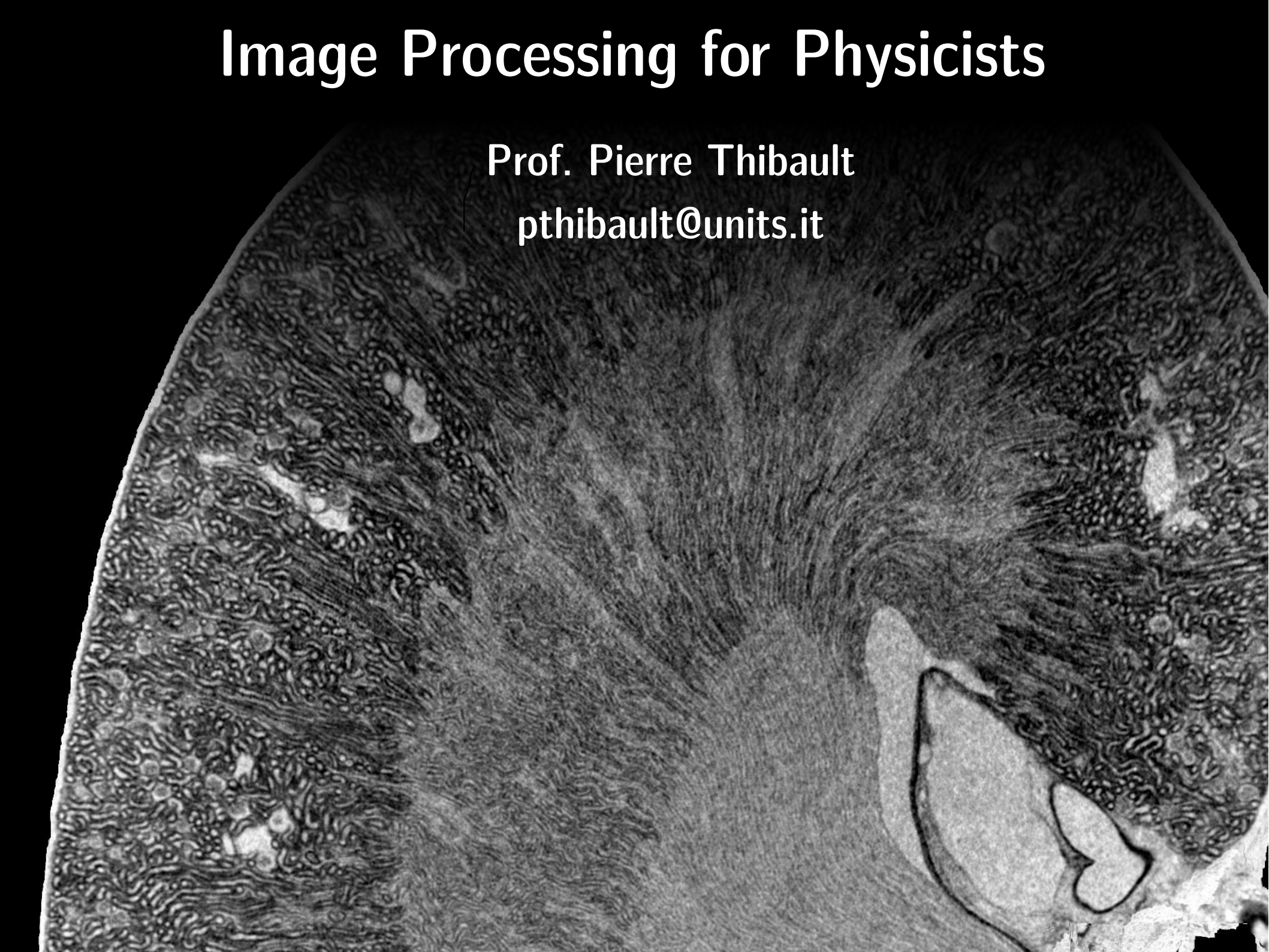
Image Processing for Physicists

Prof. Pierre Thibault

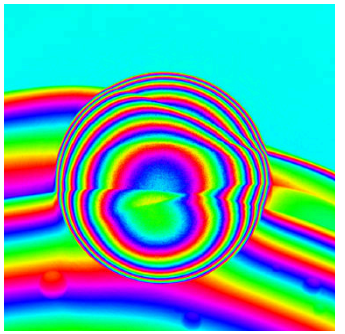
pthibault@units.it

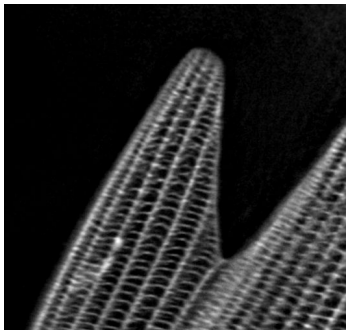


Background

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 ($\rightarrow$ involve heavy reconstruction algorithms)

http://s-baxit.optimato.eu

Syllabus

1. Spatial Domain
2. Fourier Domain
3. Sampling & Interpolation
4. Image Representations
5. Characterization Of Detection Systems
6. Imaging Systems & Wave Propagation
7. Interferometric Imaging And Imaging Of Far-Field Fourier Amplitudes
8. Tomography
9. Least Squares Optimization
10. Constrained Optimization & Maximum Likelihood Optimization

Philosophy

Techniques

Core knowledge of most common mathematical and numerical tools for imaging and microscopy, from a physicists 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

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

Admin

- In person (+ remotely if needed)
- Room T20 (department of physics)
- Tue - Thur 11:00-13:00
- Lectures + tutorials
- Weekly exercises (python)
- Final assessment: mid-February, oral

What is an image?

- We adopt the definition:

"Spatial representation of information"

- 2D (most common)
- 2D multichannel (color)
- 2D timeseries (movies)
- 3D (tomographic data, ...)
- 1D (why not?)

The imaging chain

Information

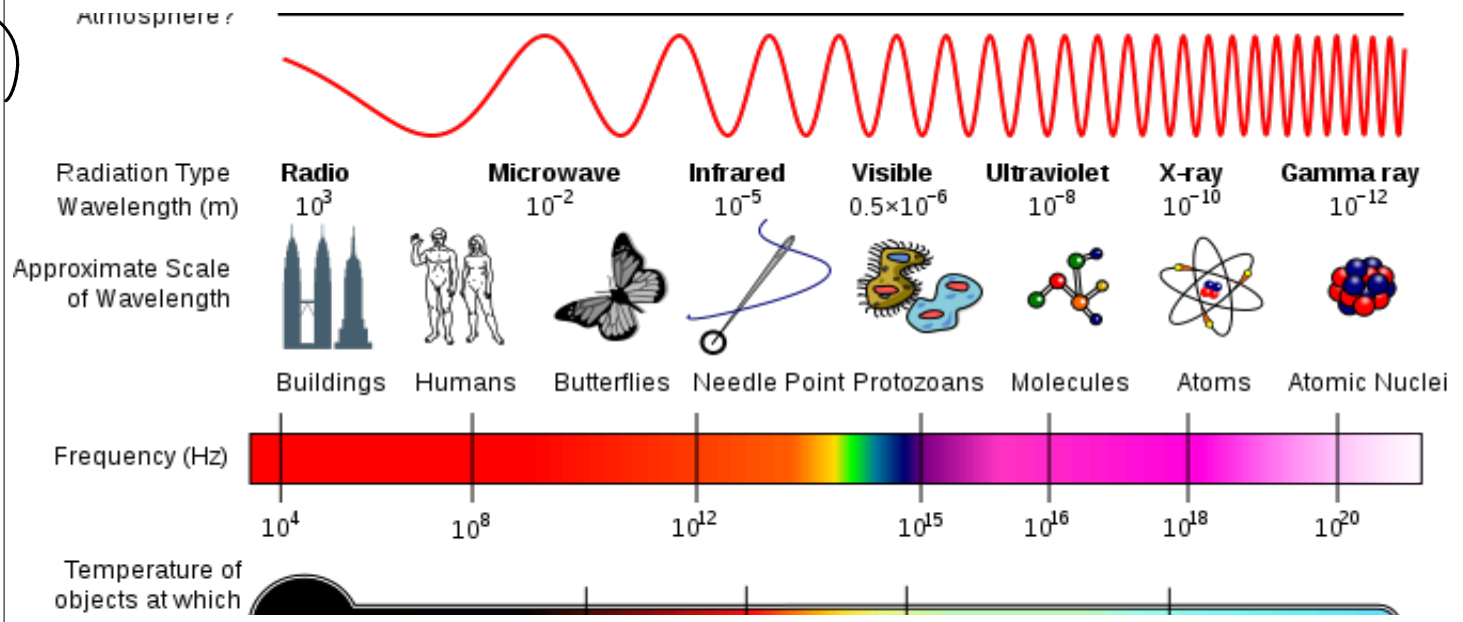
The imaging chain

Probe

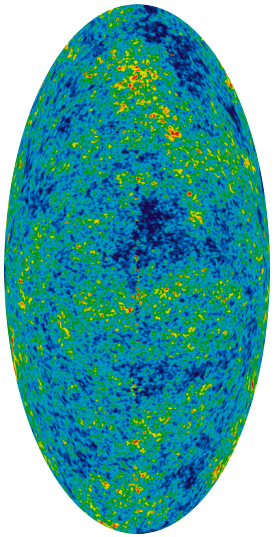
Information

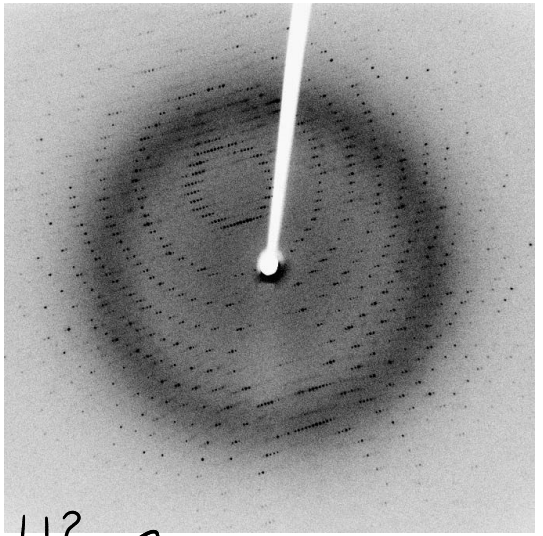
(radiation)

electromagnetic radiation



microwave





visible light? x-ray

source: http://www.wikipedia.org

http://www.brainmaps.org/

The imaging chain

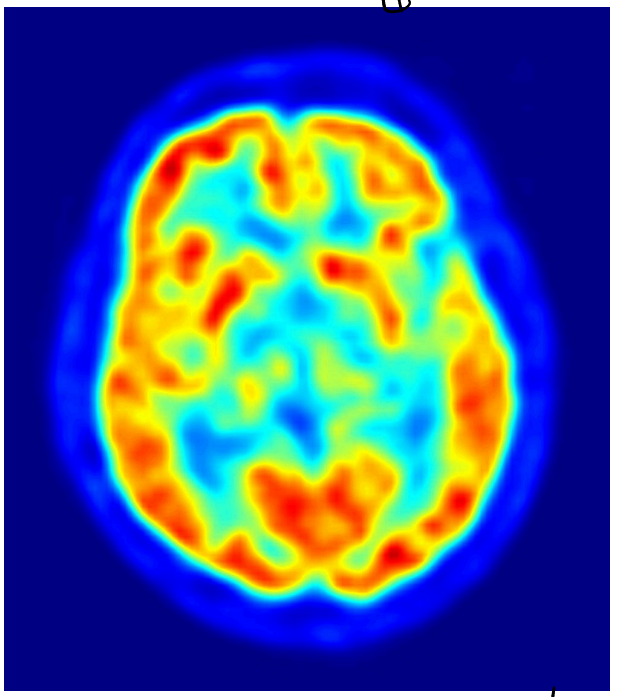
Information

Probe

particles / particle decay

scanning electron microscopy SEM

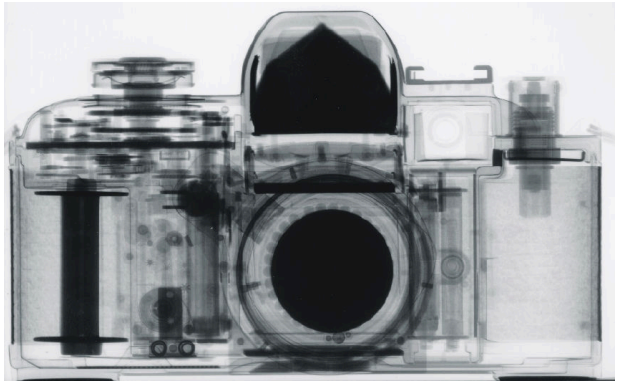
PET positron emission tomography



source: http://www.wikipedia.org

?

neutron



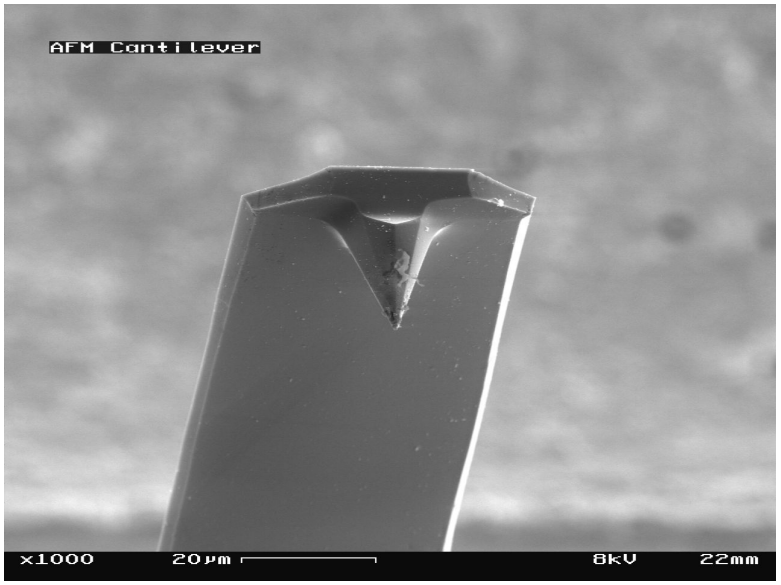
source: http://www.ati.ac.at/~neutropt/experiments/Radiography/radiography.html

