

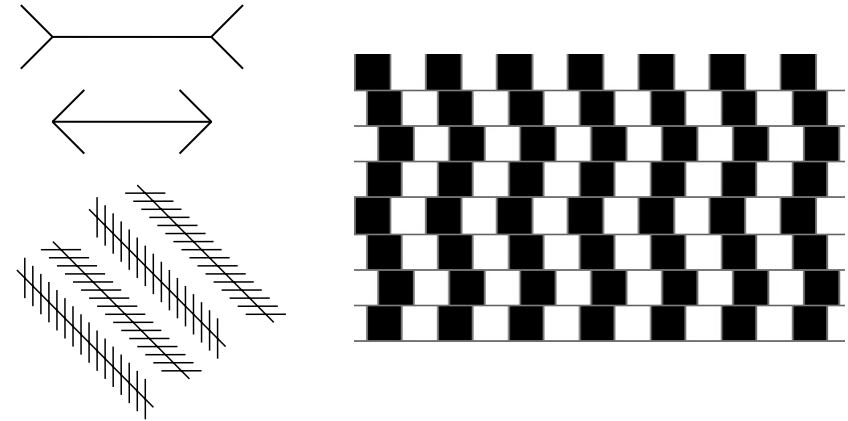
# MEDICAL IMAGING METHODS

Miklós Kellermayer

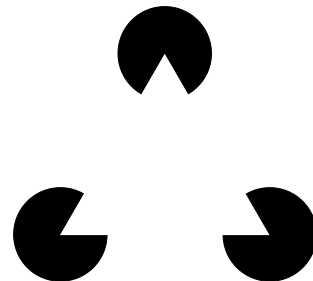
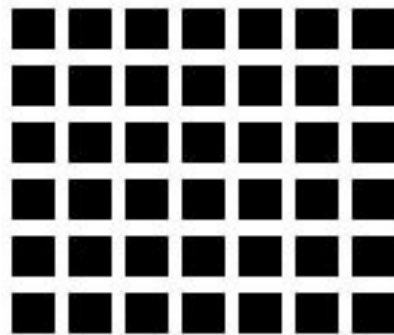
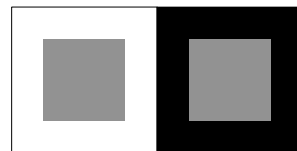
## I. The digital image

**Seeing is believing!?**  
Vision is not only the detection of image information,  
but complex processing occurs as well

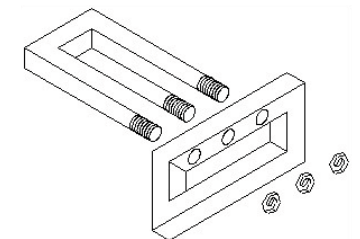
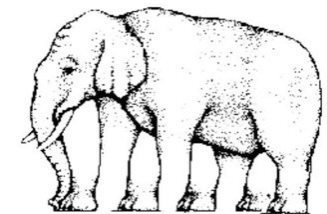
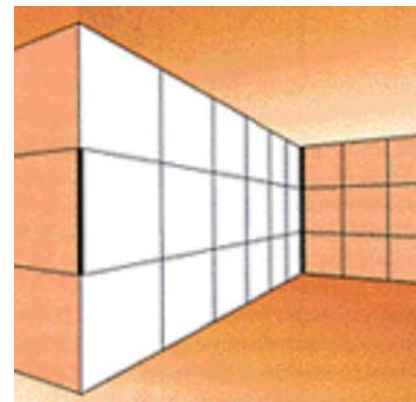
**Optical illusions – size, direction**



**Optical illusions - intensity (color density)**



**Optical illusions – space**



## Optical illusions – motion

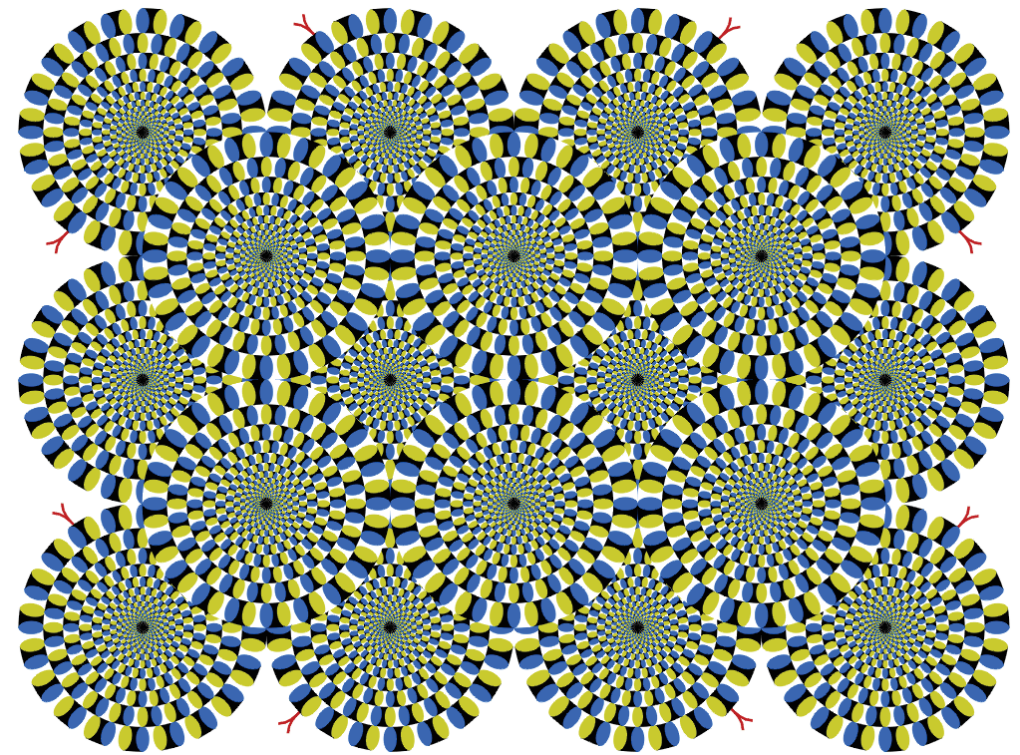
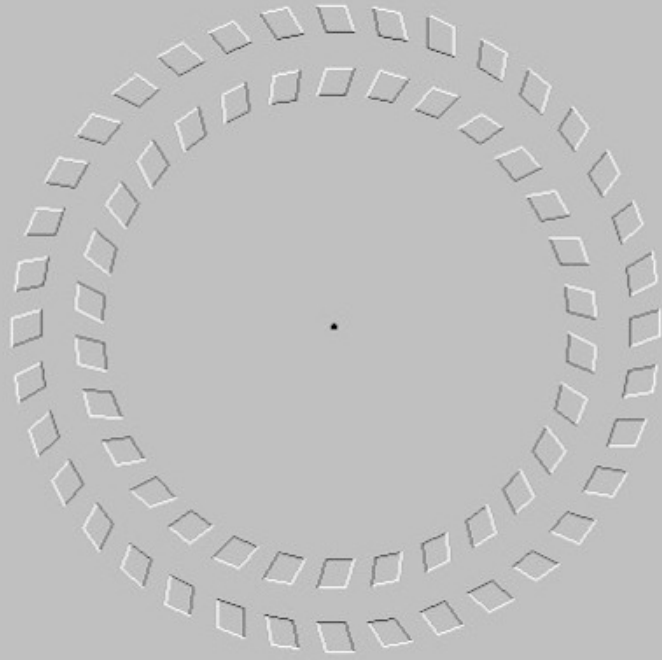
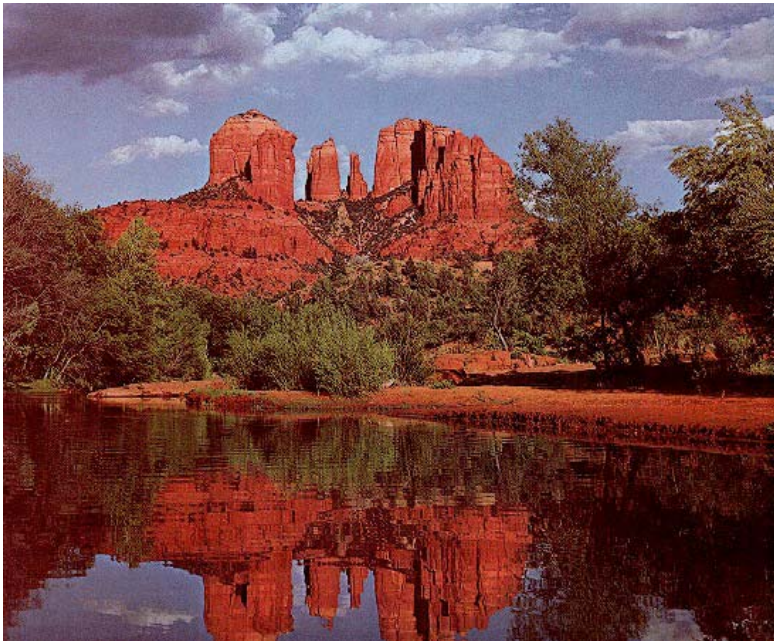
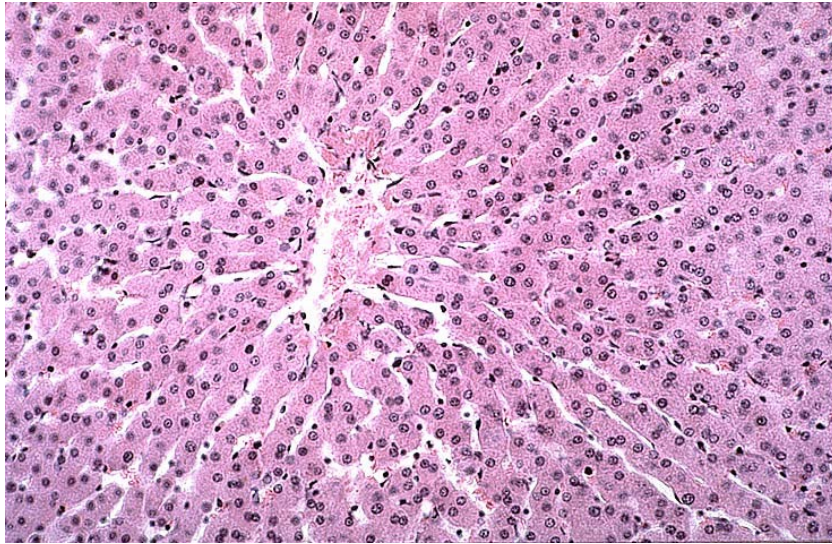


