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Biomedical Imaging

X-Ray Imaging (II)

Sebastian Kozerke

Institute for Biomedical Engineering, University and ETH Zurich, Switzerland

Today’s Learning Objectives

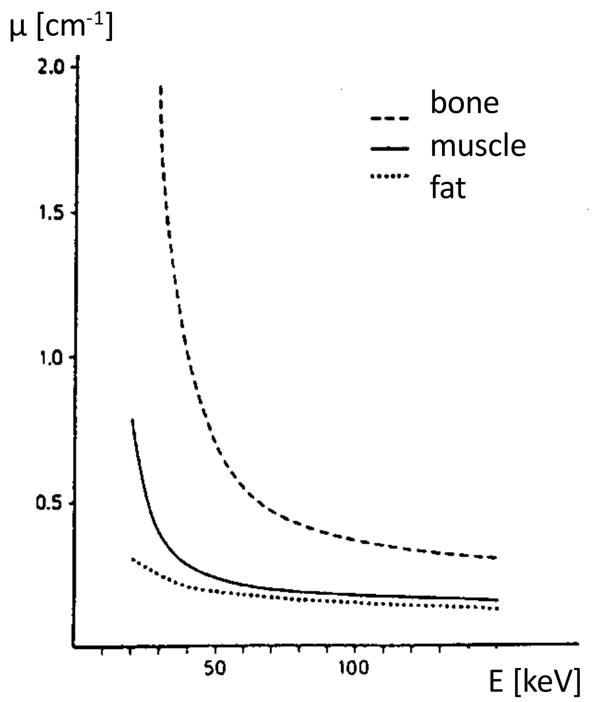
- **Describe basic X-ray detection technologies**
- **Relate image contrast to photon scattering**
- **Explain encoding and decoding of projection data**
- **Derive filtered back projection principle**
- **Implement CT encoding and decoding** (Exercise)

Resolution of imaging procedures

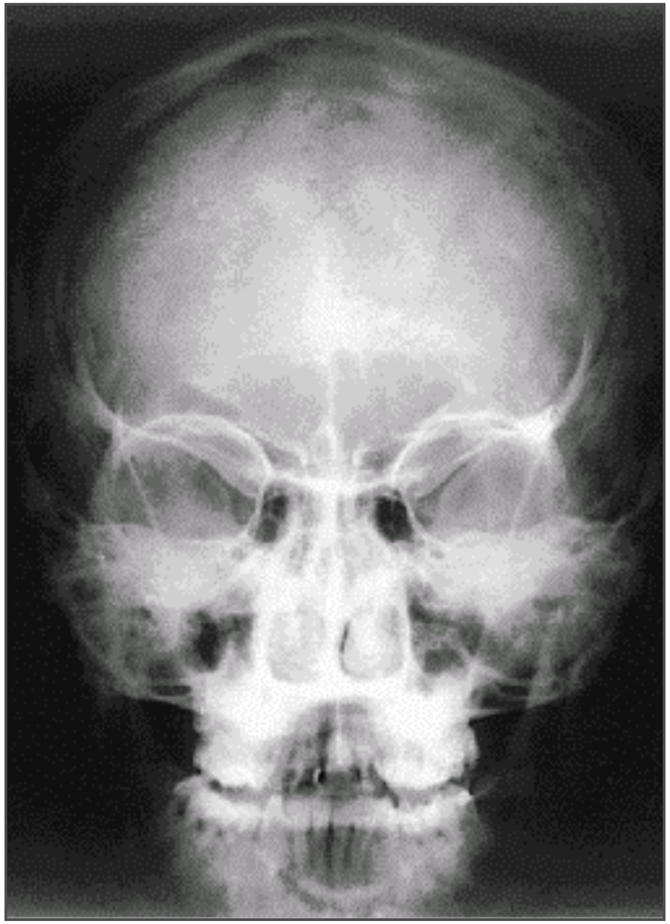
- Spatial resolution
  - Blurring of object points when projected into image
- Contrast
  - Difference in linear attenuation coefficients between tissues
- Temporal resolution
  - Sample rate of temporal recording

Resolution – Contrast

$$\text{Contrast} \propto \left(\mu_1 - \mu_0\right)\text{d}$$



Resolution – Contrast

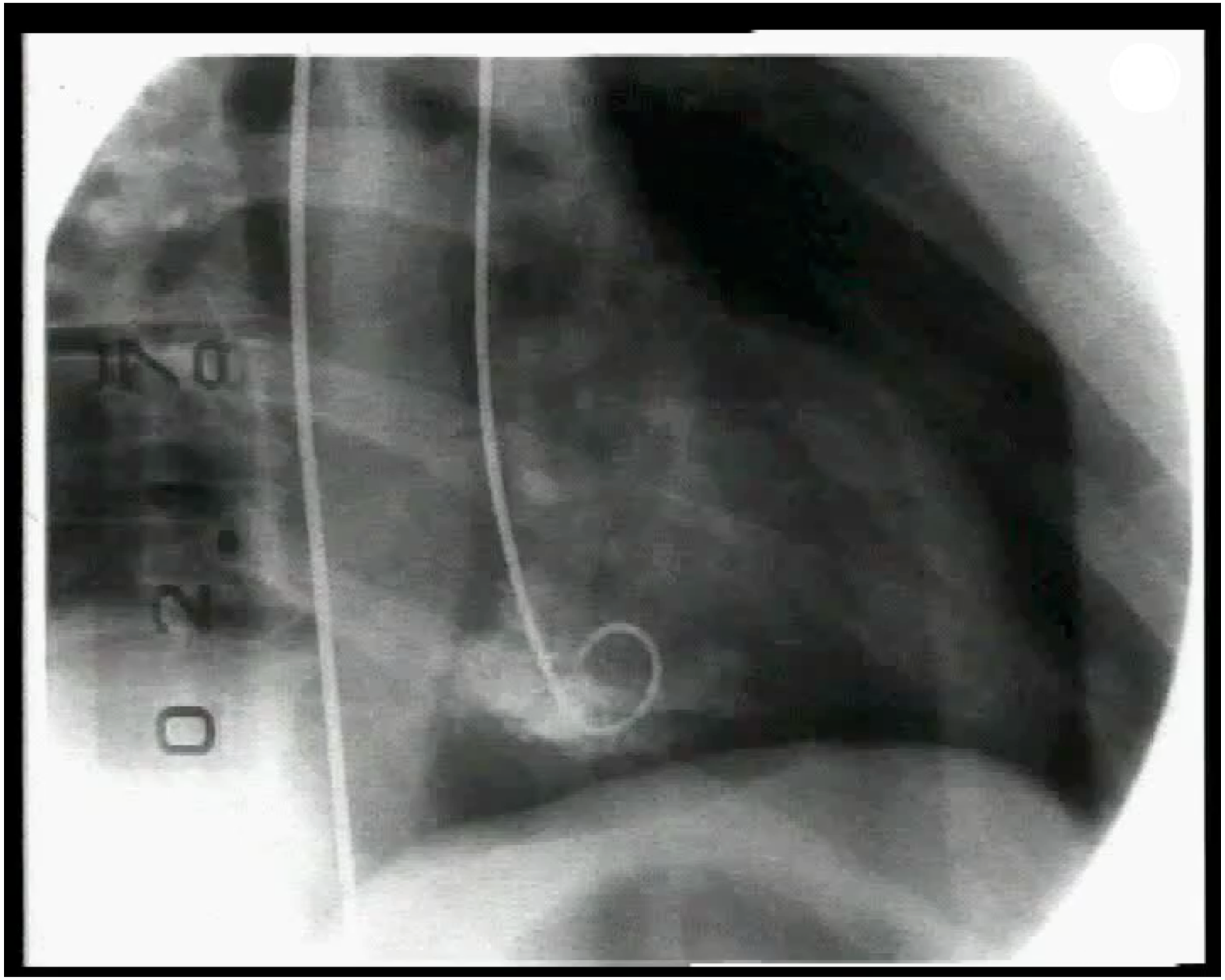


- Large contrast between bone and tissue/air
- Very little contrast among different tissues

Resolution of imaging procedures

- Spatial resolution
  - Blurring of object points when projected into image
- Contrast
  - Difference in linear attenuation coefficients between tissues
- Temporal resolution
  - Sample rate of temporal recording

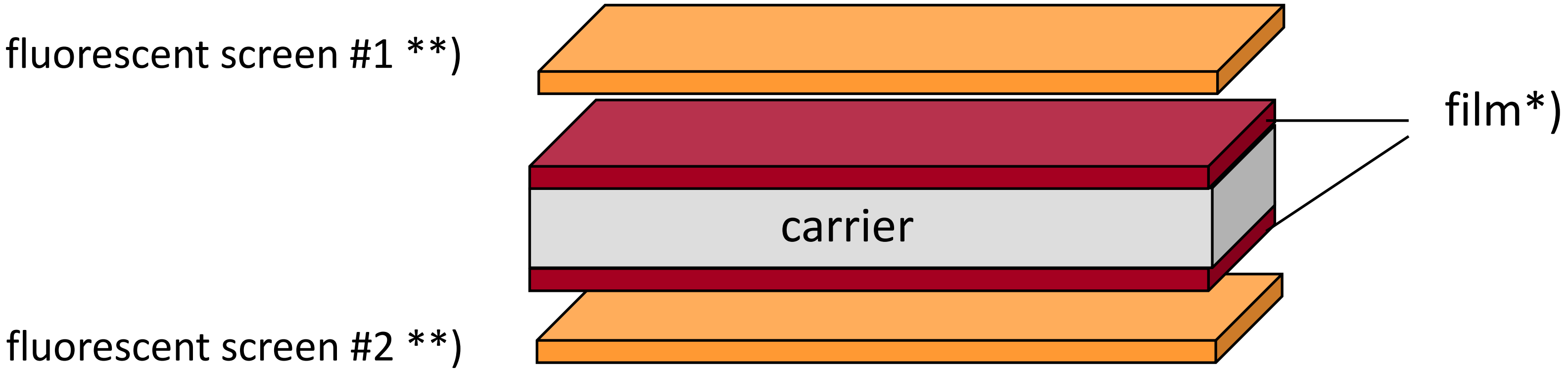
Resolution – Temporal resolution



Detector technology

Projection imaging – Photographic film

Double-sided film with intensifying screens



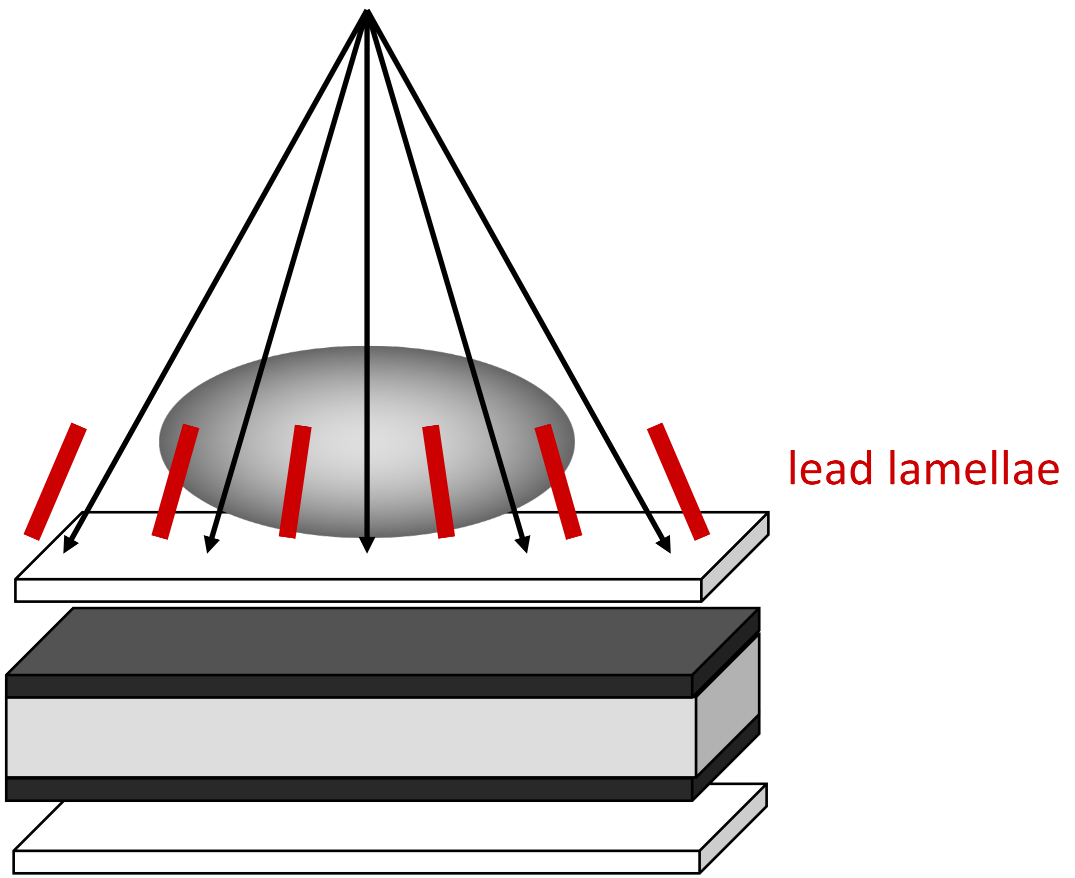
$$\text{Opacity} \propto \frac{I_0}{I}$$

*) Silver halide (AgX): compound formed between silver and silver bromide (AgBr) or silver chloride (AgCl) or silver iodide (AgI).

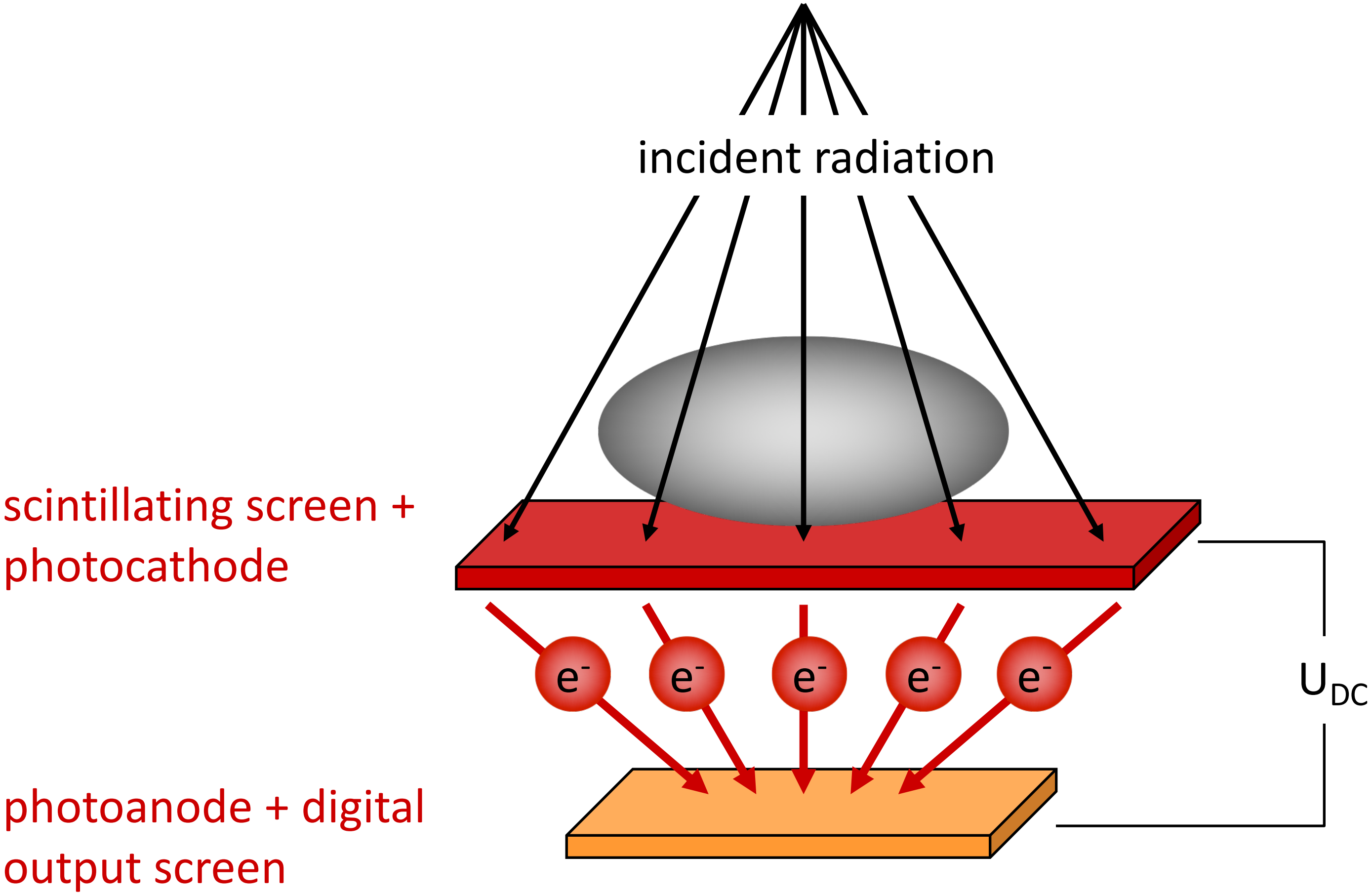
**) Fluorescence increases efficiency about 5-fold but decreases resolution

