Elaborazione di segnali e immagini per bioinformatica

Alessandro Daducci

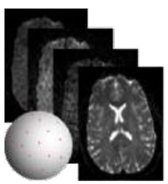
About me

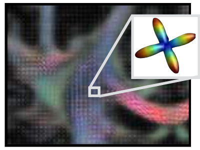
Background

- M.Sc. in *Computer Science* (Verona)
- Ph.D. in *Multimodal imaging in medicine* (Verona)
- Post-doc (EPFL, Switzerland + Sherbrooke, Canada)
- Assistant professor (Verona)

Research interests

- Diffusion MRI acquisition and reconstruction
- Fiber-tracking using convex optimization
- Applications to clinical studies





Contact

- *alessandro.daducci@univr.it*
- Office hours: enquiry by email

About the course

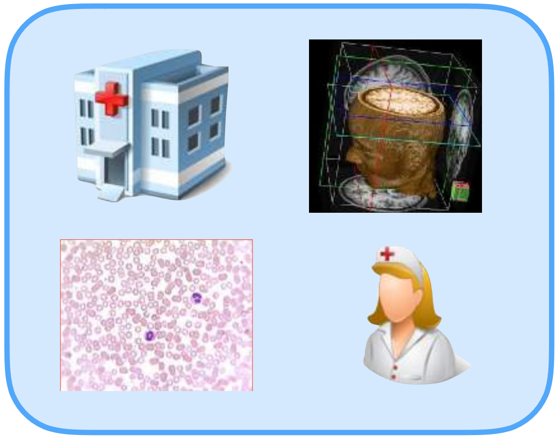


Image **Processing** **(for bioinformatics)**

About the course (2/3)

Modules

- Introduction and basic concepts
  - What is a digital image and how we can “process” it
- Image enhancement and restoration
  - How to improve the quality of an image
- Detecting simple curves
  - How to detect simple objects in an image, e.g. a line
- Image segmentation and registration
  - How to partition an image into different regions, e.g. background vs foreground
  - How to align different images
- Image compression
  - e.g. algorithms behind GIF, PNG, JPEG file formats

Laboratory

- *Hands-on sessions* to play with the tools we see in the theory sessions
- *Use* state-of-the-art software
- *Implement* some of these algorithms (in MATLAB)

About the course (3/3)

Exam

- Practical exercises in the lab
- Written test about the course topics

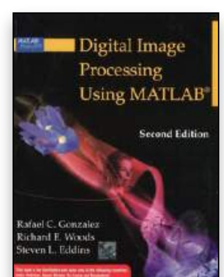
Classes schedule

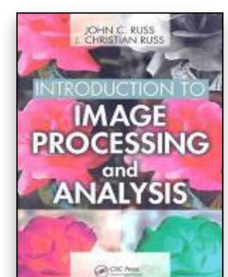
- Breaks?
- Public holidays?
- Theory and lab sessions

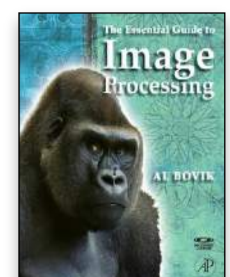
Tuesday	10:30 - 12:30	Lecture	Aula E
Wednesday	10:30 - 13:30	Hands-on session	Lab Delta
Thursday	10:30 - 12:30	Lecture	Aula C

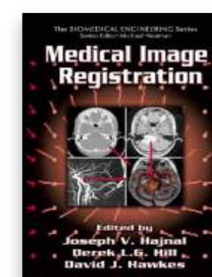
Credits (sources of inspiration for this course)

- Reference books





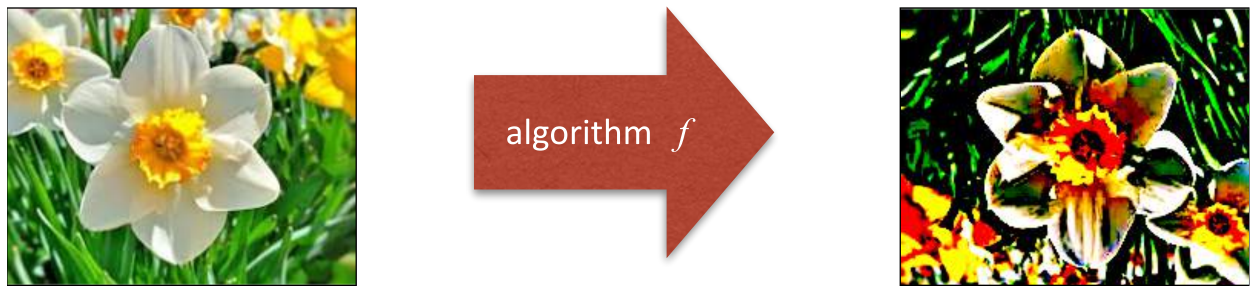




- Courses
  - **Prof. Tom Fletcher** - University of Utah, USA
- Other
  - Google images, Wikipedia and many other websites

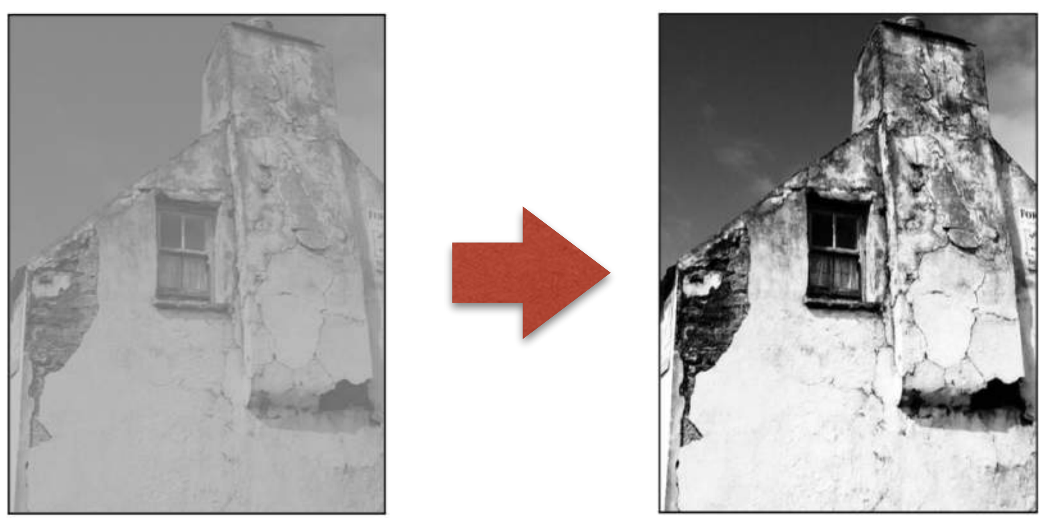
What is image processing?

- Image processing is the study of any algorithm that takes an **image as input** and returns an **image as output**



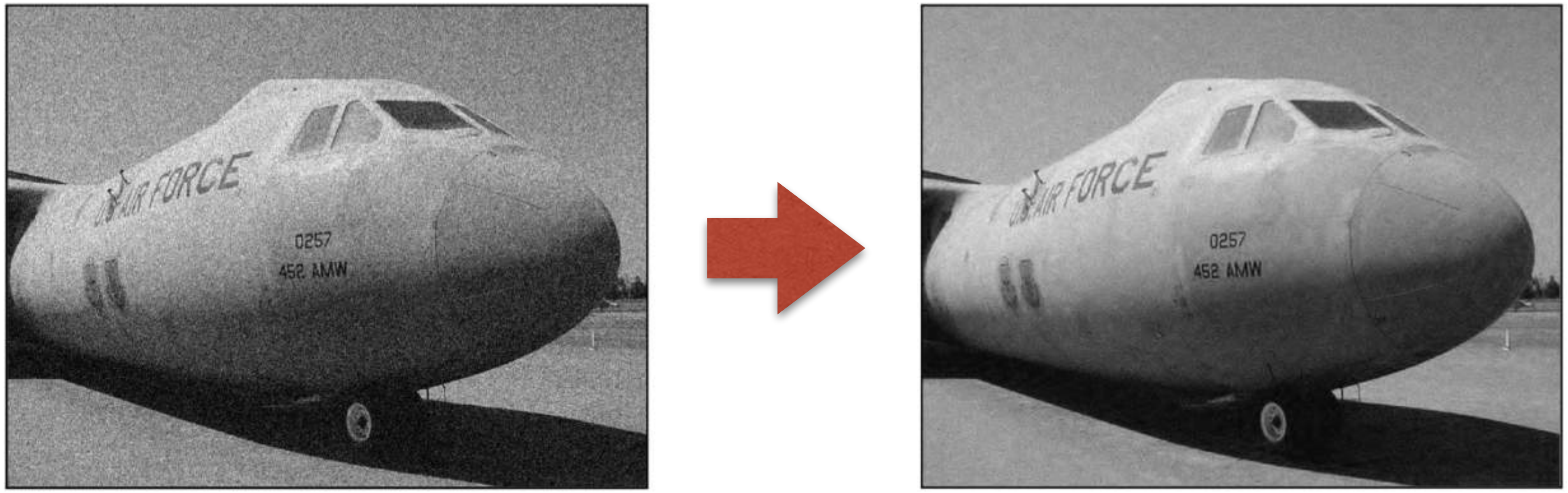
I $\qquad$ $J = f(I)$

- Example: **enhancement**

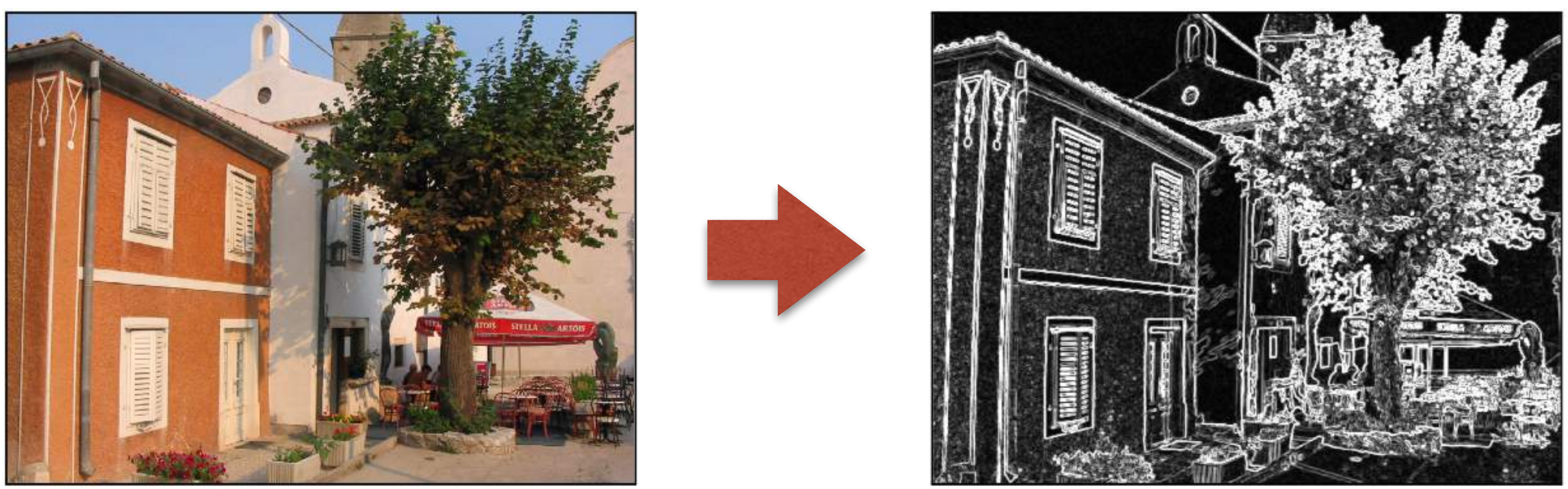


Input image : I $\qquad$ Output image : J

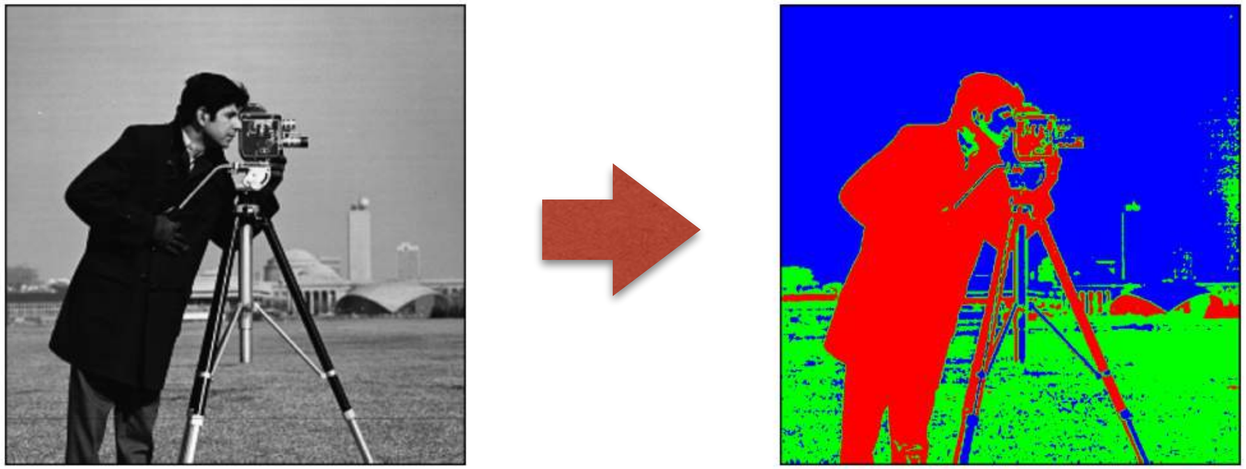
- Example: **noise removal**



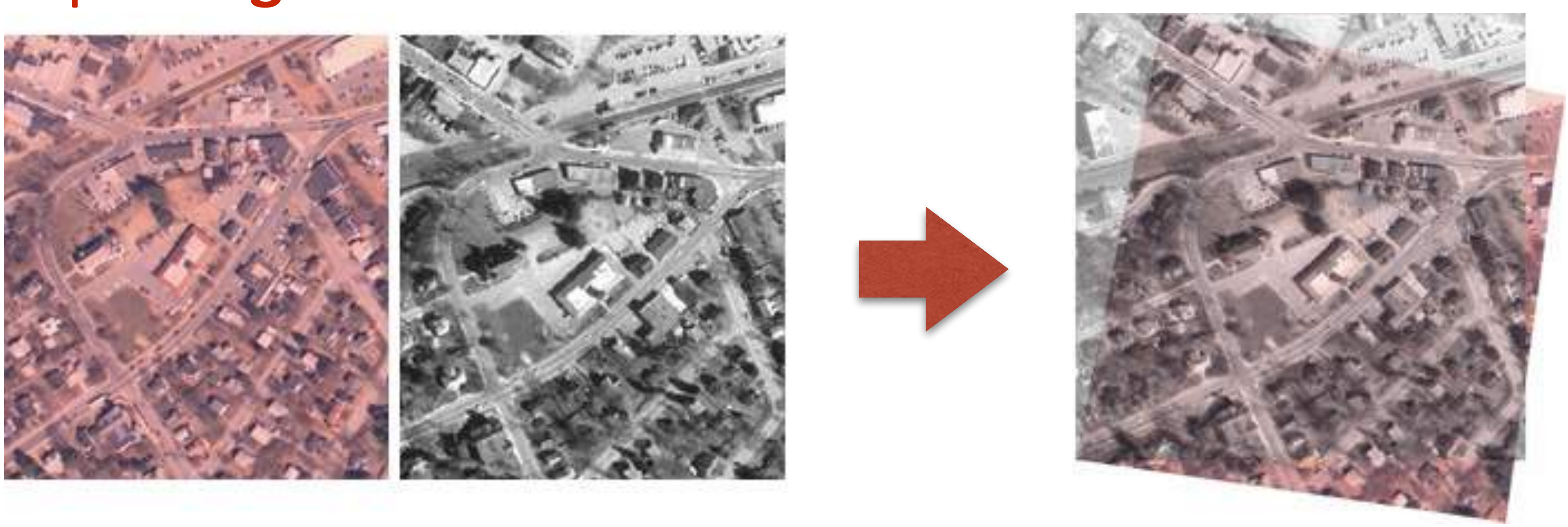
- Example: **feature detection**



- Example: **segmentation**



- Example: **registration**



- Example: **restoration**

Damaged

Restored

- Example: **compression**

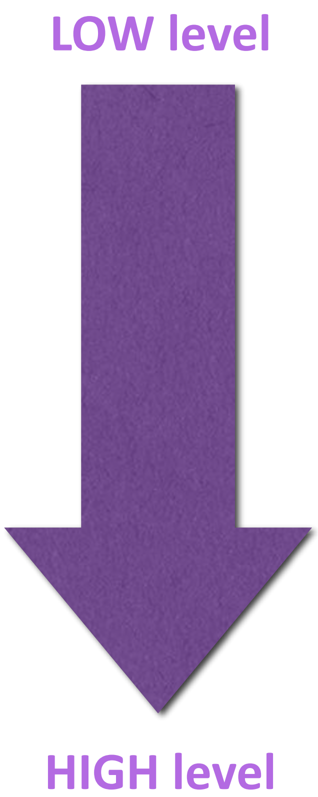
Original (1.9MB)

