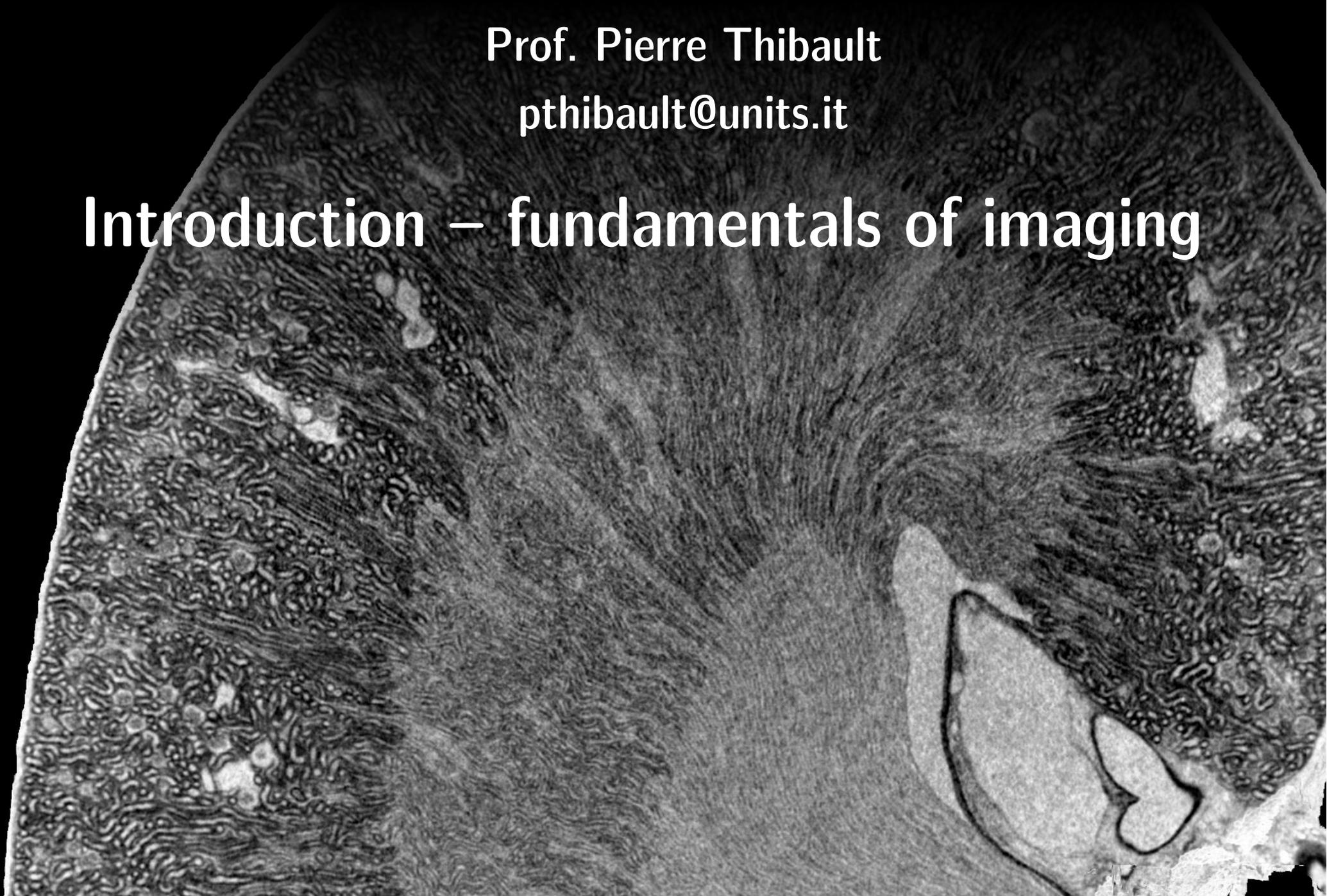


# Image Processing for Physicists

Prof. Pierre Thibault

[pthibault@units.it](mailto:pthibault@units.it)

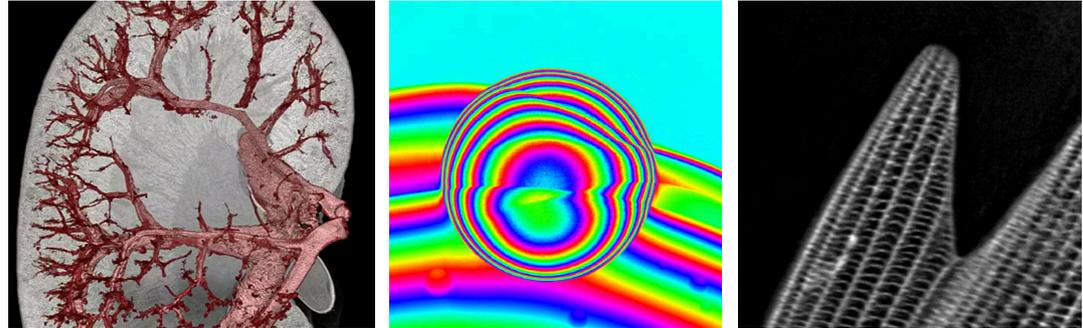
Introduction – fundamentals of imaging



# For the curious

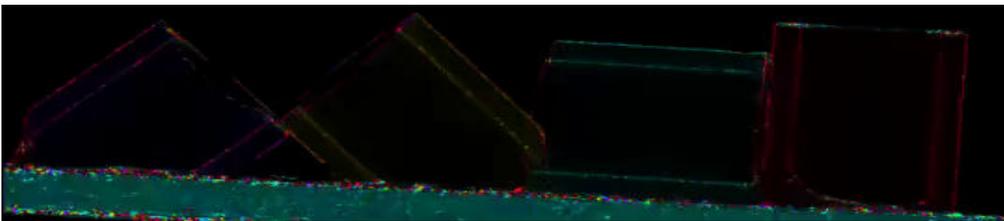
*Pierre Thibault [pi-er ti-bo]*

- From Québec
- PhD USA
- Postdoc #1: Switzerland
- Postdoc #2: Germany
- Academic work: UK
- UniTS since Sept. 2020



My research:

- X-ray imaging and tomography
- Specifically: new methods that exploit coherence and redundancy in datasets (→ computational imaging)



<http://s-baxit.optimato.eu>

# Syllabus

1. Image processing in the spatial and Fourier domains
2. Filters, Sampling & Interpolation
3. Image representations
4. Linear Imaging Systems
5. Wave Propagation and Image detection
6. Interferometric Imaging
7. Tomography & Medical Imaging
8. Introduction to Optimization: Least Squares, Maximum likelihood and Maximum A Posteriori Principles.

# Philosophy

## Techniques

Core knowledge of most common mathematical and numerical tools for imaging and microscopy, from a physicist's view point.

## Coding skills

Opportunity to improve (python) coding proficiency (more *scripting* than *programming*).

## Decoding

Learning the terminologies to understand quickly research work that use imaging.

## Critical thinking

Learn to identify the proper tools for a specific imaging need, analyse and criticise image processing operations found in the literature.

# Admin

- Wed 13:00-15:00: Room 4B (H2bis)
- Thu 12:00-14:00: Room 4B (H2bis)
- Lectures + tutorials
- Weekly exercises (python)
- Final assessment: 10 min presentation + discussion

# What is an image?

- We adopt the definition:

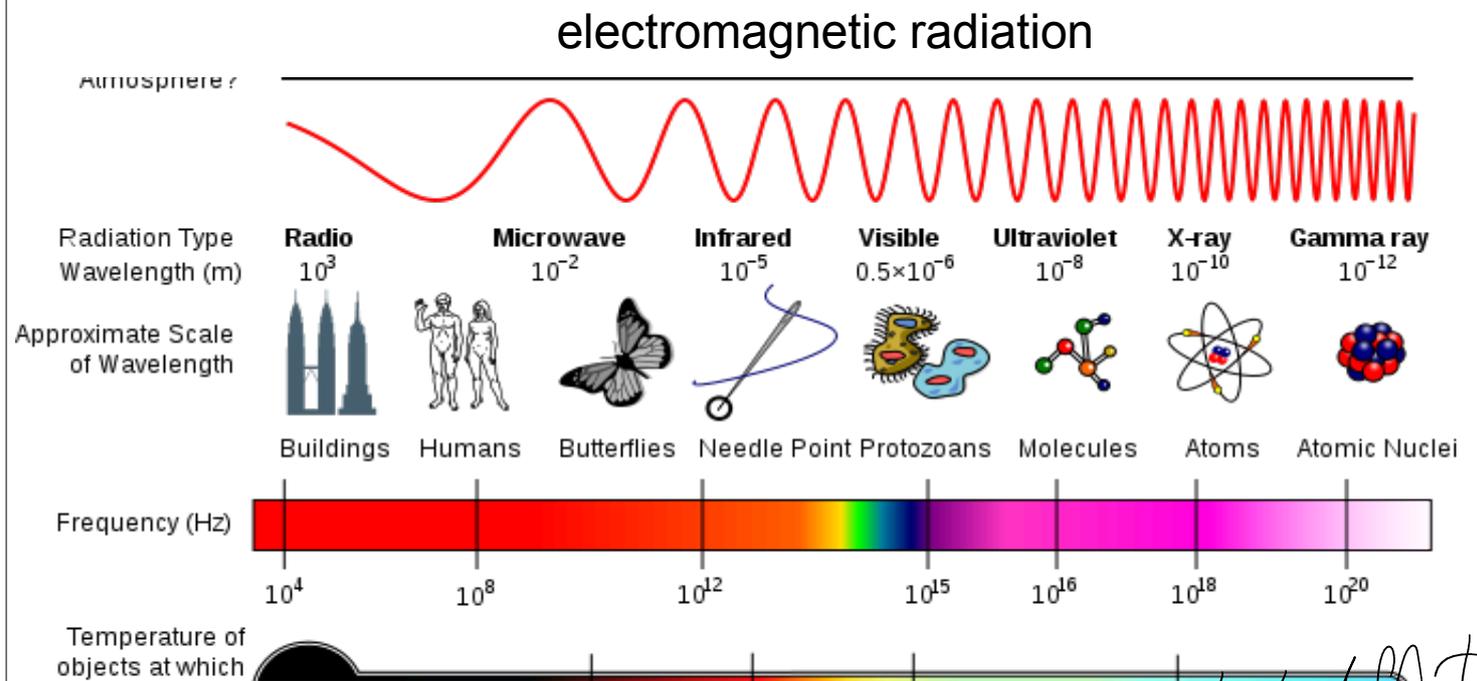
“Spatial representation of information”

- 2D (most common)
- 2D multichannel (e.g. color)
- 2D time series (movies)
- 3D (tomographic data, ...)
- 1D (why not?)

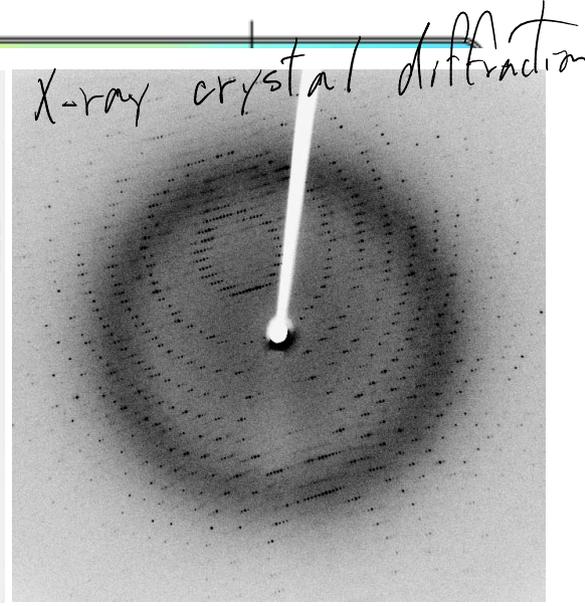
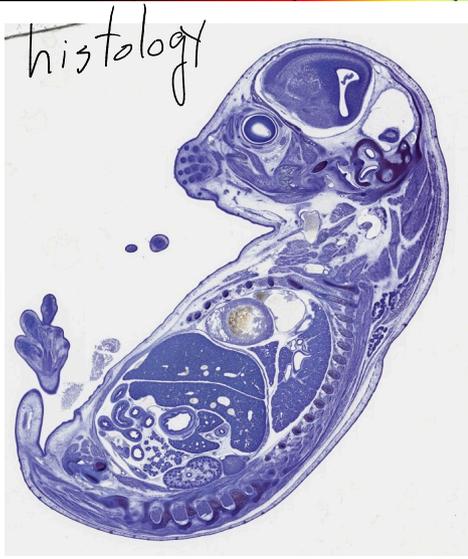
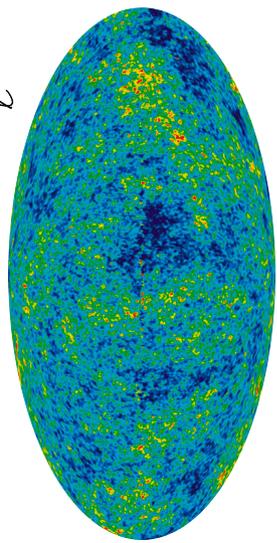
# The imaging chain

Information

Probe



*microwave background radiation*



source: <http://www.wikipedia.org>

<http://www.brainmaps.org/>

# The imaging chain

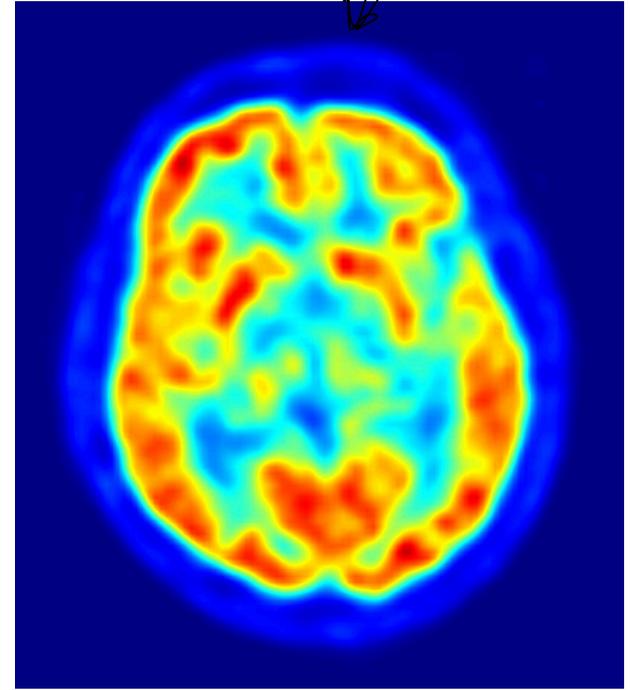
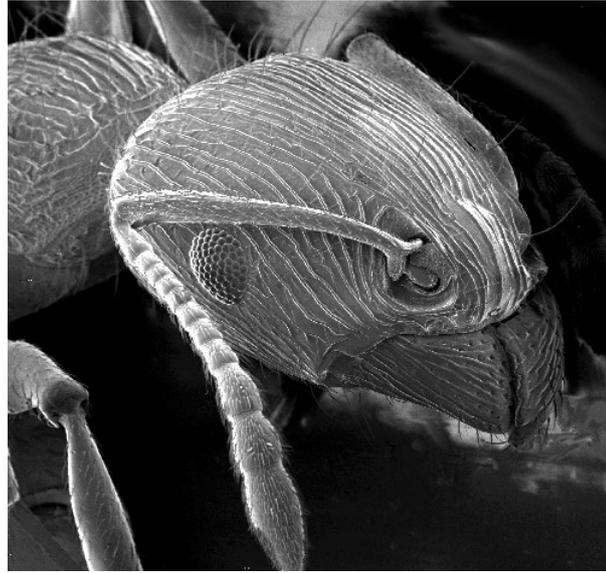
Information

Probe

particles / particle decay

PET  
↓

SEM  
Scanning  
electron  
microscopy

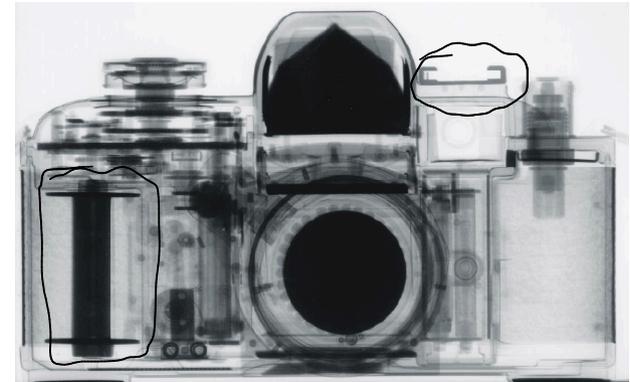


source: <http://www.wikipedia.org>

SPECT



neutron  
radio  
graph  
←



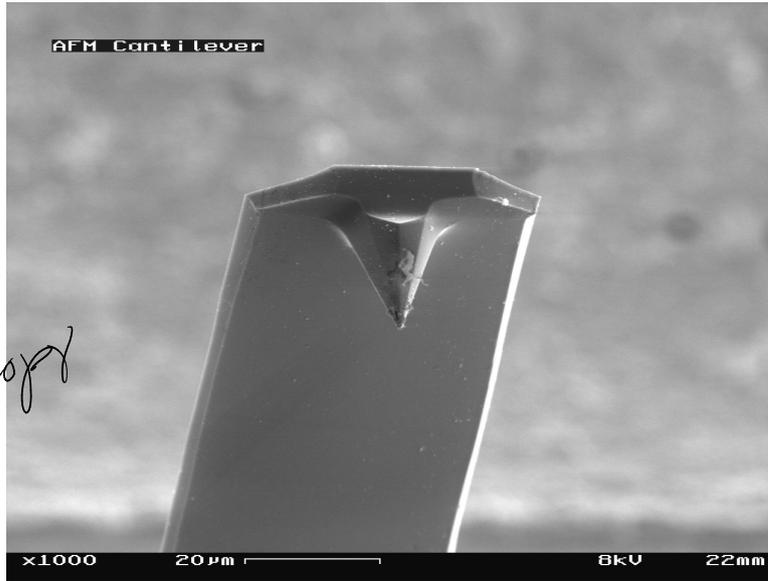
source: <http://www.ati.ac.at/~neutropt/experiments/Radiography/radiography.html>

# The imaging chain

pressure, force, magn./elec. fields, ...