Projection imaging – Anti scatter grids

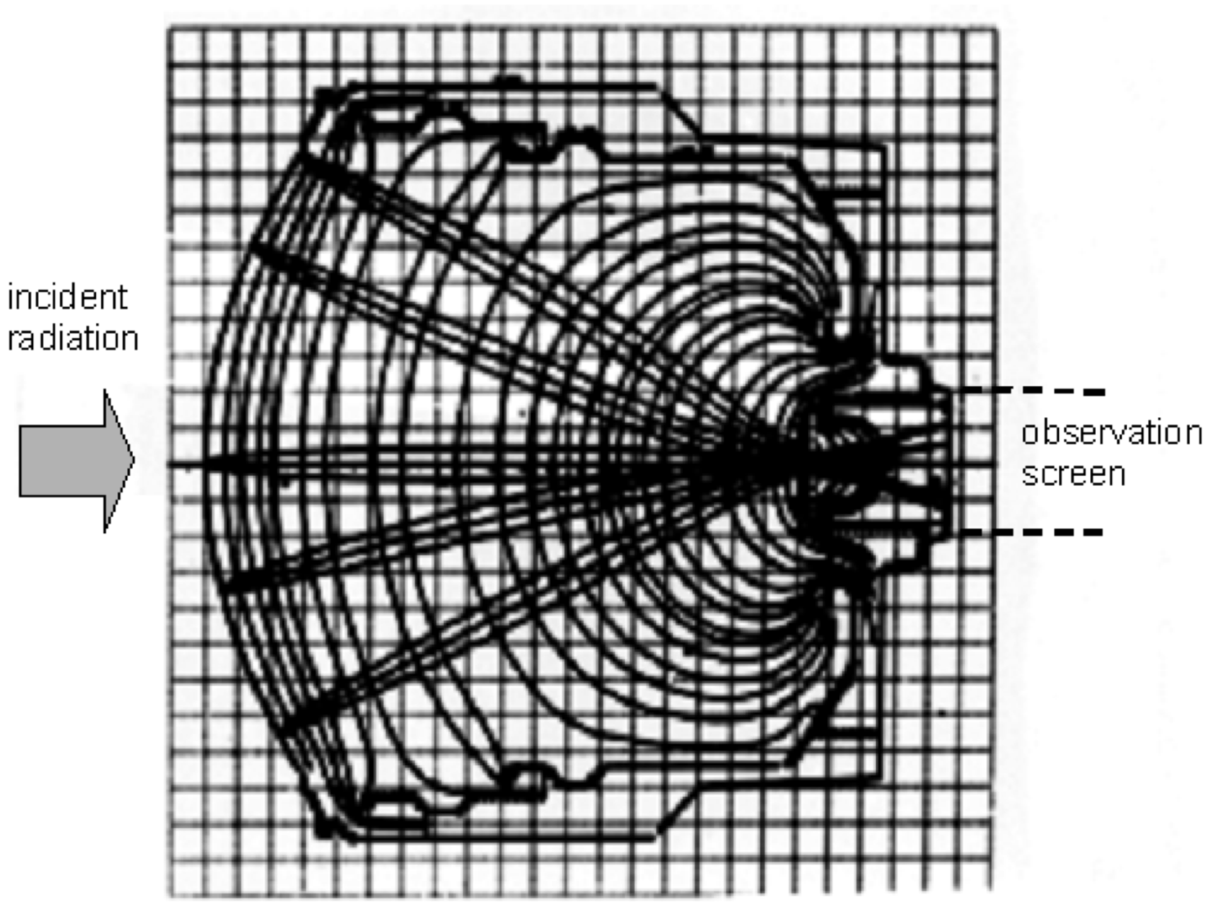
Film with anti-scatter grid



Projection imaging – Image intensifier

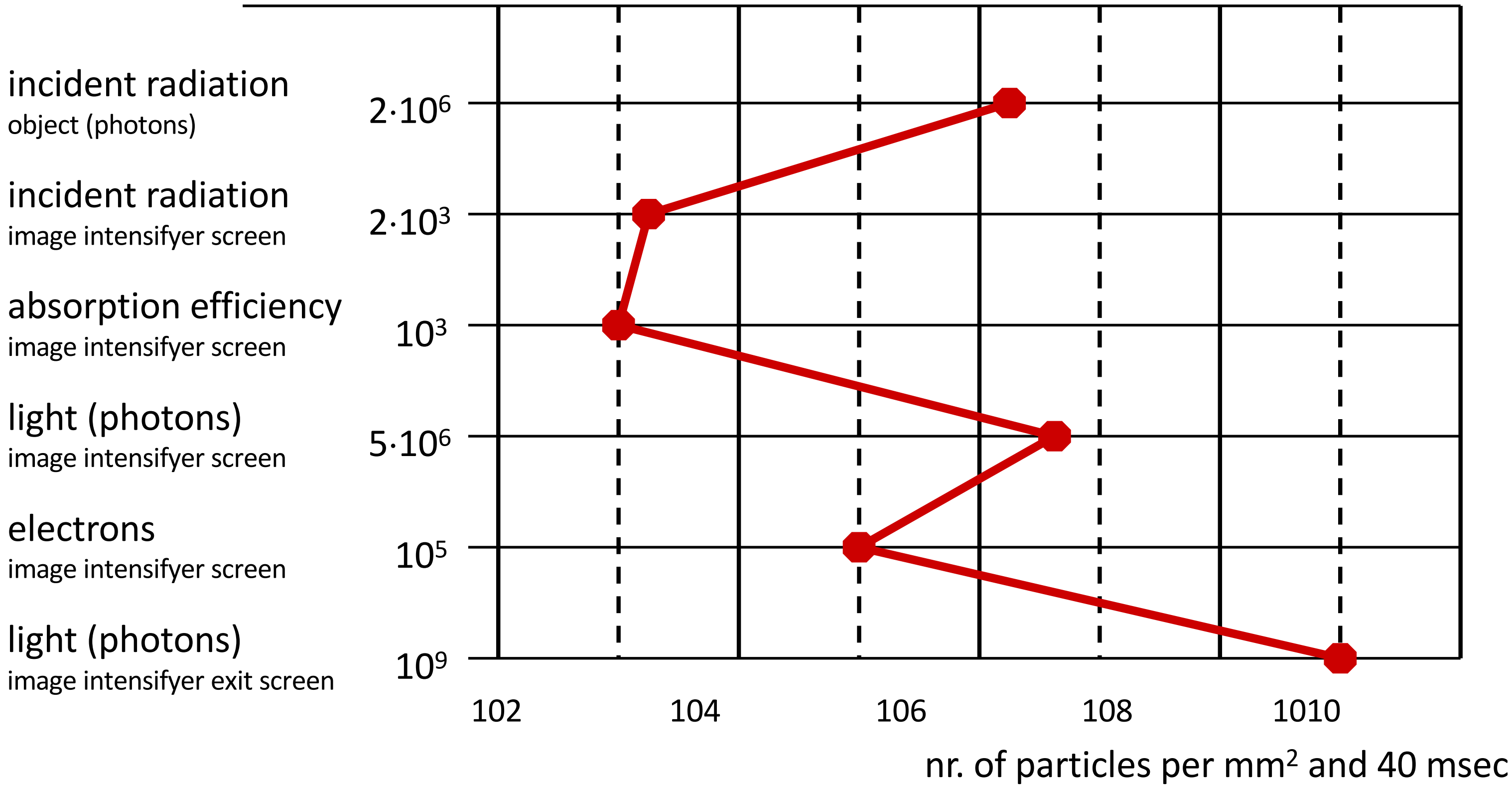


Projection imaging – Image intensifier



Projection imaging – Summary

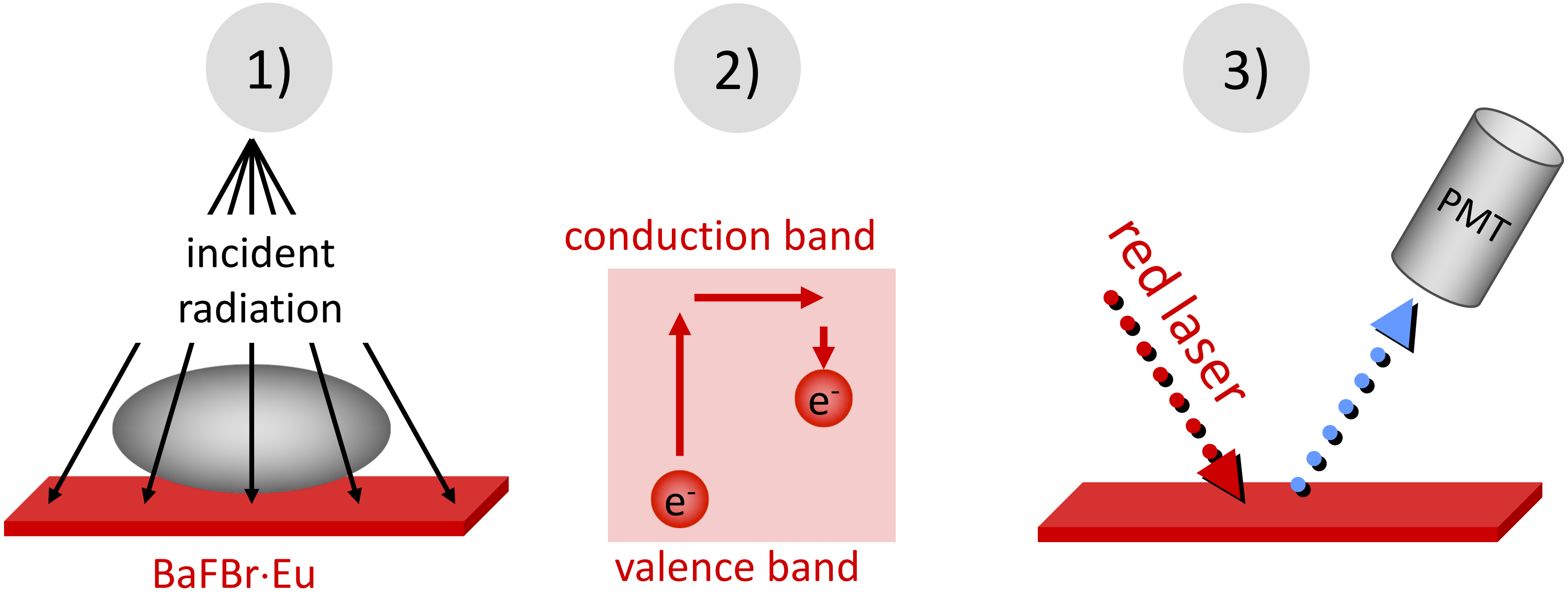
Particle statistics in a typical X-ray chain



Digital X-ray

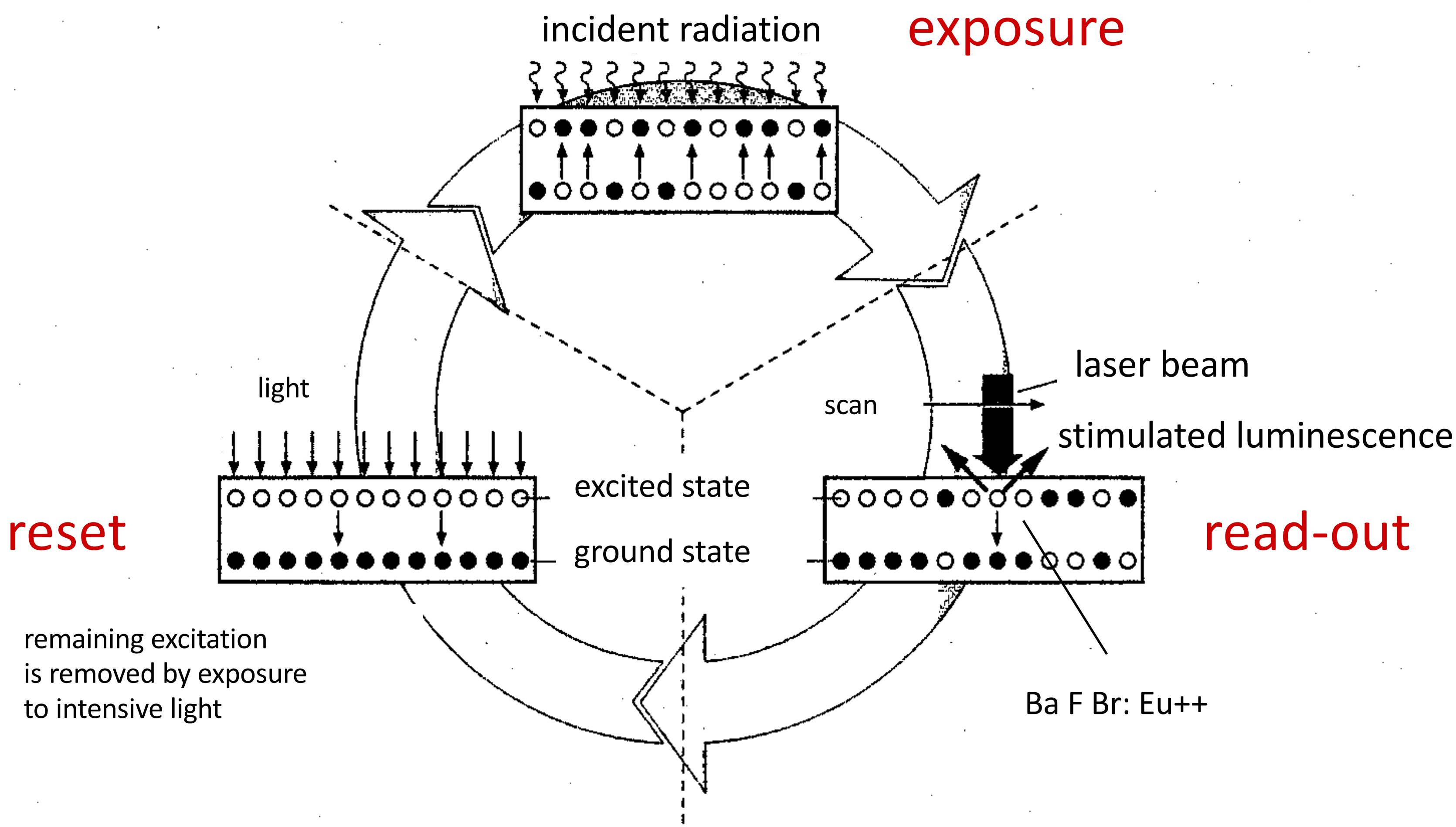
Image conversion

Luminescence using barium fluorohalide (BaFBr:Eu)