Image: information that is visible ... or not?

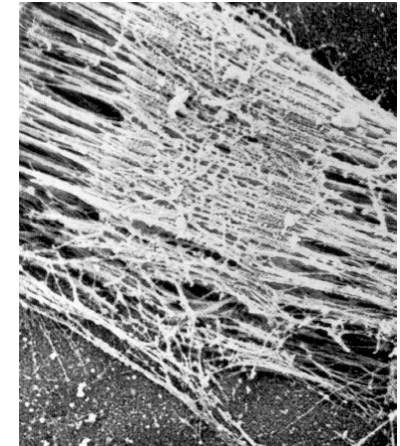




**Light microscopic image**  
Hepatic lobule

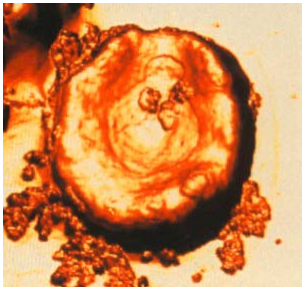


**Scanning electron microscopic images**

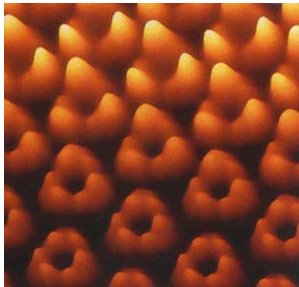


**Atomic force microscopic images**

Red blood cell



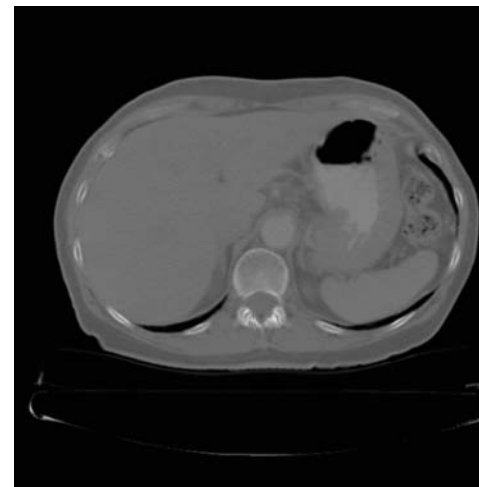
bacteriorhodopsin



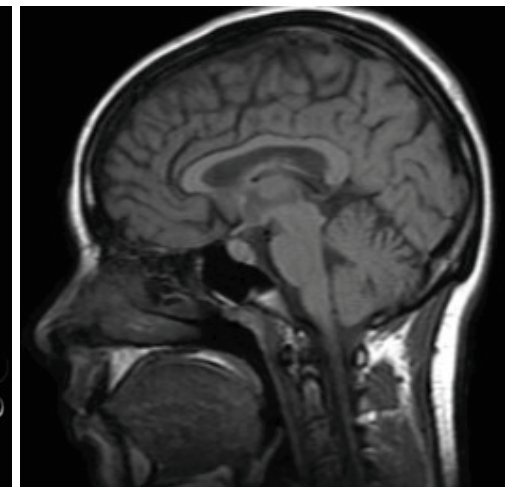
DNA



CT



MRI

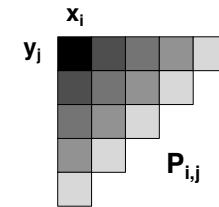


## Digital Image Analysis

1. The digital image
  - a. Generation
  - b. Characteristics
2. Image enhancement techniques
  - a. Contrast manipulation
  - b. Convolution
  - c. Rank operations
3. Geometric transformations
4. Fourier transformation
5. Thresholding and segmentation
6. 3D image analysis

## The digital image

**Digital image:** information displayed at different discrete spatial points in the form of color. 2 or 3 dimensional array or matrix of picture elements.

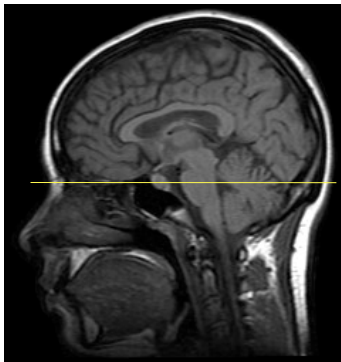


### Characteristics of the digital image:

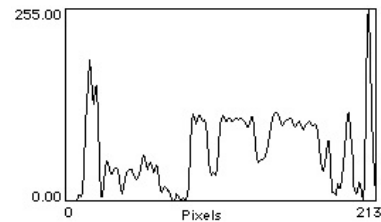
1. *Picture element: pixel (pix=picture; element)*
2. *Information associated with the pixel:*
  - a. XY location: coordinates related to spatial resolution
  - b. Color depth: intensities related to color (or grayscale) resolution
3. *Spatial resolution:*  
Number of resolved pixels in the X and Y directions.
4. *Grayscale/color depth:*  
Number of resolved colors/grayscale intensities (bit)  
(BUT: color is not necessarily real; e.g. AFM, CT, MRI)

## THE COLOR HISTOGRAM

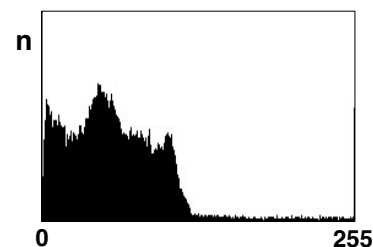
(intensity histogram, "grayscale" histogram)



Resolved intensities may be displayed as a function

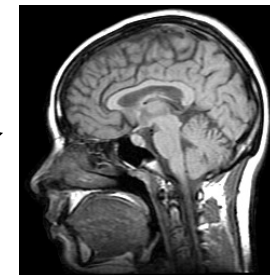
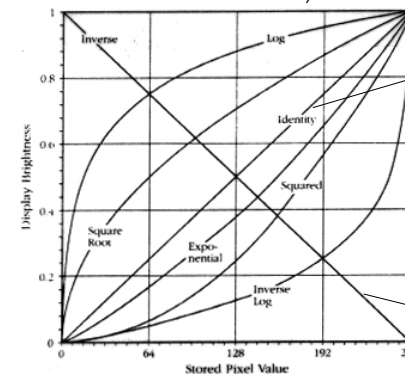


**Histogram:** relative frequency of colors or grayscale intensities in the image



## Image enhancement techniques I. Contrast manipulation A.

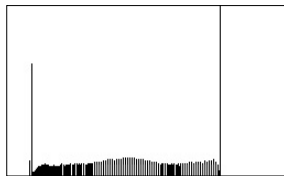
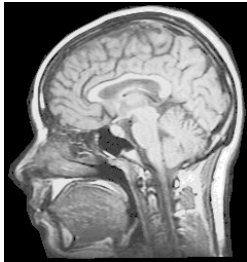
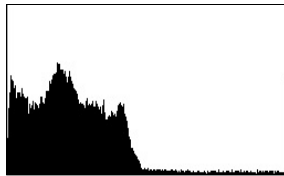
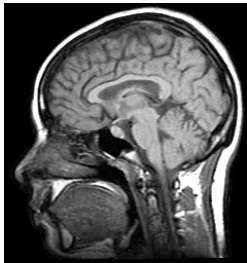
**Contrast transfer function:**  
assigns color to pixel densities (expressed in numerical values)



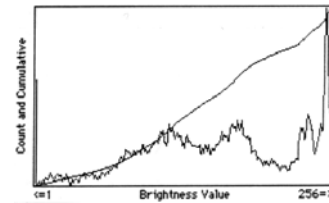
## Contrast manipulation B.