Compressed (230 KB, 12%)

Compressed (126 KB, 7%)

Relationship to other fields

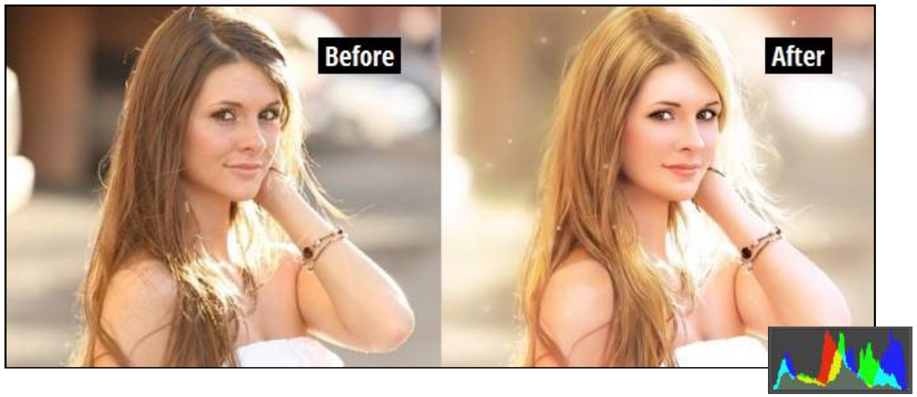
- **Image Processing**
  - Image enhancement, noise removal, feature detection …
- **Image Analysis**
  - Segmentation, image registration, matching …
  - Extract information, make a medical diagnosis …
- **Computer Vision**
  - Object detection/recognition, shape analysis, tracking
  - Use of Artificial Intelligence and Machine Learning

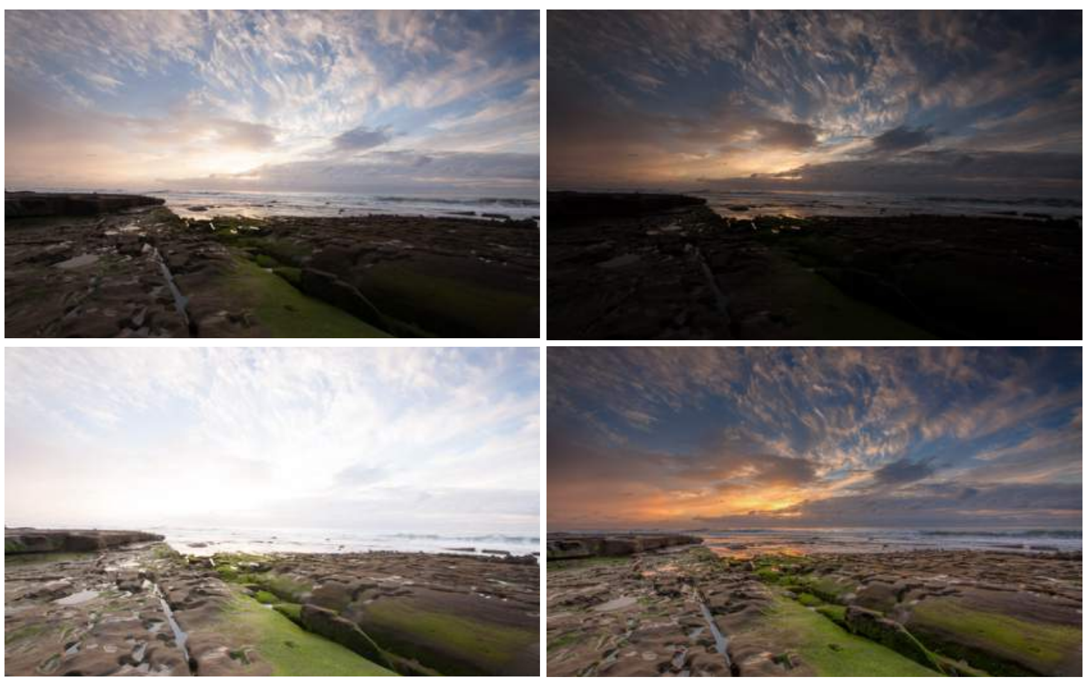


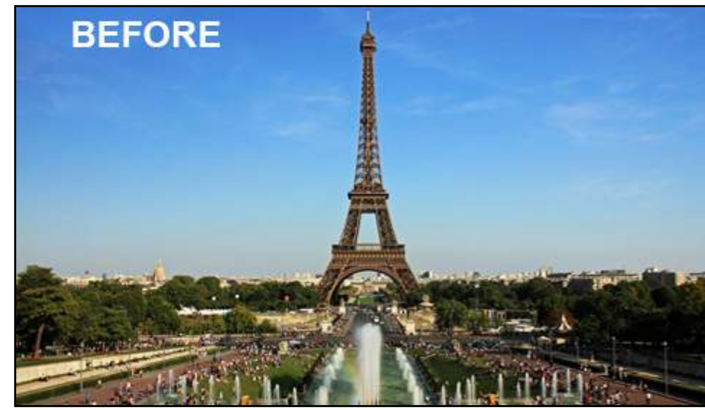
- **NB: Computer Graphics**
  - Deals with the **synthesis and visualization of images** from a model/representation

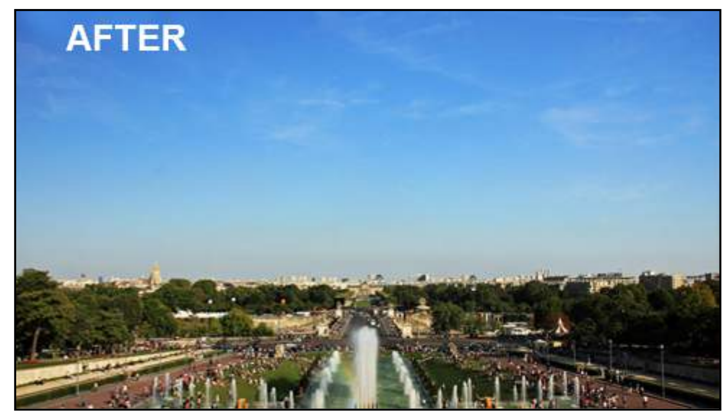
Applications of image processing (1/3)

Photography



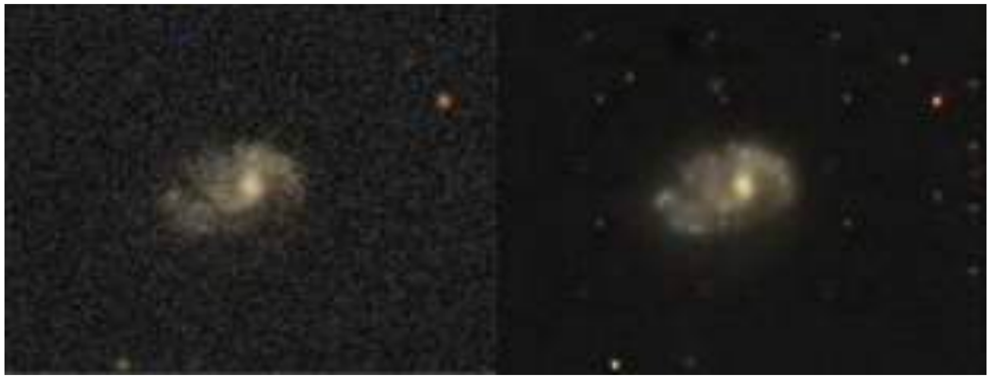


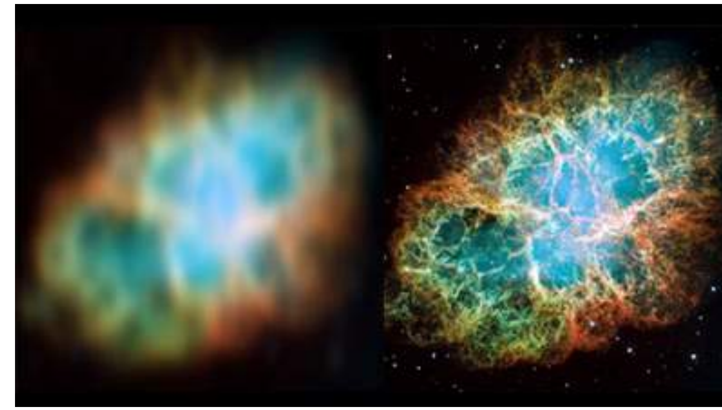




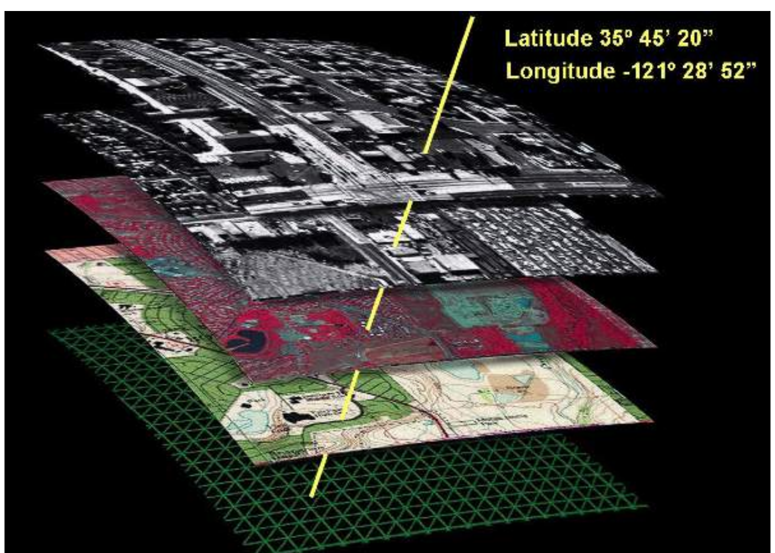
Applications of image processing (2/3)

- Astronomy



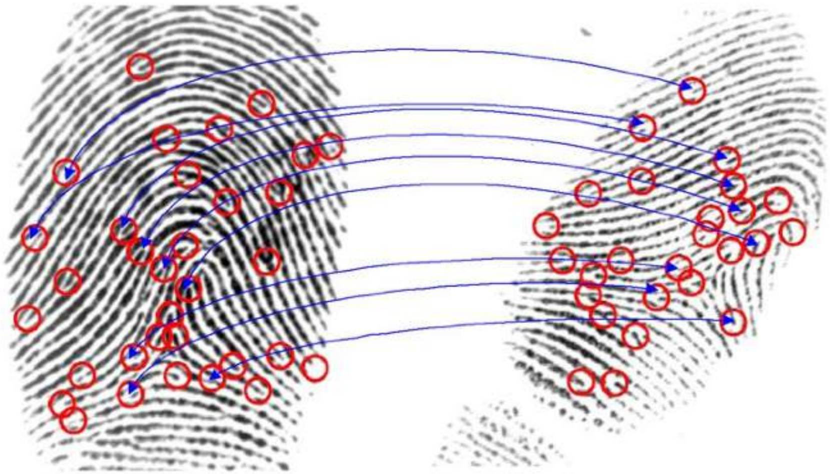


- Satellite images

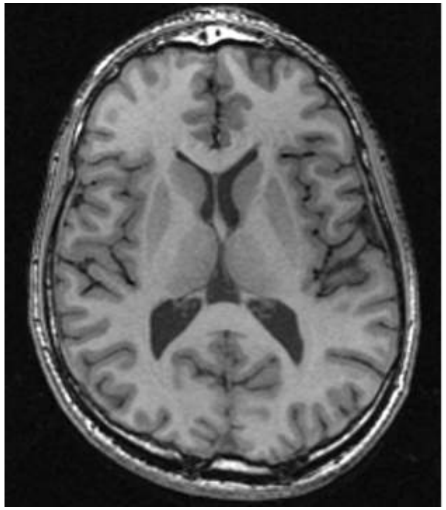


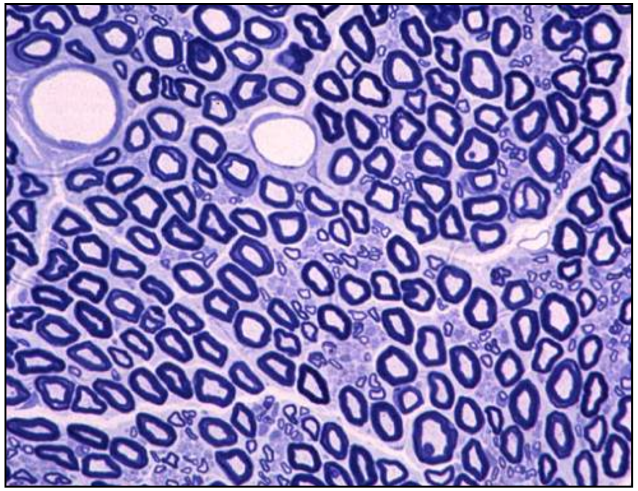
Applications of image processing (3/3)

- Security



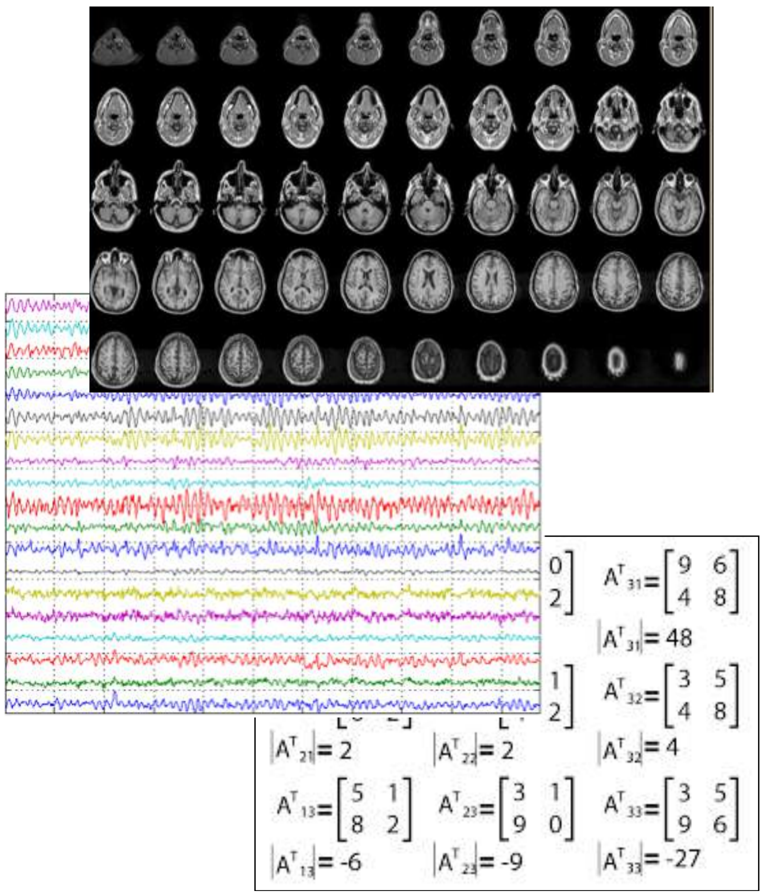
- Medicine and biology

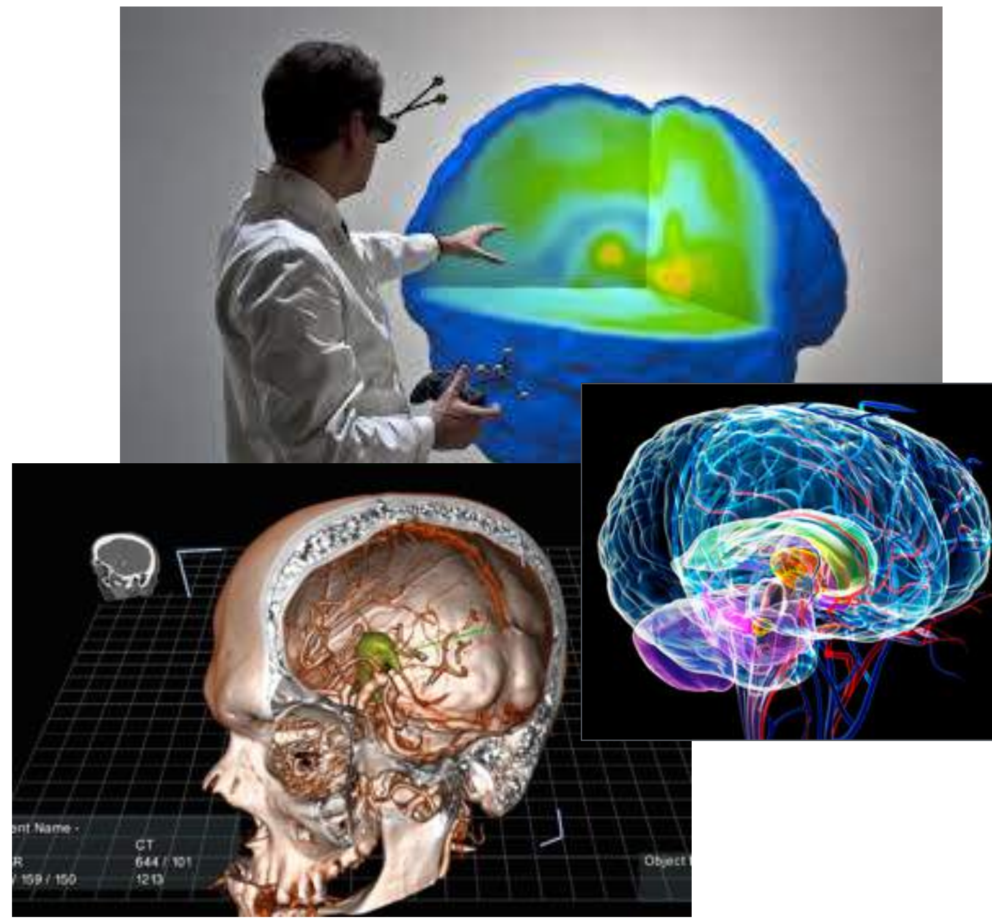




Visualization

- Not for the fun of creating beautiful images…
- …but to provide information in a form usable by doctors

