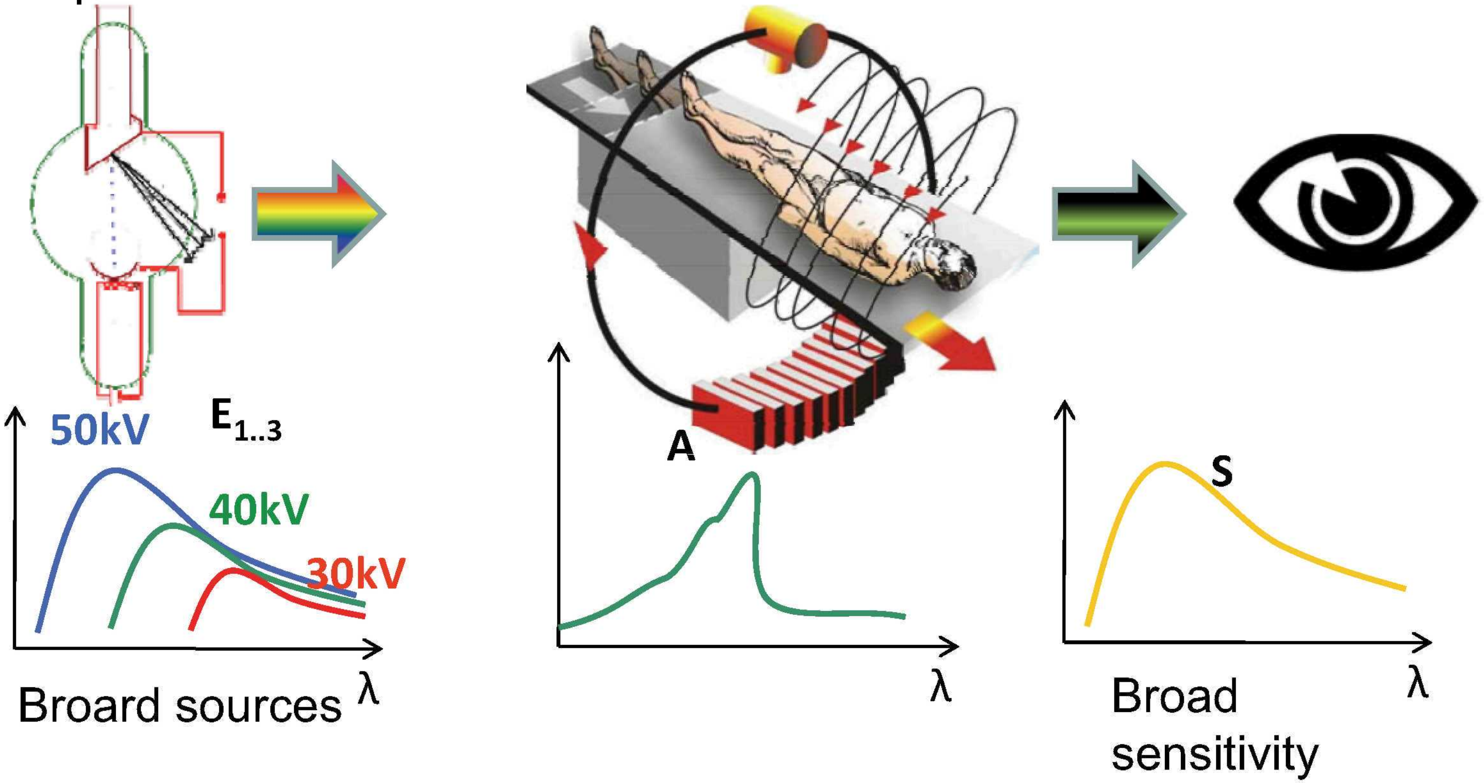
Spectral properties **R** might as well be assessed with various **E** rather than various **S.** We obtain a **1 times K** vector containing a spectrum from each measurement.



Sources of spectral data

Example: Multispectral CT

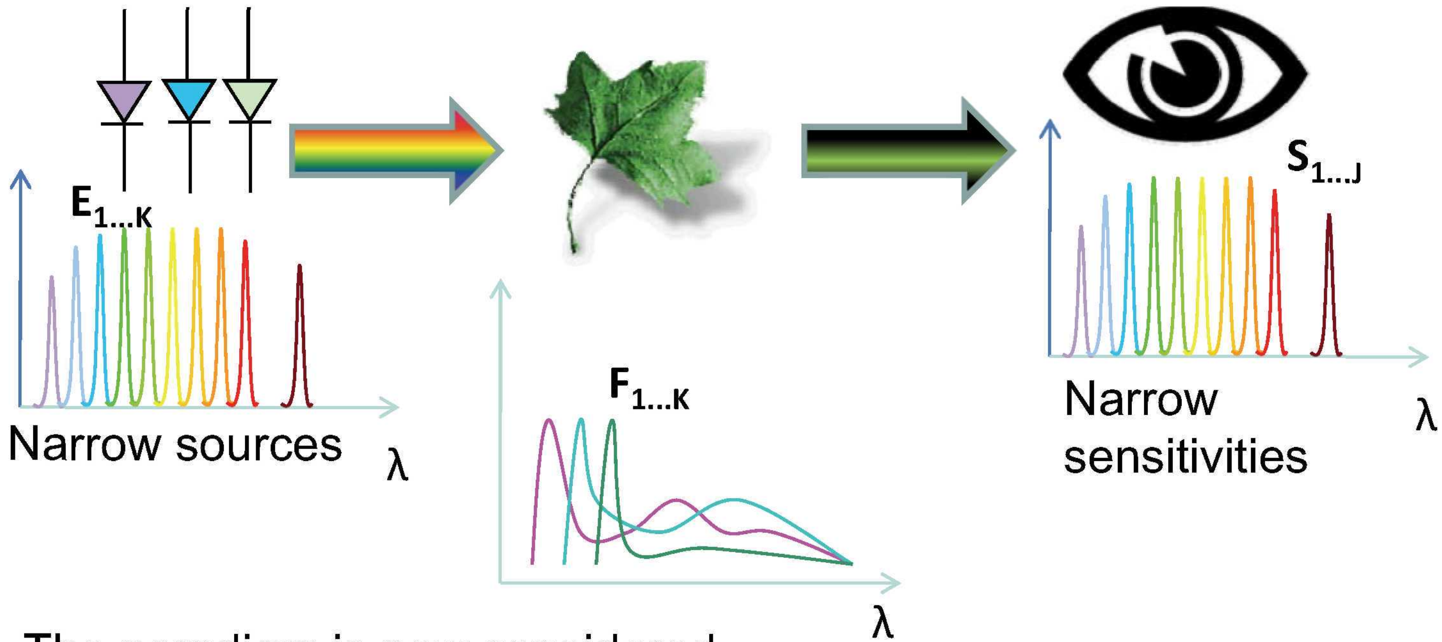
Different organs are distinguished by spectral properties accessed by changing X-ray tube voltage to produce different **E**. We obtain a **1 times 3** vector containing a spectrum from each measurement



Sources of spectral data

Example: Fluorescence

The 2D EEM spectral properties **F** can be assessed with various **E** and various **S.** We obtain a **K times J** matrix containing a excitation emission surface from each measurement. Data are **rearranged** into a **1 times KJ** vector and one dimension is discarded.



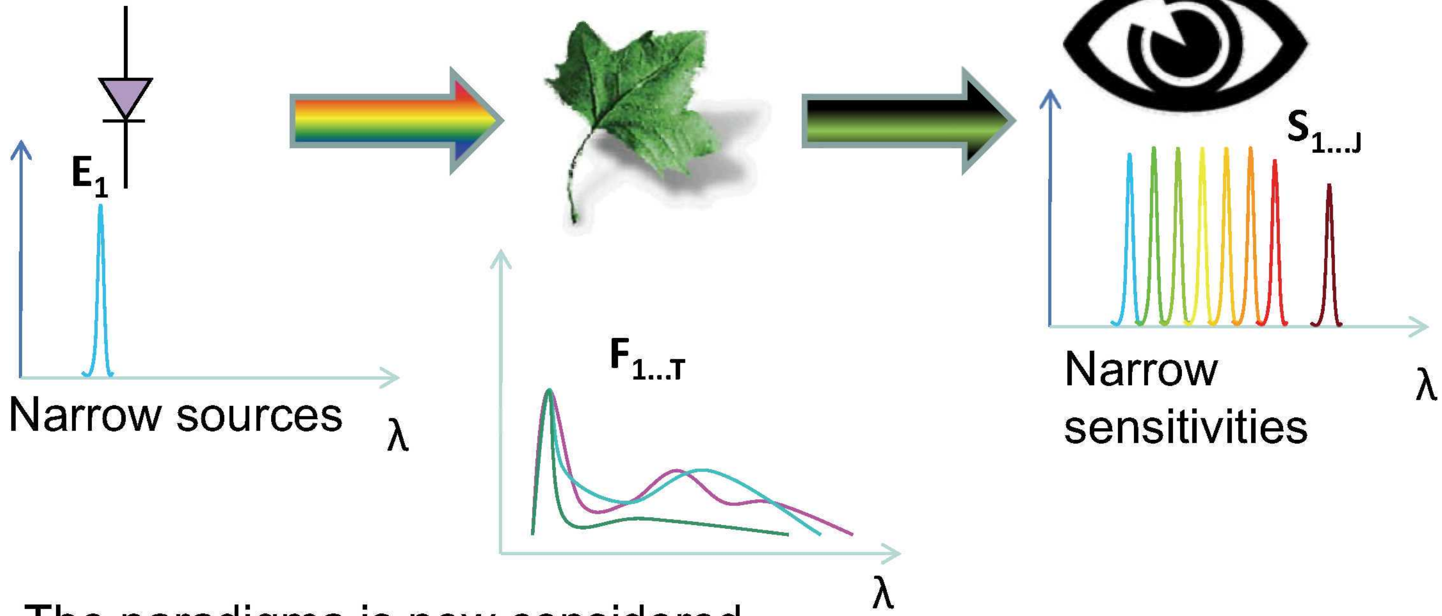
The paradigm is now considered

$$U_{channel(k,j)} = \int_0^\infty F_{(E_{k(\lambda)},\lambda)} S_{j(\lambda)} d\lambda$$

Sources of spectral data

Example: Fluorescence

Fluorescence properties **F** can be assessed at various bleaching times **t,** or at different sample temperature**T** to study photokinetics. Resulting light is studied at various **S.** We obtain a **K times J** matrix containing a excitation emission surface from each measurement. Data are **rearranged** into a **1 times KJ** vector and one dimension is discarded.



The paradigma is now considered

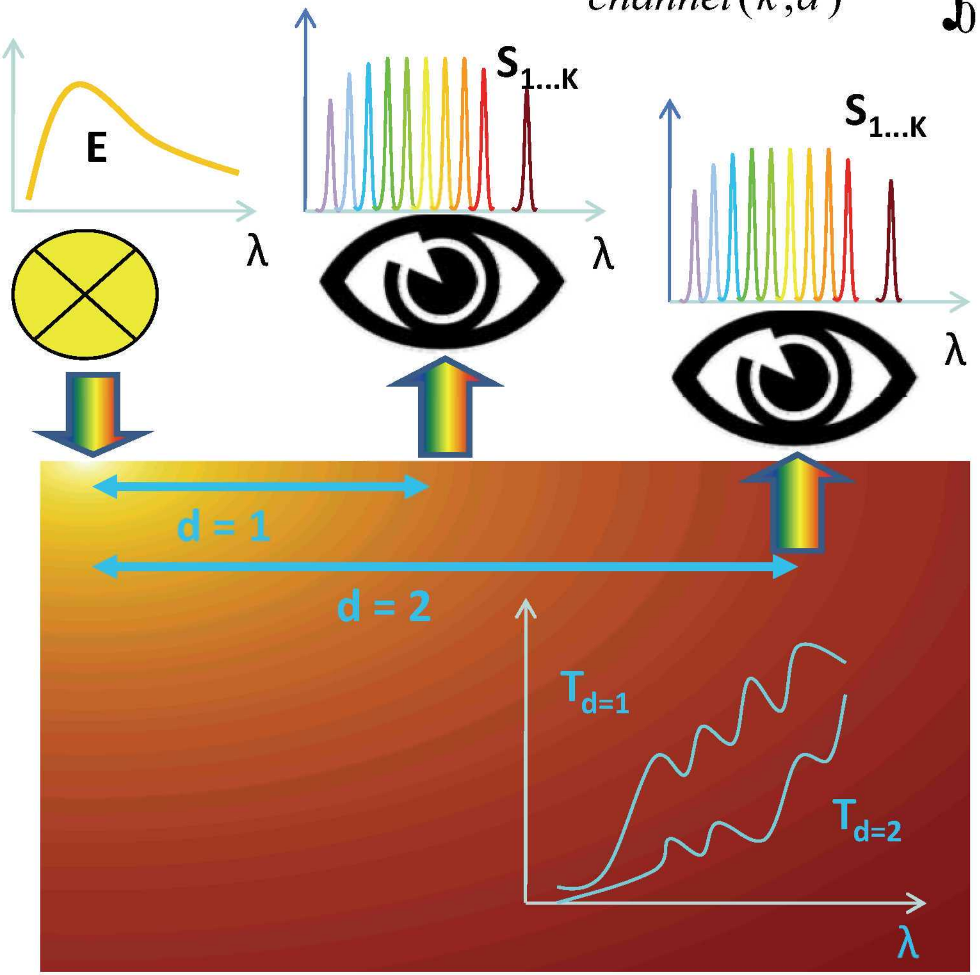
$$U_{channel(k,j)} = \int_0^\infty F_{(t,\lambda)} S_{j(\lambda)} d\lambda$$

Sources of spectral data

Example: Scattering properties

Scattering properties can be accessed by tranmission spectras **T** from several path lengths **d**. A **K times 2** matrix is obtained and rearranged into a **1x2K** vector from each measurements.

$$U_{channel(k,d)} = \int_0^\infty E_{(\lambda)} T_{(d,\lambda)} S_{k(\lambda)} d\lambda$$

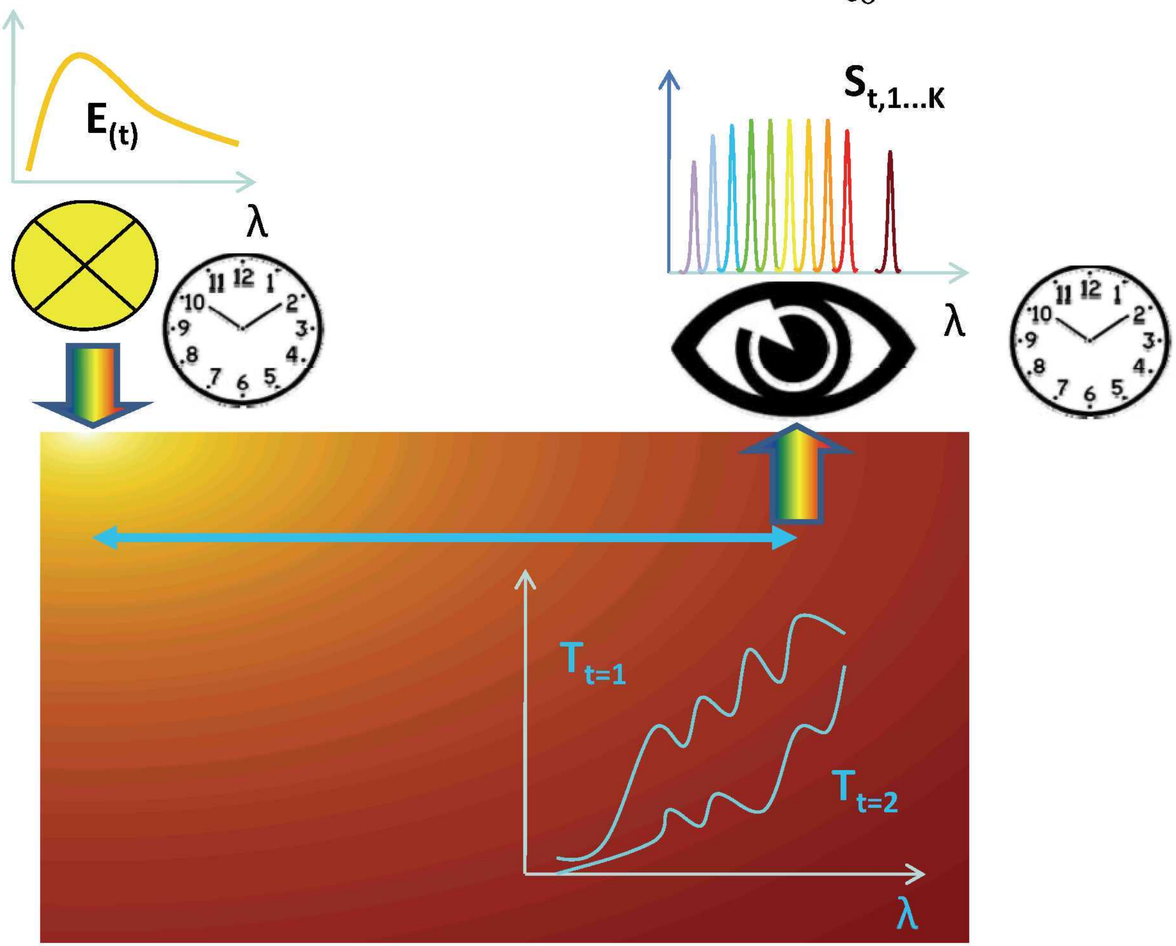


Example: Time resolution

Scattering properties can be accessed by tranmission spectras **T** from several travel times **t**. A **K times T** matrix is obtained and rearranged into a **1xTK** vector from each measurement.