*Magnetic Resonance Imaging*

Probe



*Atomic Force Microscopy*



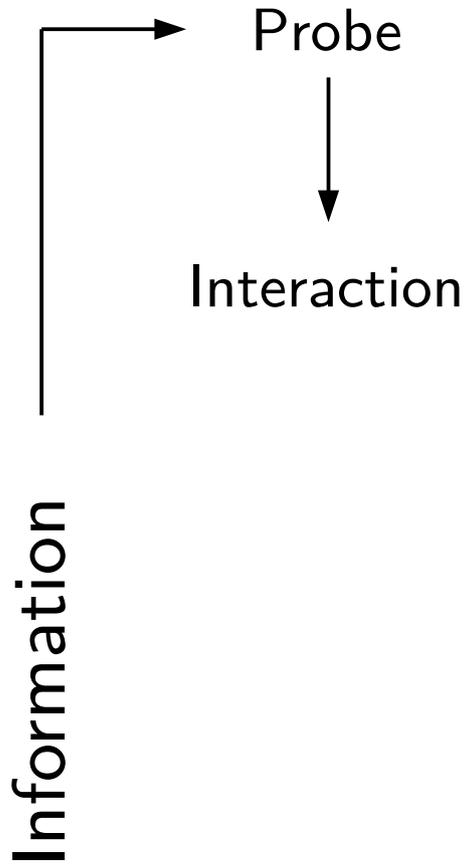
Information



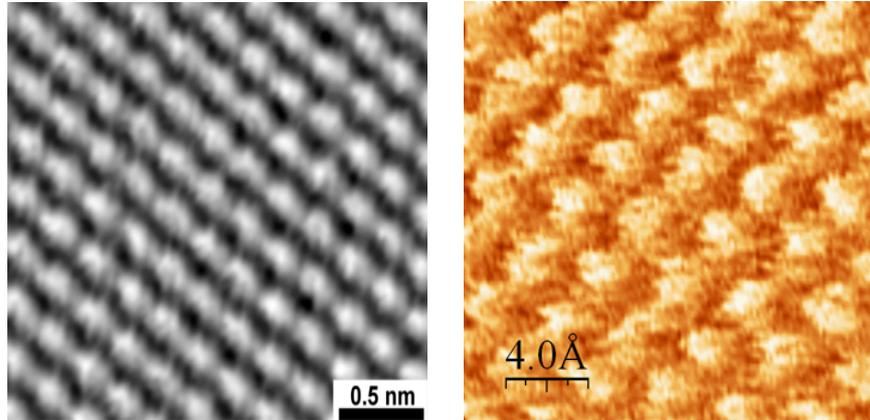
*ultra sound*

source: <http://www.wikipedia.org>

# The imaging chain

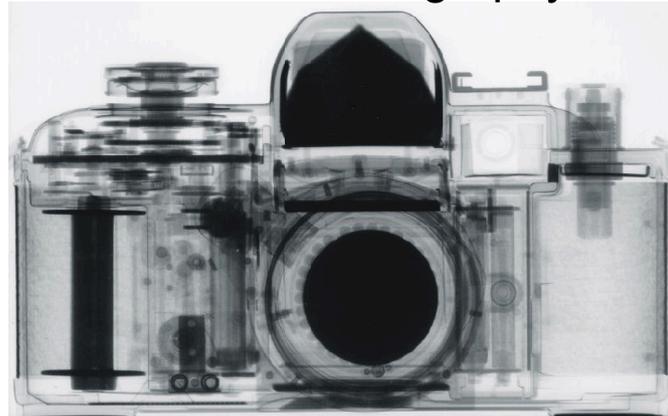


STM HOPG AFM

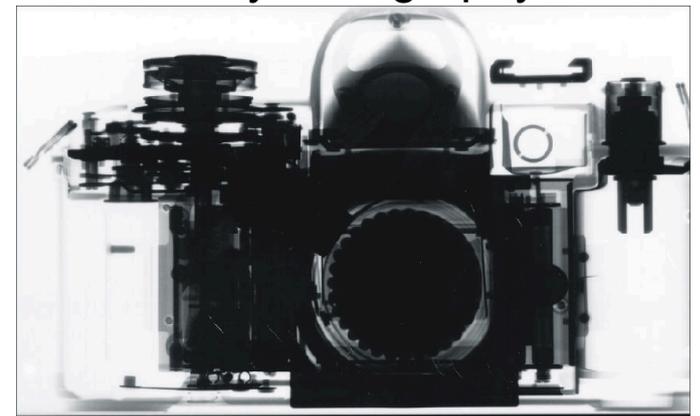


source: <http://www.wikipedia.org>

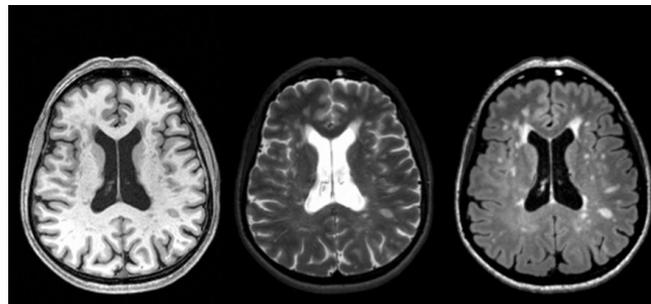
Neutron radiography



X-ray radiography



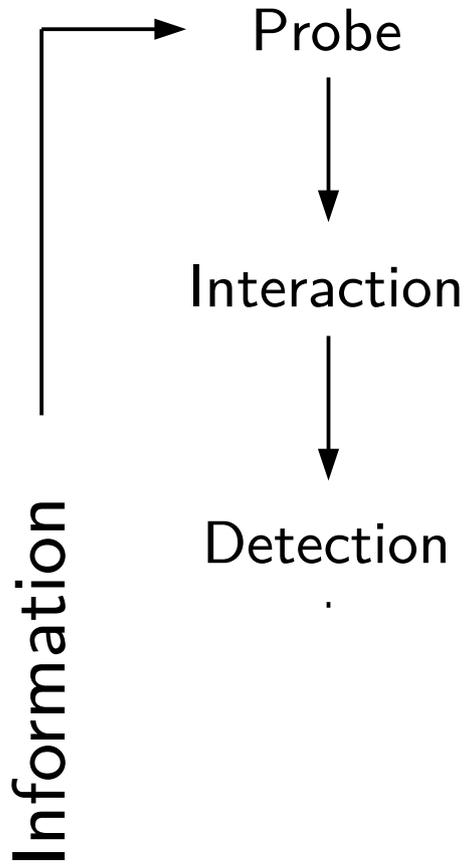
source: <http://www.ati.ac.at/~neutropt/experiments/Radiography/radiography.html>



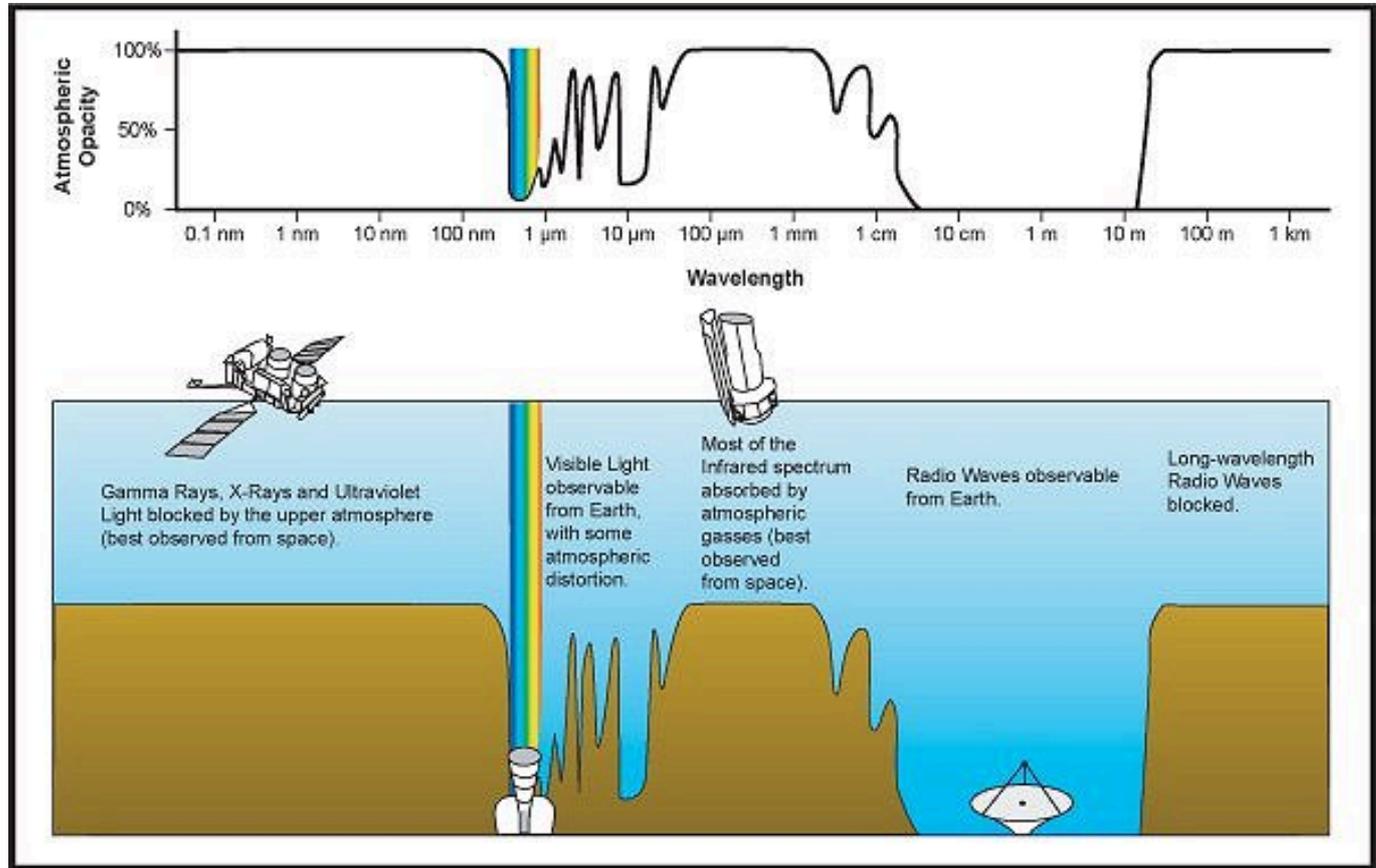
Brain MRI (T1, T2, FLAIR)

<http://www.mrforschung.med.uni-goettingen.de>

# The imaging chain



Information has to reach detector

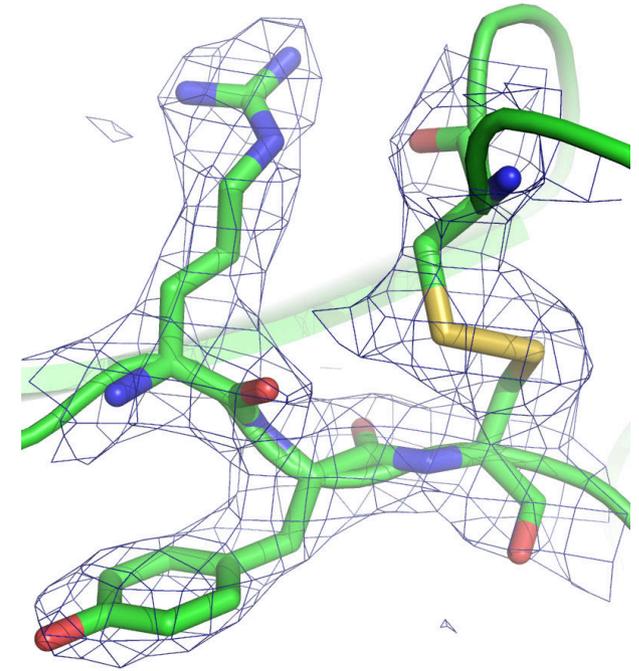
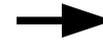
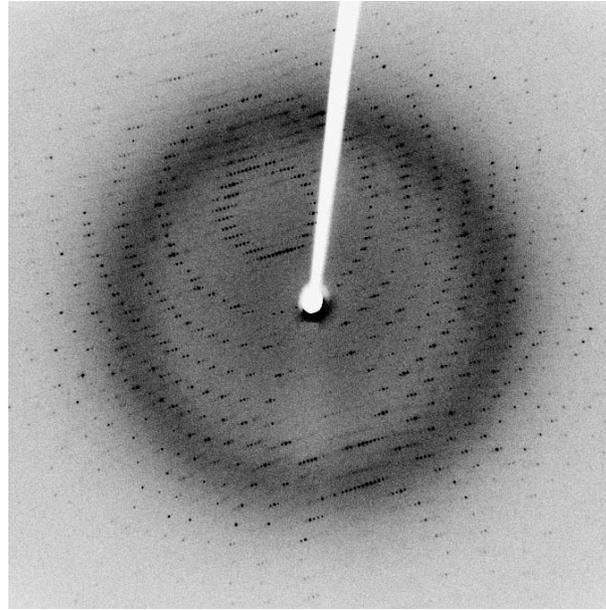
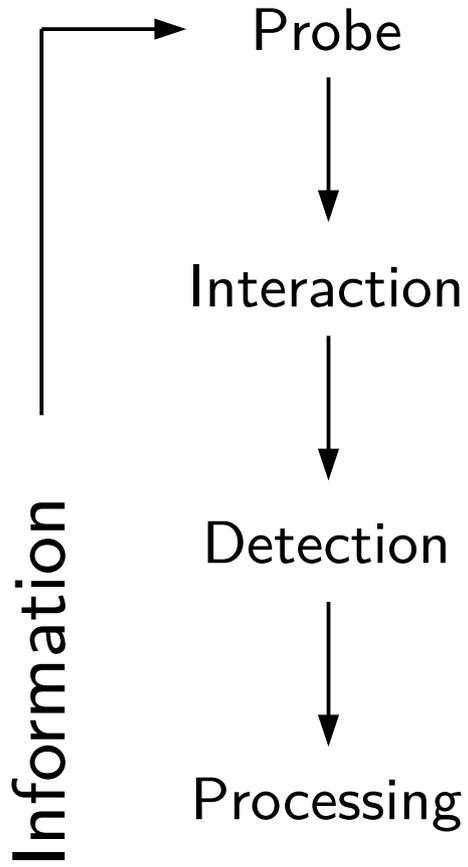