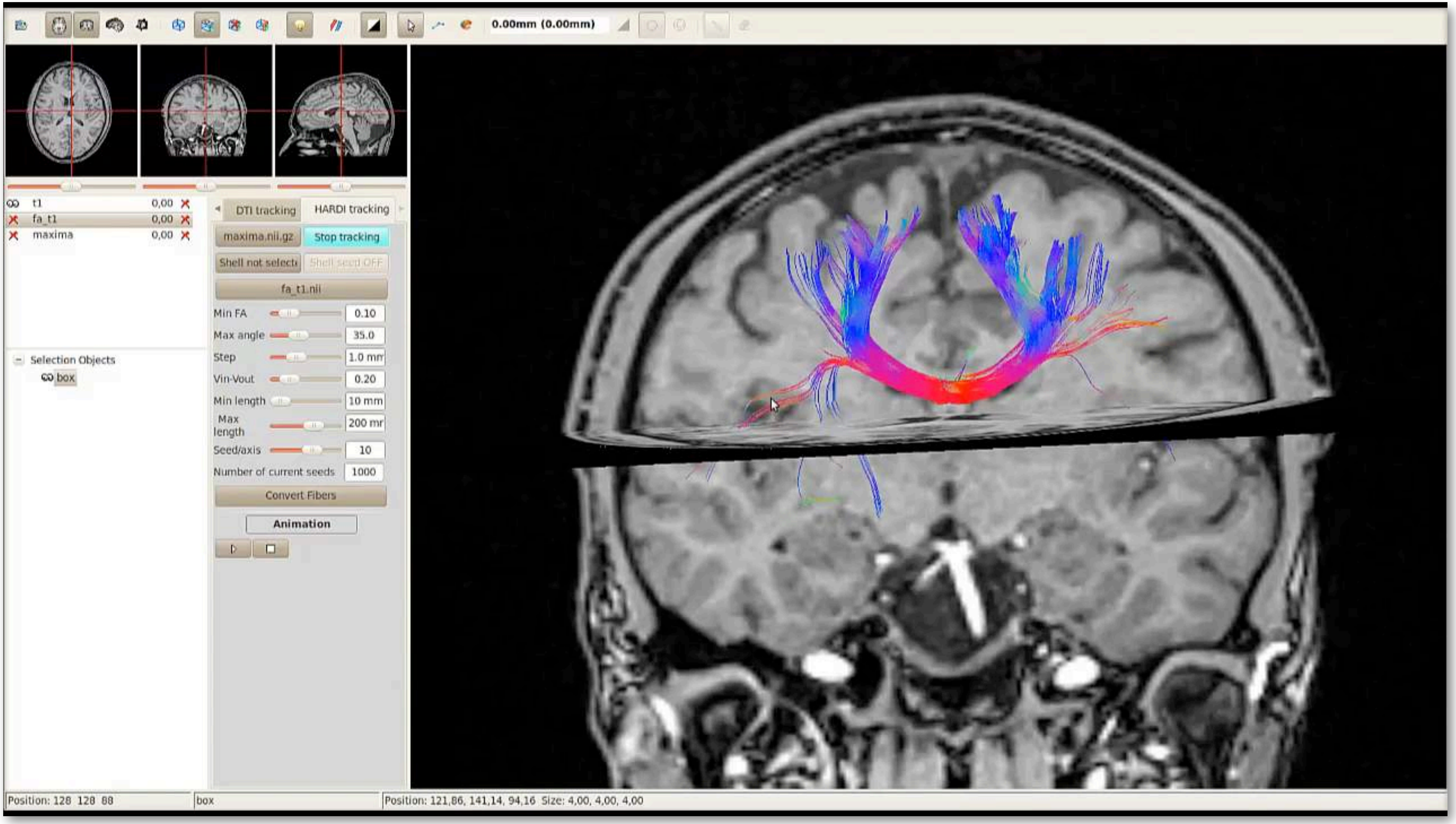




Why do we need image processing? (1/6)

[video from Matthew Rowe]

Why do we need image processing? (1/6)



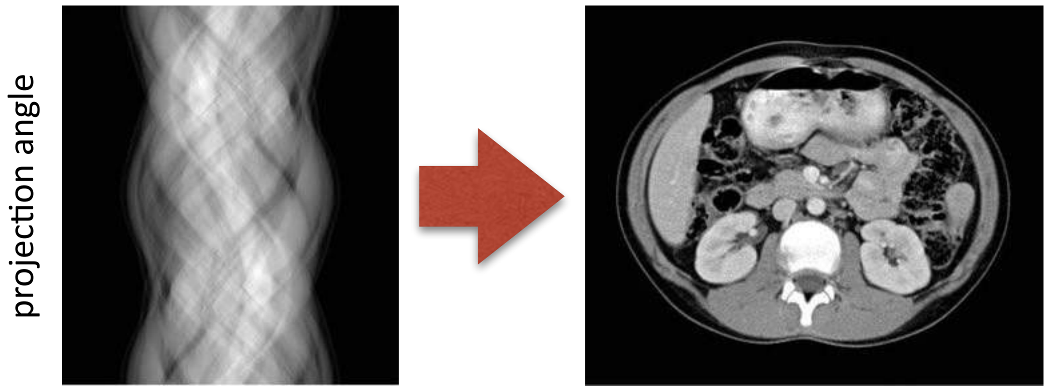
[video from Maxime Chamberland]

Why do we need image processing? (1/6)

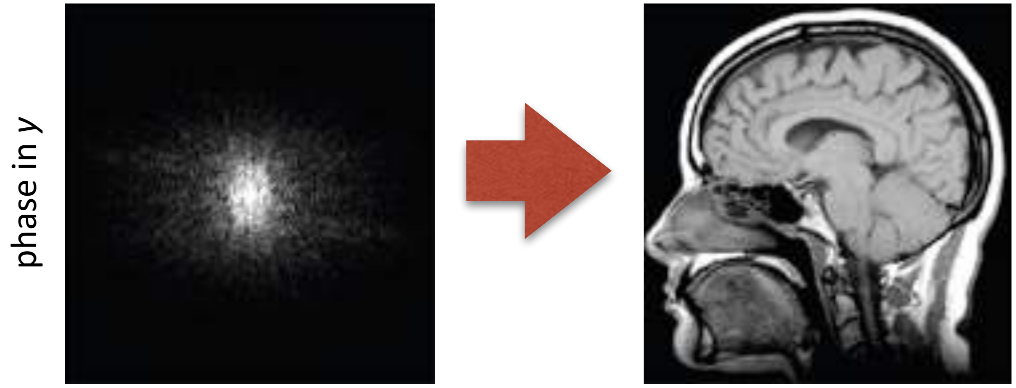
[video from Maxime Descoteaux]

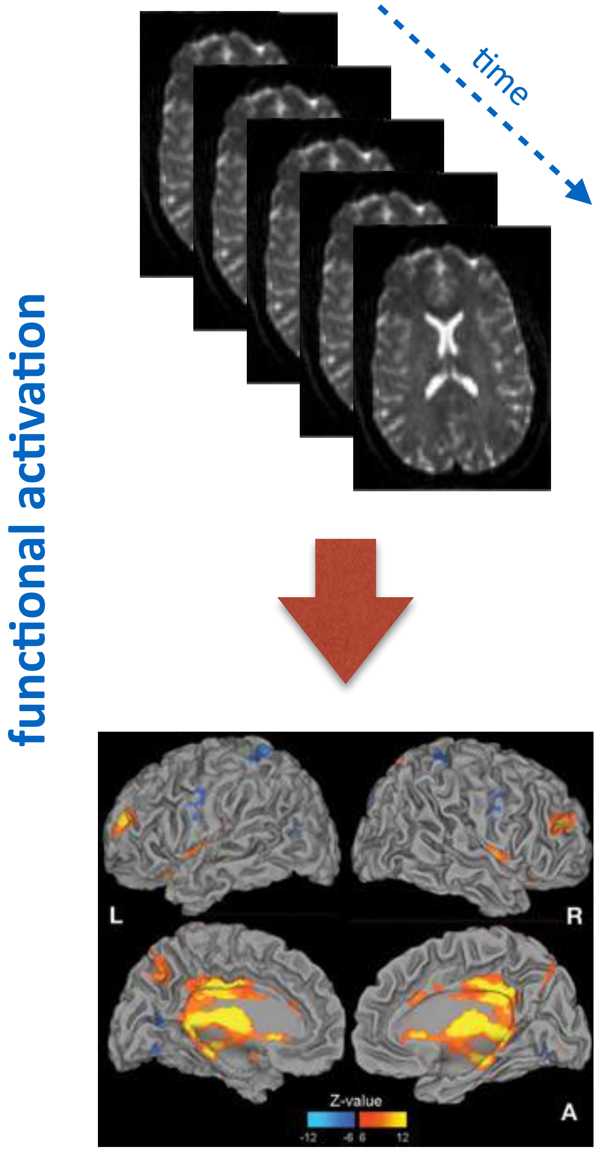
Reconstruction

CT acquisition



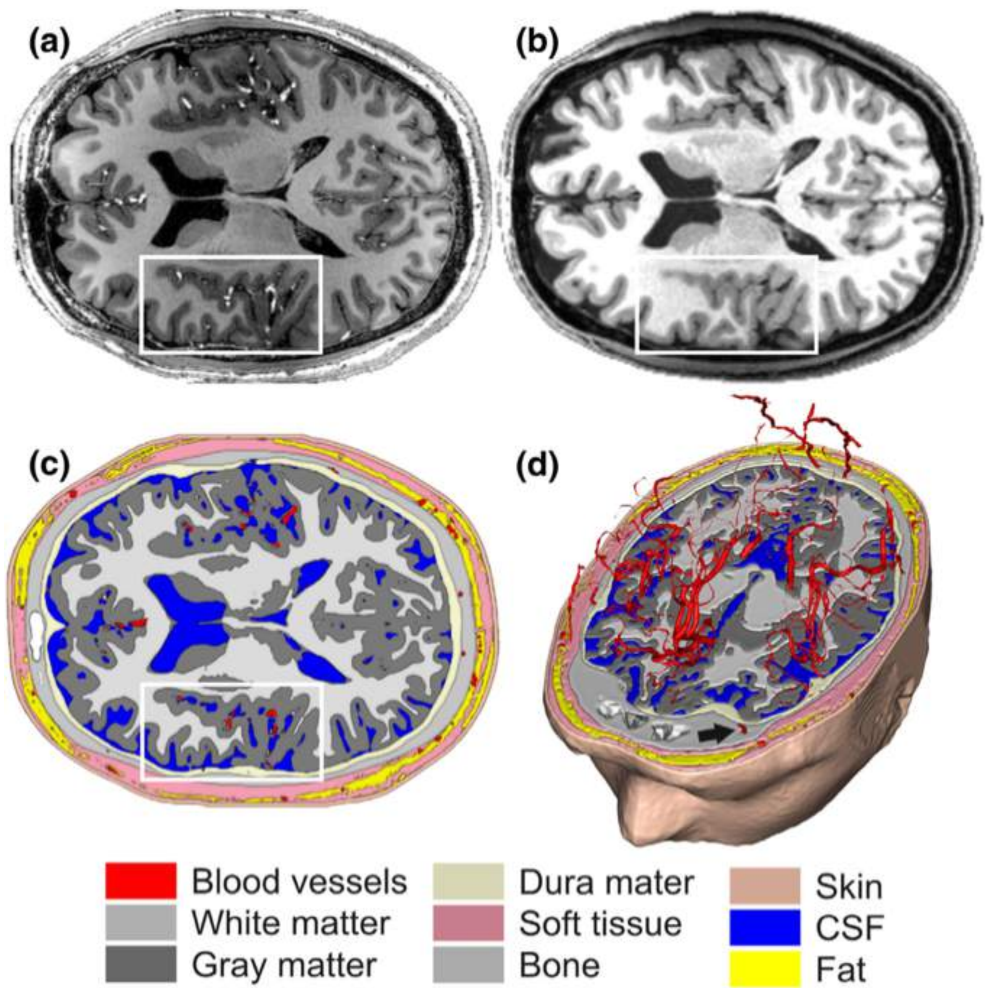
MRI acquisition



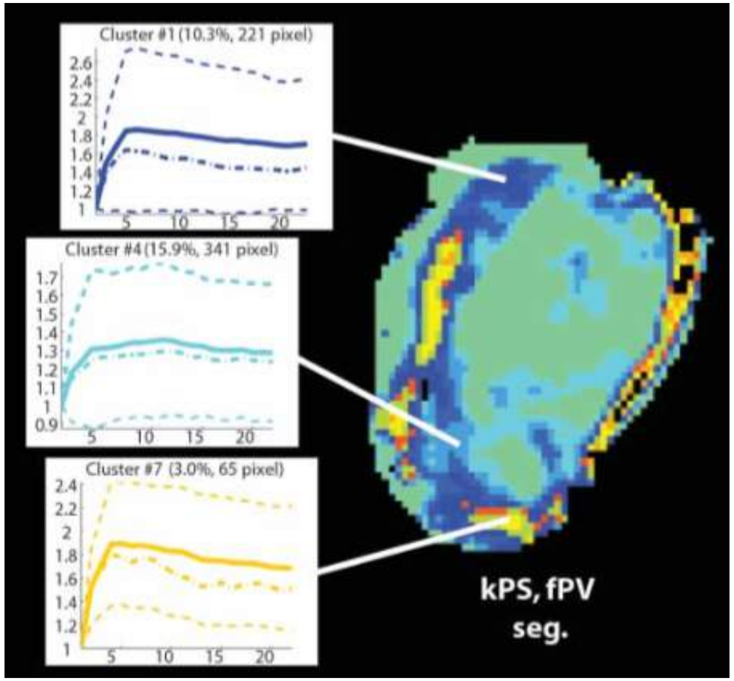


Segmentation

Quantify/study different tissues



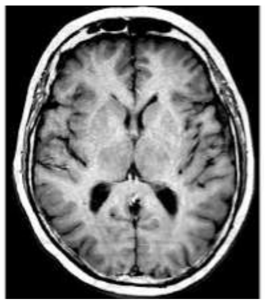
Detect tissue abnormalities



Registration

Compare different subjects

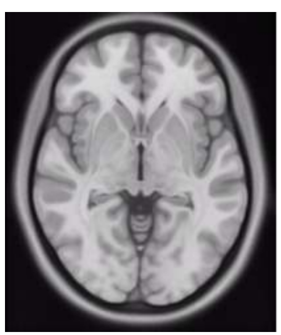
subject 1



subject 2

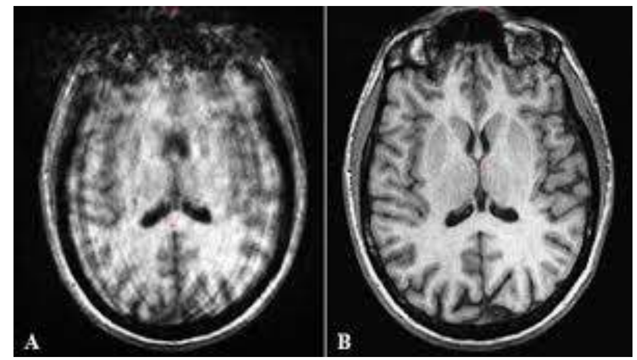
......