$$U_{channel} = \int_0^\infty E_{(\lambda,t_0)} T_{(\lambda,\Delta t)} S_{(\lambda,t_T)} d\lambda$$

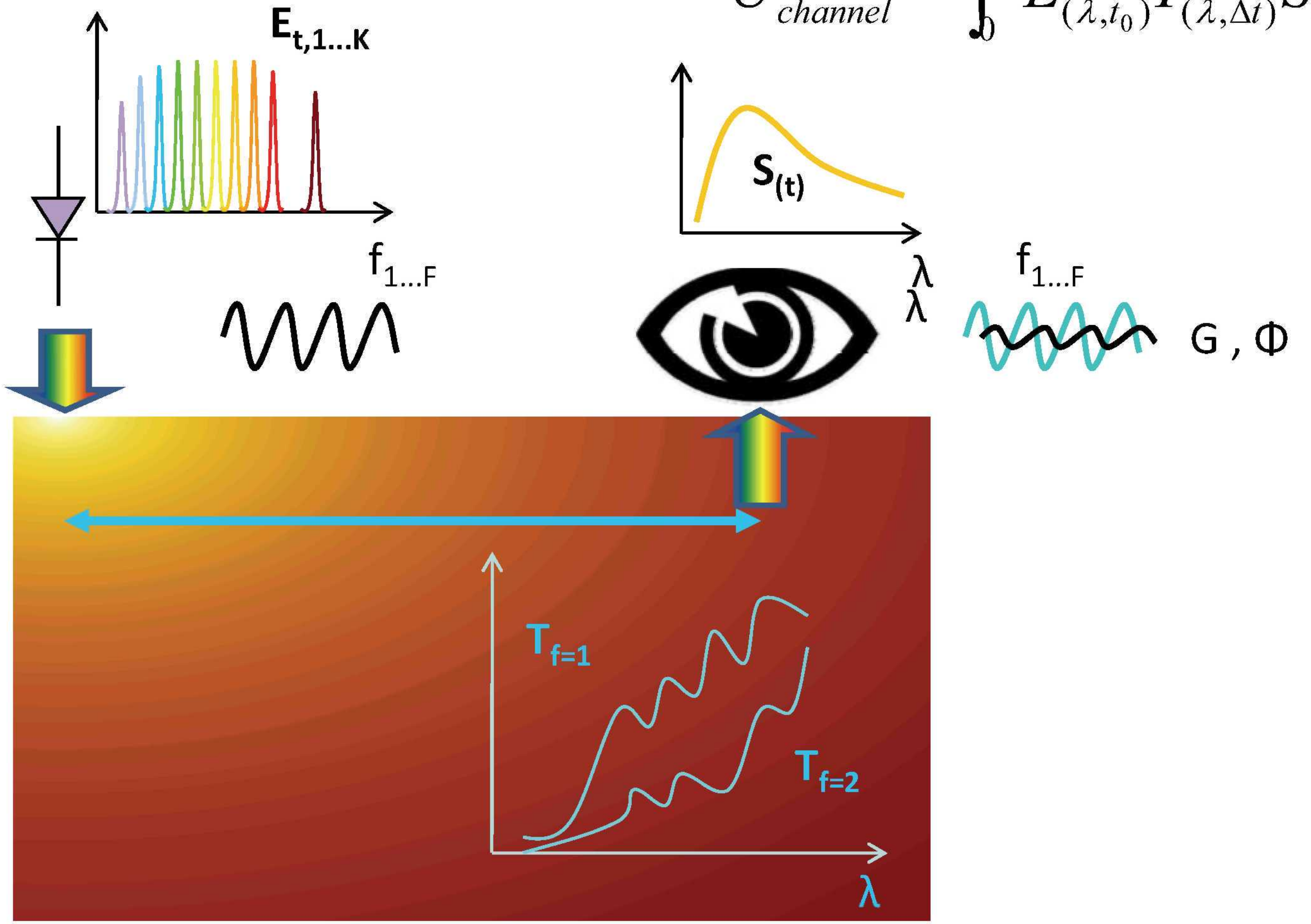
Sources of spectral data



Example: Time resolution

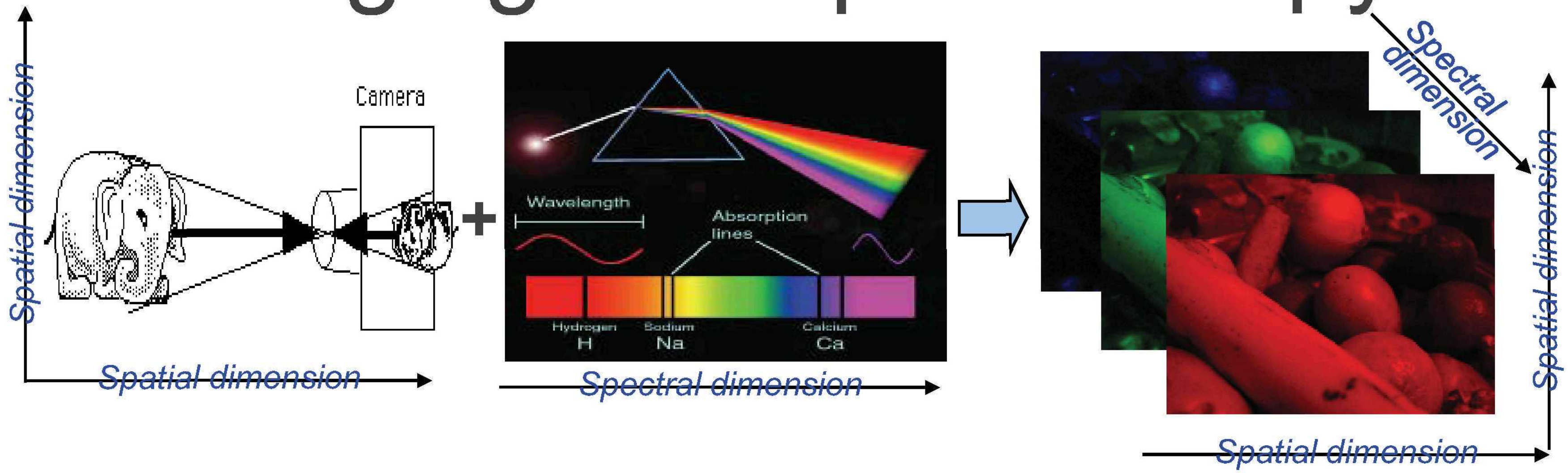
Scattering and fluorescence properties causing delays can be studied equally in time or frequency domain. Spectras **T** from several modulation frequencies **f are obtained**. A **K times F** matrix is obtained and rearranged into a **1xFK** vector from each measurement.

$$U_{channel} = \int_0^\infty E_{(\lambda,t_0)} T_{(\lambda,\Delta t)} S_{(\lambda,t_T)} d\lambda$$



Sources of spectral data

Imaging and spectroscopy



- **Imaging**. Obtaining a BW picture, a 2D matrix with spatial information of the sum of all wavelength
- **Spectroscopy**. Obtaining a 1D vector with all wavelengths in one point.
- **Multi spectral imaging**. Obtaining a 3D matrix with spectral information in each spatial point.

Example 1: A multi spectral CT scan would have three spatial dimensions and on spectral, equals 4D

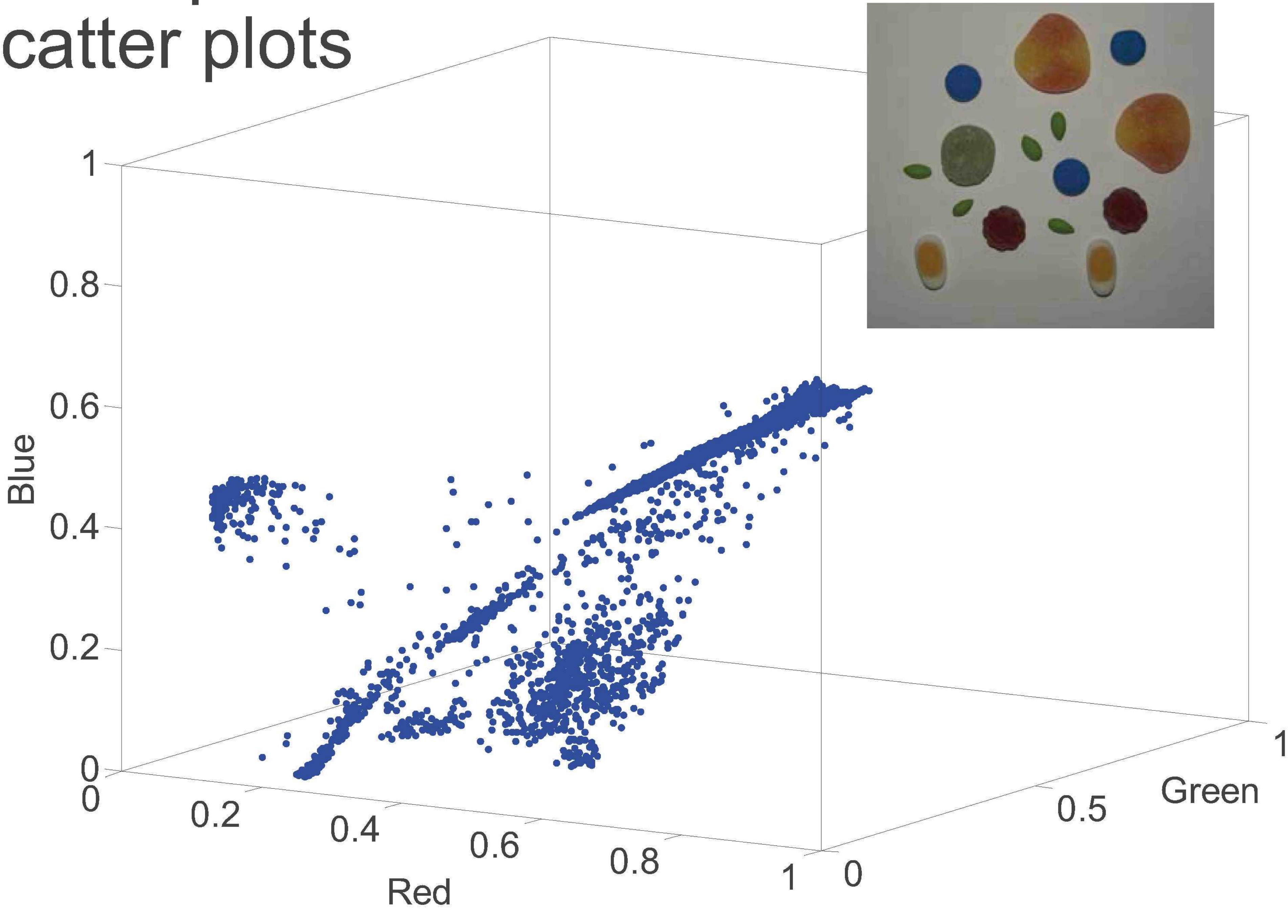
Example 2: A real-time CT scan, will have above four dimension plus a temporal, equals 5D

Discretization

Subject to discretization:	Light intensity	Light energy	Space	Time
Domain:	Dynamical -	Spectral -	Spatial -	Temporal -
Discretized by:	Bits	Spectral bands	Pixels / Voxels	Frames
Resolution:	Dynamic -	Spectral -	Spatial -	Temporal -
Res. limited by:	Signal to noise ratio / photons	Channel / illumination bandwidth	Point spread function	Exposure time / flash envelope
Range:	Dynamic -	Spectral -	Field of view	Recording time

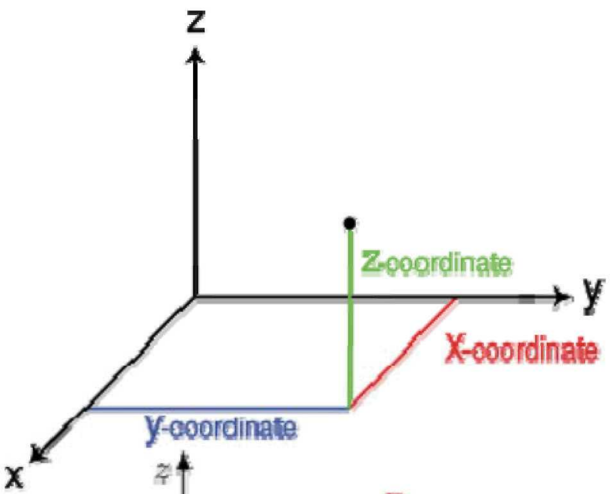
Table 1: Comparison terms associated with discretization along various domains.