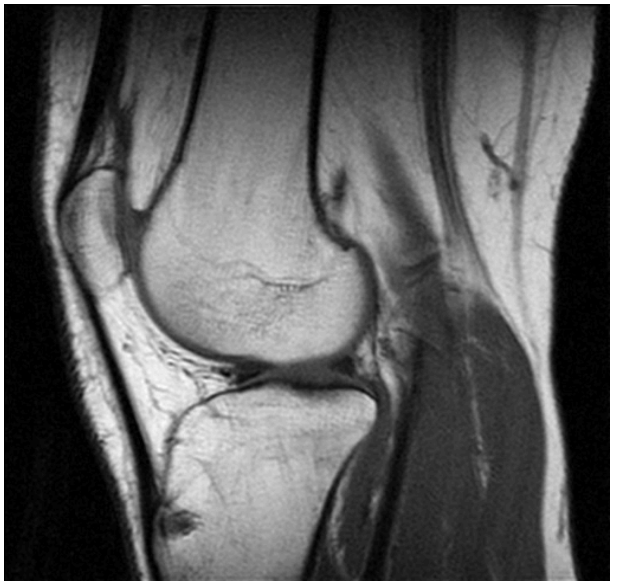
The imaging chain

Probe

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

MRI





ultrasound

source: http://www.wikipedia.org

Information

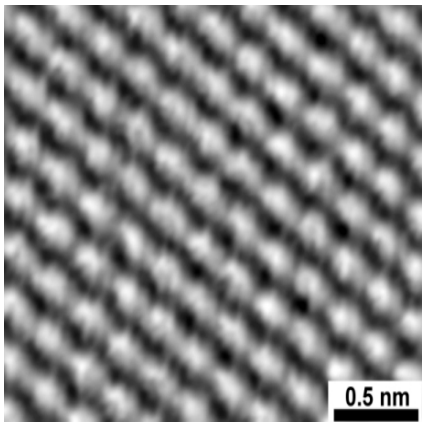
The imaging chain

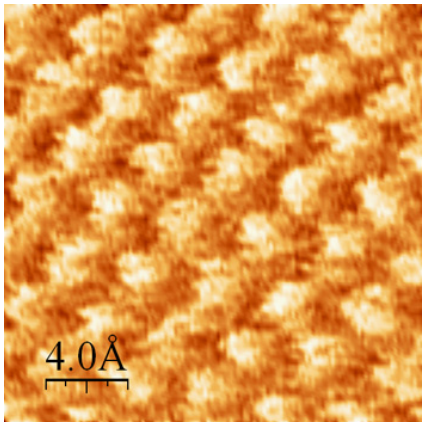
Probe

Interaction

Information

STM **HOPG** AFM

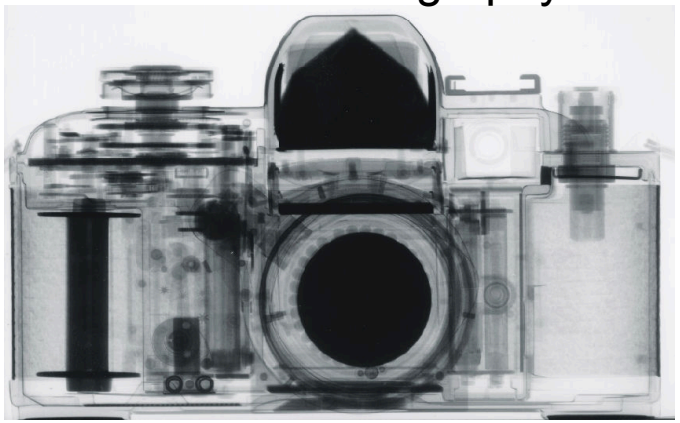




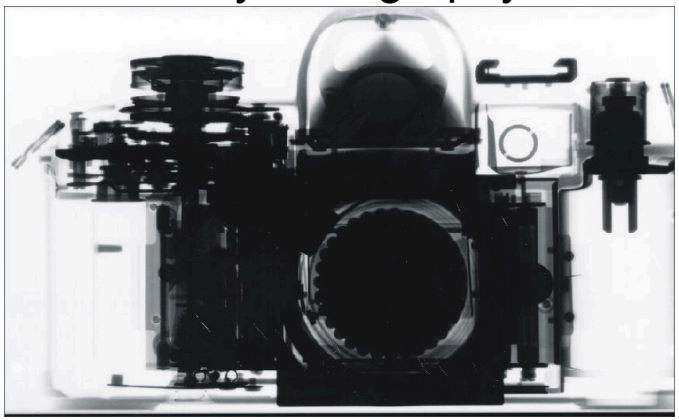
scanning probe

source: http://www.wikipedia.org

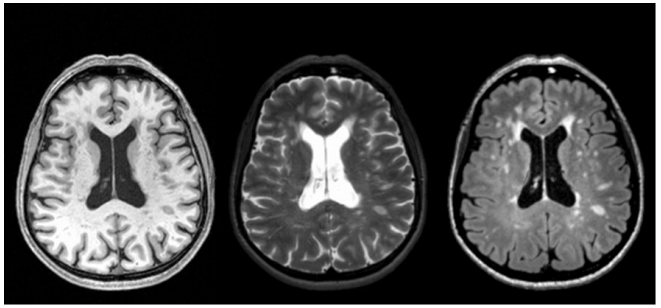
Neutron radiography



X-ray radiography



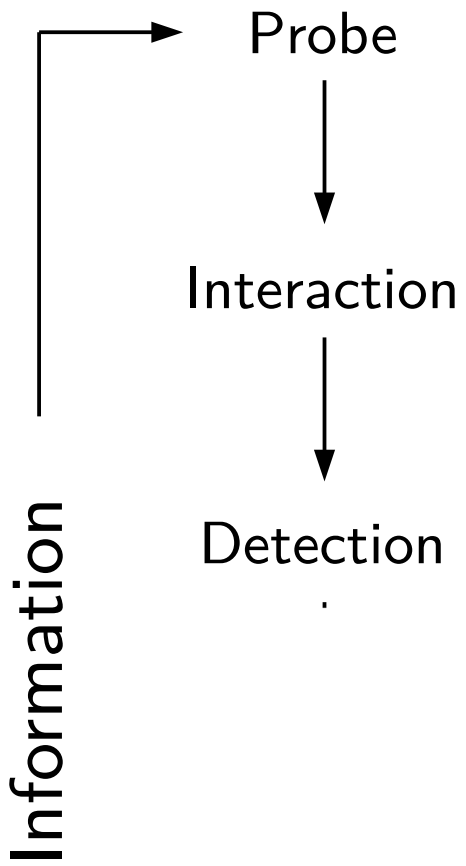
source: http://www.ati.ac.at/~neutropt/experiments/Radiography/radiography.html



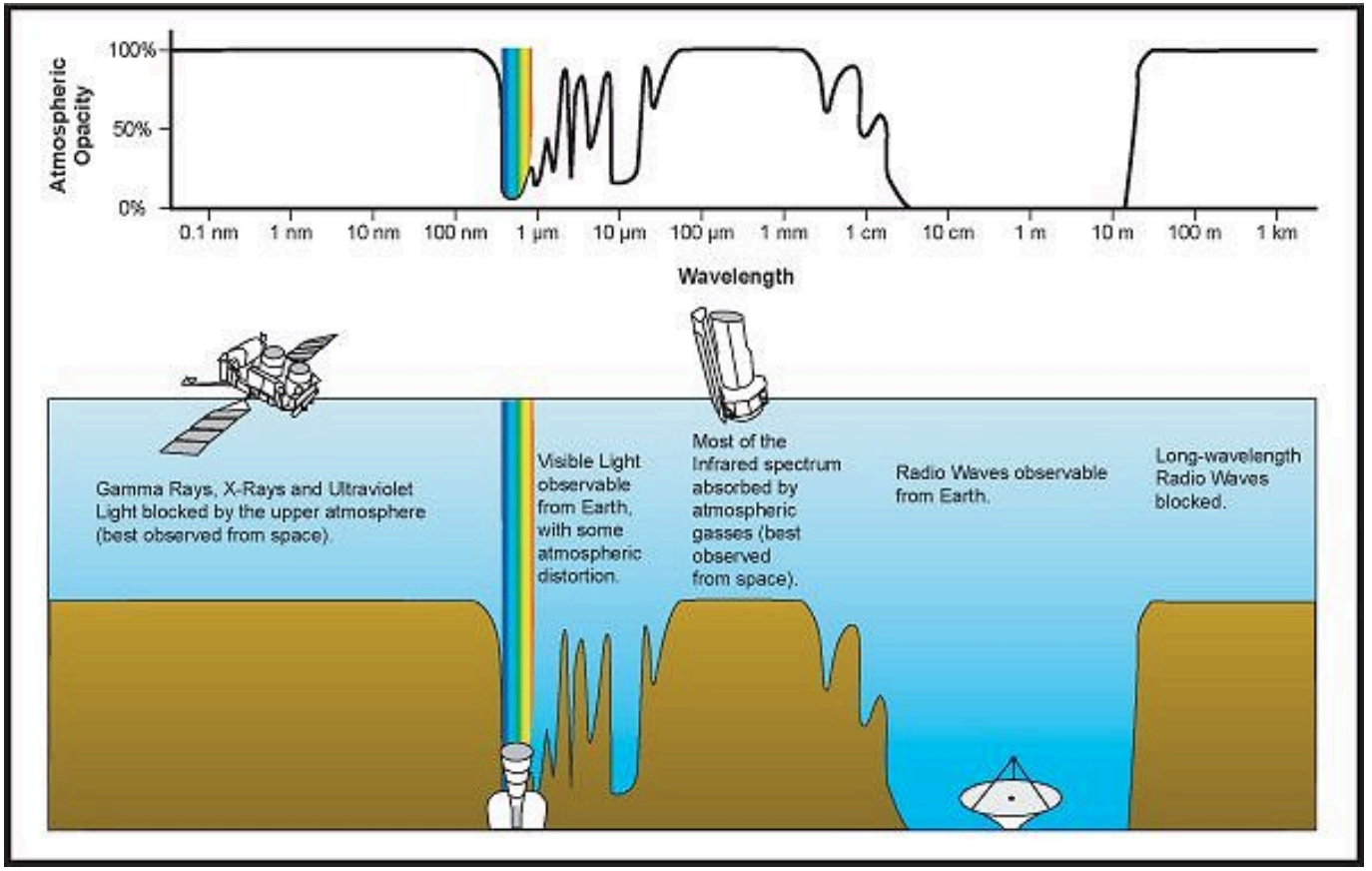
Brain MRI (T1, T2, FLAIR)

