Medical Image Analysis

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Department of Computer Science & Engineering

Syllabus

- **Classical Approaches:** Introduction to image processing and medical imaging modalities, denoising and enhancement, Tissue and Cell Segmentation: clustering, active contours and level sets based approaches, Medical Image alignment: rigid and deformable registration
- **Machine Learning and Deep Learning Approaches:** Fundus Image analysis, Retinal Vessel Segmentation, MRI image analysis and segmentation, 3D brain reconstruction from and MRI slices and analysis, Microscopic image analysis and interpretation, Ultrasonography image analysis, X-Ray and CT image segmentation, diagnosis and prognosis of various diseases, Correlation between different medical imaging modalities and conversions, augmenting clinical measurements with medical imaging modalities for diseases diagnosis and prognosis

Course Logistics

- Instructor: Angshuman Paul
- Contact: apaul@iitj.ac.in
- TA: Jayant Mahawar (mahawar.2@iitj.ac.in)
- Class hours:
  - Tuesday: 3-3:50 PM
  - Wednesday: 2-2:50 PM
  - Friday: 2-2:50 PM

Course Logistics

- Course project
- Reading group
- Quiz
- Viva
- Minor and Major
- All are compulsory

Books and Study Materials

- Book:
  - Fundamentals of Medical Imaging by Paul Suetens
  - Medical Imaging Signals and Systems by Jerry L. Prince and Jonathan M. Links
- Other useful books:
  - Introduction to Medical Image Analysis, by Rasmus R. Paulsen and Thomas B. Moeslund
- Other books & Online materials: Will be informed from time to time

Prerequisites

- Digital Image Processing
- Computer Vision
- ML
- DL

Medical Images

Medical Images

James Clerk Maxwell

https://www.britannica.com/biography/James-Clerk-Maxwell

Medical Images

James Clerk Maxwell

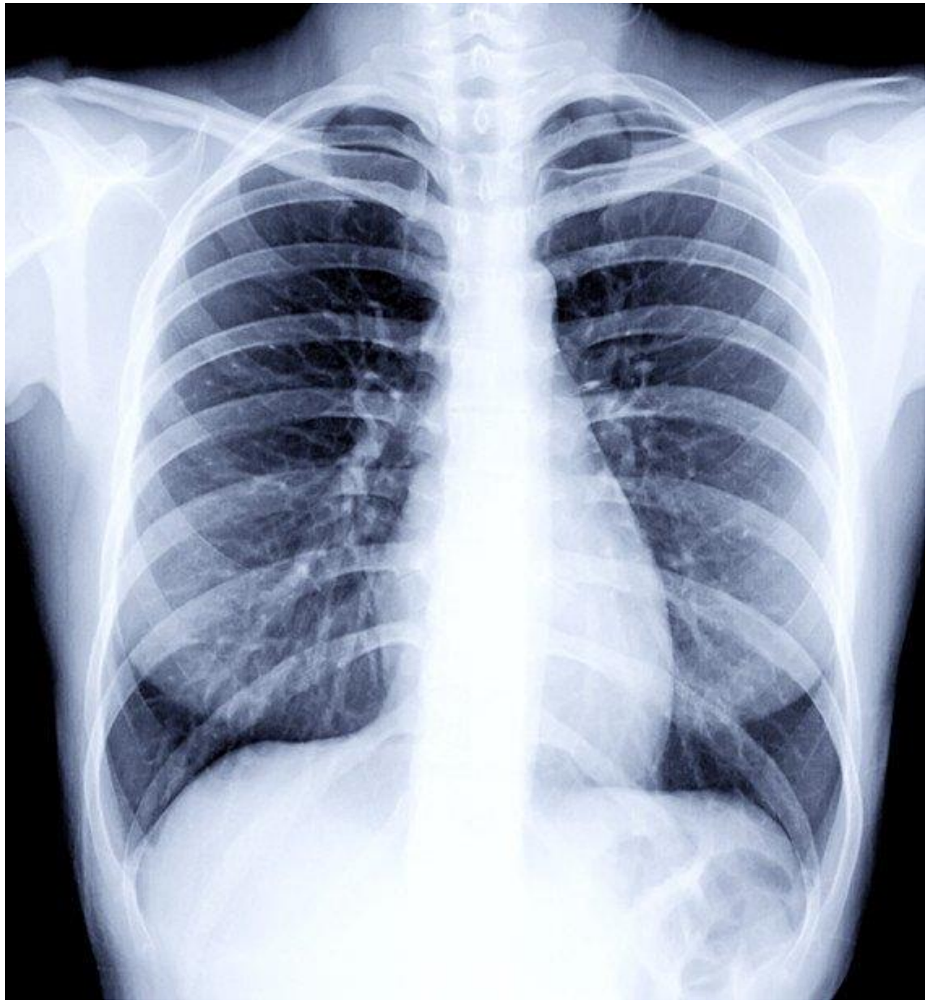
$$\nabla \cdot \mathbf{D} = \rho$$
$$\nabla \cdot \mathbf{B} = 0$$
$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$
$$\nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t}$$

https://www.britannica.com/biography/James-Clerk-Maxwell

Medical Images

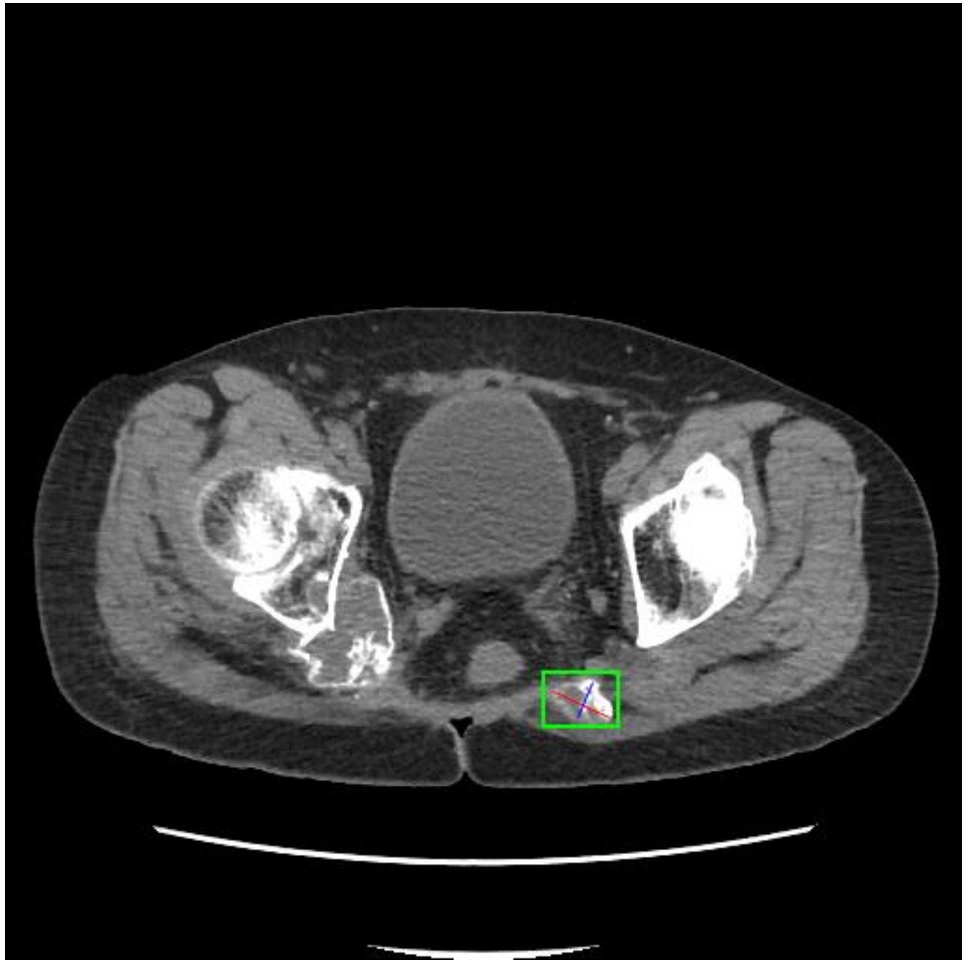
- Most medical images are results of EM waves
  - X-ray and CT
  - MRI
  - Histopathology & other optical microscopy images
  - PET
  - OCT
- Some medical images use sound waves
  - Ultrasound

Medical Images: X-ray



https://www.drugs.com/health-guide/x-rays.html

Medical Images: CT

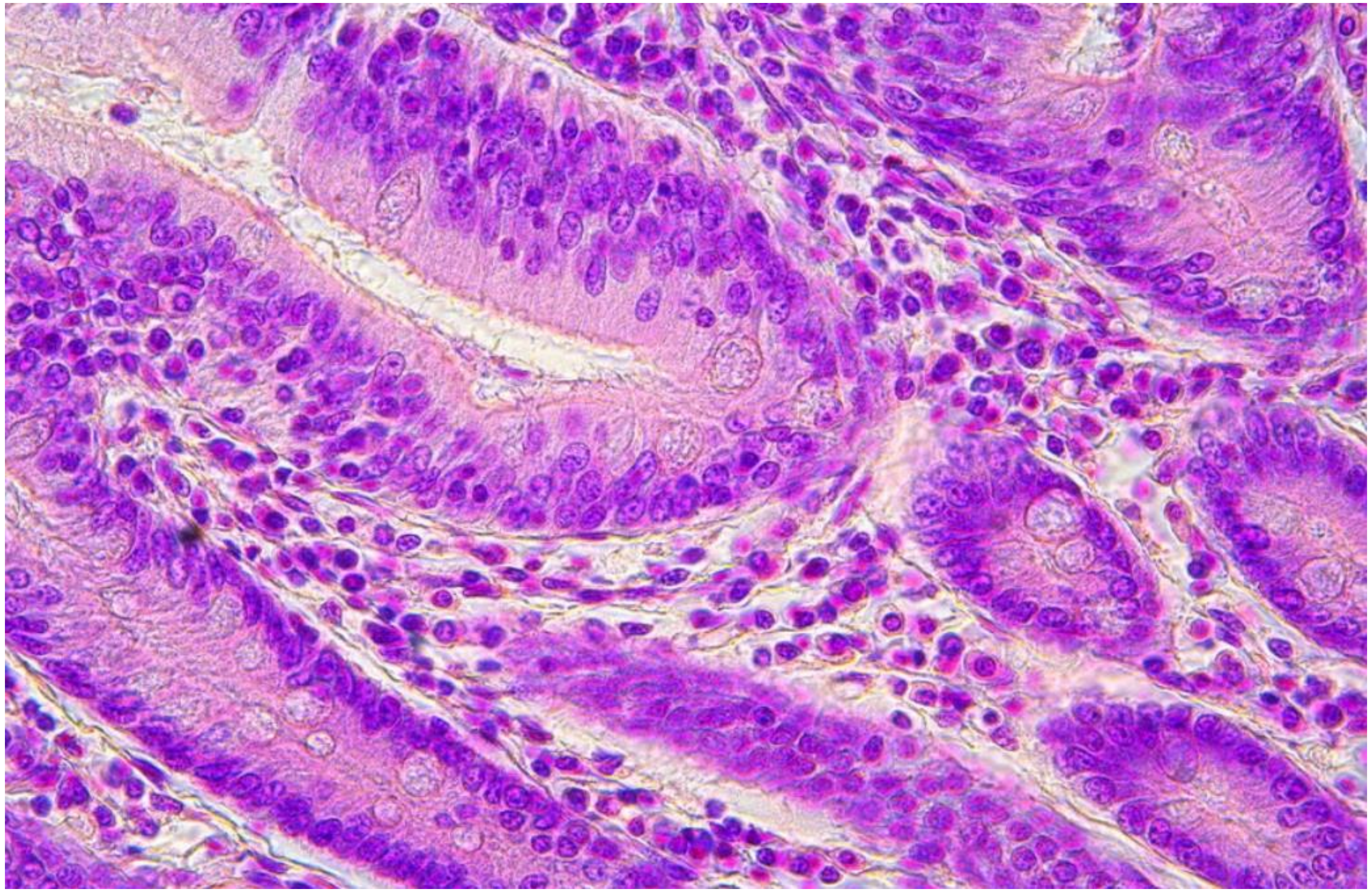


https://paperswithcode.com/dataset/deeplesion

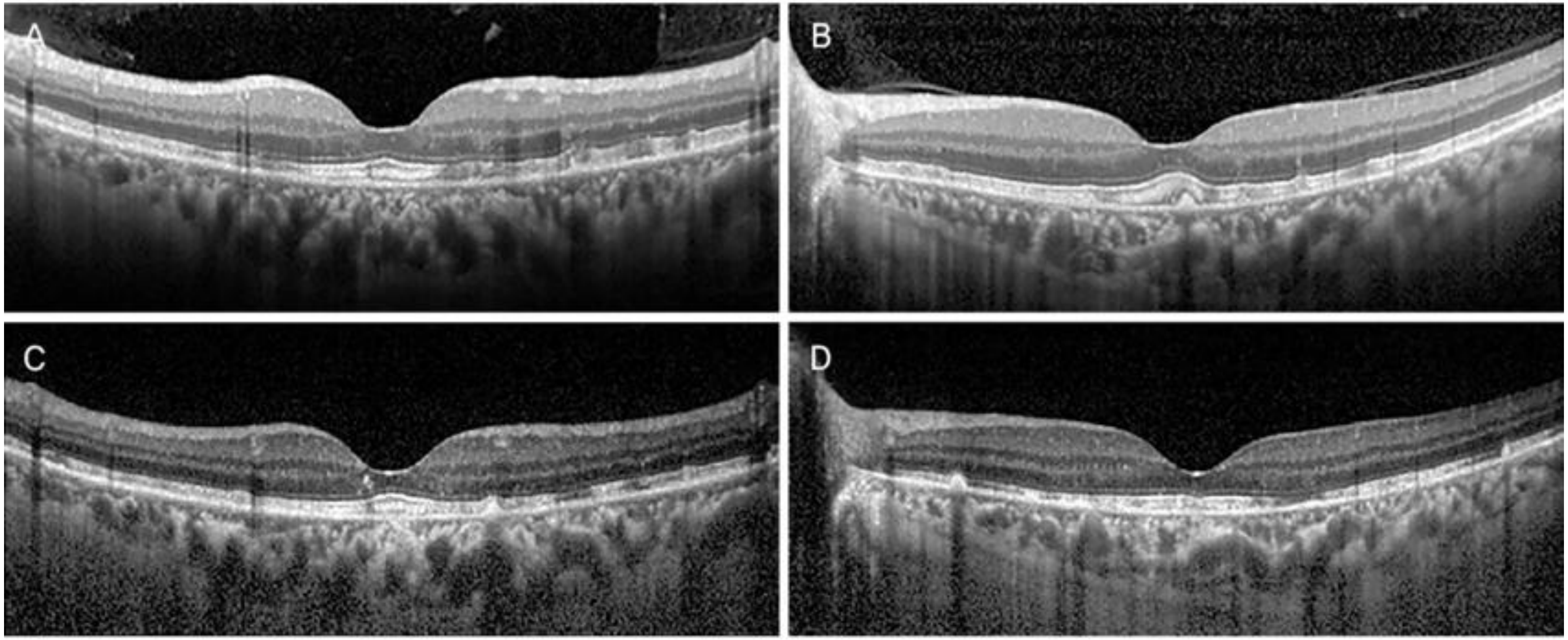
Medical Images: MRI

https://www.kaggle.com/datasets/navoneel/brain-mri-images-for-brain-tumor-detection