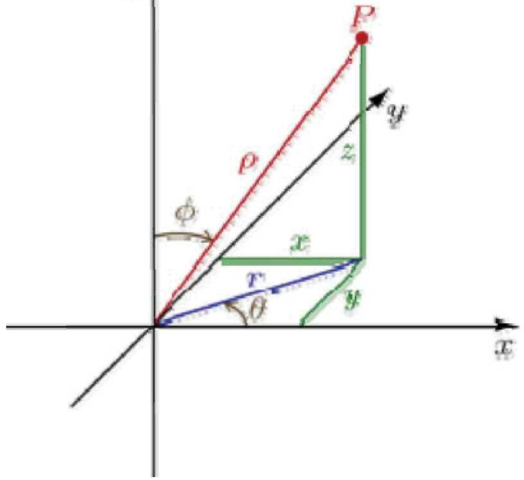
Color spaces and scatter plots

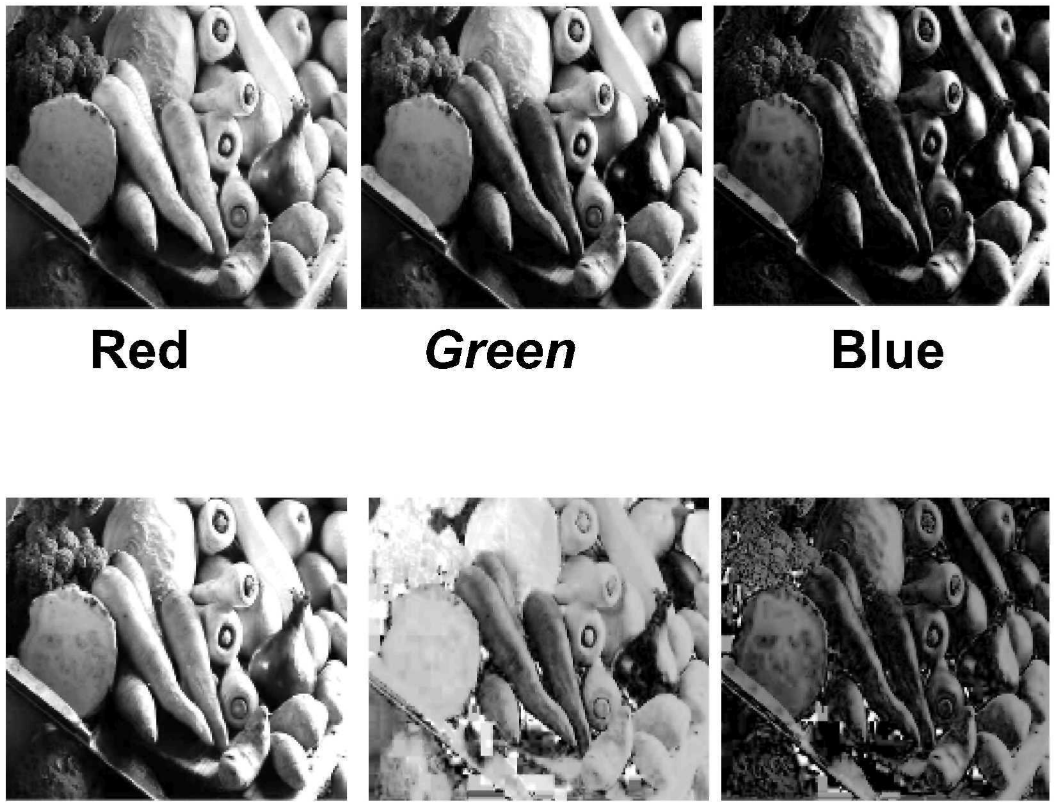


Colour spaces

- **Cartesian coordinates [dim1 dim2 dim3 ... dimN]**
- **Spheric coordinates [abs ang1 ang2 ... angN]**
- **Conical**
- **Others**
  - ***What are the units in either of the colour spaces?***





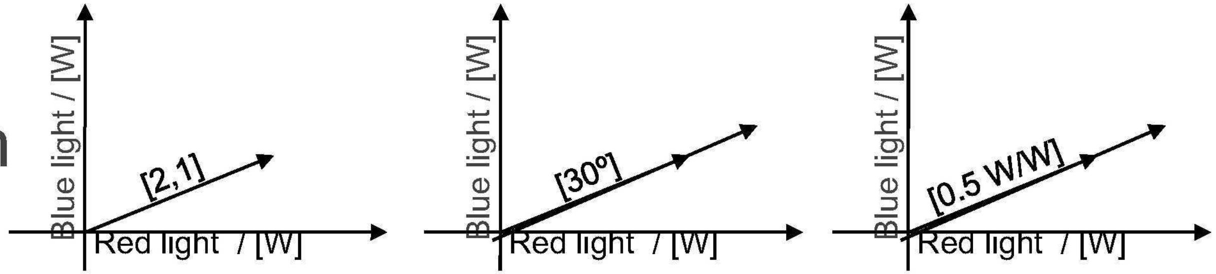


Red ***Green*** **Blue**

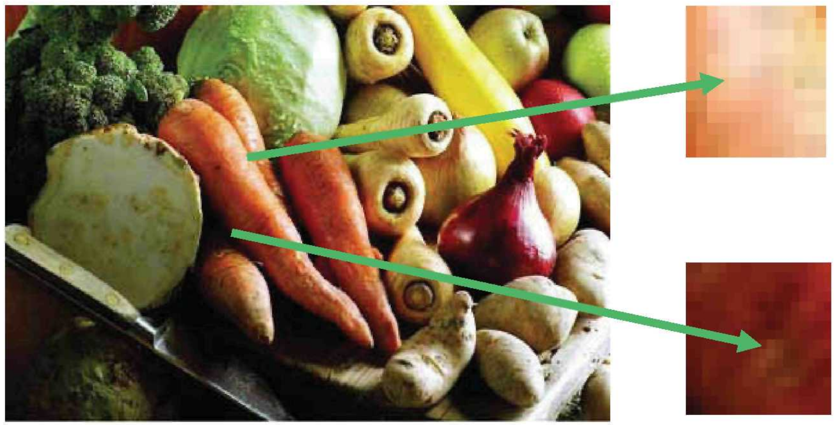
Intensity **ang1** **ang2**

Unit-less functions

- Unitless functions cancels effects of variating illumination and shadows suposing that the illumination is "white"

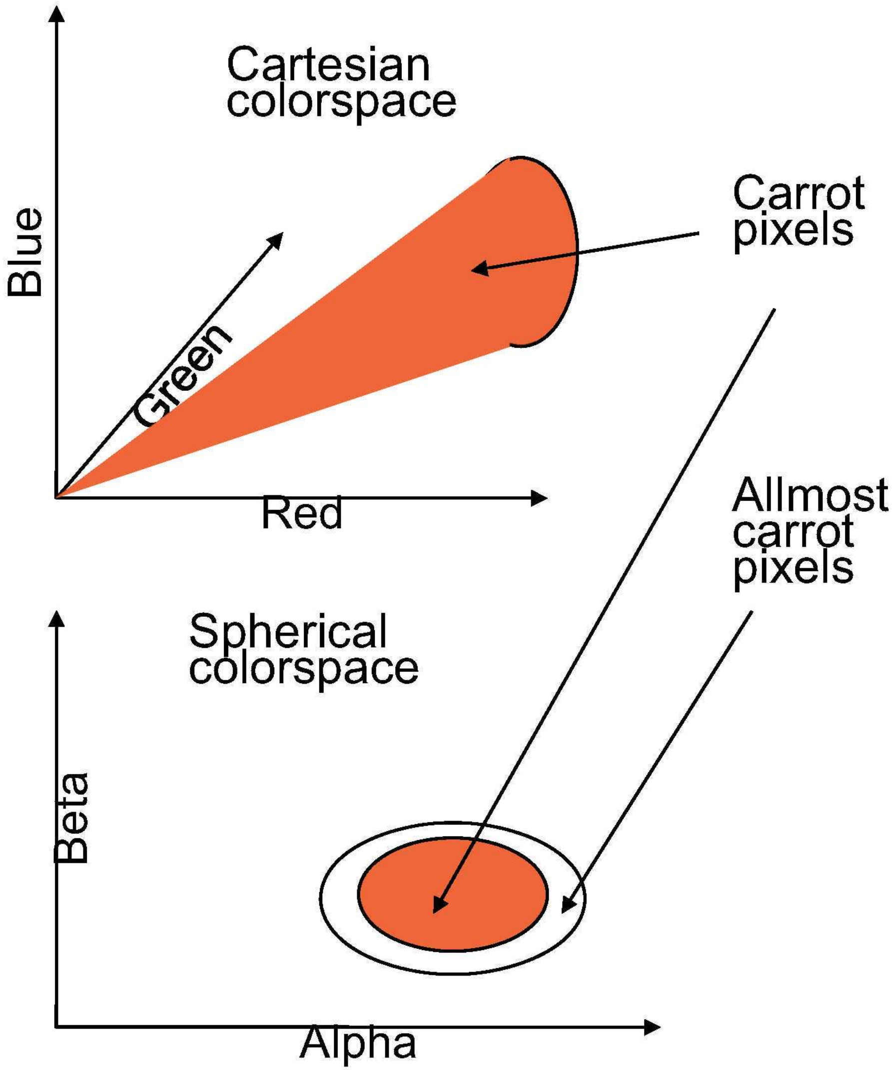


- Units can be cancelled by rational functions or trigonometrical functions

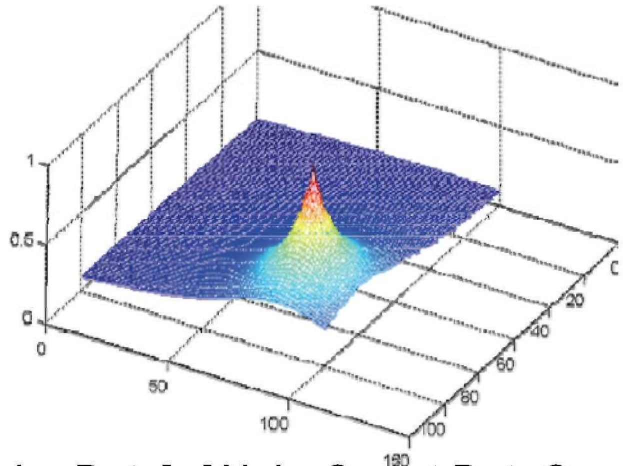


- When units are cancelled brightness information is lost

Dividing colour spaces



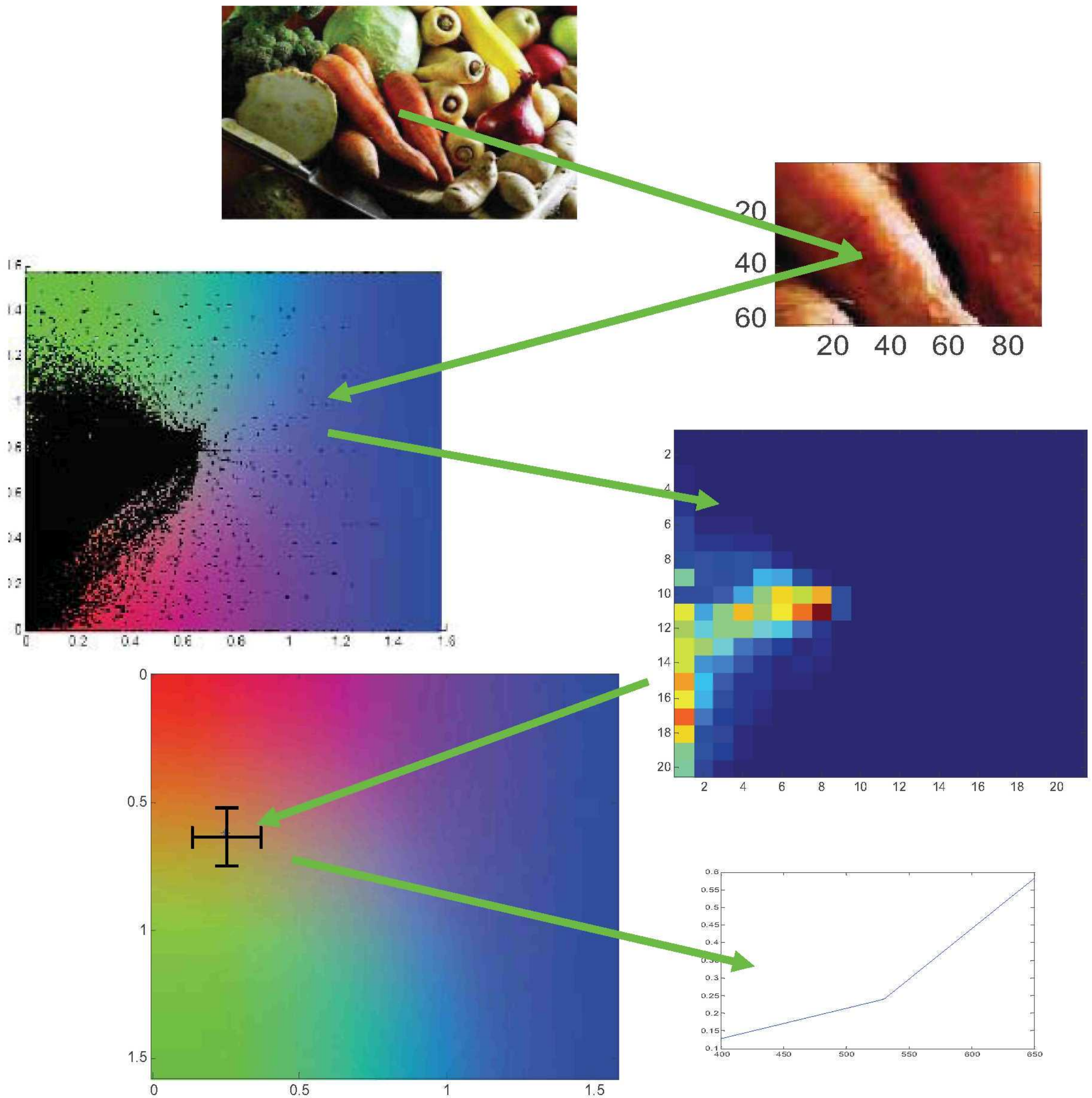
- **During the creation of a contrast function one divide the N-dim space into regions**
- **If irrelevant information is discharged the formulation will be easier**
- **Gradual functions determines to which grade a pixel is a carrot**
- **Example:**



isCarrot=1/(1+norm([Alpha Beta]- [AlphaCarrot BetaCarrot]))

Identification in colour spaces

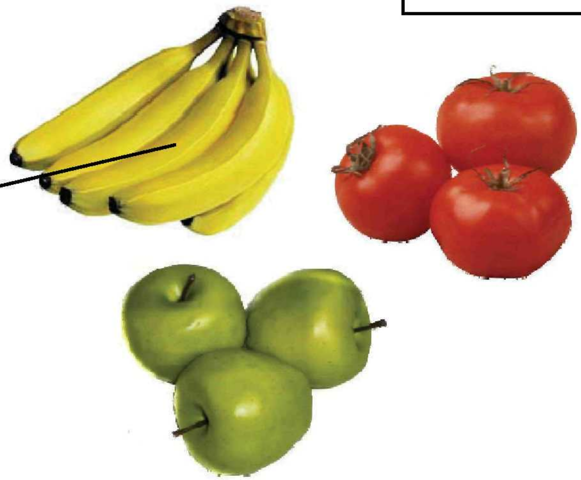
- 3 colour channels: → 2 unit-less angles in a spherical colour space
- The pixels of the carrots: become locations in the color plane
- The distribution has a shape, mean-vector, and variations.
- Imagine how the distribution would look like with more color channels

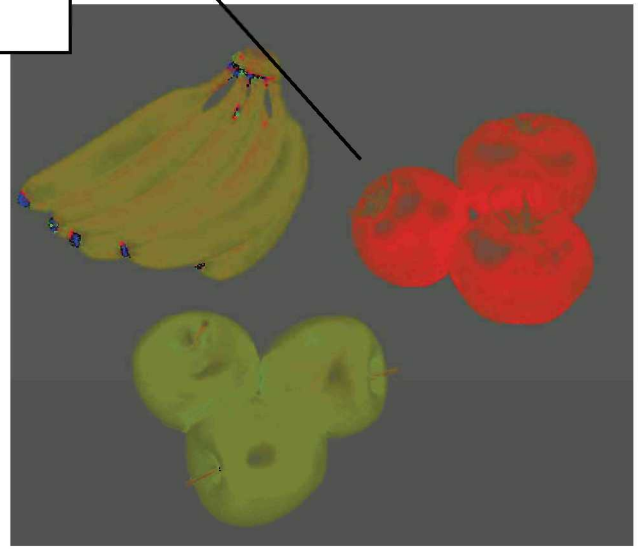


Decisive banana contrast function:

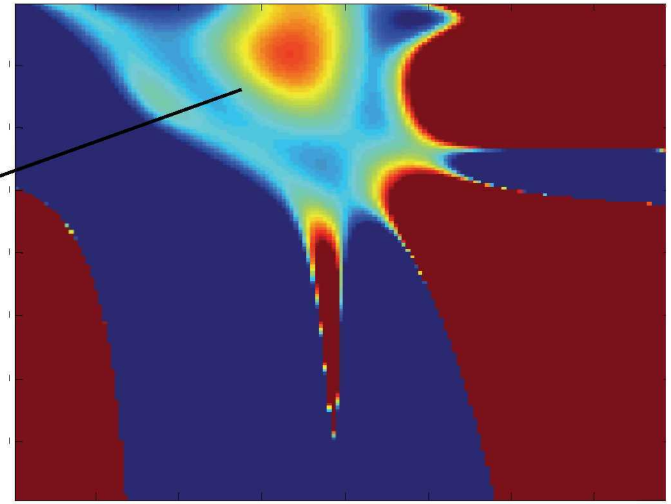
Unit-less processing

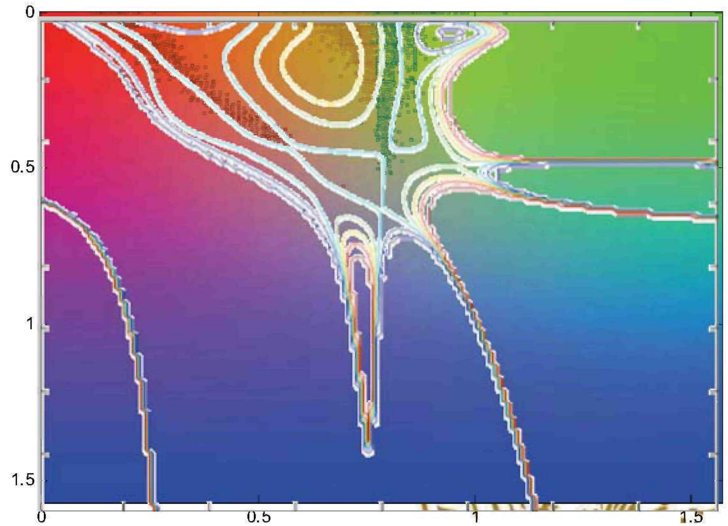
Red, green or red and green?