source: <http://www.wikipedia.org>



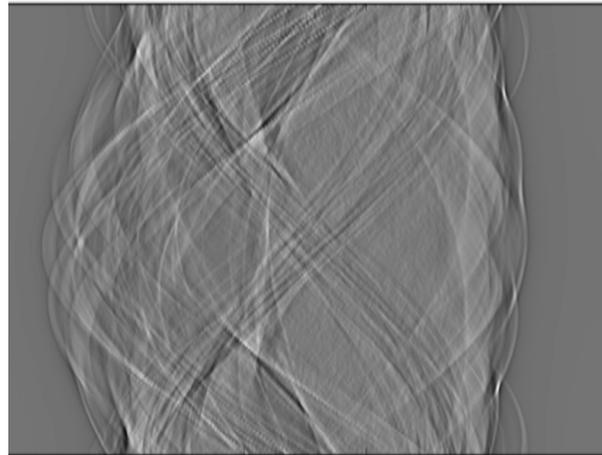
# The imaging chain

*protein crysallography*



source: <http://www.wikipedia.org>

Reconstruction from hard to interpret raw data



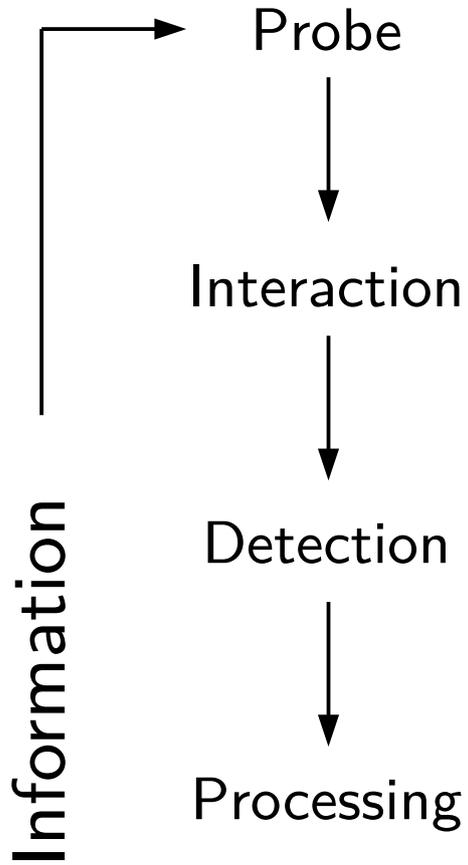
*Computed Tomography*



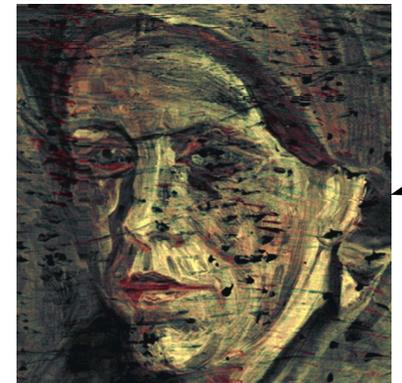
source: P.Thibault, M.Bech

# The imaging chain

X-ray fluorescence

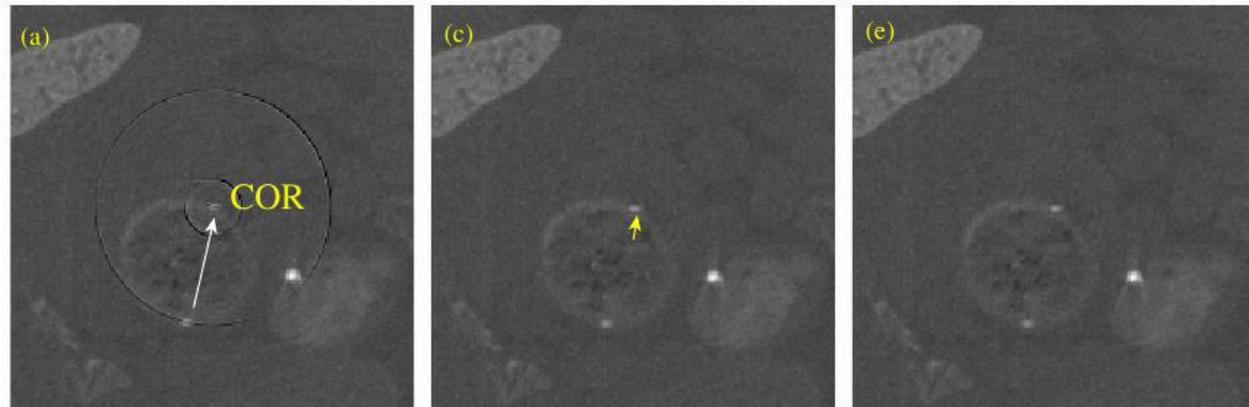


analysis, feature extraction, ...



source: J. Dik, et al. *Anal. Chem.* 80, 6436-6442 (2008)

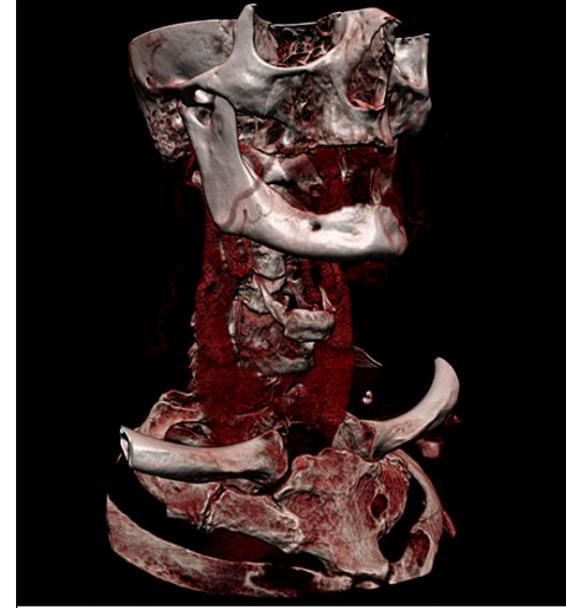
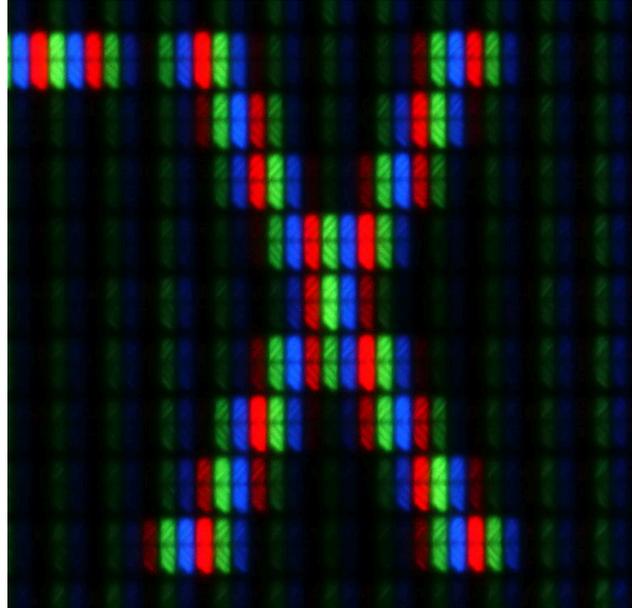
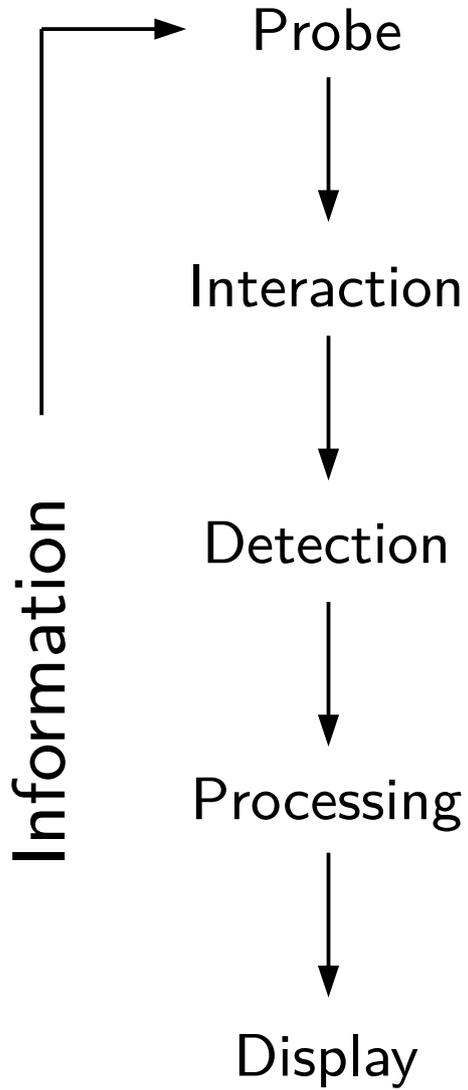
Error correction, artifact reduction, ...



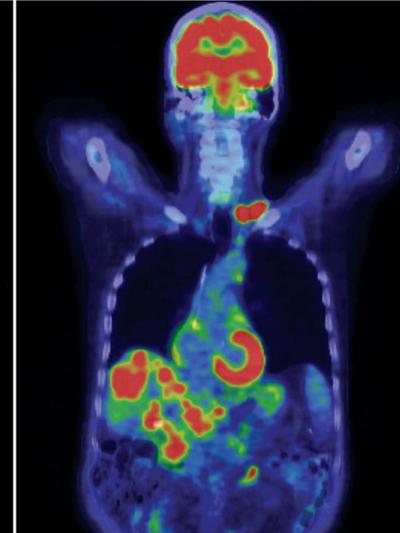
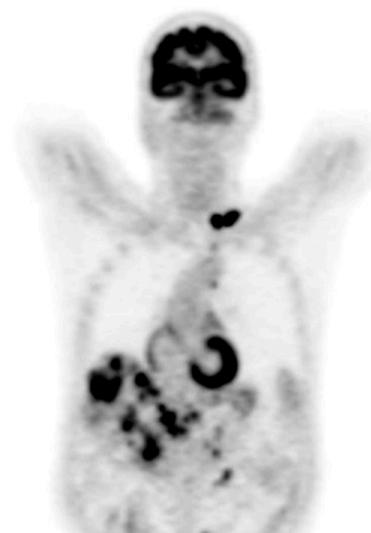
source: E. M. Abu Anas et al. *Phys. Med. Biol.* 55 6911 (2010)

# The imaging chain

*iso surface*  
↙

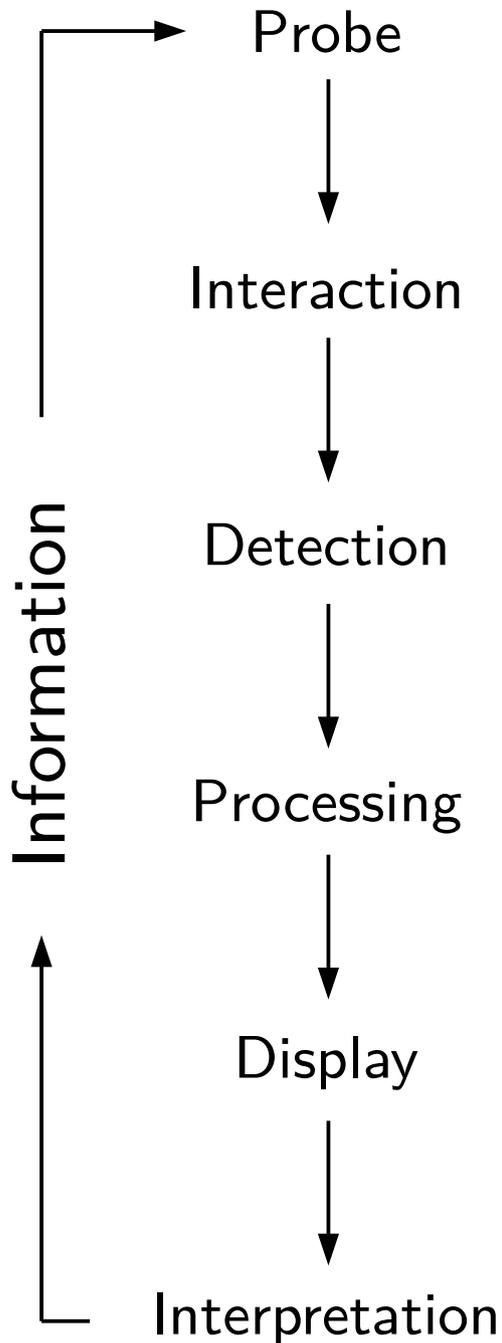


source: <http://www.wikipedia.org>

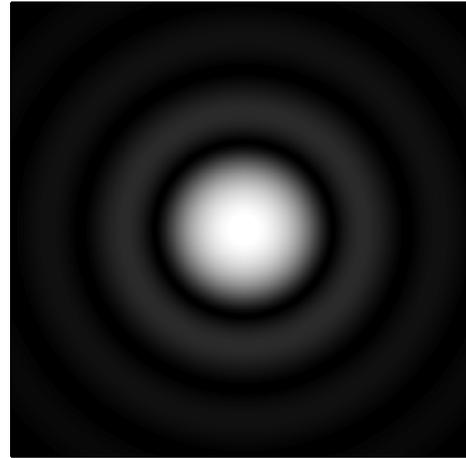


source: <http://www.aztechradiology.com>

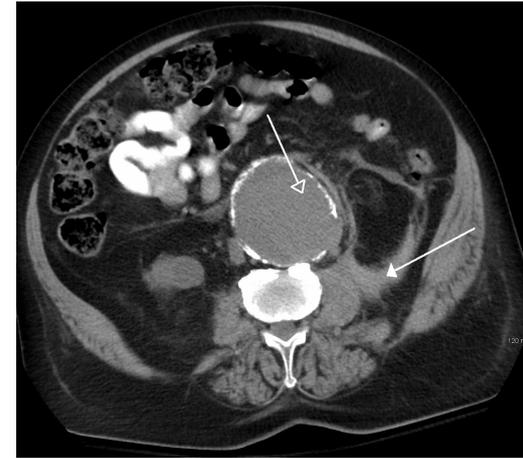
# The imaging chain



Extraction of information not always straightforward



Airy disc



ruptured aorta (deadly)

source: <http://www.wikipedia.org>

Extraction depends on level of education

We are part of the imaging system!

# Digitization, sampling, quantization

Data (nowadays) almost always discrete

Discrete representation of a continuous function



# Digitization, sampling, quantization

What is a pixel?

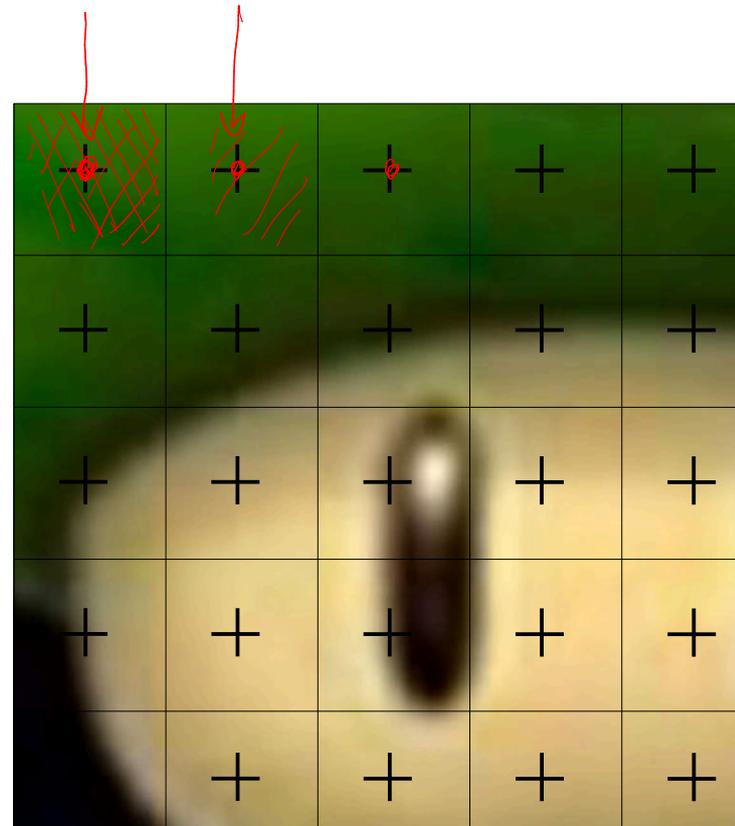
*"picture element"*

sample of continuous function,

with coordinates and value(s)

- value at coordinate
- mean over pixel area
- ...