subject N

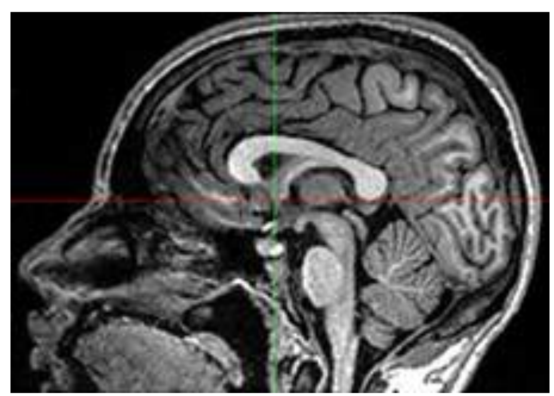


common template

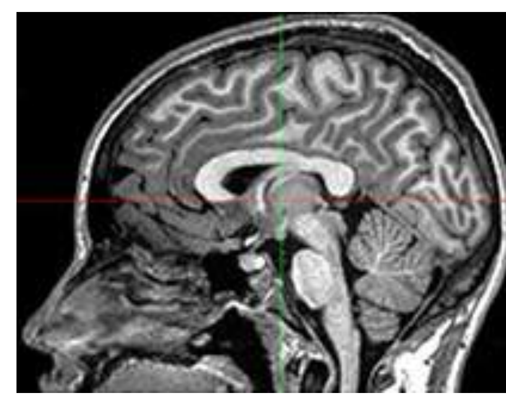
Subject motion



Detect changes in longitudinal studies



first scan

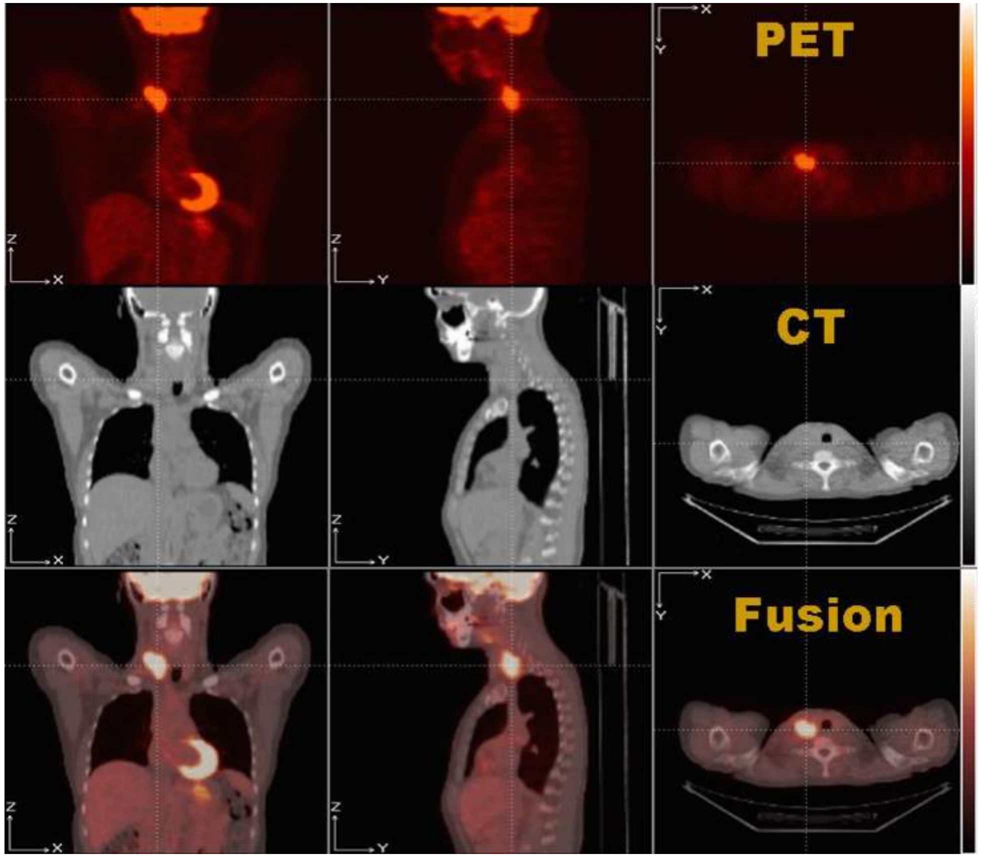


second scan

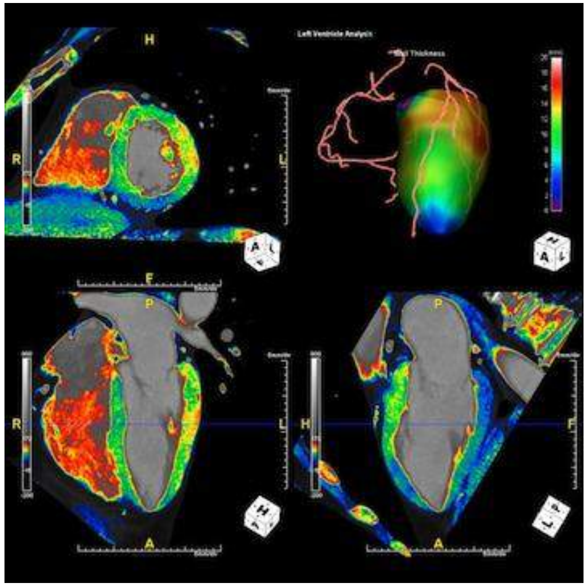
Why do we need image processing? (5/6)

- Data fusion

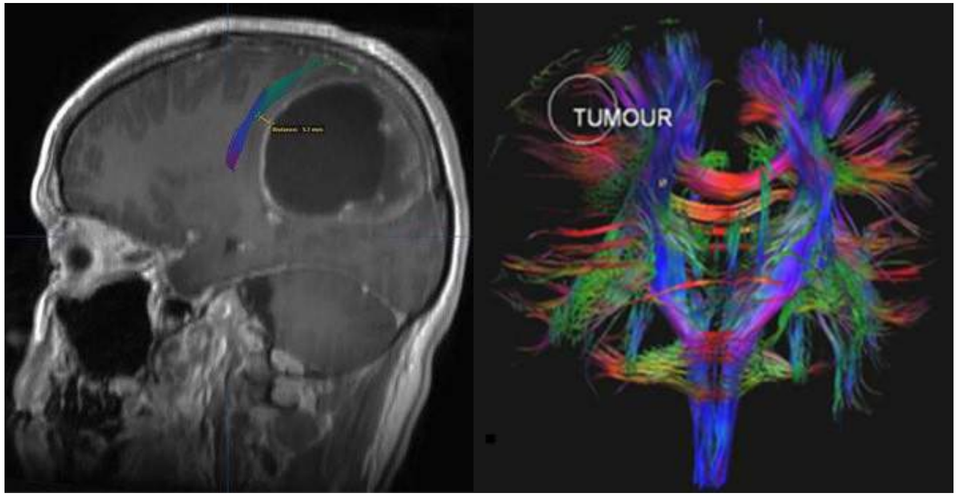
Improve accuracy



Merge different information

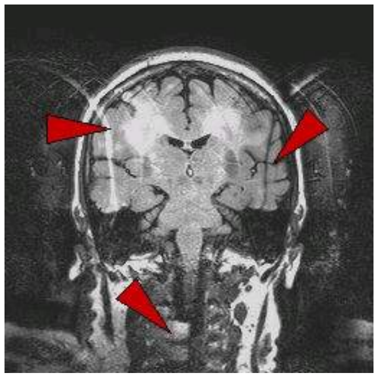


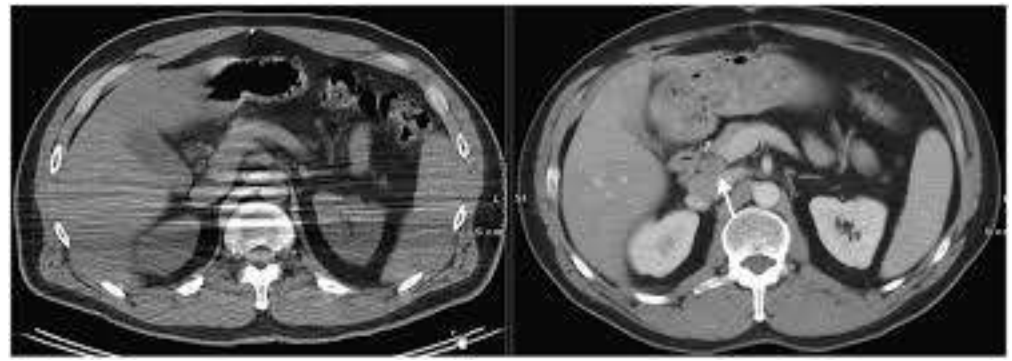
Help making decisions

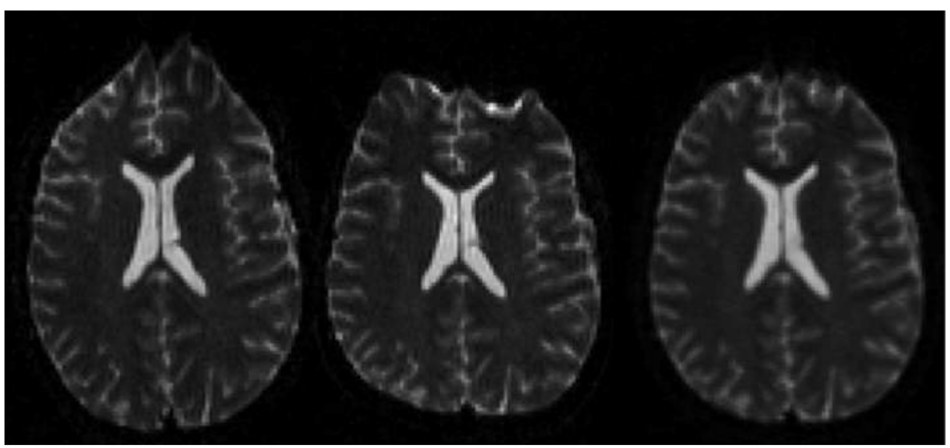


Why do we need image processing? (6/6)

- Artifact correction



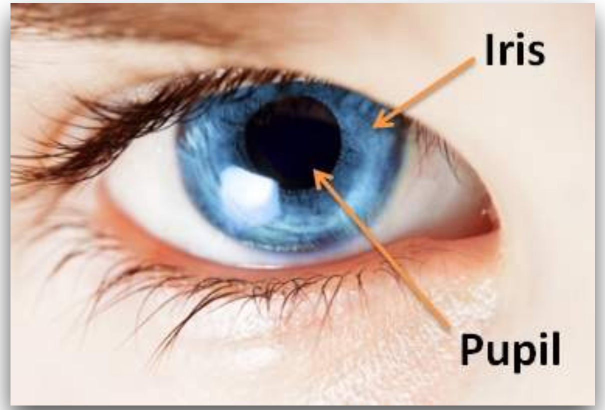


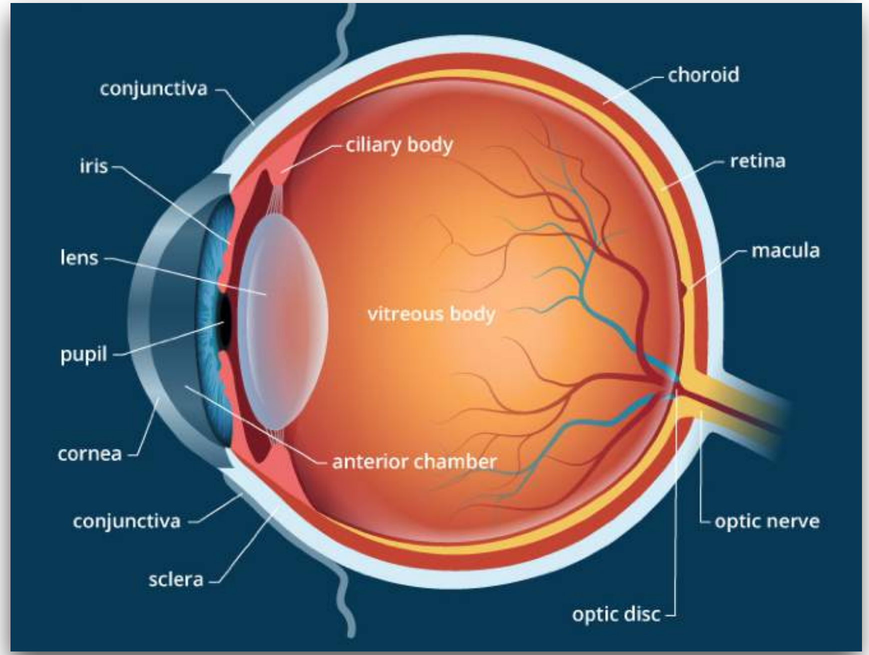


How can we actually "process" an image?

Human vision

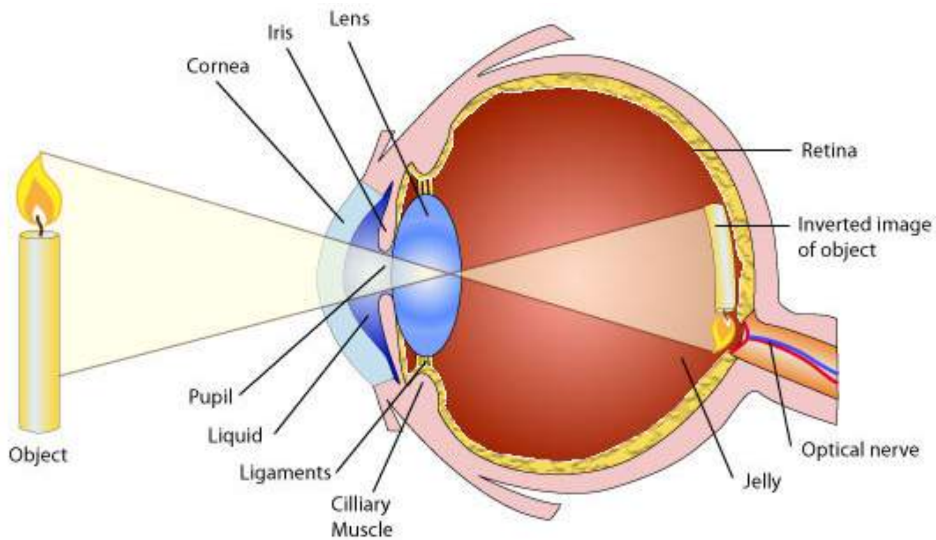
Eye anatomy





How do we *see*?