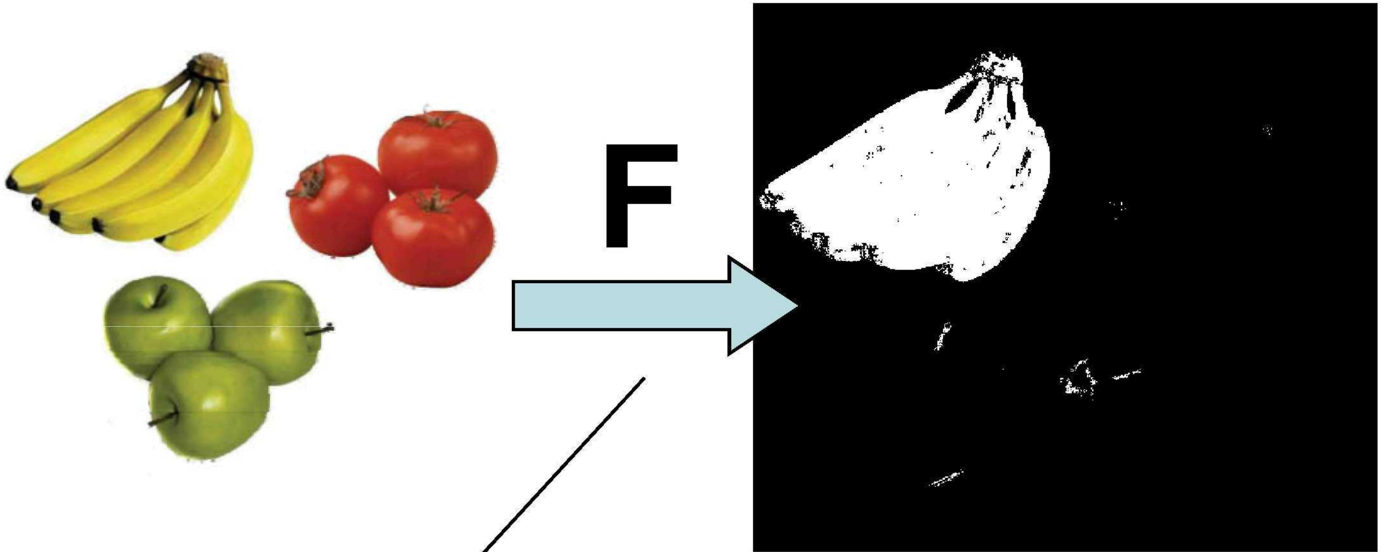


2D polynomial contrast function





Evaluation



Nothing but a matrix multiplication!

Treshold -> True and false

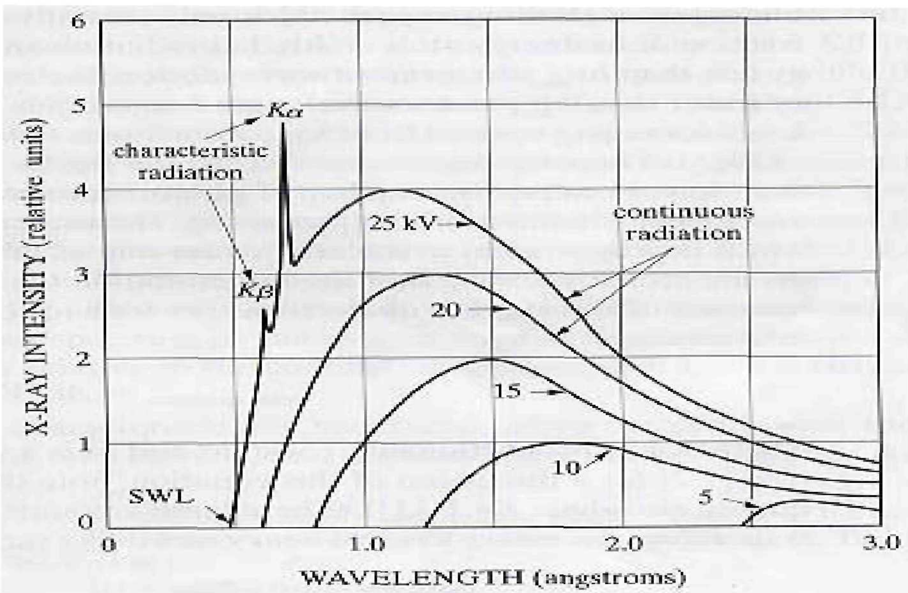
Third-World multispectral imaging?

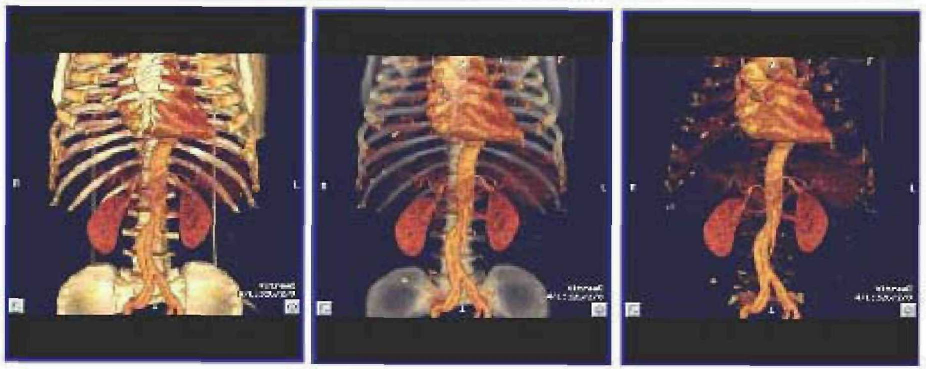
Examples of components pricing for multispectral imaging:

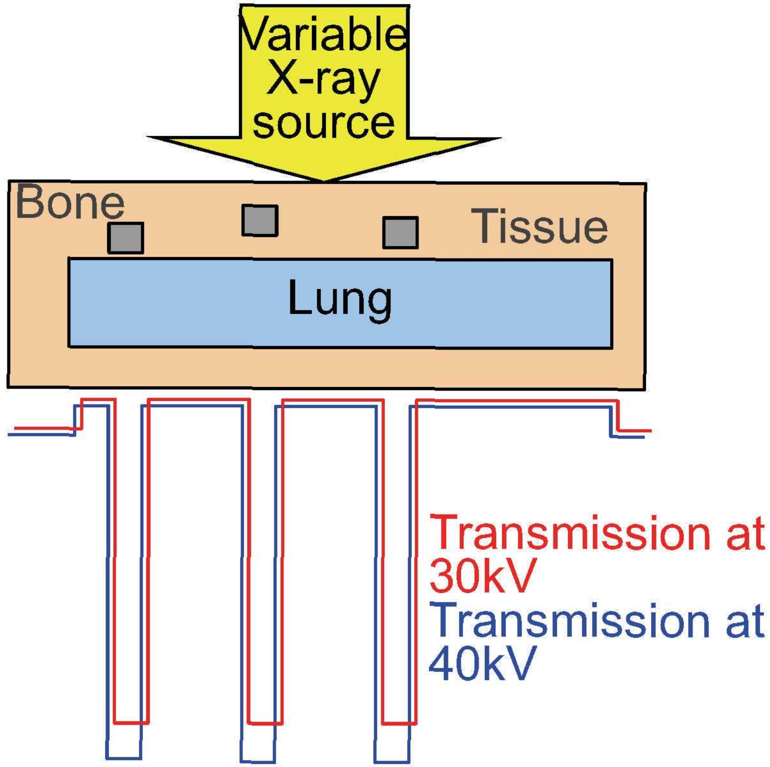
Multispectral satellite	100 000 000$	
PET/CT scanner	2 000 000$	
Imaging Fourier transform spectrometer	500 000$	
Commercial push broom	200 000$	
IR Focal Plane Array (FPA) imager	100 000$	
Tunable wavelength filter	50 000$	
Optical table	10 000$	
Scientific imager	5 000$	
Optical scanning stage	3 000$	
Fiber spectrometer	1 000$	
Diffraction grating	500$	
Industrial CMOS imager / Commercial RGB camera	200$	Limit of realism
LEGO, LabView microcontroller, steppers, encoders, sensors	200$	
Interference filter	60$	
Absorption filter	20$	
Polarization filter	10$	
Light Emitting Diode, LED	1$	
Google earth, multispectral satellite data	0$	!!!

Multi spectral X-ray

- **By changing the tube voltage, the ”colour” of the X-rays is changed.**
- **Different tissues, bone, liquids and gasses have different absorptions spectres**

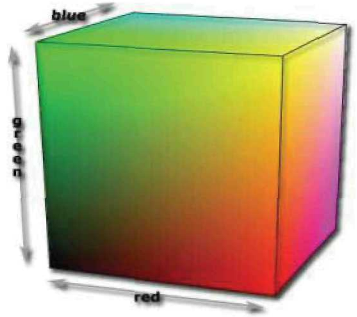


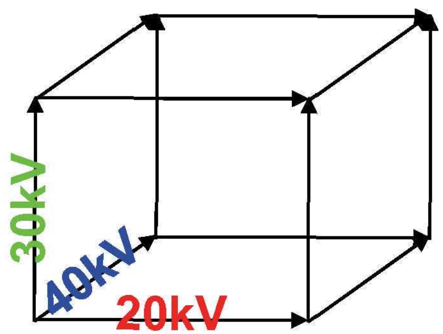




$$T_{30} - \beta * T_{40} = T_{contrast}$$

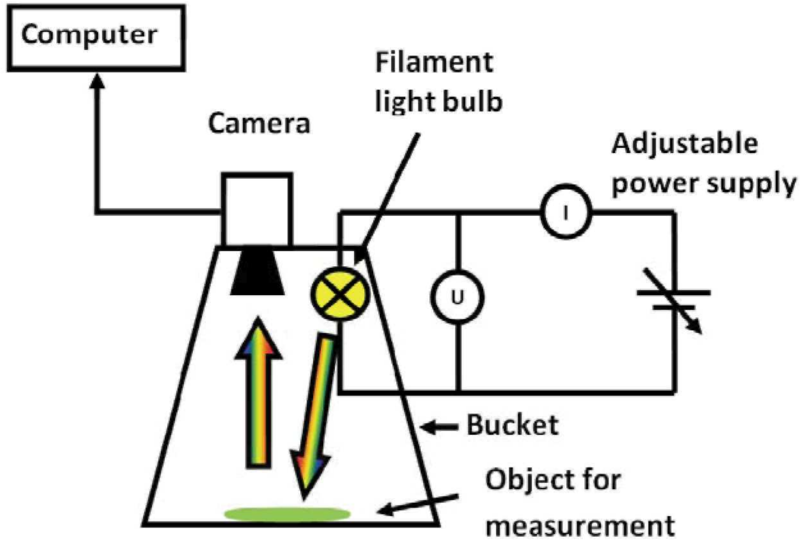
Contrast function for lungs

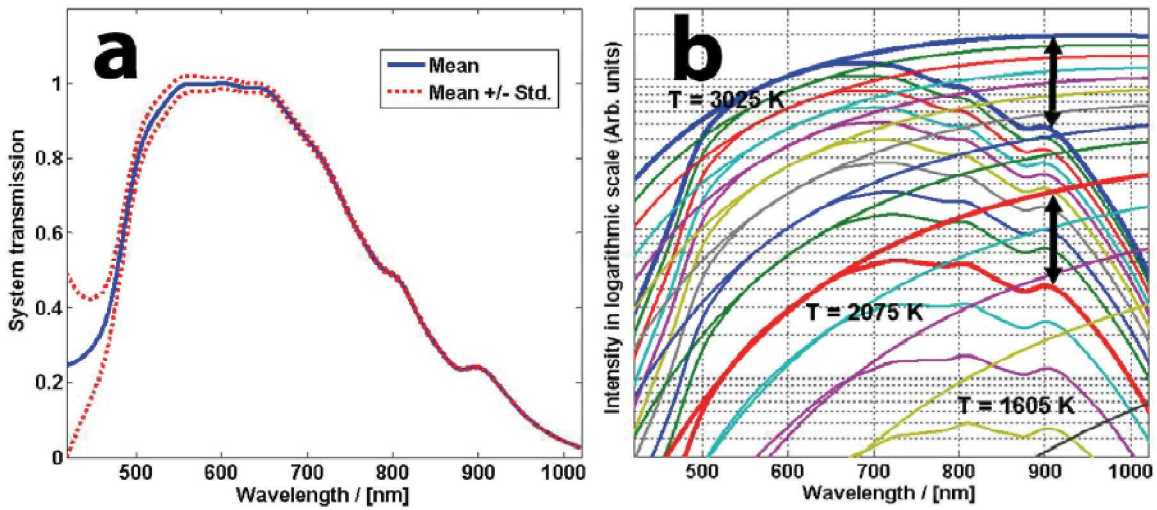




Wien Shift Imaging

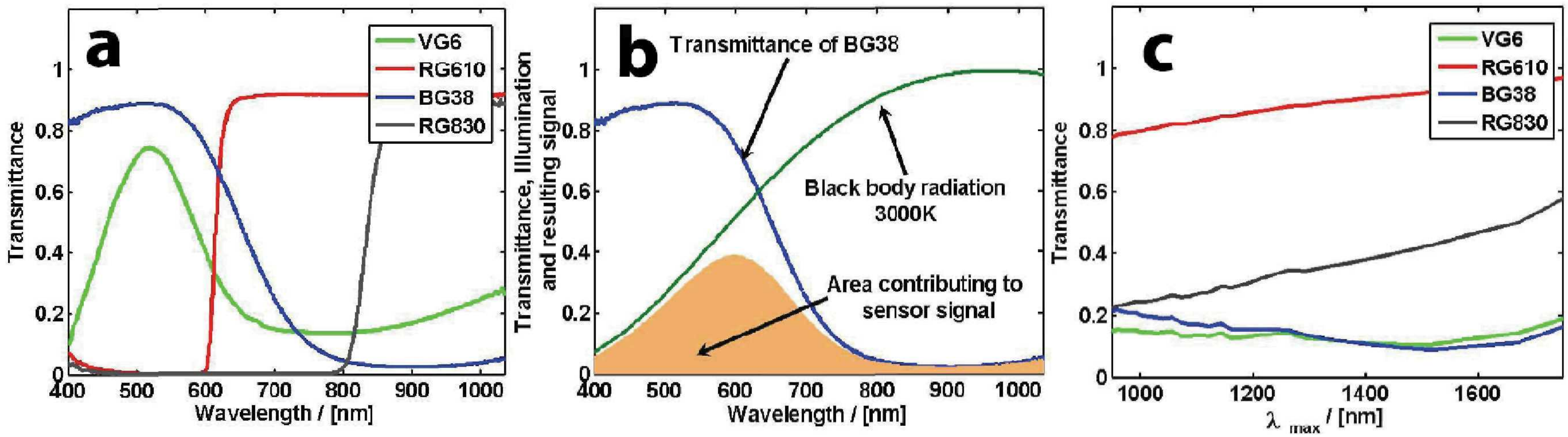
- Simulation of multispectral X-ray
- Educational exercise