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

The imaging chain



Information has to reach detector



source: http://www.wikipedia.org

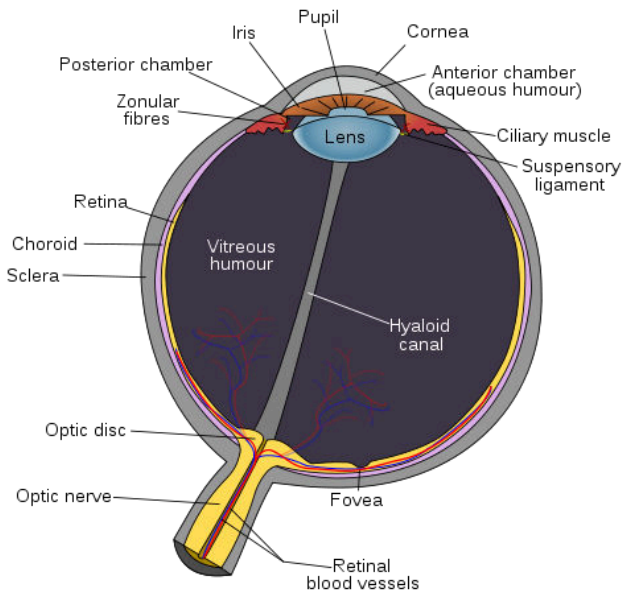
The imaging chain

Information

Probe

Interaction

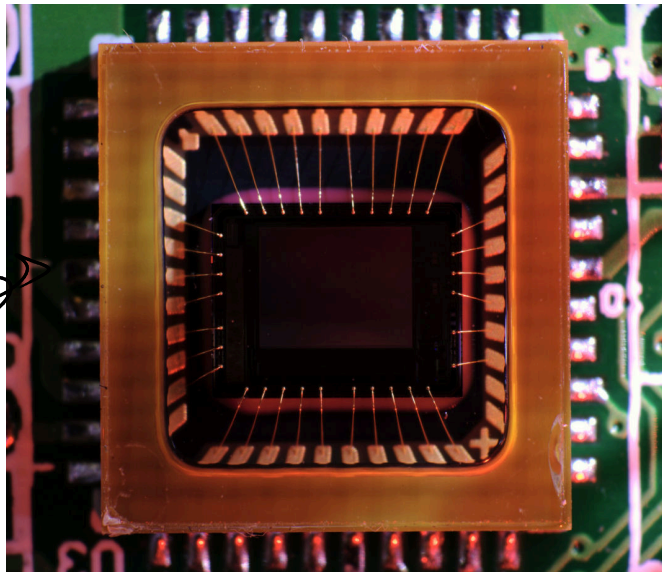
Detection



biological, chemical, electronic, interferometric detectors

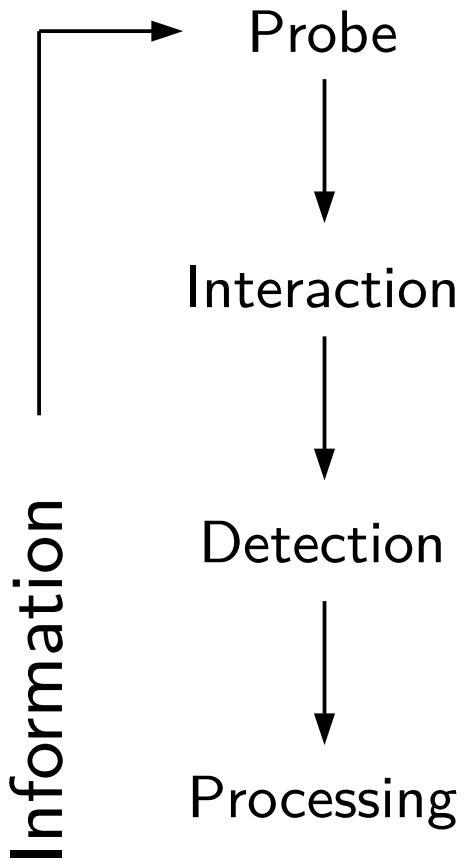
CCD

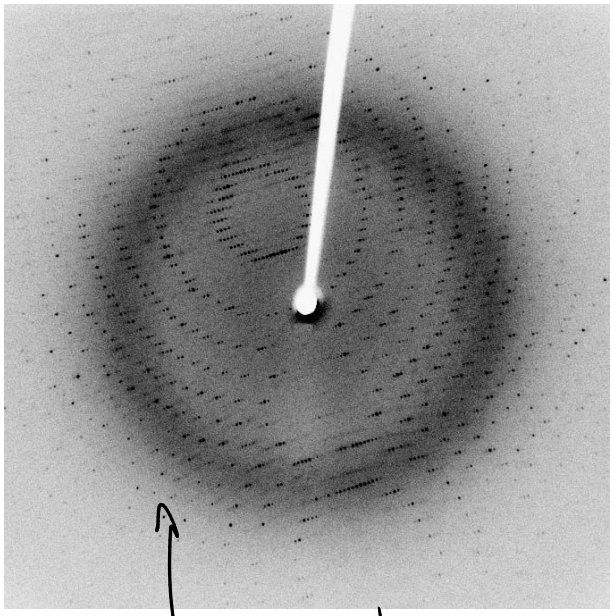
pixel-array detectors



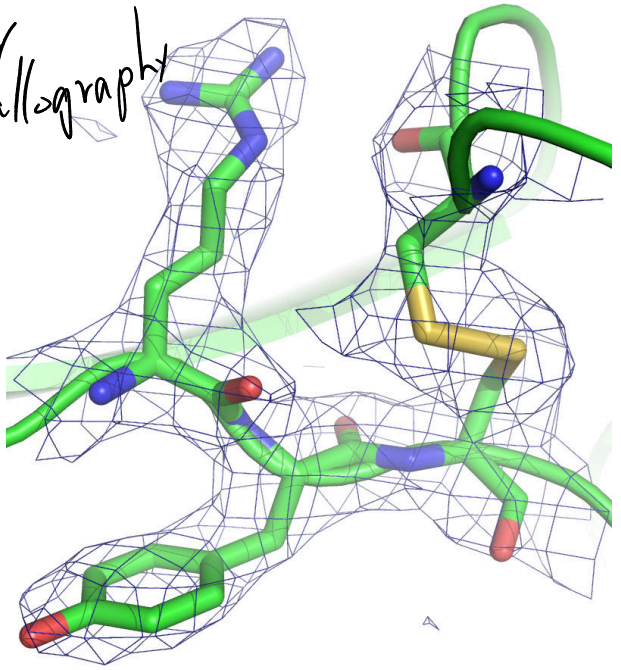
source: http://www.wikipedia.org

The imaging chain



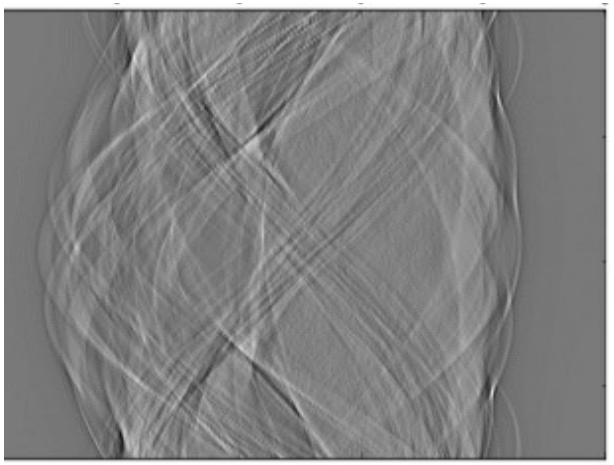


X-ray crystallography

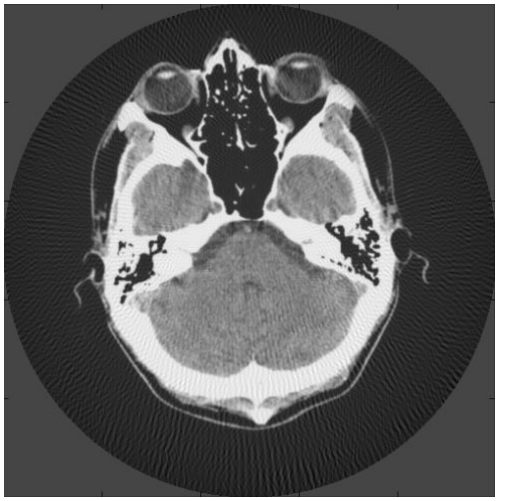


source: http://www.wikipedia.org

Reconstruction from hard to interpret raw data

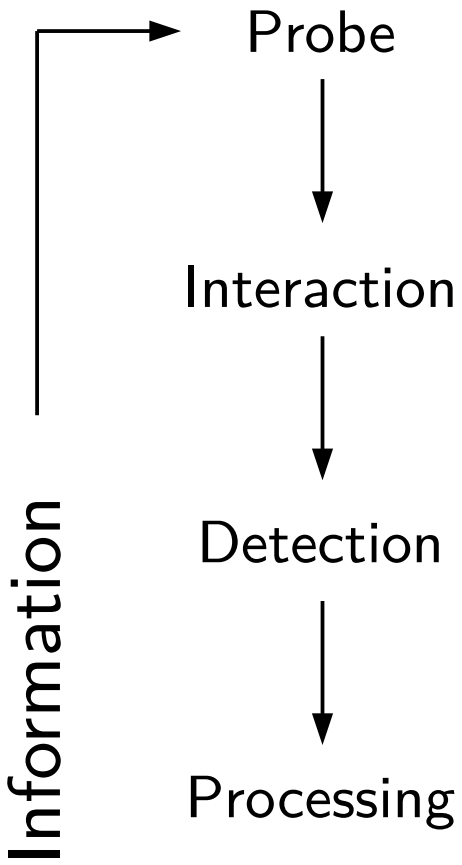


tomography

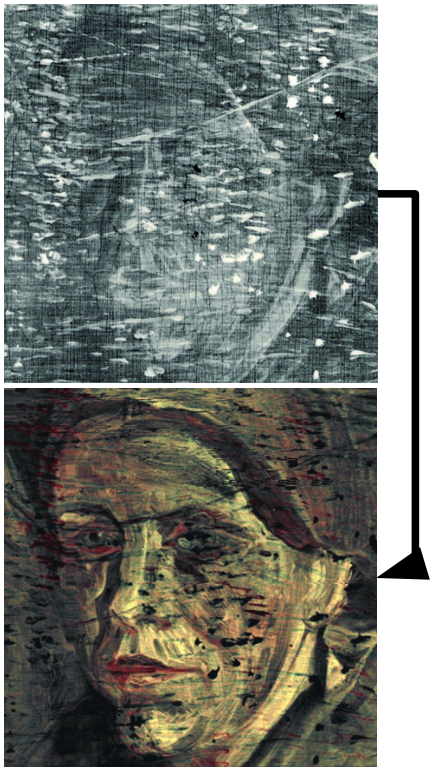


source: P.Thibault, M.Bech

The imaging chain

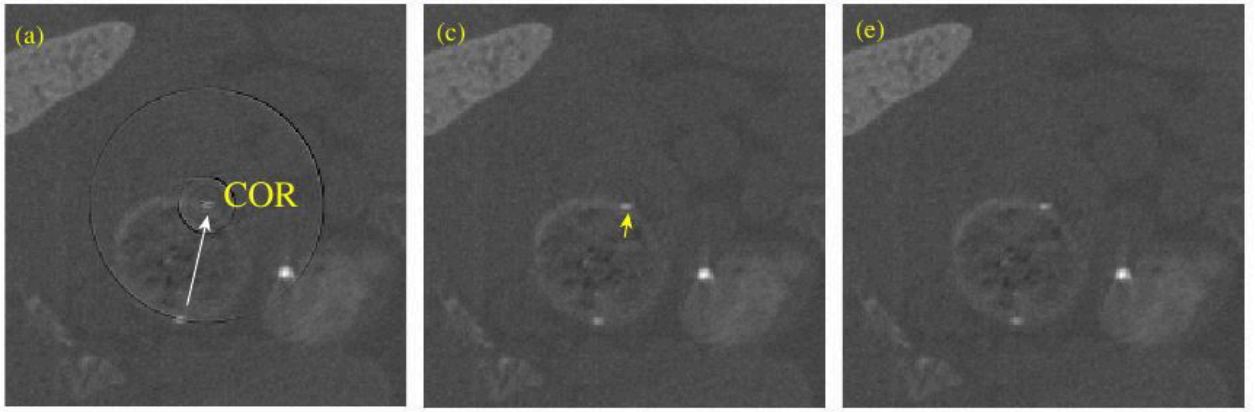


analysis, feature extraction, ...



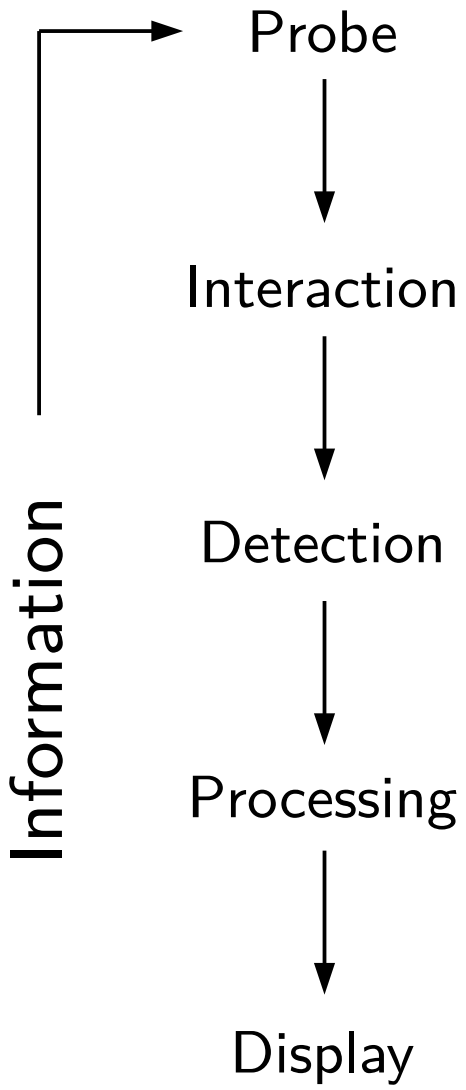
source: J. Dik, et al. Anal. Chem. 80, 6436-6442 (2008)

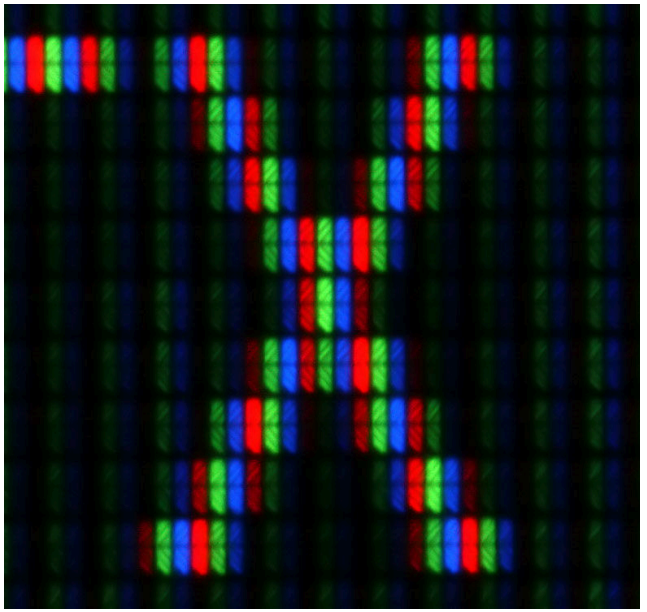
Error correction, artifact reduction, ...

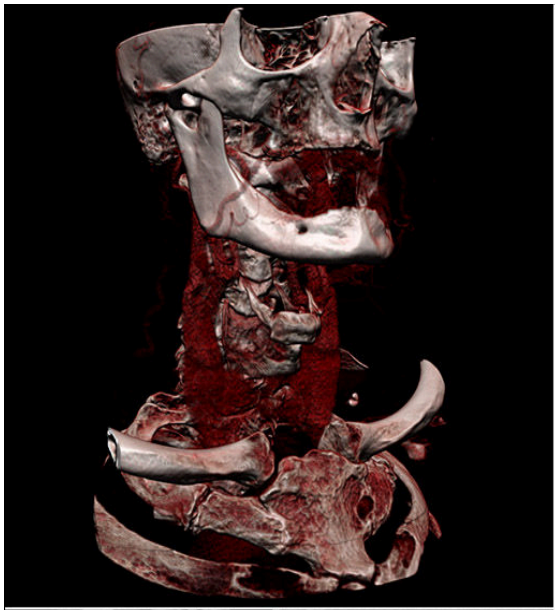


source: E. M. Abu Anas et al. Phys. Med. Biol. ***55*** *6911 (2010)*

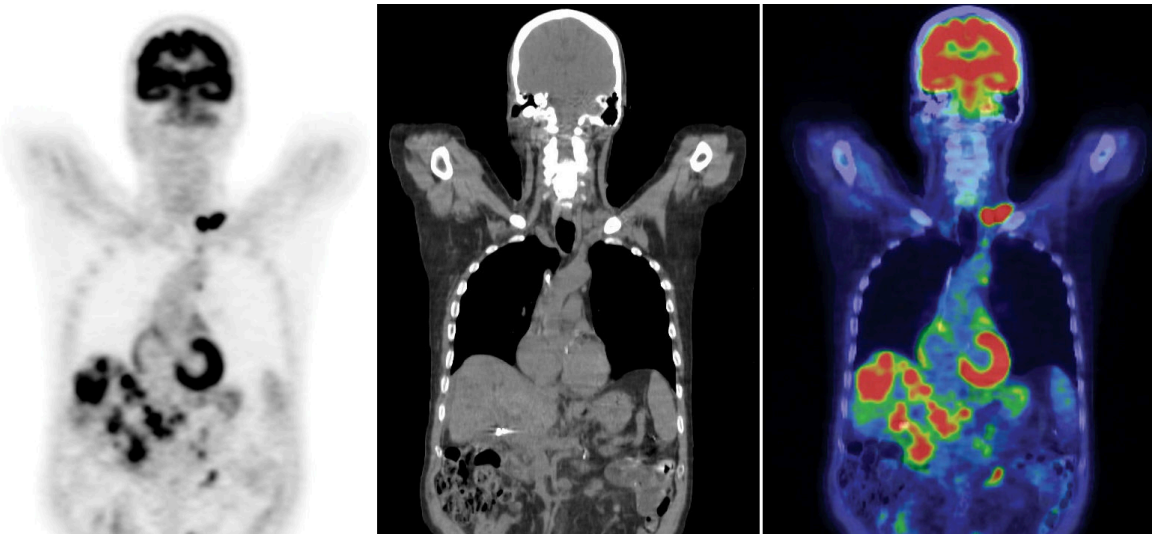
The imaging chain





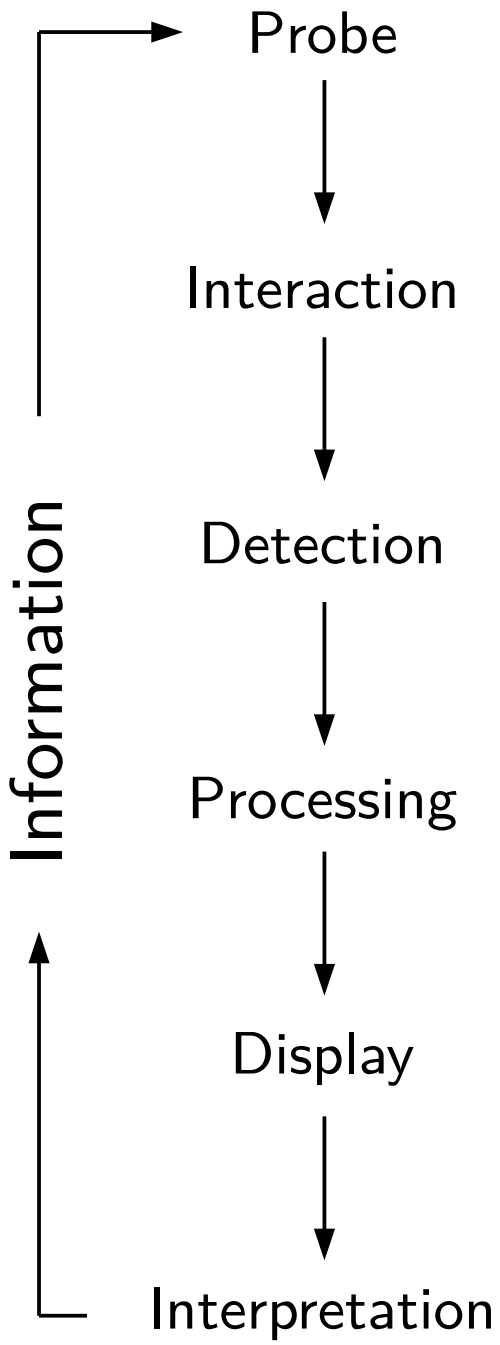


source: http://www.wikipedia.org

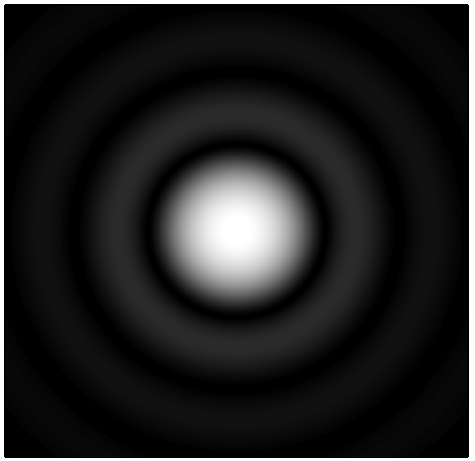


source: http://www.aztechradiology.com

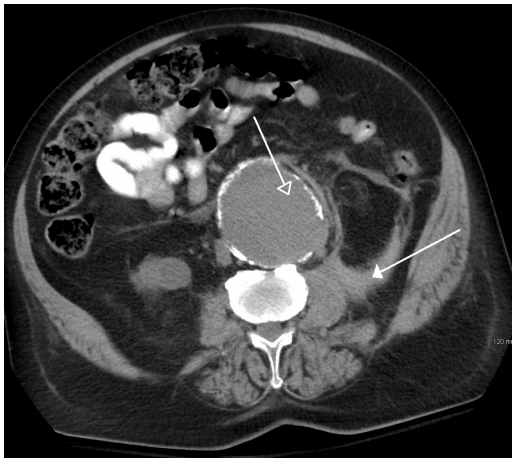
The imaging chain



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

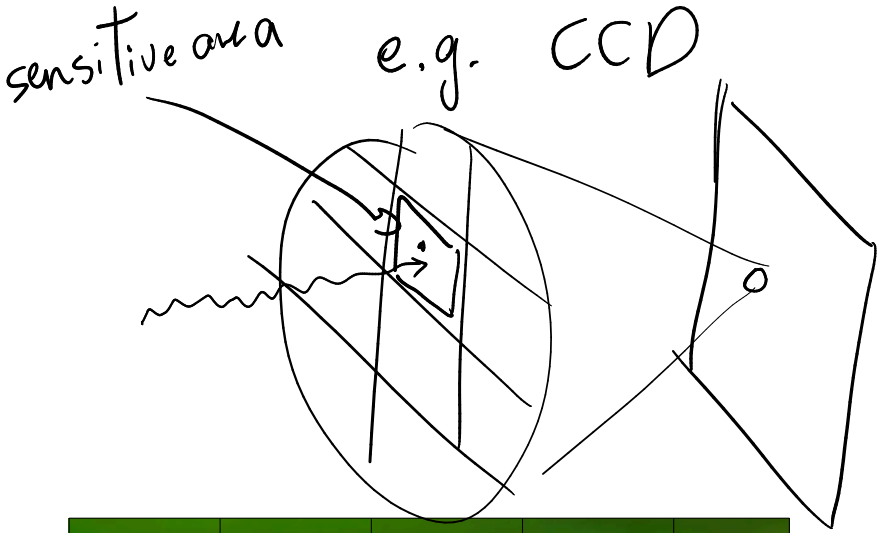
Discrete representation of a continuous function

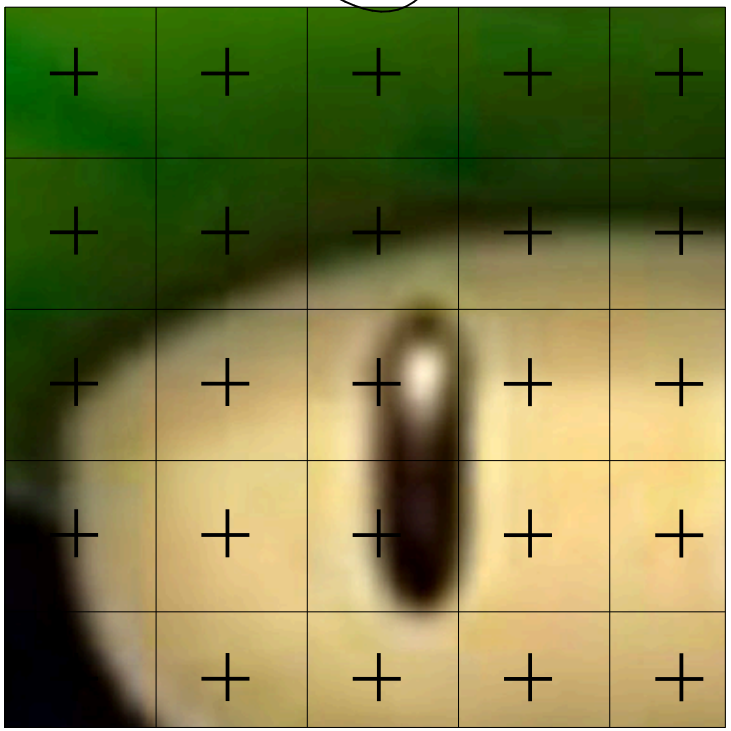
Digitization, sampling, quantization

What is a pixel?

sample of continuous function,

with coordinates and value(s)





- value at coordinate

- mean over pixel area

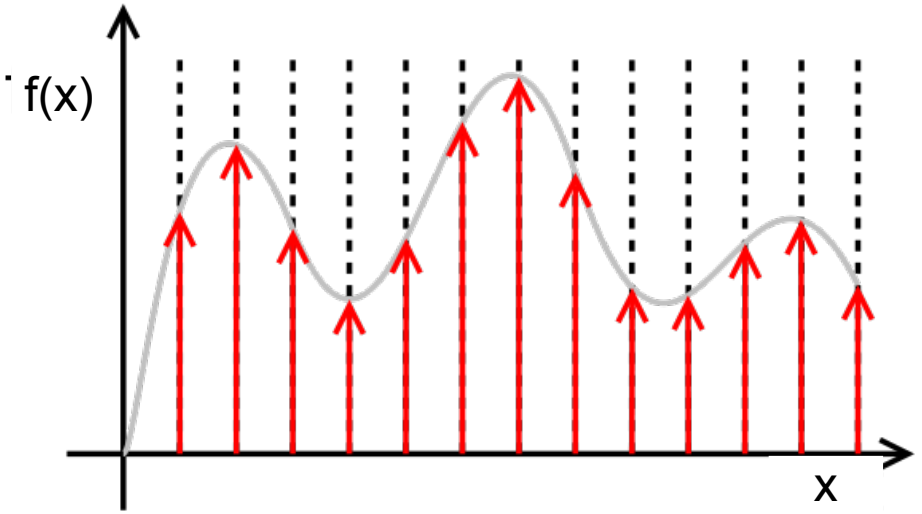
- ...