Medical Images: Histopathology

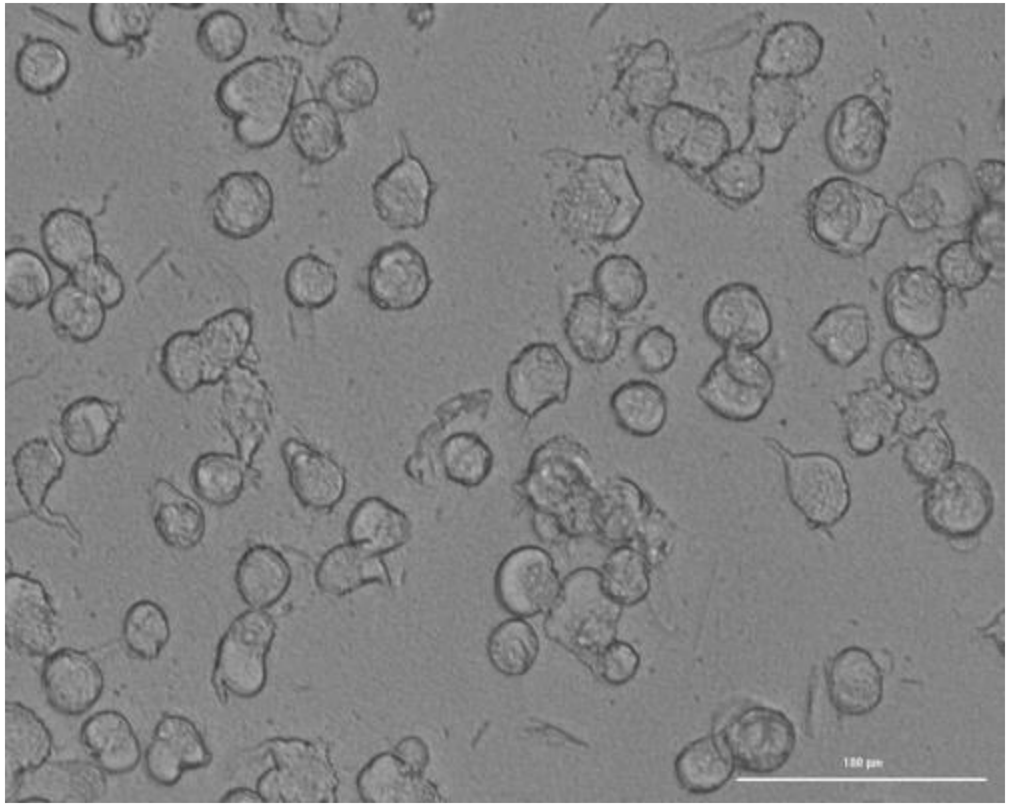


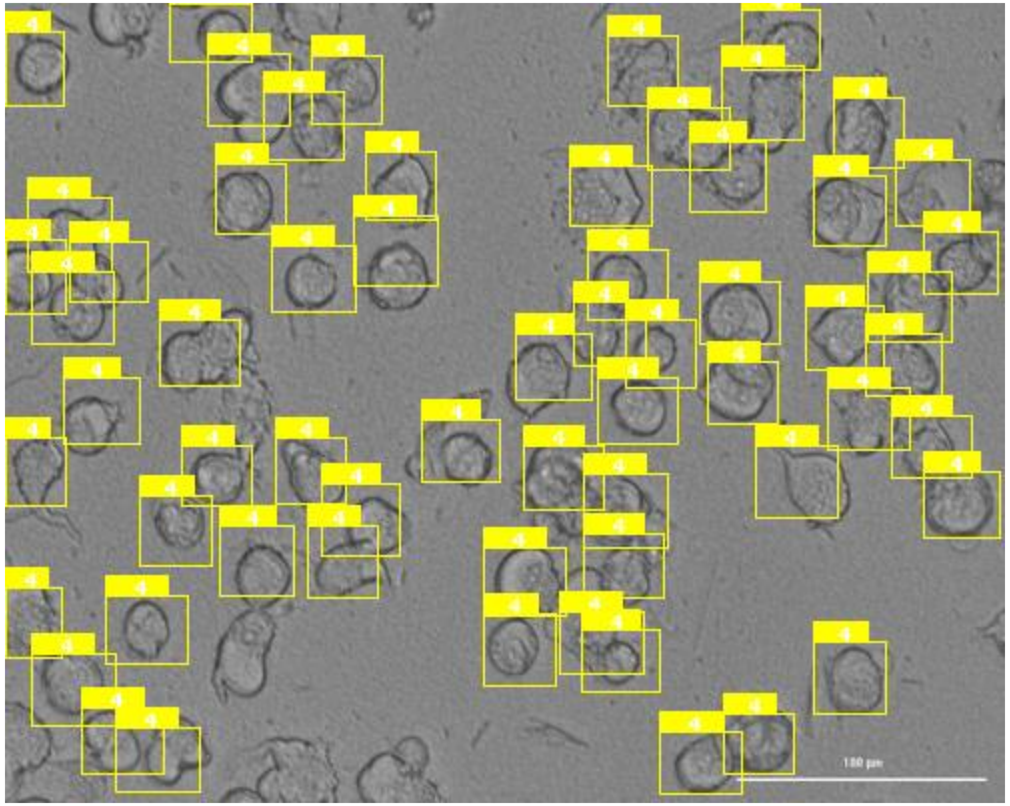
Medical Images: SDOCT



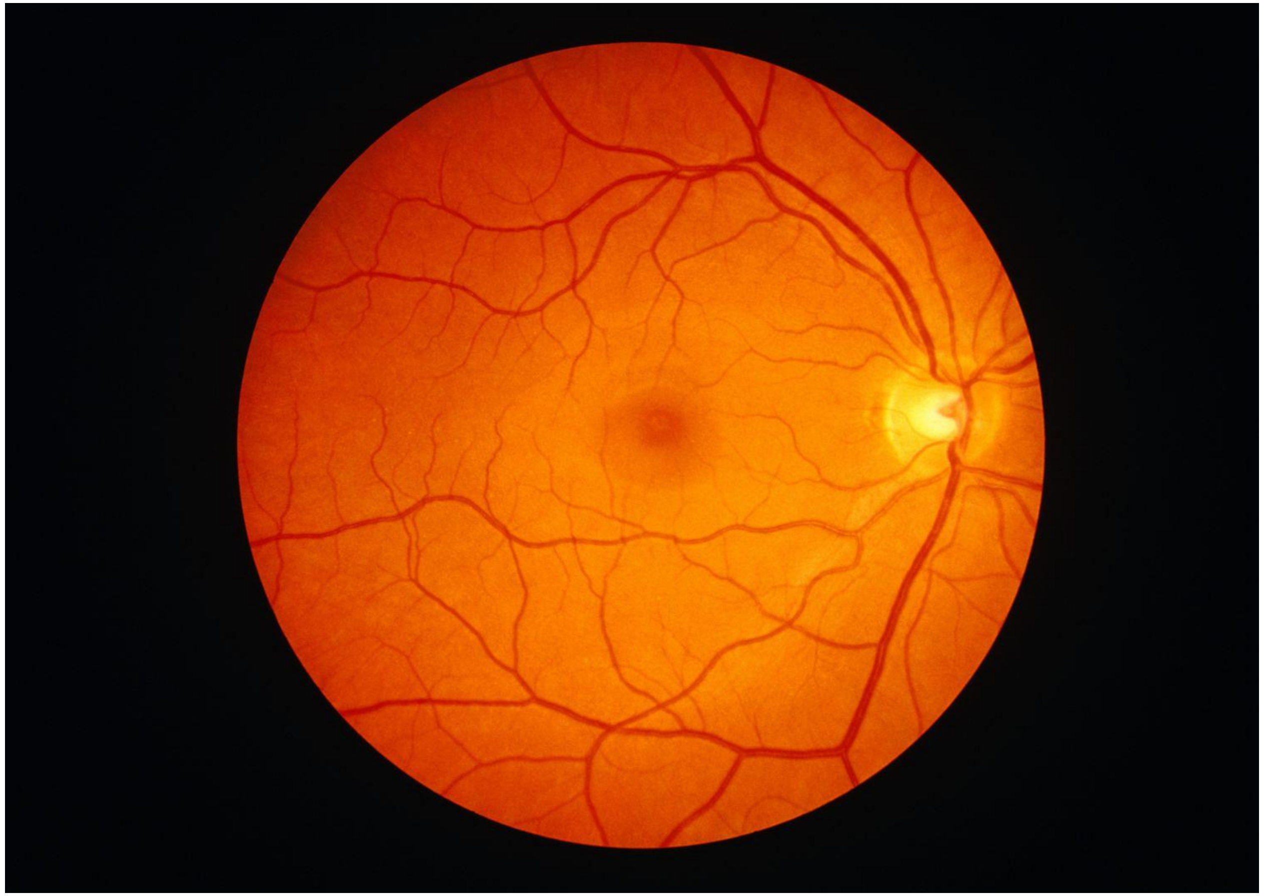
https://www.researchgate.net/figure/Spectral-domain-optical-coherence-tomography-SD-OCT-of-the-patient-SD-OCT-of-the-right_fig3_335918458

Medical Images: Cell Images





Medical Images: Retinal Images



https://www.verywellhealth.com/digital-retinal-imaging-3884662

What is Medical Image Analysis

- Use of ML, CV, IP techniques for the diagnosis of medical images

Why Medical Image Analysis

- To make decision support systems
  - Better diagnosis
    - By making an automated diagnosis to assist the clinician
    - By improving the quality of the images
  - Faster
  - Facilitating telemedicine applications
  - Affordable health care

Present Status

- Unprecedented progress in recent years
- Human level or super-human accuracies in several occasions
- FDA approval for decision support systems

Present Status: Challenges

- Generalizability
- Explainability
- Cost of annotation
- Computational requirements
- Others

Why Study MedIA?

- To know the classical and SOTA approaches
- Improve the existing approaches
  - Push the boundary of our ability
- Designing new approaches
  - To address the major challenges
- Use the understandings/ innovations from this area in solving problems of other fields

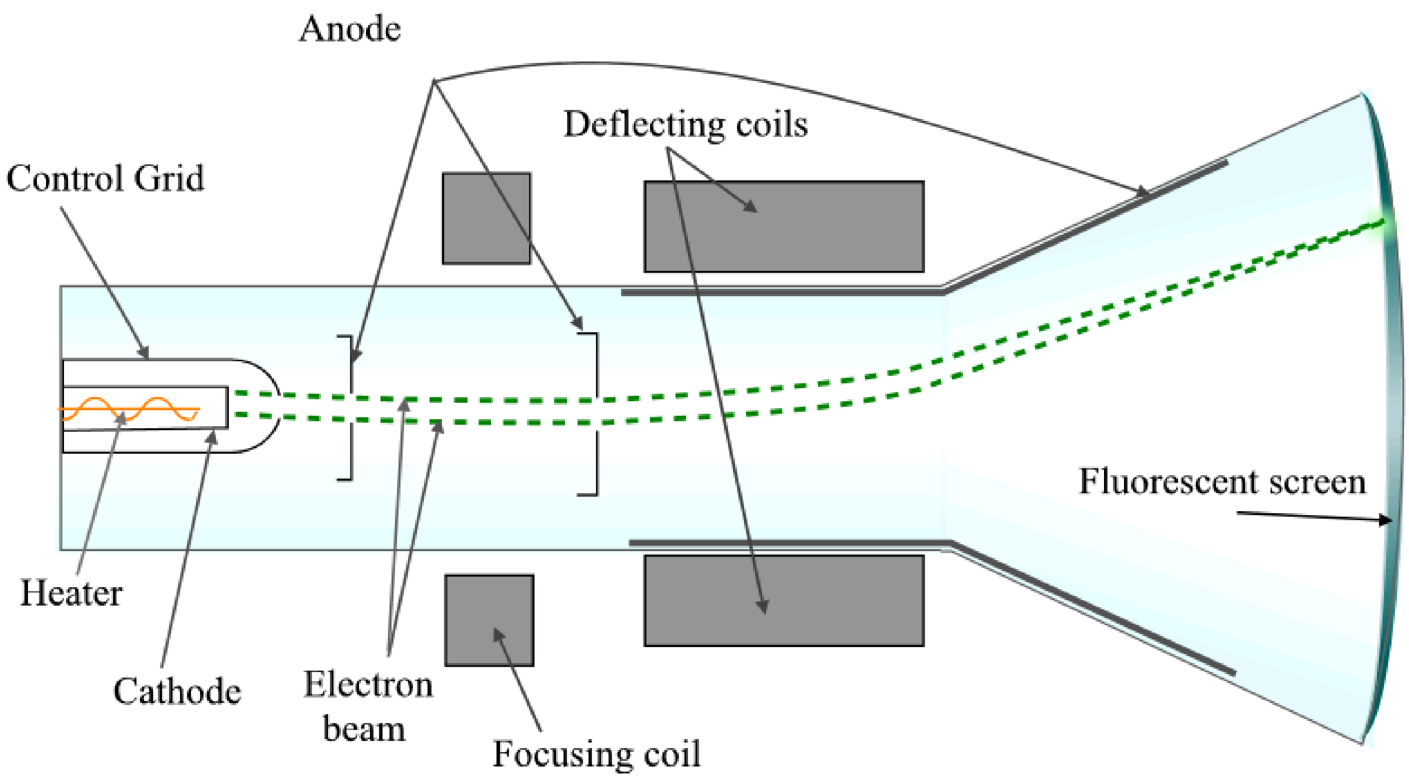
X-ray

- Serendipity

X-ray

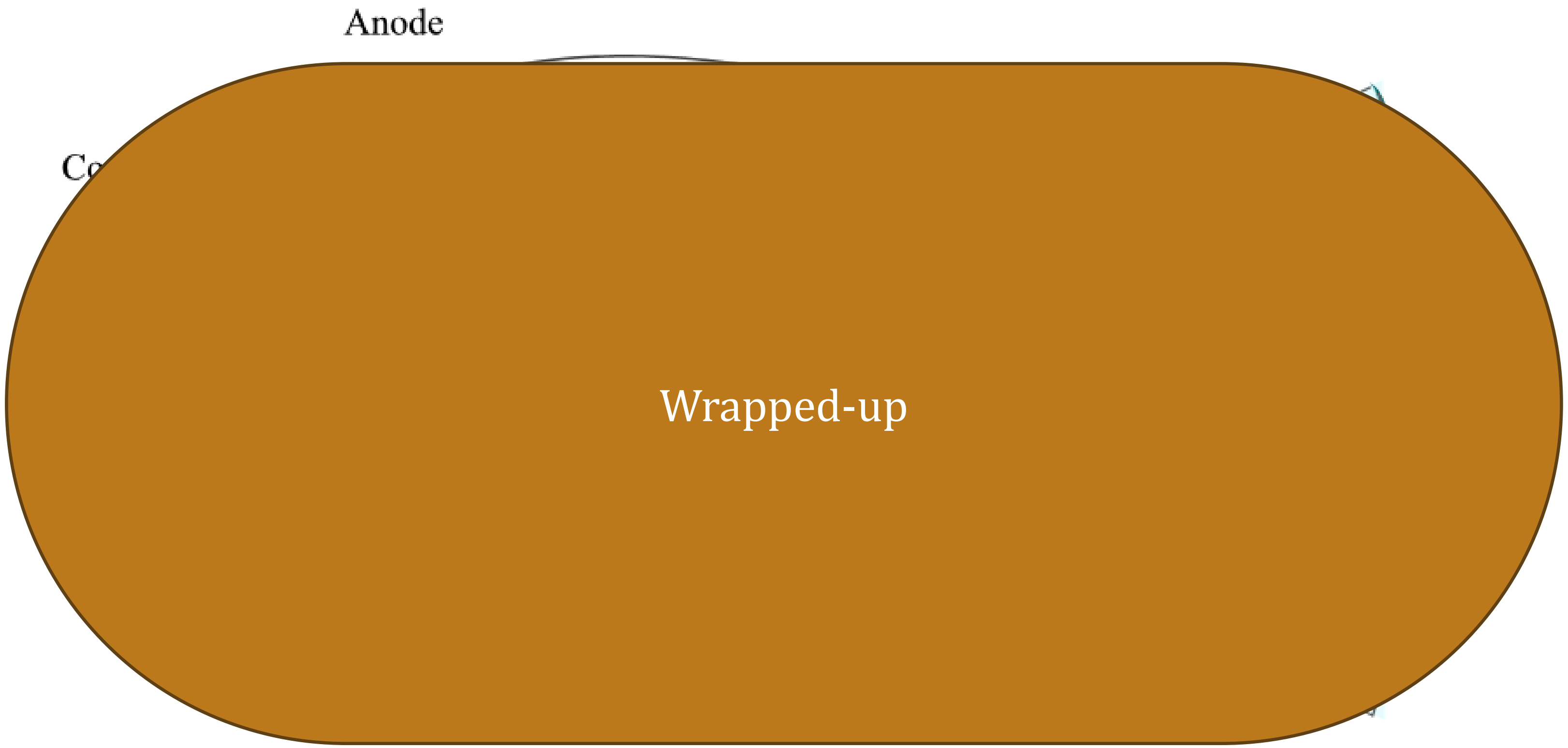
- Wilhelm Conrad Röntgen
- 1895
- First observed: 1869

What is X-ray



https://en.wikipedia.org/wiki/Cathode-ray_tube

What is X-ray



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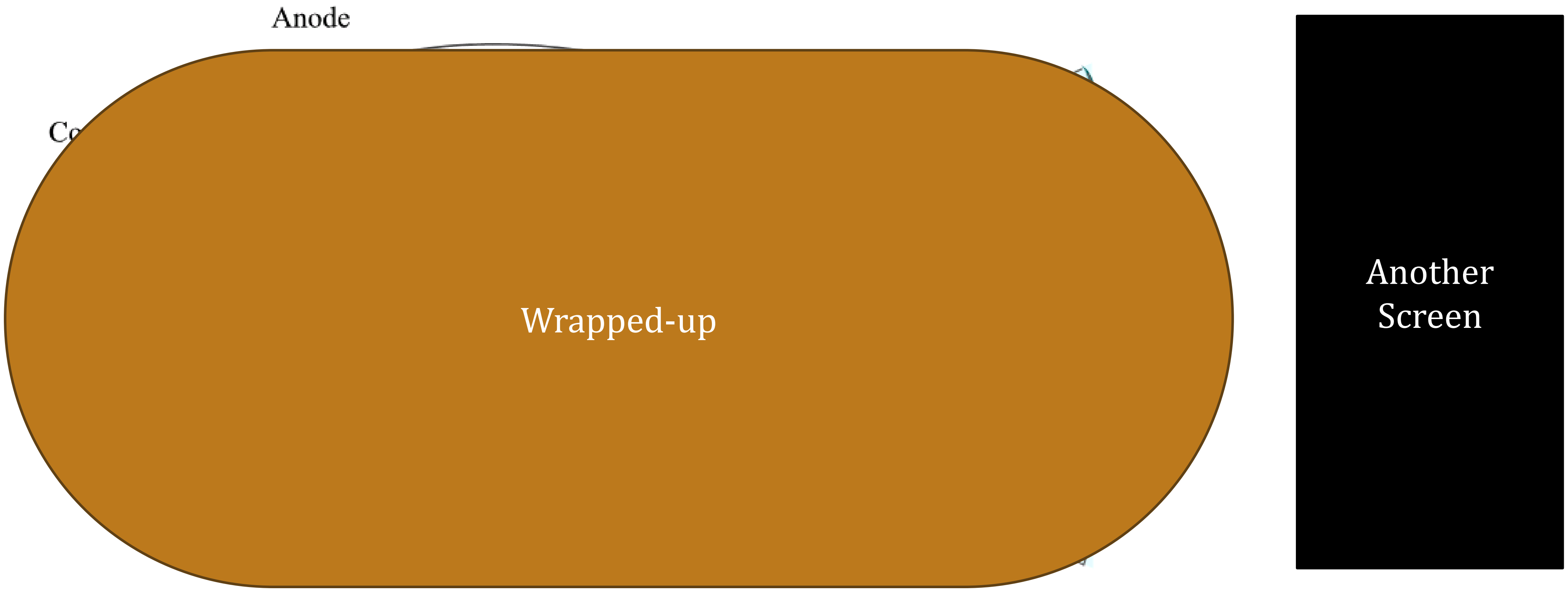