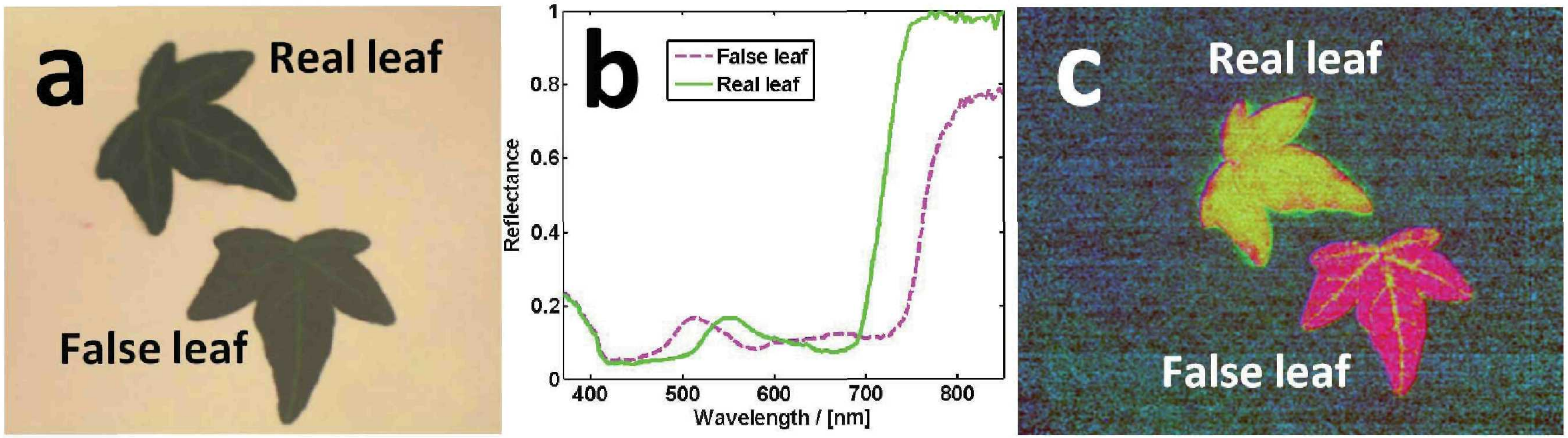




M. Brydegaard 2009

Wien Shift Imaging





LED based system for imaging transmission spectroscopy

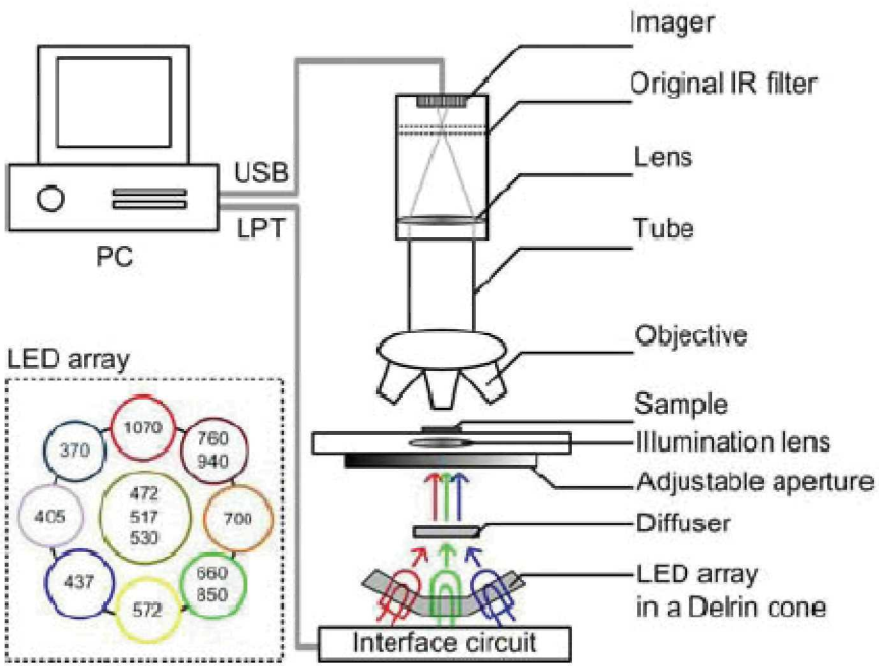


Fig. 1. Arrangement for multi-spectral transmission microscopy employing multiple LED illumination.

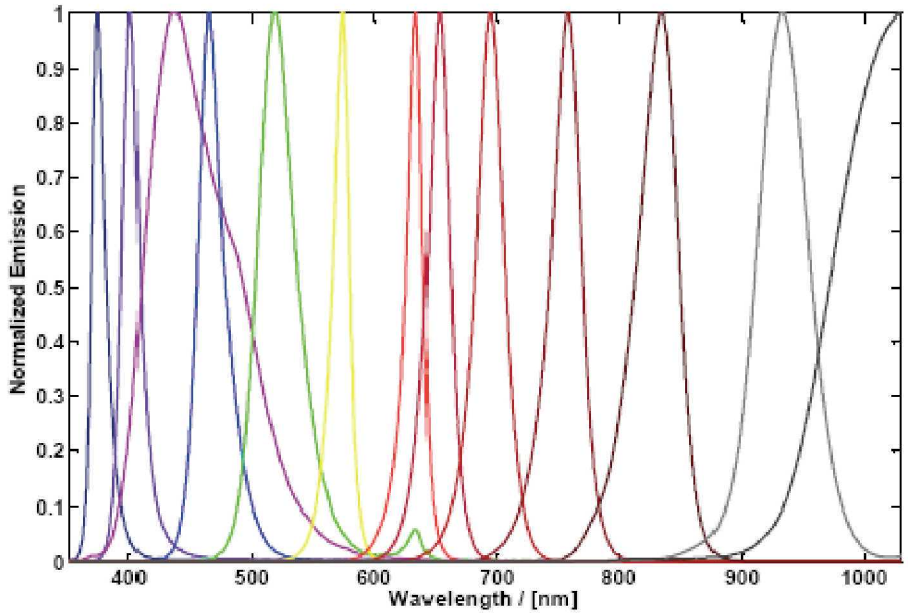


Fig. 2. Normalized spectral emissions of the different LED sources used in the multi-spectral microscope.

The 200$ microscope!

Spectral domain – Hair measurements

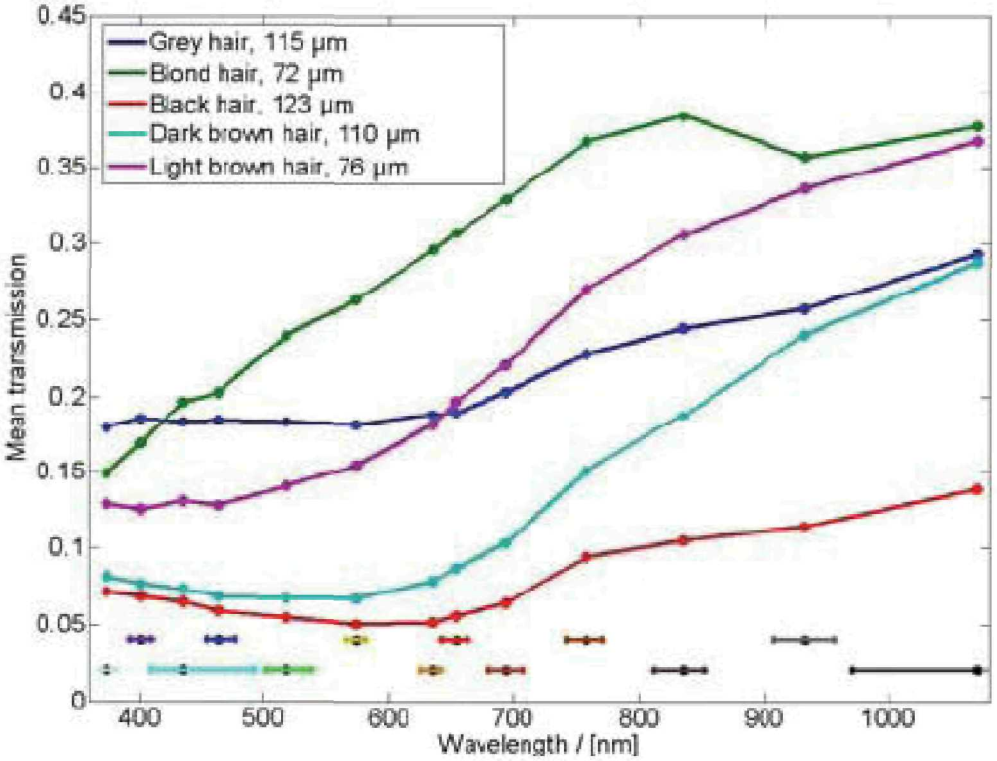


Fig. 5. Transmission spectra of hair strands from five individuals. The symbols in the lower part indicate λ_{max} and FWHM for each spectral band.

Applications:
Forensic science
Zoology
Cosmetics

Spatial and spectral domain

- Spatial – spectral studies
- Assessment of refraction index
- Polarization phenomena

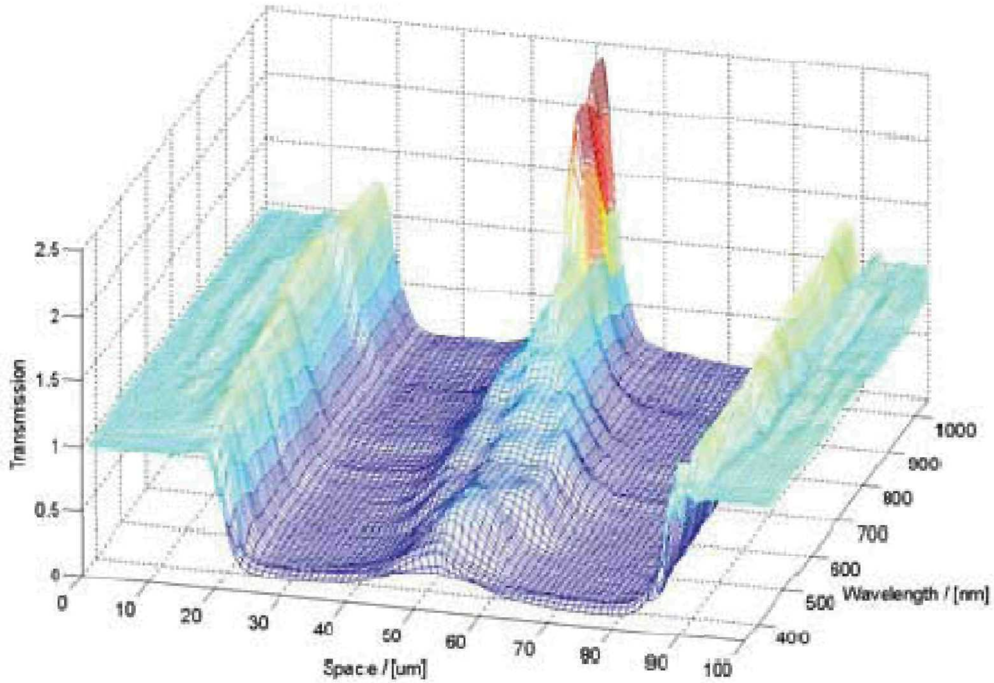
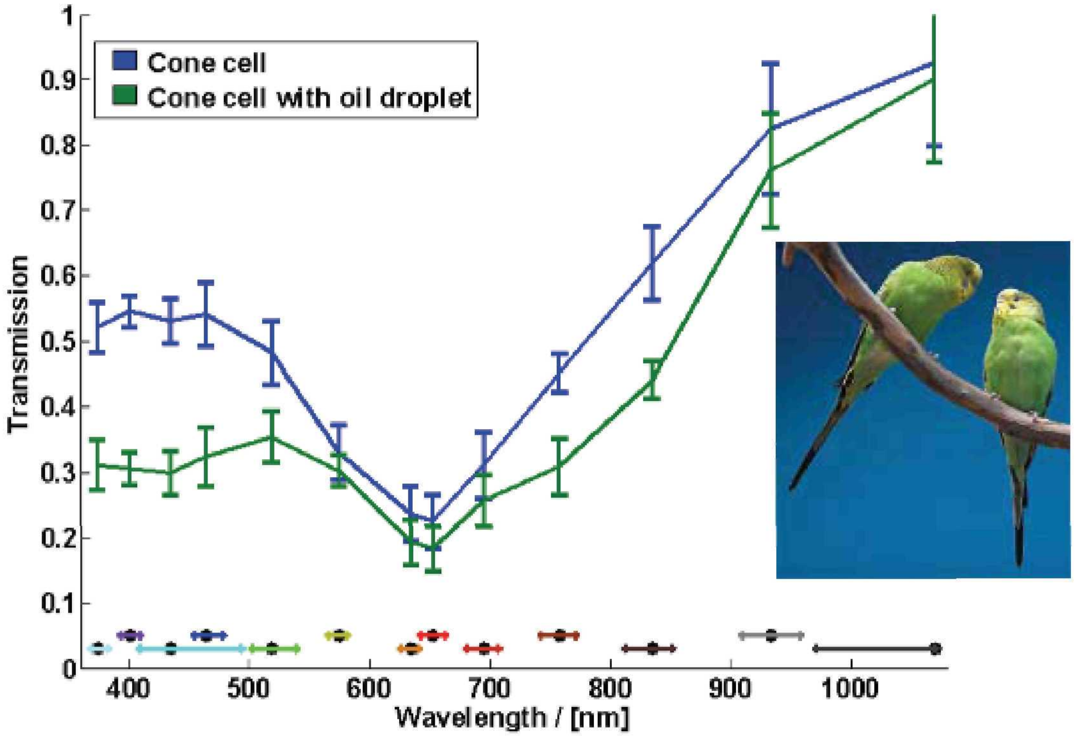
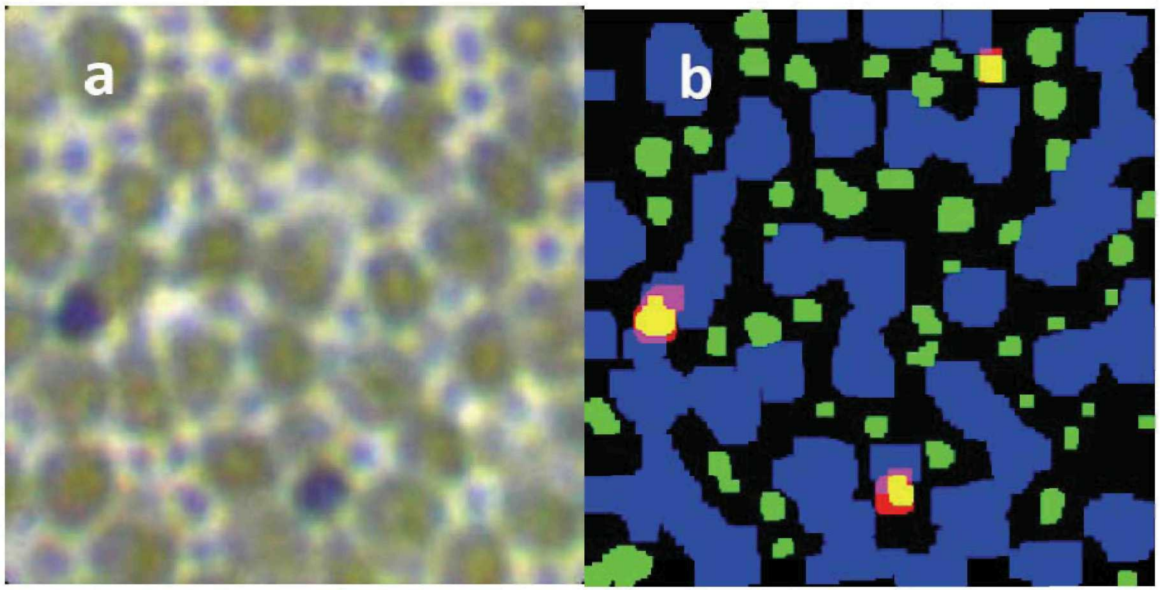


Fig. 6. Transmission cross section for a blond hair, represented in terms of one spatial and one spectral dimension.