NOT a box-like image feature

Digitization: sampling + quantization

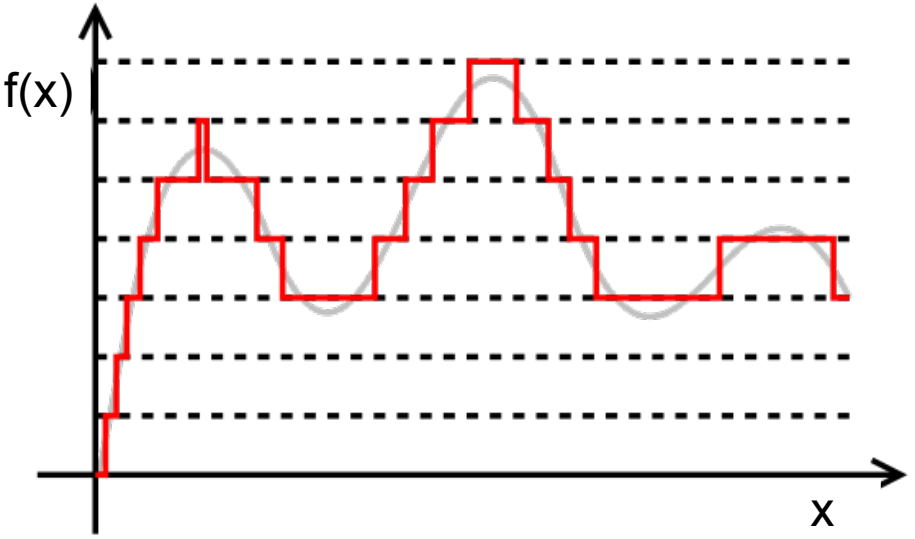
Digitization in space:

sampling



Digitization in 'intensity':

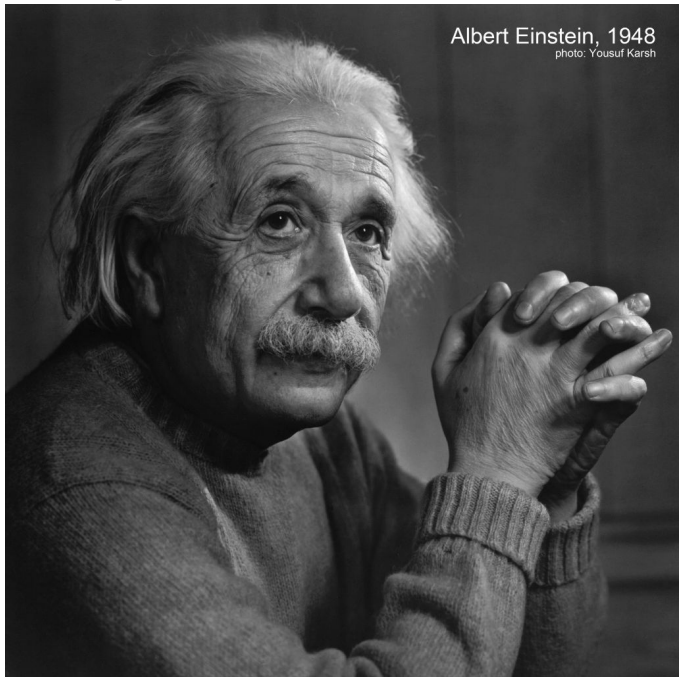
quantization



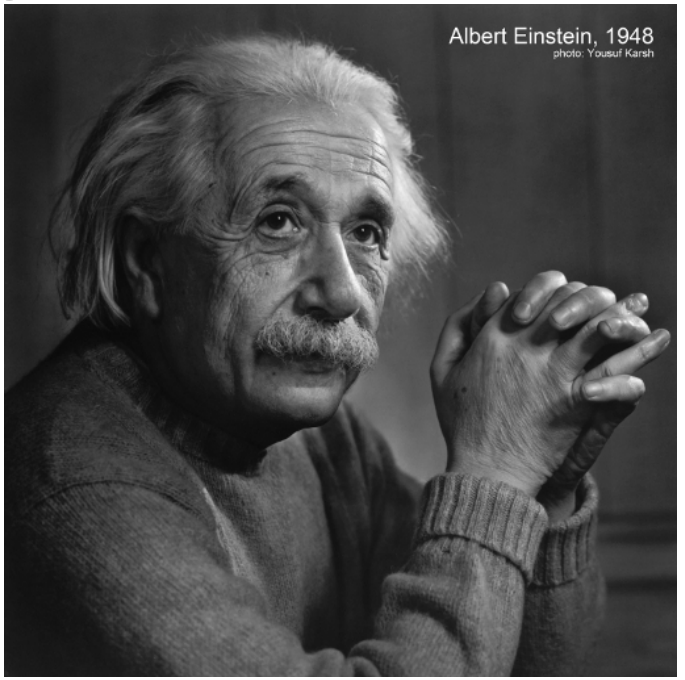
source: http://www.wikipedia.org

Digitization: sampling + quantization

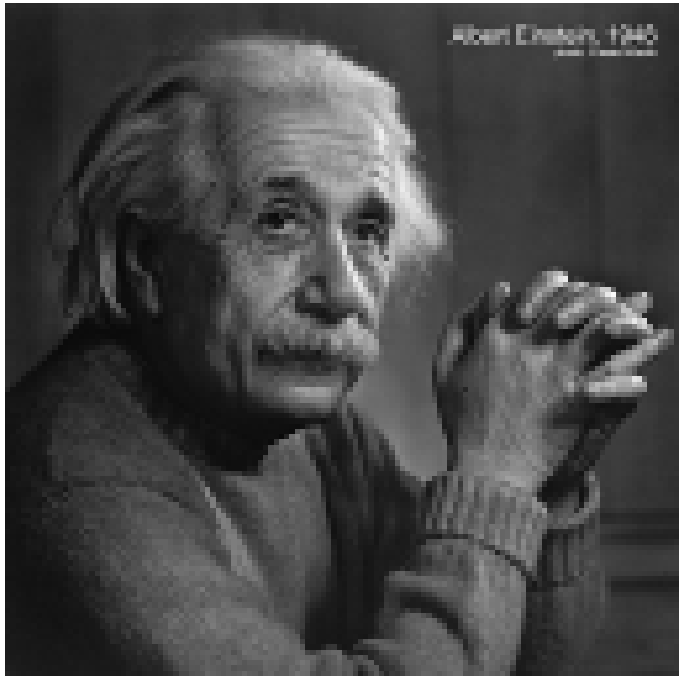
2048 x 2048



256 x 256



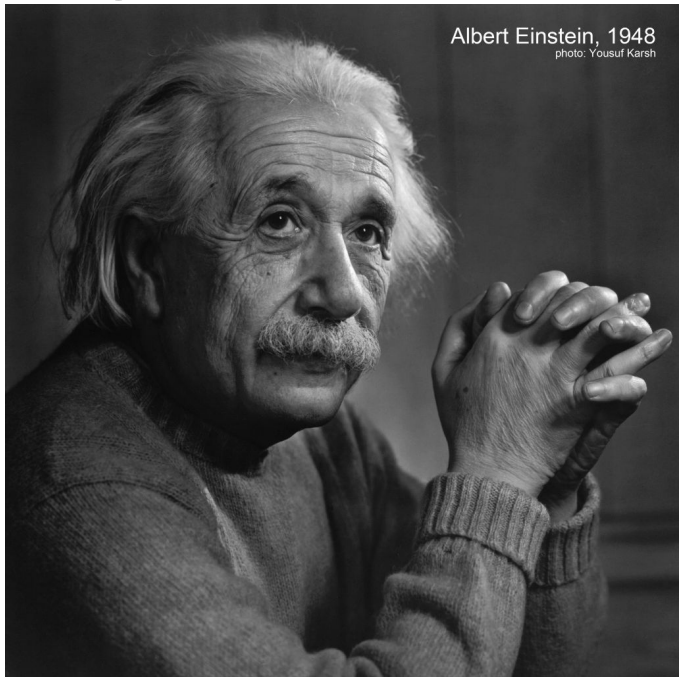
128 x 128



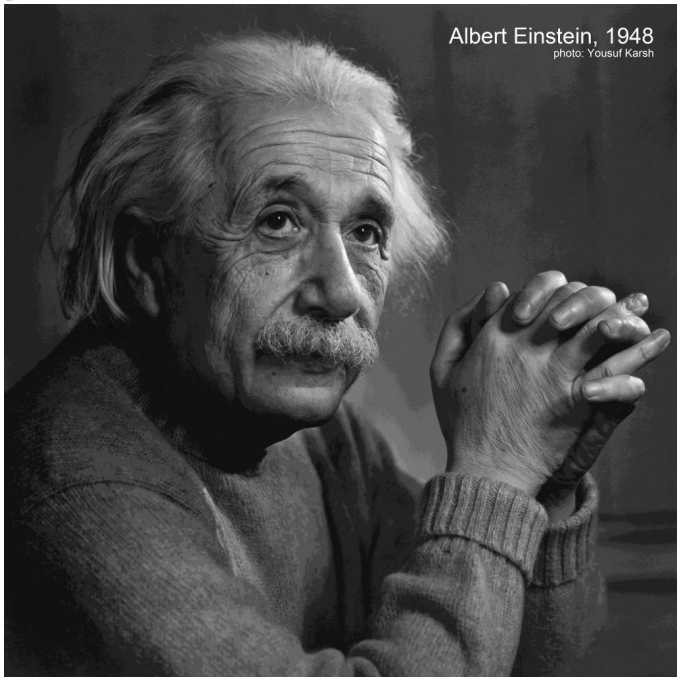
32 x 32

Digitization: sampling + quantization

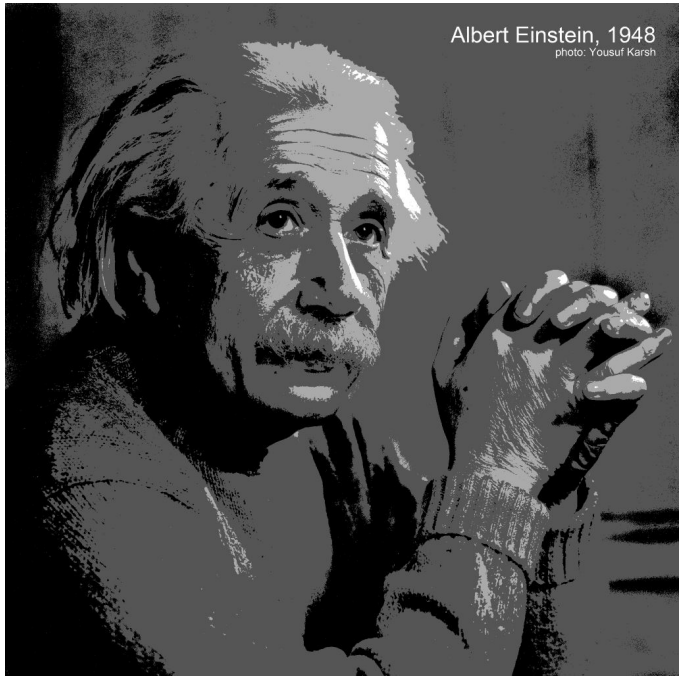
16 bit = 16.777.216 levels



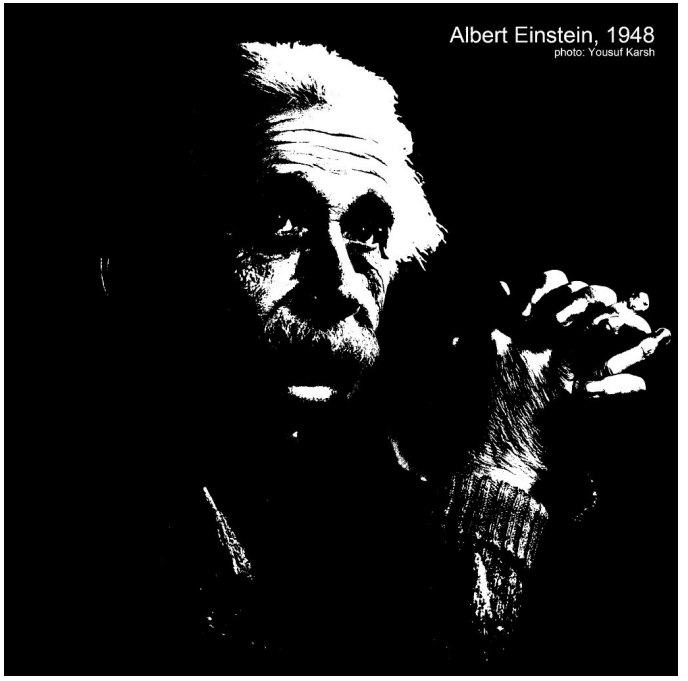
4 bit = 16 levels



2 bit = 4 levels



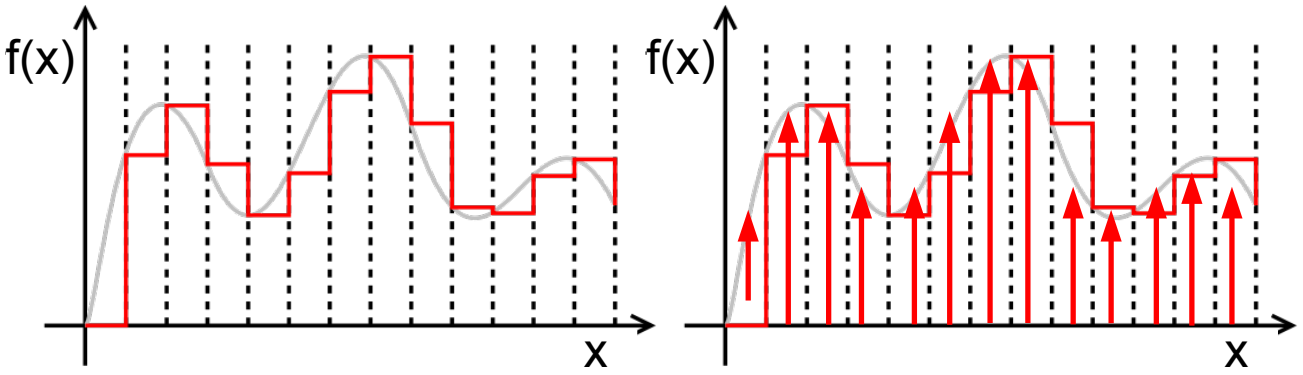
1 bit = 2 levels



Interpolation

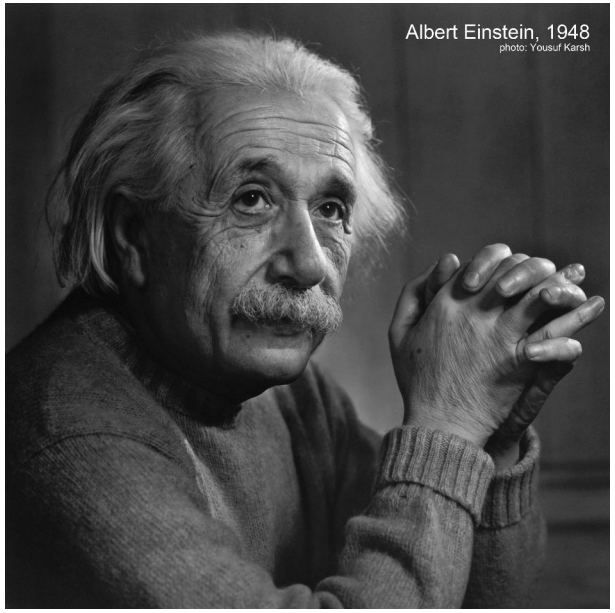
Change sampling

and quantization

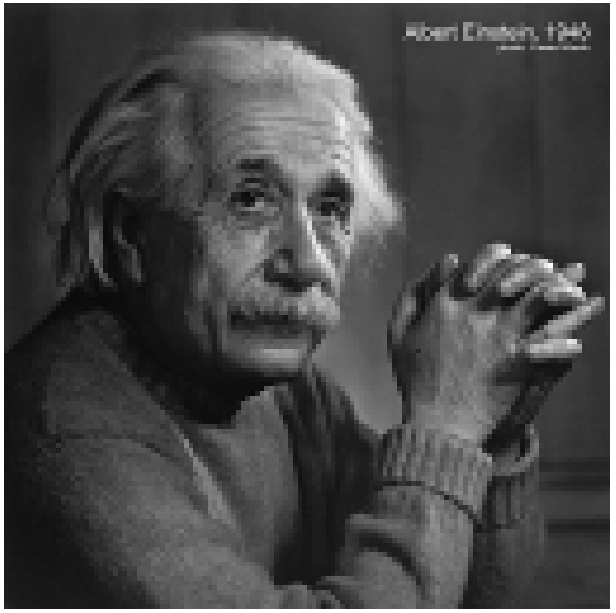


Loss of information (fine details)