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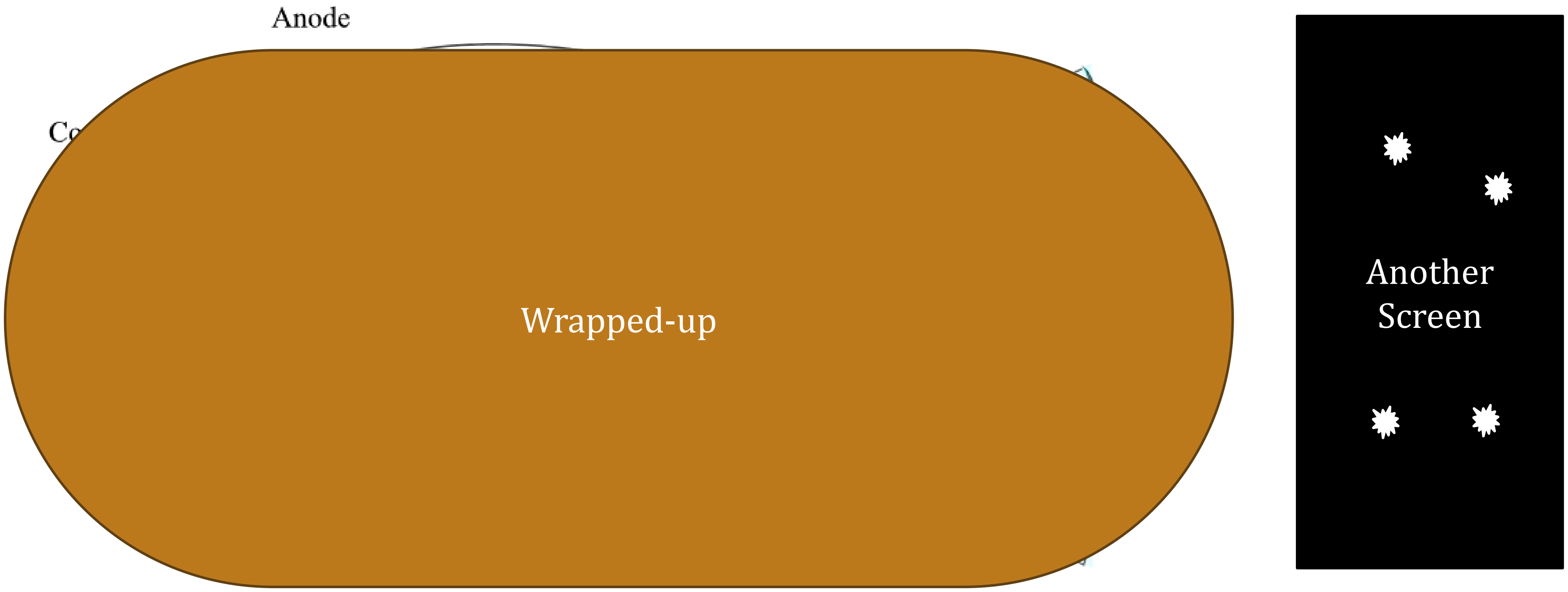
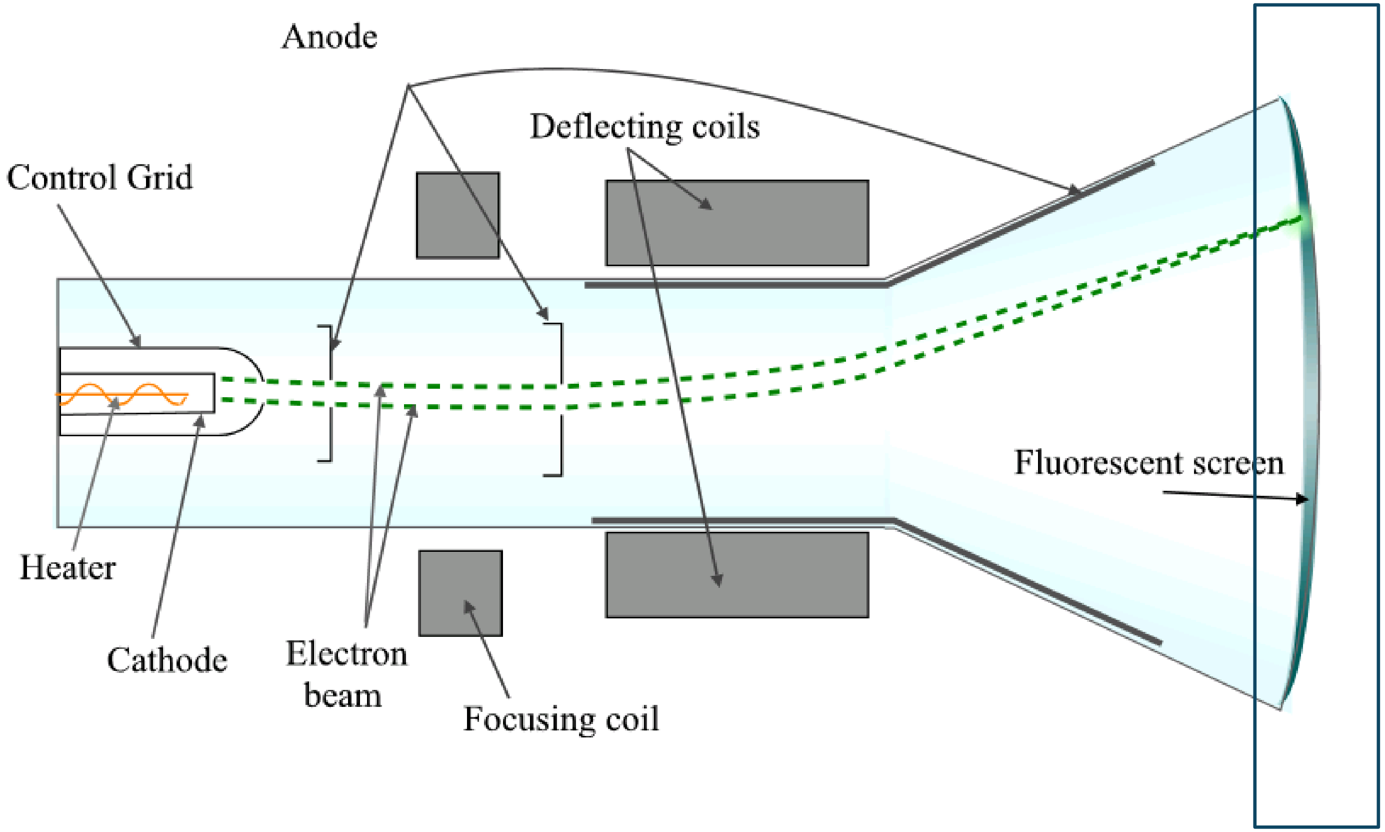
What is X-ray



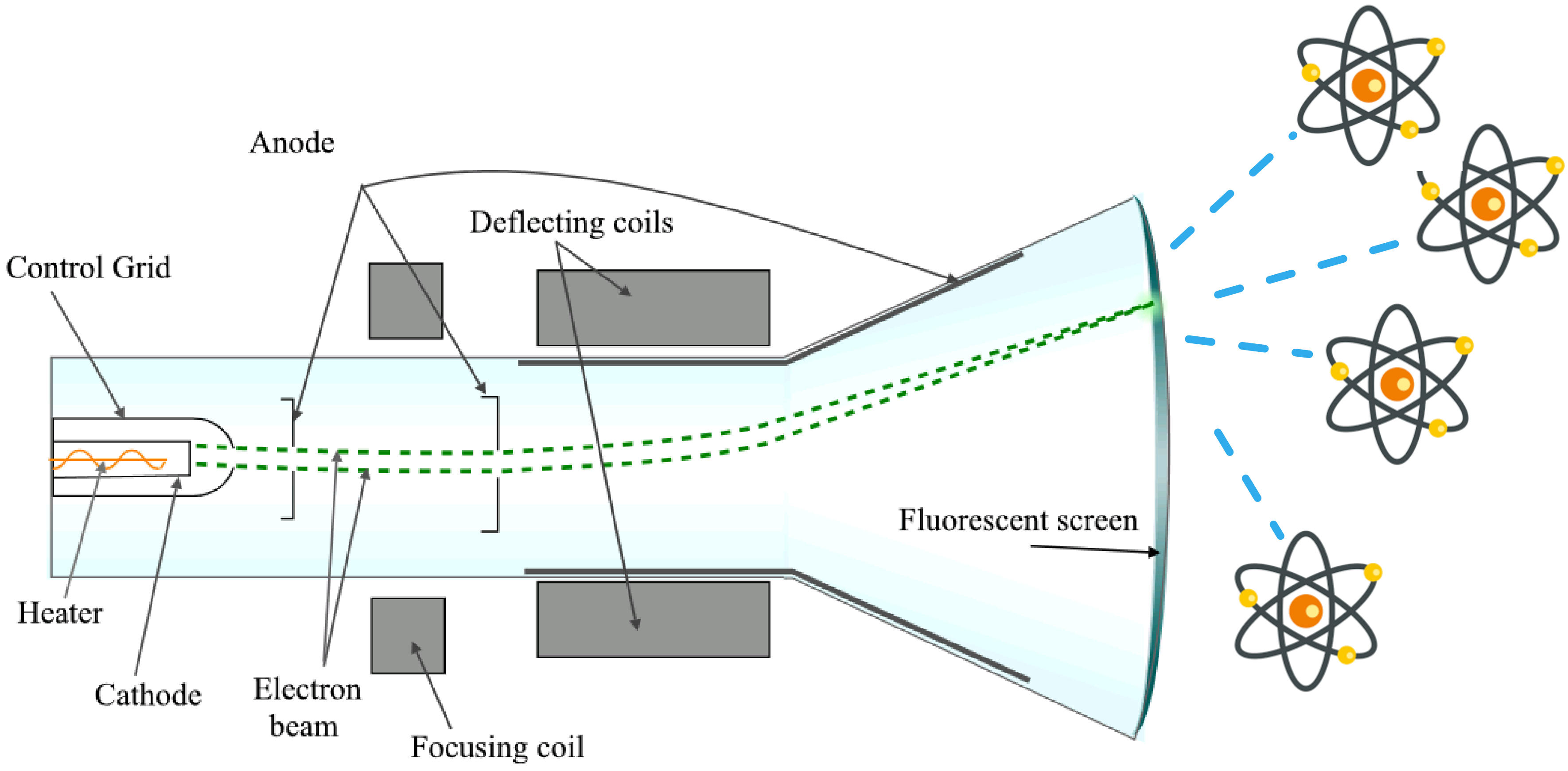
https://en.wikipedia.org/wiki/Cathode-ray_tube

What Happens Internally



https://en.wikipedia.org/wiki/Cathode-ray_tube

What Happens Internally



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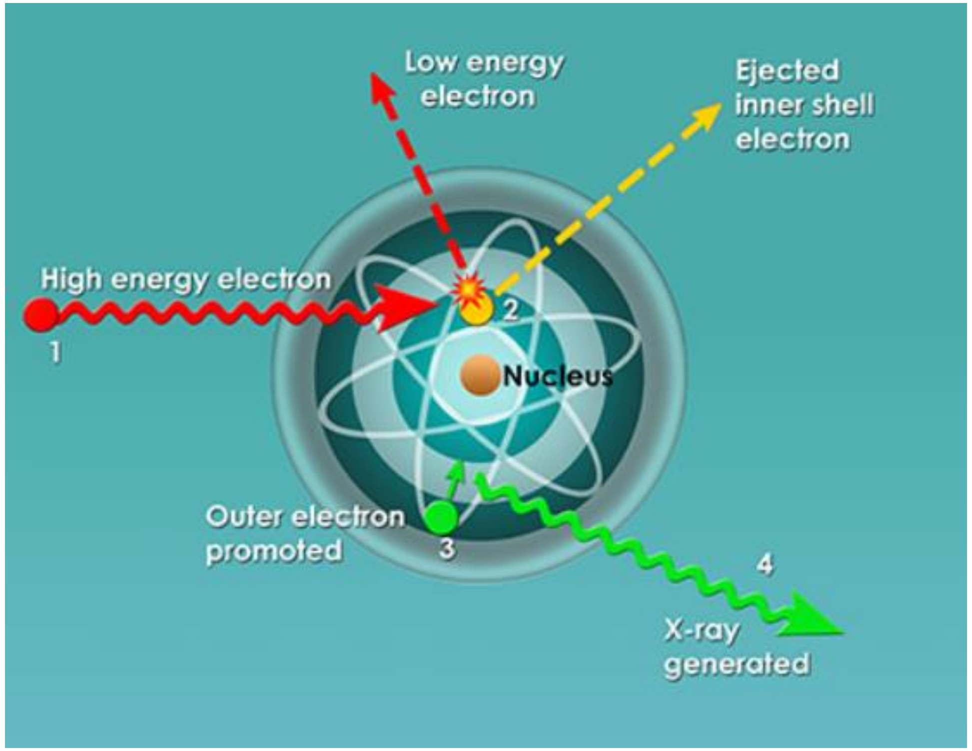
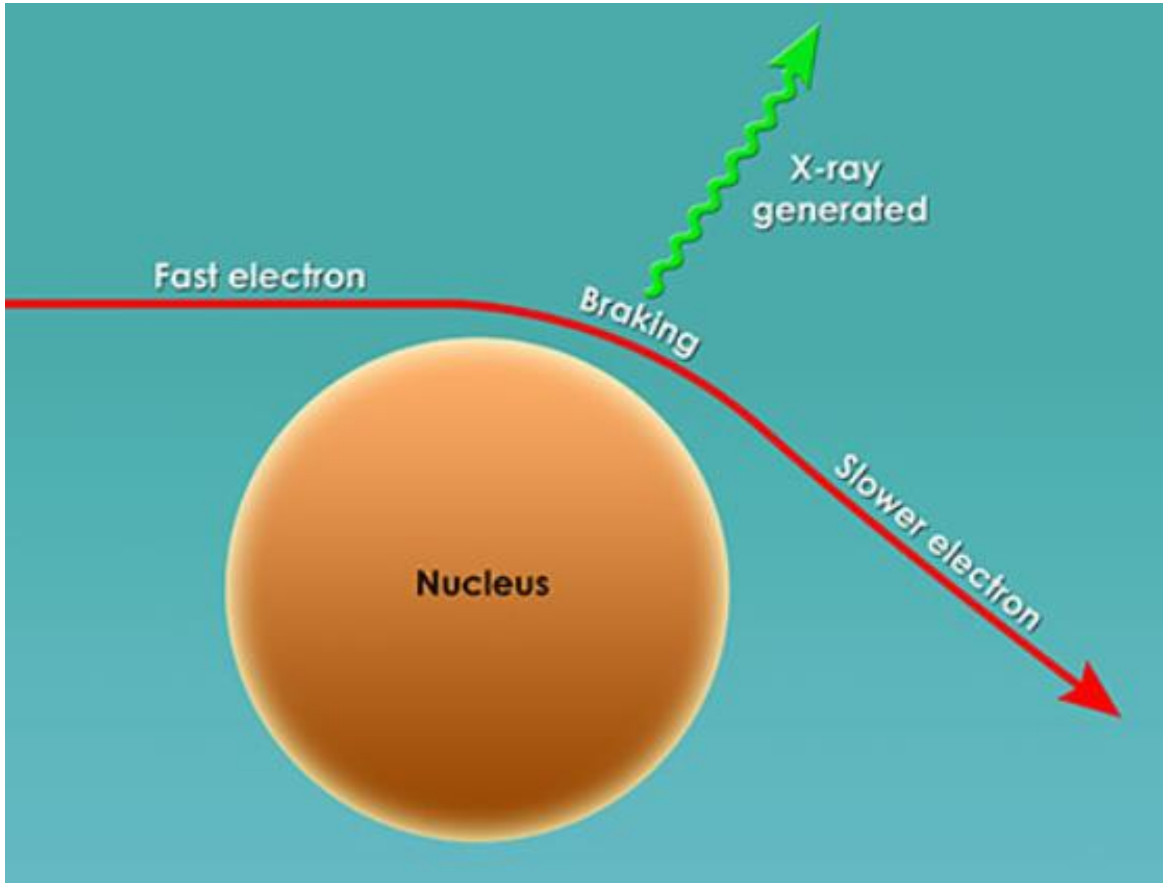
Characteristics Generation



When a high energy electron (**1**) collides with an inner shell electron (**2**) both are ejected from the tungsten atom leaving a 'hole' in the inner layer. This is filled by an outer shell electron (**3**) with a loss of energy emitted as an X-ray photon (**4**)

https://www.radiologymasterclass.co.uk/tutorials/physics/x-ray_physics_production#top_2nd_img

Bremsstrahlung/Braking X-ray Generation



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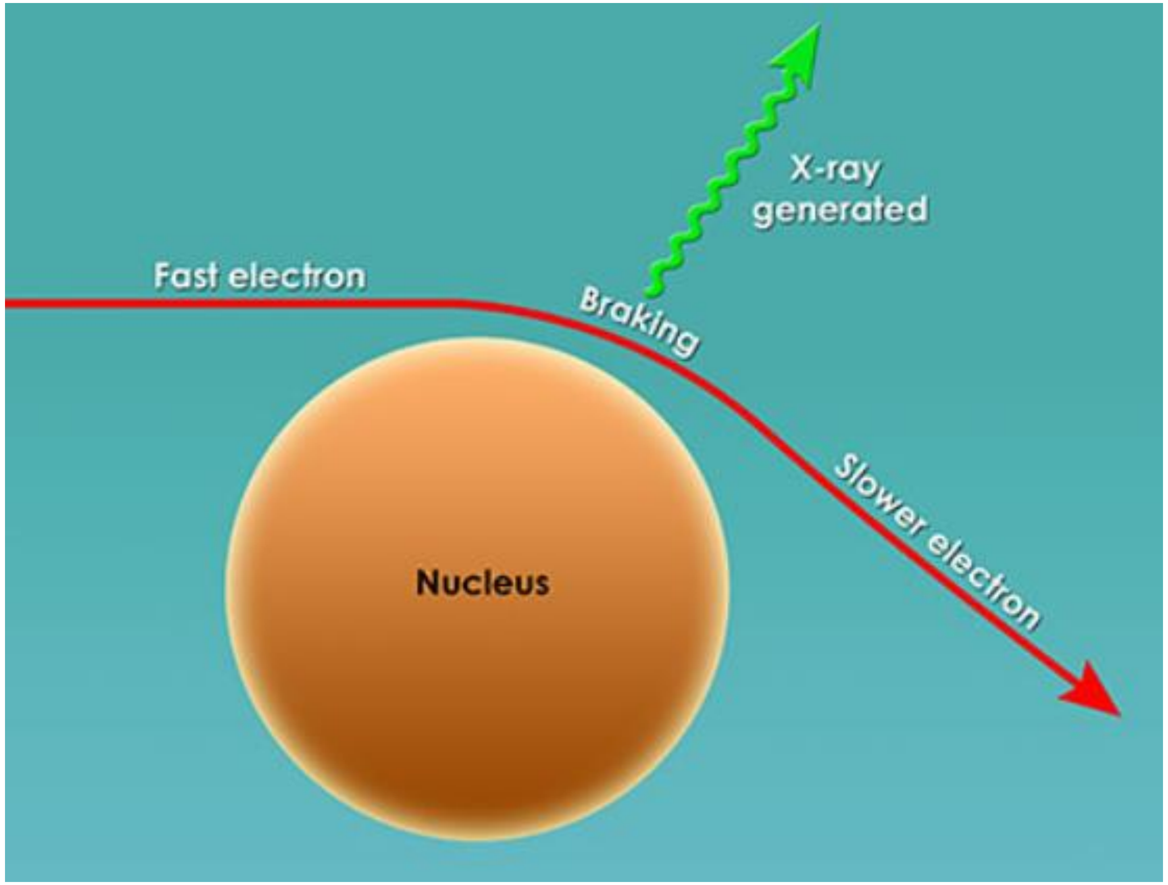
Bremsstrahlung/Braking X-ray Generation