### Histogram equalization

Goal: best use of the available color/grayscale range



The cumulative histogram of the image is used as its contrast transfer function



## Image enhancement techniques II.

### Convolution

Special transformation between two functions (the image and the kernel)

Kernel operations

„smoothing” kernel

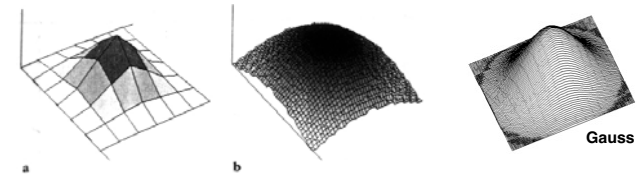
1	1	1
1	1	1
1	1	1

$$P_{x,y}^* = \frac{\sum_{i,j=-m}^{+m} W_{i,j} \cdot P_{x+i,y+j}}{\sum_{i,j=-m}^{+m} W_{i,j}}$$

„smoothing” convolution

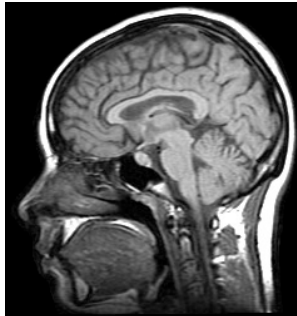
P=original pixel intensity  
x,y=coordinates of the pixel on which operation is being executed  
P\*=modified pixel intensity  
±m=size of kernel (distance from x,y coordinate)  
W=weight of kernel at a given i,j coordinate  
i,j=coordinates within kernel (integers between -m and +m)

Various kernels



## Image enhancement techniques II. Convolution

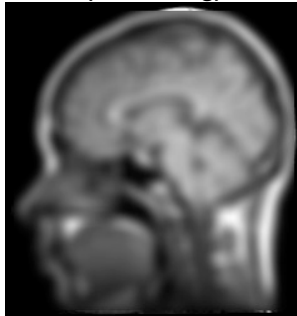
Original image



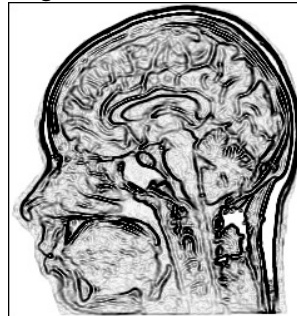
Sharpening



Gauss (smoothing)



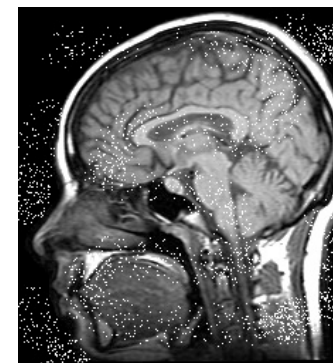
Edge detection



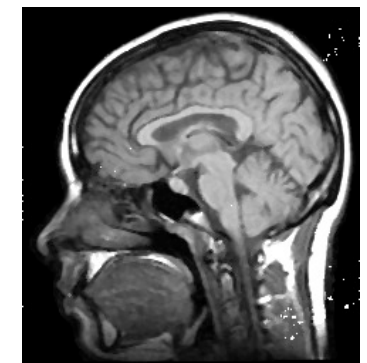
## Image enhancement techniques III. Rank operations

Principle: the pixel is exchanged for another from its ranked neighborhood (e.g., min, max, median)

Noise removal using median filtering:



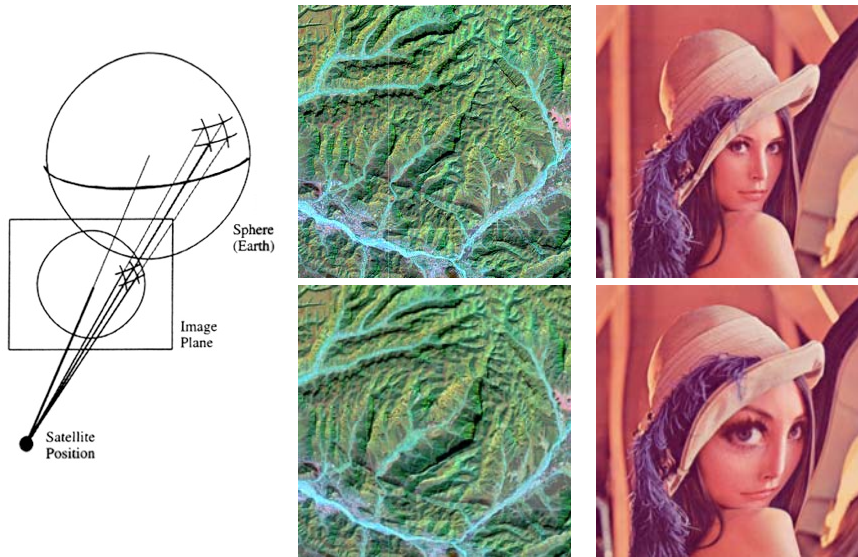
3x3 median filter





## Geometric transformations

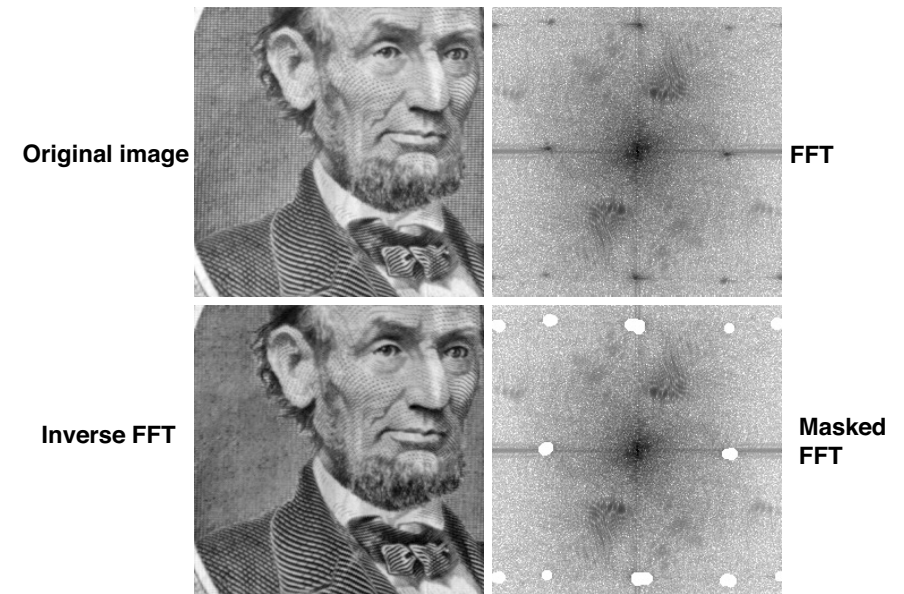
Basic problem: 2D image from 3D object



## IV. Fourier transformation

Fourier principle: any function may be generated as the sum of a sine function and its harmonics.

Fourier transform -> spectral density: displays the contribution of a given frequency.