- Light *enters* through the **pupil**
  (changes size depending on the amount of light)
- Light is *focused* by the **lens**
- Light is *projected* (inverted) onto the **retina**, where it is collected
- Image *transmitted* to the brain through the **optic nerve**

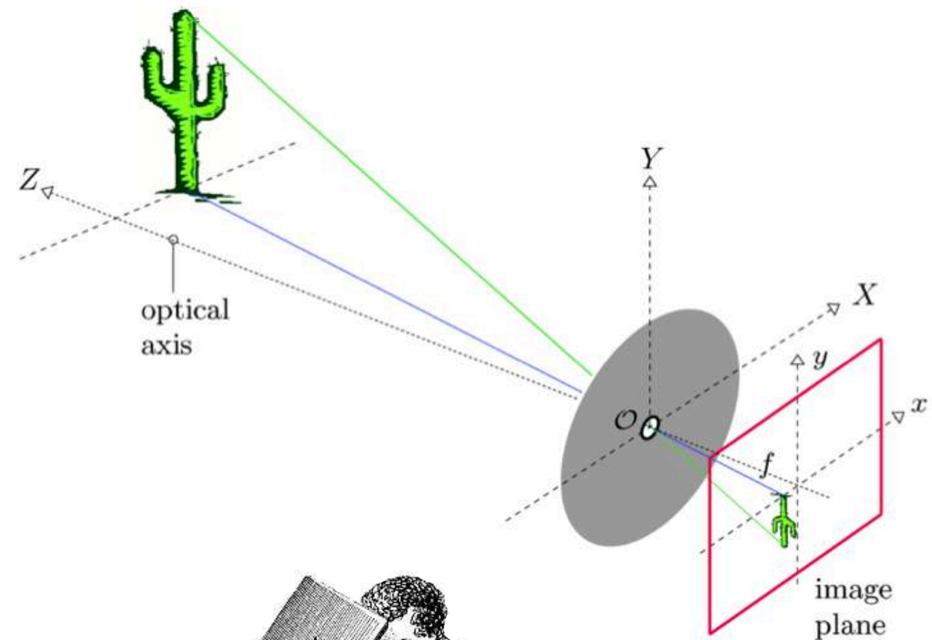


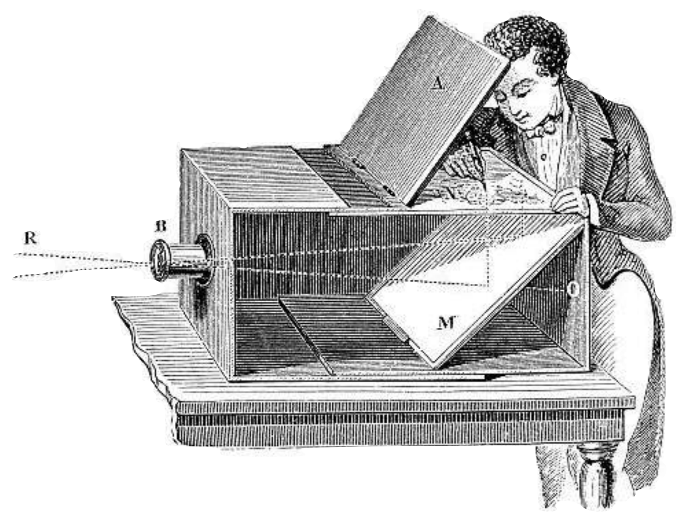
Standard photography: pinhole camera

- Simple camera *without lenses* but with a *tiny aperture*



- *Light* passes through the aperture
  (can change size depending on the amount of light)
- An *image* is projected (*inverted*)
  on the opposite side of a
  dark room (i.e. *camera obscura*)
- A *photographic film* is impressed





Standard (film) photography (2/2)

Photographic film properties

- A photograph is an **analog** and **continuous** signal
  - x, y (*spatial plane*)
  - z (*intensity*)

- Can resolve insanely **fine details**
- Any zoom is virtually possible

To **convert** such an image to **digital form** requires:

- Digitizing the *spatial coordinates* ➡ **sampling**
- Digitizing the *intensities/amplitudes* ➡ **quantization**

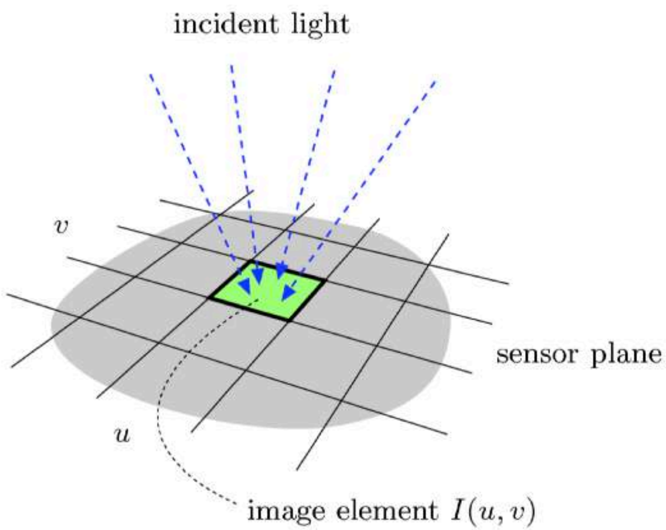
NB: this is an **analog to digital** conversion

- e.g. temperature is *analog*, but a **digital thermometer** reads *discrete values*

Digital photography (1/4)

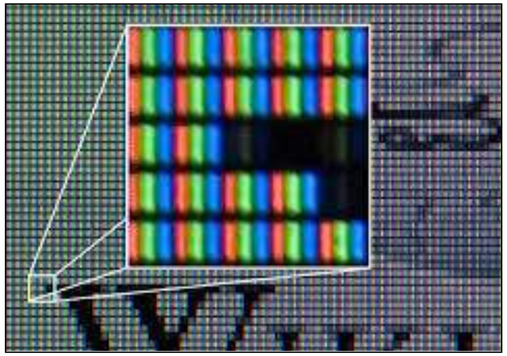
Digital photography: *sampling*

- A **finite number of sensors** arranged in a grid
- Each records the *incident light* at that position
- Each element is called **pixel**
  (i.e. *pic*ture *el*ement)



Notes

- Each pixel actually contains *multiple sensors*

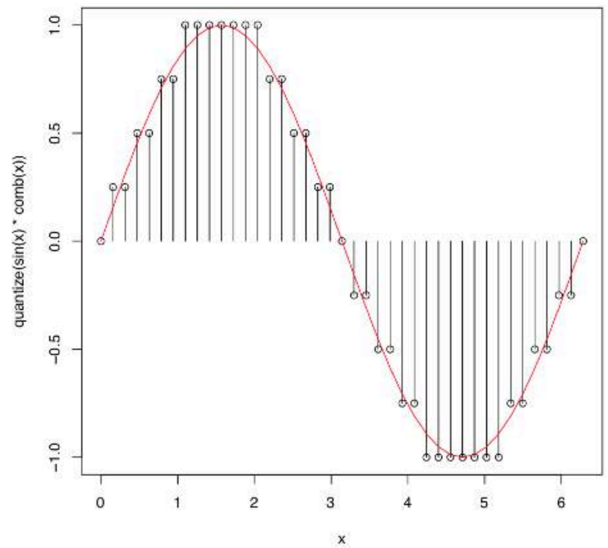


Red Green Blue

- In this course we will focus on **monochrome images** (or *grayscale*)
- Most image processing algorithms can be *extended to color images*

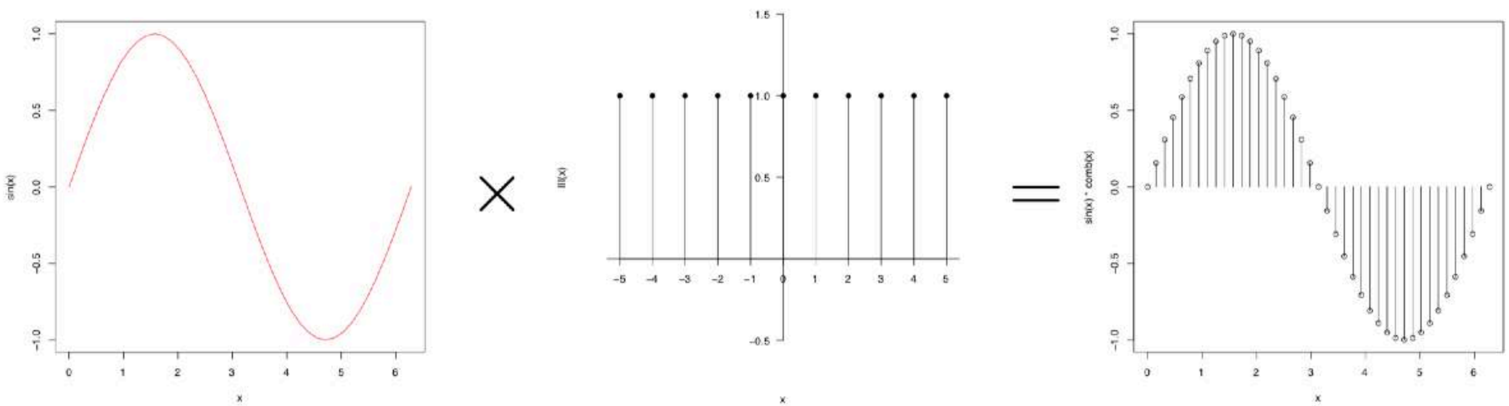
Digital photography: *quantization*

- To store pixels digitally, we also need to *discretize their amplitudes/intensities*



Note

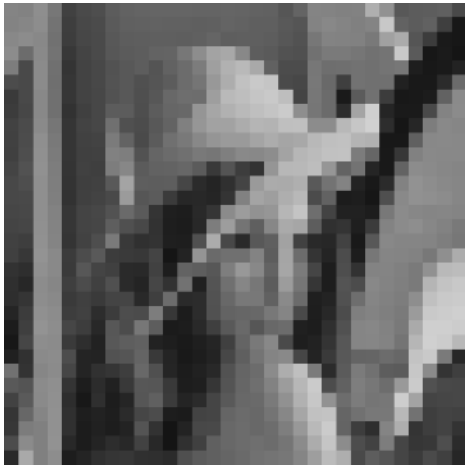
- Spatial *sampling* = multiplication of a *continuous signal* with a *comb function*



Effect of **sampling**

256x256 pixels

64x64 pixels



32x32 pixels

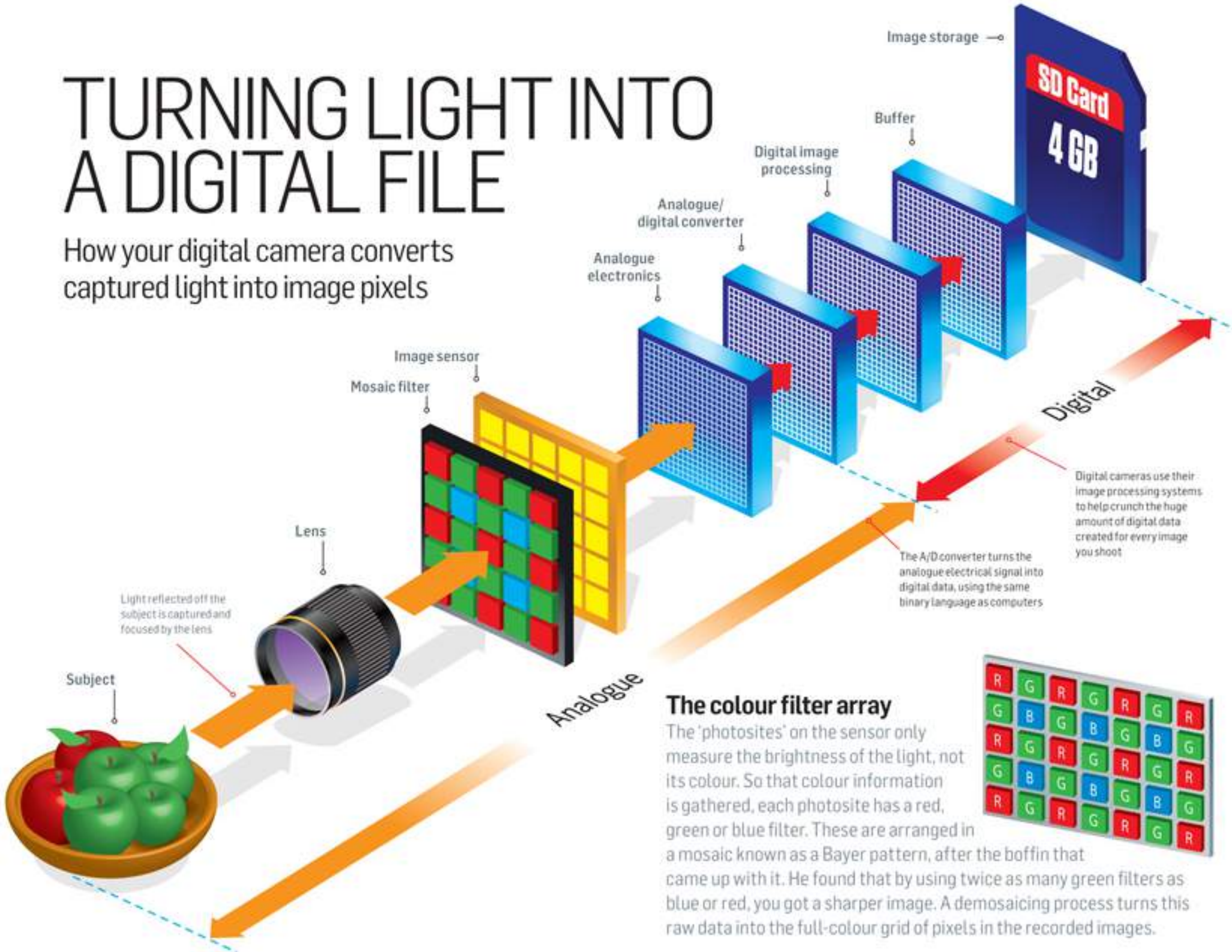
Effect of **quantization**

256 gray levels

8 gray levels

4 gray levels

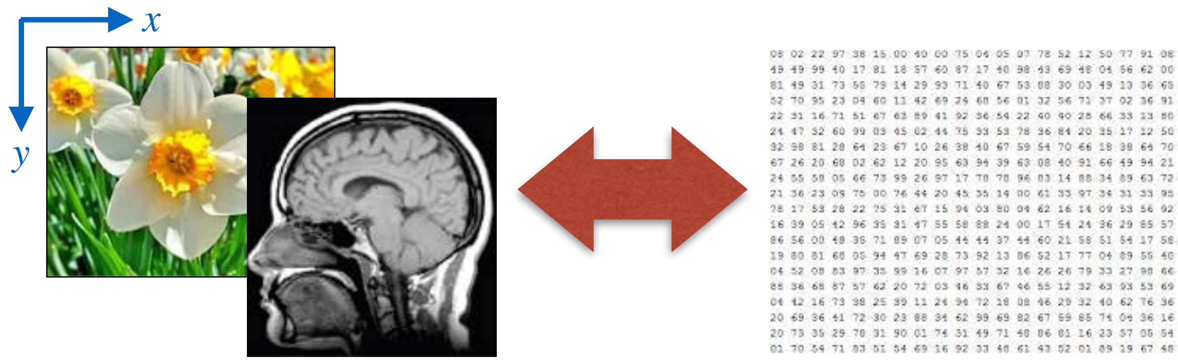
Digital photography (4/4)



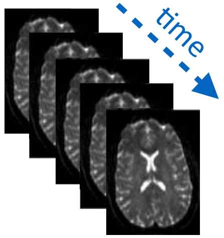
What is a digital image?