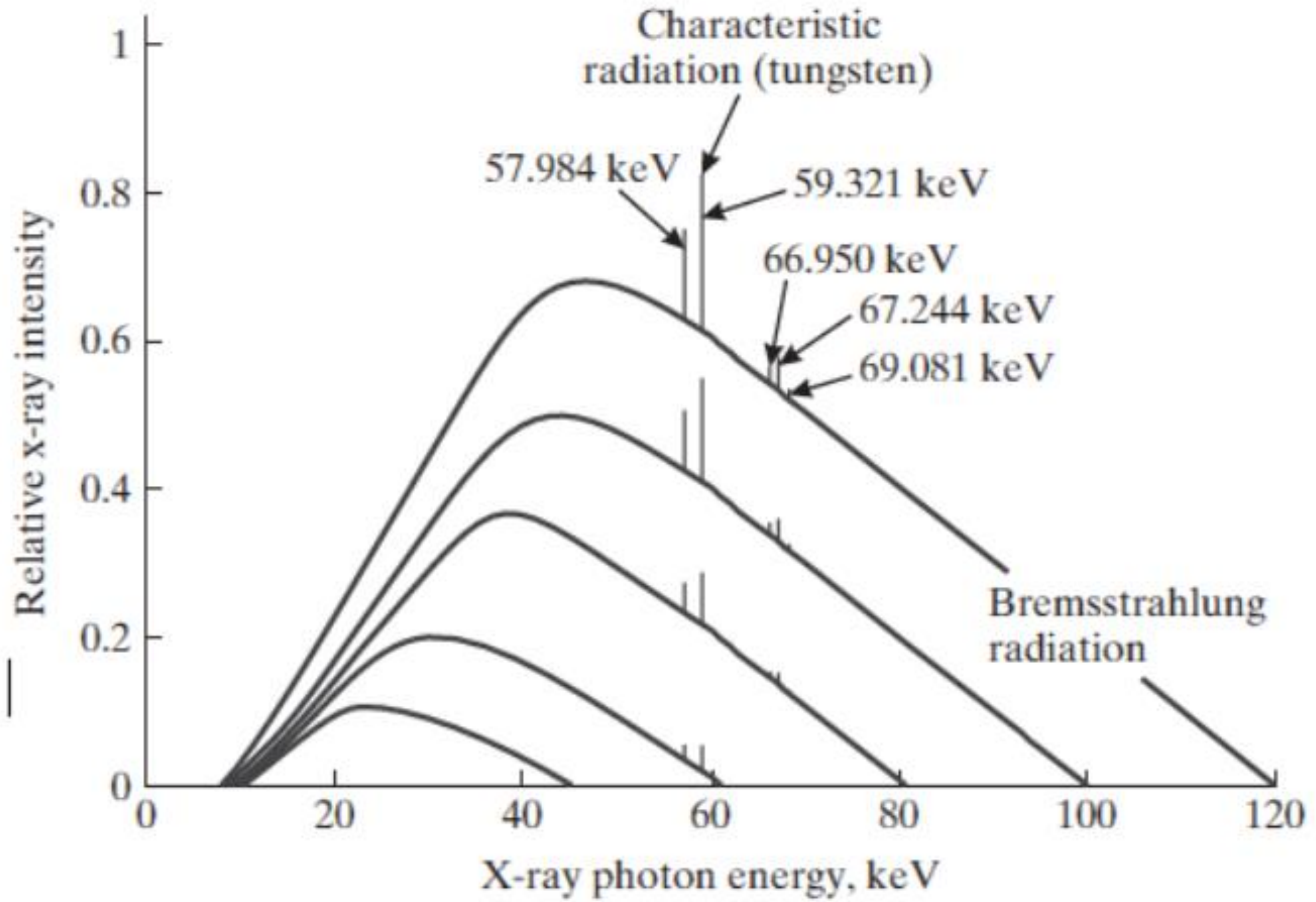


- When an electron passes near the nucleus it is slowed and its path is deflected. Energy lost is emitted as a bremsstrahlung X-ray photon.
- Bremsstrahlung = Braking radiation
- Approximately 80% of the population of X-rays within the X-ray beam consists of X-rays generated in this way.

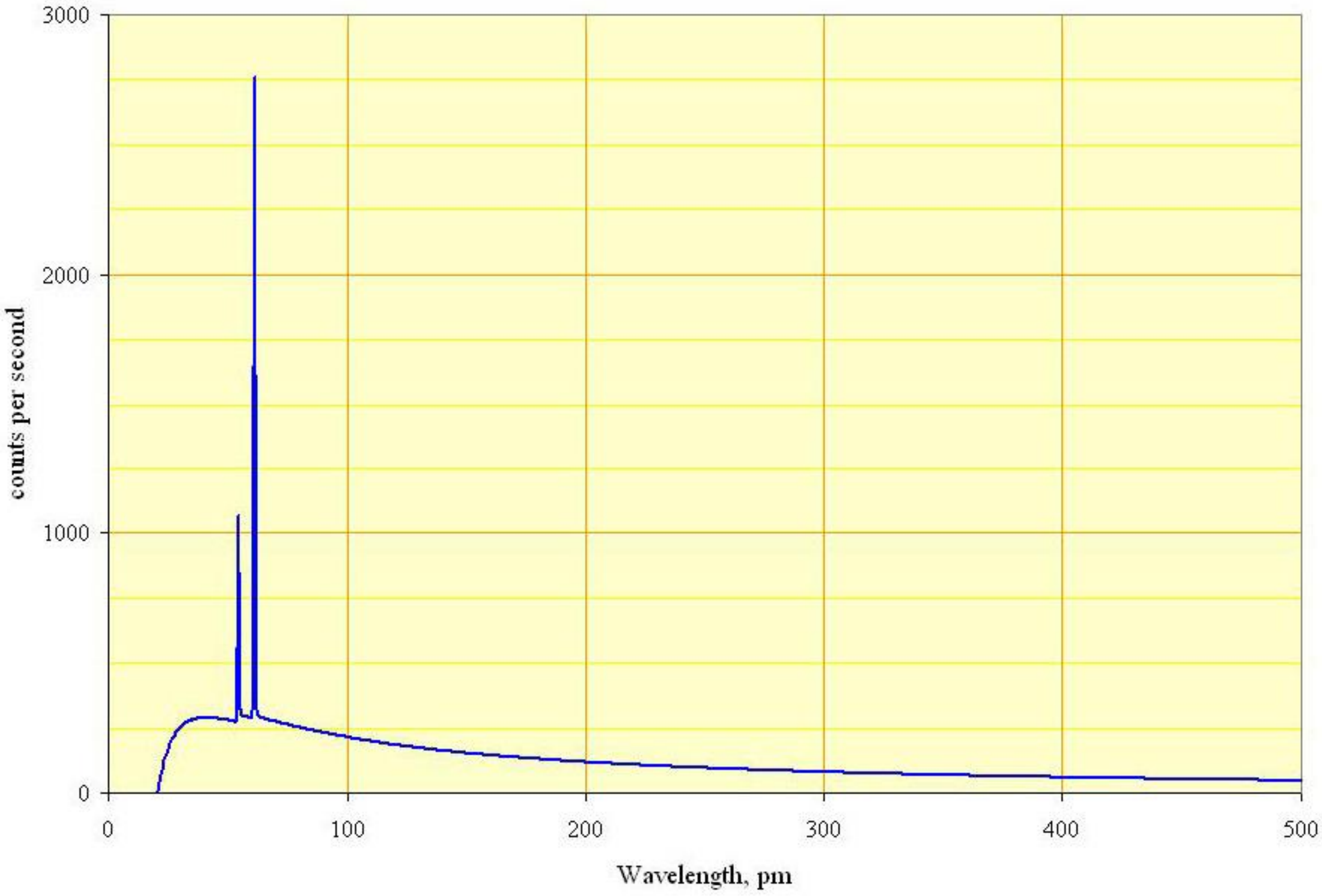
- **Primary source of x-ray from x-ray tube**

https://www.radiologymasterclass.co.uk/tutorials/physics/x-ray_physics_production#top_2nd_img

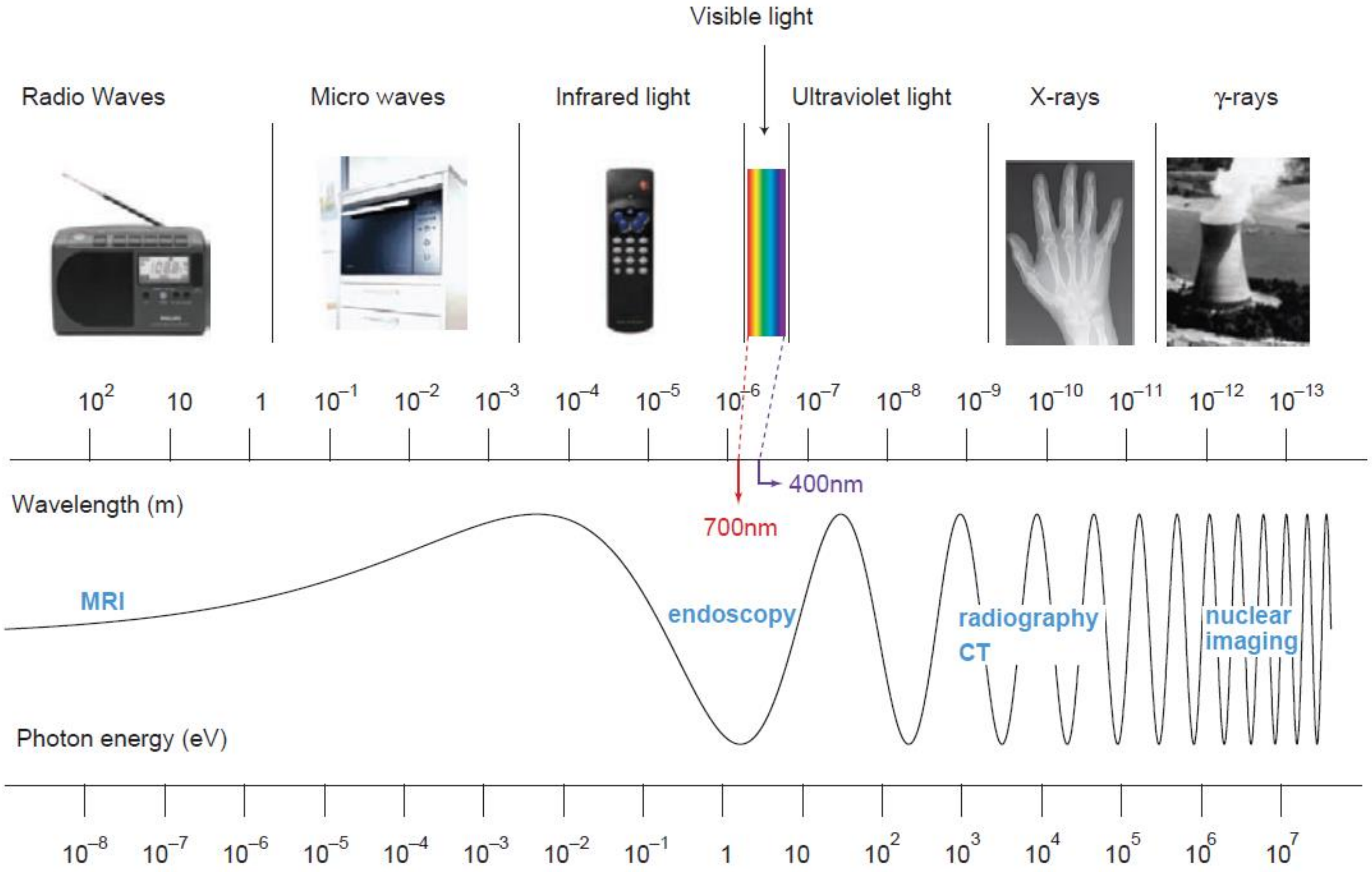
X-ray Generation



X-ray Generation



EM Spectrum


Visible light
Radio Waves
Micro waves
Infrared light
Ultraviolet light
X-rays
γ-rays
10^{2} 10 1 10^{-1} 10^{-2} 10^{-3} 10^{-4} 10^{-5} 10^{-6} 10^{-7} 10^{-8} 10^{-9} 10^{-10} 10^{-11} 10^{-12} 10^{-13}
400nm
Wavelength (m)
700nm
MRI
endoscopy
radiography
CT
nuclear imaging
Photon energy (eV)
10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 1 10 10^{2} 10^{3} 10^{4} 10^{5} 10^{6} 10^{7}

EM Spectrum

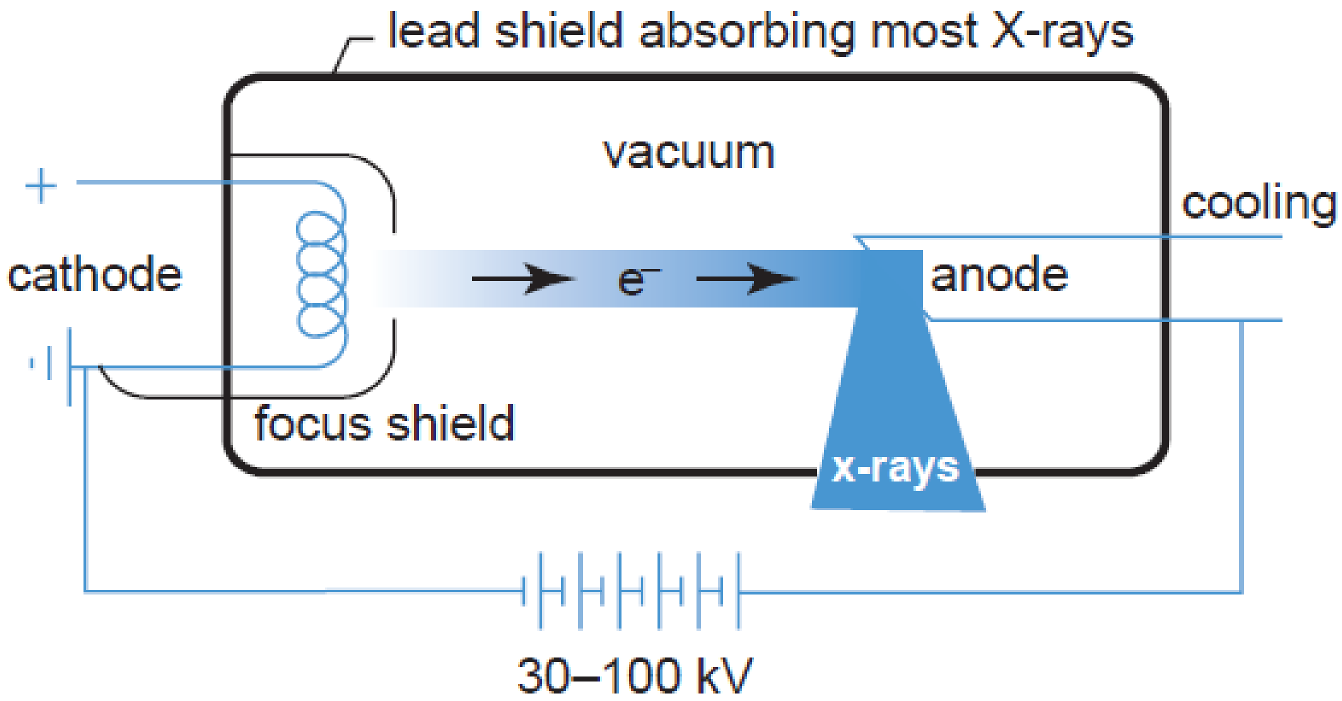
TABLE 4.2

The EM Spectrum

Frequency Range	Wavelengths	Photon Energies	Description
1.0×10^5–3.0×10^{10} Hz	3 km–0.01 m	413 peV–124 μeV	Radio waves
3.0×10^{12}–3.0×10^{14} Hz	100–1 μm	12.4 meV–1.24 eV	Infrared radiation
4.3×10^{14}–7.5×10^{14} Hz	700–400 nm	1.77–3.1 eV	Visible light
7.5×10^{14}–3.0×10^{16} Hz	400–10 nm	3.1–124 eV	Ultraviolet light
3.0×10^{16}–3.0×10^{18} Hz	10 nm–100 pm	124 eV–12.4 keV	Soft x-rays
3.0×10^{18}–3.0×10^{19} Hz	100–10 pm	12.4–124 keV	Diagnostic x-rays
3.0×10^{19}–3.0×10^{20} Hz	10–1 pm	124 keV–1.24 MeV	Gamma rays

Adapted from Johns and Cunningham, 1983.