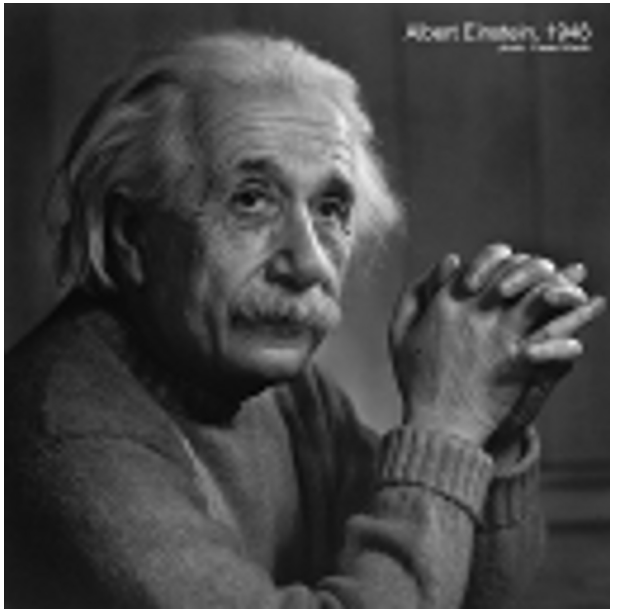
2048 x 2048



128 x 128



2048 x 2048 cubic



Interpolation

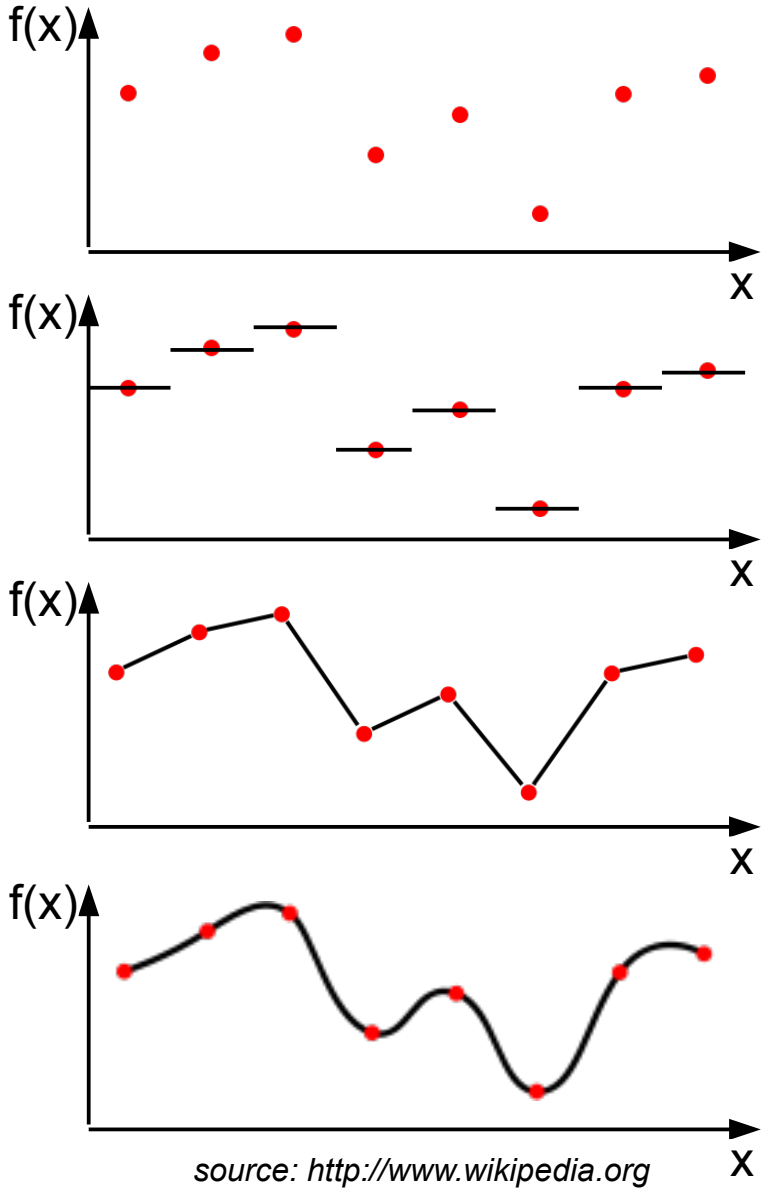
Various interpolation methods available

sampled points

nearest neighbor

linear

spline



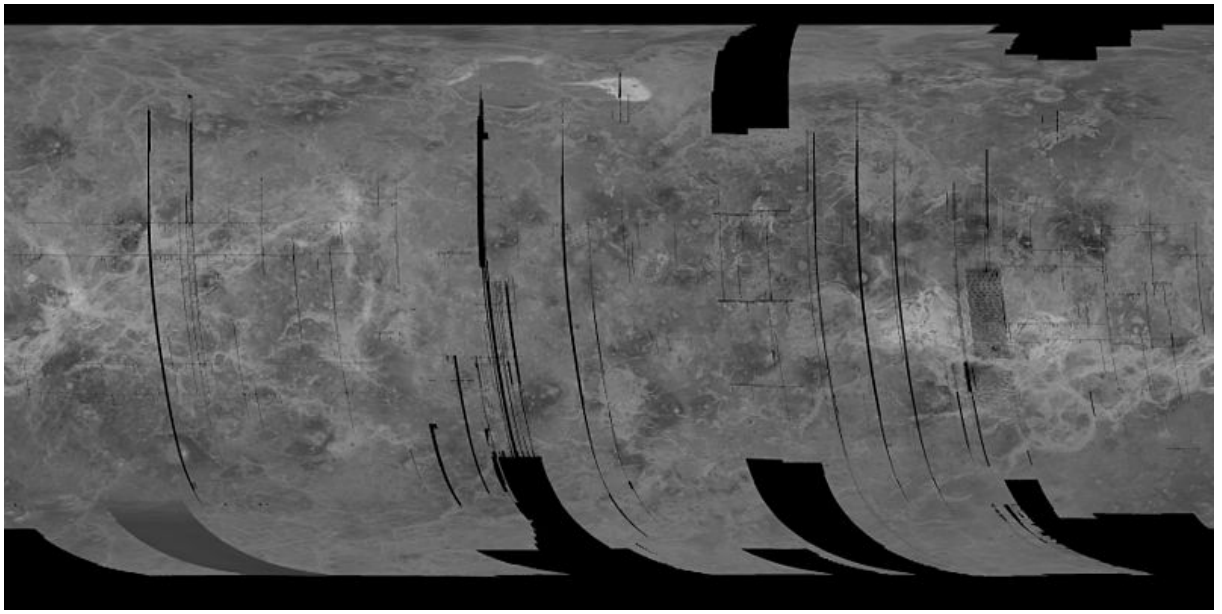
source: http://www.wikipedia.org

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?

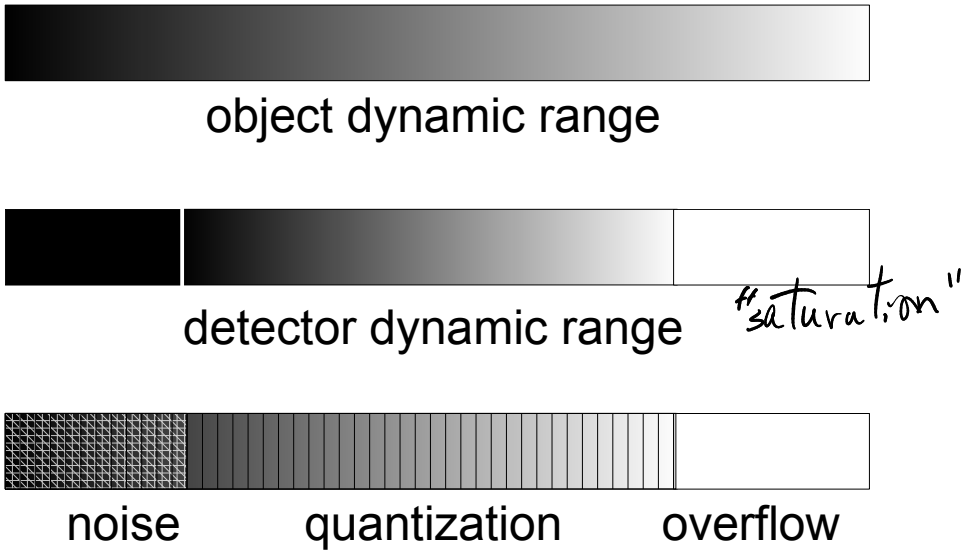
Dynamic range

Quantization restricted to

dynamic range of detector

Loss of information

(low,high intensities)



Long exposure

Short exposure

HDR fused image

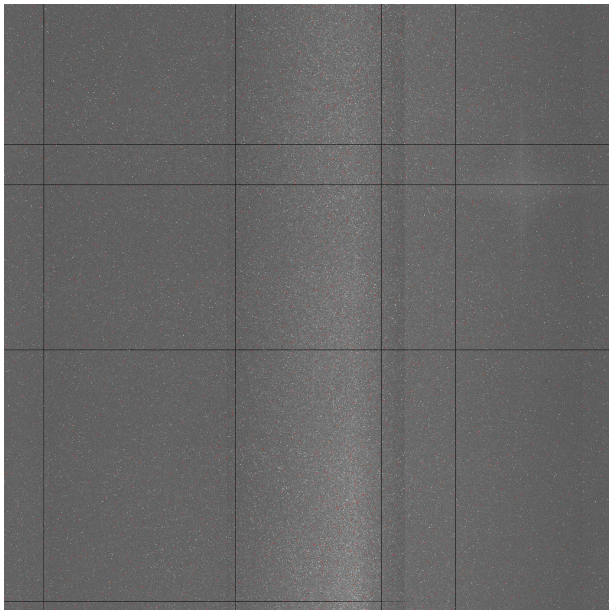
source: http://www.wikipedia.org

Image noise

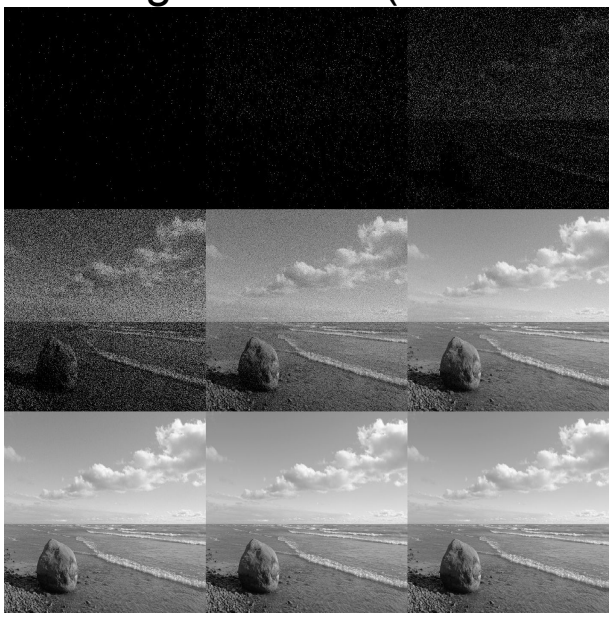
Is (unfortunately) always present

Characterization by source

Detector dark current

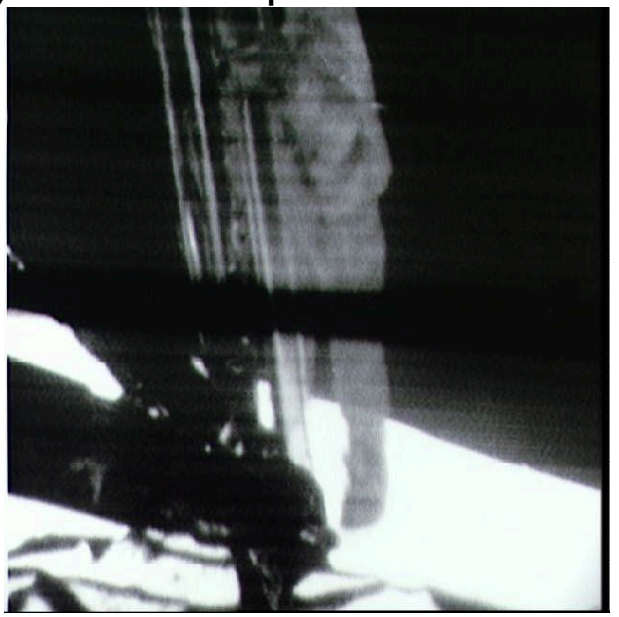


Counting statistics (shot noise)