NOT a box-like image feature

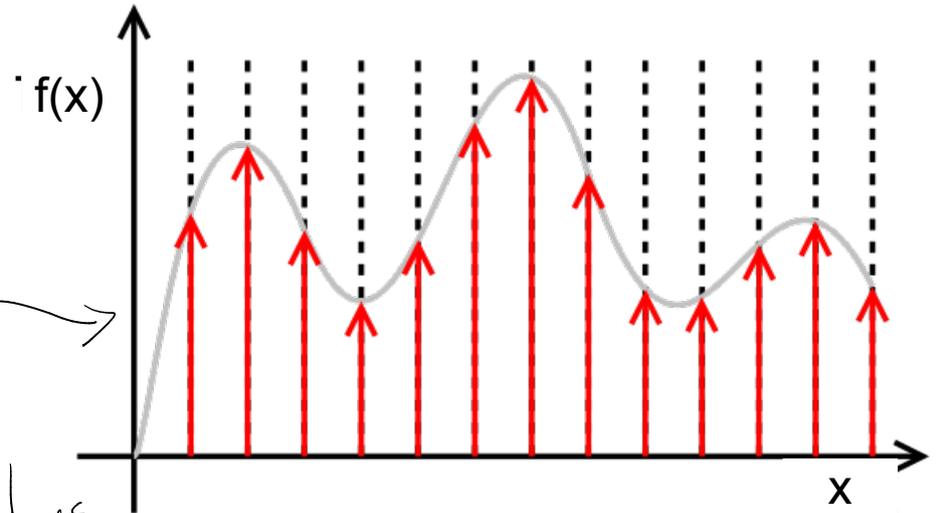


# Digitization: sampling + quantization

Digitization in space:

sampling

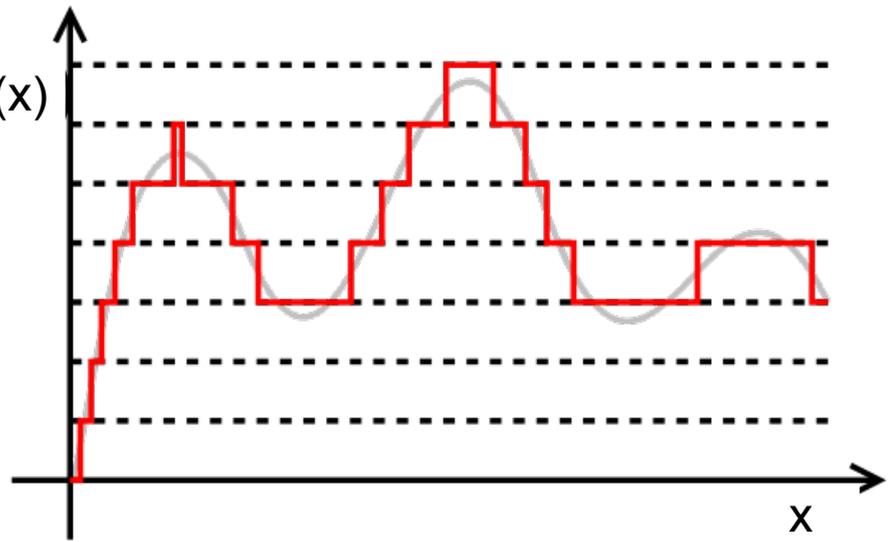
*crucial step* →



Digitization in 'intensity':

quantization

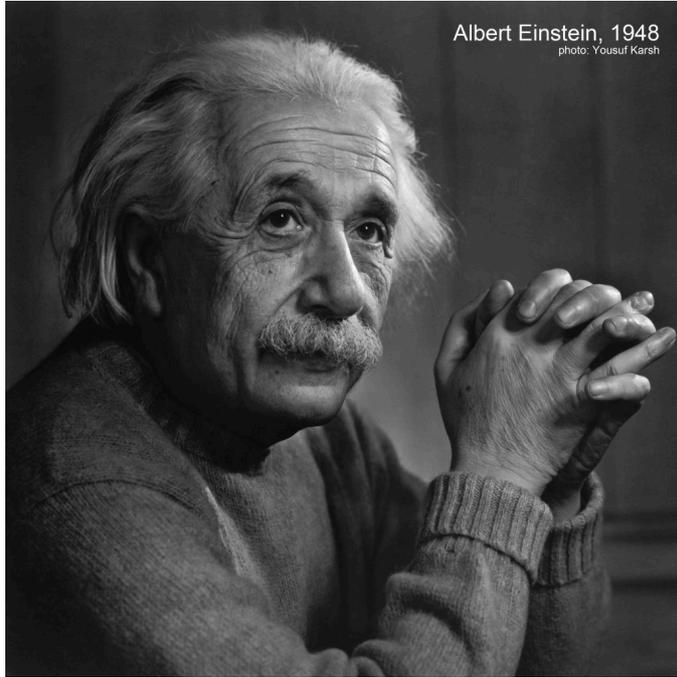
*typically crucial* ↘



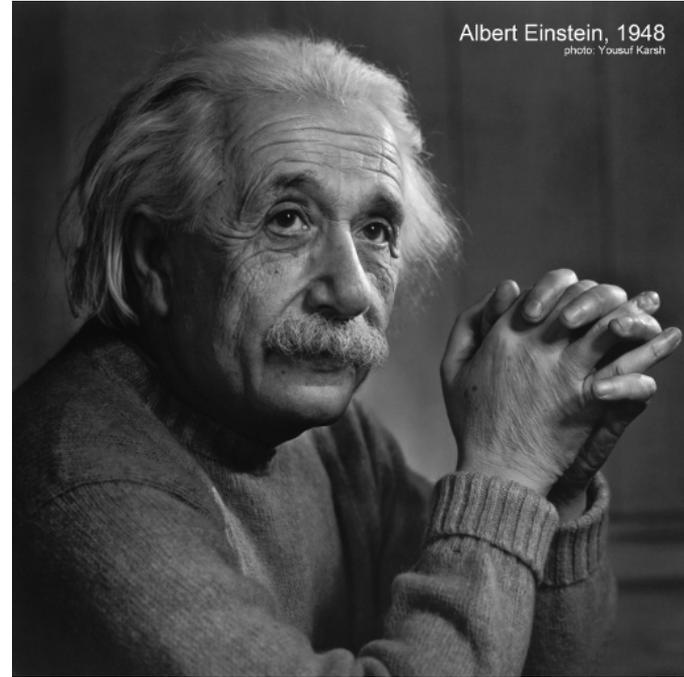
source: <http://www.wikipedia.org>

# Digitization: sampling + quantization

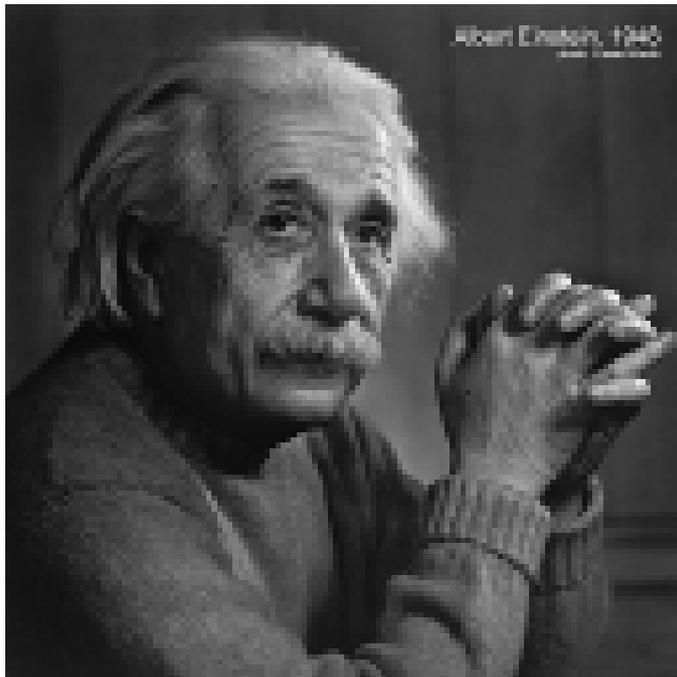
2048 x 2048



256 x 256



128 x 128

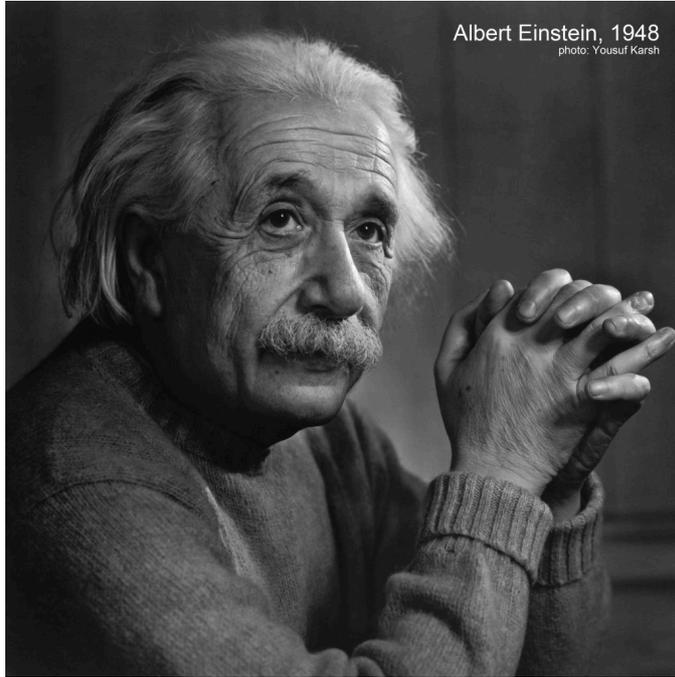


32 x 32

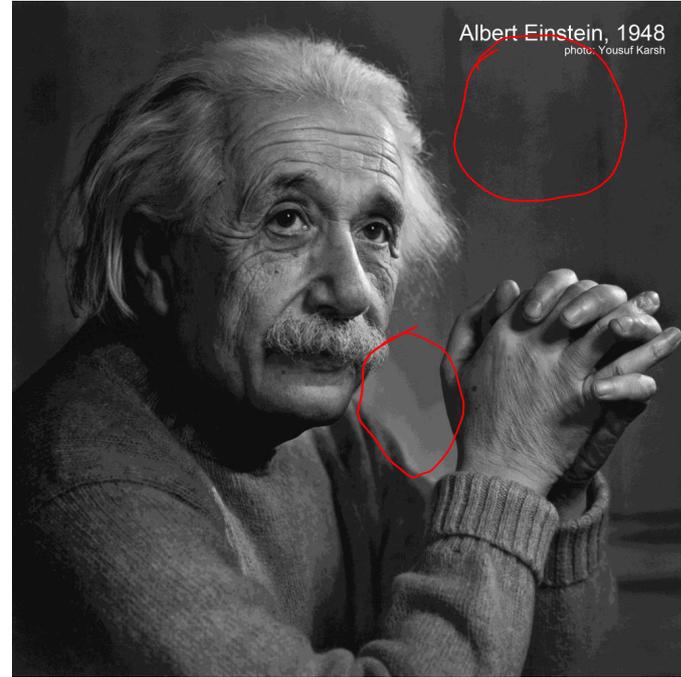


# Digitization: sampling + quantization

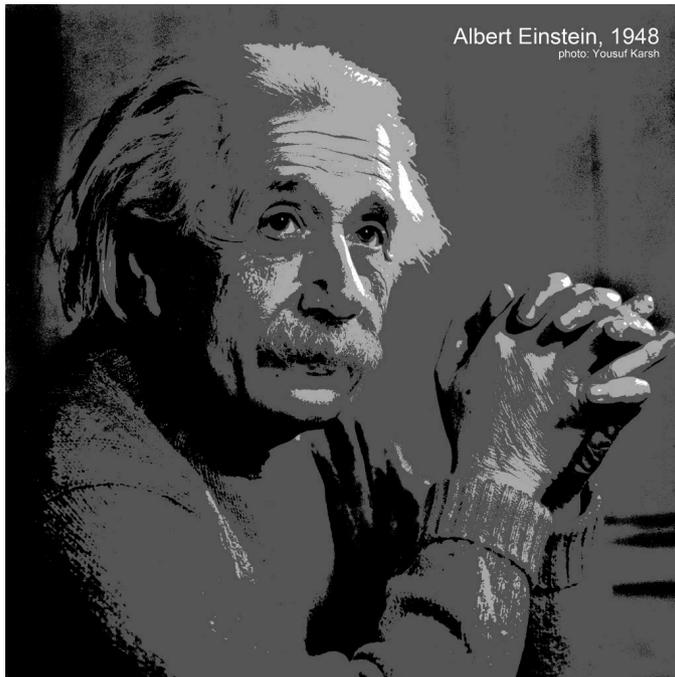
16 bit = 16.777.216 levels



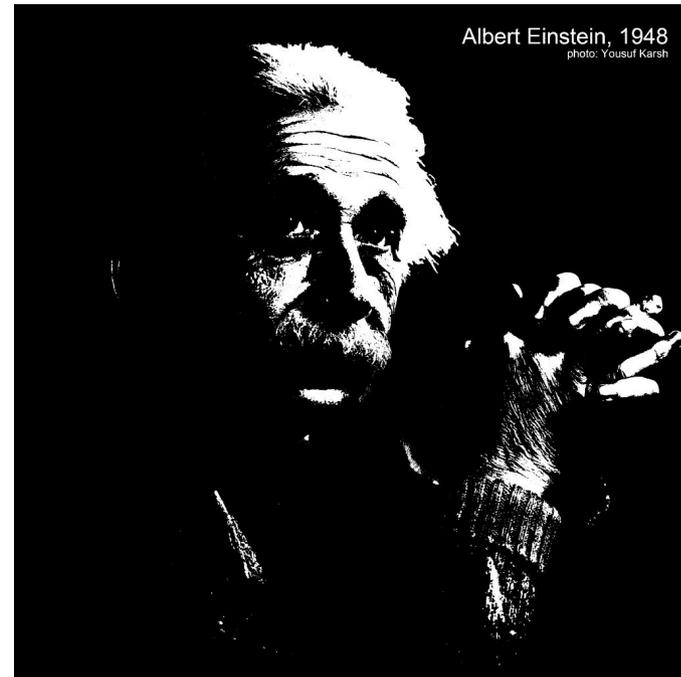
4 bit = 16 levels



2 bit = 4 levels



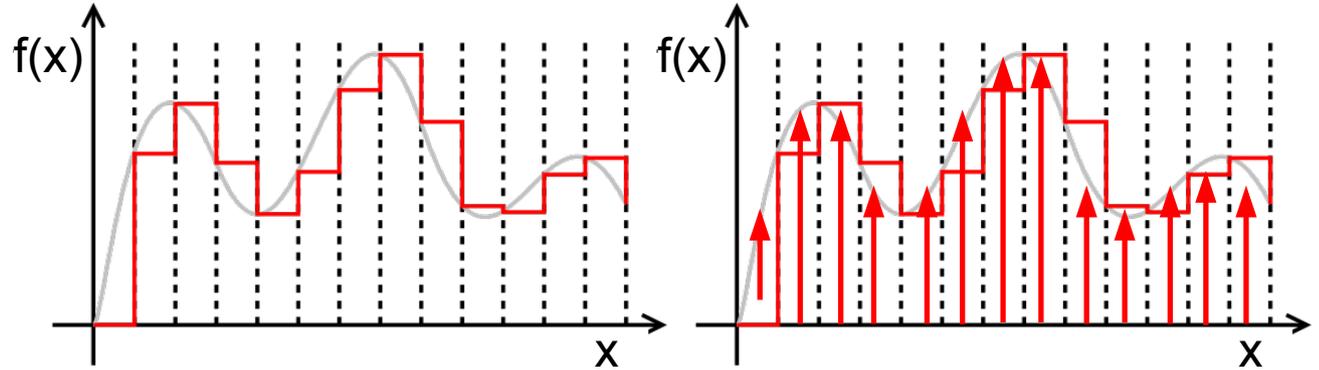
1 bit = 2 levels



binary image  
↙

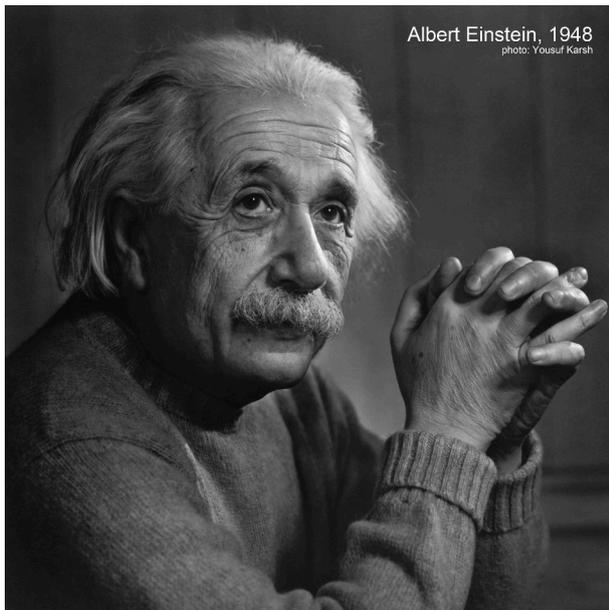
# Interpolation

Change sampling  
and quantization

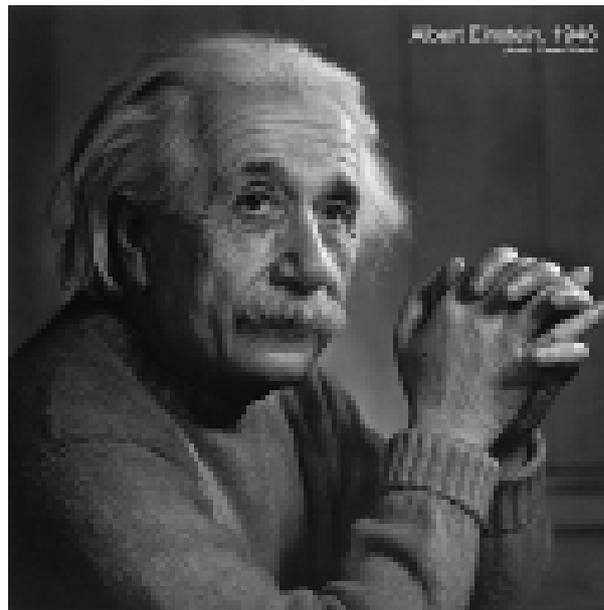


Loss of information (fine details)