Generation of X-ray



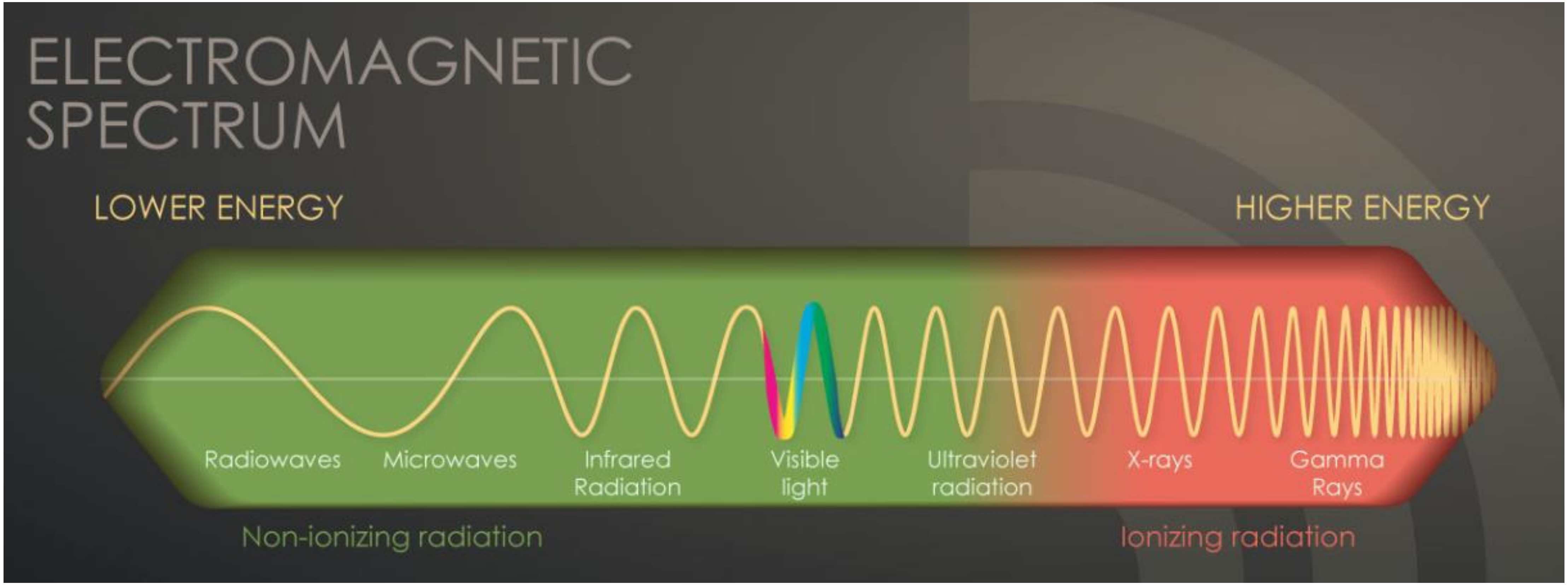
Interaction of X-ray with Matter

- $E = h\nu$
- X-ray Photons
- May be absorbed by electrons of atoms
  - Electron will get sufficient energy to escape the atom
  - Creation of ions
- Ionizing radiation

Interaction of X-ray with Matter

- $E = h\nu$
- X-ray Photons
- May be absorbed by electrons of atoms
    - Electron will get sufficient energy to escape the atom
    - Creation of ions
- Ionizing radiation
- Photons with energy less than 13.6 eV are nonionizing
    - Cannot eject an electron from its atom, but are only able to raise it to a higher energy shell (excitation)

Ionizing Radiation



https://www.cdc.gov/nceh/radiation/ionizing_radiation.html#:~:text=radiation%2C%20click%20here-,What%20is%20ionizing%20radiation%3F,and%20pass%20through%20these%20materials.

Ionizing Radiation

- Useful for diagnostic imaging (such as x-ray)

- Ionizing activity can alter molecules within the cells of our body
  - May cause eventual harm (such as cancer)

- Intense exposures to ionizing radiation may produce skin or tissue damage.

Processes of X-ray Interaction

- Photons can interact in different ways

- Rayleigh scattering or coherent scattering
  - Low energy photons: $< 30\ keV$
  - Absorbed by an electron and immediately released again as of a new photon with the same energy but traveling in a different direction
  - Non ionizing
  - Usually not observed during standard x-ray imaging
  - May be observed during mammography

Processes of Ionization

- Photoelectric absorption
  - Higher energy photon
  - Absorbed by an electron and the electron escapes the atom
  - Travels in the same direction as that of the incident photon
  - Ionizing

Processes of Ionization

- Compton scattering
  - Higher energy photon
  - Incident photon transfers partial energy to an electron
  - The electron escapes the atom
  - A photon with remaining energy travels in a different compared to that of the incident photon
  - Ionizing

Processes of Ionization

- Pair production
  - Electron-positron pair is created from an incident photon
  - Positron meets another electron and annihilates producing energy
  - The energy is released in the form of a photon pair travelling in opposite directions
  - Used in nuclear medicine

Processes of Ionization

- At even higher energy, photon may cause nuclear reactions
- Not used in medical applications

Medical Usage

First x-ray of human body

Medical Usage

- X-ray is attenuated by different tissues

- The more the atomic number of an element, the more the attenuation
  - Bone: Ca (Z=20)
    - More attenuation, output photon with less energy
    - Bright regions in x-ray films
  - Soft tissue: C (Z=6), H (Z=1), O (Z=8)
    - Less attenuation, output photon with more energy
    - Dark regions in x-ray films

Medical Usage

Intensity of outgoing beam I_{out} I_{in} Intensity of incoming beam

Medical Usage

$$I_{\text{out}} = I_{\text{in}}\, e^{-\mu d}$$

Homogeneous medium, photons of single energy

μ: Attenuation coefficient

Function of photon energy and medium

$$\mu(10\,\text{keV}, H_2O) = 5\,\text{cm}^{-1}$$
$$\mu(100\,\text{keV}, H_2O) = 0.17\,\text{cm}^{-1}$$
$$\mu(10\,\text{keV}, \text{Ca}) = 144\,\text{cm}^{-1}$$
$$\mu(100\,\text{keV}, \text{Ca}) = 0.40\,\text{cm}^{-1}.$$

Medical Usage

$$I_{\text{out}} = I_{\text{in}}\, e^{-\mu\, d}$$

Homogeneous medium, photons of single energy

$$I_{\text{out}} = I_{\text{in}}\, e^{-\int_{x_{\text{in}}}^{x_{\text{out}}} \mu(x)\, dx}$$

Heterogeneous medium, photons of single energy

$$I_{\text{out}} = \int_0^{\infty} \sigma(E)\, e^{-\int_{x_{\text{in}}}^{x_{\text{out}}} \mu(E,x)\, dx}\, dE$$

Heterogeneous medium, photon of multiple energy

X-ray Equipment

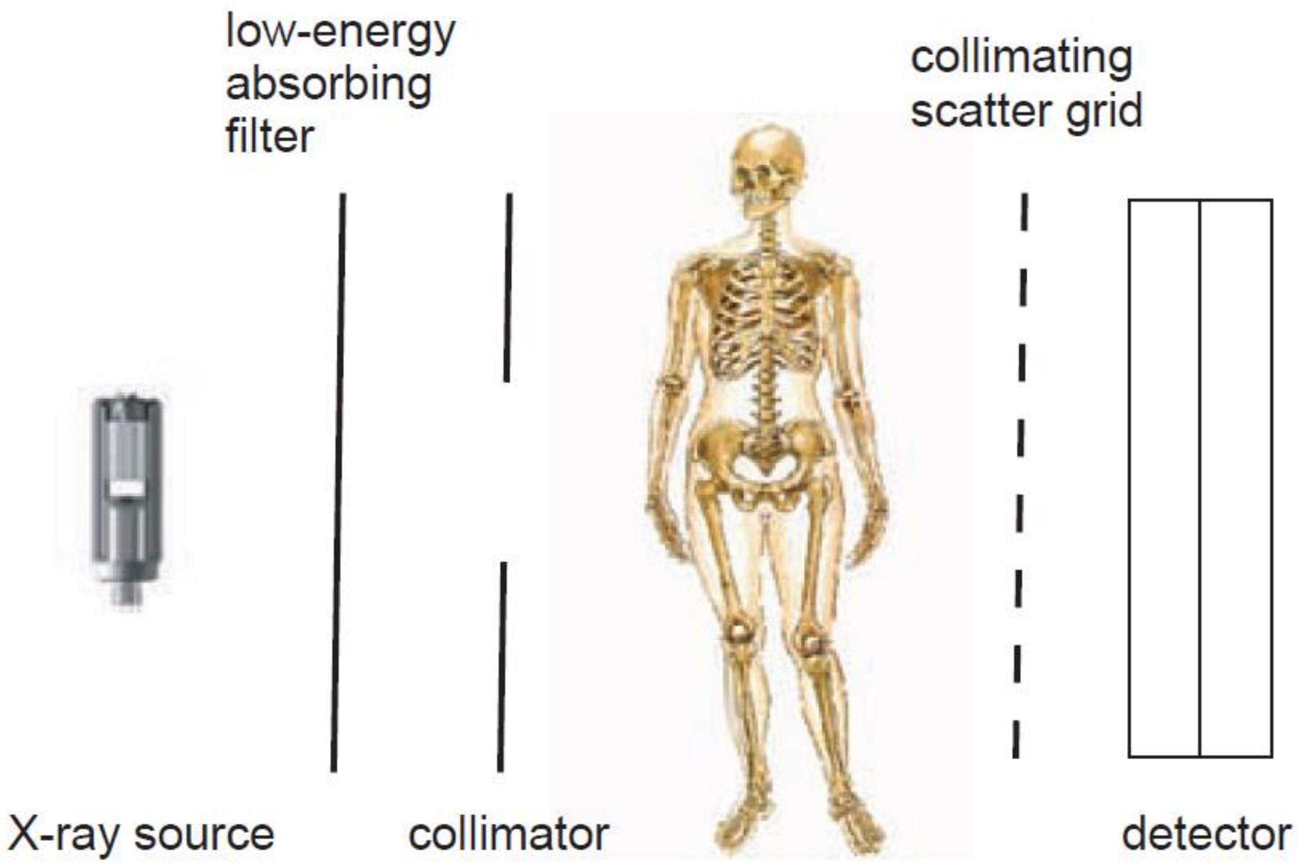


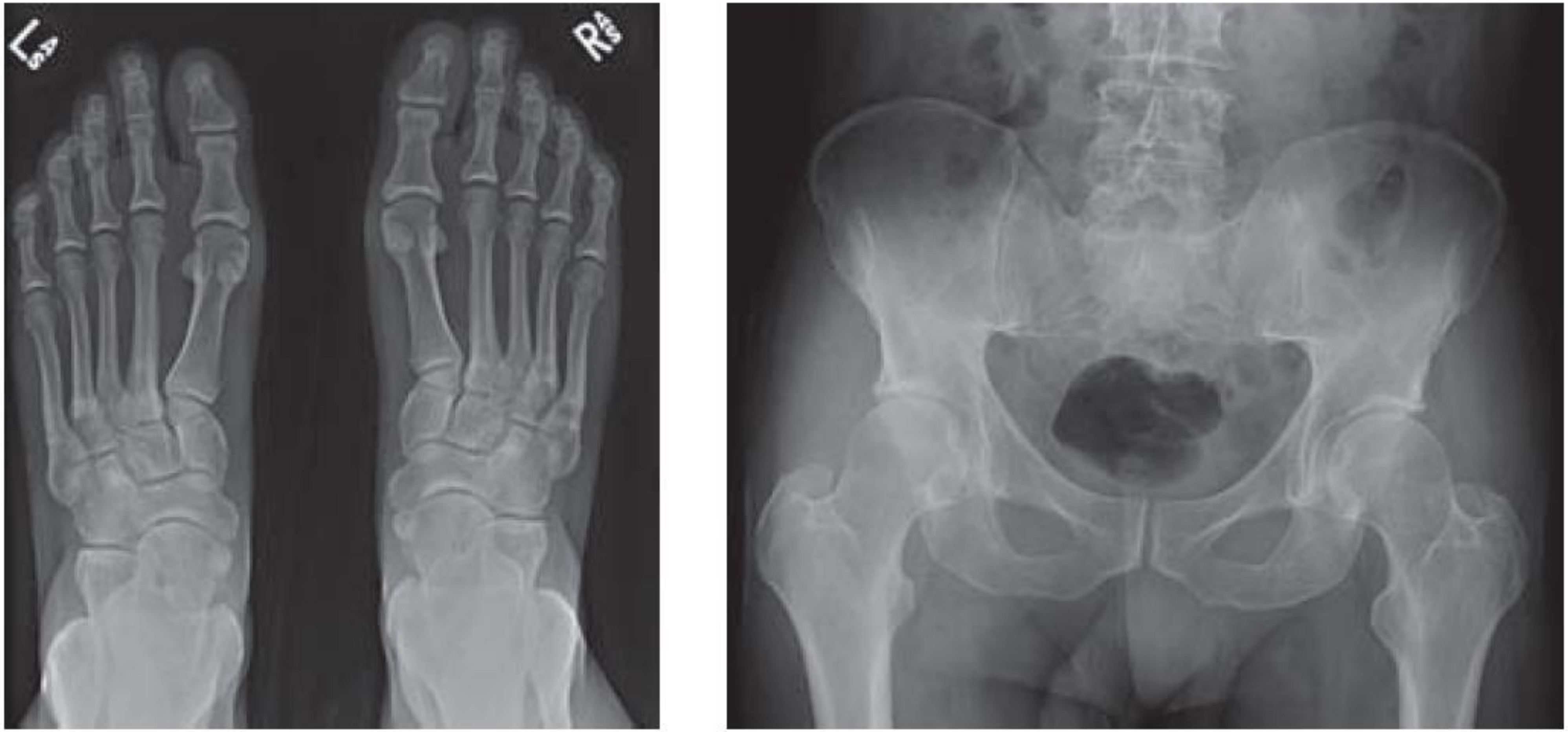
Figure 2.9 Schematic representation of the radiographic imaging chain.

(a)

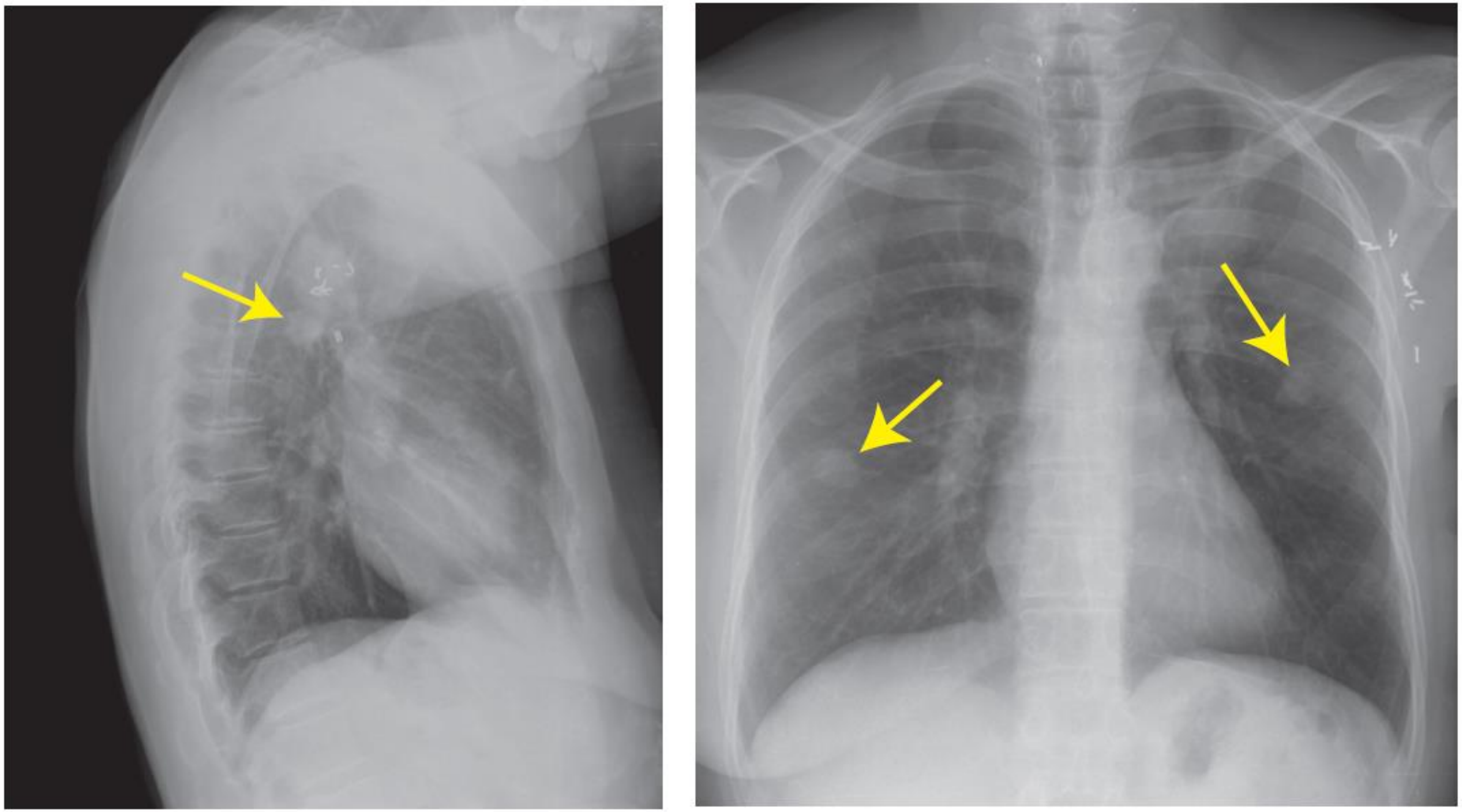
(b)

(c)

(d)

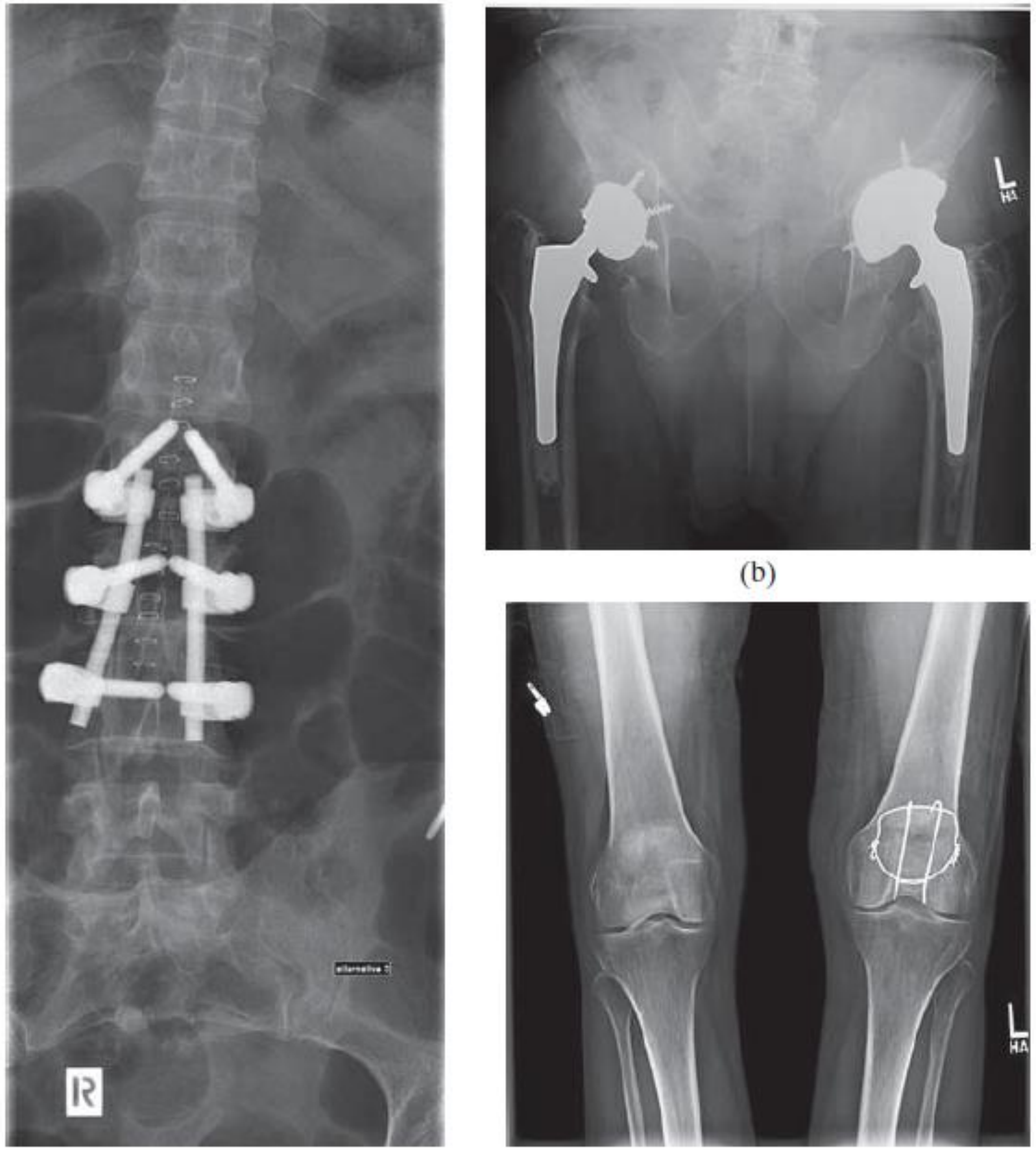


(e) (f)



(a) (b)

Figure 2.15 Radiographic chest image showing multiple lung metastases. (Courtesy of Professor J. Verschakelen, Department of Radiology.)