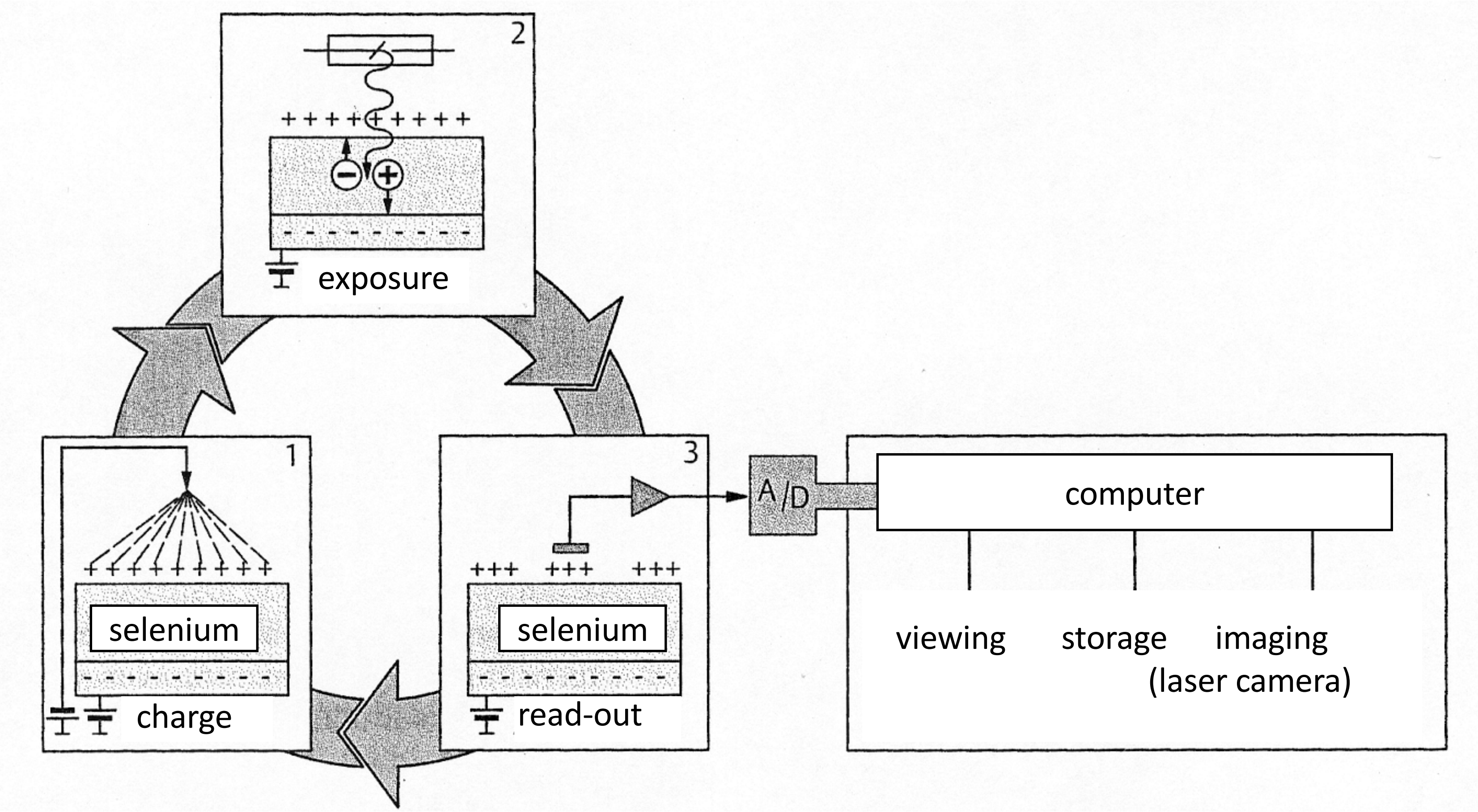


- absorbed x-rays liberate e- from valence band to conduction band; e^- get trapped
- scanning red laser stimulates trapped electrons
- reflected light is collected in photo multiplier tube + stored as digital image