source: http://wikipedia.org

Acquisition



source: http://nasaimages.org

Image noise

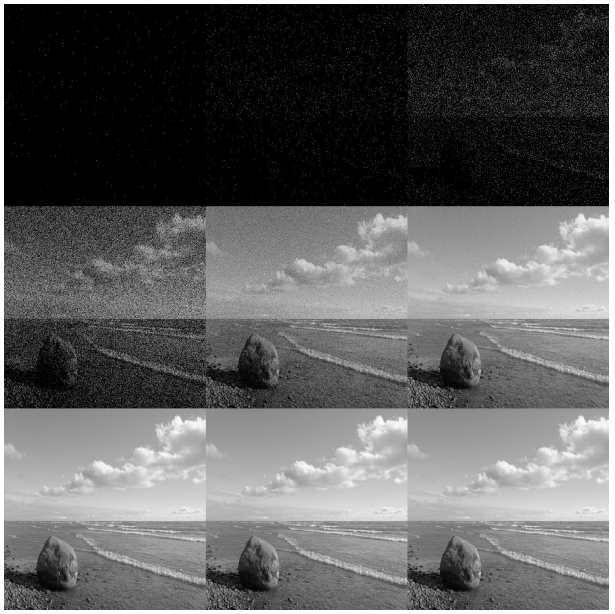
Is (unfortunately) always present

Characterization by source

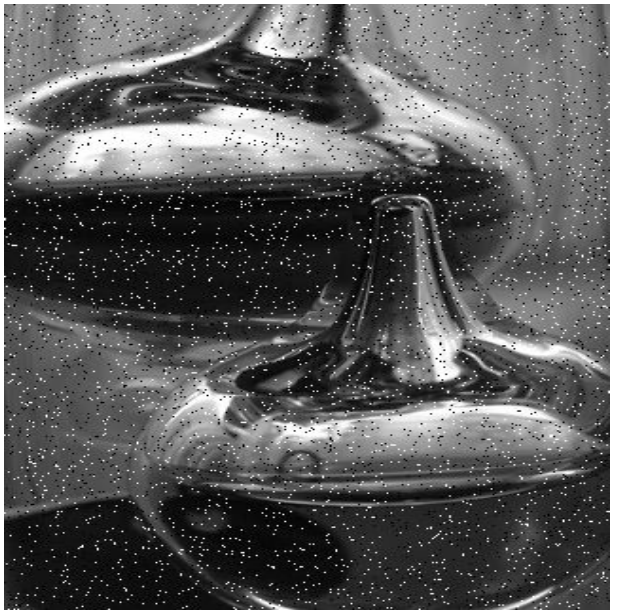
Characterization by density function

Gaussian distribution

Poisson distribution



Fat-tail distributions



source: http://www.wikipedia.org

Image noise

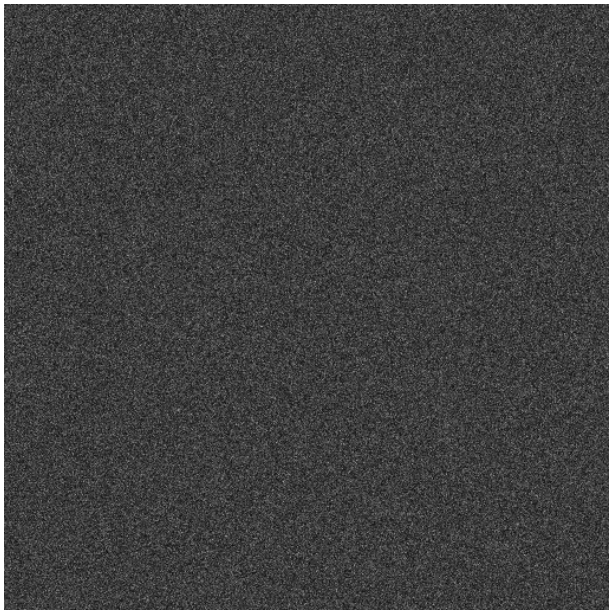
Is (unfortunately) always present

Characterization by source

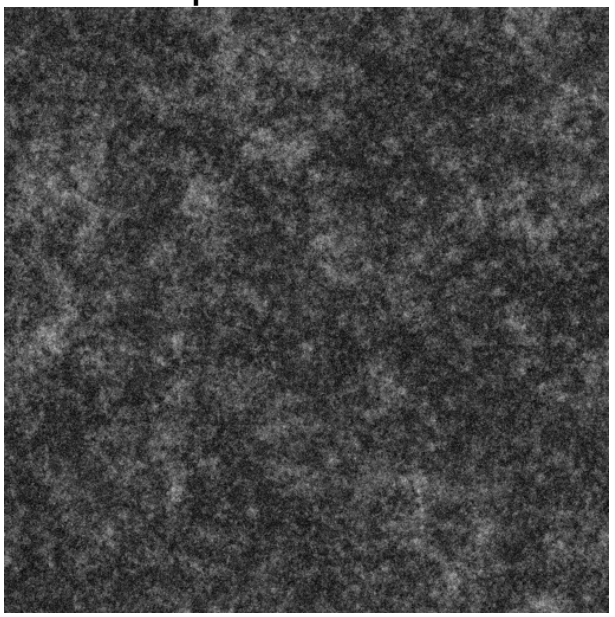
Characterization by density function

Characterization by spatial correlations

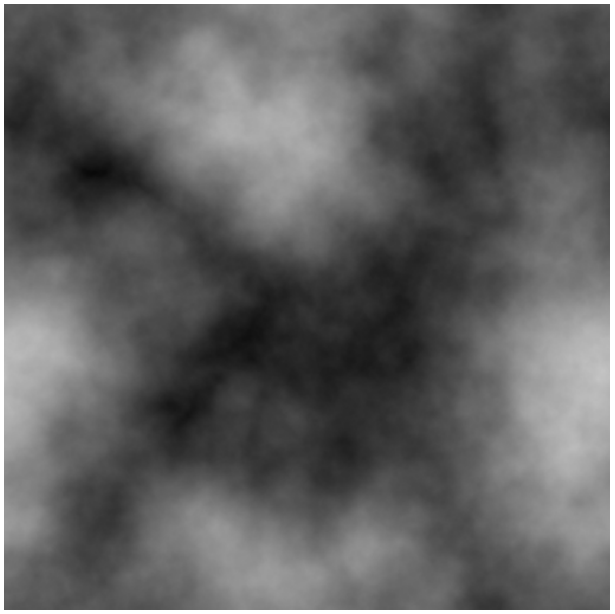
white noise



pink noise



red noise



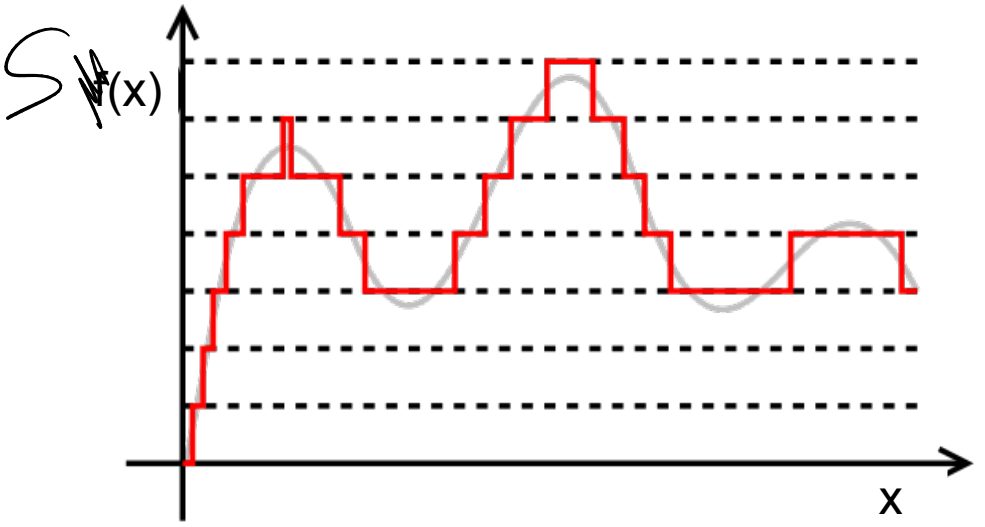
source: http://www.wikipedia.org

Signal and contrast

Signal

"Intensity"

S



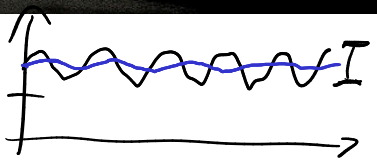
Contrast

$$C = S(x_1) - S(x_2)$$

Visibility

$$\frac{C}{\langle S \rangle}$$

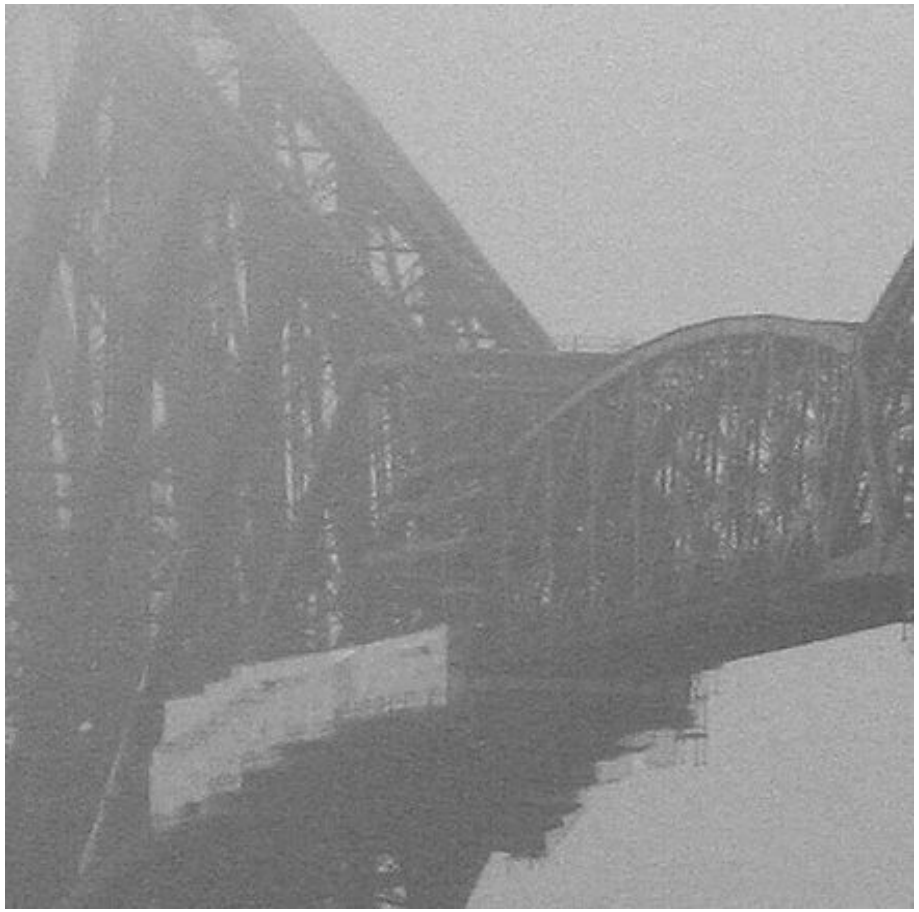
e.g. fringes.