(a) (b) (c)

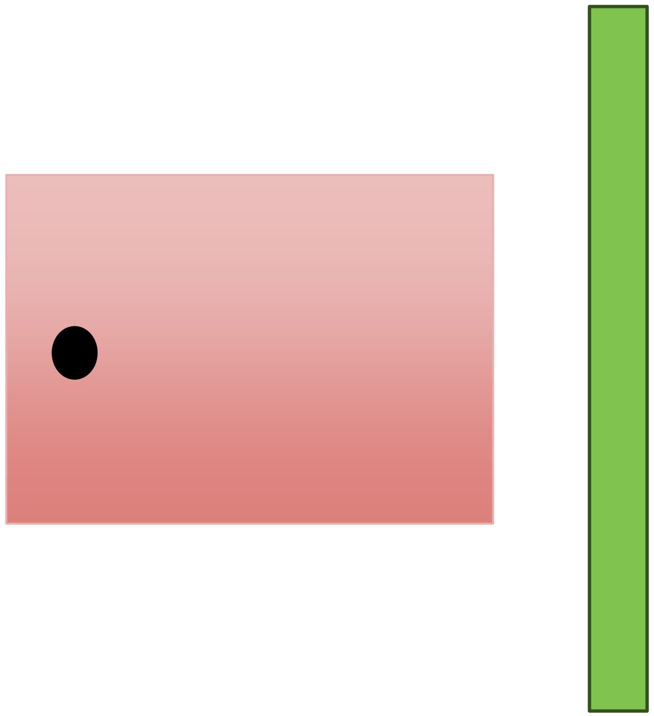
Figure II.2
X-ray images of (a) the spine shown a surgical fixation device, (b) the pelvis showing two artificial hip joints, and (c) the knee showing bone fixation wires. Image (a) courtesy of Philips Healthcare. Images (b) and (c) courtesy of GE Healthcare.

X-ray Equipment

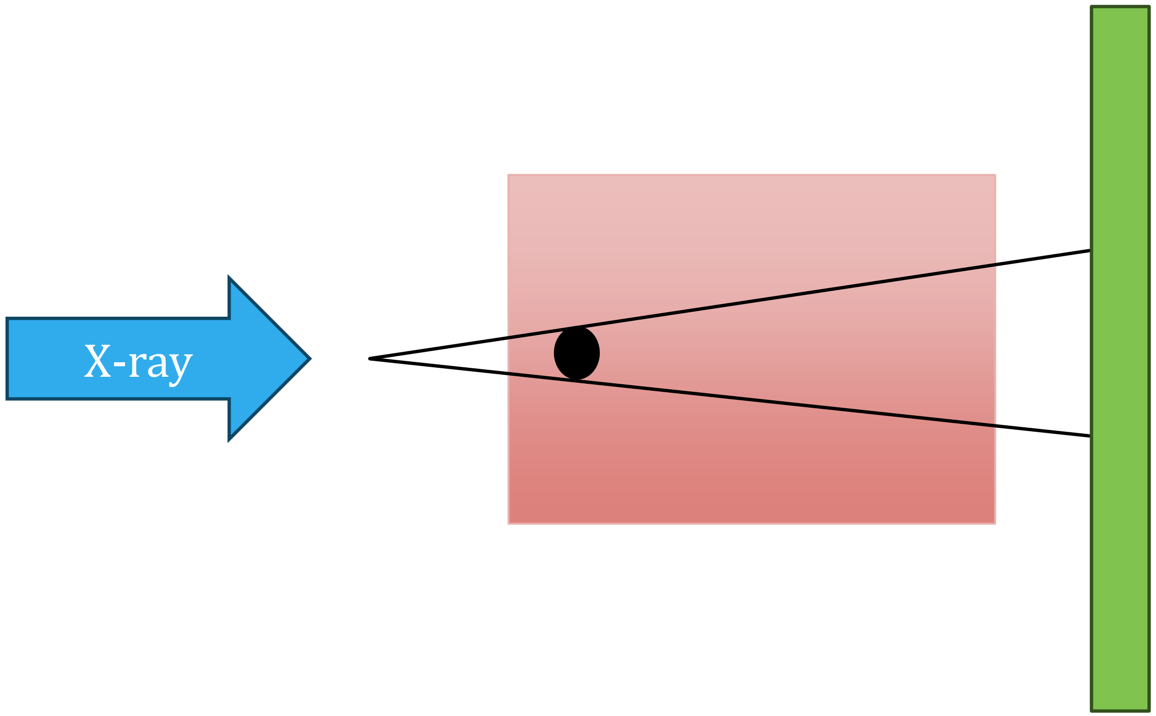
Issues in X-ray

- Noise: Quantum noise
  - Due to the statistical nature of X-rays
- Artifacts: Due to scratches in the detector, dead pixels, unread scan lines, inhomogeneous X-ray beam intensity (heel effect), afterglow

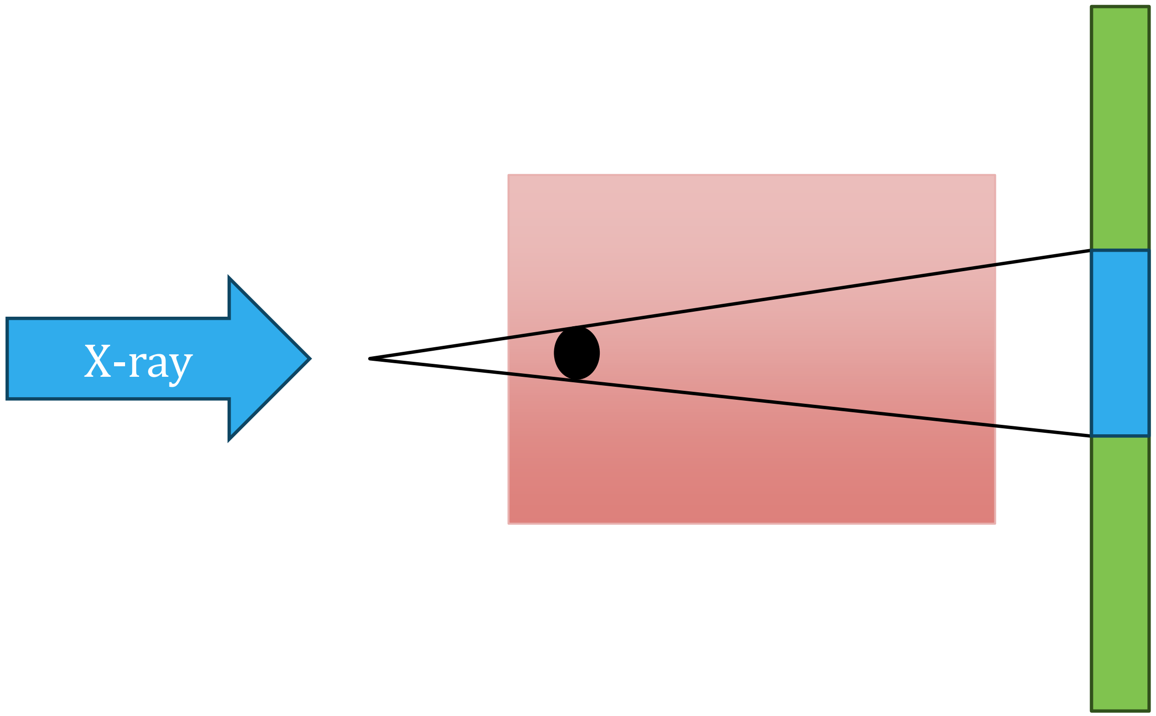
Limitations in X-ray Imaging



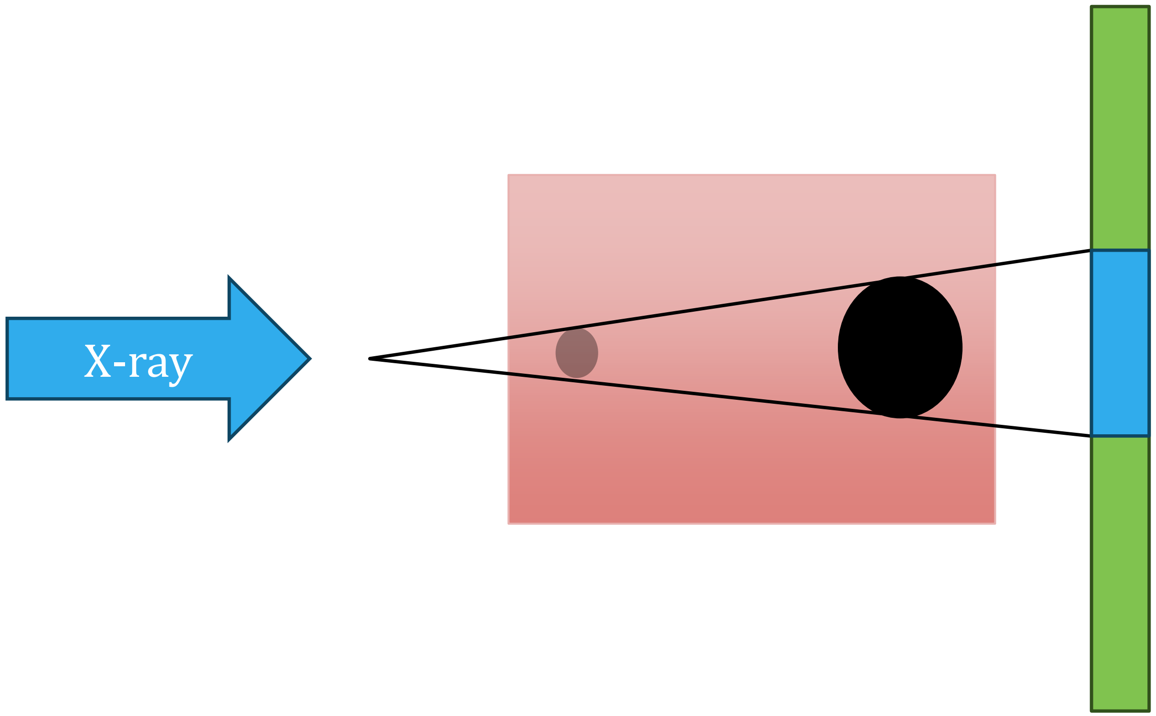
Limitations in X-ray Imaging



Limitations in X-ray Imaging



Limitations in X-ray Imaging



Attenuation

$$I_{\text{out}} = I_{\text{in}}\, e^{-\mu\, d}$$

Homogeneous medium, photons of single energy

$$I_{\text{out}} = I_{\text{in}}\, e^{-\int_{x_{\text{in}}}^{x_{\text{out}}} \mu(x)\, dx}$$

Heterogeneous medium, photons of single energy

μ: Attenuation coefficient

Function of photon energy and medium

$$\mu(10\,\text{keV}, H_2O) = 5\,\text{cm}^{-1}$$
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$$\mu(10\,\text{keV}, \text{Ca}) = 144\,\text{cm}^{-1}$$
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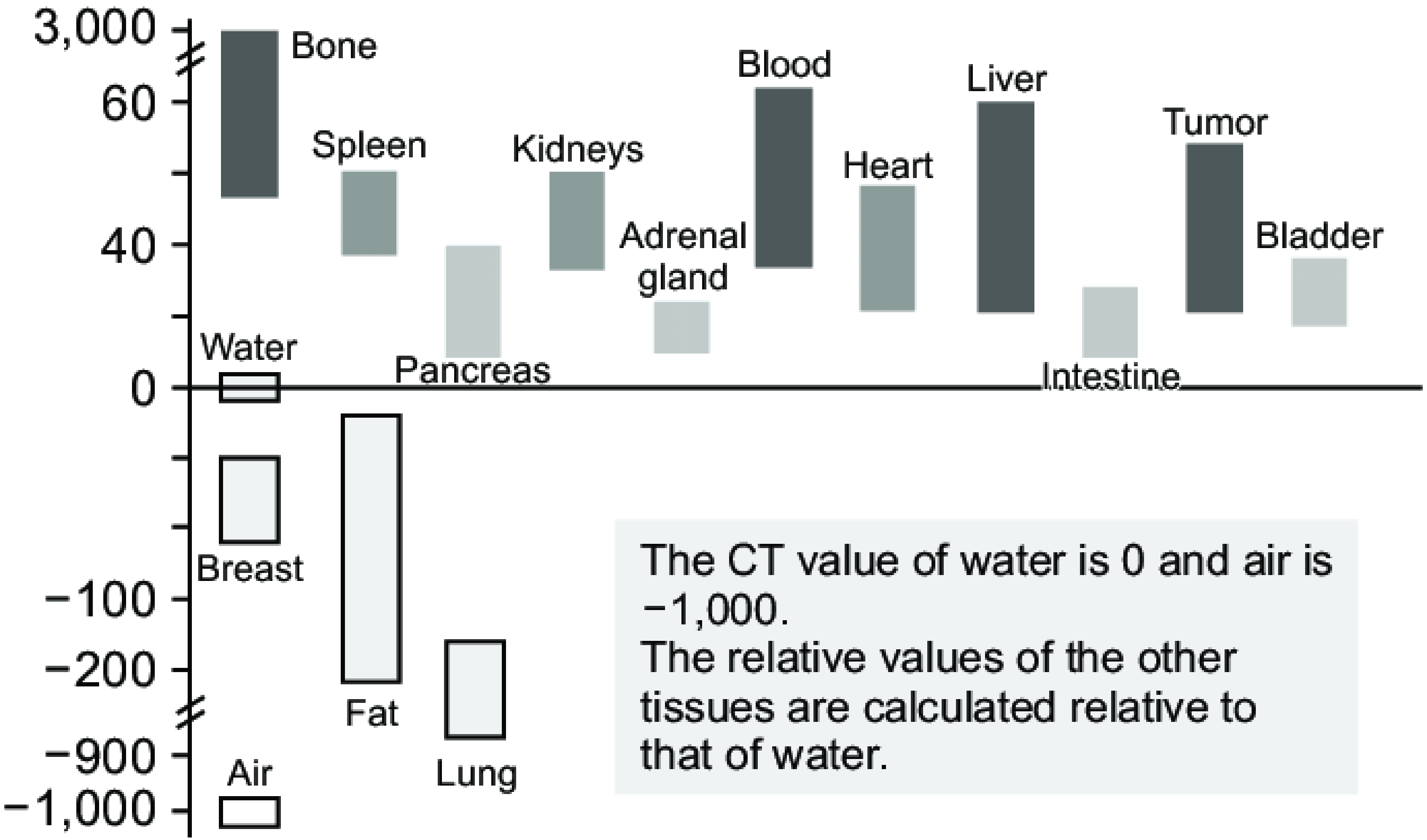
CT Number

μ: Attenuation coefficient
(Function of photon energy and medium)

$$\text{CT Number (in HU)} = \frac{\mu - \mu_{H_2O}}{\mu_{H_2O}} \times 1000$$

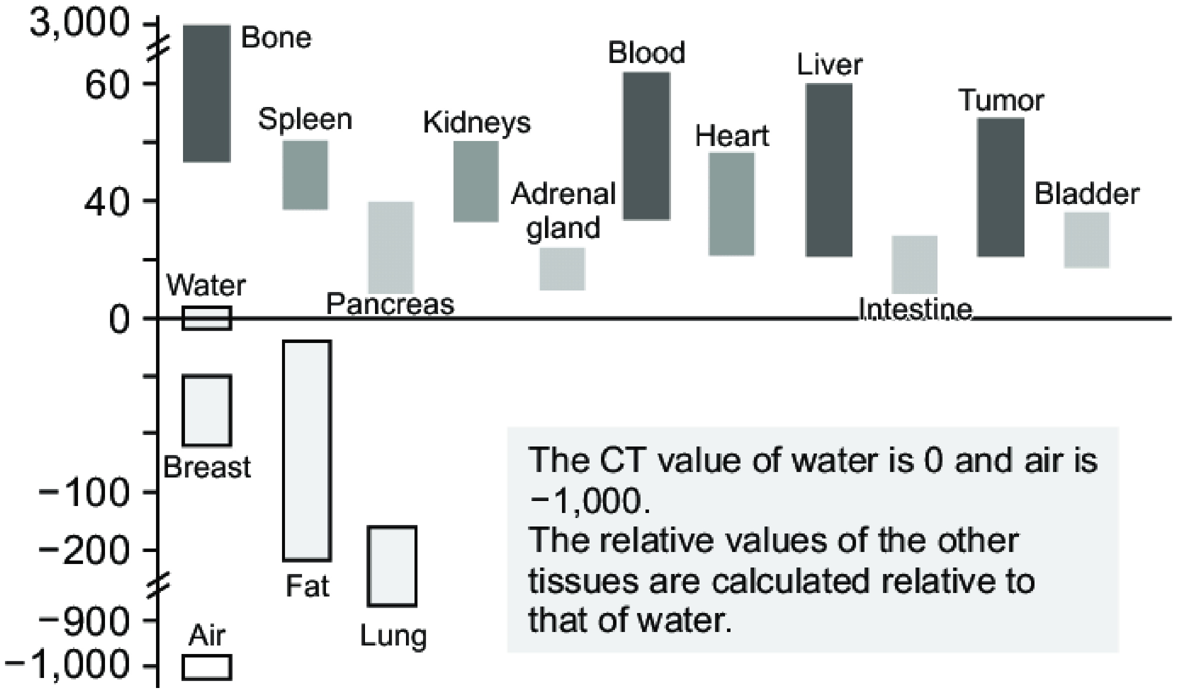
Hounsfield unit

CT Number



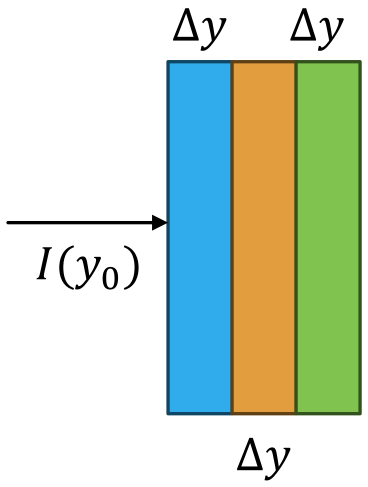
3,000
60
40
0
−100
−200
−900
−1,000
Bone
Spleen
Kidneys
Adrenal gland
Blood
Heart
Liver
Tumor
Bladder
Water
Pancreas
Intestine
Breast
Fat
Lung
Air
The CT value of water is 0 and air is −1,000.
The relative values of the other tissues are calculated relative to that of water.