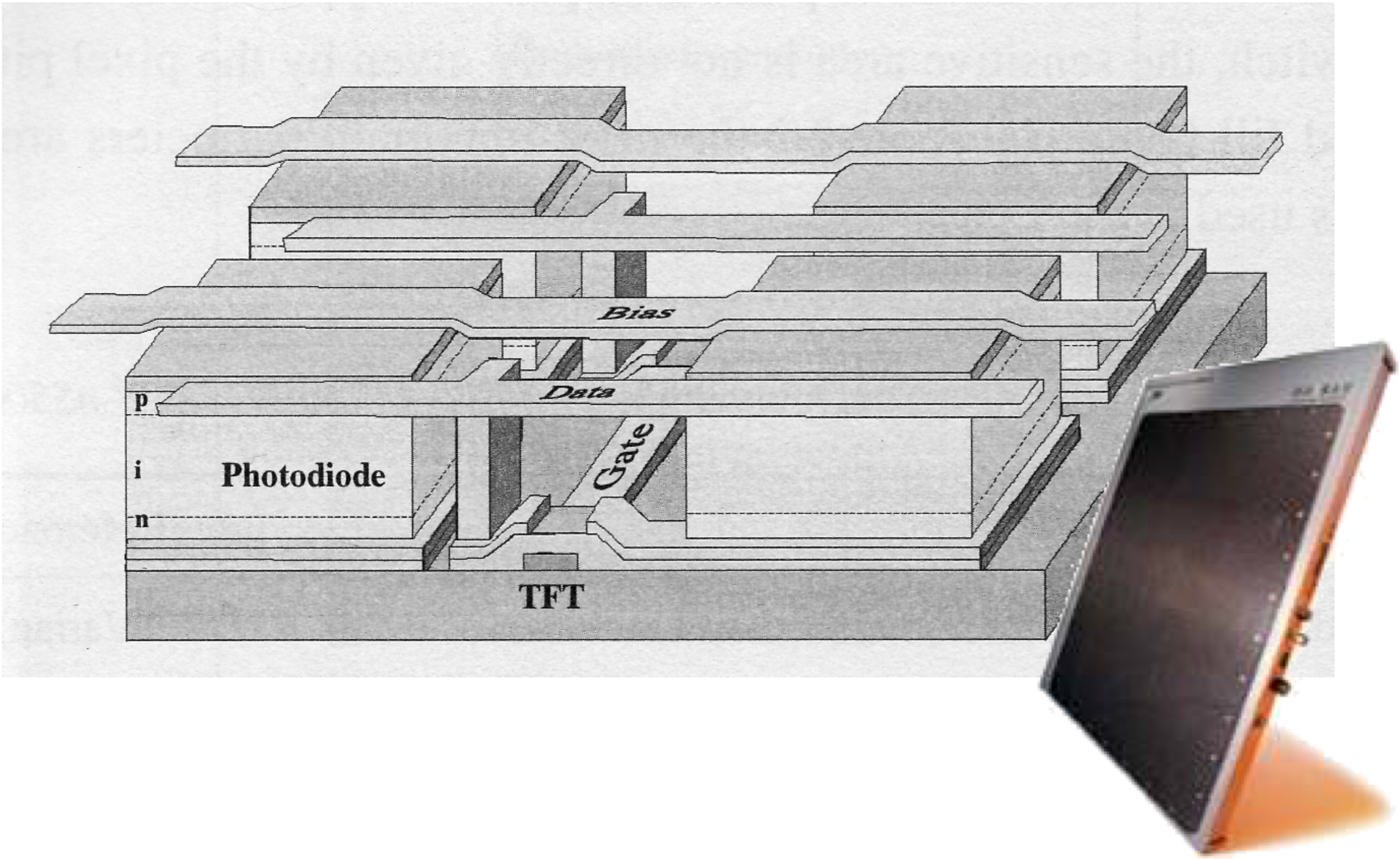
Digital Luminescence



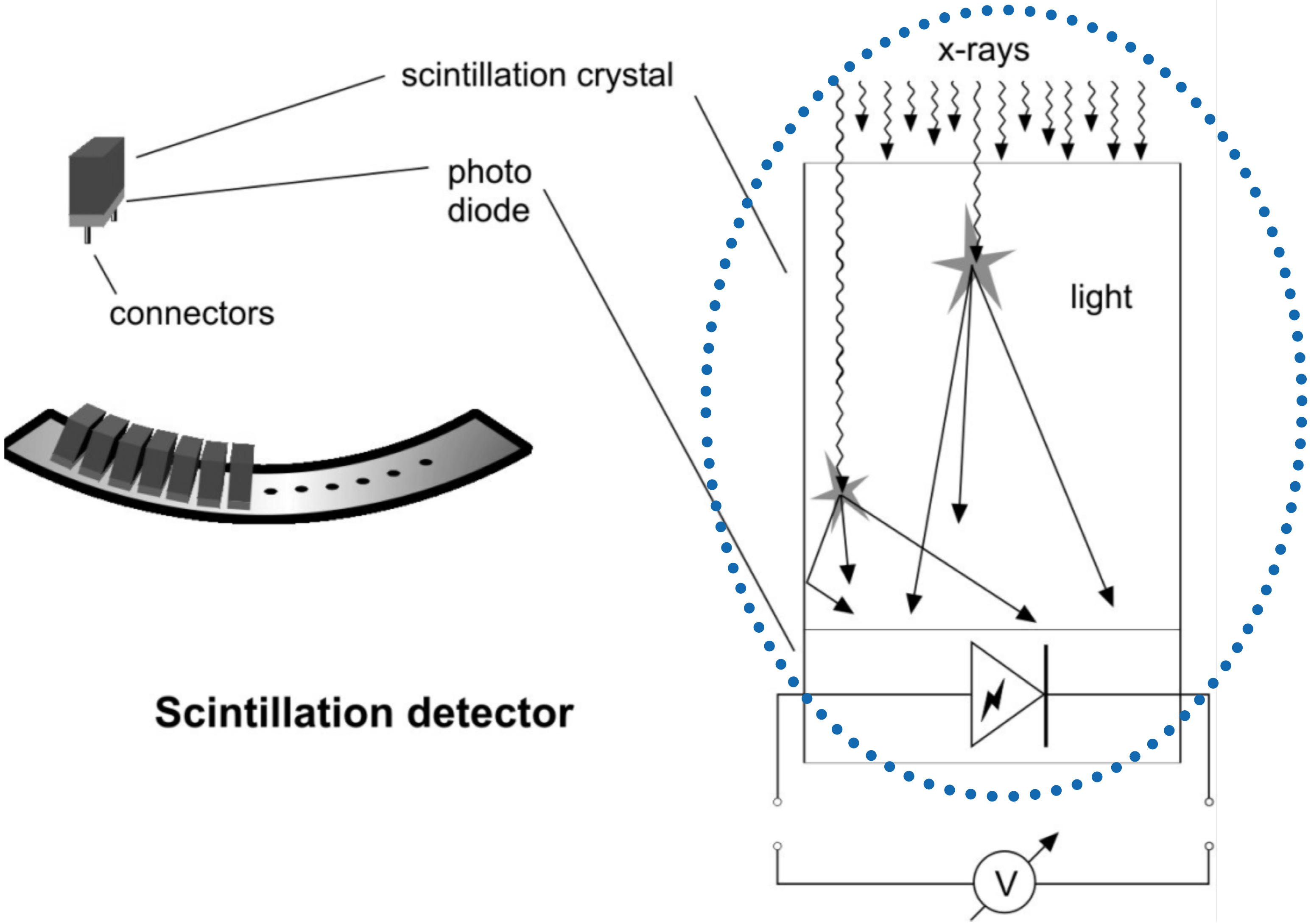
Selenium Detector



Silicium Detector

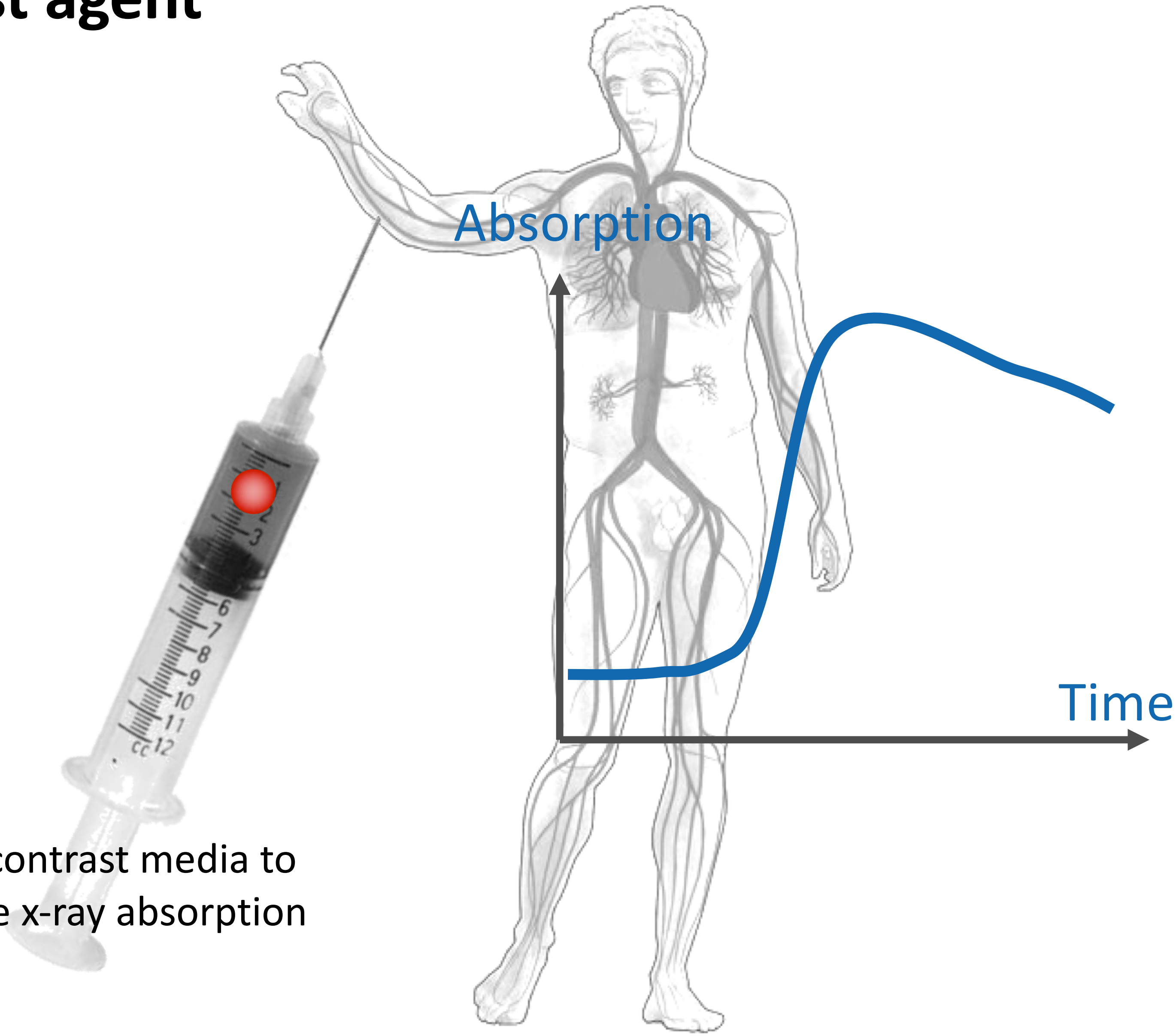


Scintillation Detector



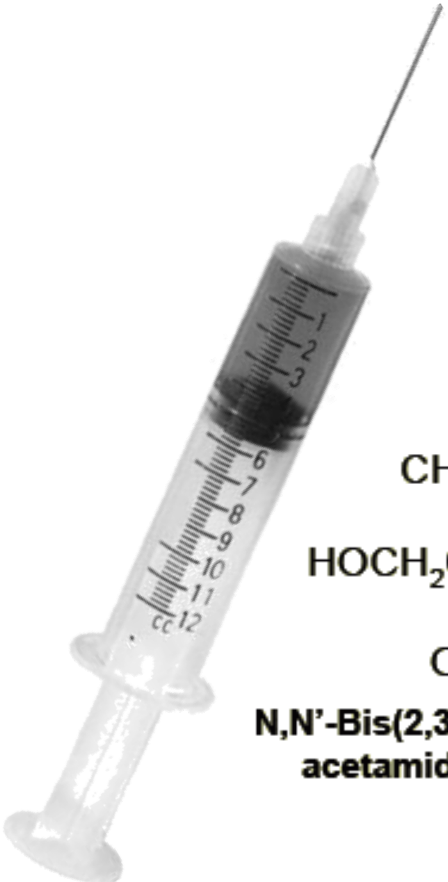
Scintillation detector

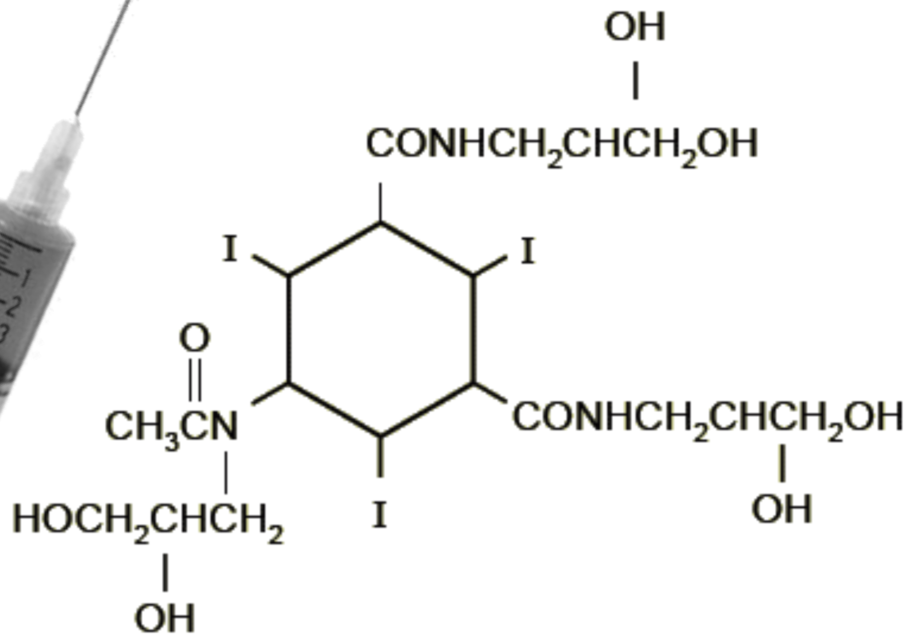
Contrast agent



Iodine contrast media to increase x-ray absorption

Contrast agent

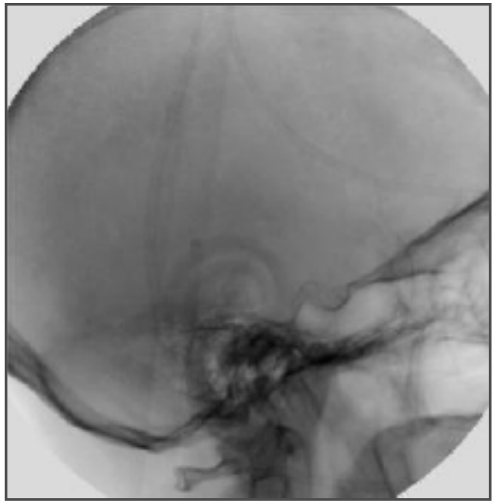




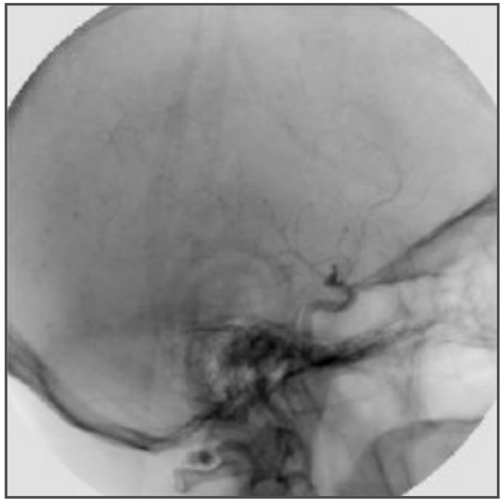
N,N'-Bis(2,3-dihydroxypropyl)-5-[N(2,3-dihroxypropyl)-acetamido]-2,4,6-triiodoisophthalamide [Iohexol]
(140-350 mgI/mL)

Digital Subtraction

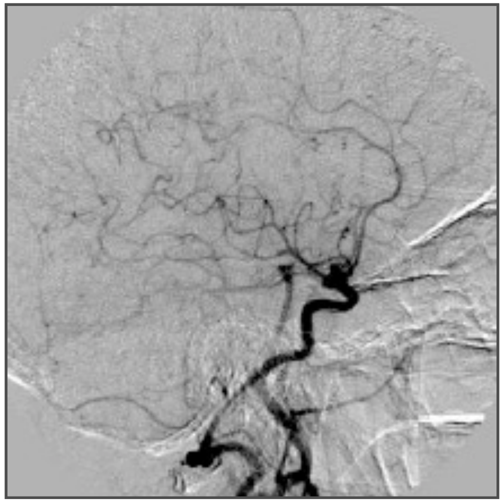
pre-contrast



post-contrast



difference+enhancement



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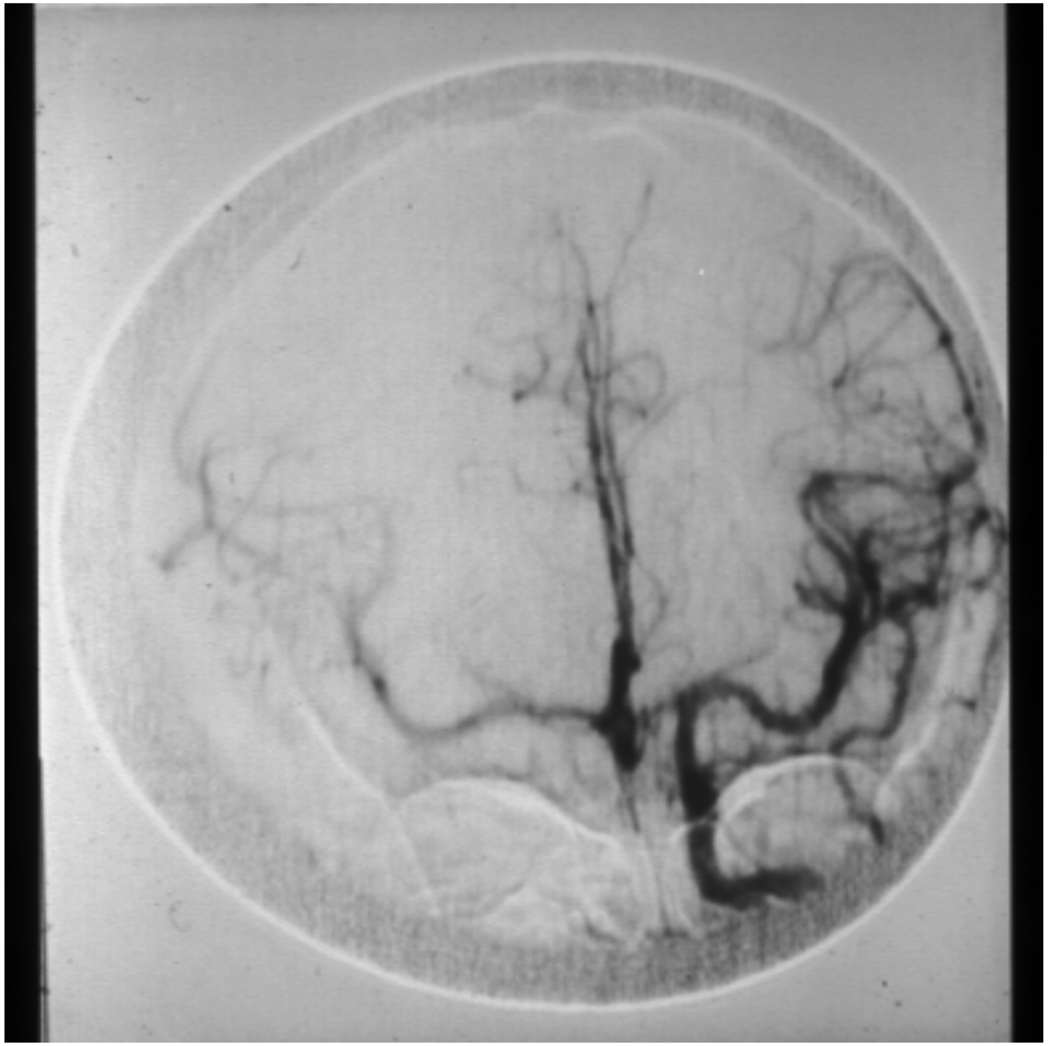
DSA Angiography

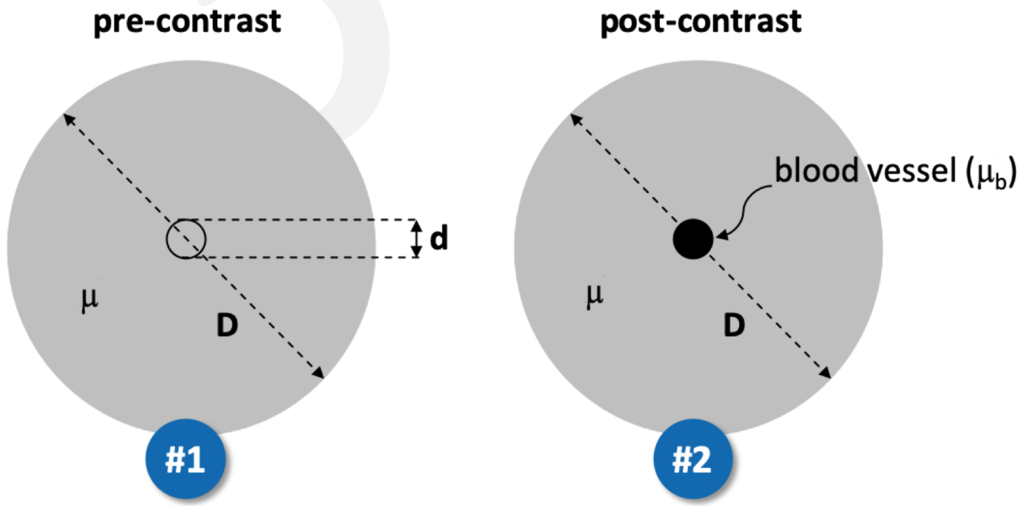
Real-time DSA Angiography



Clicker Activity (5 min)

Digital Subtraction Angiography is performed including a pre-contrast measurement #1 and a post-contrast measurement #2. The contrast agent increases the linear attenuation coefficient in blood. What is the image contrast of projection through the center point of the setup?

- Contrast ~ (μ_b*d - μ*D)
- Contrast ~ (μ_b *D - μ *d)
- Contrast ~ (μ_b - μ)*d



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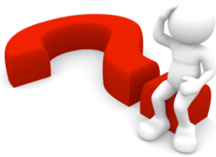
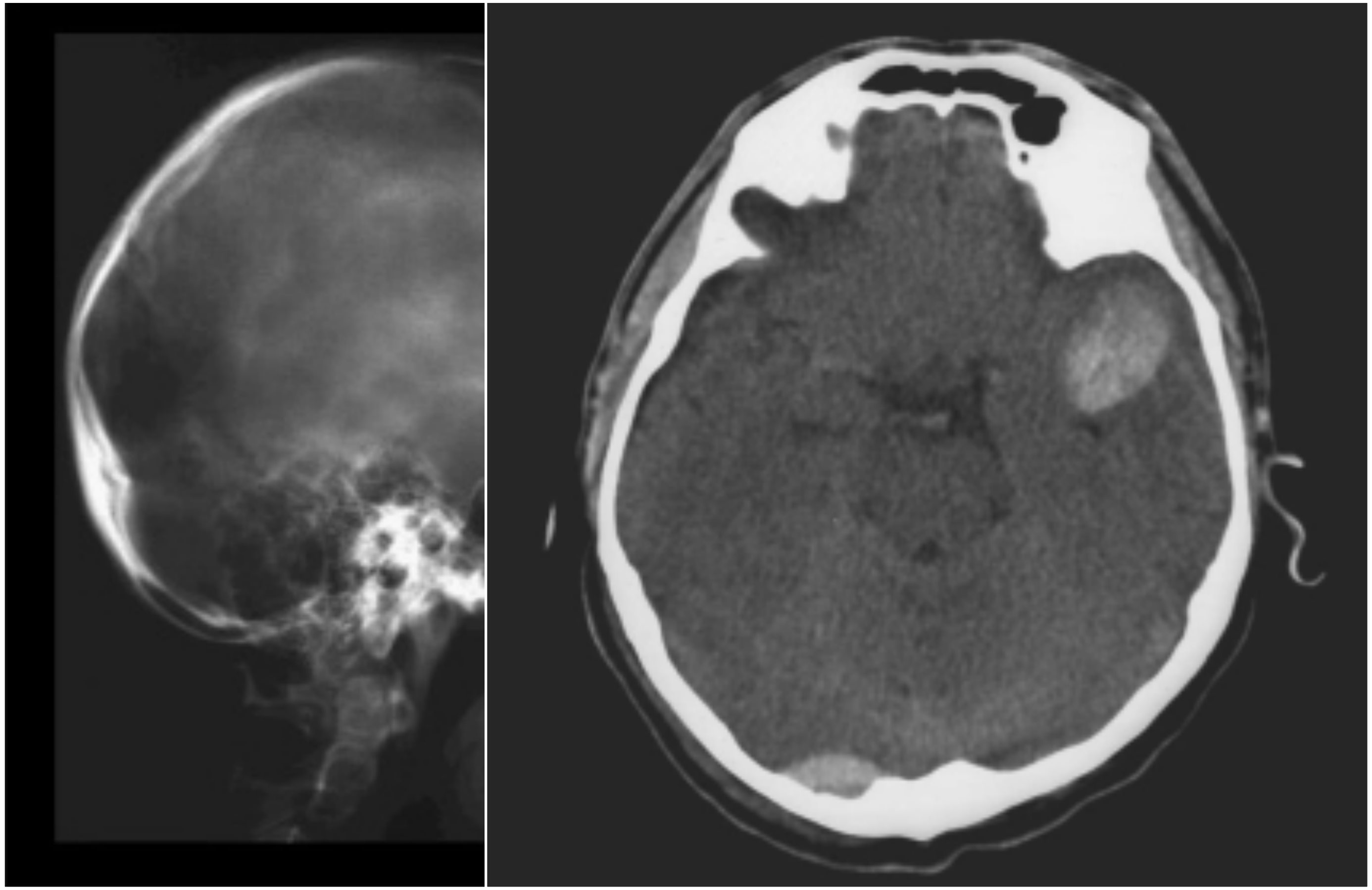
Clicker Activity (Notes)



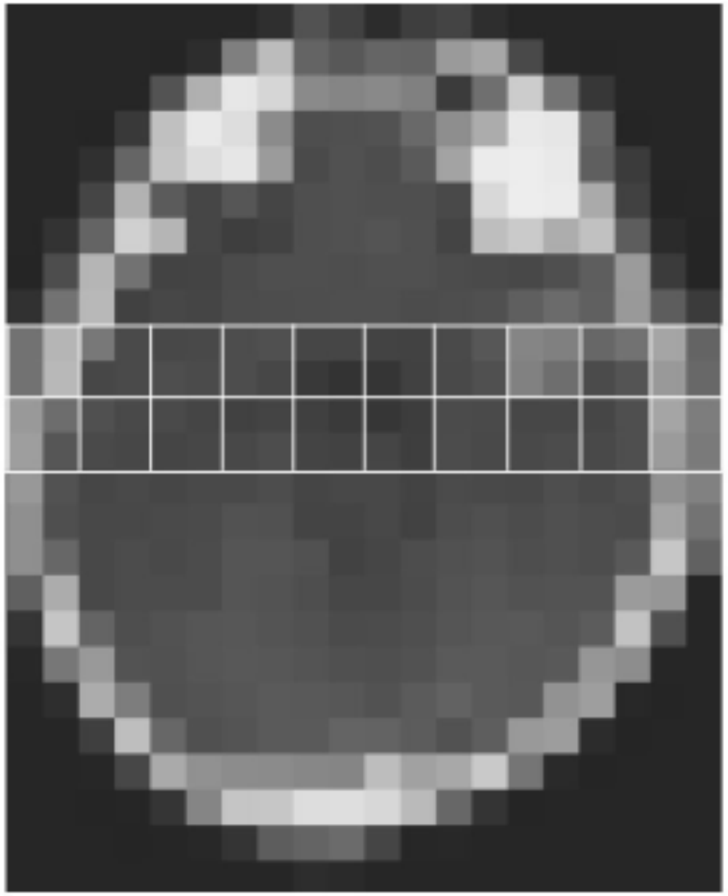
Computed Tomography

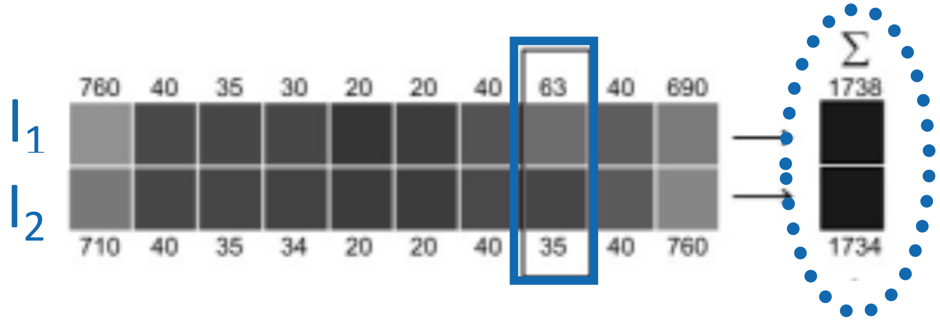
Problem



Adapted from Kalender WA, Computed Tomography, ISBN 3-89578-216-5

Problem





$$\text{Contrast} = \frac{\ln(I_1) - \ln(I_2)}{\ln(I_1) + \ln(I_2)}$$

Adapted from Kalender WA, Computed Tomography, ISBN 3-89578-216-5

Projection versus Tomographic imaging

- Projection imaging

  = 3D structures are collapsed onto 2D image:

  - details are obscured
  - low soft-tissue contrast
  - not quantitative

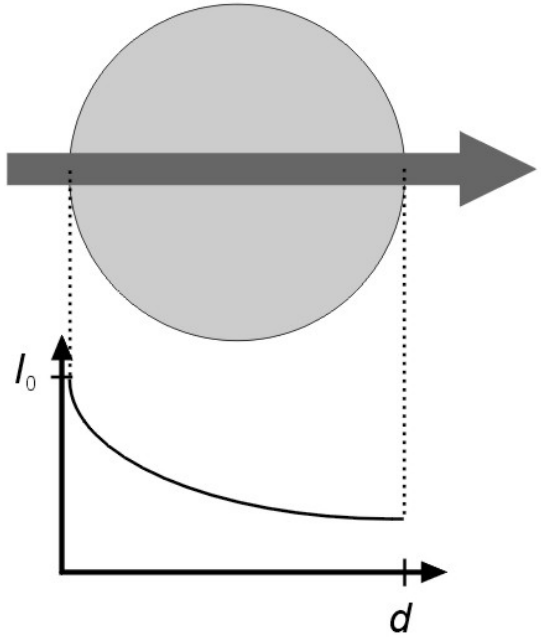
- Tomographic imaging

  = 3D structure is resolved:

  - slices ("gr: Tomos = slice")
  - Computed image reconstruction
  - Projection imaging and CT share same principles of x-ray generation, interaction, detection

CT – Reconstruction problem

1) Homogeneous object, monochromatic radiation



$$I = I_0 \cdot e^{-\mu \cdot d}$$

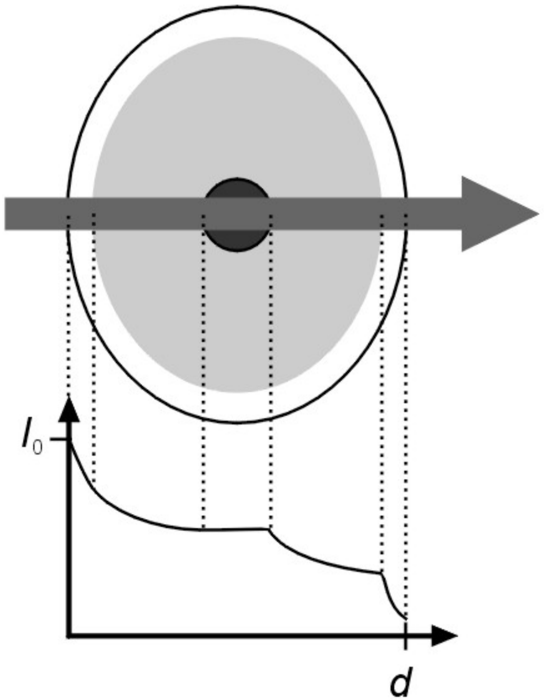
$$P = \ln \frac{I_0}{I} = \mu \cdot d$$

$$\mu = \frac{1}{d} \cdot \ln \frac{I_0}{I}$$

Adapted from Kalender WA, Computed Tomography, ISBN 3-89578-216-5

CT – Reconstruction problem

2) Inhomogeneous object, monochromatic radiation



$$I = I_0 \cdot e^{-\mu_1 \cdot d_1 - \mu_2 \cdot d_2 - \mu_3 \cdot d_3 - \dots} =$$

$$= I_0 \cdot e^{-\left[\sum_{i=1}^{n} \mu_i d_i\right]} = I_0 \cdot e^{-\int_0^d \mu \, ds}$$

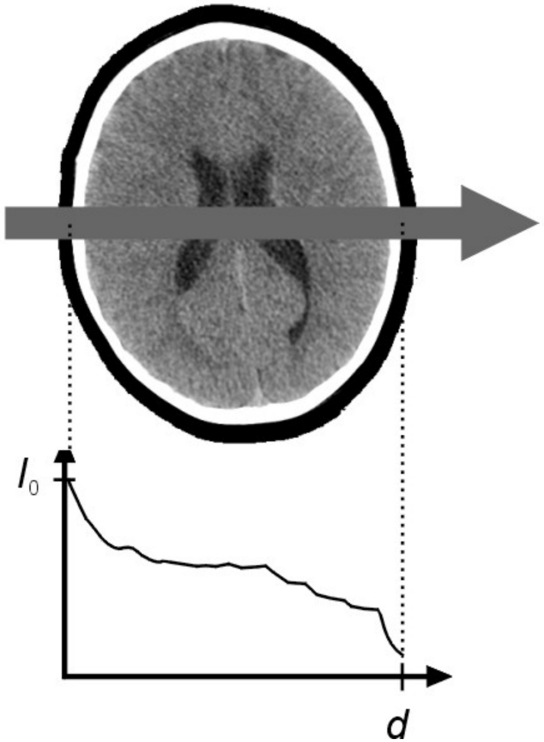
$$P = \ln \frac{I_0}{I} = \sum \mu_i d_i$$

$$\mu_i = ?$$

Adapted from Kalender WA, Computed Tomography, ISBN 3-89578-216-5

CT – Reconstruction problem

3) Inhomogeneous object, polychromatic radiation



$$I = \int_0^{E_{\max}} I_0(E) \cdot e^{-\int_0^d \mu(E)\, ds} \, dE$$

$$P = \ln \frac{I_0}{I}$$

$$\mu(x, y) = ?$$

Adapted from Kalender WA, Computed Tomography, ISBN 3-89578-216-5

CT – History

- Johann Radon, 1917

  - mathematical foundation for tomographic image reconstruction

- Allan Cormack, 1963

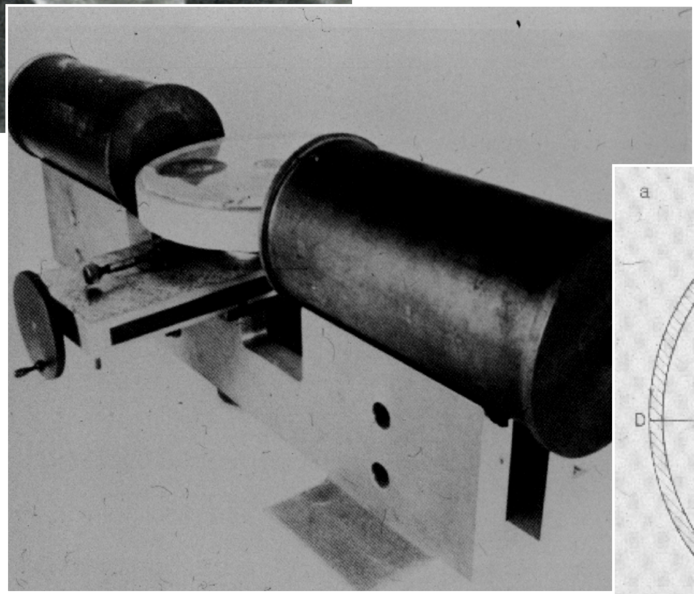
  - first experiments with axial tomography

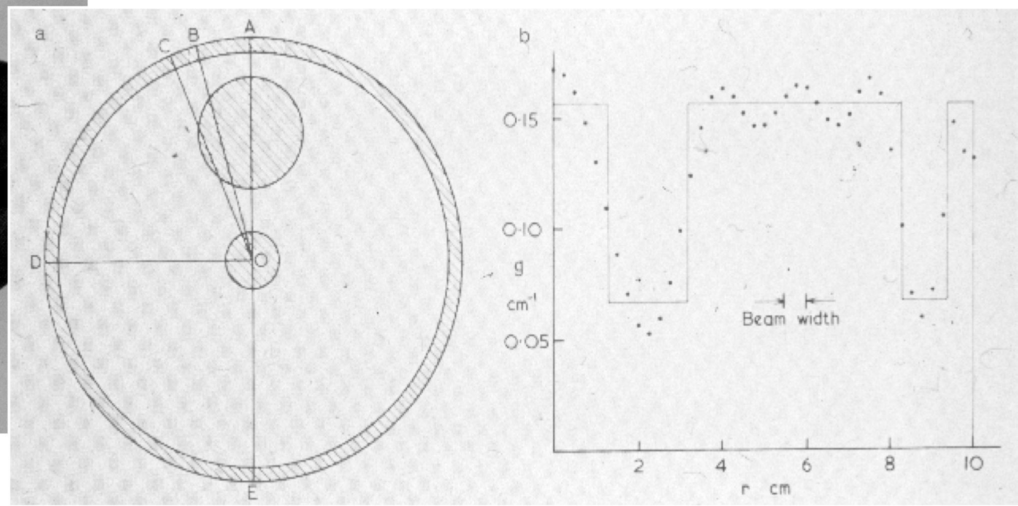
- Godfrey Hounsfield, 1972

  - first clinical prototype; manufactured at EMI Ltd., England

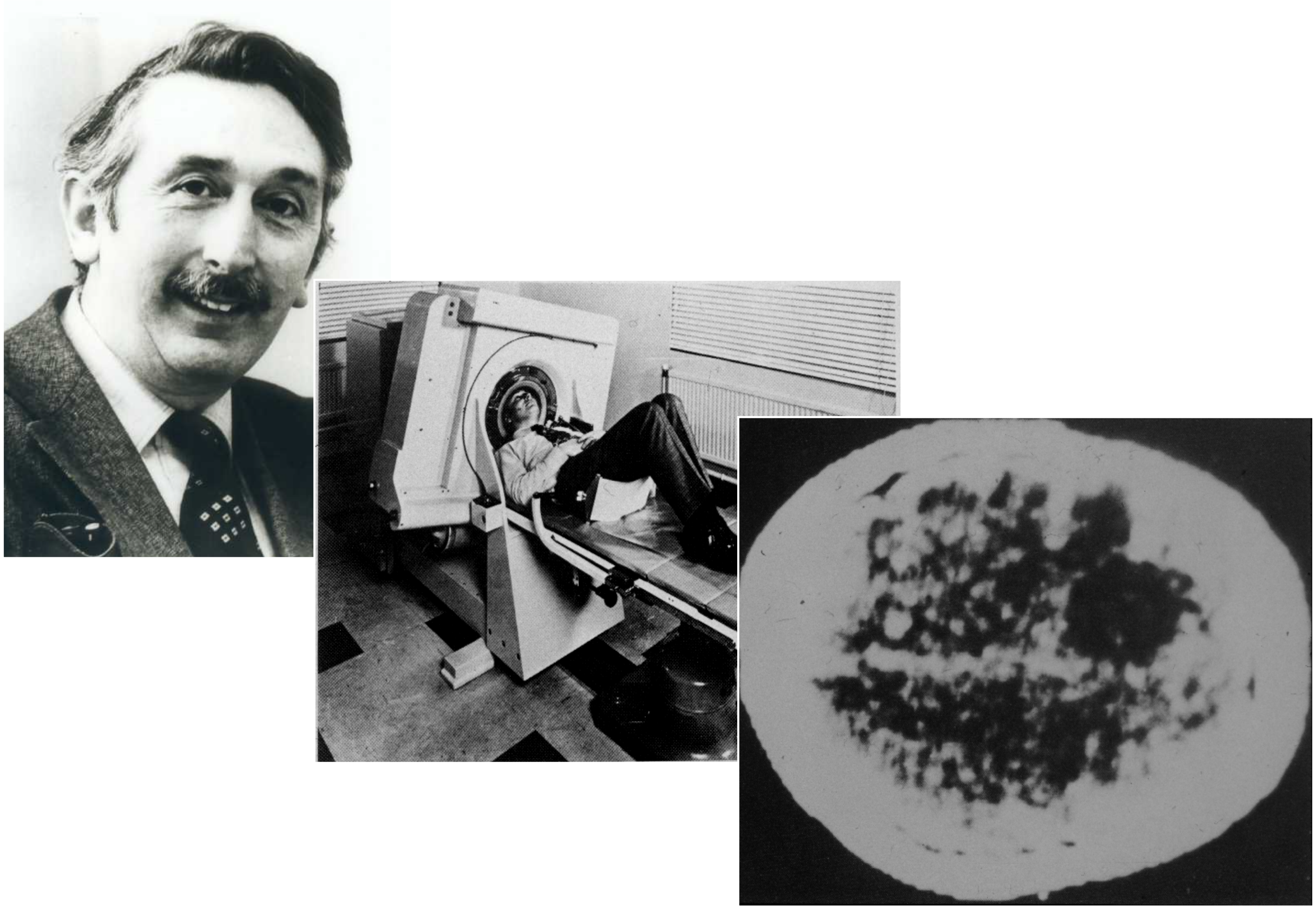
(Cormack and Hounsfield shared Nobel prize in 1979)