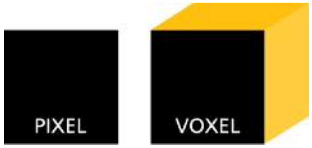
What is a digital image? (1/4)

- The output of *sampling* and *quantization* is a actually a **2D matrix of numbers**



- Notes
  - *Coordinates* not not limited to **2D**
  - *Values* not limited to **scalar** or **real values**
  - Pixel vs voxel
    - *Pixel* = "picture element"
    - *Voxel* = "volume element"





- Two main **representations** for a digital image
  - As **functions**
  - As **matrices**

Representing images as **discrete functions**

- We can think of the *intensity of an image* as a function of position (u, v)
- Let $\Omega \subset \mathbb{N}^2$ be the *image domain*. Then an image is a **discrete function**:

$$I : \Omega \to \mathbb{R}$$

Example

A simple image

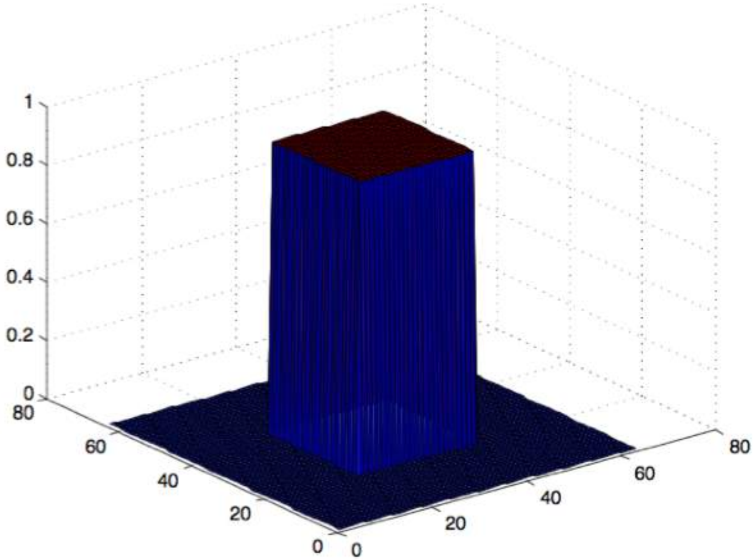


Image function as a height field

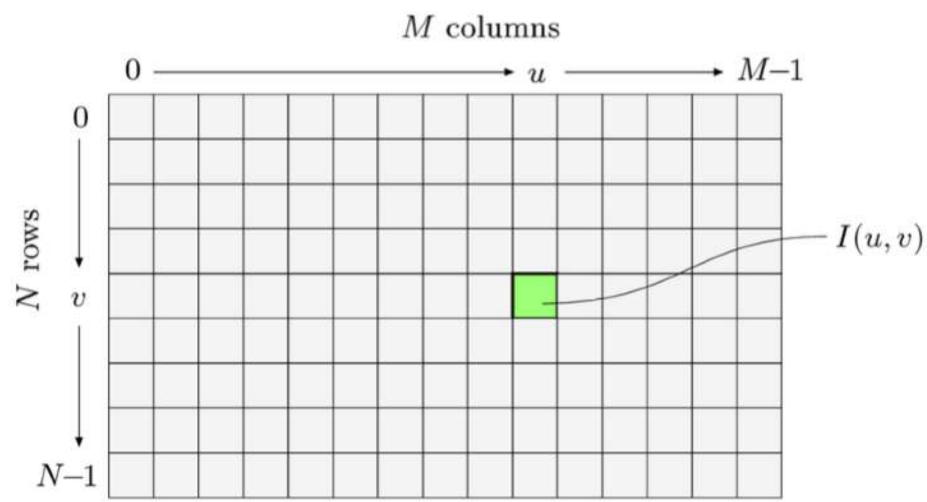
What is a digital image? (3/4)

Representing images as **matrices**

- The *coordinates* u and v encode the spatial position (u, v)
- The number in (u, v) is the *intensity of the pixel* $I(u, v)$, i.e. $f(u, v)$

$$I(u,v) = \begin{bmatrix} f(0,0) & f(0,1) & \cdots & f(0,N-1) \\ f(1,0) & f(1,1) & \cdots & f(1,N-1) \\ \vdots & \vdots & & \vdots \\ f(M-1,0) & f(M-1,1) & \cdots & f(M-1,N-1) \end{bmatrix}$$

- The data structure is simply a **2D array of values**:



- The values in the array can be *any data type* stored in a camera/computer
  (8-bit, 16-bit…, signed/unsigned etc)

What is a digital image?

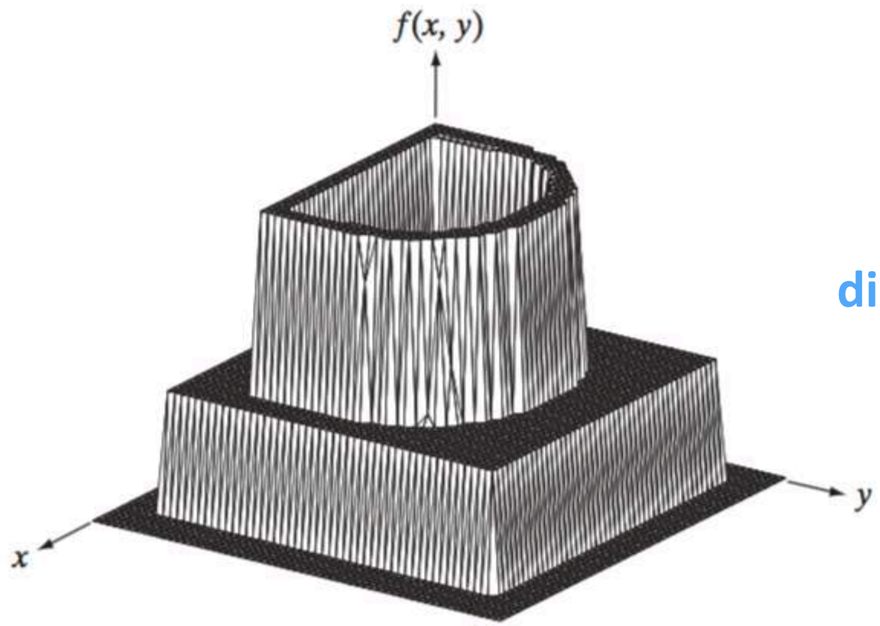
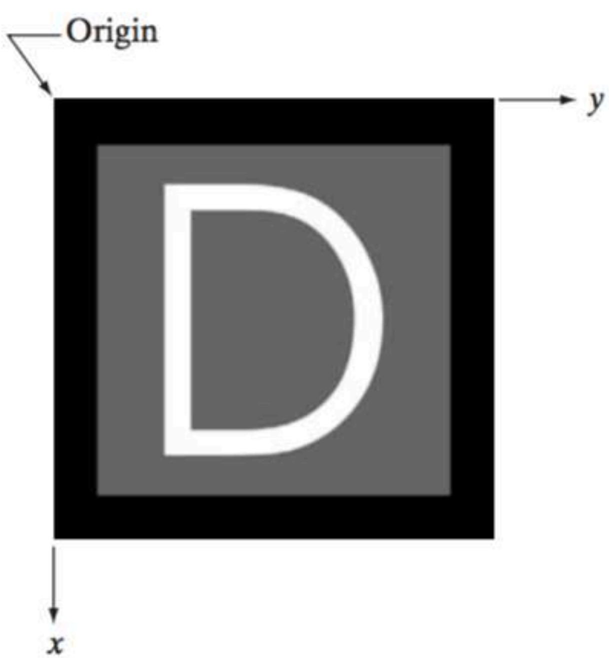


image as a **discrete function**

image displayed as a **photo**



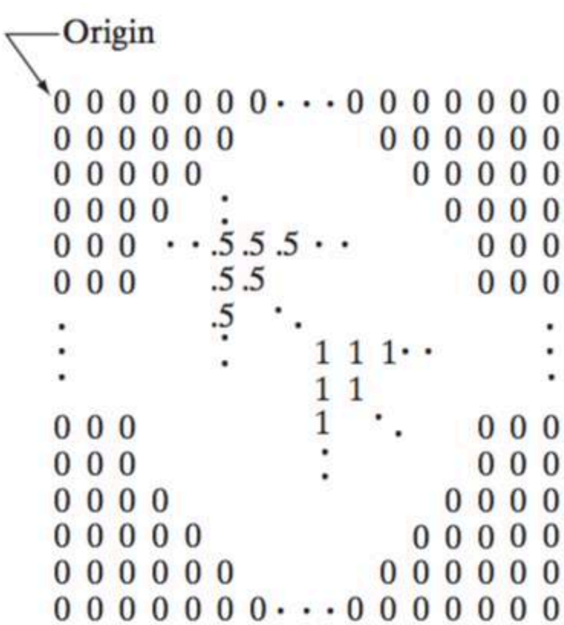
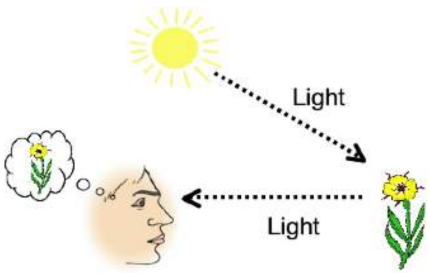


image as a **matrix**

Digital photography vs biomedical images (1/4)

Images formed by **interaction** with tissues/organs

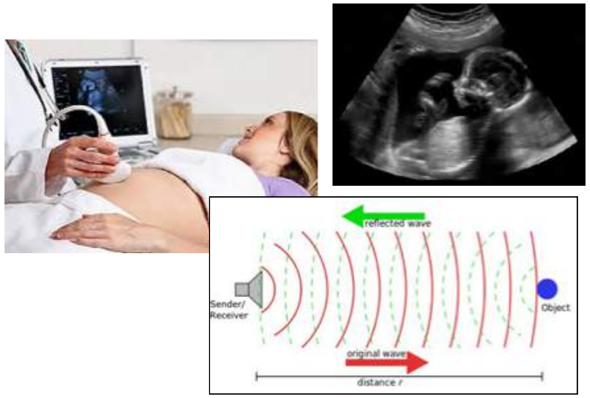
- Photography
  - reflection of light
- Biomedical images
  - emission and absorption of signal
  - different mechanisms to provide contrast



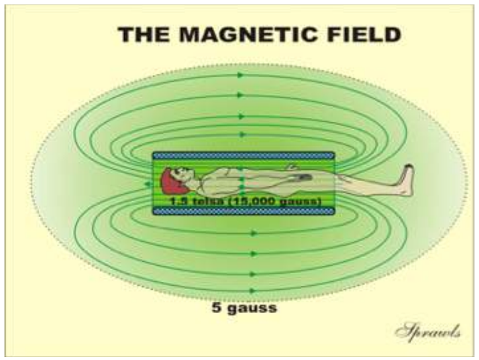
Positron Emission Tomography

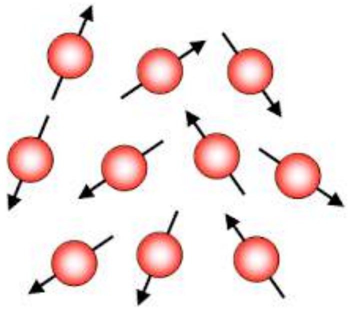
X-rays

Ultrasounds



Magnetic Resonance Imaging

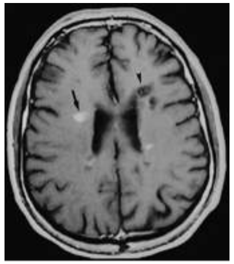


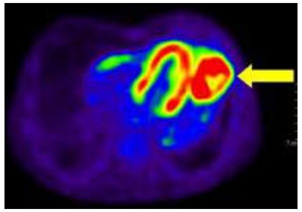


Digital photography vs biomedical images (2/4)

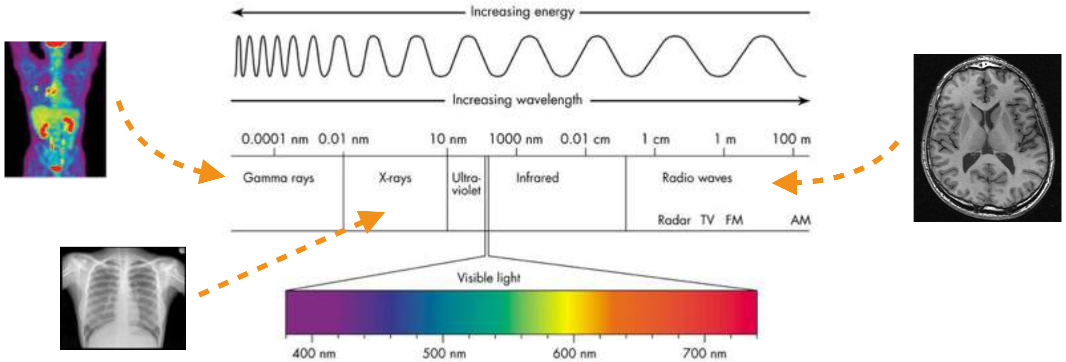
- Represent various **physical properties**

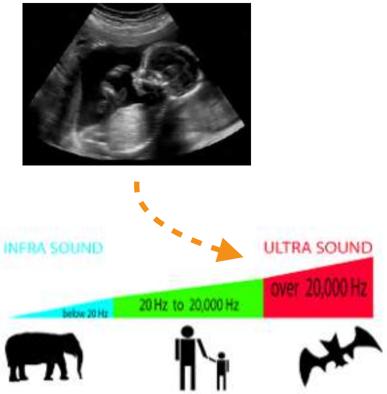




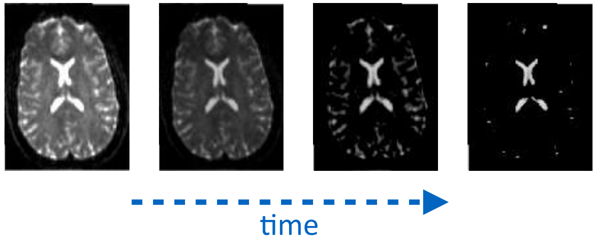


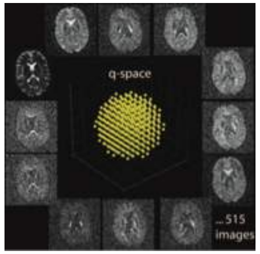
- Use **electromagnetic** and **audio** spectrums





- Are not limited to **2D**



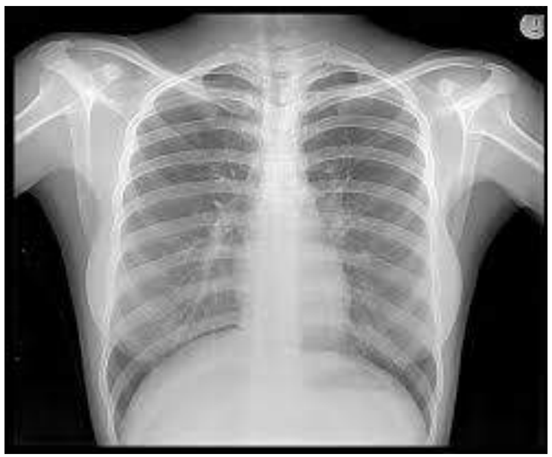


NB: diffusion MRI is a **7D modality**!

Digital photography vs biomedical images

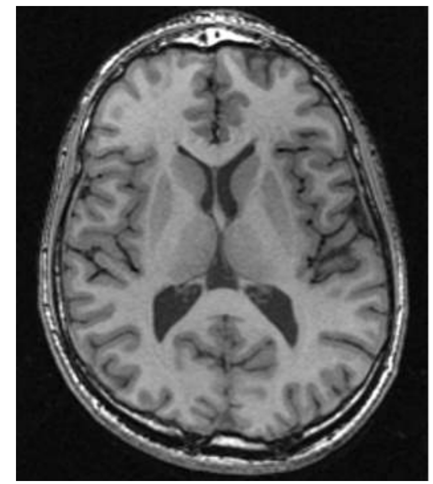
- Application: study "**anatomy**" or "**structure**"

X-rays

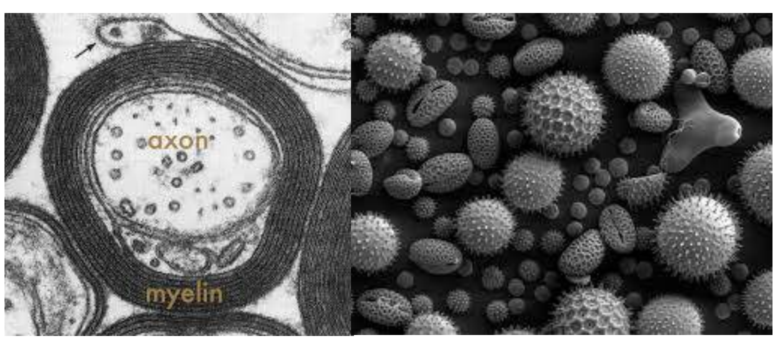


CT

MRI



electron microscopy



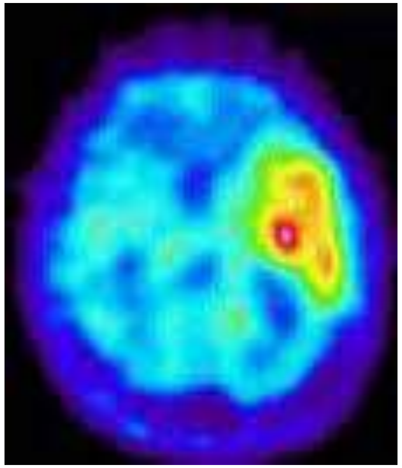
US

Digital photography vs biomedical images (4/4)