CT Number

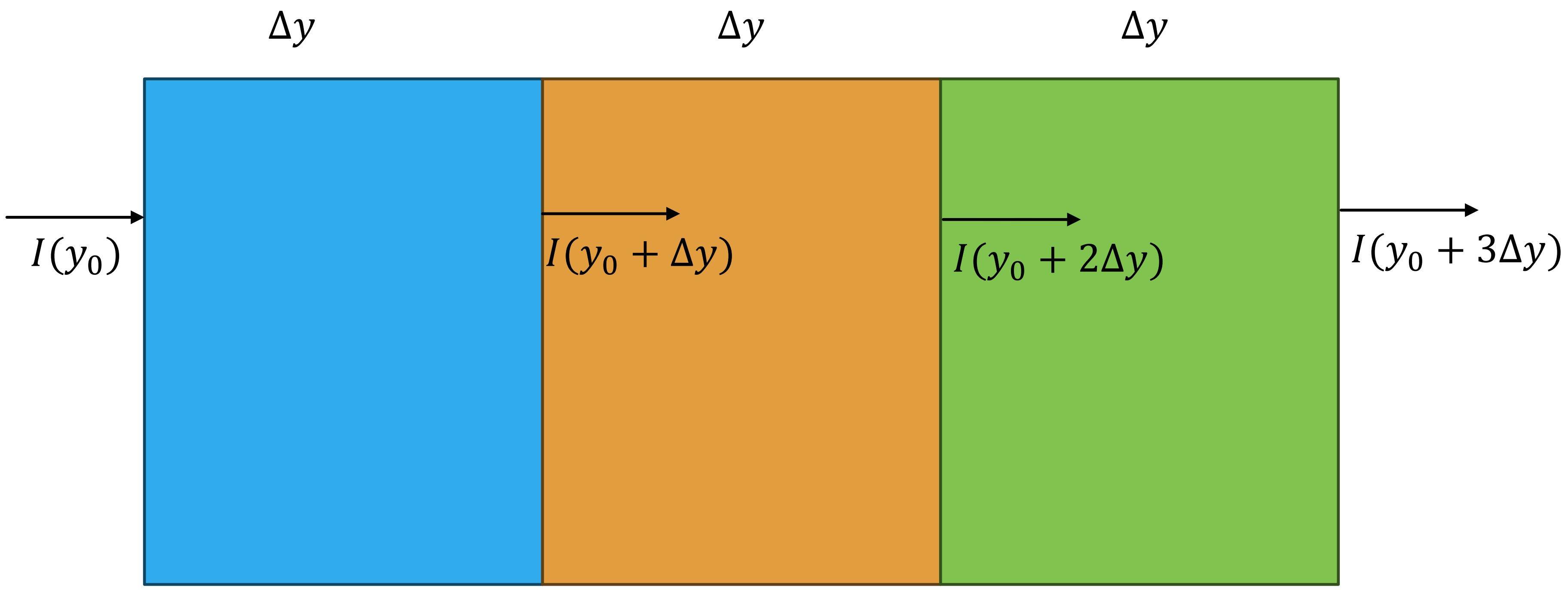


So, if we find μ from an image, we can get information about tissues and abnormalities

CT Number

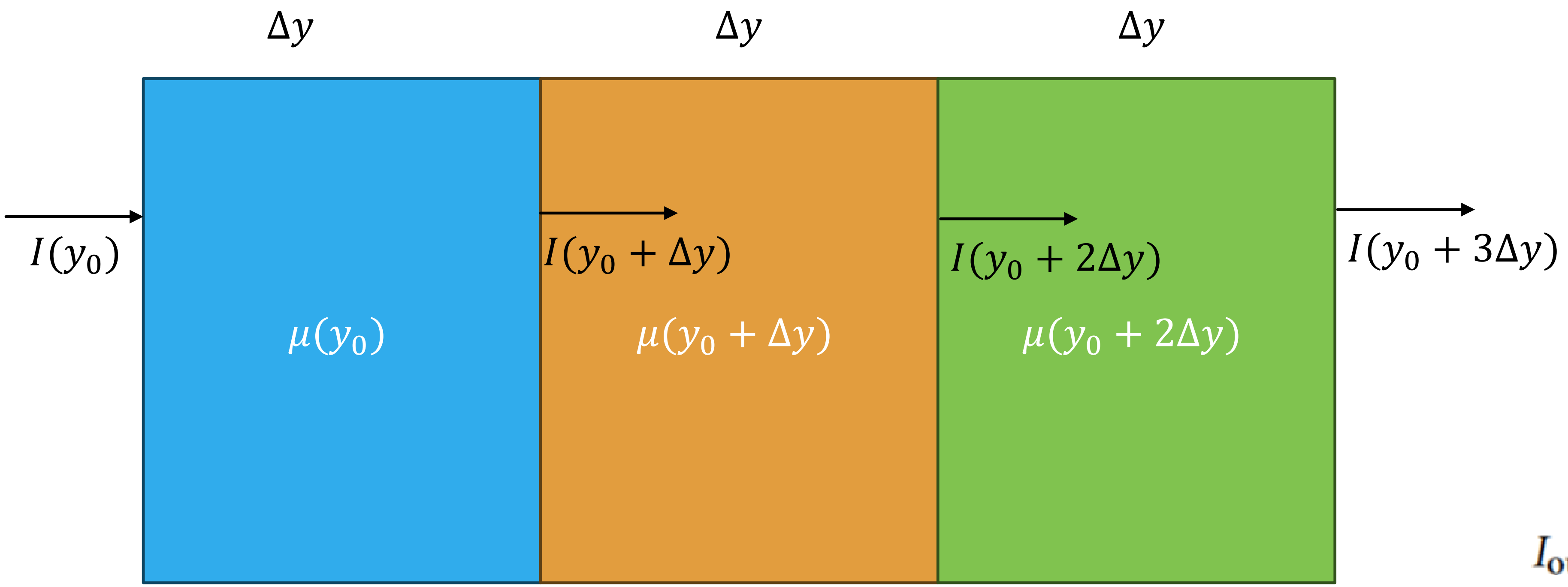


CT Number



Δy
Δy
Δy
$I(y_0)$
$I(y_0 + \Delta y)$
$I(y_0 + 2\Delta y)$
$I(y_0 + 3\Delta y)$

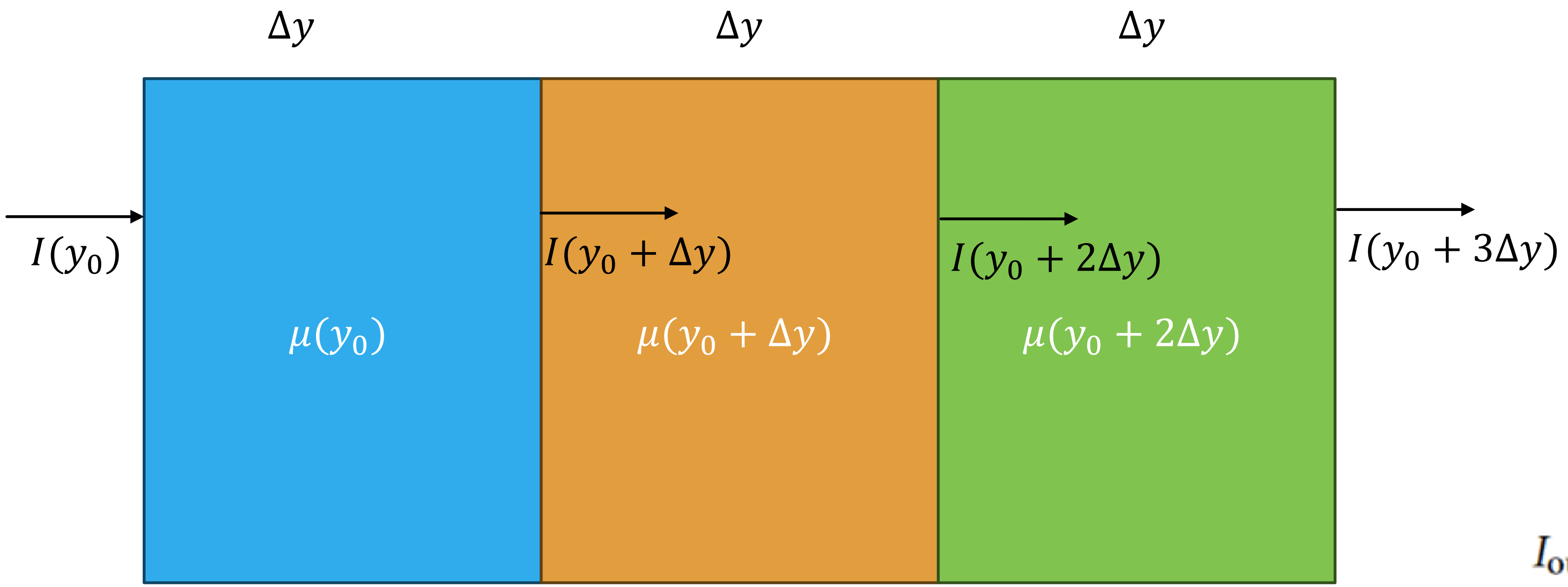
CT Number



$$I_{\text{out}} = I_{\text{in}}\, \mathrm{e}^{-\mu\, d}$$

$$I(y_0 + \Delta y) = I(y_0)e^{-\mu(y_0)\Delta y}$$

CT Number

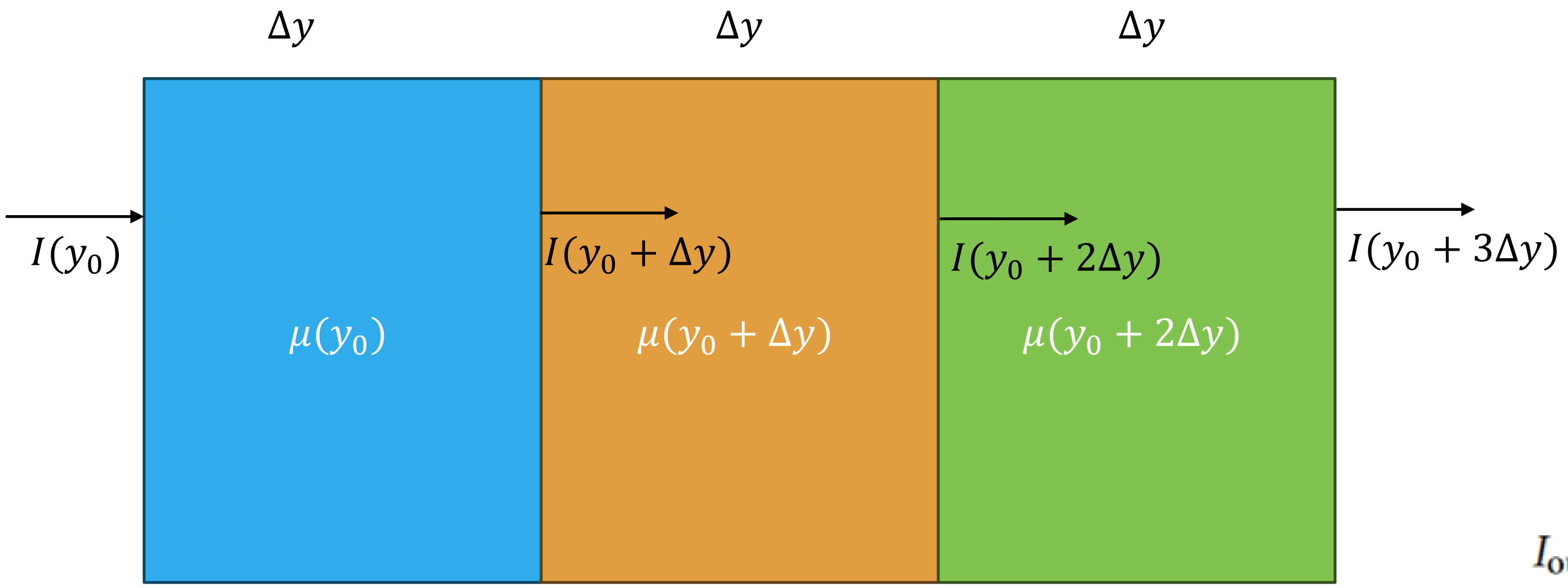


$$I_{\text{out}} = I_{\text{in}}\, e^{-\mu\, d}$$

$$I(y_0 + \Delta y) = I(y_0)e^{-\mu(y_0)\Delta y}$$

$$I(y_0 + 2\Delta y) = I(y_0 + \Delta y)e^{-\mu(y_0+\Delta y)\Delta y}$$

CT Number

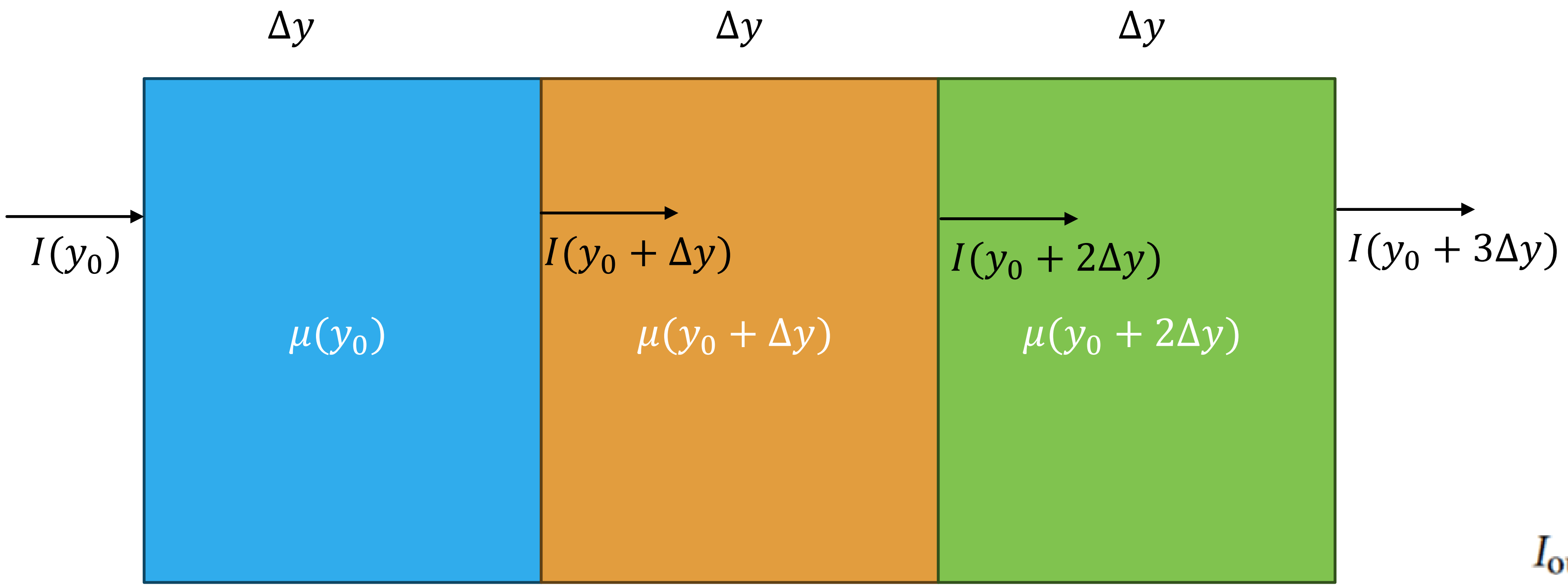


$$I_{\text{out}} = I_{\text{in}}\, e^{-\mu\, d}$$

$$I(y_0 + \Delta y) = I(y_0)e^{-\mu(y_0)\Delta y}$$

$$I(y_0 + 2\Delta y) = I(y_0)e^{-\mu(y_0)\Delta y}e^{-\mu(y_0+\Delta y)\Delta y}$$