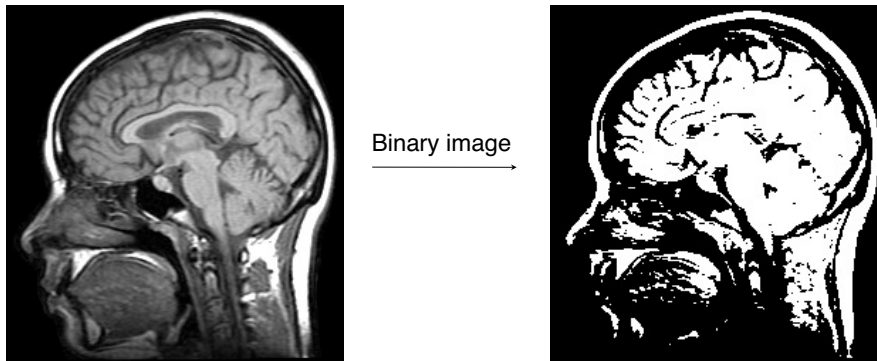


## Thresholding, segmentation

**Principle:** The image is partitioned according to certain parameters.

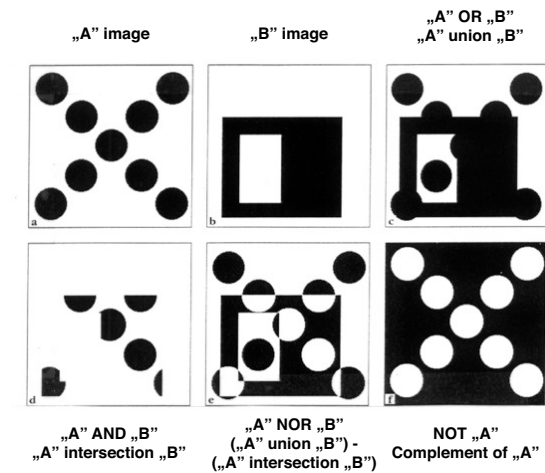
**Execution:**

1. Select a certain grayscale range of the image
2. The selected pixels form the "foreground"
3. The rest of the pixels form the "background"



## Binary operations I.

Boolean operations

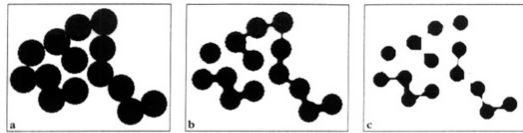


## Binary operations II.

### Erosion, dilatation, Opening, Closing

Moving pixels from the foreground to the background and *vice versa*

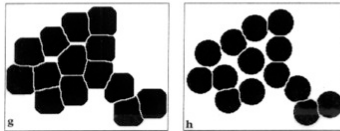
Erosion ->



Dilatation ->



Boolean operation ->



Result: separation of touching objects

## Binary operations III.

### Skeletonization, Outlining

Erosion and dilatation with certain rules

Original image



Binary image



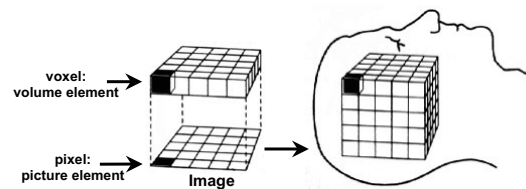
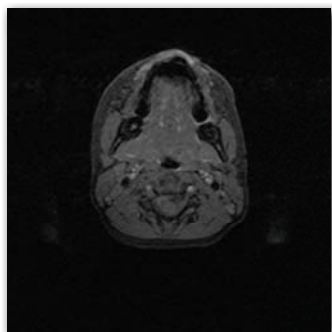
Skeletonized image



Outlined image



## 3D image processing



Spatial projection  
(„volume rendering“)

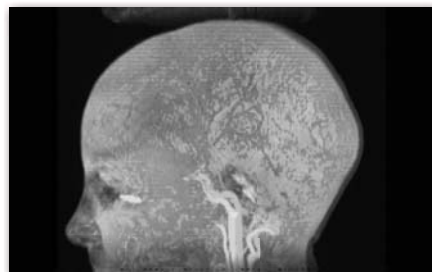
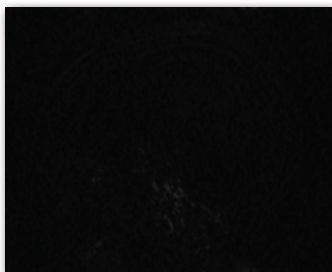
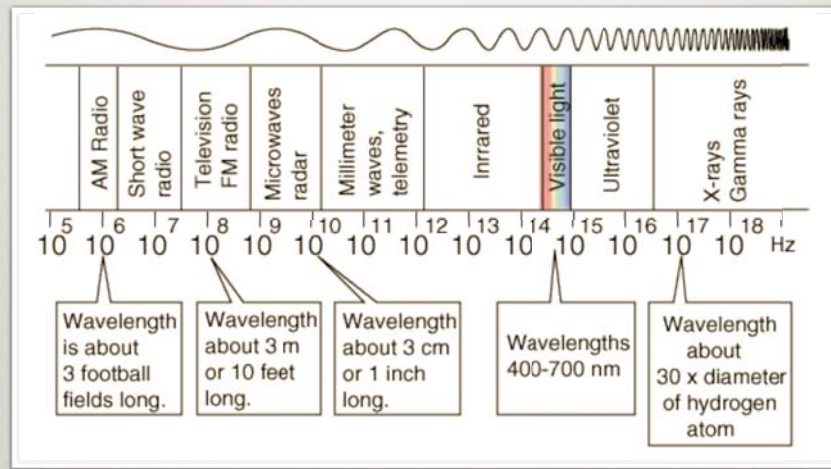


Image format of medical diagnostics: DICOM (Digital Imaging and Communications in Medicine)

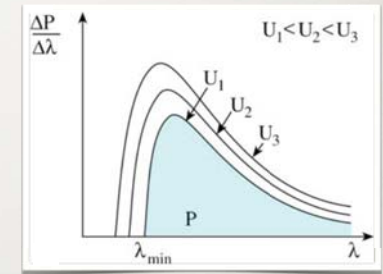
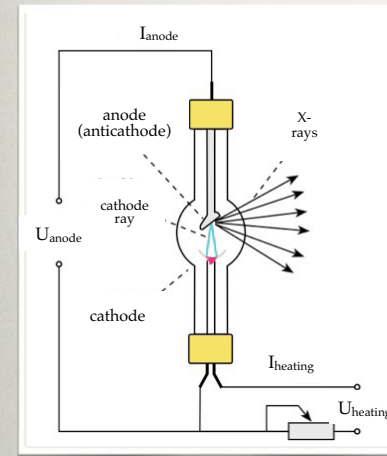
## II. X-ray imaging

# X-RAYS ARE ELECTROMAGNETIC WAVES



Wavelength 10 - 0.01 nm. Frequency 30x10<sup>15</sup> - 30x10<sup>18</sup> Hz. Energy 120 eV - 120 keV.

# GENERATION OF X-RAY



Duane-Hunt formula:

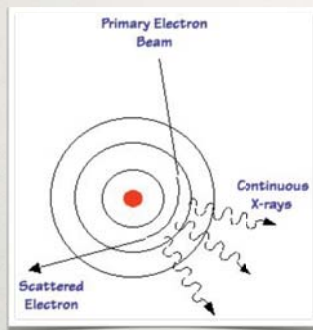
$$\lambda_{\min} = \frac{hc}{e} \cdot \frac{1}{U_{\text{anode}}}$$

h=Planck's constant  
c=speed of light  
e=elementary charge

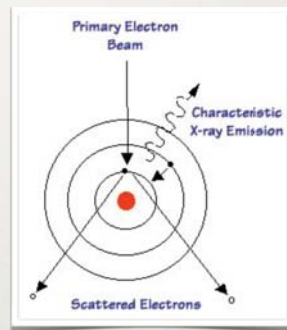


Rotating anode X-ray tube

# MECHANISMS OF X-RAY GENERATION



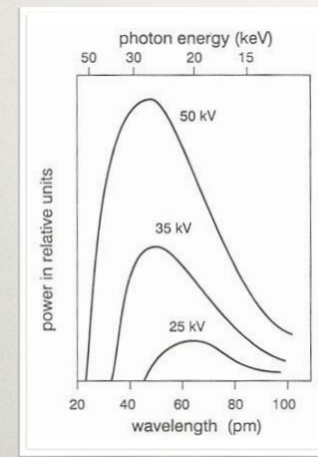
"Bremsstrahlung"  
Breaking radiation  
Deceleration radiation



Characteristic radiation  
X-ray fluorescence

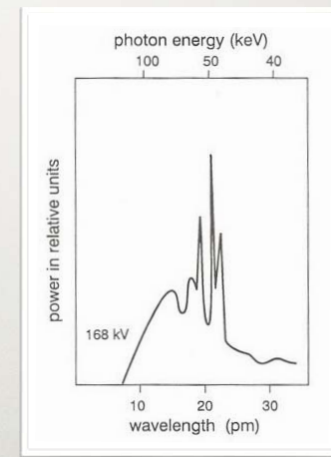
# SPECTRAL FEATURES OF X-RAY

"Bremsstrahlung"