Object identification

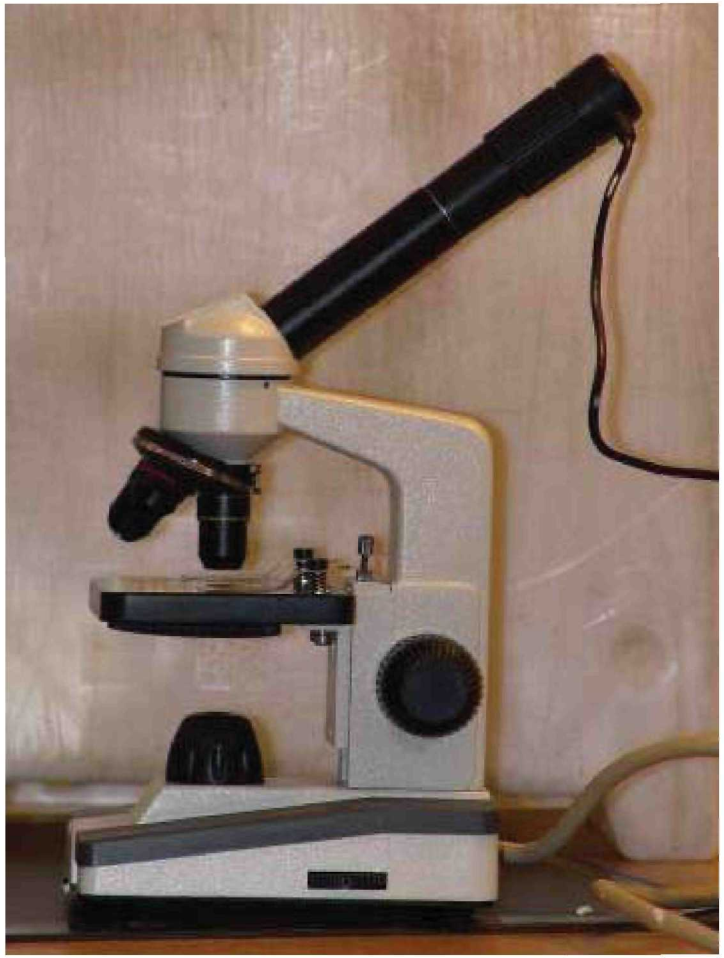
- Spatial stretching by land mark technique
- Information compression
- Multivariate modeling
- Morphological binary operations: erosion and dilation
- False color representation





Possible further development

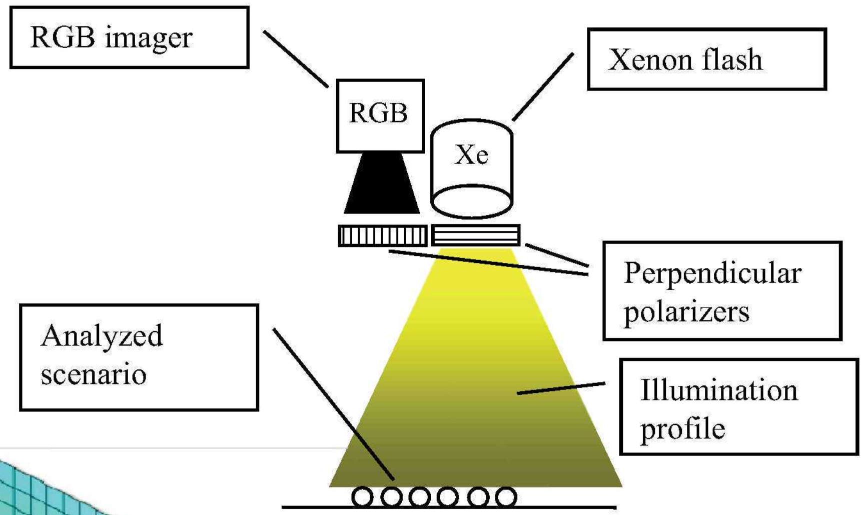
- Synchronization and Flashing
- Improved stray light rejection
- Reflecting objective, automated focus or spatial disconsolation
- Imaging fluorescence spectroscopy
  - Emission excitation acquisition
  - Life time imaging
- Angular discrimination
  - Back scattering geometry
  - Dark field
  - Assessment of μ_a, μ_s, g
  - Multi spectral microscopic tomography
- Polarization studies

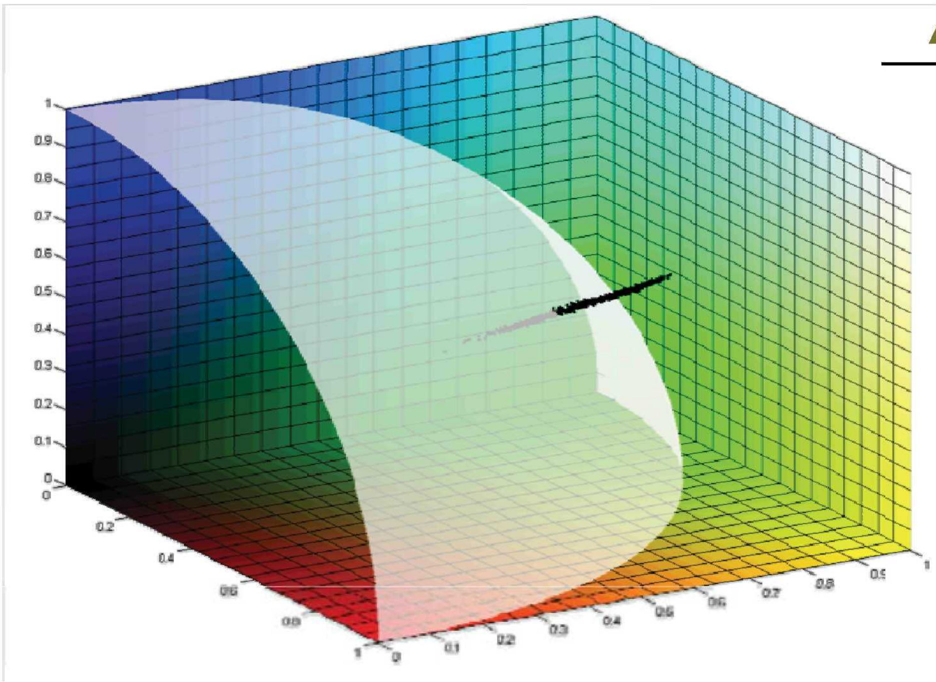


RGB imagers

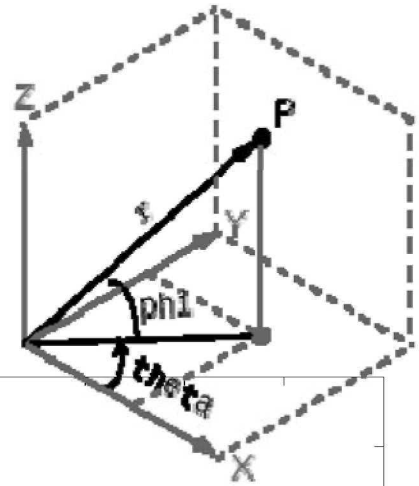
- Controlled illumination

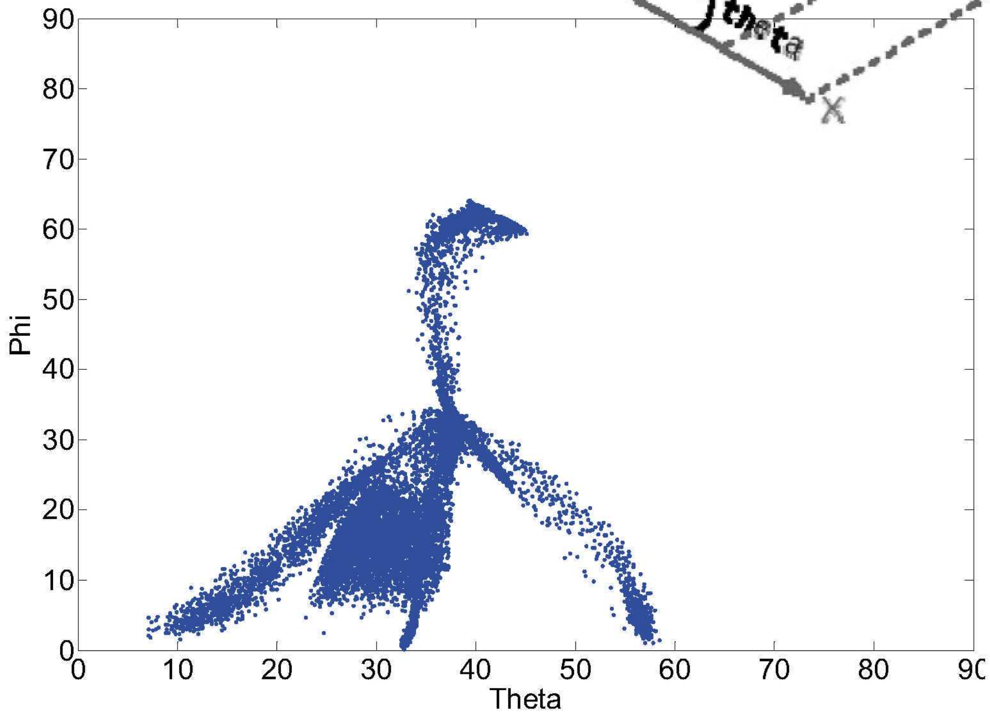
- Ensuring multiple scattering





EEM and RGB decomposition

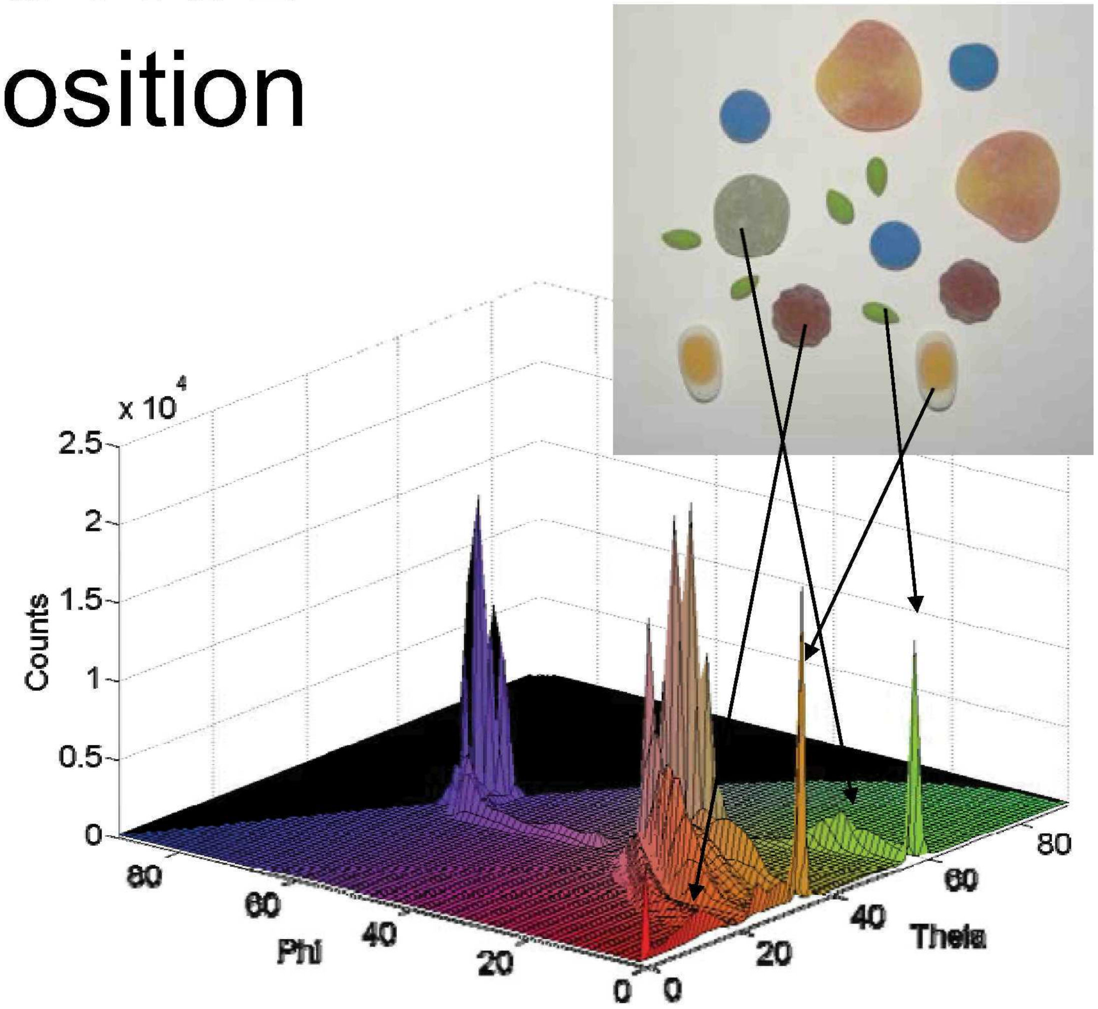




- Unit-less processing
- Concentration of observations?
- Multidimensional histograms