CT – Allan Cormack

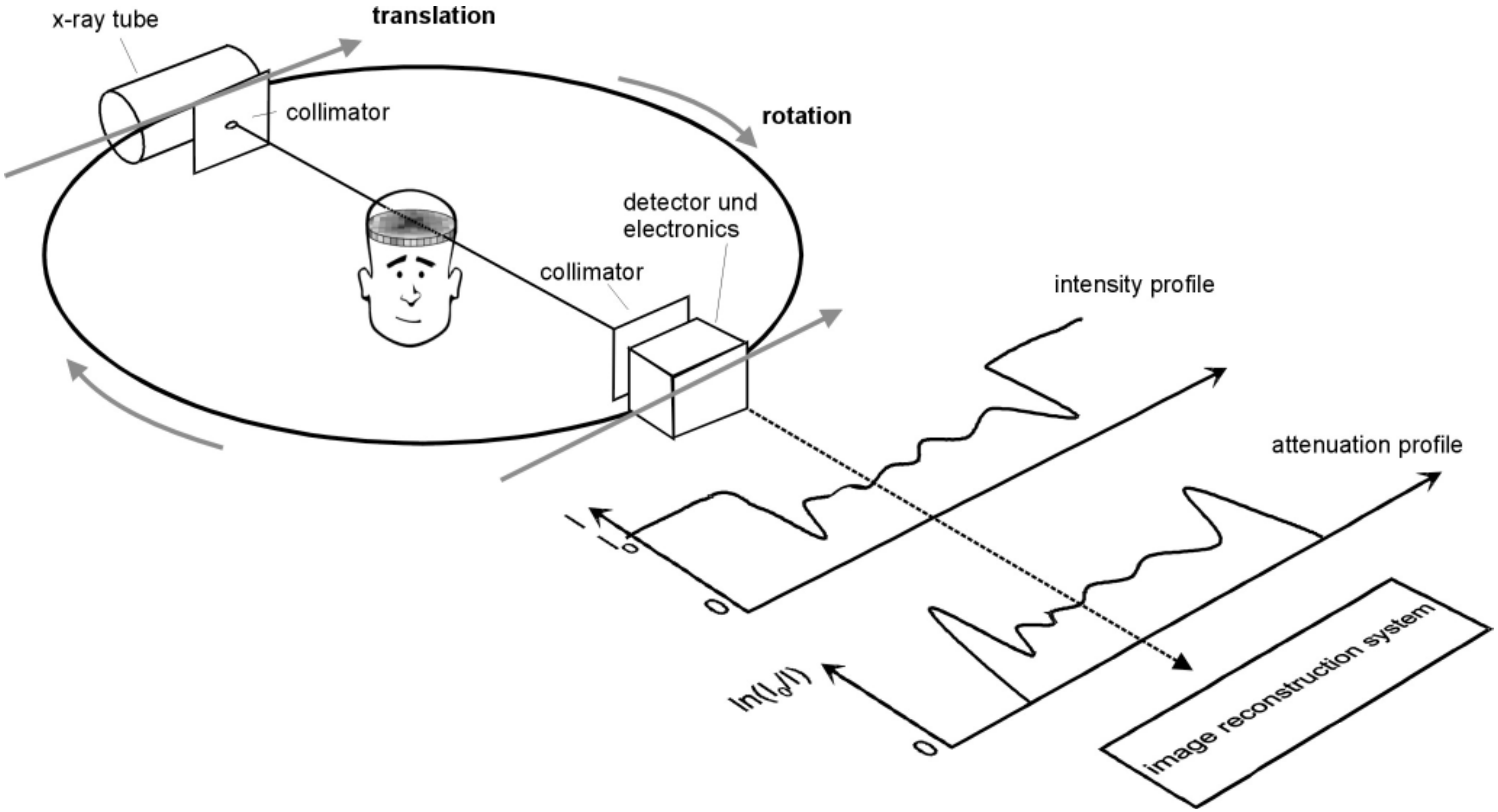




CT – Godfrey Hounsfield



CT – Principle



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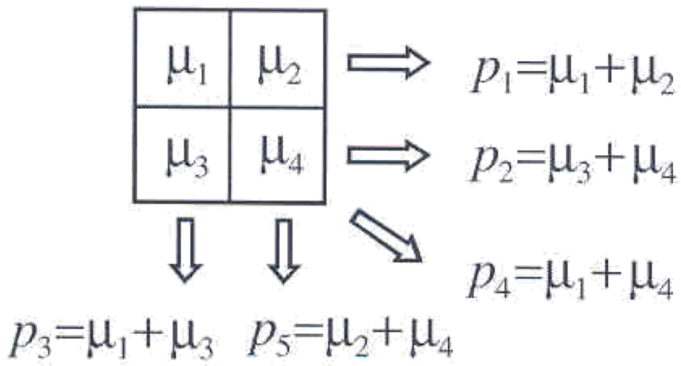
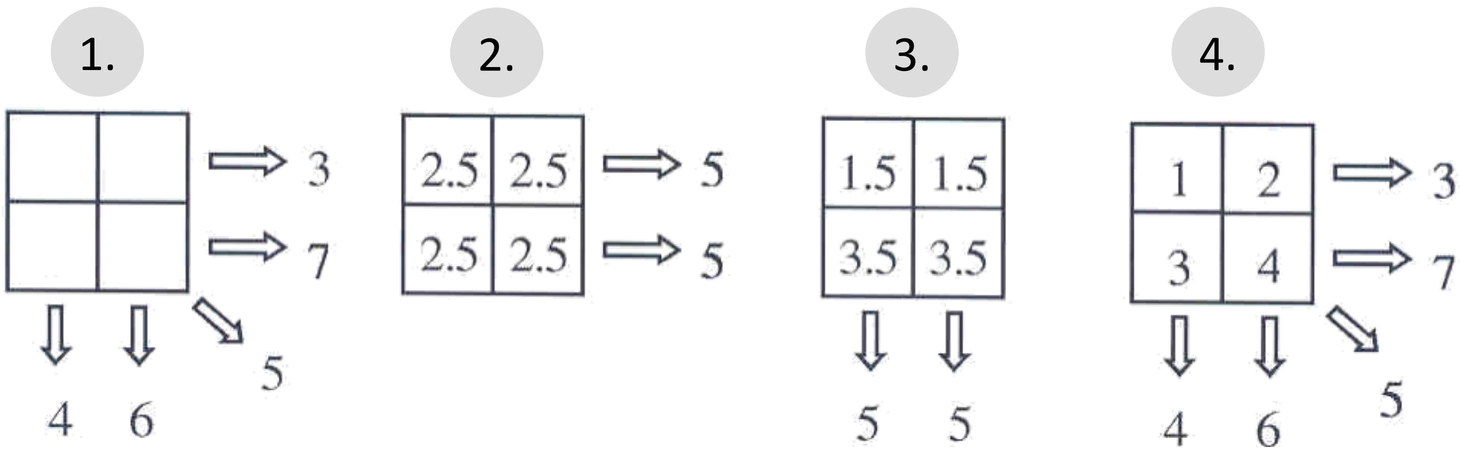
CT – Image reconstruction

- Direct inversion (solving N unknowns from at least N equations)



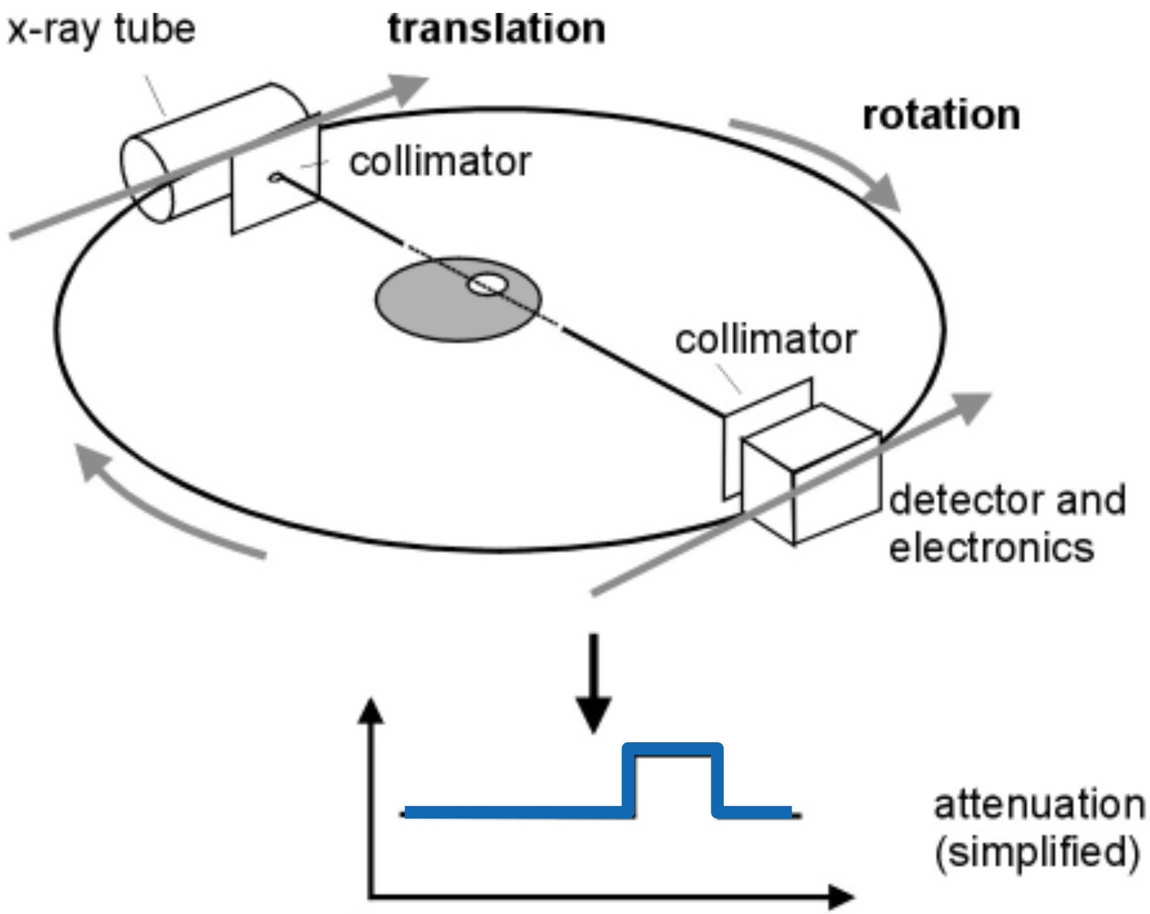
- Iterative reconstruction



(image estimation, pseudo-projection, minimization of residuum)

CT – Image reconstruction

- Backprojection



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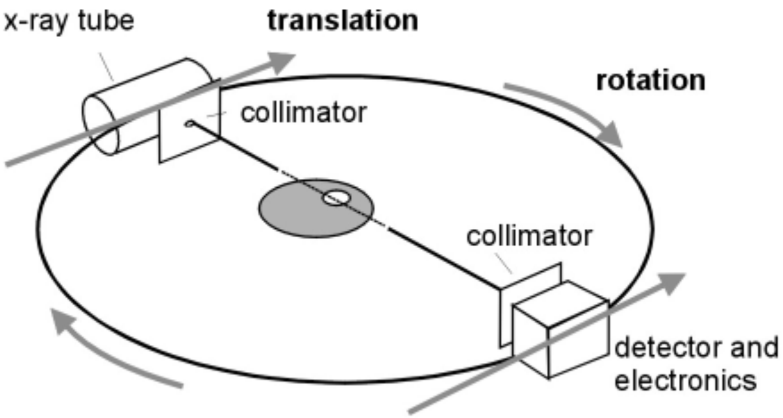
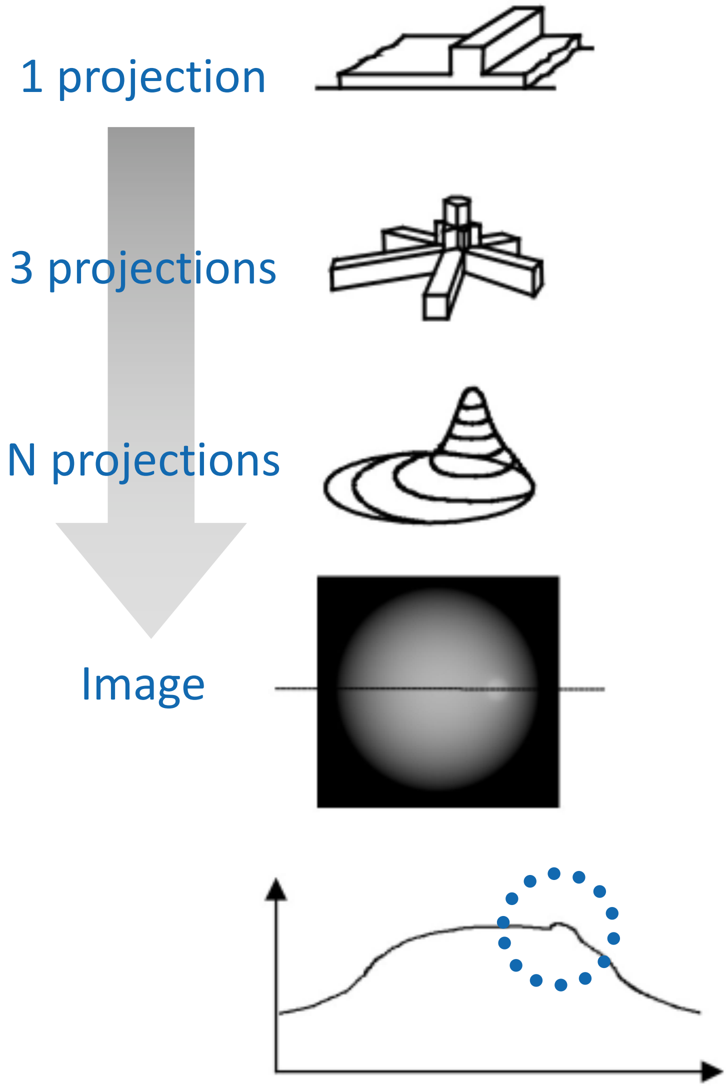
CT – Image reconstruction

- Backprojection





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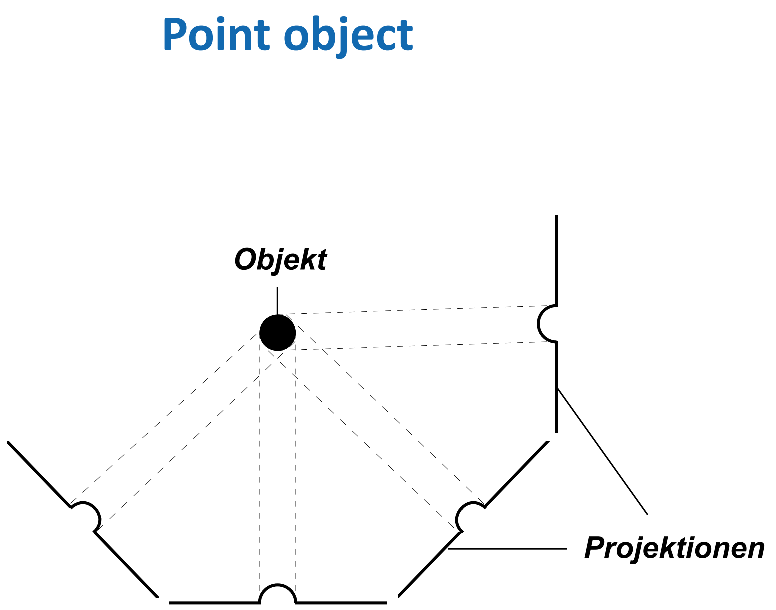
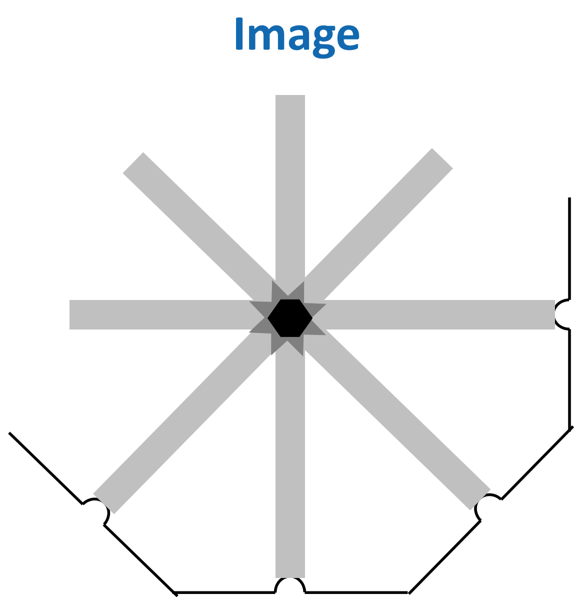
CT – Image reconstruction

- Backprojection – Point Spread Function (PSF)





PSF is obtained if

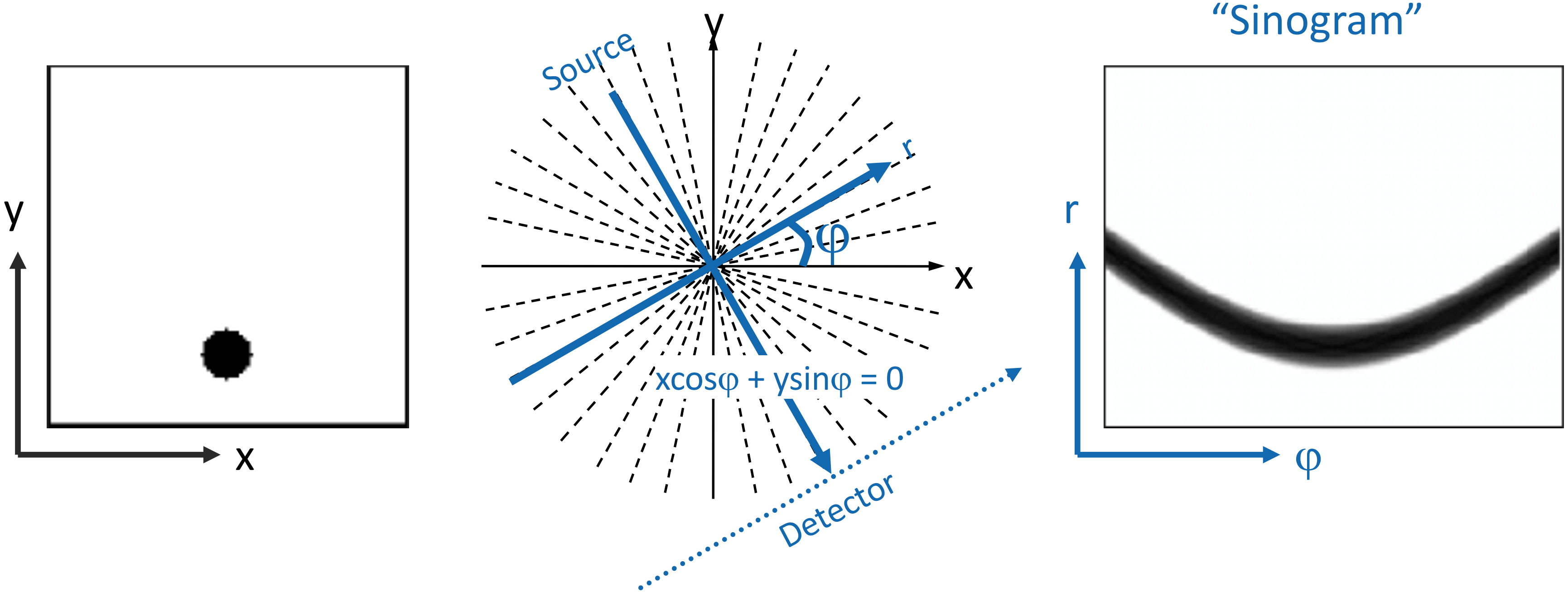
1) $\text{radius}_{\text{object}} \rightarrow 0$
2) number of projections $\rightarrow \infty$
3) number samples per projection $\rightarrow \infty$

$$\mathrm{PSF} \propto \left|\frac{1}{r}\right|$$

CT – Image reconstruction

- Radon transform

$$P_\varphi(r) = R[\mu](r,\varphi) = \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} \mu(x,y)\,\delta(x\cos\varphi + y\sin\varphi - r)\,dxdy$$