Continuous spectrum

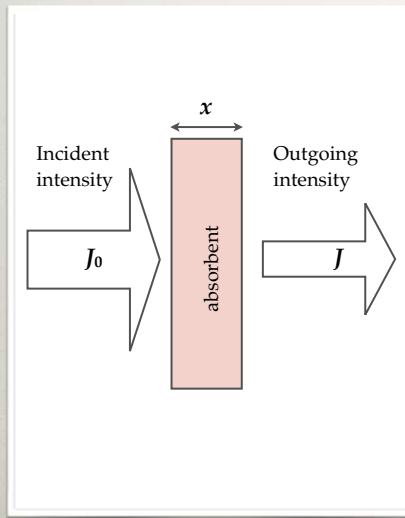
Characteristic radiation



Linear spectrum



# X-RAY ABSORPTION



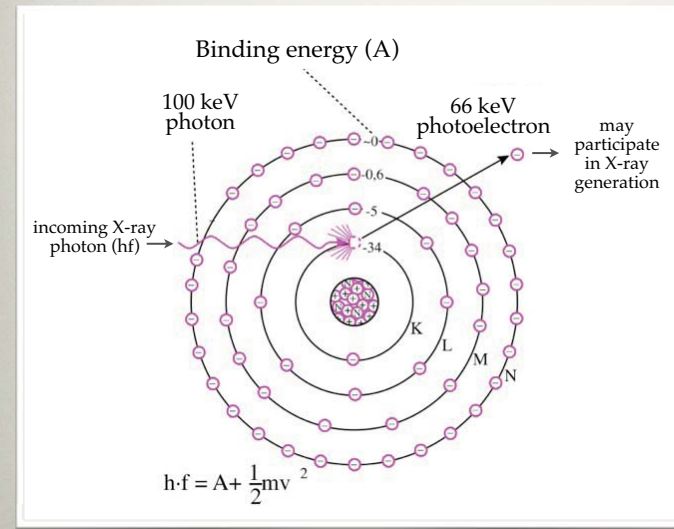
Exponential attenuation principle

$$J = J_0 e^{-\mu x}$$

$$\mu = \mu_m \rho$$

$\mu$ =attenuation coefficient  
 $\mu_m$ =mass attenuation coefficient ( $\text{cm}^2/\text{g}$ )  
 $\rho$ =density ( $\text{g}/\text{cm}^3$ )

# X-RAY PHOTOEFFECT

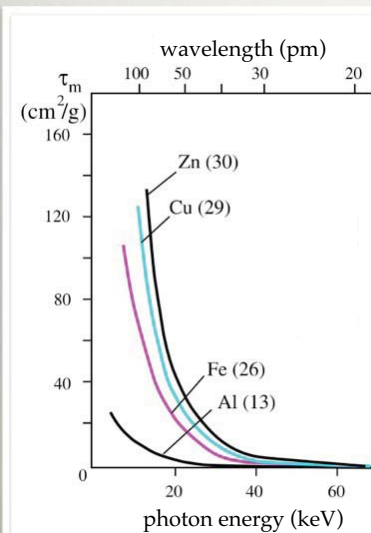


Main effect in diagnostic X-ray!

Photoeffect attenuation coefficient:

$$\tau = \tau_m \rho$$

# PHOTOEFFECT ATTENUATION DEPENDS STRONGLY ON ATOMIC NUMBER



$$\tau_m = \text{const} \cdot \frac{Z^3}{\epsilon^3} = C \cdot \lambda^3 \cdot Z^3$$

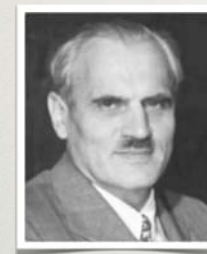
For multi-component system:  
 "effective atomic number" ( $Z_{\text{eff}}$ )

$$Z_{\text{eff}} = \sqrt[n]{\sum_{i=1}^n w_i Z_i^3}$$

$\epsilon$ =photon energy  
 $Z$ =atomic number  
 $w$ =mole fraction  
 $n$ =number of components

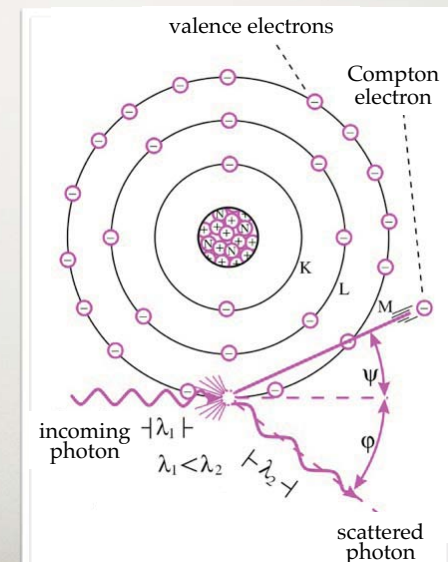
Material	$Z_{\text{eff}}$
Air	7.3
Water	7.7
Soft tissue	7.4
Bone	13.8

# COMPTON SCATTER

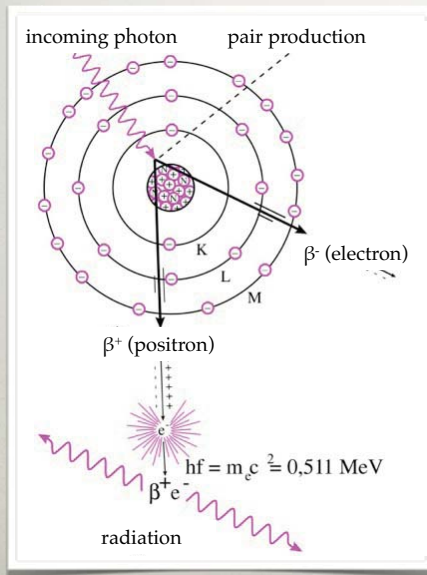


Arthur Holly Compton  
 (1892-1962)

$$hf = A + hf_{\text{scatt}} + E_{\text{kin}}$$



# PAIR PRODUCTION



Energy balance:

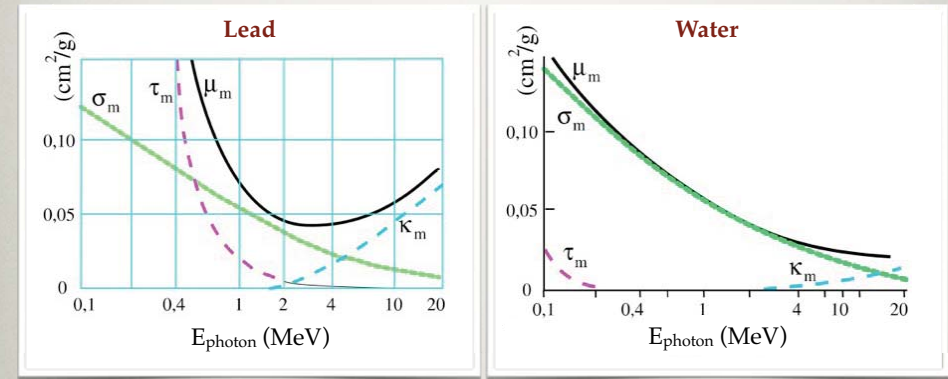
$$hf = 2m_e c^2 + 2E_{kin}$$

$m_e$ =mass of electron  
 $c$ =speed of light

Pair production relevant in high-energy X-ray photons,  $\gamma$ -radiation.