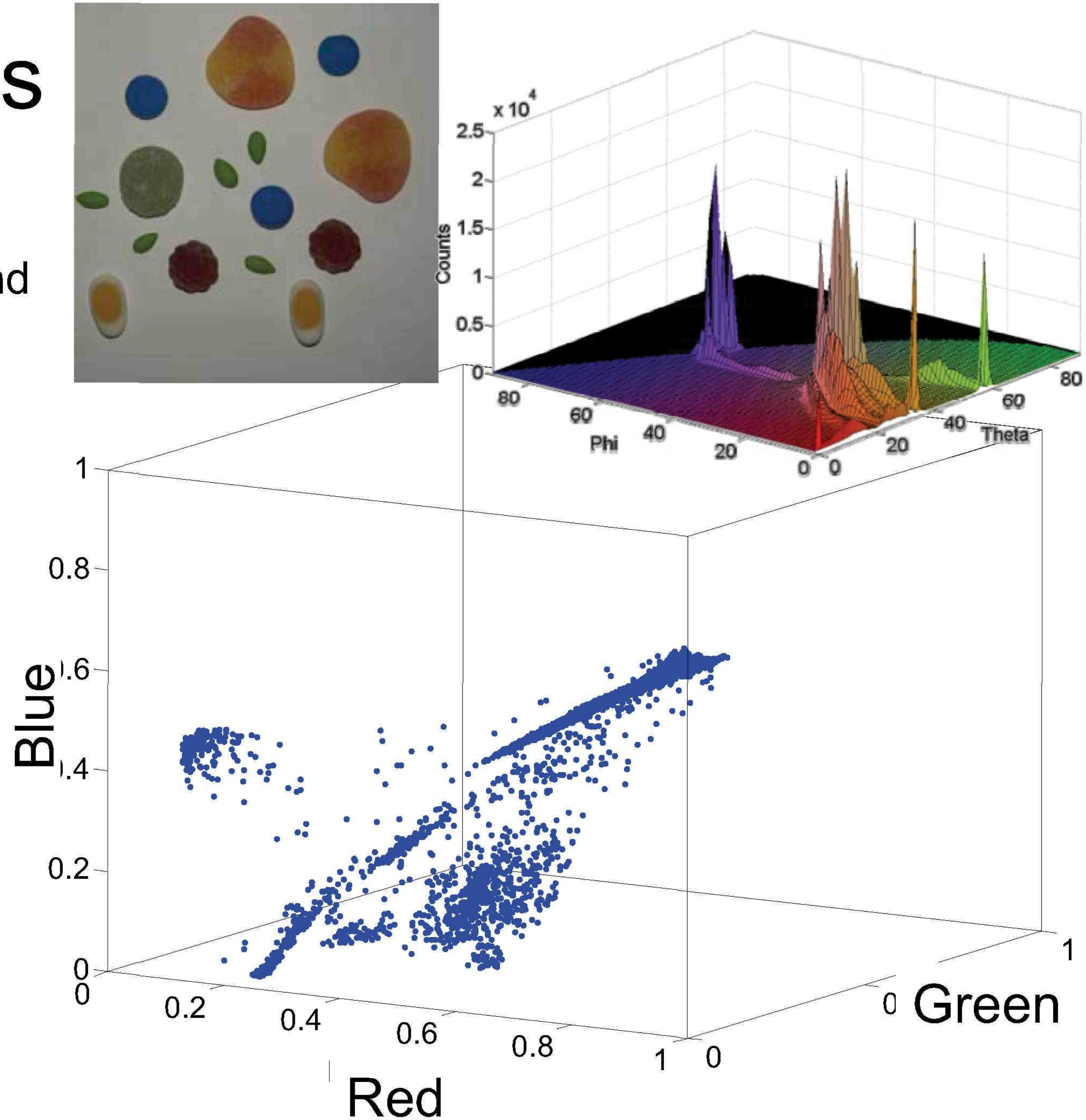
EEM and RGB decomposition

- Spectra, images or photon histograms?
- CCD, pixels and bins



2D histograms

- Histograms, spectra and images
- Distribution decomposition

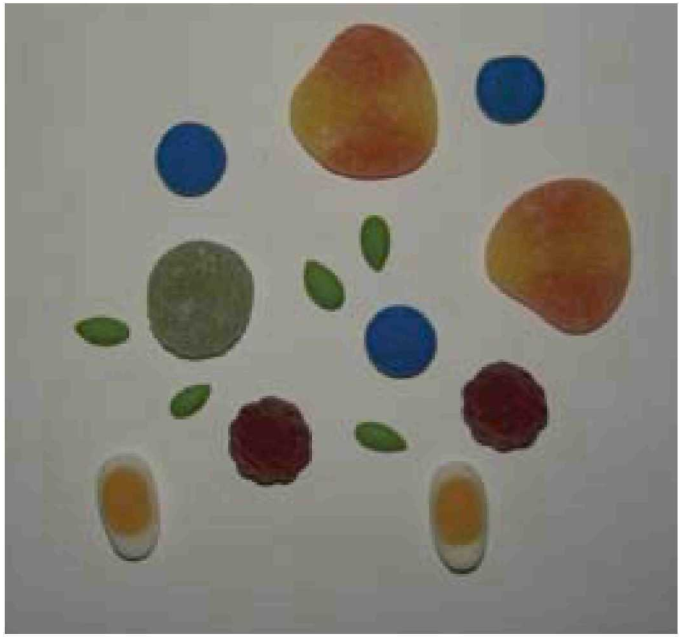


Candy counting, how many?

$Y=F(U)$

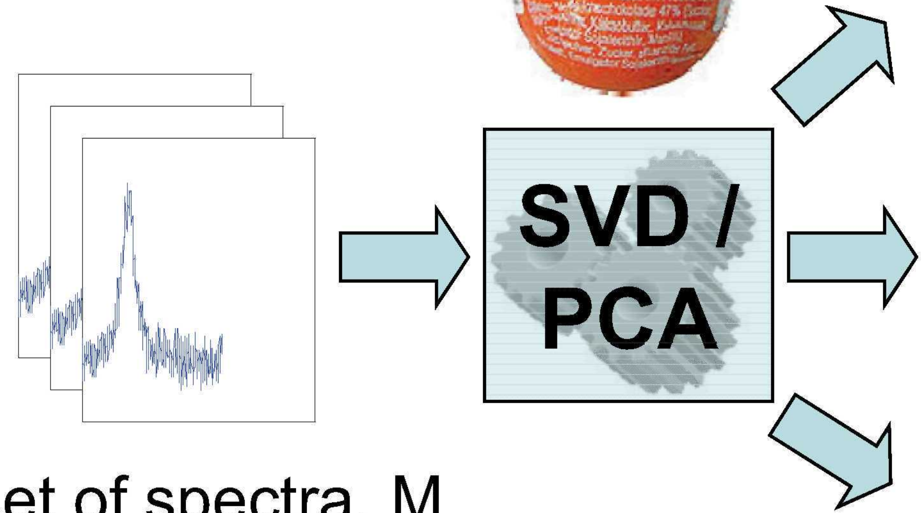
$Y=k_0+k_1*u_1+\ldots k_8*u_8$

Residuals and quality



Type	Peaches	Green gum	Red gum	Blue tablet	Green seed	Eggs	Orange tablet
Reality	2	1	2	3	5	2	0
Estimated	1.97	1.04	1.88	2.72	5.36	2.09	0.04

Principal Component Analysis (PCA)
Singular Value Decomposition (SVD)



New base functions, or *principal components* (PCs, V)

Eigen values σ in Σ related to residuals and importancy of each PC

Linear coefficients or *loadings,* U, reduced representation of M

Set of spectra, M

$$M = U \Sigma V^*$$

Matlab: svd / princomp

A new representation of M

Coefficient describing the amount of ingredient PC1 in individual n

1st base function, or principal component

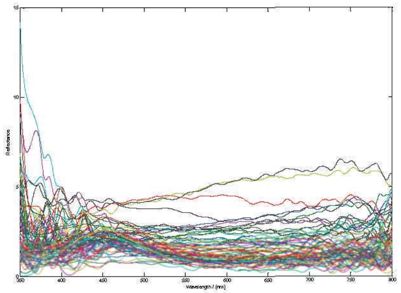
$$m_n = c_{n,1}\sigma_1 PC1 + c_{n,2}\sigma_2 PC2 + c_{n,3}\sigma_3 PC3 + \ldots$$

Eigenvalue, importance of component 1

Spectrum for individual n

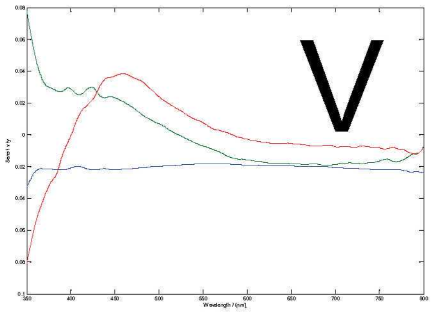
Truncation of representation

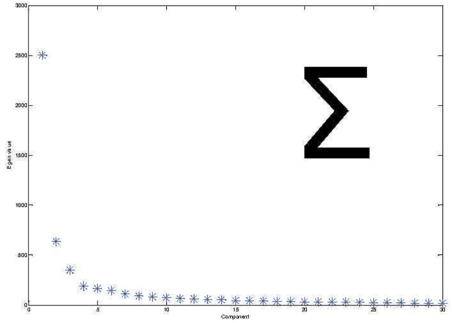
Principal Component Analysis (PCA)
Singular Value Decomposition (SVD)

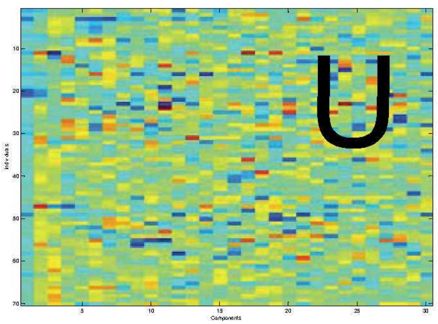


Set of spectra, M

SVD / PCA





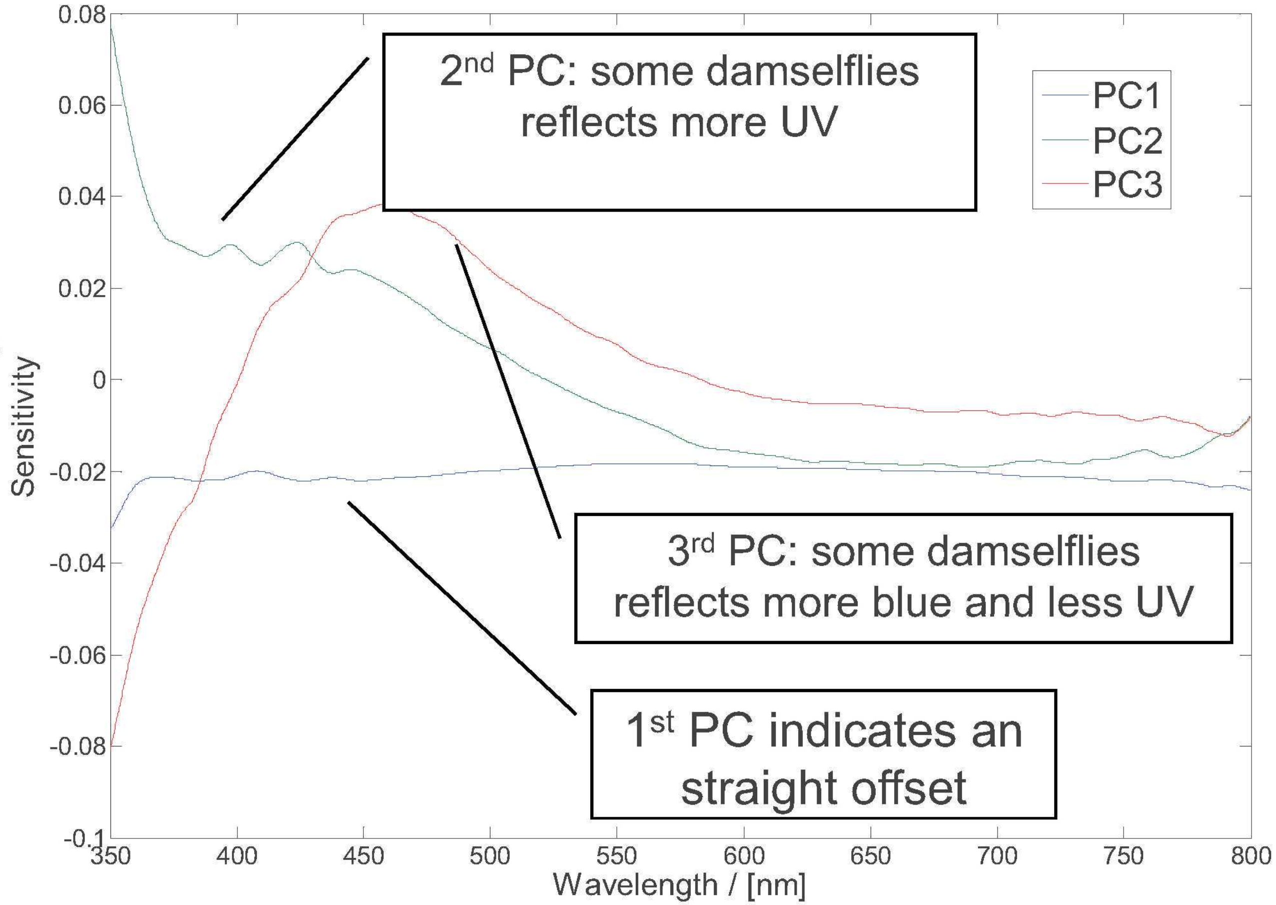


$$M = U \Sigma V^*$$

Matlab: svd / princomp

V, the new base spectra

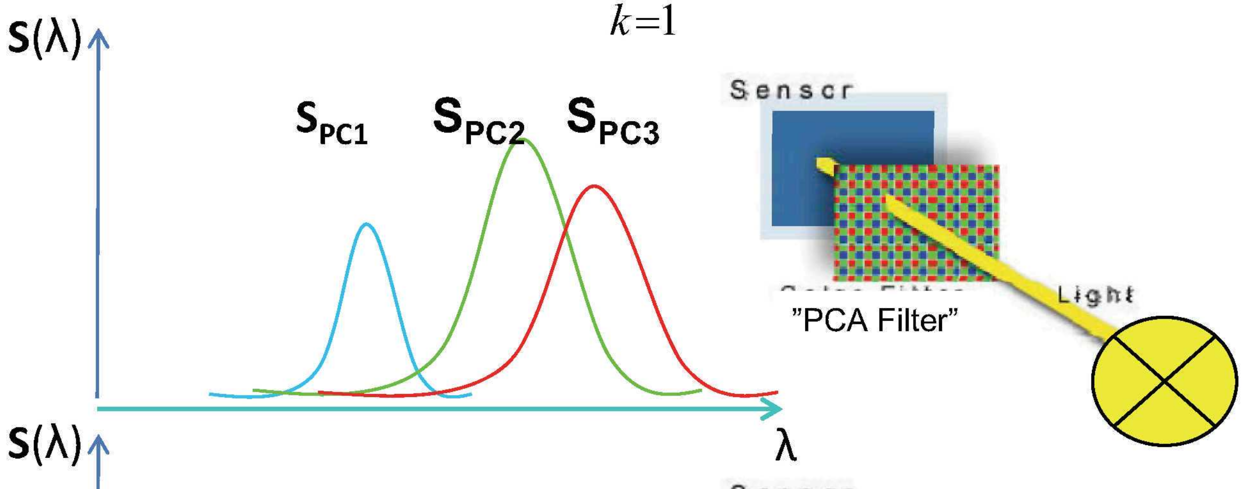
- These new base functions are generated from the variance in the set of spectra
- This information indicates were in the spectrum the samples varies
- A perfect instrument or LIDAR to classify damselflies, should have these sensitivity curves
- Note: Orthogonal base functions: PC1'*PC2=0

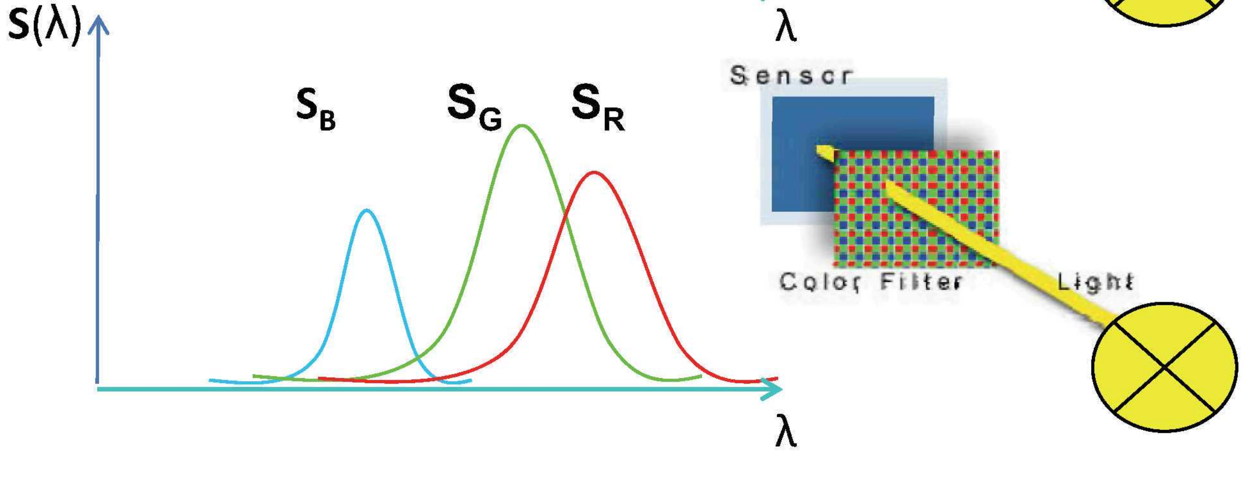


SVD/PCA - Sensitivity Analogy:

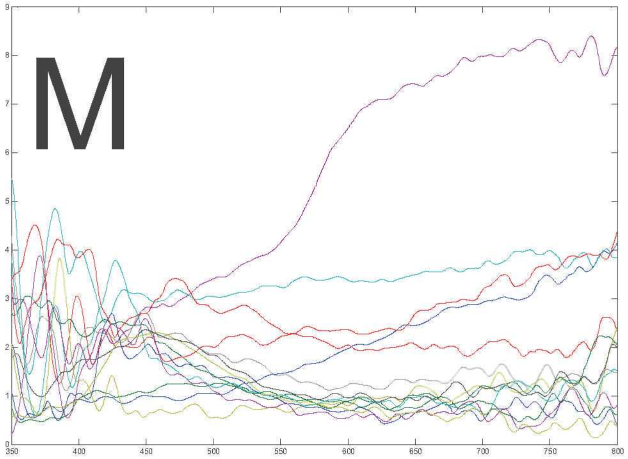
We realize that what fall into the loading c_1 is in fact R seen with the sensitivity PC1. Only that this time the sensitivity is optimized for the variance in the spectral data set.