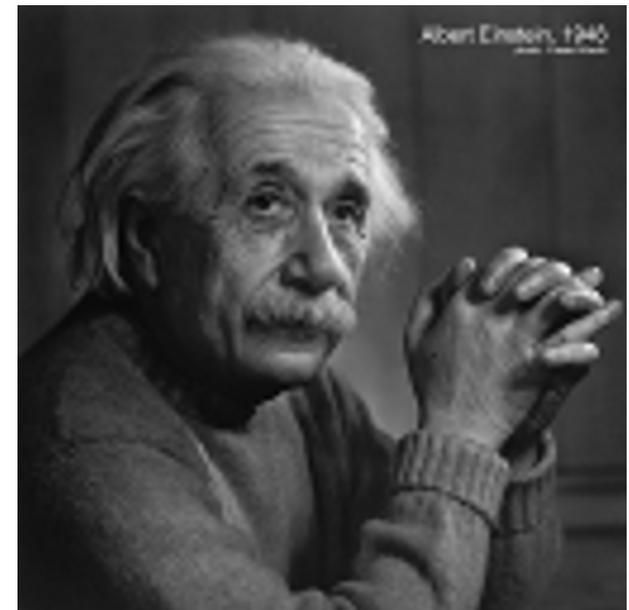
2048 x 2048



128 x 128

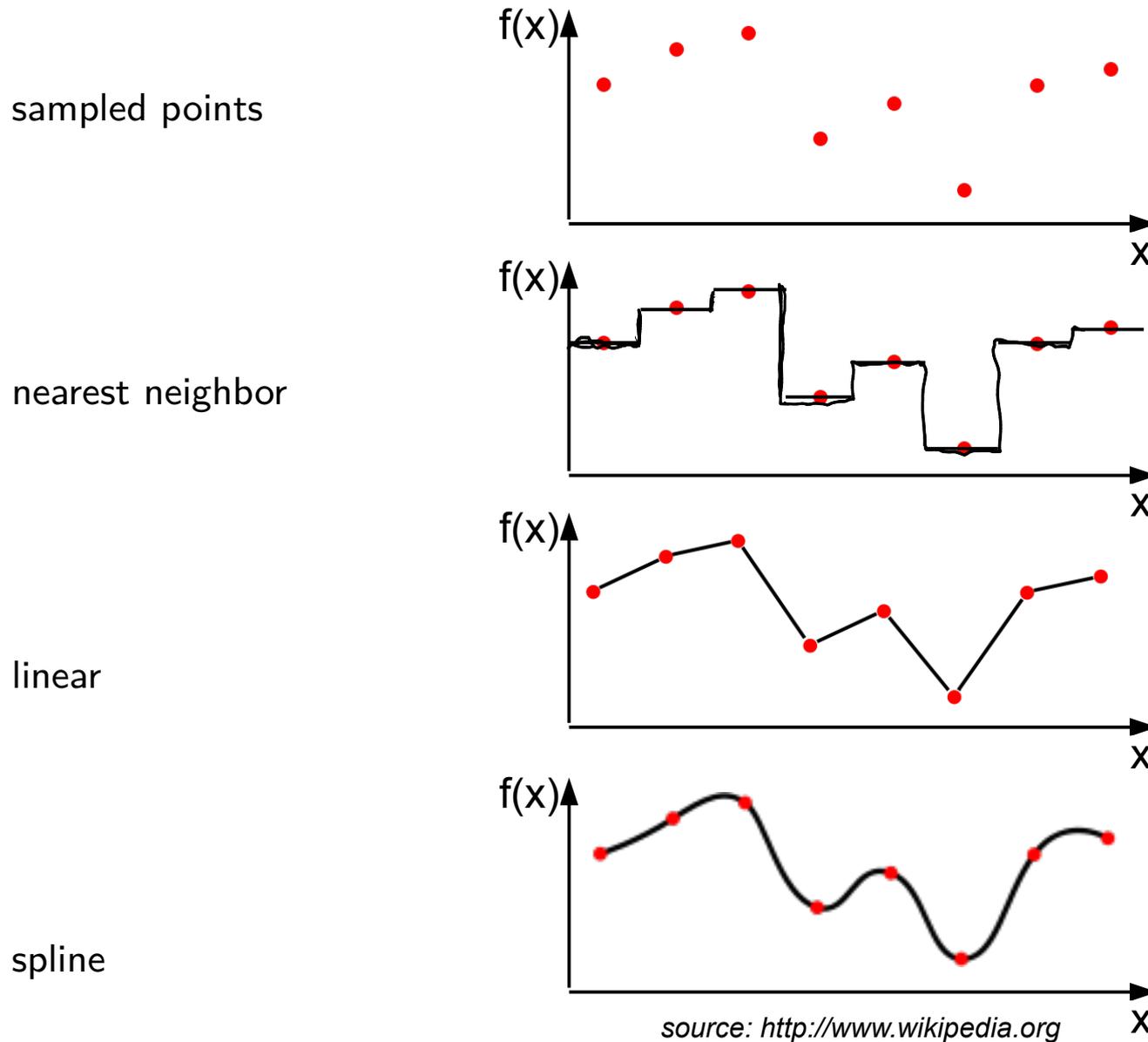


2048 x 2048 cubic



# Interpolation

Various interpolation methods available

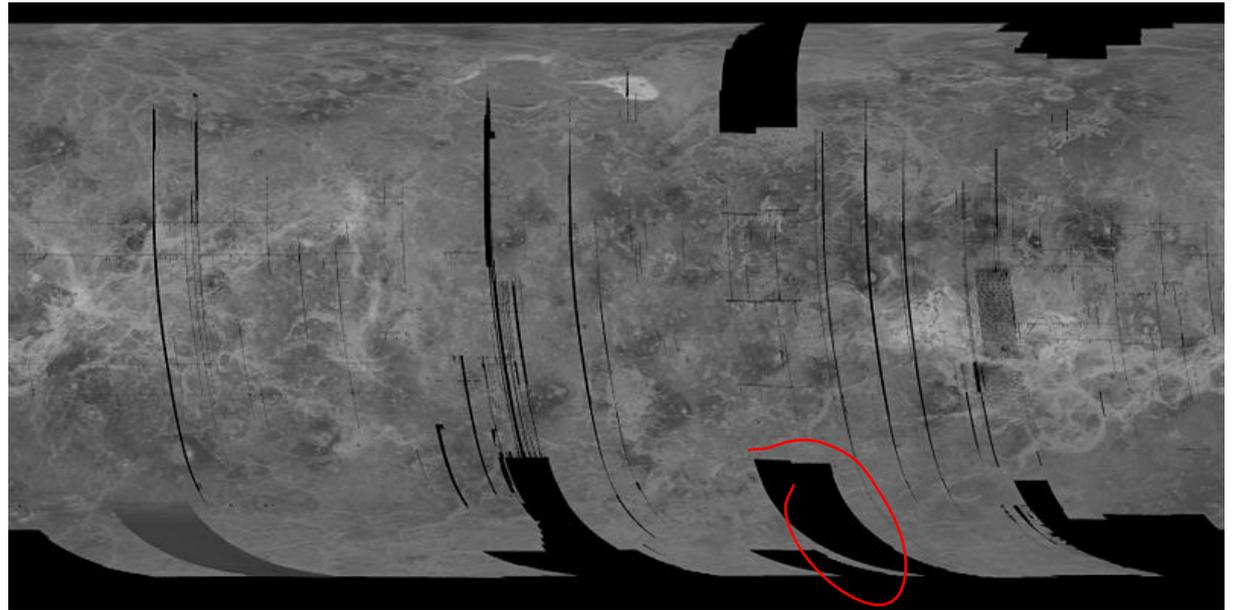


# Field of view

Sampling restricted to field of view of detector

Stitching of multiple  
fields of view

*Venus surface from Magellan orbiter*

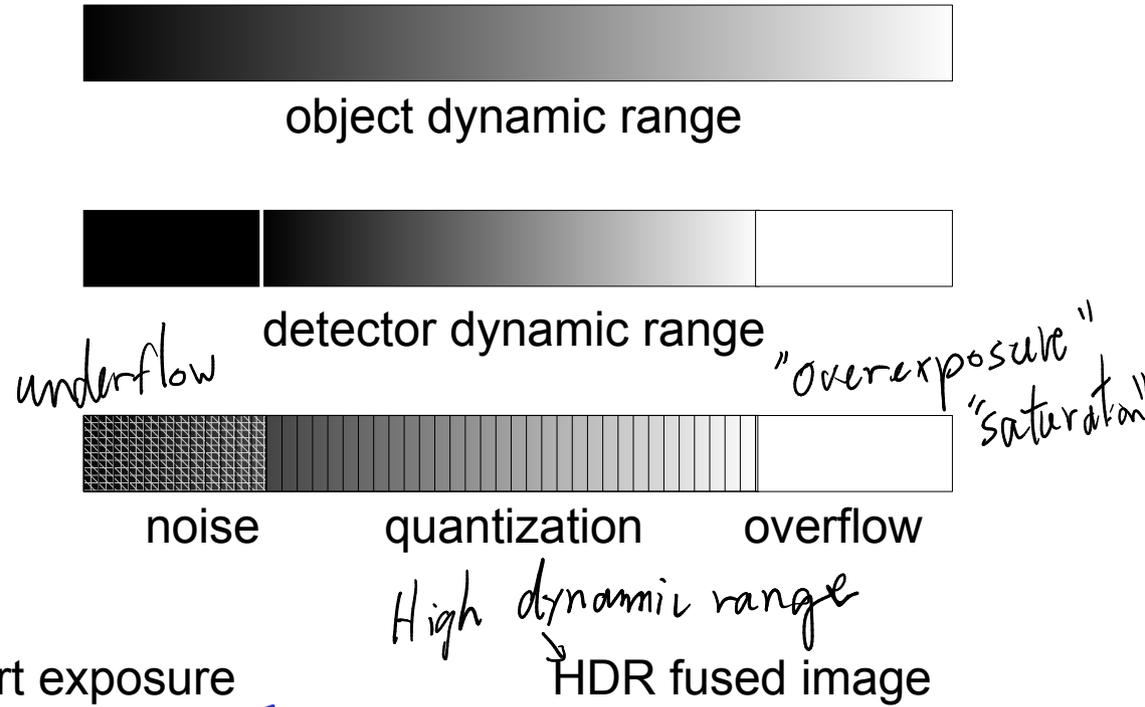


*source: <http://www.wikipedia.org>*

Accounting for missing data?

# Dynamic range

Quantization restricted to  
dynamic range of detector  
Loss of information  
(low, high intensities)



Long exposure

Short exposure



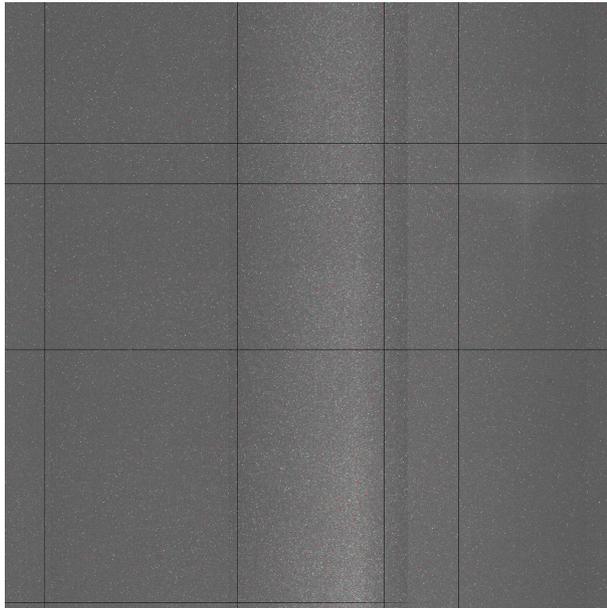
source: <http://www.wikipedia.org>

# Image noise

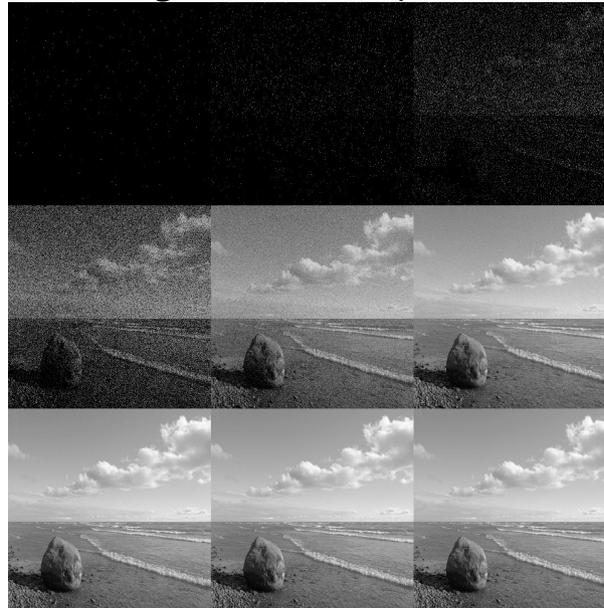
Is (unfortunately) always present

Characterization by source

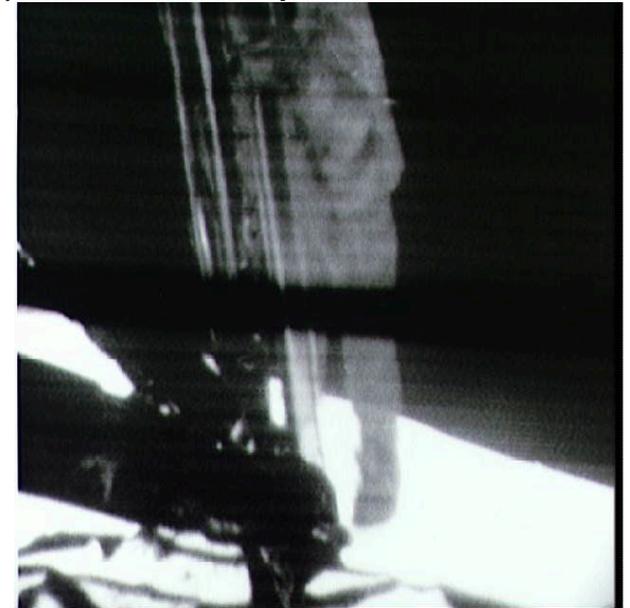
Detector dark current



Counting statistics (shot noise)