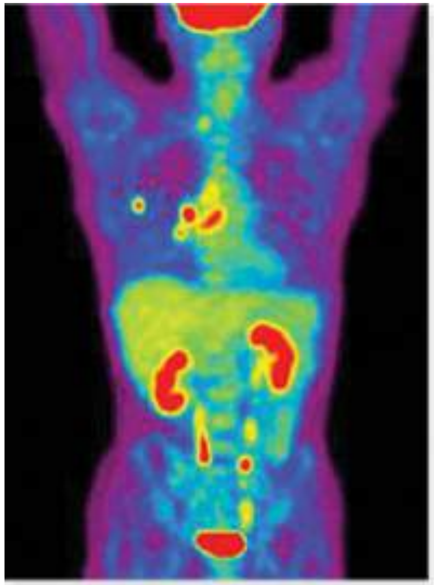
- Application: study “**function**” or “**activity**”

functional MRI

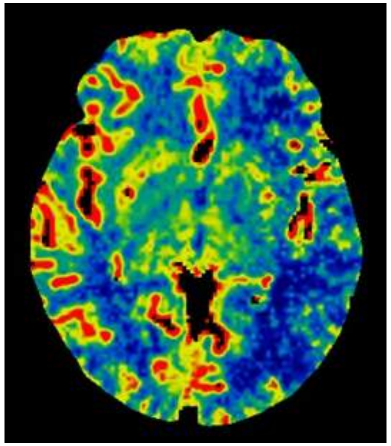
SPECT



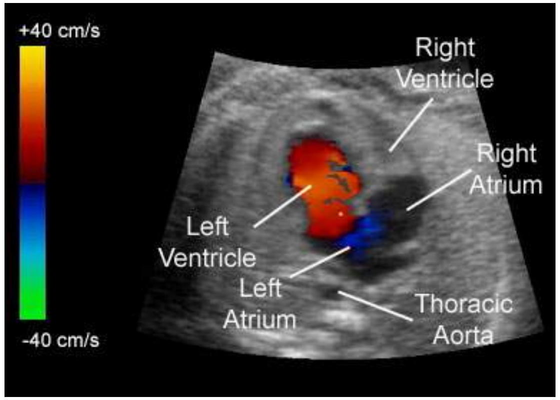
PET



perfusion CT



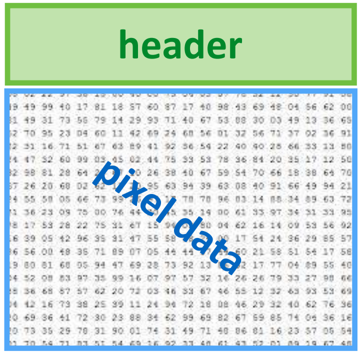
doppler US



Important image properties (1/7)

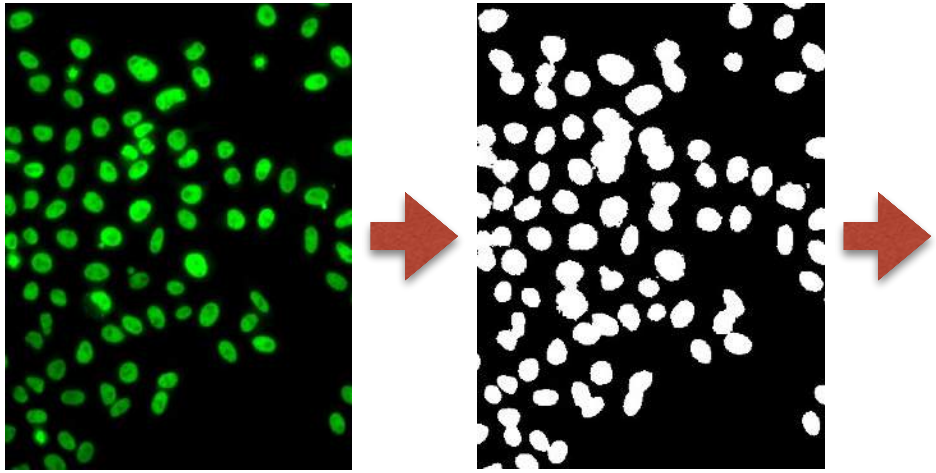
Metadata is required for correct interpretation

- Which parameters were used to produce the image?
- How is data stored?
- How was the patient positioned inside the scanner?
- Patient name, age, sex?



Example

- *Quantify* the amount of antibodies



32754 pixels:

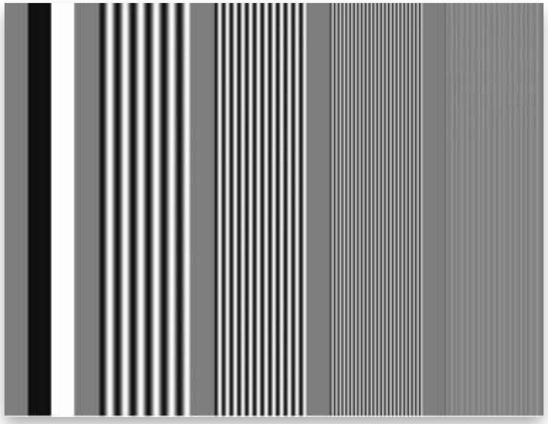
how many μm^2?

TIFF header

II*.......	TIFF header IFD0 entries
....	IFD0-00 SubfileType
....	IFD0-01 Compression
....	IFD0-02 ImageDescription
....	IFD0-03 Make
....	IFD0-04 Model
....	IFD0-05 Orientation
....	IFD0-06 XResolution
....	IFD0-07 YResolution
(...........	IFD0-08 ResolutionUnit
1.......&...	IFD0-09 Software
2.......6...	IFD0-10 ModifyDate
J...........	IFD0-11 SubIFD
........3...	IFD0-12 PreviewImageStart
....	IFD0-13 PreviewImageLength
....	IFD0-14 YCbCrPositioning
i...........	IFD0-15 ExifOffset
....|....J...	IFD0-16 PrintIM
4...........	IFD0-17 SR2Private
....SONY DSC	Next IFD

Spatial resolution

- It's a measure of the <u>smallest discernible detail</u> in an image
  - i.e. the ability to differentiate two objects in the image
- Can be expressed in many ways:
  - *pixel count*, e.g. megapixels
  - *dots (pixel) per unit distance*, e.g. DPI (dots per inch) or PPI (points per inch)
- NB: image size by itself does not tell the complete story
  - To be meaningful, spatial resolution must be stated **with respect to spatial units**
  - It depends on the **properties of the system** creating the image
  - Example (from wikipedia)



High pixel count, but probably low-cost lenses

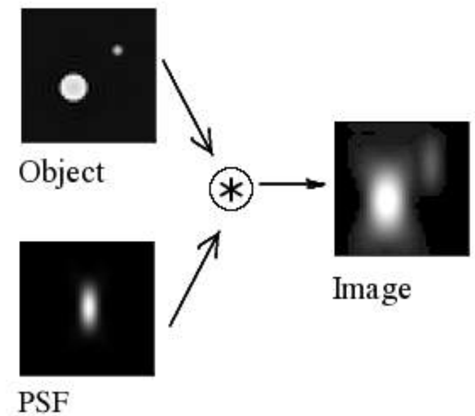
Lower pixel count, but probably better lenses

Important image properties (3/7)

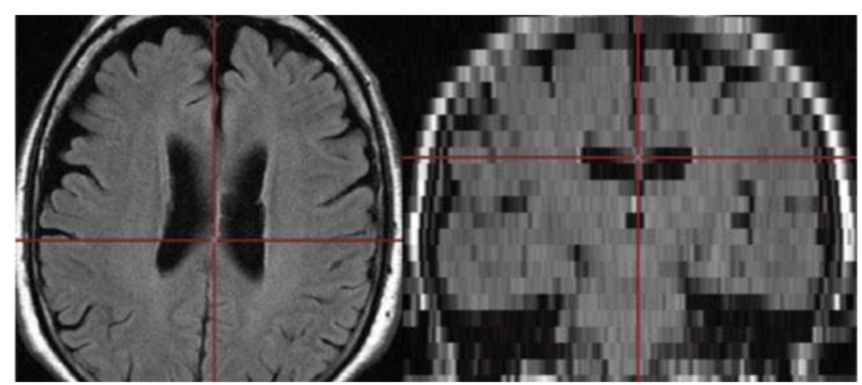
- In **biomedical images**, resolution depends on many factors
  - **Nominal** ability to resolve fine details → intrinsic blur
  - Point spread function (PSF) = response of an imaging system to a point source
  - *High* resolution = distinguish *smaller* objects

TABLE 1-1 THE LIMITING SPATIAL RESOLUTIONS OF VARIOUS MEDICAL IMAGING MODALITIES. THE RESOLUTION LEVELS ACHIEVED IN *TYPICAL* CLINICAL USAGE OF THE MODALITY ARE LISTED

MODALITY	SPATIAL RESOLUTION (mm)	COMMENTS
Screen film radiography	0.08	Limited by focal spot size and detector resolution
Digital radiography	0.17	Limited by size of detector elements and focal spot size
Fluoroscopy	0.125	Limited by detector resolution and focal spot size
Screen film mammography	0.03	Highest resolution modality in radiology, limited by same factors as in screen film radiography
Digital mammography	0.05–0.10	Limited by same factors as digital radiography
Computed tomography	0.3	About ½ mm pixels
Nuclear medicine planar imaging	2.5 (detector face), 5 (10 cm from detector)	Spatial resolution degrades substantially with distance from detector
Single photon emission computed tomography	7	Spatial resolution worst towards the center of cross-sectional image slice
Positron emission tomography	5	Better spatial resolution than the other nuclear imaging modalities
Magnetic resonance imaging	1.0	Resolution can improve at higher magnetic fields
Ultrasound imaging (5 MHz)	0.3	Limited by wavelength of sound



- **NB**: acquisition can be **anisotropic**!



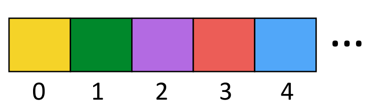
A-P : high resolution
L-R : high resolution
I-S : low resolution

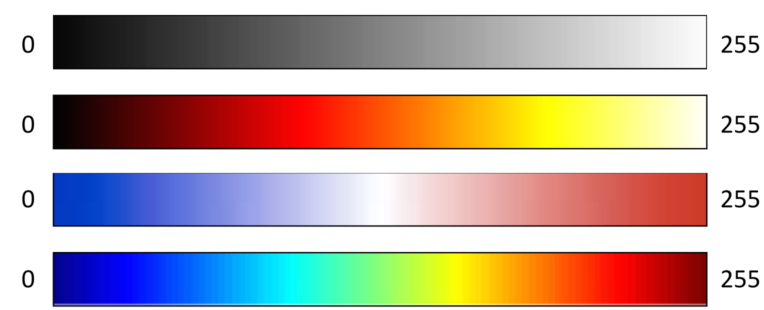
Intensity resolution (a.k.a. pixel/voxel depth)

- It's the <u>smallest discernible change</u> in intensity levels
- Number of bits to encode the information in each pixel/voxel
- Typical data types:
  - signed/unsigned byte (8-bit)
  - signed/unsigned short (16-bit)
  - signed/unsigned int (32-bit)
  - float (32-bit) and double (64-bit)

NB: photometric interpretation

- Grayscale (e.g. CT and MRI)
  - Intensity of physical phenomenon, no a real "color"
  - The "color" is associated when displaying using *colormaps*
- Color palette or indexed (e.g. SPECT and PET)
  - Image must be displayed with color *stored* in the voxel





NB: attention to *jet/rainbow* colormap

NB: **typical mistakes** when opening an image

- Signed or unsigned?

129 = *10000001* → = 129 unsigned; = -1 signed

- Endian-ness?

16-bit integer
two bytes (*b1* and *b2*) → *b1* *b2* (big-endian) or *b2* *b1* (little-endian)

1025 = *00000100* *00000001* →
00000100 *00000001* = 1025 — big-endian (many scanner workstations)
00000001 *00000100* = 260 — little-endian (intel x86 and x86-64)

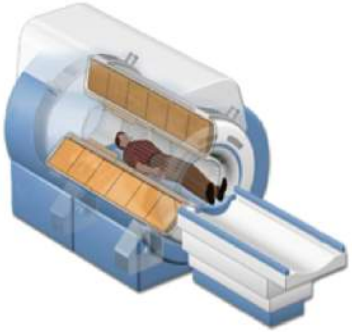
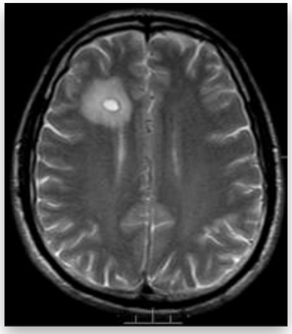
- Is data scaled?
  - Often, values are stored as *integers* but *scaling parameters* are given in the header

stored *232* (unsigned 8-bit) + Scaling slope: **10.0** Scaling intercept: **0.5** → *2320.5* (float 32-bit) intended

  - **NB**: always perform post-processing in float!

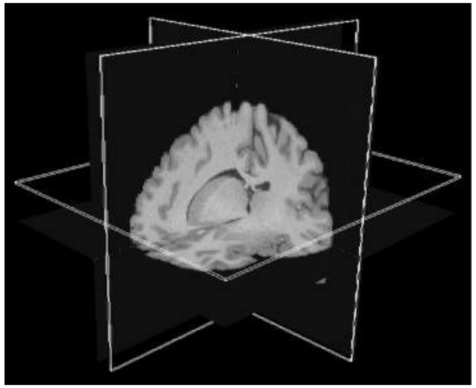
Image orientation

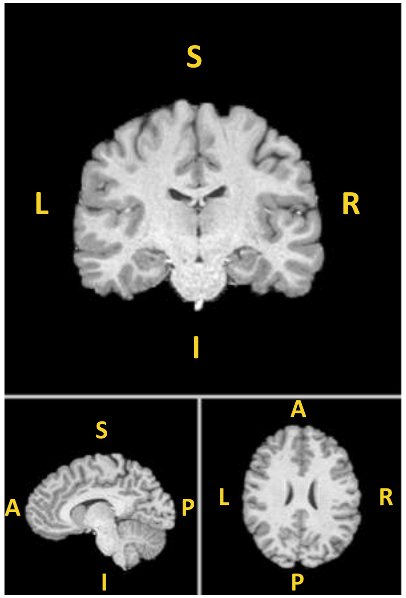
- For some analyses, it is **very important to know** the *exact location* of the subject/sample inside the scanner
  - e.g. in which hemisphere is the lesion? Left or right?

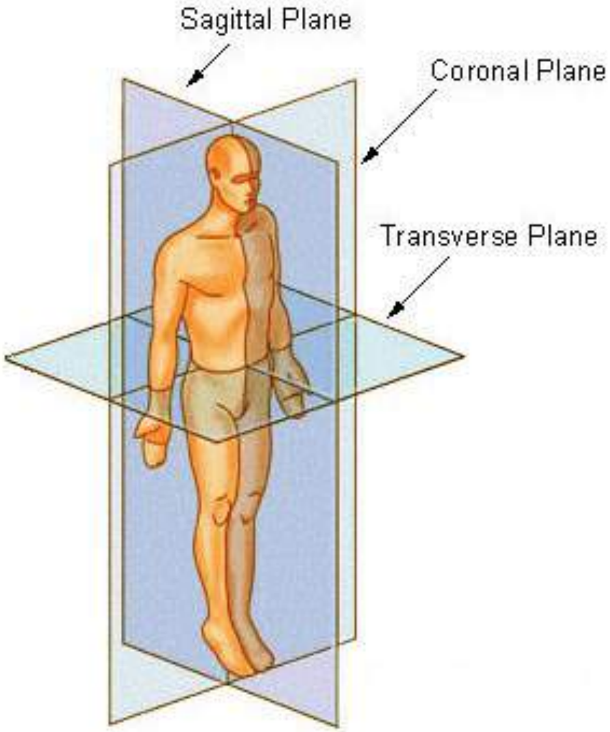



Usually, medical images displayed by *anatomical planes*

- Sagittal
  - divides *left* (**L**) and *right* (**R**)
- Coronal
  - divides *anterior* (**A**) and *posterior* (**P**)
- Transverse (or axial)
  - divides *superior* (**S**) and *inferior* (**I**)

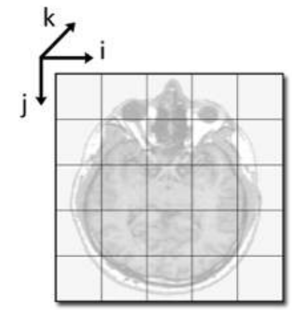


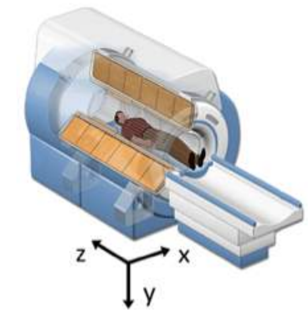


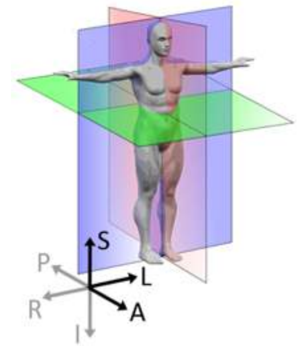


Coordinate systems

- **Image** space (*i, j, k*)
  - voxel indices, no notion of "*physical dimensions*"
- **World** space (*x, y, z*)
  - actual coordinates [in *mm*] w.r.t. the scanner
  - scaling, rotation and translation
- **Patient** space (*L, A, S*)
  - coordinates w.r.t. anatomical planes