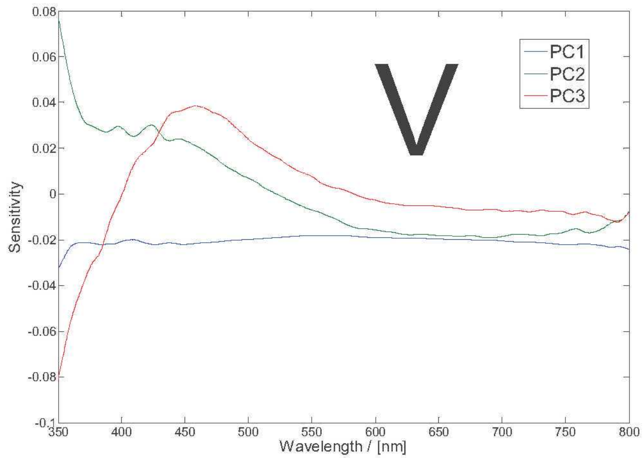
$$c_1 \sim \sum_{k=1}^{K} M_k PC1_k$$





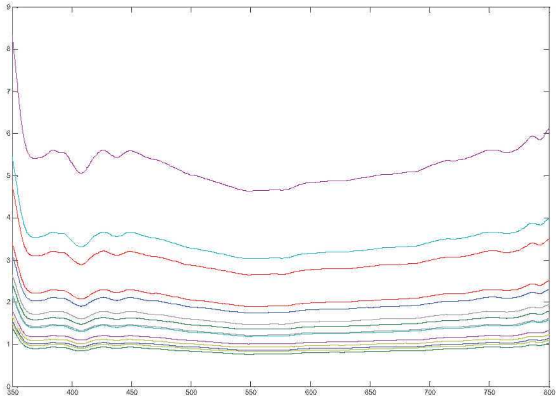
Reconstruction of M





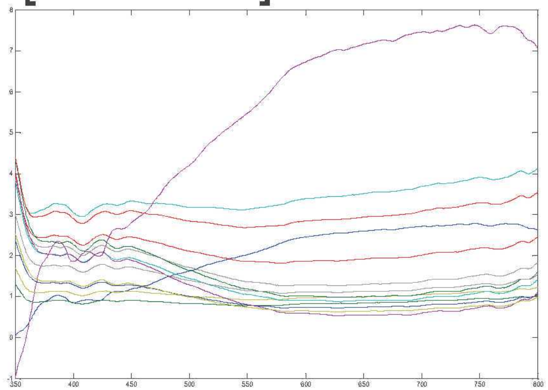
[PC1]

M_{red}



[PC1 PC2]

M_{red}



[PC1 PC2 PC3]

M_{red}

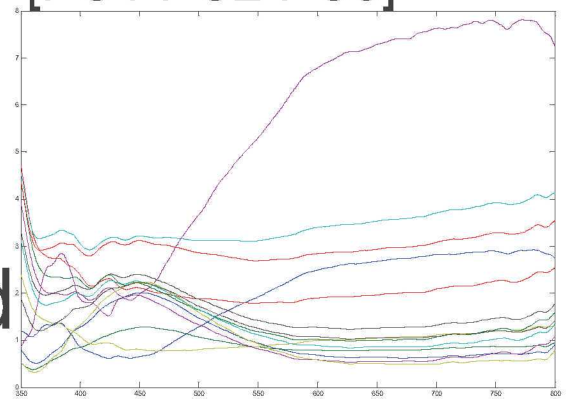
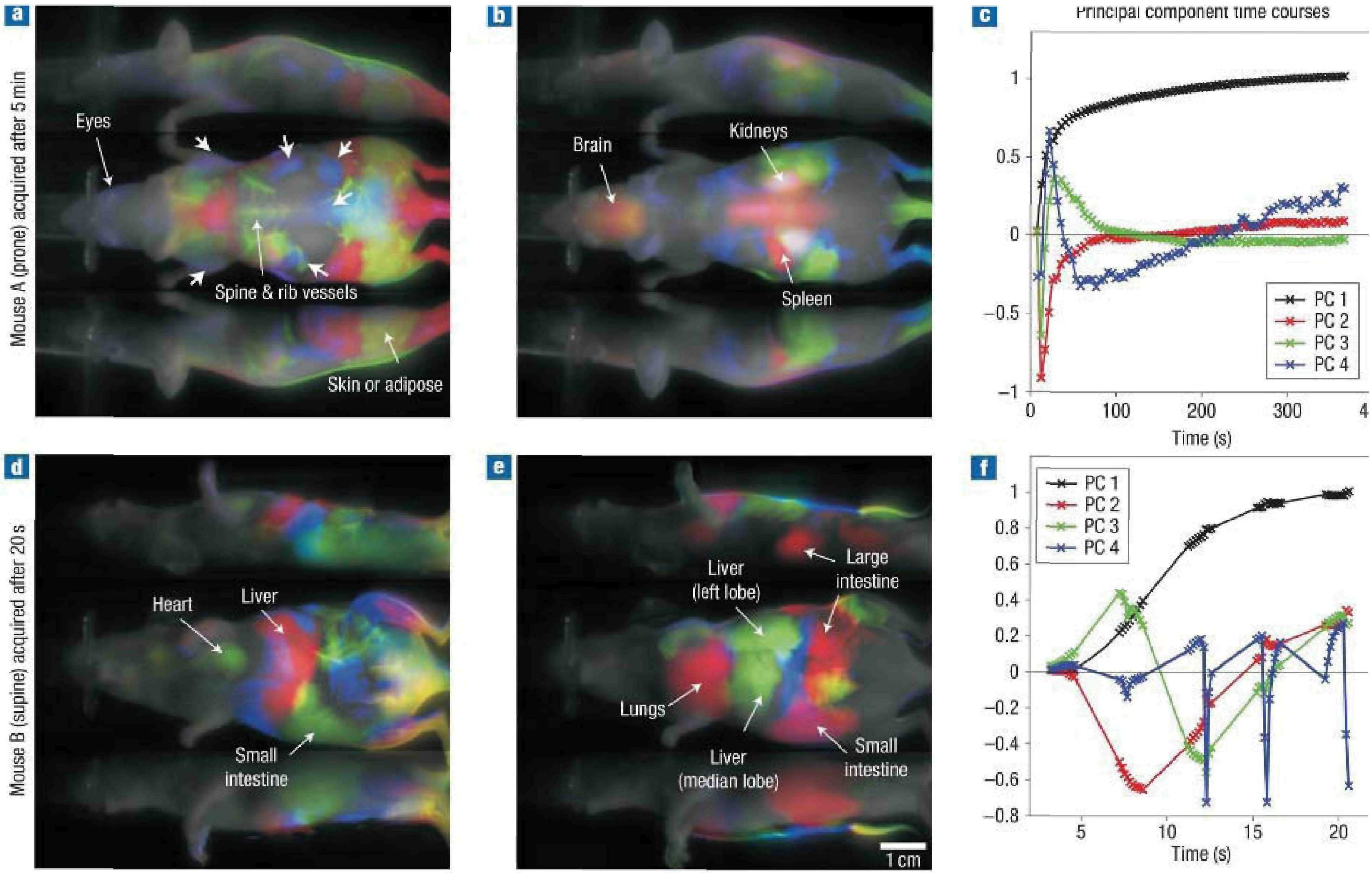


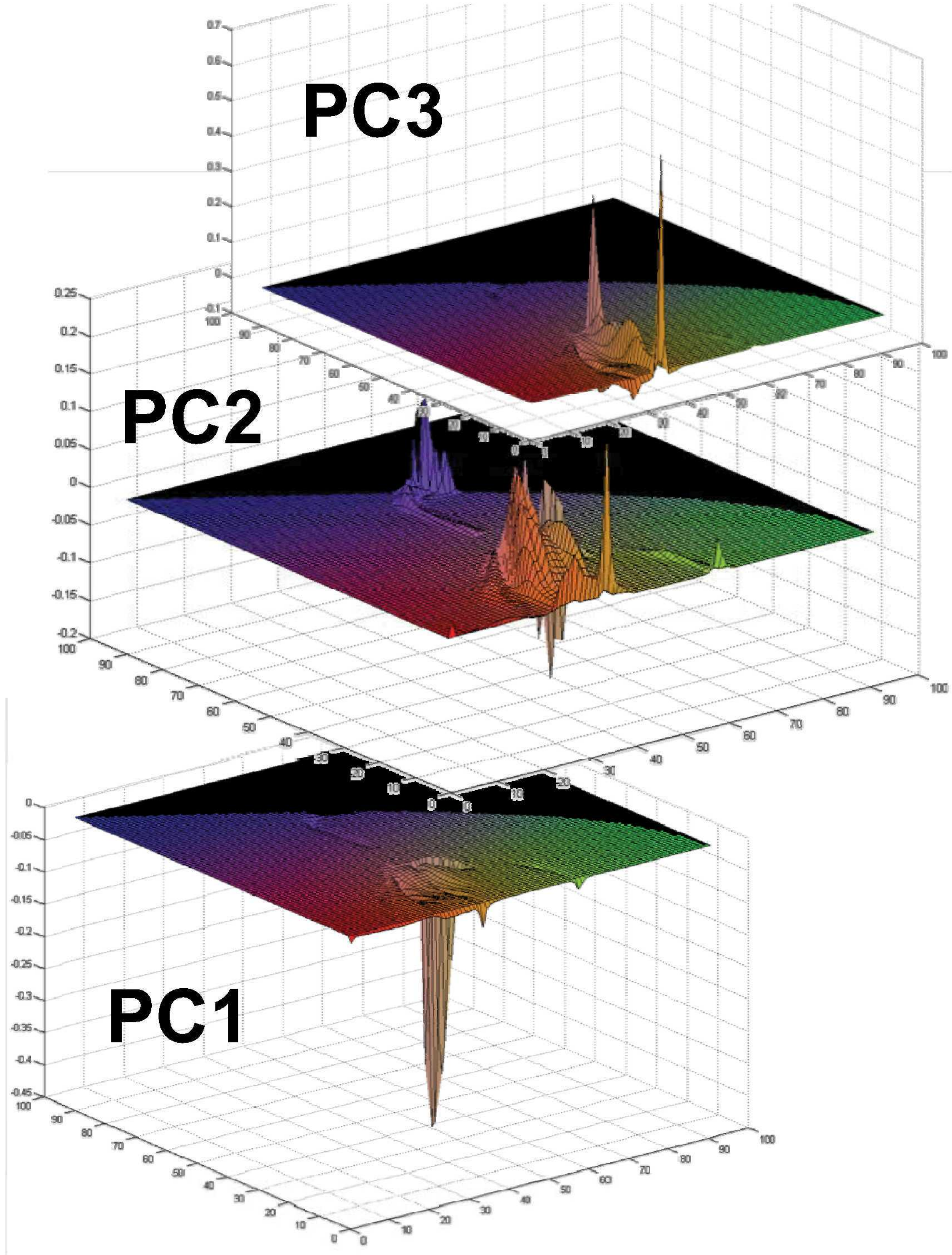
Image decomposition, Time



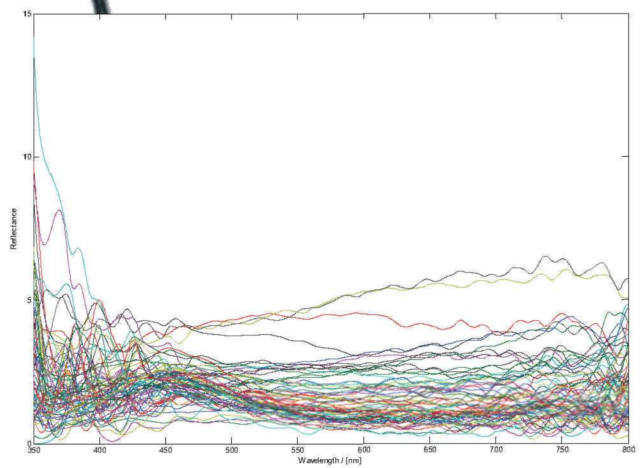
Nature, Hillman 2008

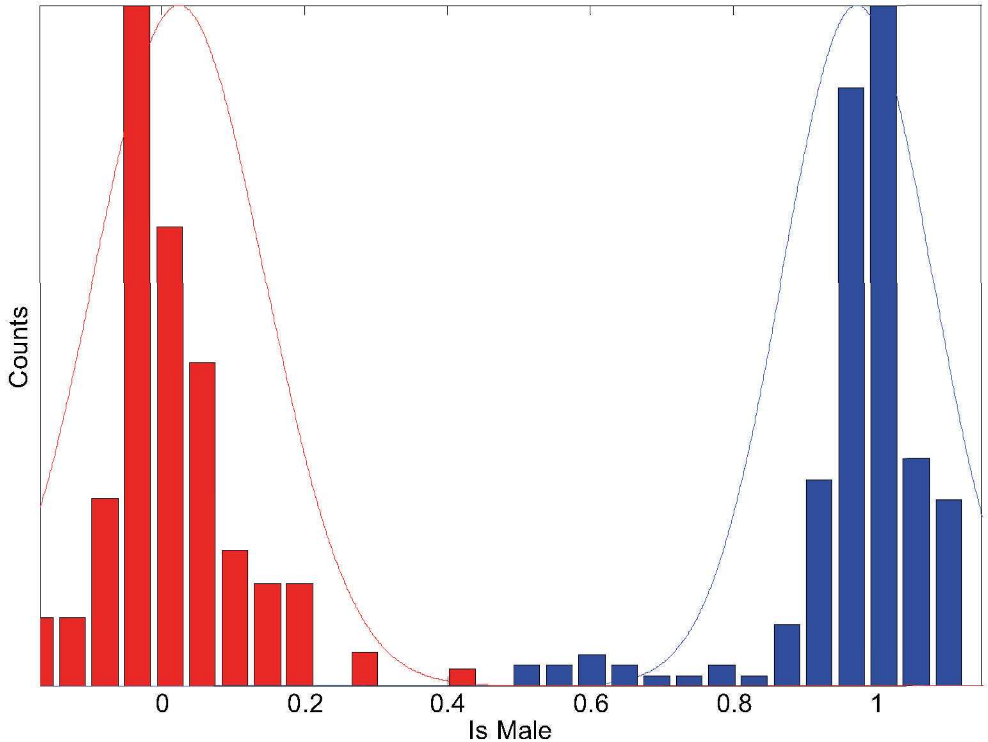
2D principal components

- Orthogonal planes
- U reduced representation of M
- How many of each?



Who is who?





Females

Males

$$Q = \frac{|\mu_{F(A)} - \mu_{F(B)}|}{\mathrm{sqrt}(\delta_{F(A)} + \delta_{F(B)})}$$

F(R)

Y=k0+k1*u1+…k5*u5