Acquisition



source: <http://wikipedia.org>

source: <http://nasaimages.org>

# Image noise

Is (unfortunately) always present

Characterization by source

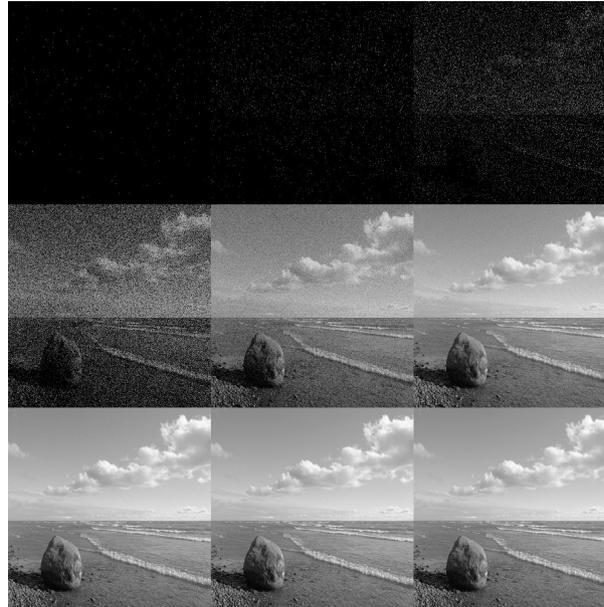
Characterization by density function

salt & pepper

Gaussian distribution



Poisson distribution



Fat-tail distributions



source: <http://www.wikipedia.org>

# Image noise

Is (unfortunately) always present

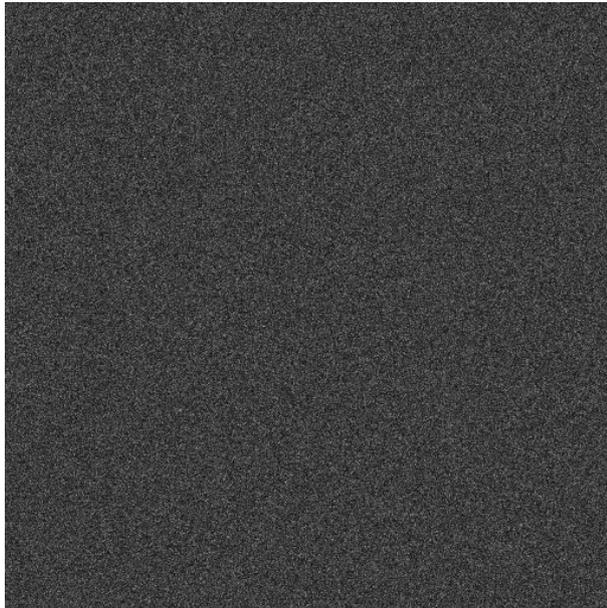
Characterization by source

Characterization by density function

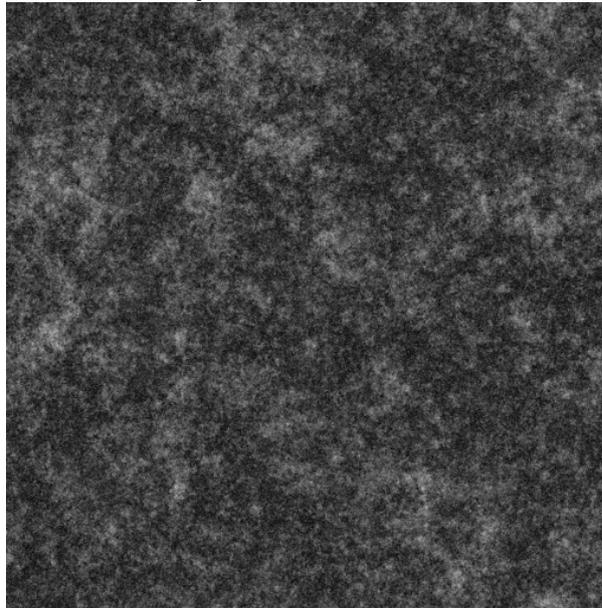
Characterization by spatial correlations

*uncorrelated pixels*

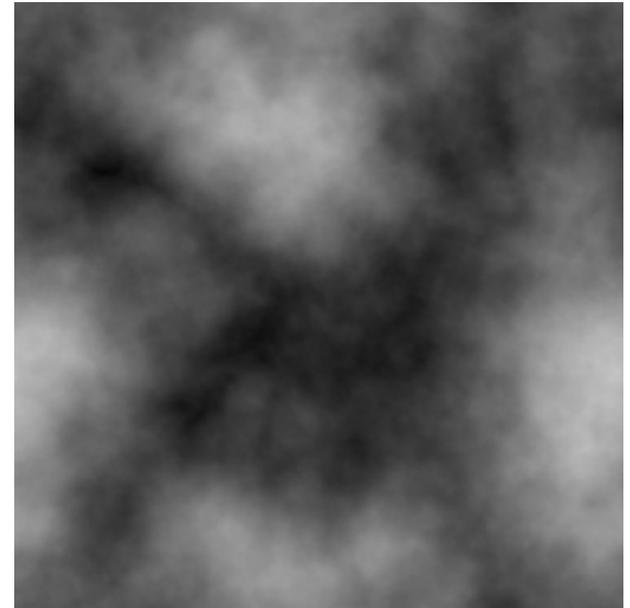
white noise



pink noise



red noise



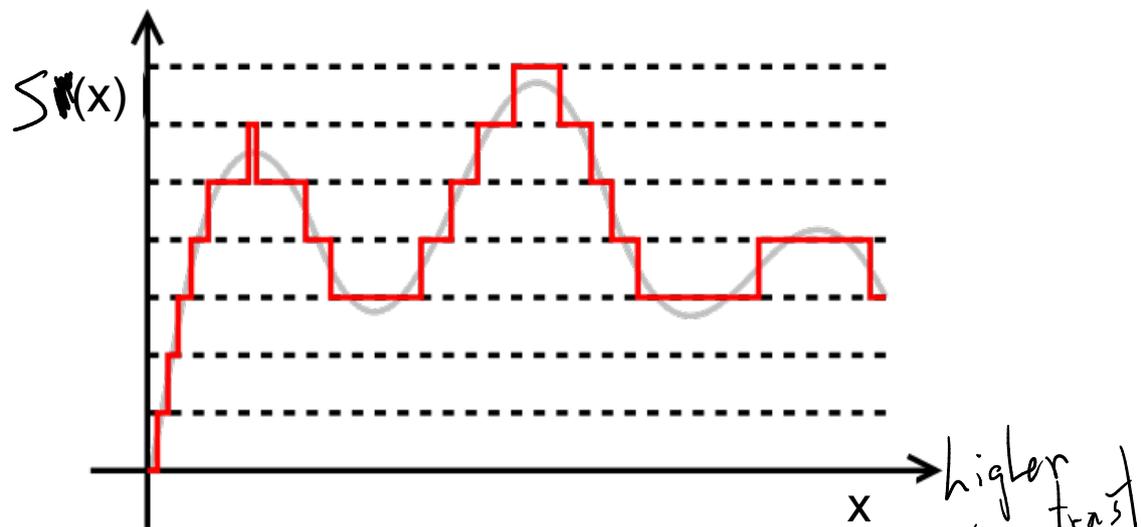
source: <http://www.wikipedia.org>

# Signal and contrast

## Signal

(Image itself)

for example:  $S(x, y)$



## Contrast

in general:  $|S(x_2, y_2) - S(x_1, y_1)|$

e.g. global:  $\max S - \min S$

## Visibility

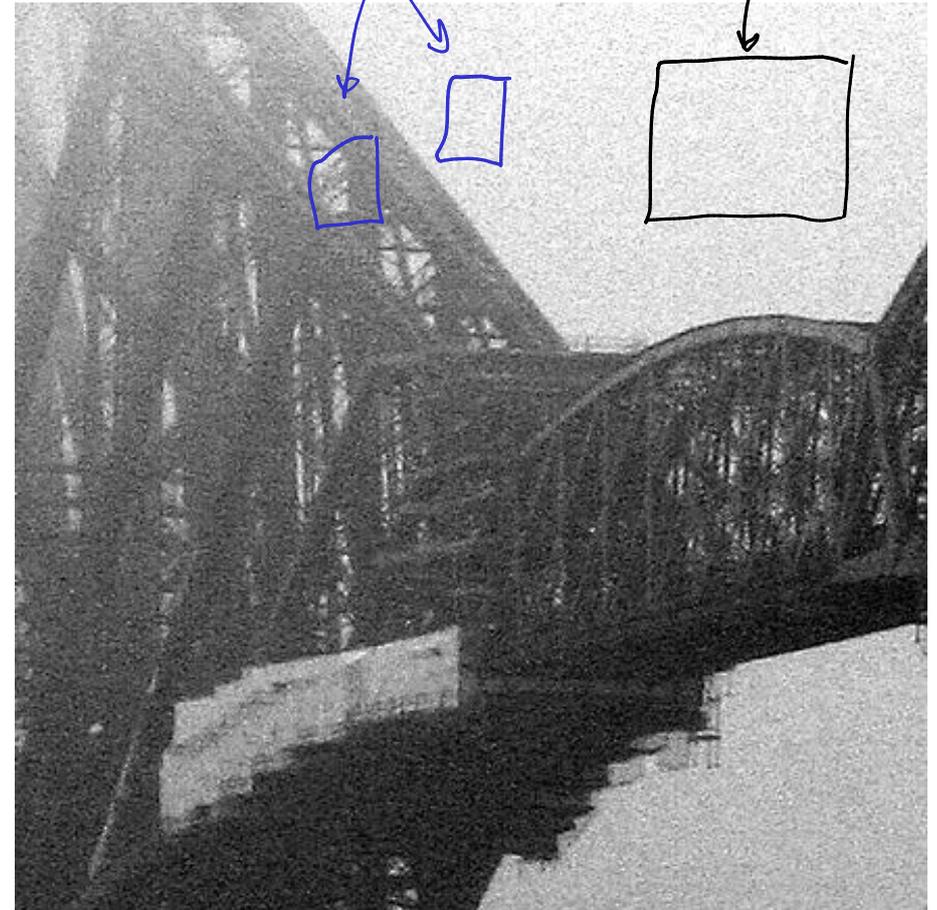
$$\frac{\max S - \min S}{\langle S \rangle}$$

(one possible definition)  $\langle S \rangle$



# Contrast and noise

- Higher contrast, higher noise (← for a single image)
- constant contrast-to-noise



C/N

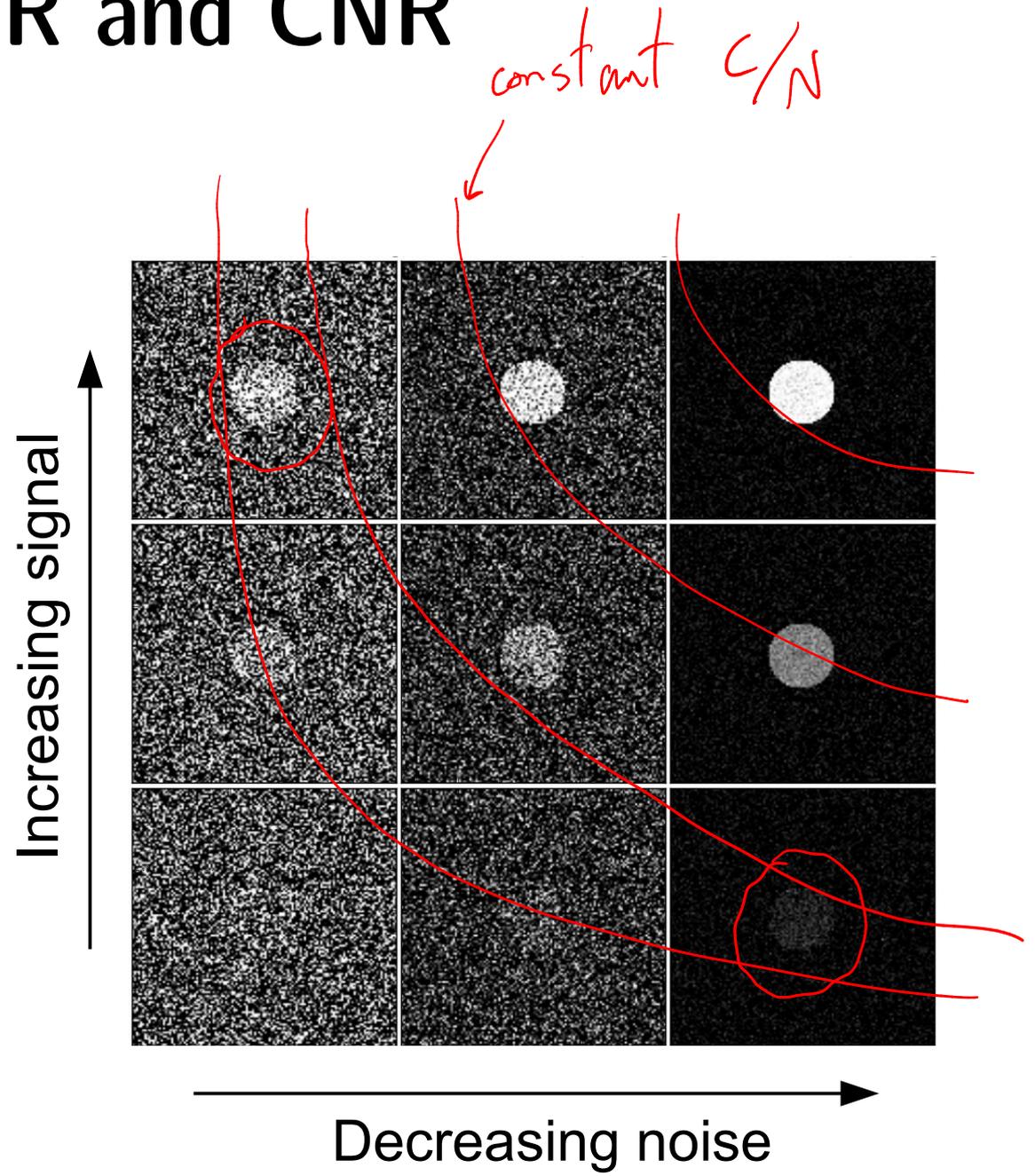
# SNR and CNR

Signal-to-noise

$$\frac{S}{\sigma}$$

Contrast-to-noise

$$\frac{|S_2 - S_1|}{\sigma}$$

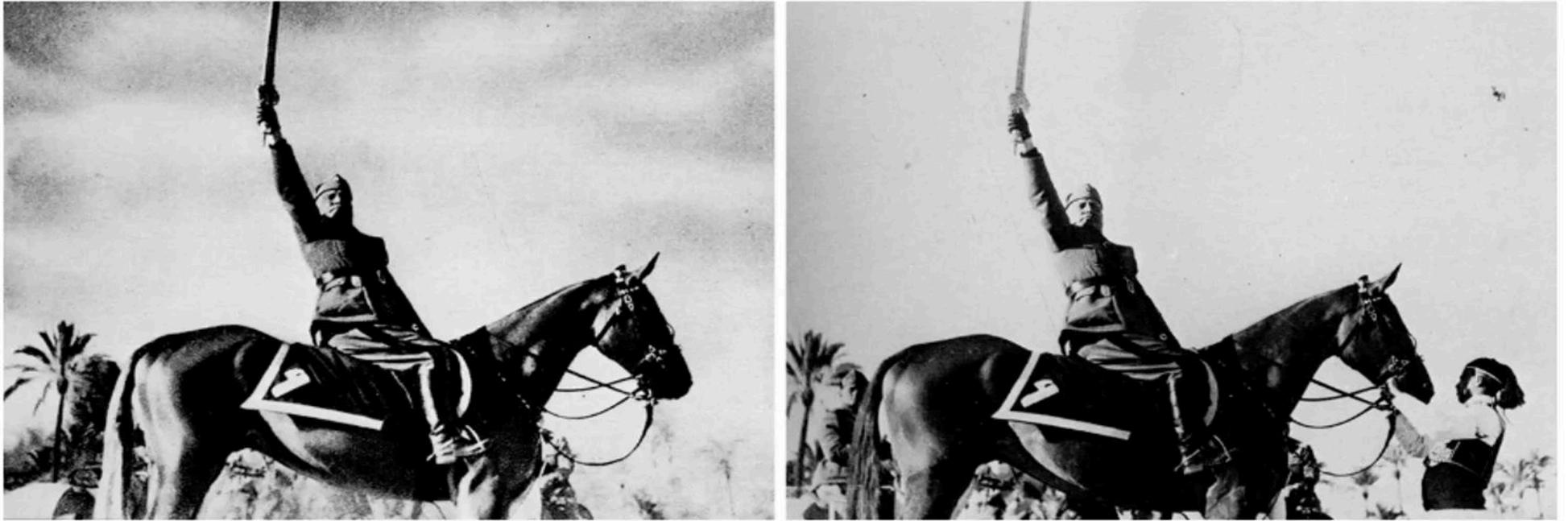


# Ethics of image processing



Nikolai Yezhov removed from original photo (1937)

# Ethics of image processing



Helper removed from Mussolini's "sword of Islam" photo (1937)

# Ethics of image processing

**EDITORIALS**

NATURE | Vol 439 | 23 February 2006

## Not picture-perfect

*Nature's* new guidelines for digital images encourage openness about the way data are manipulated.