# ATTENUATION MECHANISMS

Dependence on photon energy and material



$$\mu = \tau + \sigma + \kappa$$

$\mu_m$ =mass attenuation coefficient

$\sigma_m$ =Compton effect mass attenuation coefficient

$\tau_m$ =photoeffect mass attenuation coefficient

$\kappa_m$ =pair production mass attenuation coefficient

# SUMMARY OF ATTENUATION MECHANISMS

Mechanism	Variation of $\mu_m$ with E	Variation of $\mu_m$ with Z	Energy range in tissue
Rayleigh	$\sim 1/E$	$\sim Z^2$	1 - 30 keV
photoelectric	$\sim 1/E^3$	$\sim Z^3$	10 - 100 keV
Compton	falls gradually with E	independent $\sim Z$	0.5 - 5 MeV
pair production	rises slowly with E	$\sim Z^2$	> 5 MeV

Main contrast mechanism in diagnostic X-ray:  
photoelectric effect ( $\sim Z^3$ )

# IMAGING WITH X-RAY

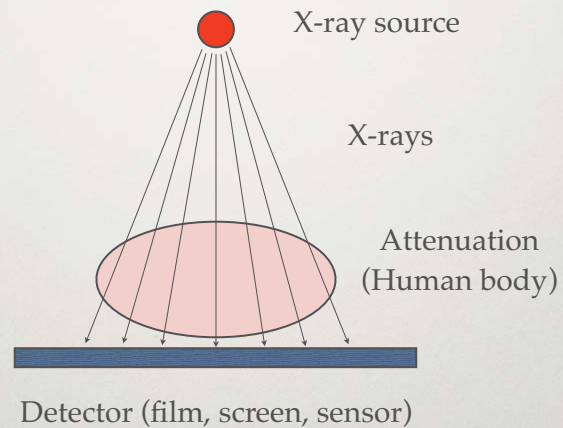


Wilhelm Konrad Röntgen (1845-1923)



Hand mit Ringen (Hand with Ring): print of Wilhelm Röntgen's first "medical" X-ray, of his wife's hand, taken on 22 December 1895 and presented to Professor Ludwig Zehnder of the Physik Institut, University of Freiburg, on 1 January 1896. The dark oval on the third finger is a shadow produced by her ring.

# PRINCIPLE OF X-RAY IMAGING



# THE X-RAY IMAGE

$$J = J_0 e^{-(\mu_1 x_1 + \mu_2 x_2 + \mu_3 x_3 + \dots)}$$

$$\lg \frac{J_0}{J} = (\mu_1 x_1 + \mu_2 x_2 + \mu_3 x_3 + \dots) \cdot \lg e$$

$\mu$  and  $x$  are attenuation coefficient and thickness of elementary volume unit lying in the direction of X-ray beam.

**X-ray image is summation image.**  
 "X-ray image", "radiographic image", "roentgenogram".  
**Contrast arises due to relative attenuation.**

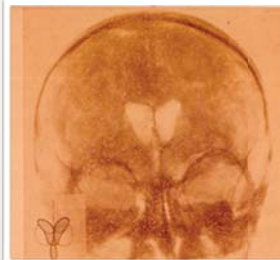


# RADIOGRAPHIC CONTRAST

Bowels (positive contrast)



Air (negative contrast)



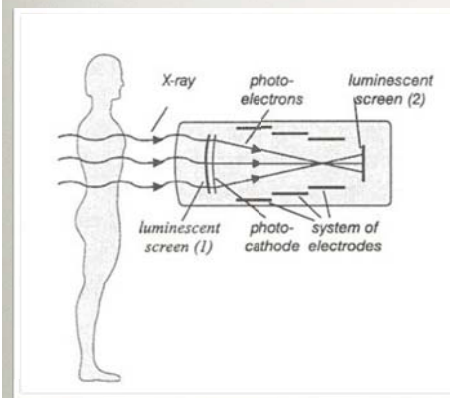
Large intestine (double contrast)



Small intestine (double contrast)



# IMPROVING THE X-RAY IMAGE THE IMAGE INTENSIFIER



"C-arm"



Possibility of image digitization.



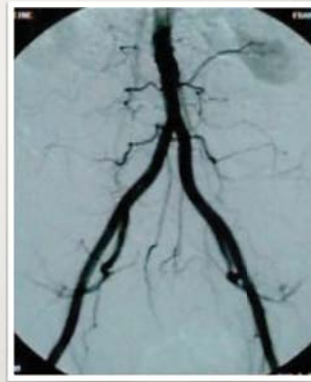
## DIGITAL SUBTRACTION ANGIOGRAPHY (DSA)



Image 1  
native



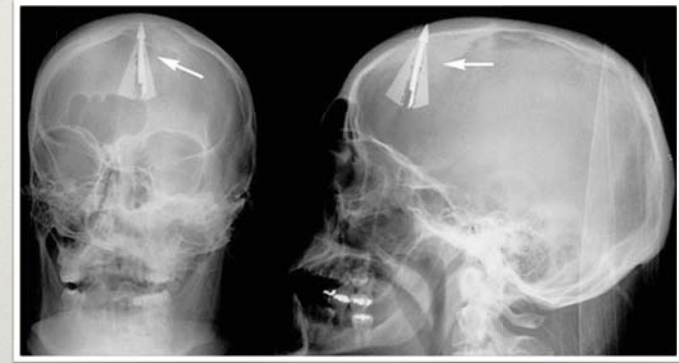
Image 2  
contrast



DSA image  
contrast-native

## IMPROVING X-RAY IMAGING II. SPATIAL RESOLUTION

Bi-directional X-ray imaging



Bi-directional cranial X-ray of an individual who tried to commit suicide with a crossbow.

## Improving X-ray imaging: the CAT scanner

### History

- Röntgen, Hounsfield and Cormack
- 1967: first CAT scan
- 1972: prototype
- 1974: first clinical CAT image (head)
- 1976: whole body CAT scan
- 1979: Nobe-prize
- 1990: spiral CAT scanner
- 1992: multislice CAT scanner
- 2006: 64 slice (and more...)
- multiple and hybrid modes: SPECT-CT, PET-CT, Dual-source CT



Godfrey Hounsfield



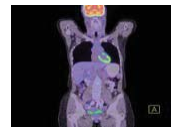
Allan Cormack



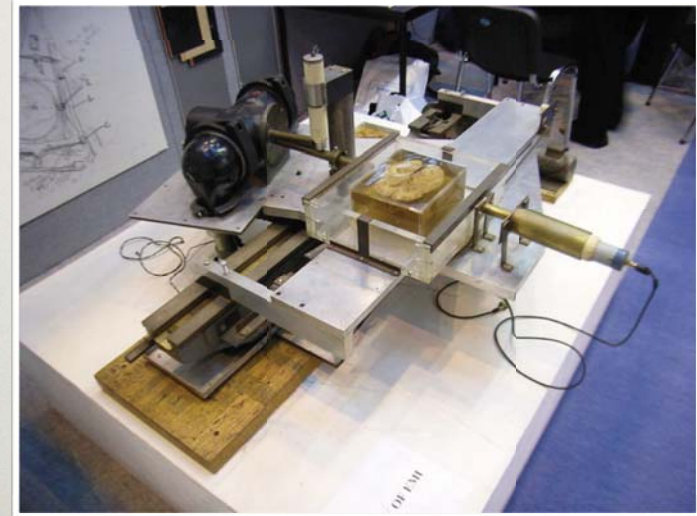
„Siretom“ head  
scanner (1974)



128x128 pixel image  
(1975)

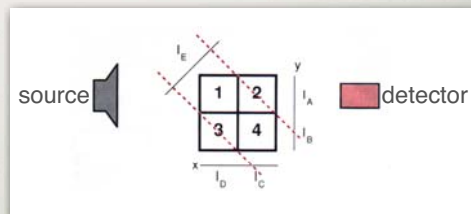
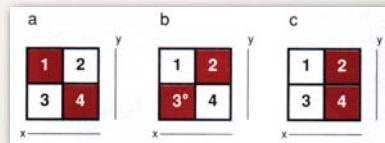
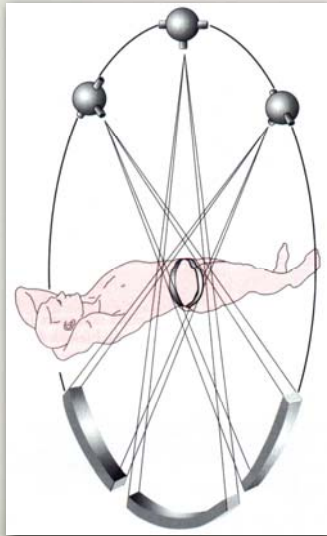


## PROTOTYPE CT SCANNER

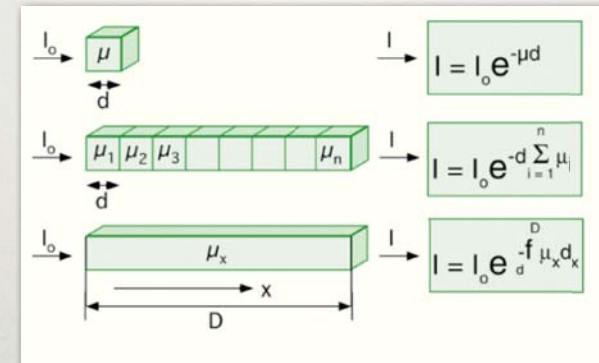


The very first ct scanner prototype. Invented by Hounsfield at EMI.