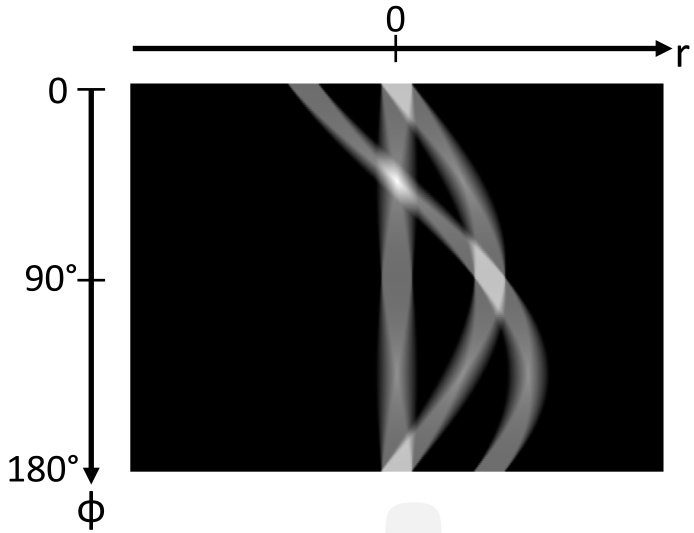


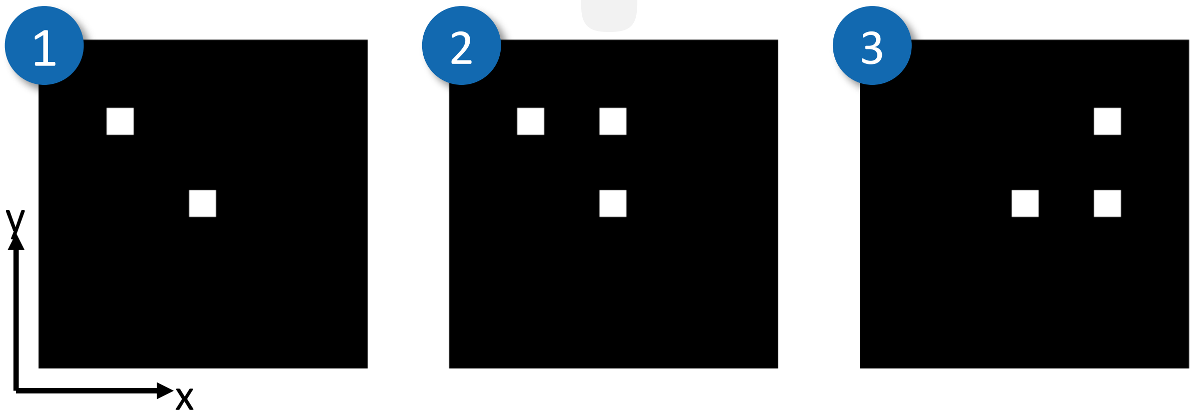
Radon transform = Image encoding principle in CT

Clicker Activity (5 min)

Which object does the sinogram below correspond to?

- Object #1
- Object #2
- Object #3





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CT – Image reconstruction

- Inverse transform (I)

$$P_{\varphi}(r) = R[\mu](r,\varphi) = \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} \mu(x,y)\,\delta(x\cos\varphi + y\sin\varphi - r)\,dxdy$$

"Wanted"

Radon found analytical solution but it's numerically impractical

"Use Fourier transform"

$$F\{P_{\varphi}(r)\} = \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} \mu(s,r)\,e^{-iur}\,drds$$

CT – Image reconstruction

- Inverse transform (II)

$$F\{P_\varphi(r)\} = \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} \mu(s,r)e^{-iur}drds$$

$$F\{P_\varphi(u)\} = \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} \mu(x,y)e^{-iu(x\cos\varphi+y\sin\varphi)}dxdy$$

$$F\{P_\varphi(p,q)\} = \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} \mu(x,y)e^{-ixp}e^{-iyq}dxdy$$

Reconstruction formula

$$\mu(x,y) = \frac{1}{4\pi^2}\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} F\{P_\varphi(p,q)\}e^{ixp}e^{iyq}dpdq$$

CT – Image reconstruction

- Inverse transform (III)

$$\mu(x,y) = \frac{1}{4\pi^2}\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} F\left\{P_\varphi(p,q)\right\} e^{ixp} e^{iyq}\, dp\, dq$$

$$\mu(x,y) = \frac{1}{4\pi^2}\int_{0}^{\pi}\int_{-\infty}^{+\infty} F\left\{P_\varphi(u)\right\} e^{iur} |u|\, du\, d\varphi$$

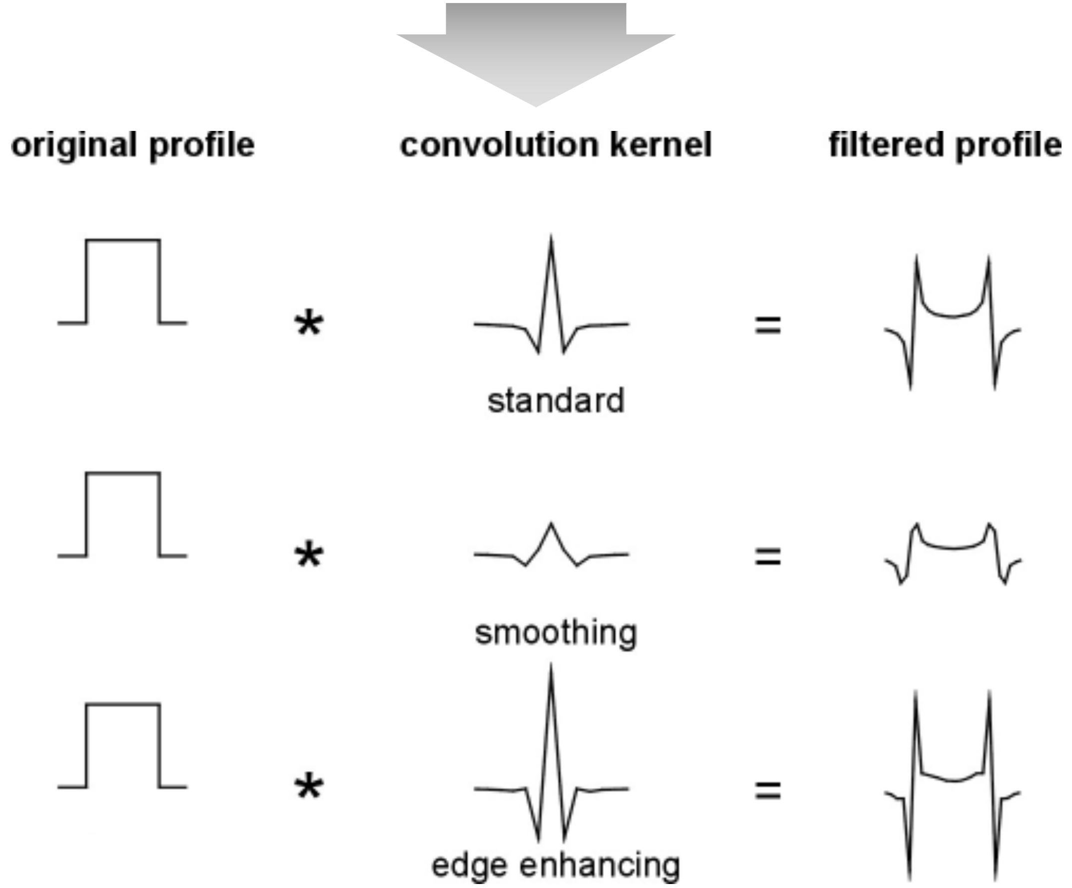
1. F{Pφ (u)} is weighted by |u|
2. F{Pφ (u)} |u| is inversely transformed
3. and summed over all angles φ (=backprojection)

$$\text{Image} = \text{Filter} * \text{Object} \leftrightarrow F\{\text{Image}\} = F\{\text{Filter}\} \cdot F\{\text{Object}\}$$

CT – Image reconstruction

- Convolution backprojection

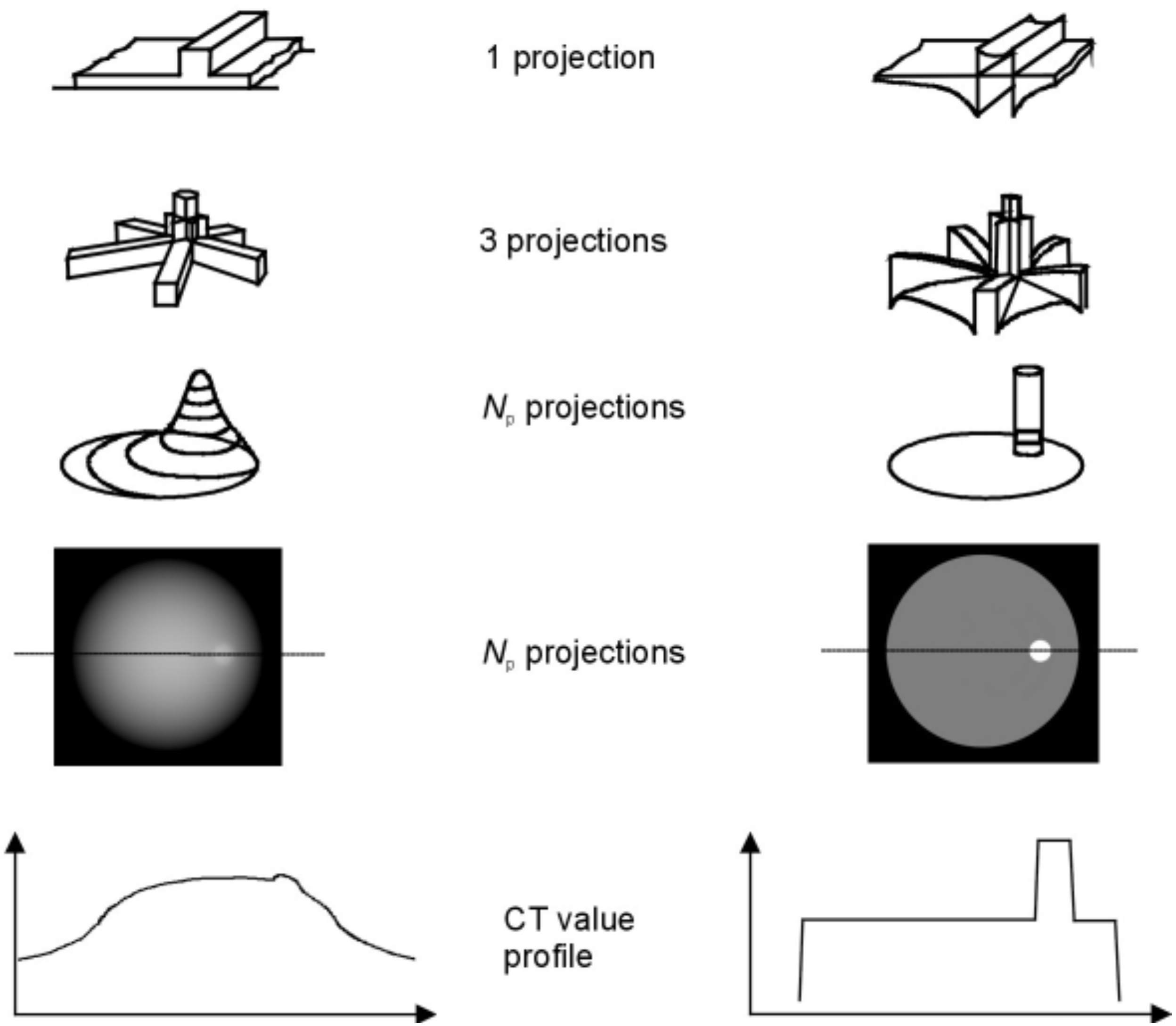
$$\text{Image} = \text{Filter} * \text{Object} \leftrightarrow F\{\text{Image}\} = F\{\text{Filter}\} \cdot F\{\text{Object}\}$$



Adapted from Kalender WA, Computed Tomography, ISBN 3-89578-216-5

CT – Image reconstruction

without pre-filtering **with pre-filtering**



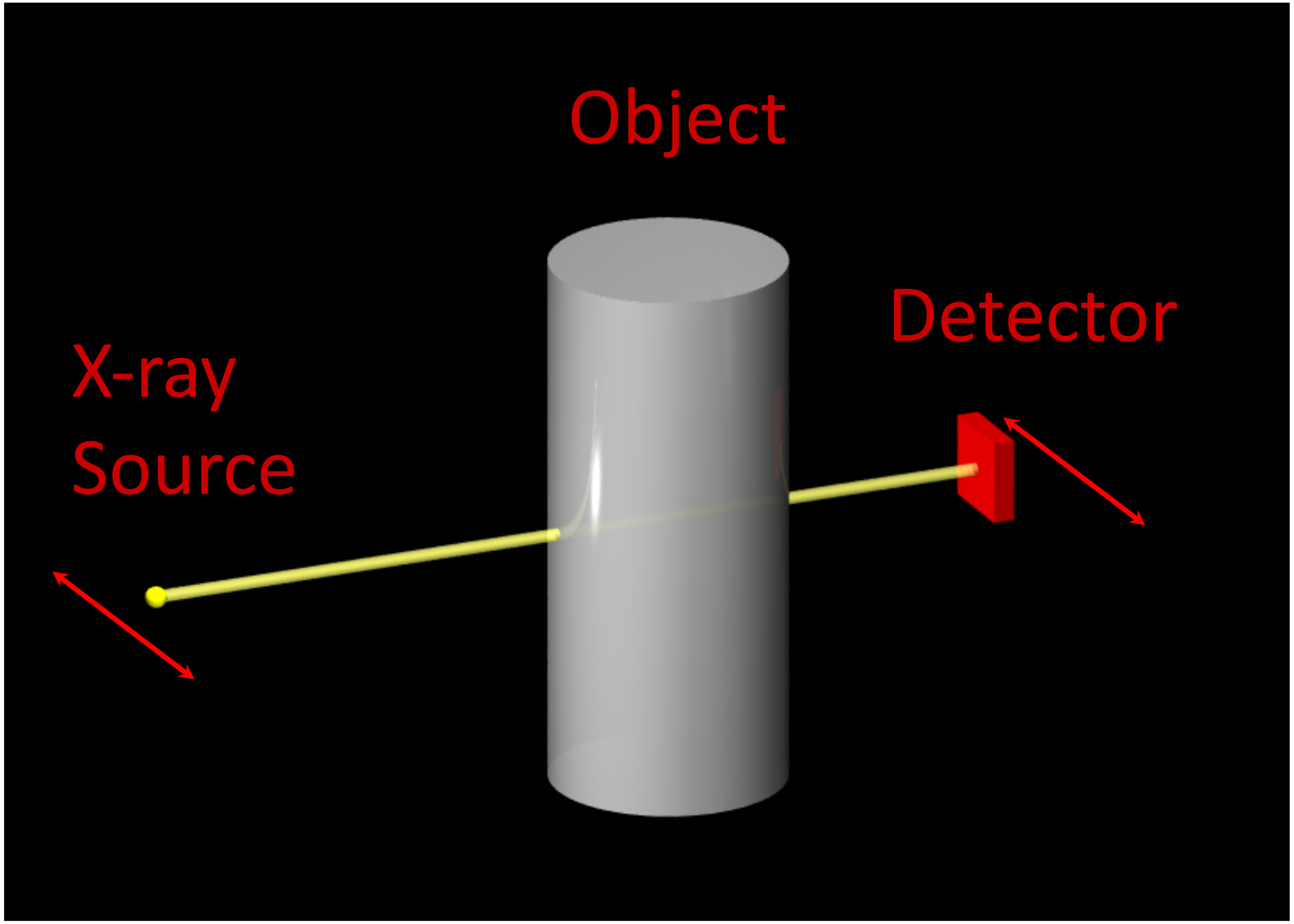
Adapted from Kalender WA, Computed Tomography, ISBN 3-89578-216-5