**R**esearchers struggle to amass good data and present them in as clear a fashion as possible. But what do we mean by 'clear' when it comes to images? In days gone by, whether we liked it or not, data acquired at the bench were not much different from what was published. In a biomedical lab, for example, samples

that had been radio-labelled and separated on a gel were recorded on X-ray film. Composite figures were assembled, with lettering carefully placed around the mounted film. If a control was forgotten or a gel was uneven, the graduate student or postdoc was sent back into the lab to get it right 'for publication'. If a speck of dust on the film obscured data in the original photograph, another picture was taken. Slicing films to rearrange the order of samples, or to splice in a control group that was actually part of another gel, was not common because it took almost as much skill to do that as to rerun the experiment.

It is doubtful that scientists were more angelic then than now. It is

# Ethics of image processing

EDITORIALS

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**"In short, any digital technique that isn't applied to the entire image is suspect and needs to be explicated to the reader."**

that had been radio-labelled and separated on a gel were recorded on opposite figures were assembled, with lettering and the mounted film. If a control was forgotten, the graduate student or postdoc was sent back right 'for publication'. If a speck of dust on the original photograph, another picture was to rearrange the order of samples, or to splice that was actually part of another gel, was not took almost as much skill to do that as to rerun the experiment.

It is doubtful that scientists were more angelic then than now. It is

# Multichannel images

When spatial information is more than a scalar



Source: <http://apod.nasa.gov/apod/ap070505.html>

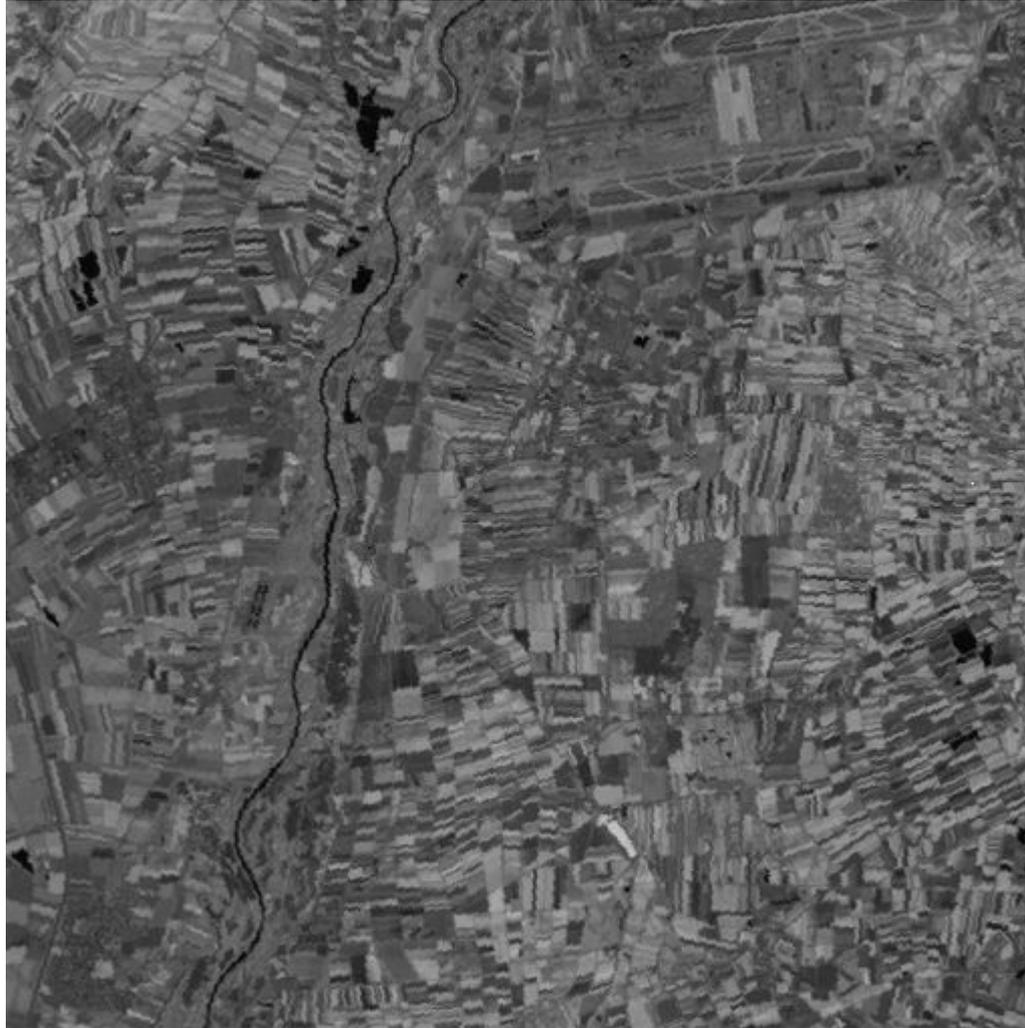
# Multichannel images



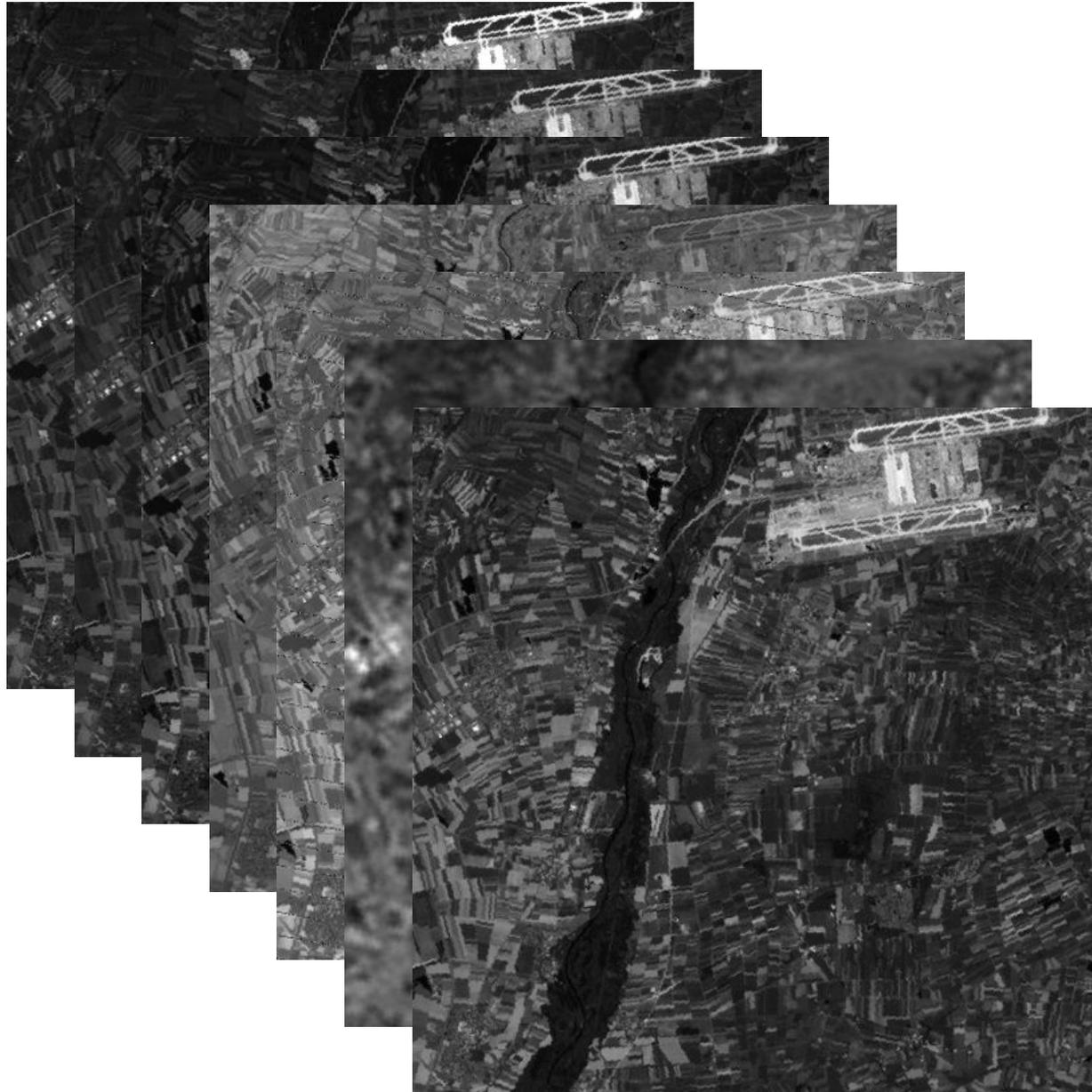
# Multichannel images



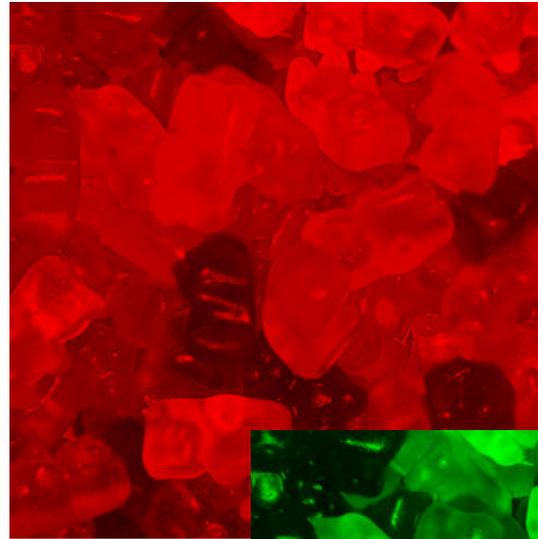
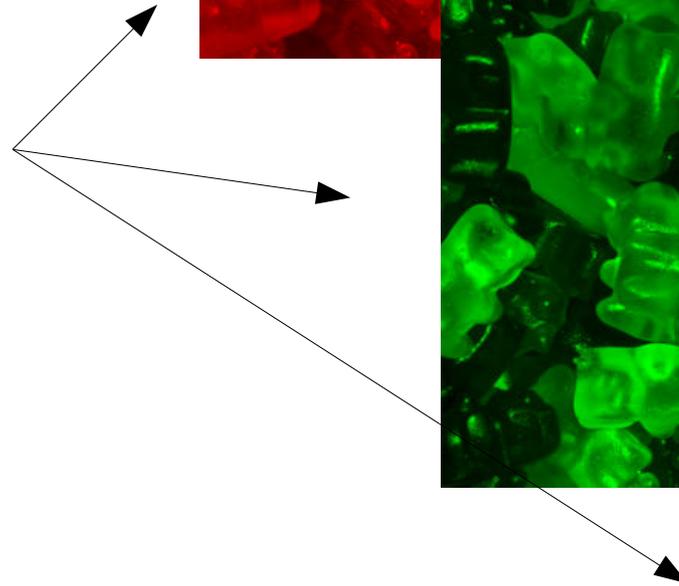
# Multichannel images