## CT FOUNDATIONS I

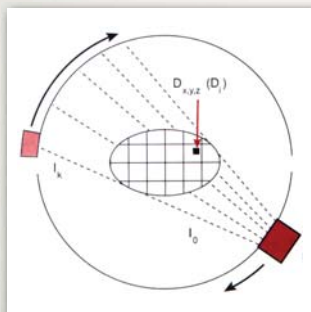


## CT FOUNDATIONS II

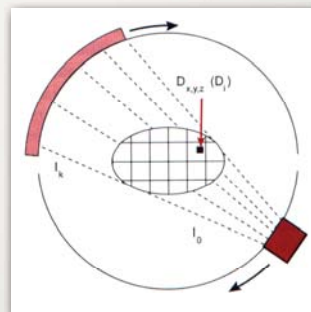


$\mu_x$ : linear attenuation coefficient

## SCANNING I

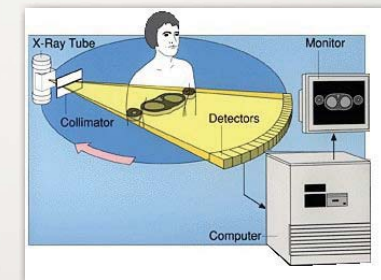
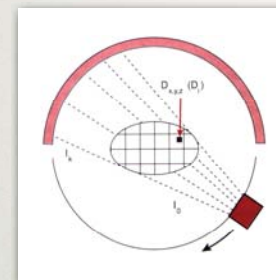


I. generation  
Single moving source  
Single moving detector



II. generation  
Single moving source  
Narrow fan-beam  
Multiple moving detectors

## SCANNING II



III-IV. generation: single moving source, wide fan-beam, multiple detectors or detector ring



closed gantry

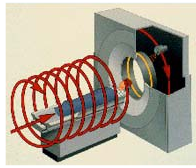


open gantry

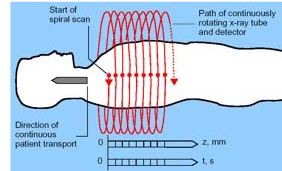


## Spiral (helical) CAT scanning

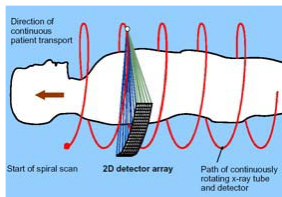
Source-detector pair rotates constantly



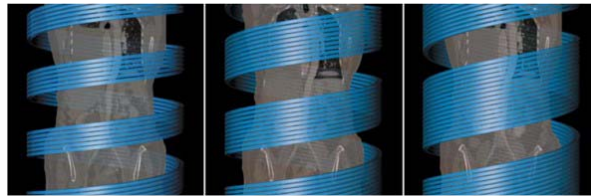
Conventional CT slice



Spiral CT slice



Multi-detector CT (MDCT)



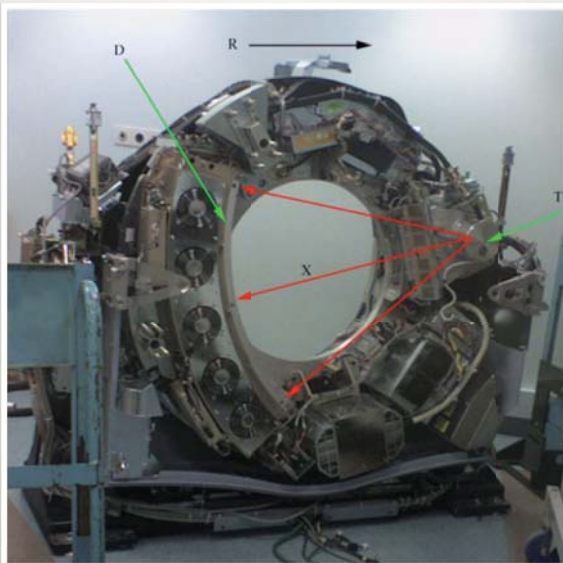
Multi-slice CT (MSCT)

## CT scanning (CAT)

- Tomographic digital imaging method that uses X-rays
- Principle: displaying differences in X-ray absorbance by the different points of the tomographic slice
- Conventional (outdated) technique:  
one slice – 2 - 4 sec,  
entire examination: 5 - 15 perc
- Spiral CT technique:  
one slice – 1 - 1.5 sec,  
entire examination: 30 - 60 sec (+ preparation)
- Multidetector spiral CT (4-64 detector array):  
one slice – 0.4 - 1 sec,  
entire examination: 5 - 15 sec

## CT SCANNER OPERATION

Detectors



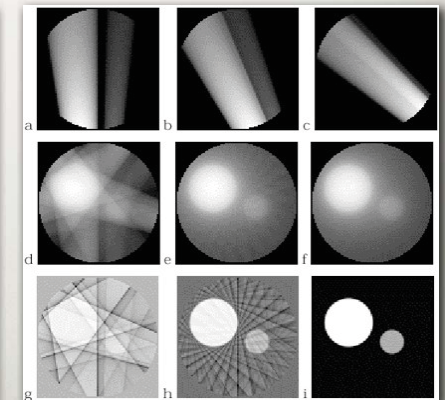
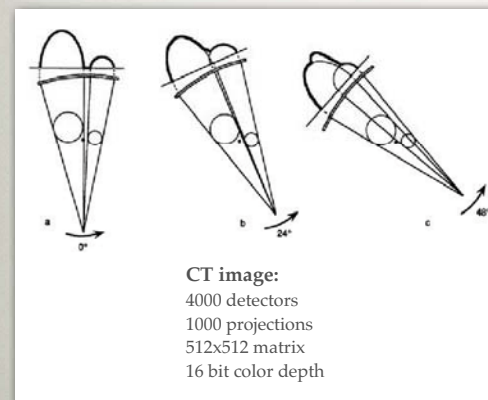
Rotation