CT – Image reconstruction

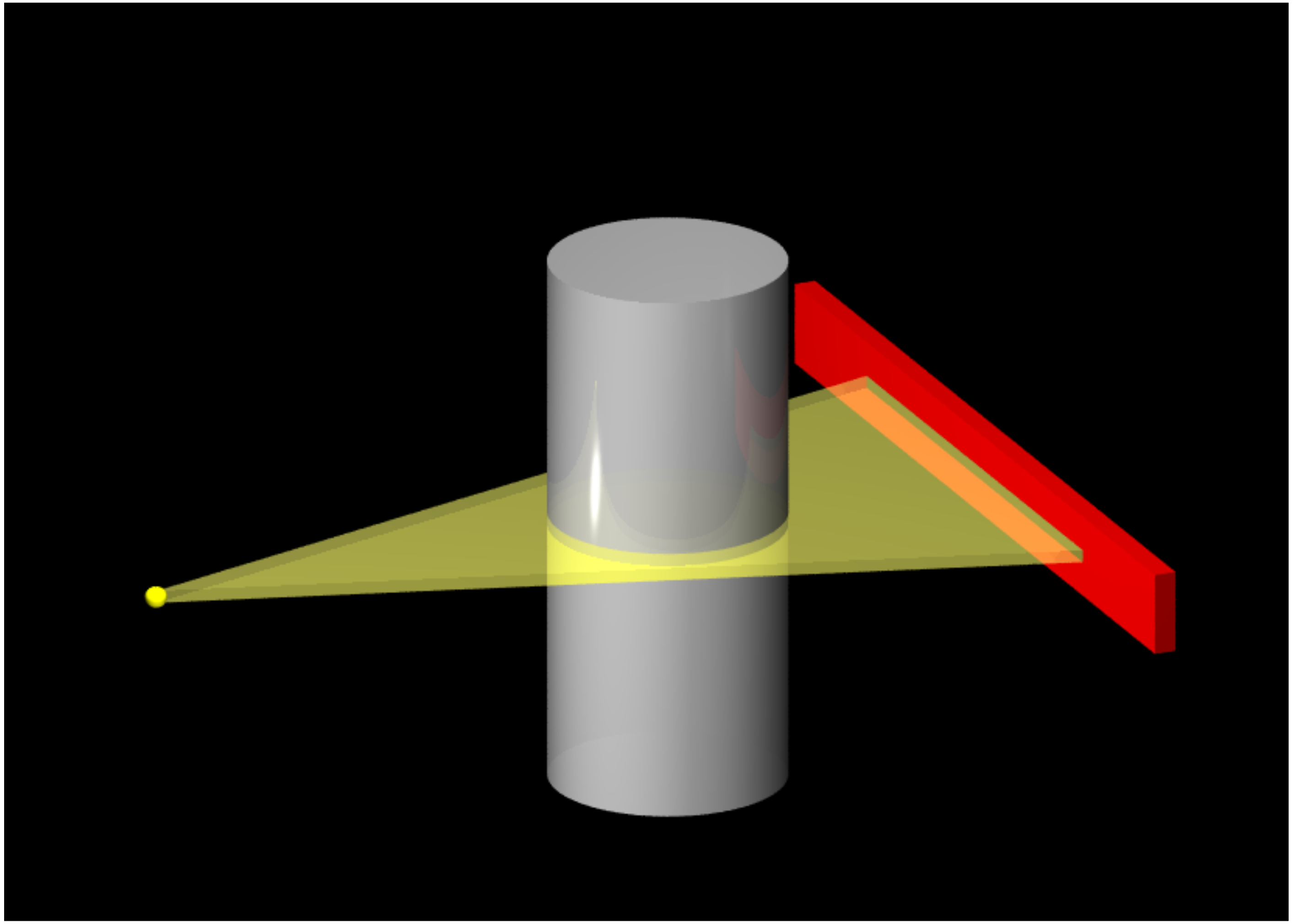
- Convolution backprojection process

From Kalender WA, Computed Tomography, ISBN 3-89578-216-5

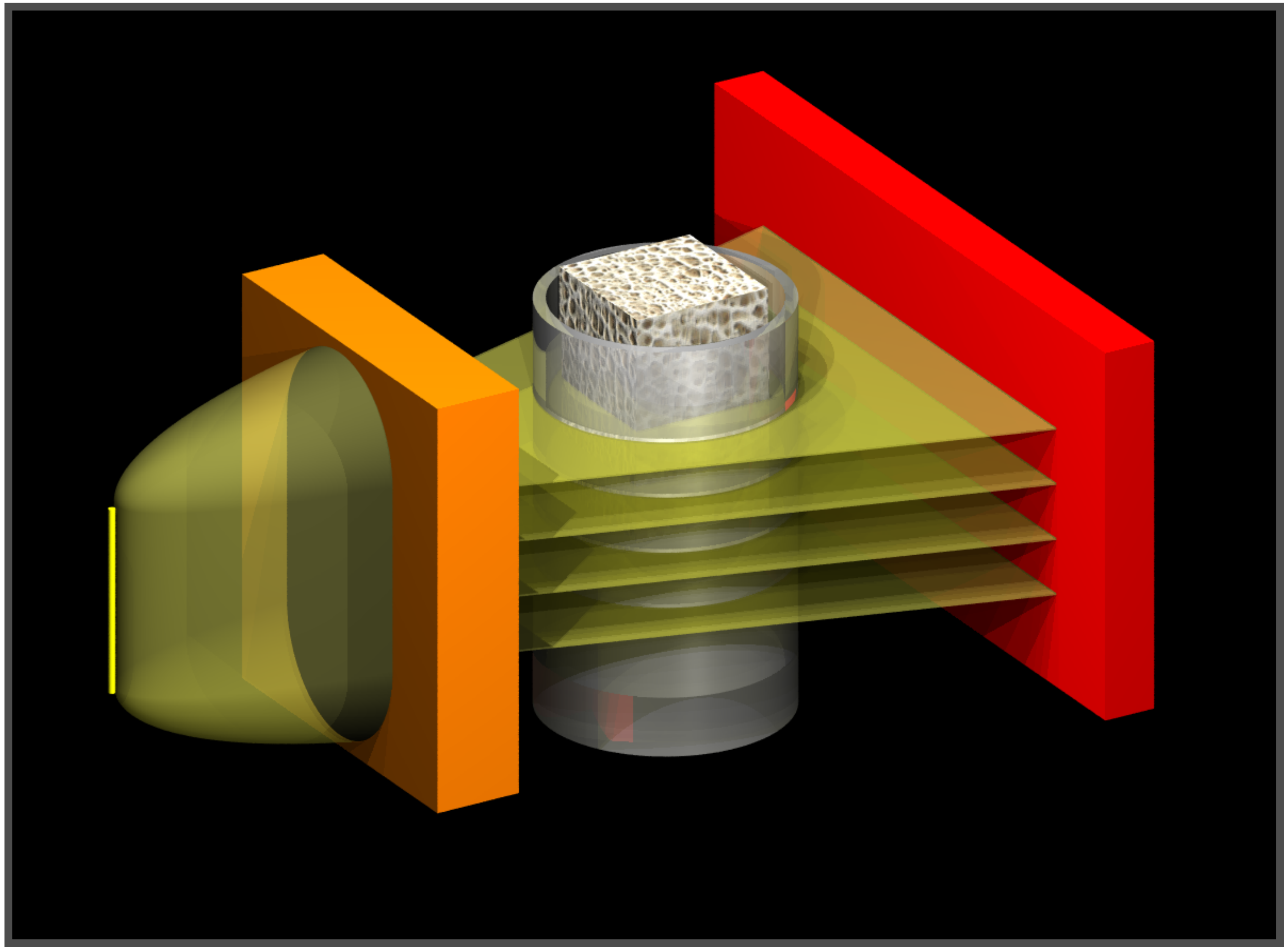
CT – Pencil beam



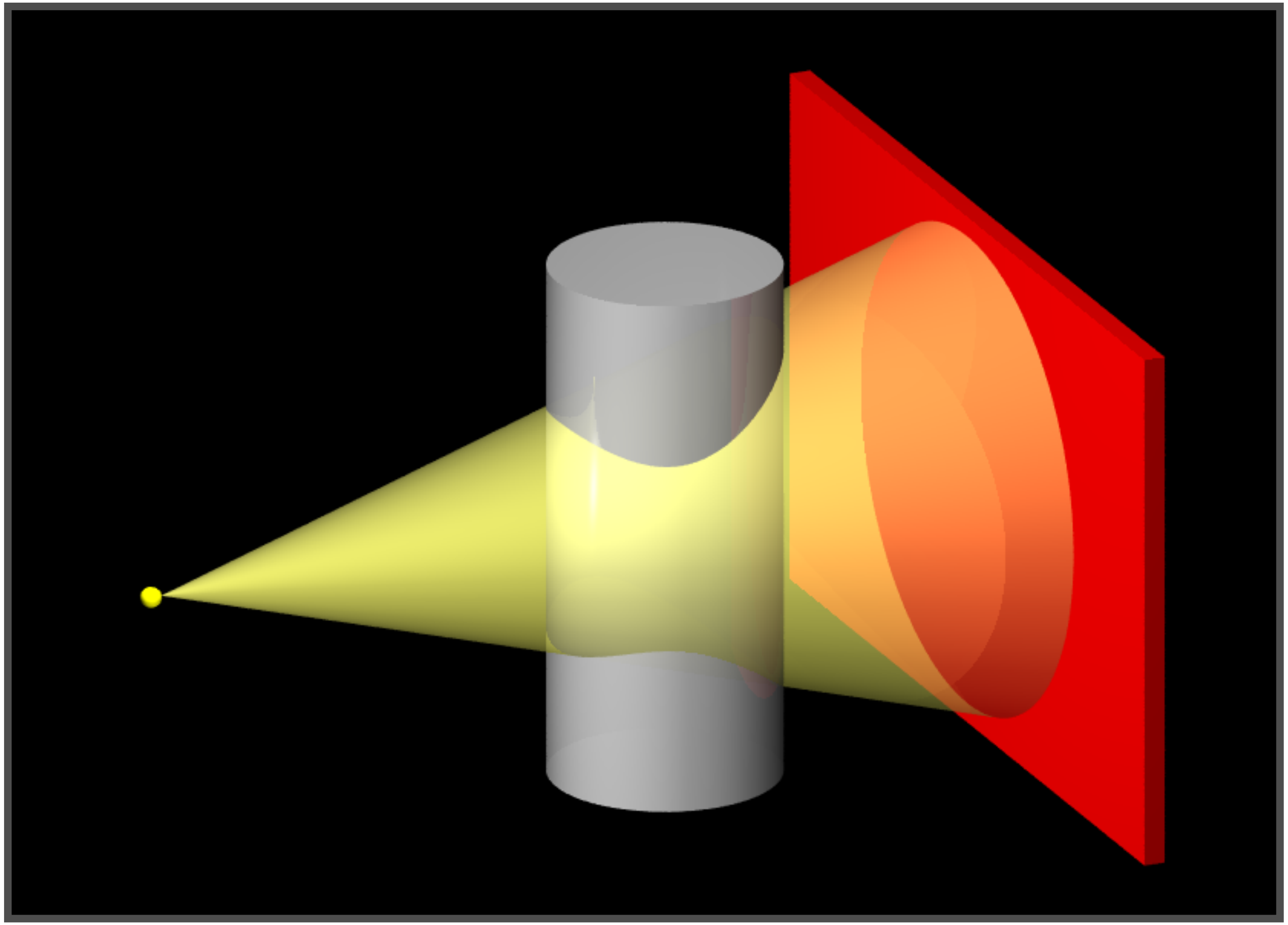
CT – Fan beam



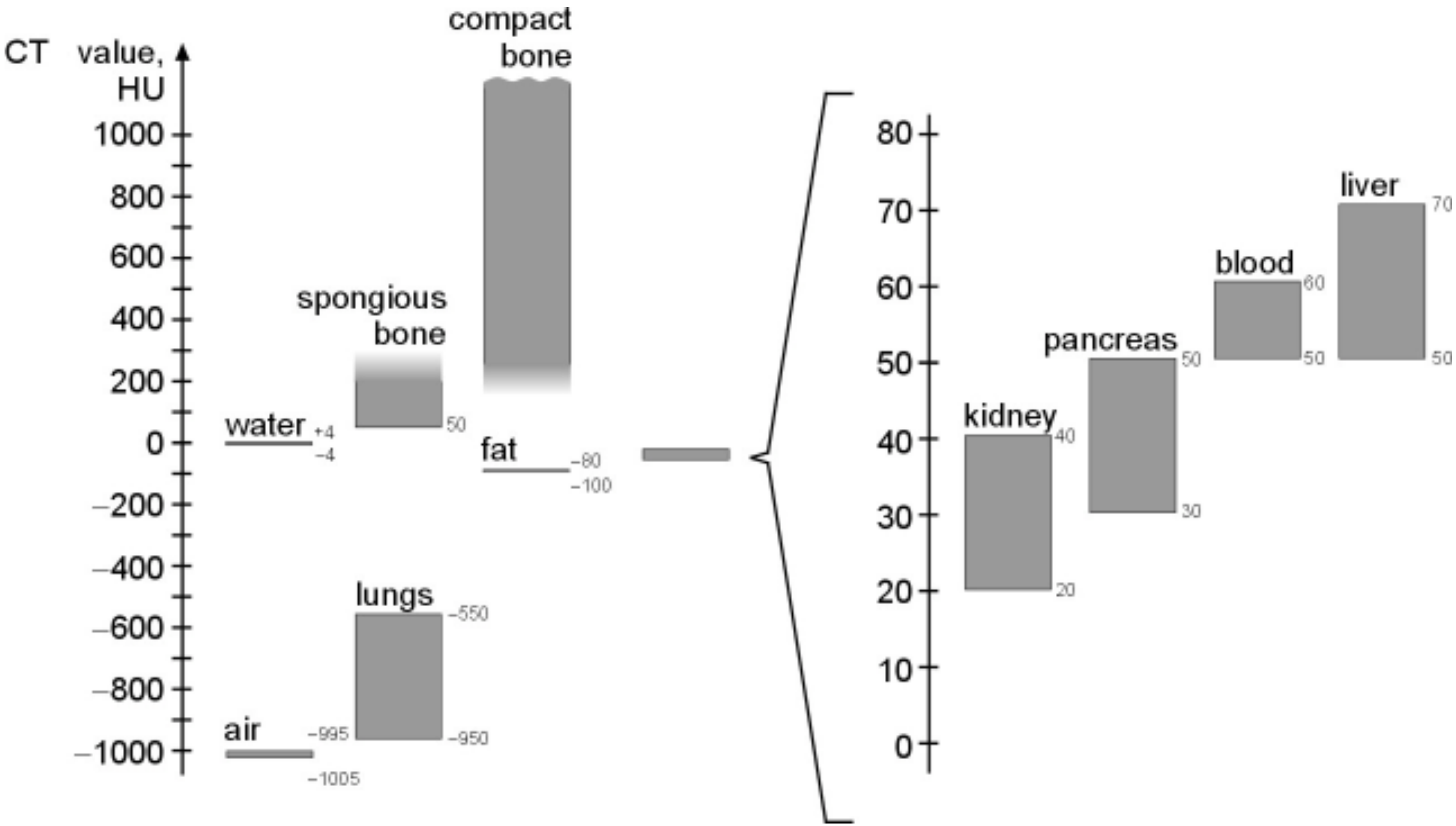
CT – Parallel fan beam



CT – Cone beam



CT – Hounsfield unit



$$\text{CT value} = \frac{(\mu - \mu_{\text{water}})}{\mu_{\text{water}}} 1000\text{HU}$$

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“The most important slides”