Contrast and noise

- Higher contrast, higher noise
- constant contrast-to-noise

intrinsic to the image



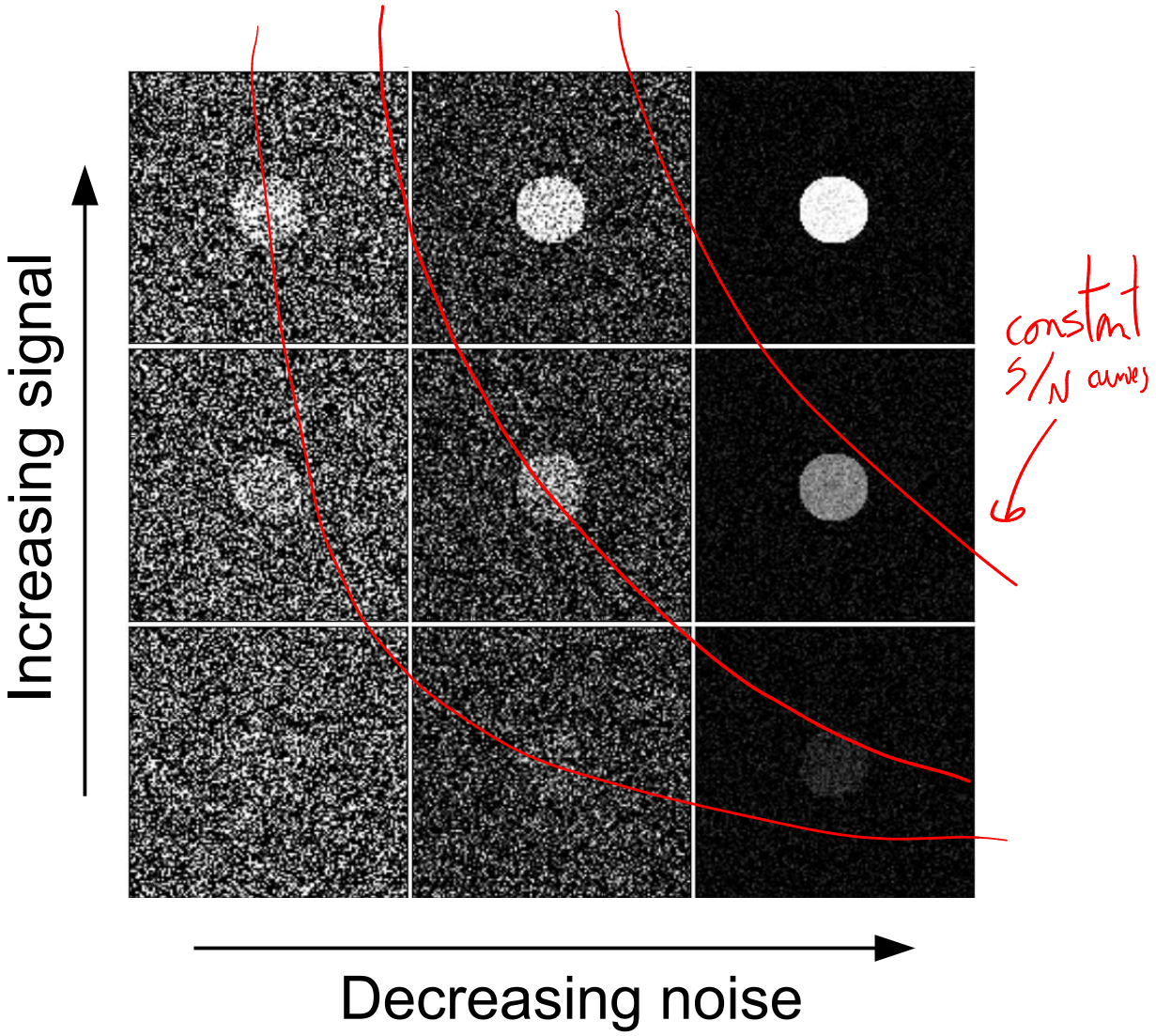
SNR and CNR

Signal-to-noise

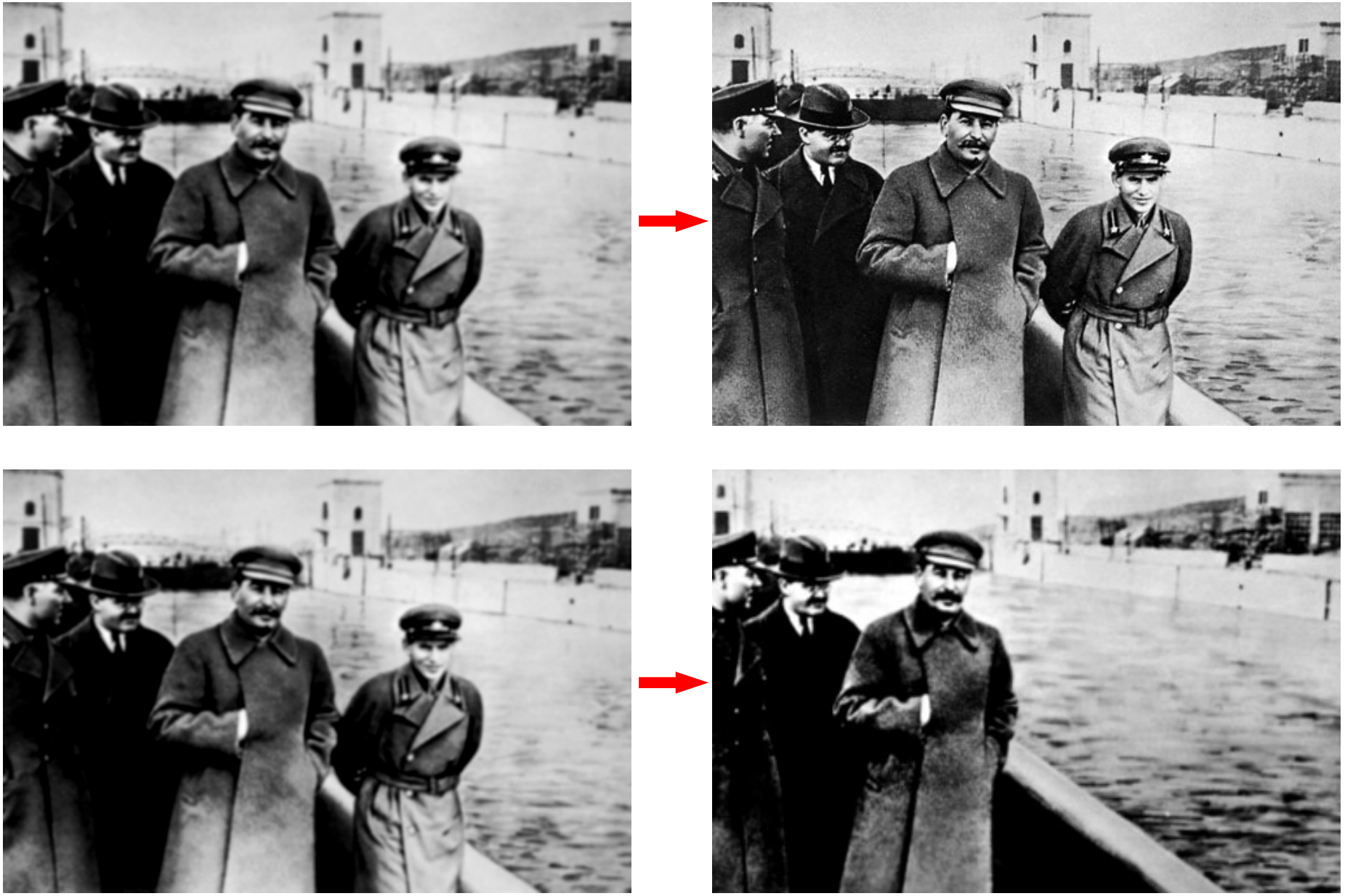
$$\frac{S}{N}$$

Contrast-to-noise

$$\frac{C}{N}$$

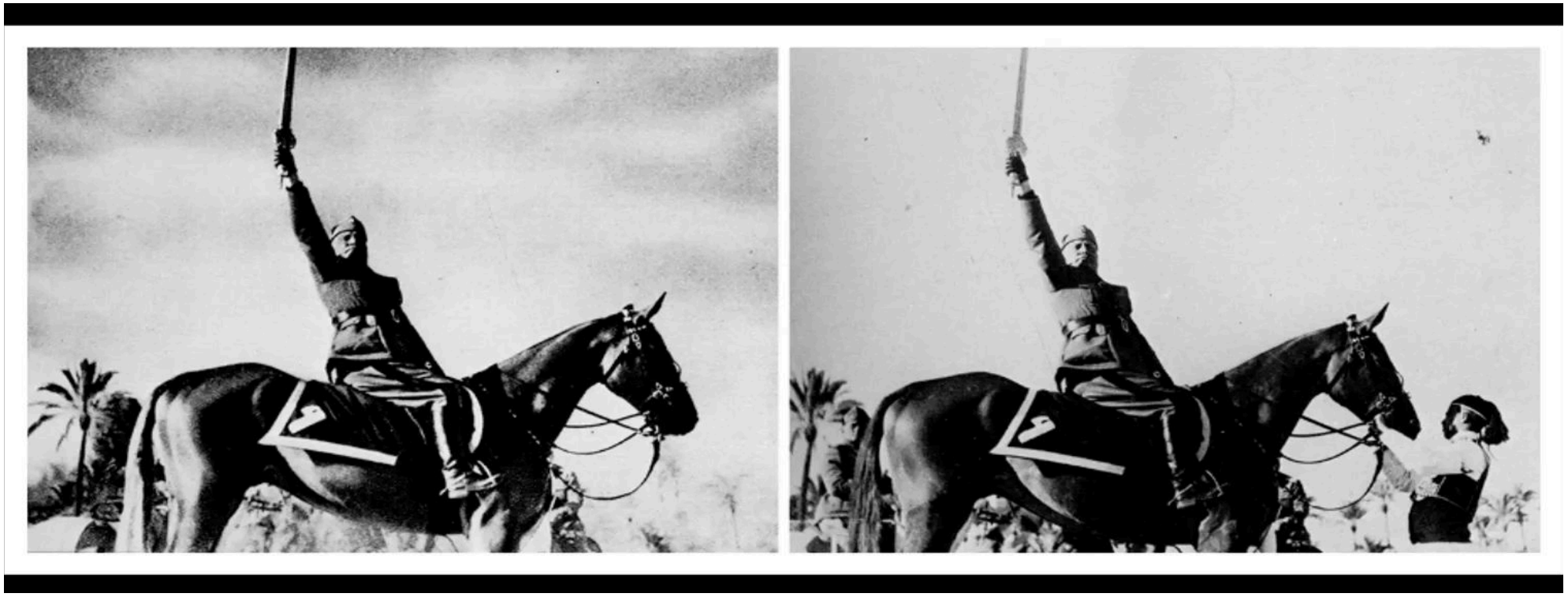


Ethics of image processing



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

Not picture-perfect

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

Researchers 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

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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."

Multichannel images

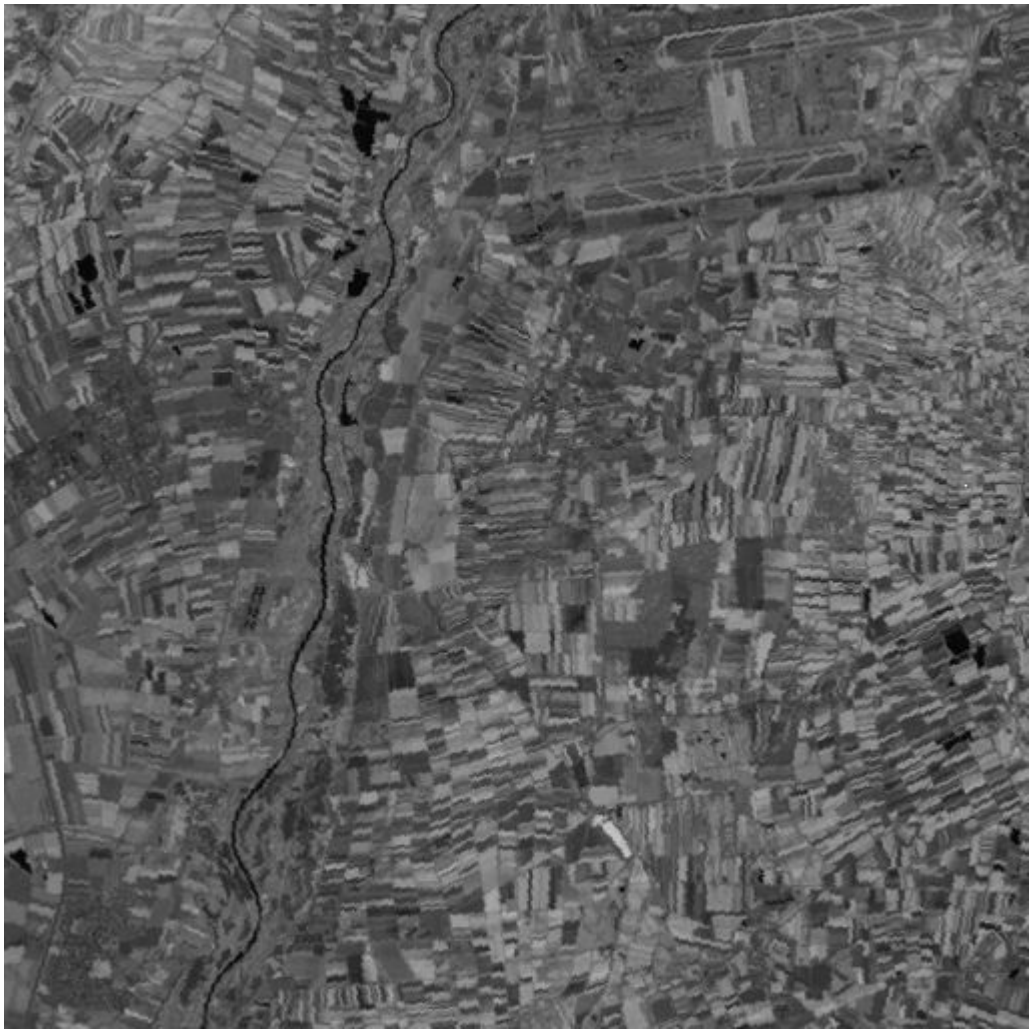
When spatial information is more than a scalar