Tube

X-ray beams

## CT IMAGE RECONSTRUCTION

1. Algebraic reconstruction techniques
2. Direct Fourier reconstruction
3. „Filtered Back Projection“

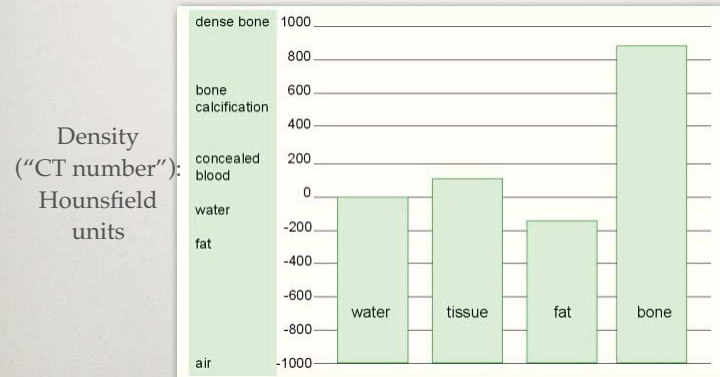




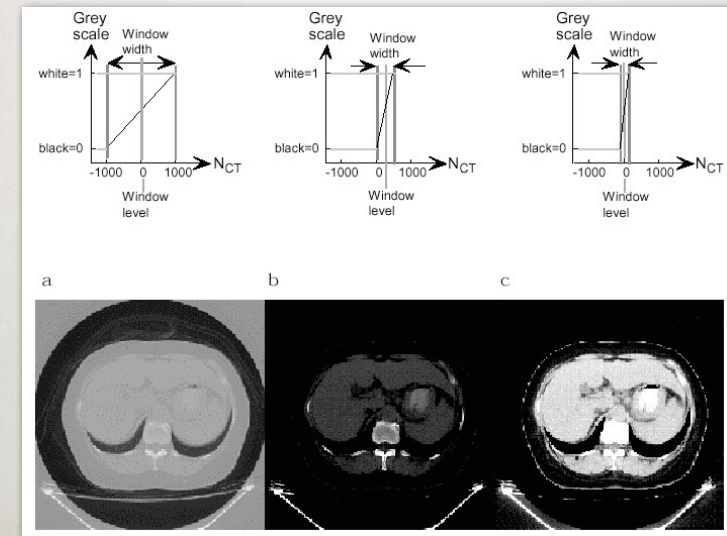
## CT IMAGE: DENSITY MATRIX

$$N_{CT} = 1000 \frac{\mu - \mu_w}{\mu_w}$$

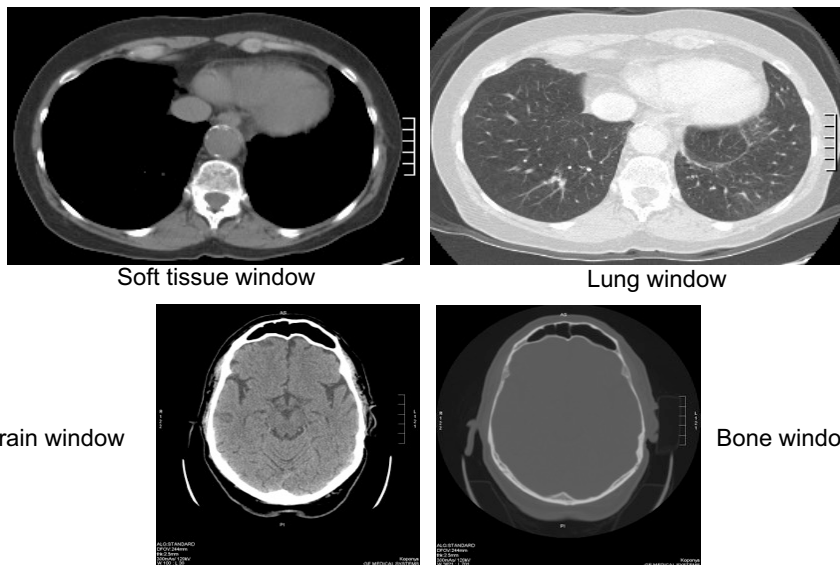
$\mu$ : attenuation coefficient of voxel  
 $\mu_w$ : attenuation coefficient of water



## CONTRAST MANIPULATION OF CT IMAGE „WINDOWING”



## Manipulation of CT contrast „Windowing”

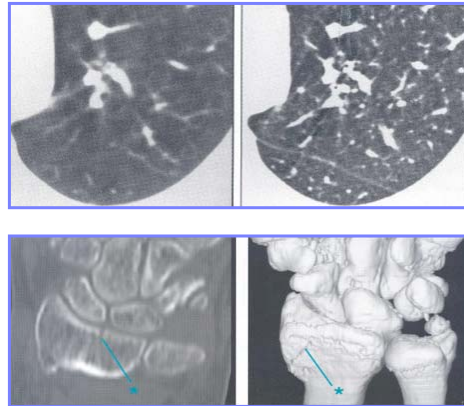


## Limitations of CAT scanning

- Ionizing radiation
- Irradiation dose up to 50-100 times that of conventional X-ray imaging!
- direct exposure to radiation
- + scattered radiation (its intensity is 1-2 orders of magnitude smaller)

## HRCT (High Resolution CT)

- Very thin (1-2 mm) slices, very high contrast resolution.
- Important in case of large contrast differences (e.g., bone - lung).
- Image processing: by using dedicated algorithms



## Dual Source CT

- Simultaneous use of two different X-ray sources and detectors.
- The two tubes are positioned perpendicular to each other, the detectors work in synchrony.
- If the sources are operated at identical accelerating voltage, 90° rotation is sufficient to generate a tomographic slice.
- The sources may also be operated at different accelerating voltages ("dual-energy mode", 80 and 140 kV). 180° rotation is required to generate an image slice.
- In dual-energy mode two image slices with different information content are generated, due to the different tissue absorbance of the X-ray photons with different energies

## CT contrast agents

- Water soluble, iodine-containing macromolecule causing enhanced absorbance (hence color density) at the sites of accumulation
- Ionic contrast agent – outdated (abandoned since the 1990s)
- Non-ionic (monomeric or dimeric, low osmolality)
- Filtration through the kidney (nephrotropic). Its filtration begins immediately.
- Applications: every X-ray based imaging method

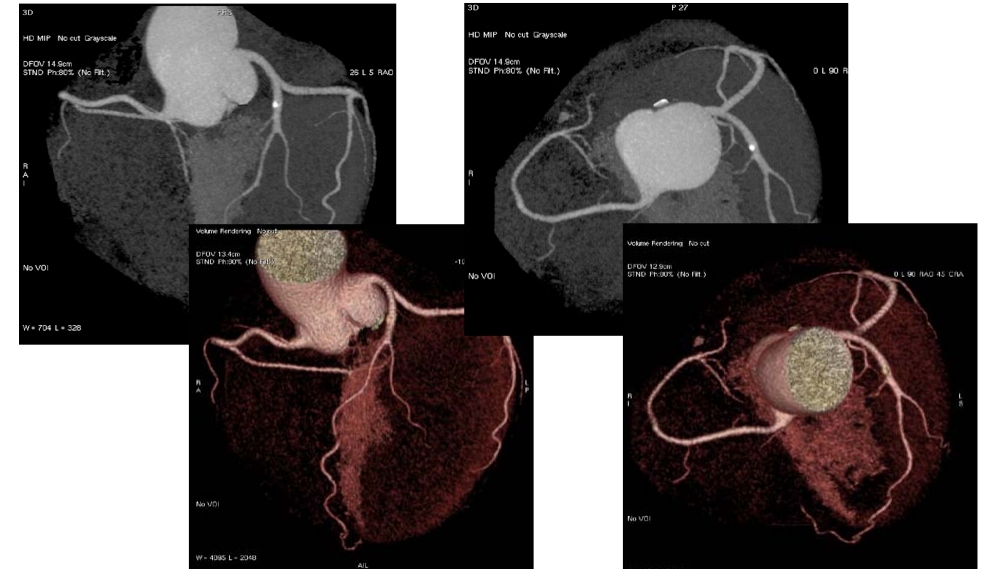
## Imaging blood vessels - CT angiography

- **Native CT:** limited applications. Only in case of severely calcified vessel walls
- **With intravenous contrast agents:**  
"conventional" technique - vessels with  $d \geq 1$  cm (aorta)
- **Spiral CT-angiography:**  
Single-detector array spiral CT - aorta branches ( $d \geq 2-3$  mm)  
Multidetector array spiral CT - peripheral vessels ( $d \geq 1$  mm)

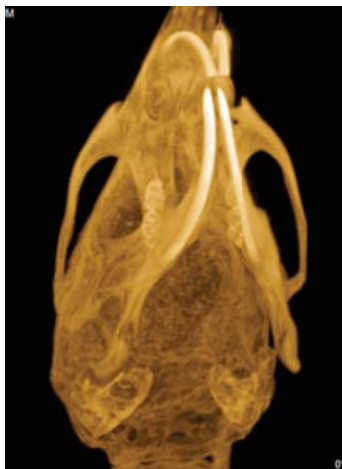
## Renal artery aneurysm CTA 8 detector-array spiral CT



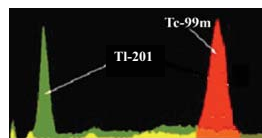
## Coronary CT-angiography (CTCA) 64-slice MDCT



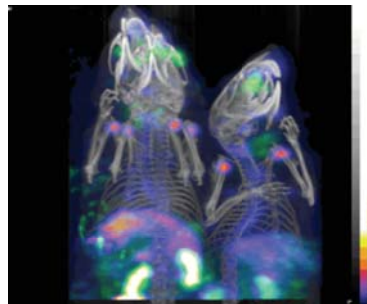
## Hybrid technologies: NanoSPECT/CT



CT: 36  $\mu$ m voxel size  
Real-time CT reconstruction (GPU)



"Dual-channel"  
SPECT

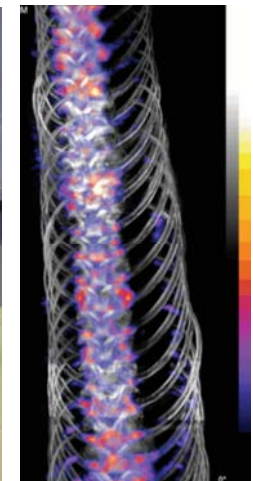


$^{99m}\text{Tc}$ -DTPA: diethylenetriaminepentaacetic (BBB) - blue/red  
 $^{99m}\text{Tc}$ -HMPAO: hexamethylpropyleneamine oxime (perfusion) - blue/red  
 $^{201}\text{Tl}$ -DDC: diethylthiocarbamate (perfusion) - green

## NanoSPECT/CT



*Boa constrictor*



Osteomyelitis,  $^{99m}\text{Tc}$ -MDP  
(methylene-diphosphonate)