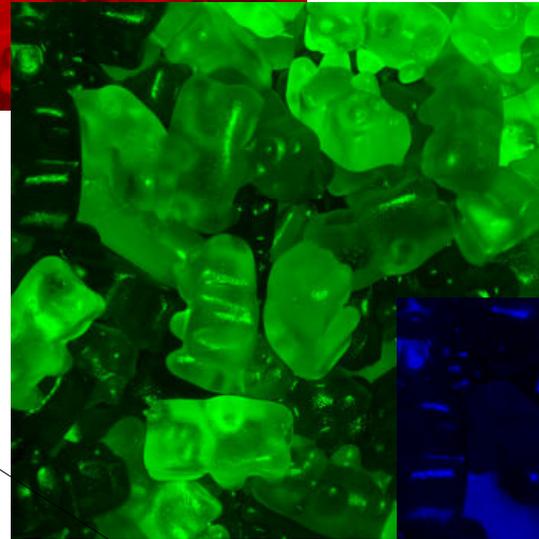
# Multichannel images



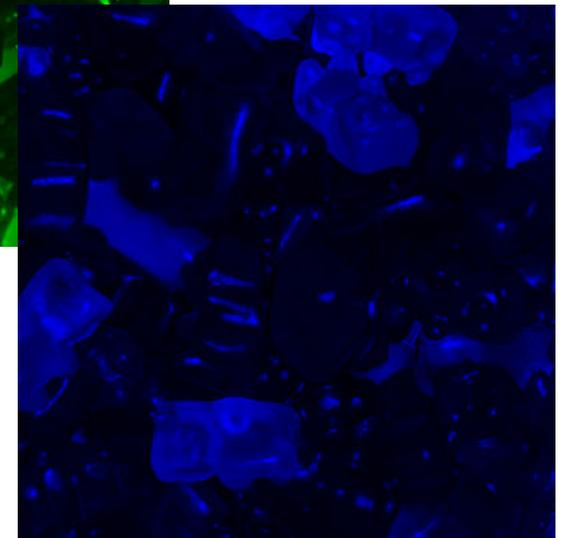
# 3-channel images



*Red*

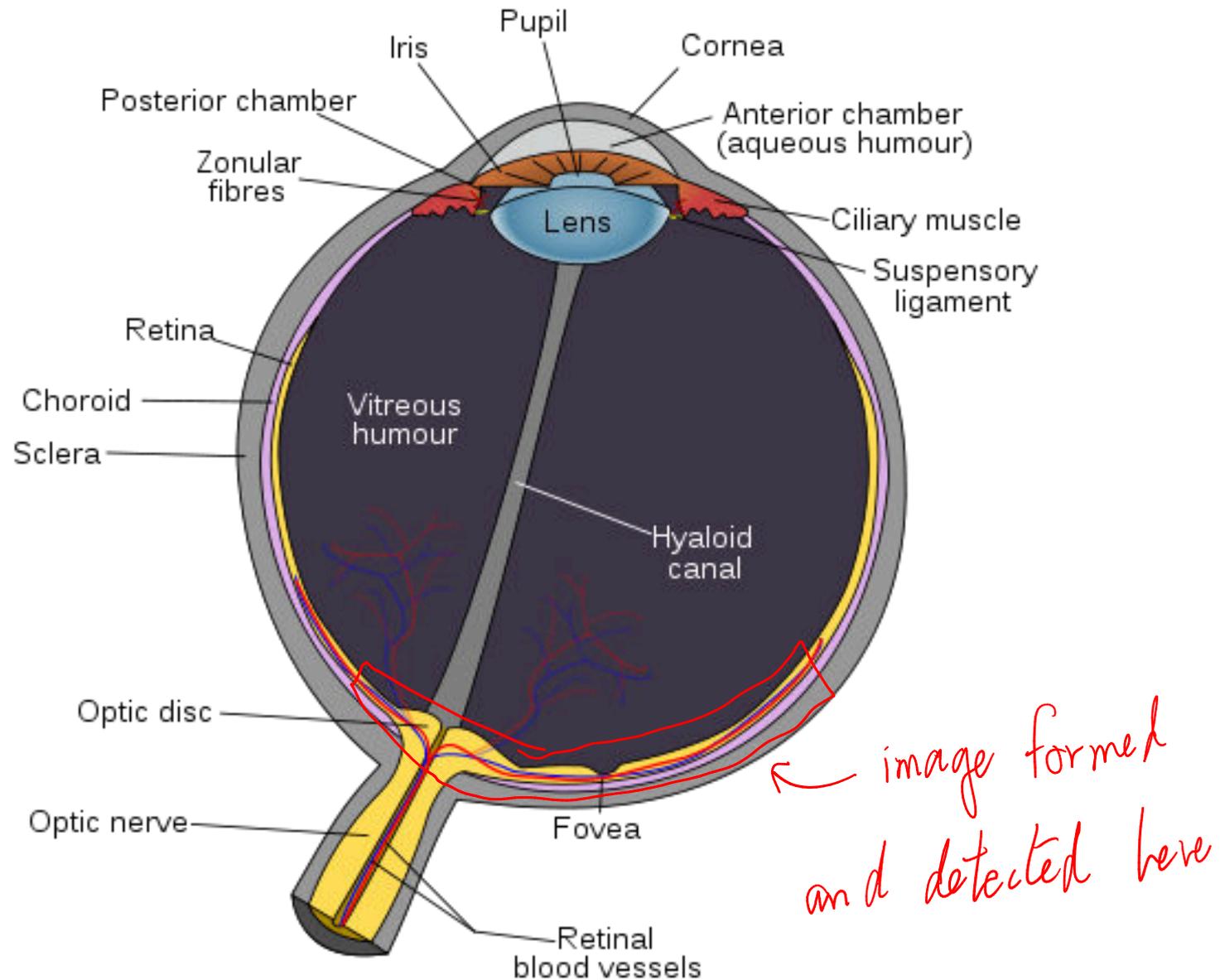


*Green*

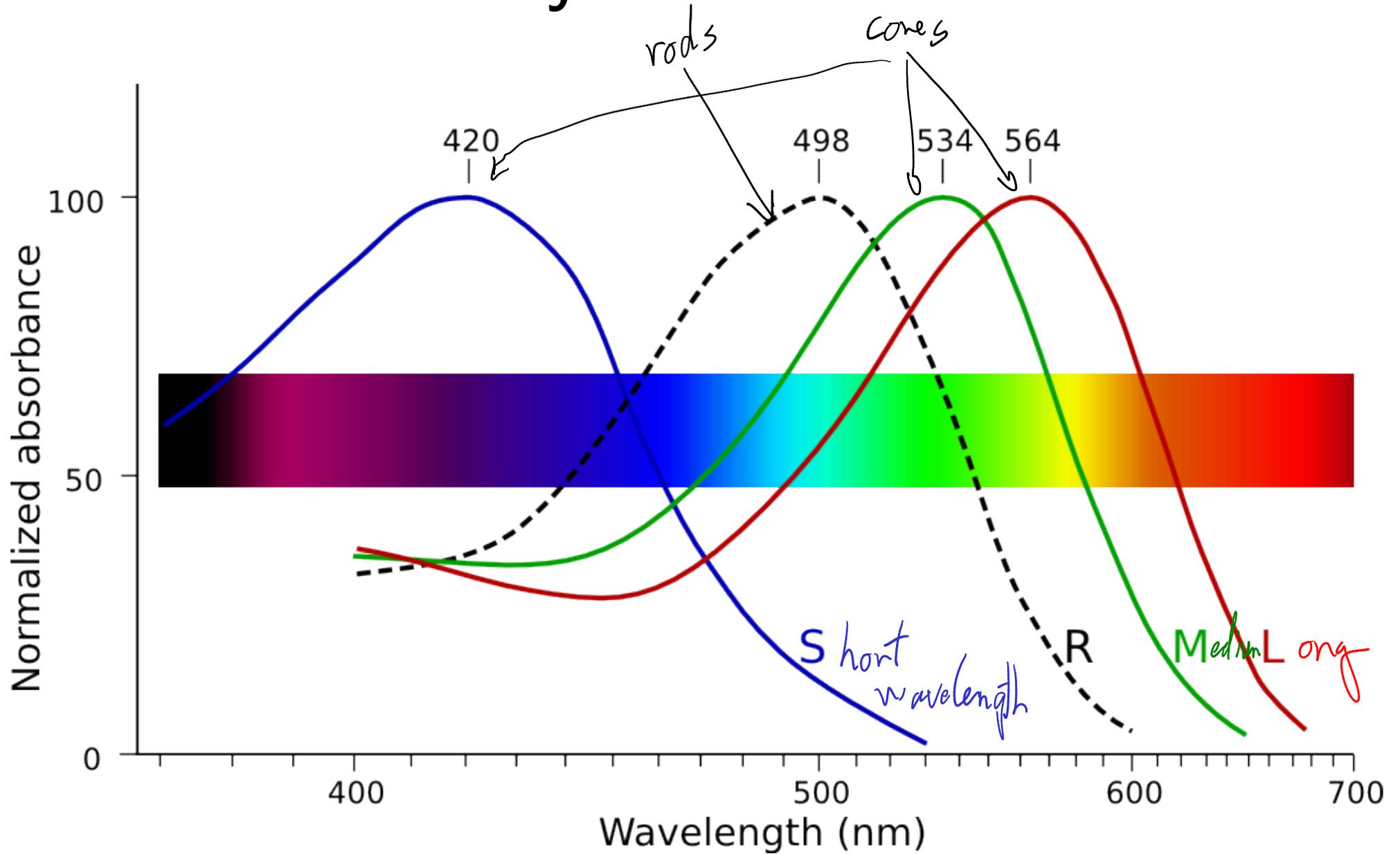


*Blue*

# The eye as a light detector



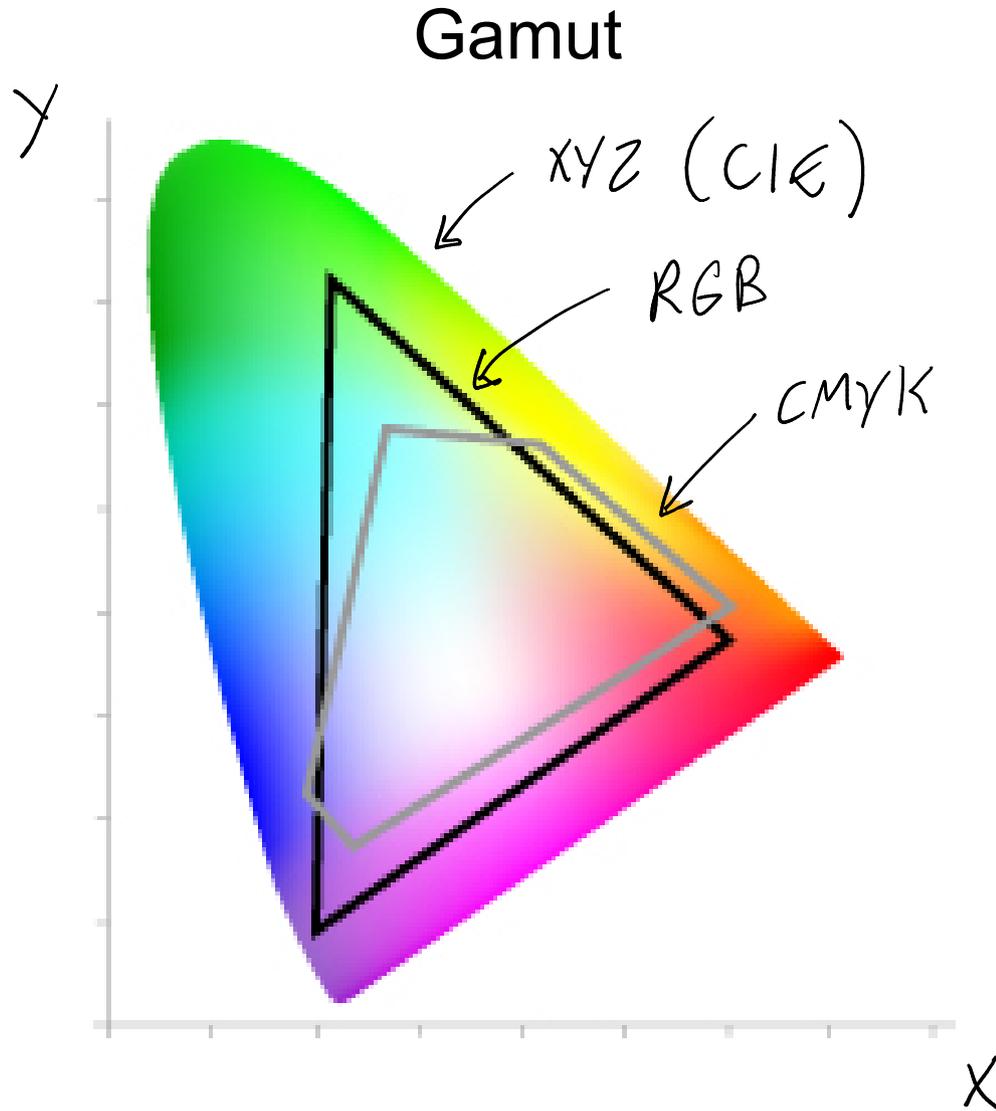
# The eye as a detector



# Color spaces

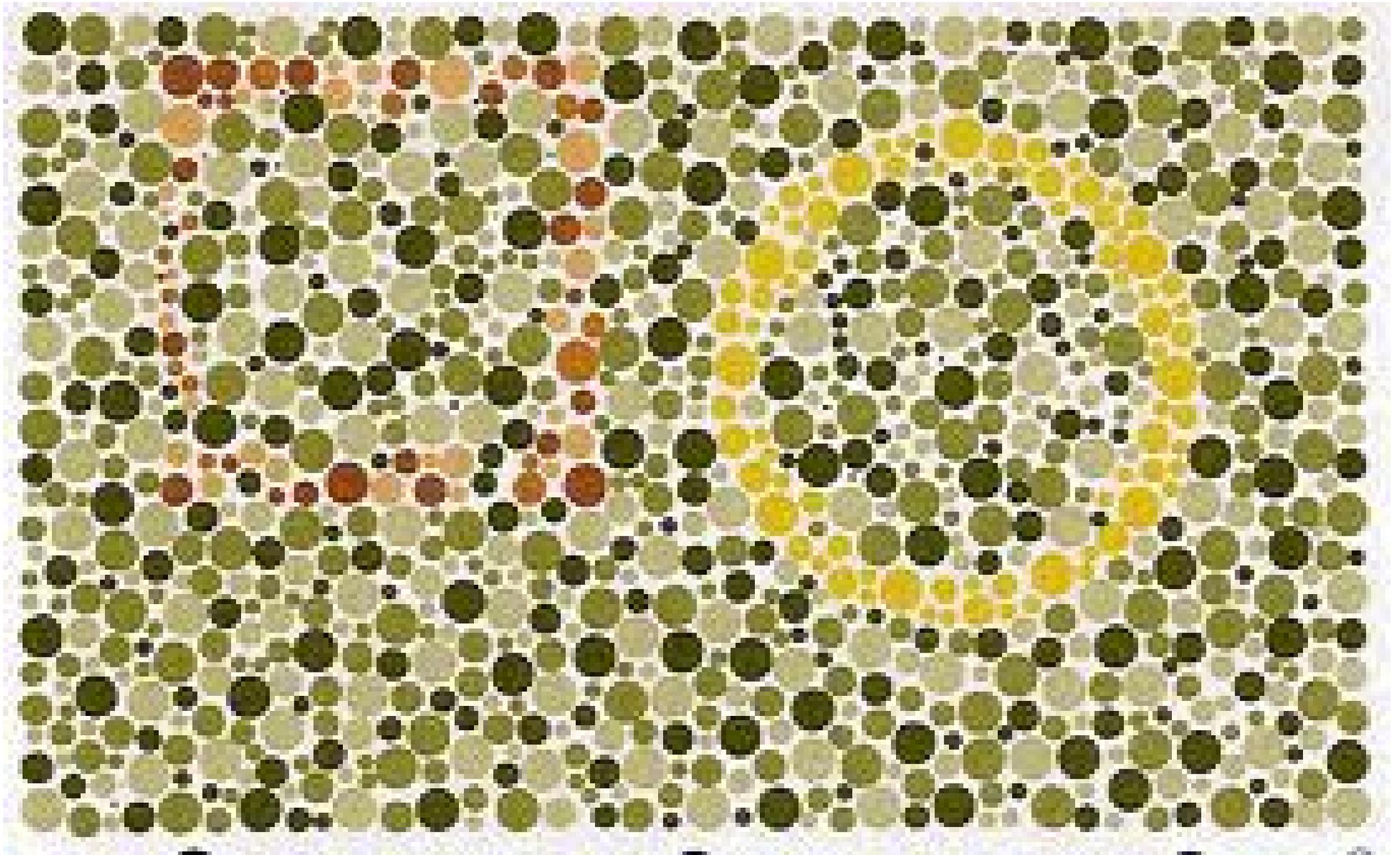
- Real signal : LMS (cone response)
- Standard: CIE XYZ
  - “Commission Internationale de l'éclairage”
  - XYZ : just a linear transform from LMS
- Most displays: RGB *red green blue*
  - Again, just a linear transform from XYZ
- Most printed support: CMYK *cyan magenta yellow black*
  - Go to 4 colors to save ink (maximize black)

# Color spaces



Source: <http://de.wikipedia.org/wiki/Lab-Farbraum>

# Color vision deficiencies

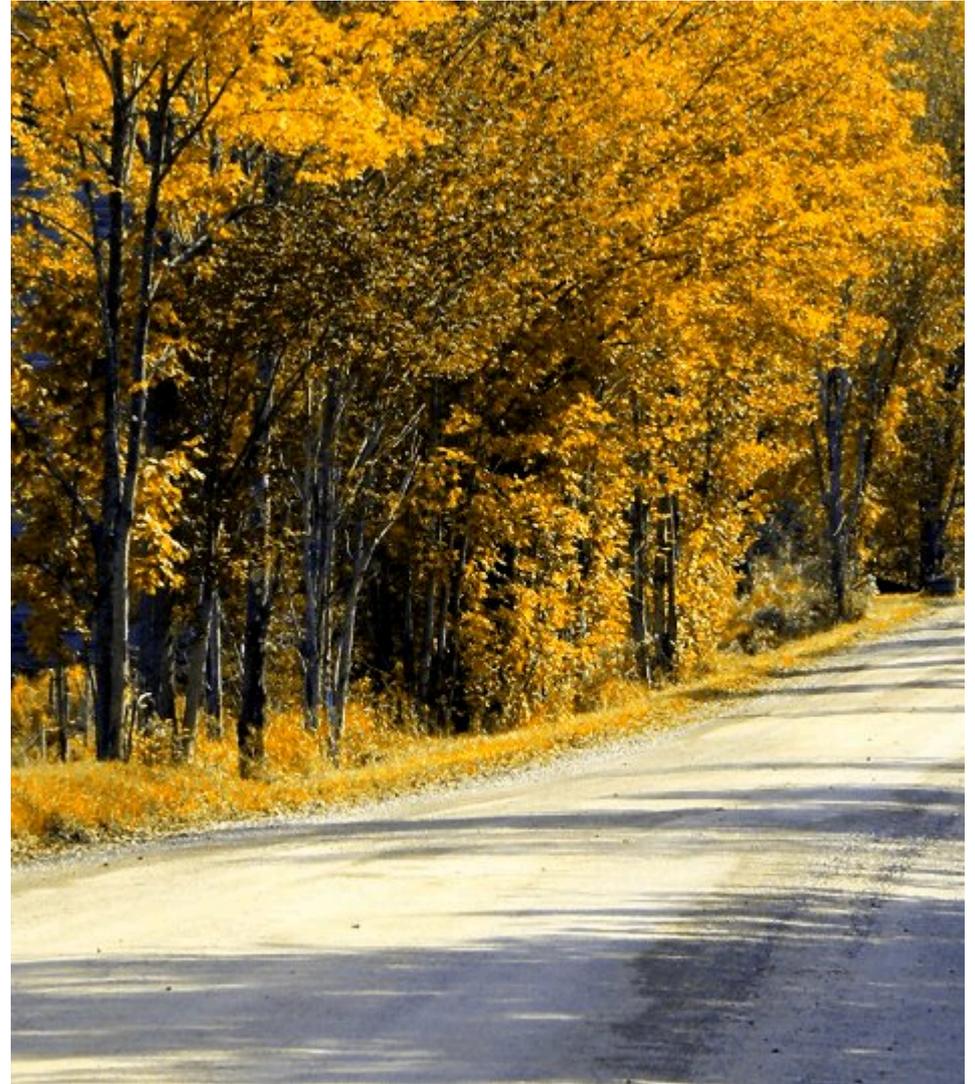


# Color vision deficiencies

Normal vision



Deuteranopia (insensitivity to green)



# The human eye

## The good

- Good spatial resolution ( $< 1\text{mm}$ )
- Very large dynamic range ( $> 10^6$ ) and automatic threshold
- Energy discrimination (colors)
- Long life-time, energy efficient, low carbon footprint

## The bad

- Relatively low sensitivity ( $> 500$  photons/s to register a conscious signal)
- Low speed (10 Hz)
- Slow trigger

# Image storage

- TIFF:
  - high dynamic range possible
  - lossless and lossy compression
- JPG:
  - lossy compression
- PNG:
  - lossless compression
- ...
- For scientific purposes: select the format that incurs no data degradation (TIFF, other general data formats (HDF, ...))

← 8 bit dynamic range  
 $2^8 = 256$  possible values

hierarchical data format ↗