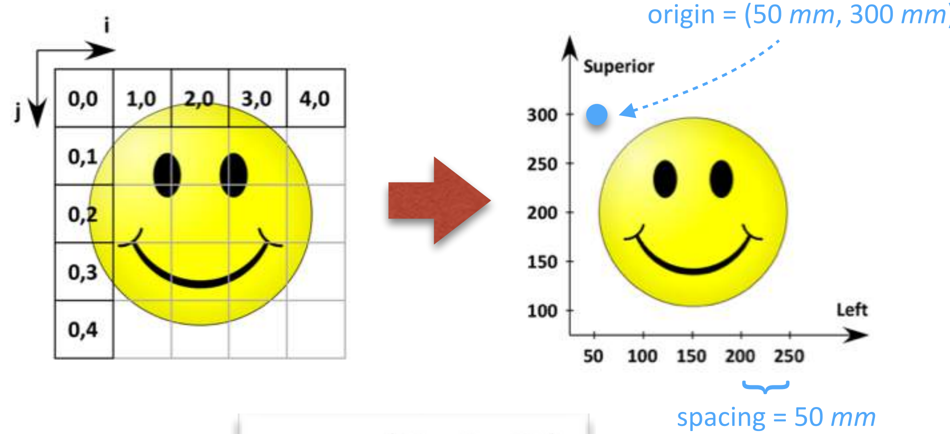


Transformation matrix

rotation/scale translation

$$\begin{pmatrix} x_1 \\ x_2 \\ x_3 \\ 1 \end{pmatrix} = \begin{pmatrix} A_{11} & A_{12} & A_{13} & t_1 \\ A_{21} & A_{22} & A_{23} & t_2 \\ A_{31} & A_{32} & A_{33} & t_3 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} i \\ j \\ k \\ 1 \end{pmatrix}$$

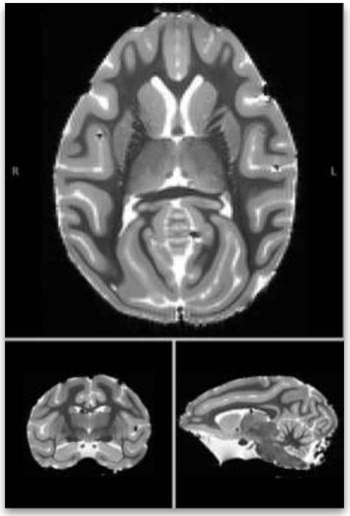
- Homogeneous coordinates
- Stored in the header



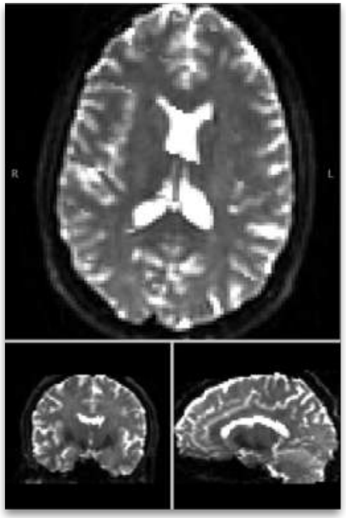
$$IJtoLS = \begin{pmatrix} 50 & 0 & 50 \\ 0 & -50 & 300 \\ 0 & 0 & 1 \end{pmatrix}$$

Image quality (1/4)

- **Trade-off** between *quality* and *patient comfort*
  - usually, higher quality requires longer acquisitions



Monkey :
- *ex-vivo*
- *1 week*

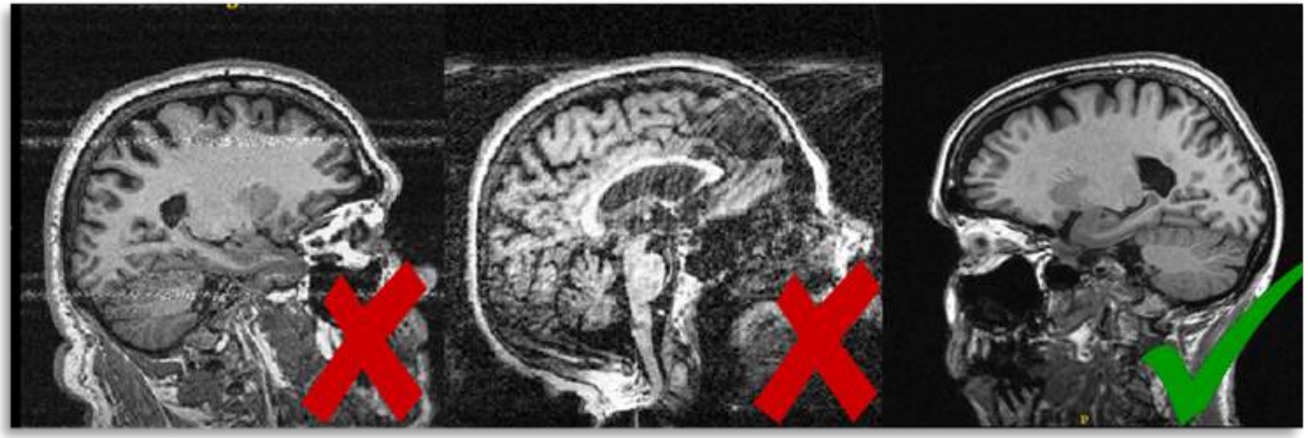


Human :
- *in-vivo*
- *25 minutes*

- Main criteria for **quality assessment**:
  1) Presence of artifacts
  2) Spatial resolution
  3) Noise level
  4) Image contrast

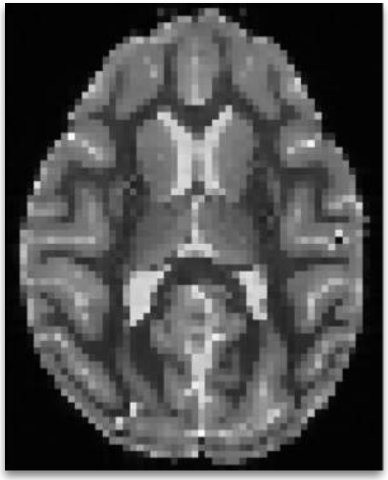
Image quality

1) Presence of **artifacts**



2) Spatial **resolution**

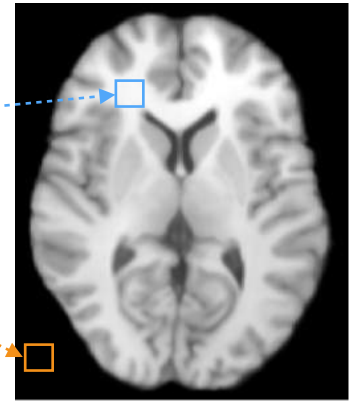
0.5 x 0.5 x 0.5 mm



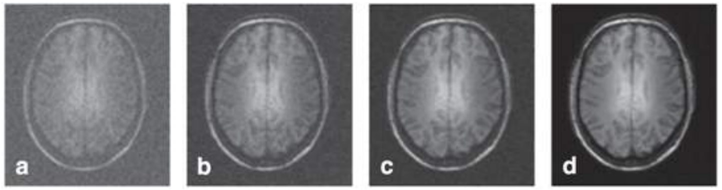
1.0 x 1.0 x 1.0 mm

3) **Signal-to-noise** ratio

- Many different definitions
- A common one is: $\mathrm{SNR} = \dfrac{\mu_S}{\sigma_N}$



- Averaging improves SNR:



4) **Contrast-to-noise** ratio

- Common definition:

$$\mathrm{CNR}_{\mathrm{AB}} = \frac{C_{\mathrm{AB}}}{\sigma_{\mathrm{N}}} = \frac{|S_{\mathrm{A}} - S_{\mathrm{B}}|}{\sigma_{\mathrm{N}}}$$

where $\mathrm{C}_{\mathrm{AB}} = |S_{\mathrm{A}} - S_{\mathrm{B}}|$ is the contrast between region *A* and *B*

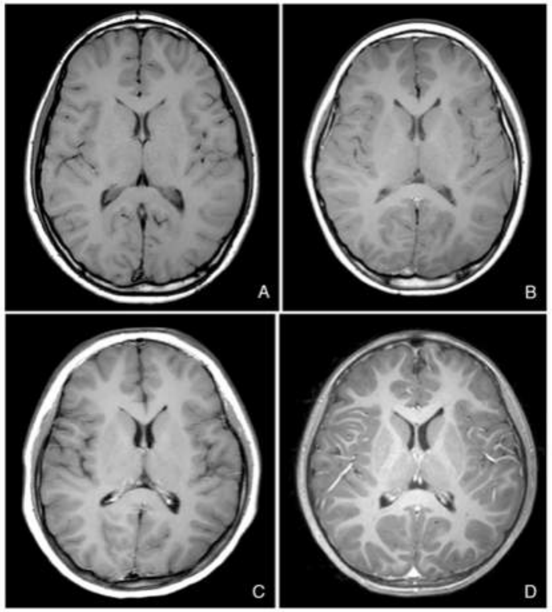
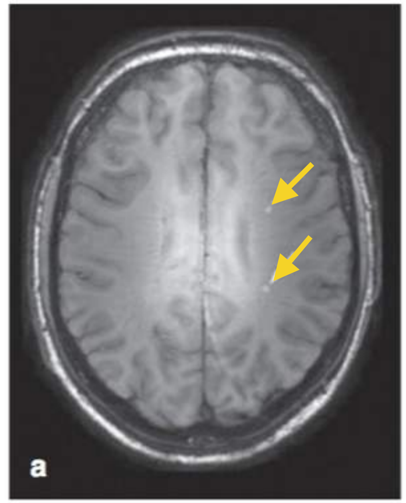
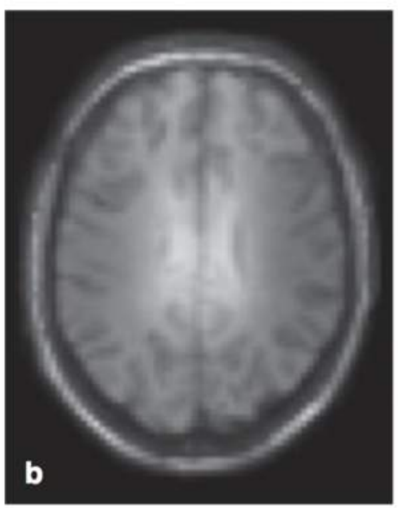


Image quality

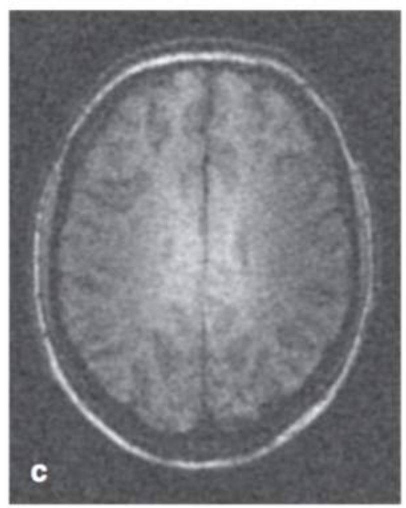
- All factors **affect diagnostic power**



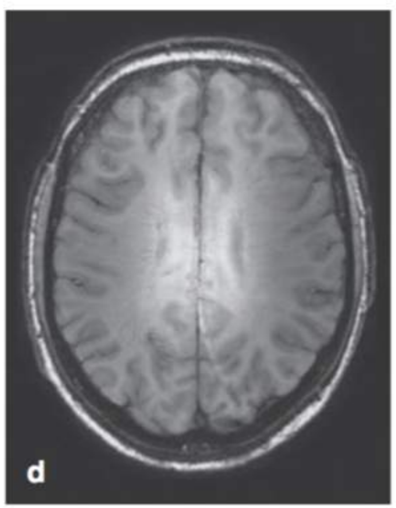
multiple sclerosis lesions **are visible** in the original image



lower resolution



lower SNR

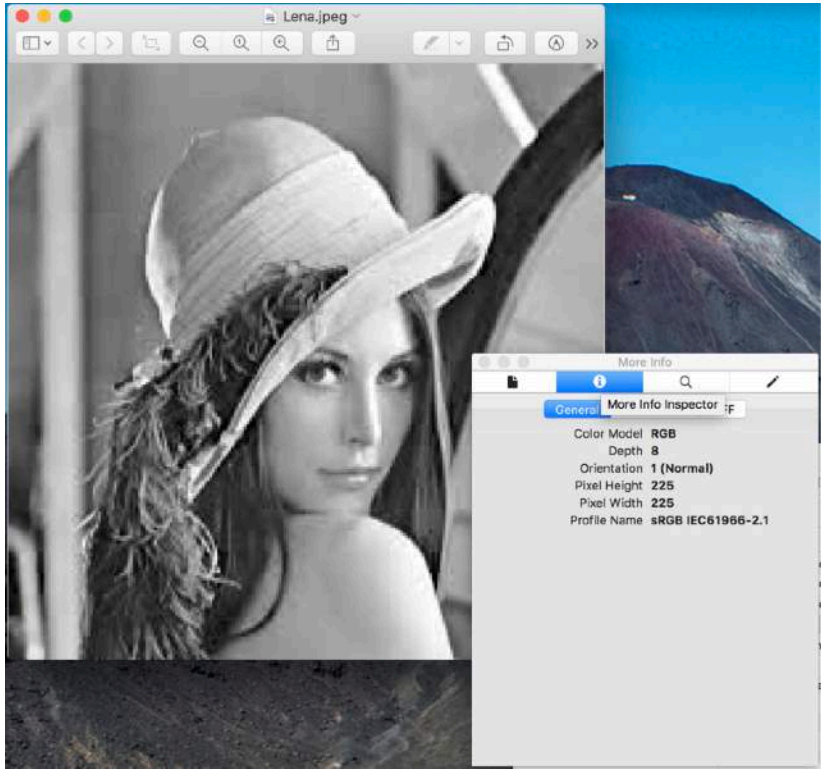


reduced CNR

File formats (1/3)

- **Image file formats** are standardized means of *organizing* and *storing* digital images

- The **pixel data** is stored along with an header containing the **metadata**
  - pixel depth, image size …
  - camera parameters (e.g. exposure)
  - GPS location
  - …



- Pixel data can be **compressed**
  - **Lossless**: no information is lost
    (but low/mild compression rates)
  - **Lossy**: some information can be lost
    (but higher compression rates)

Major file formats

File Name	Description
JPEG/JPG (Joint Photographers' Expert Group)	Most popular lossy image format. Allows users to specify what level of compression they desire.
PNG (Portable Network Graphics)	Best of lossless image formats. Widely supported across web. Allows you to include an alpha channel within file.
BMP (BitMaP)	Would avoid if possible. They offer little to no compression which results in unnecessarily large files.
TIFF/TIF (Tagged Image File Format)	Offers both compressed and uncompressed versions. Compressed are similar to PNG and uncompressed is similar to BMP.
PDF (Portable Document Format)	Most widely used document format. Great vector image format. Created by Adobe.
EPS (Encapsulated PostScript)	Most common vector image format. Standard format for print industry.
GIF (Graphics Interchange Format)	Lossless format that supports both animated and static images. Great for webpage banner ads.

File formats (3/3)

- Many **libraries** to *open, save, manipulate* and *visualize* images
- e.g. MATLAB
  - `I = imread( 'picture_01.jpeg' );`
  - `I = imread( 'picture_02.png' );`
  - `[M, N] = size( I );`
  - `imshow( I );`
  - `imwrite( I, 'my_image.jpeg' );`
  - `H = imfinfo( 'lena256.bmp' );`

```
             Filename: 'C:\Users\User\Downloads\assign1\lena256.bmp'
          FileModDate: '03-Mar-2017 21:59:45'
             FileSize: 66614
               Format: 'bmp'
        FormatVersion: 'Version 3 (Microsoft Windows 3.x)'
                Width: 256
               Height: 256
             BitDepth: 8
            ColorType: 'indexed'
      FormatSignature: 'BM'
  NumColormapEntries: 256
             Colormap: [256x3 double]
              RedMask: []
            GreenMask: []
             BlueMask: []
      ImageDataOffset: 1078
     BitmapHeaderSize: 40
            NumPlanes: 1
      CompressionType: 'none'
           BitmapSize: 65536
       HorzResolution: 0
       VertResolution: 0
        NumColorsUsed: 256
   NumImportantColors: 0
```