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

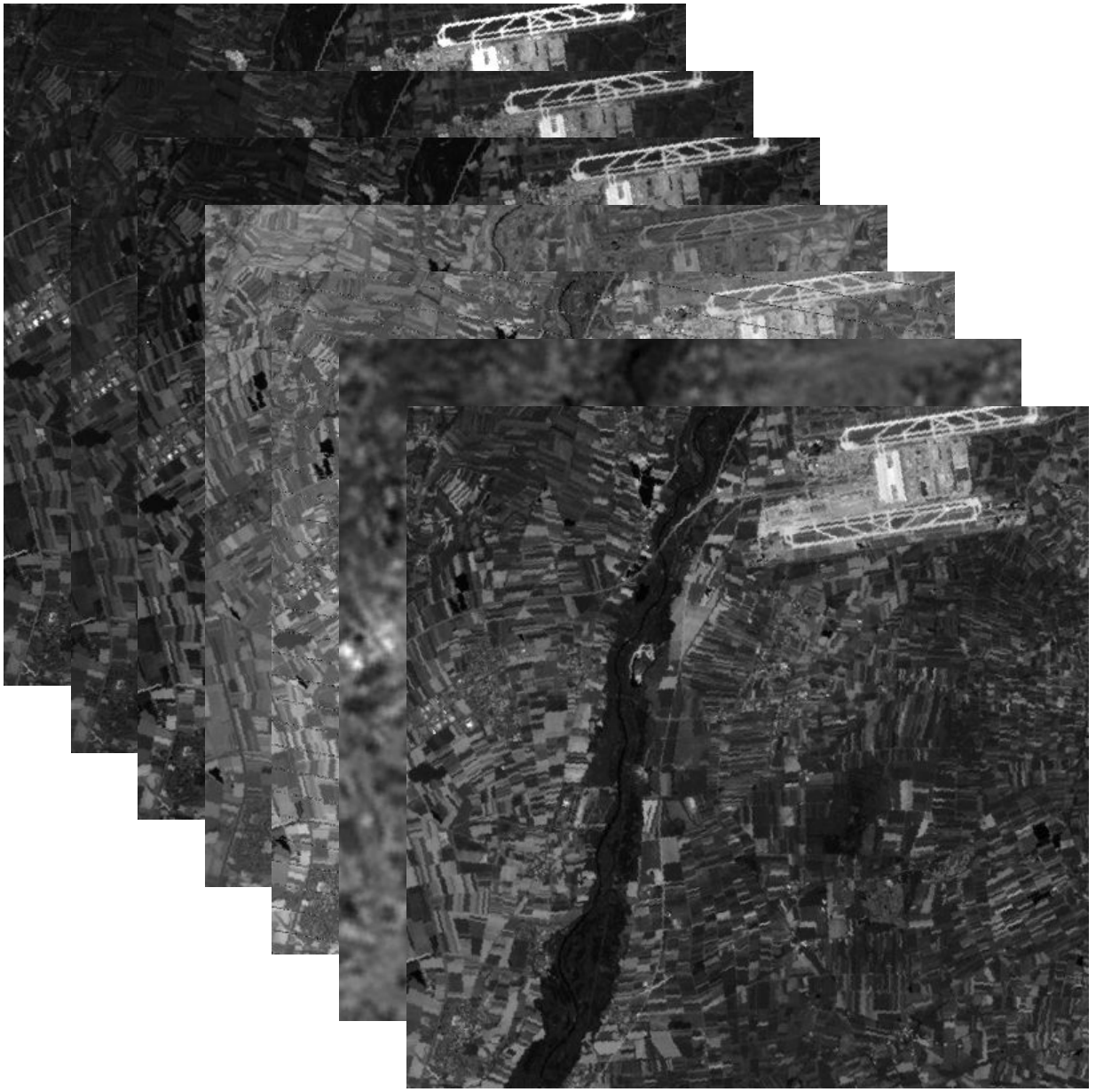
Multichannel images

Multichannel images

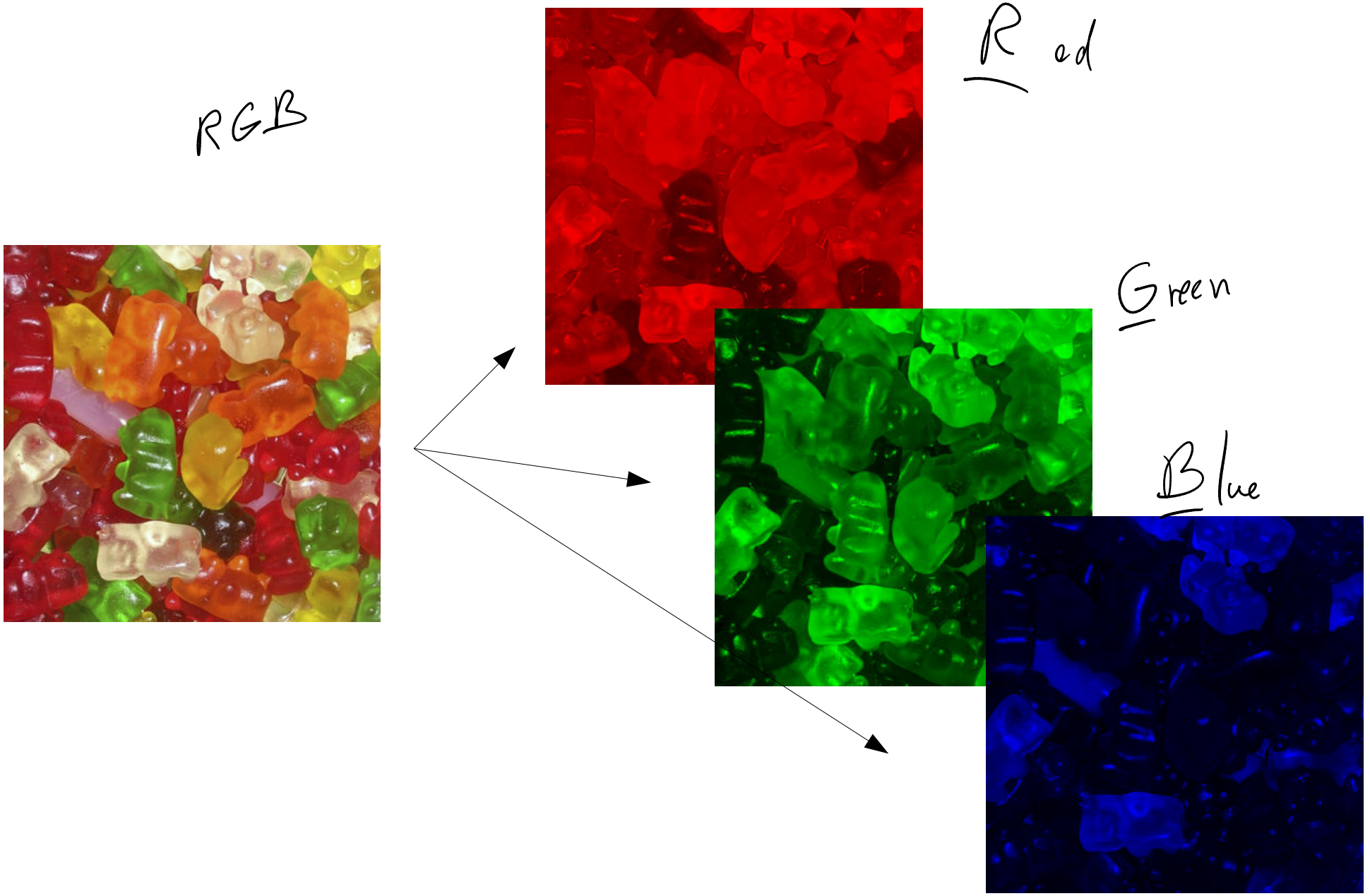
Multichannel images



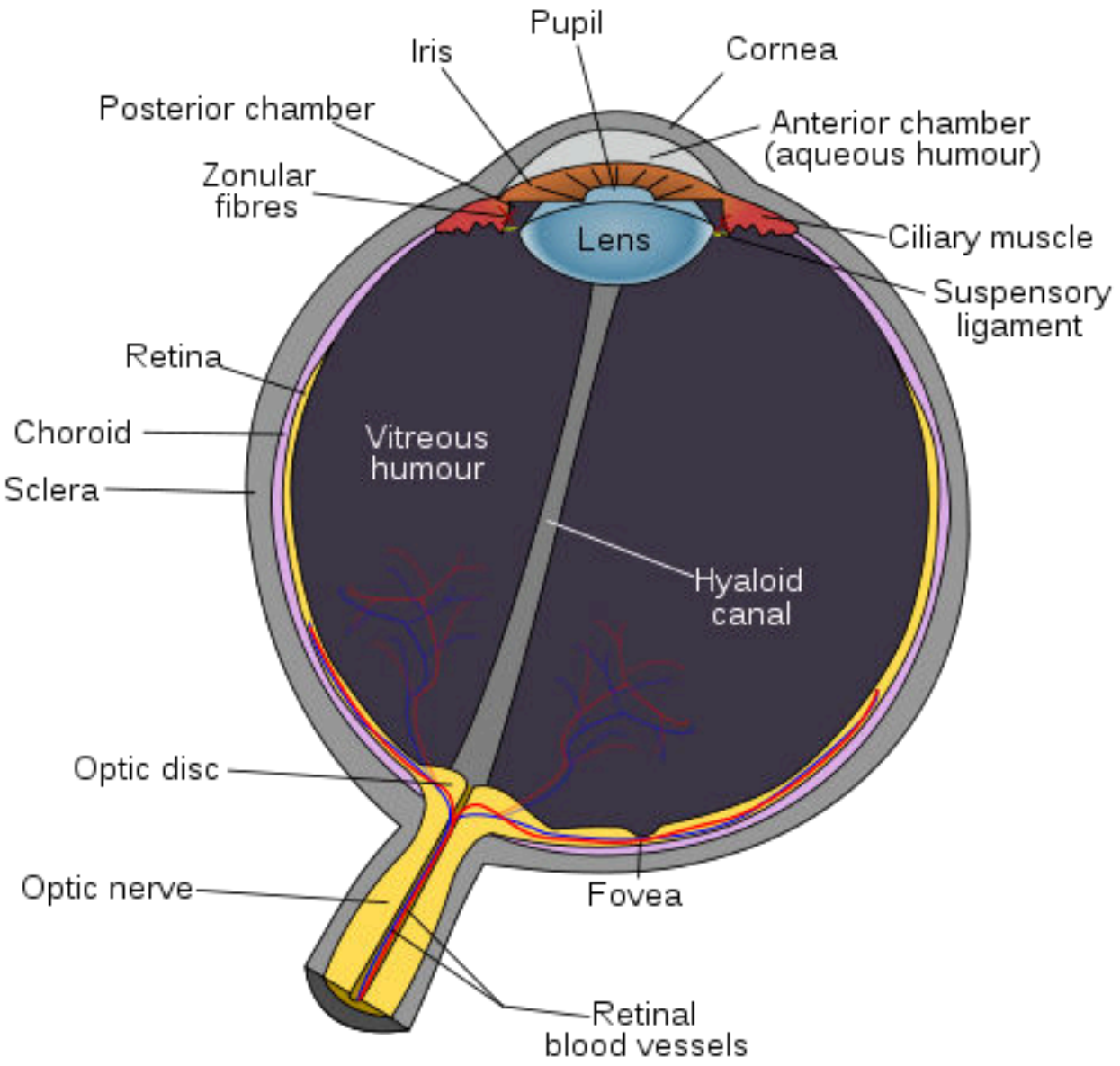
Multichannel images



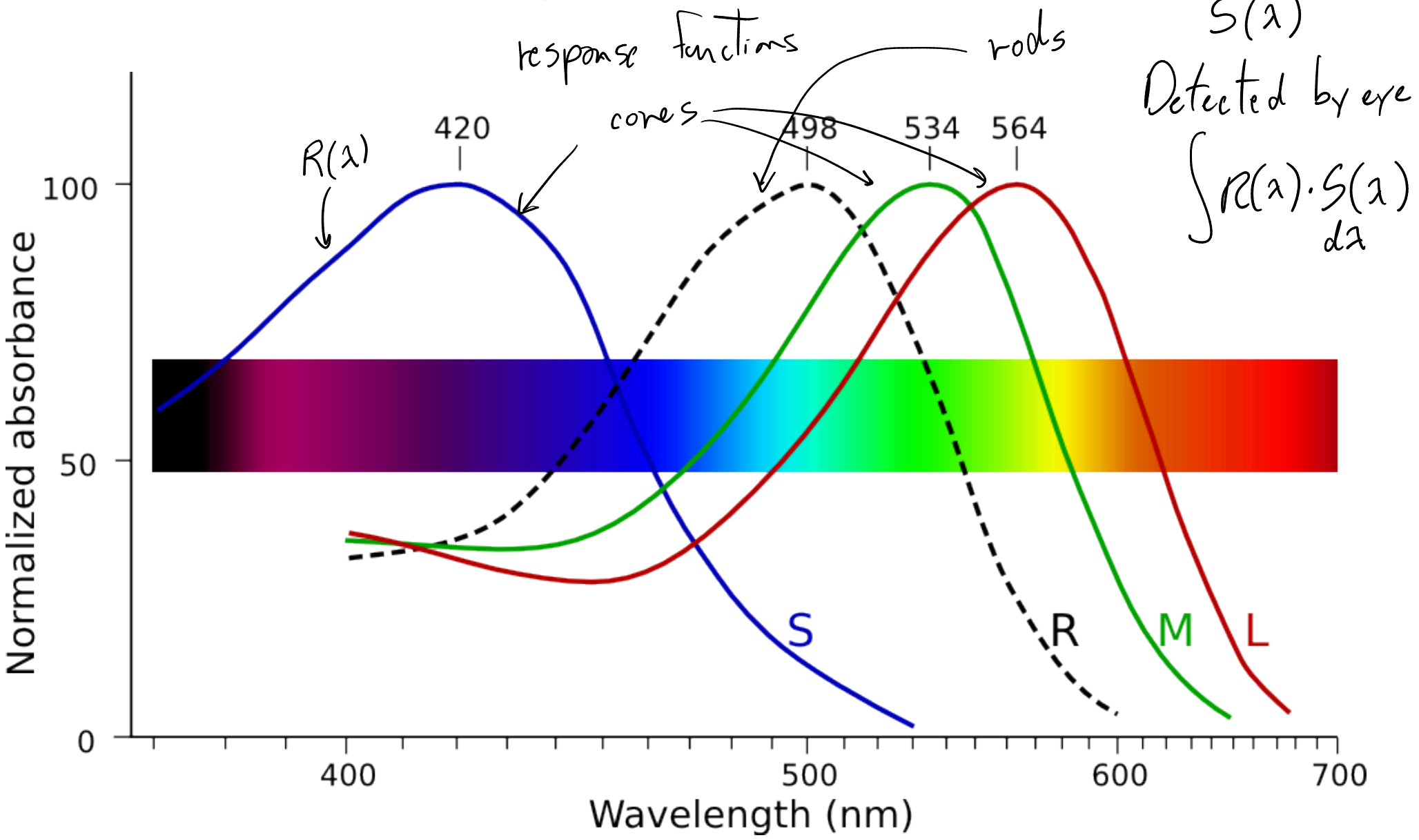
3-channel images



The eye as a light detector



The eye as a detector

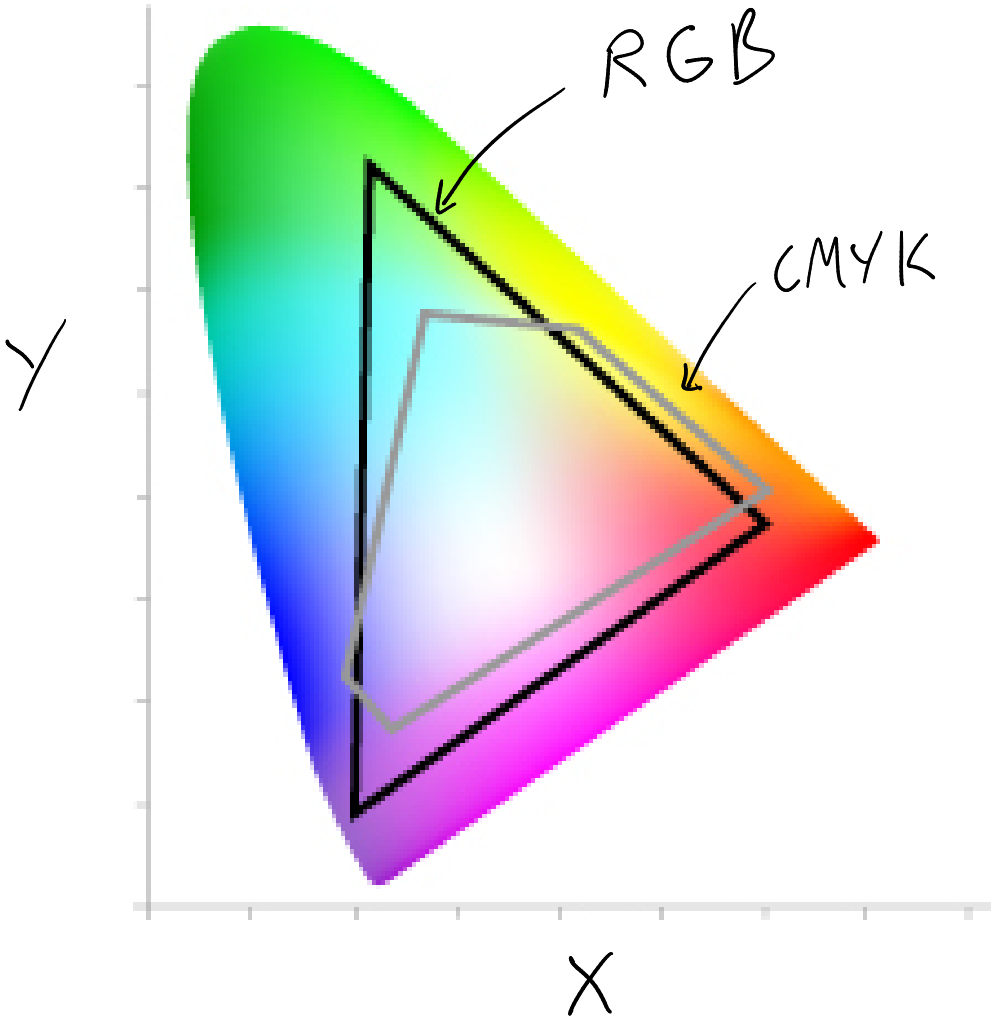


Color spaces

- Real signal : LMS (cone response)
- Standard: CIE XYZ
  - "Commission Internationale de l'éclairage"
  - XYZ : just a linear transform from LMS
- Most displays: RGB
  - Again, just a linear transform from XYZ
- Most printed support: CMYK
  - Go to 4 colors to save ink (maximize black)

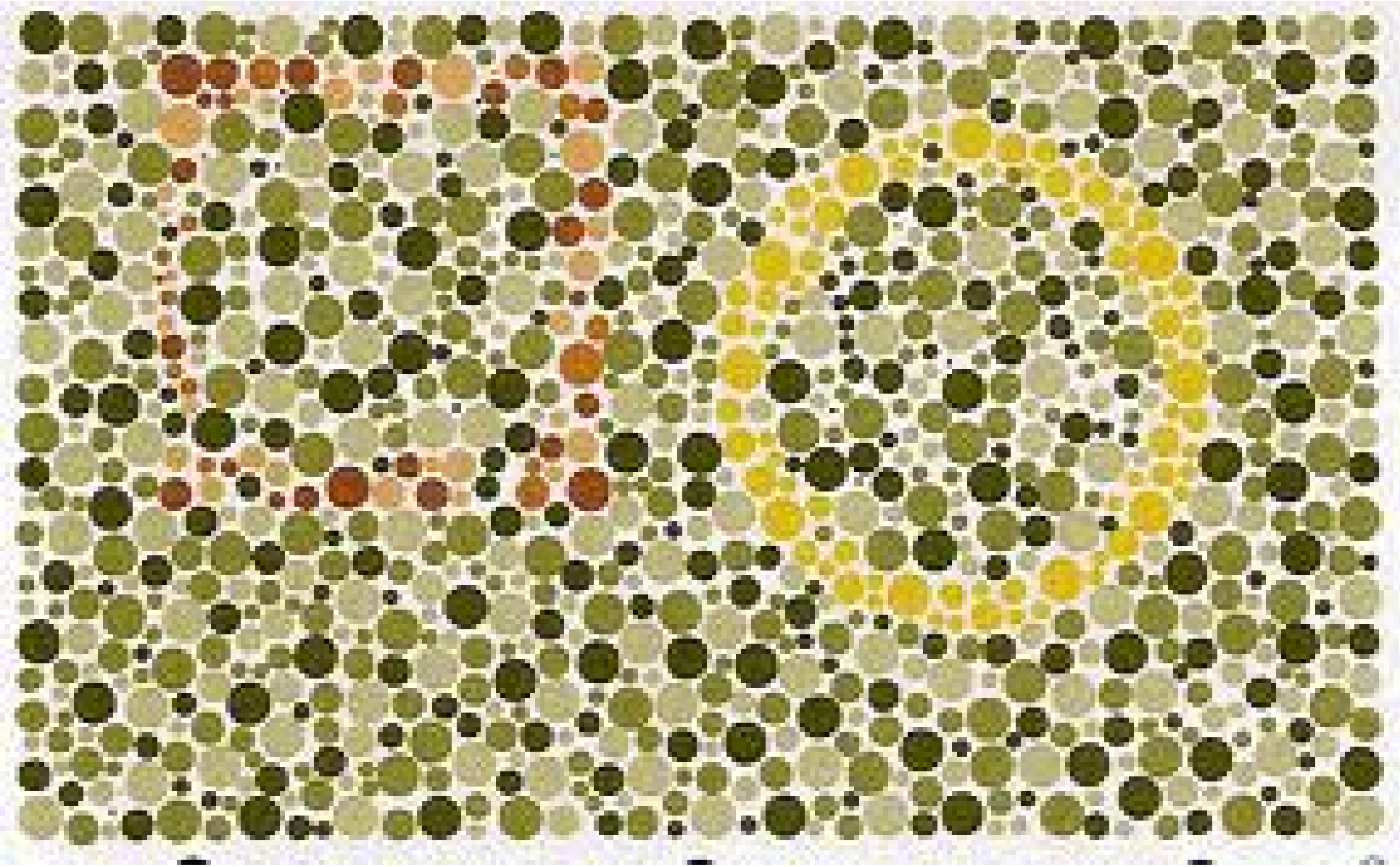
Color spaces

Gamut



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

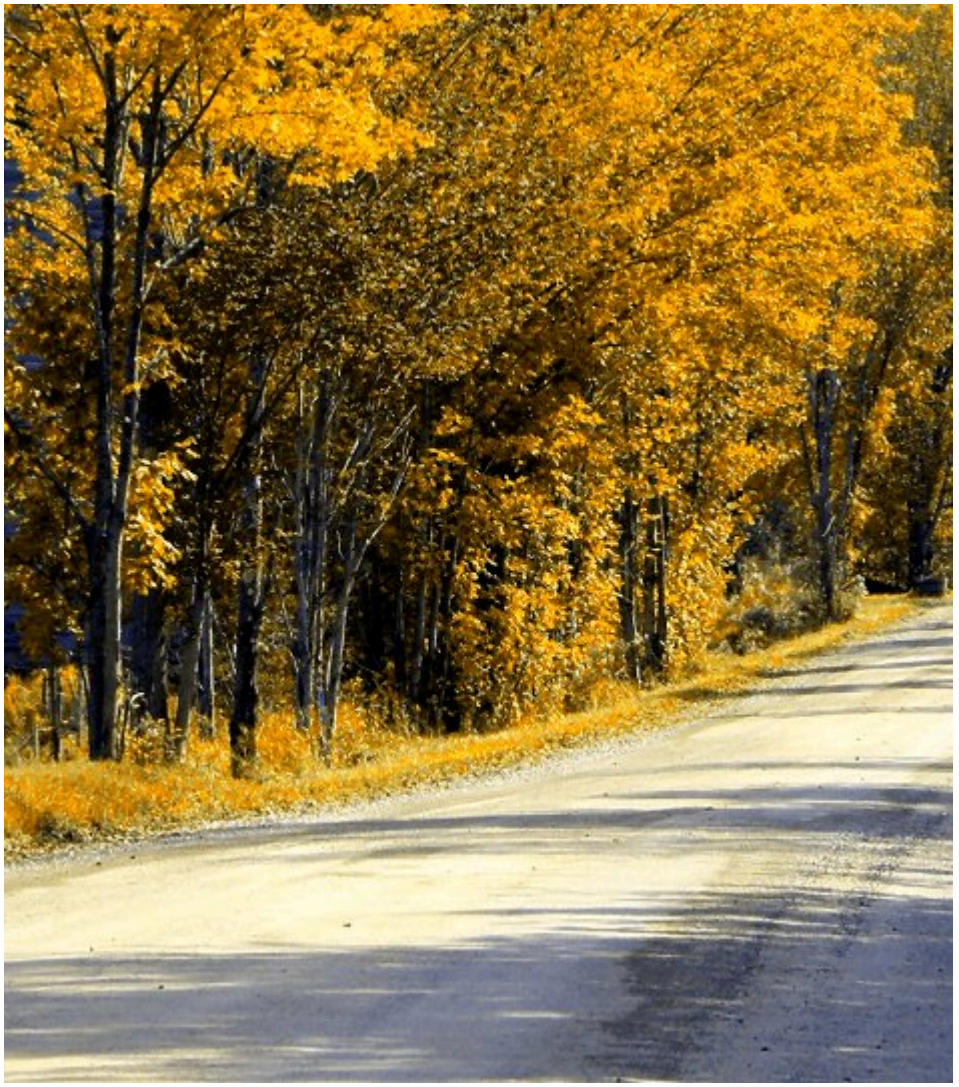
Color vision deficiencies



Color vision deficiencies

Normal vision

Deuteranopia (insensitivity to green)



The human eye

The good

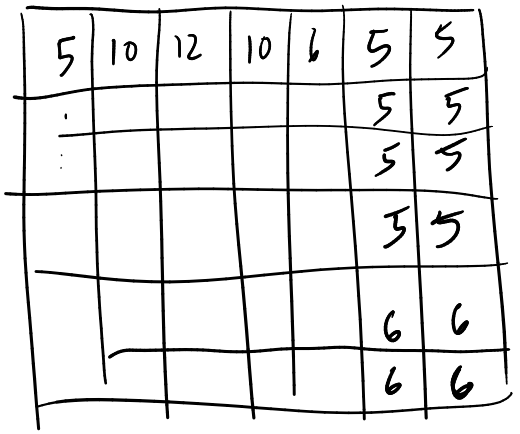
- Good spatial resolution (< 1mm)
- Very large dynamic range ($> 10^6$) and automatic threshold
- Energy discrimination (colors)
- Long life-time, energy efficient, low carbon footprint

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 (matlab, hdf5, ...)



hierarchical data format