CT Number

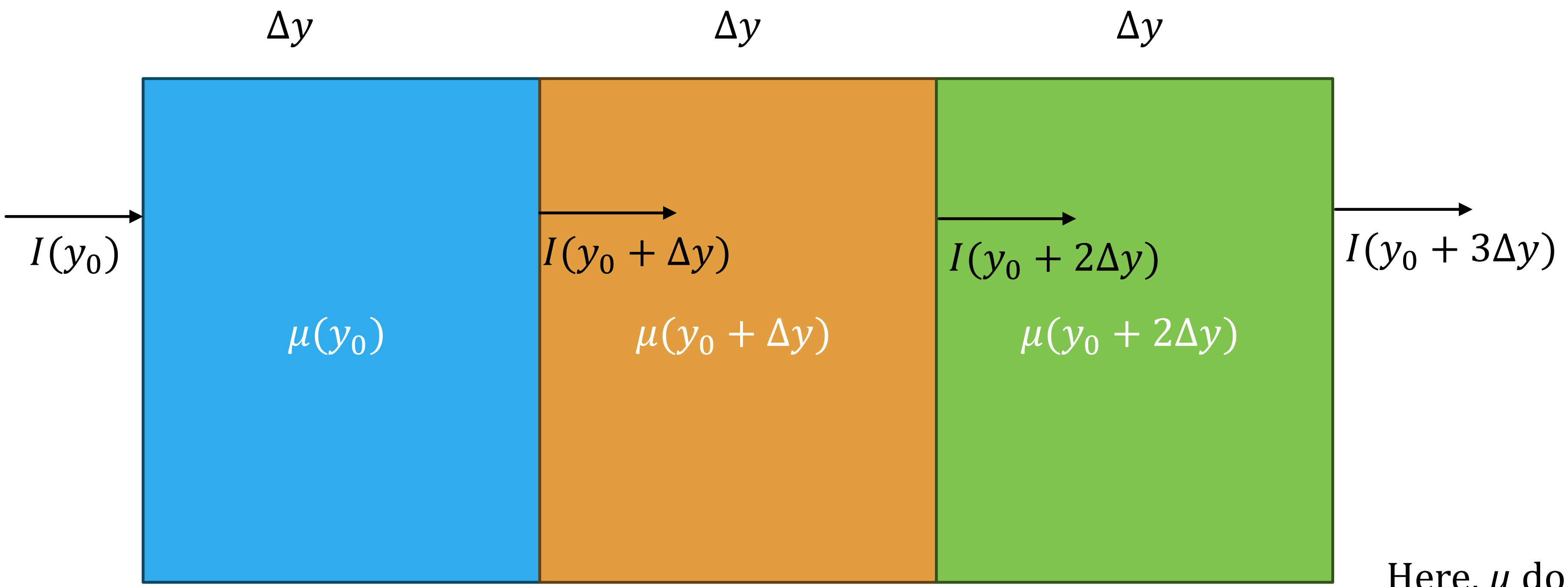


$$I_{\text{out}} = I_{\text{in}}\, e^{-\mu\, d}$$

$$I(y_0 + 2\Delta y) = I(y_0) e^{-\mu(y_0)\Delta y} e^{-\mu(y_0+\Delta y)\Delta y}$$

$$I_{out} = I(y_0) e^{-\int_{source}^{detector} \mu(y')dy'}$$

CT Number

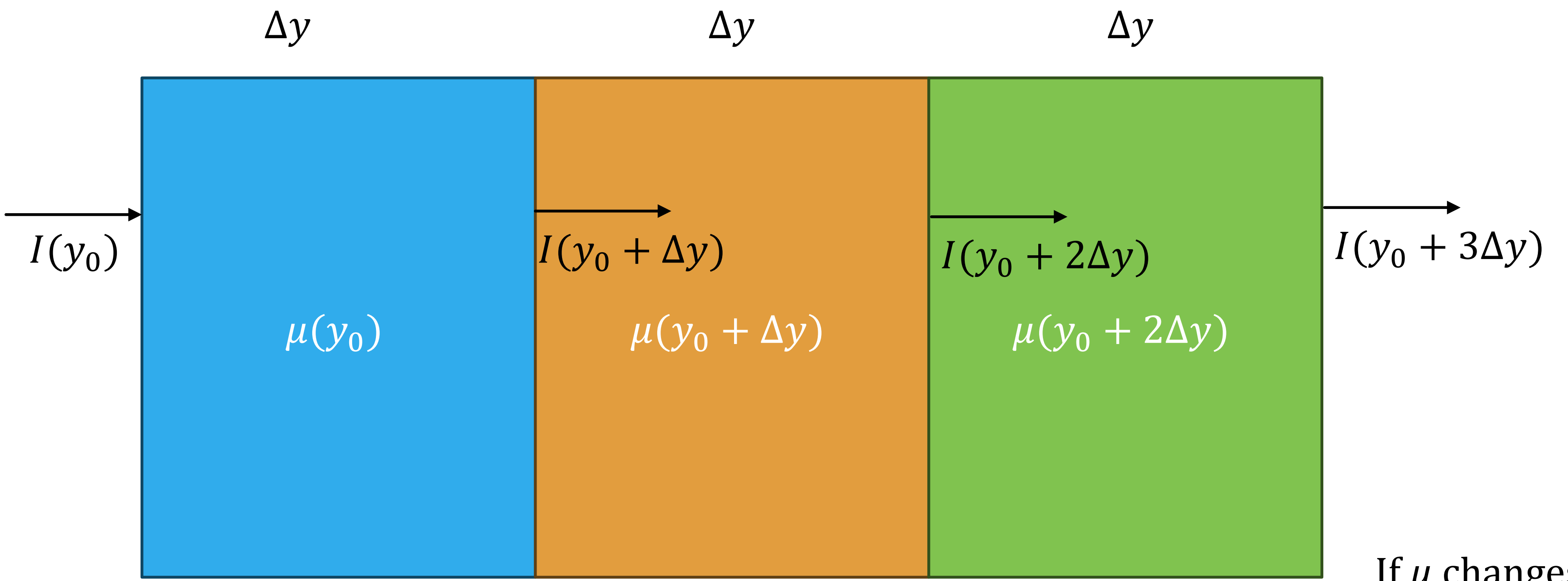


Here, μ does not change in the vertical direction

$$I(y_0 + 2\Delta y) = I(y_0)e^{-\mu(y_0)\Delta y}e^{-\mu(y_0+\Delta y)\Delta y}$$

$$I_{out} = I(y_0)e^{-\int_{source}^{detector} \mu(y')dy'}$$

CT Number

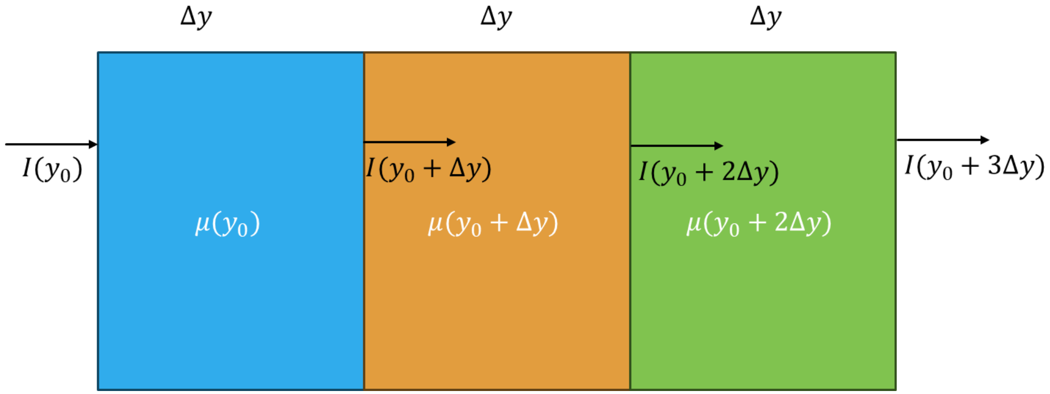


If μ changes in the vertical direction as well

$$I(y_0 + 2\Delta y) = I(y_0)e^{-\mu(y_0)\Delta y}e^{-\mu(y_0+\Delta y)\Delta y}$$

$$I_{out} = I(y_0)e^{-\int_{source}^{detector} \mu(x,y')dy'}$$

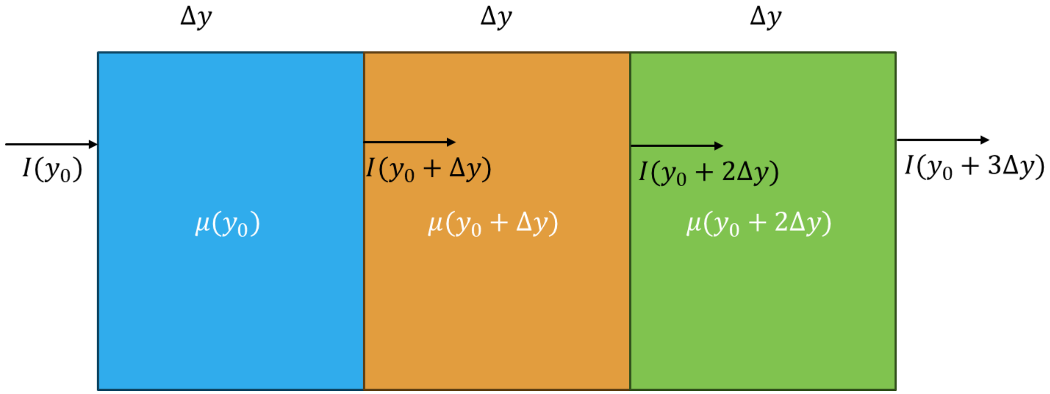
Radon Transform



$$I_{out} = I(y_0)e^{-\int_{source}^{detector} \mu(x,y')dy'}$$

$$g(x) = \int_{-\infty}^{\infty} \mu(x,y')dy'$$

Radon Transform

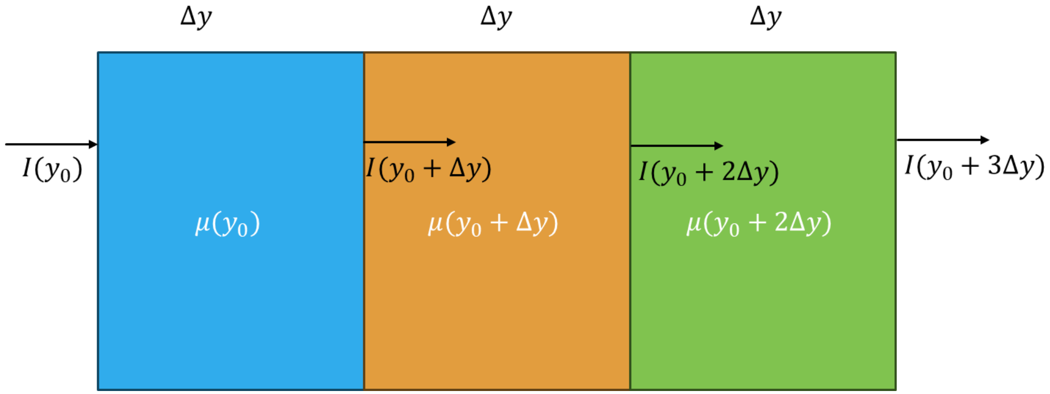


$$I_{out} = I(y_0)e^{-\int_{source}^{detector} \mu(x,y')dy'}$$

More generally

$$g(\ell,\theta) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} f(x,y)\delta(x\cos\theta + y\sin\theta - \ell)\,dx\,dy$$

Radon Transform

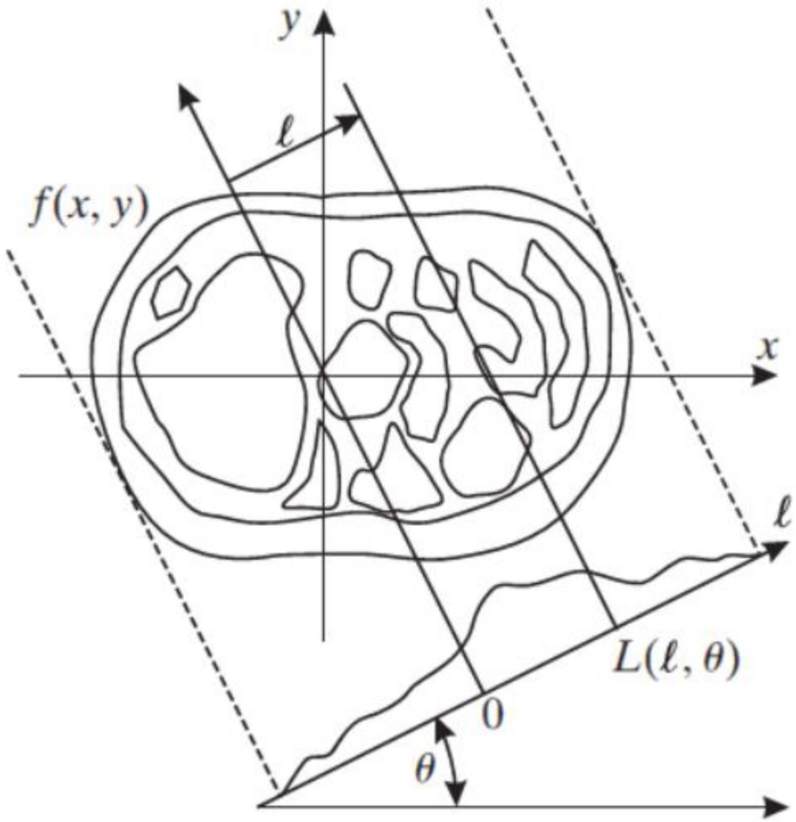


$$I_{out} = I(y_0)e^{-\int_{source}^{detector} \mu(x,y')dy'}$$

Line integral along the line $xcos\theta + ysin\theta = l$

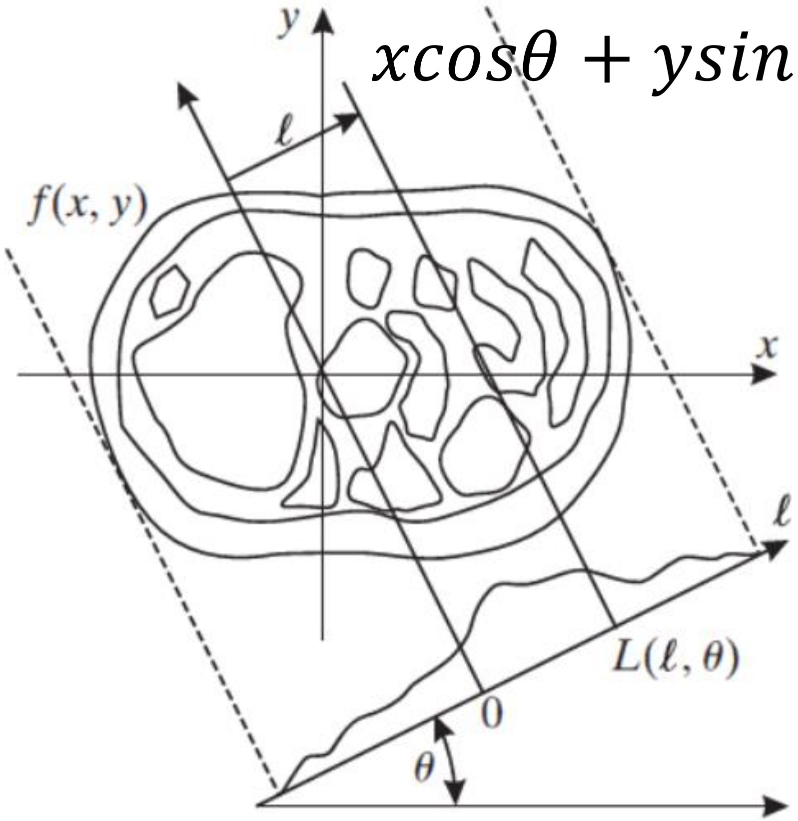
$$g(\ell,\theta) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} f(x,y)\delta(x\cos\theta + y\sin\theta - \ell)\,dx\,dy$$

Radon Transform



Radon Transfo

$$x cos\theta + y sin\theta = l$$



Radon Transform

Line integral along the line $xcos\theta + ysin\theta = l$

Line integral along the line $xcos\theta + ysin\theta = l$

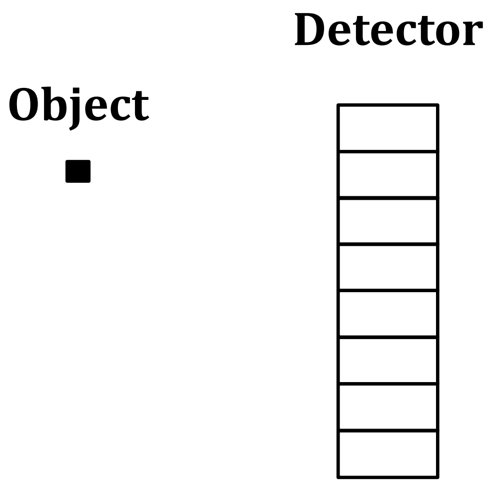
$$g(\ell, \theta) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} f(x, y) \delta(x \cos \theta + y \sin \theta - \ell) \, dx \, dy$$

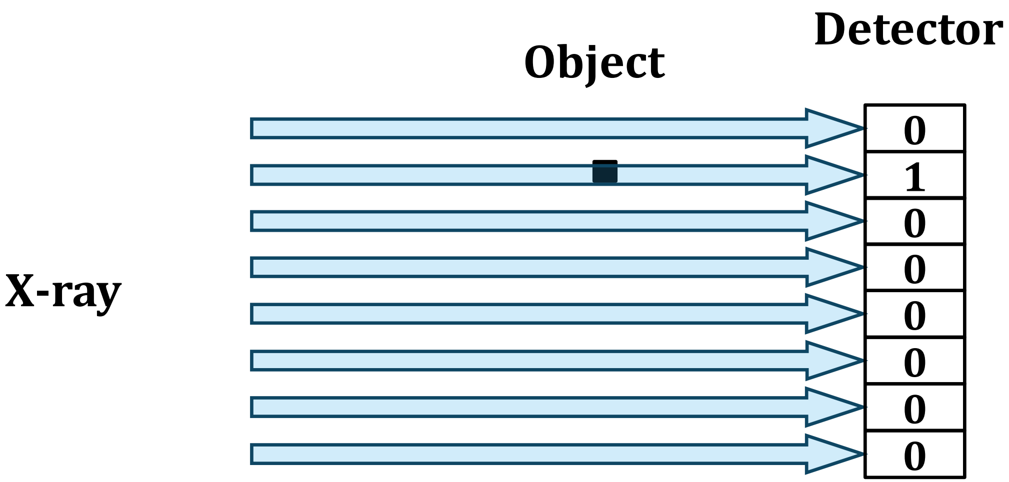
Radon Transform

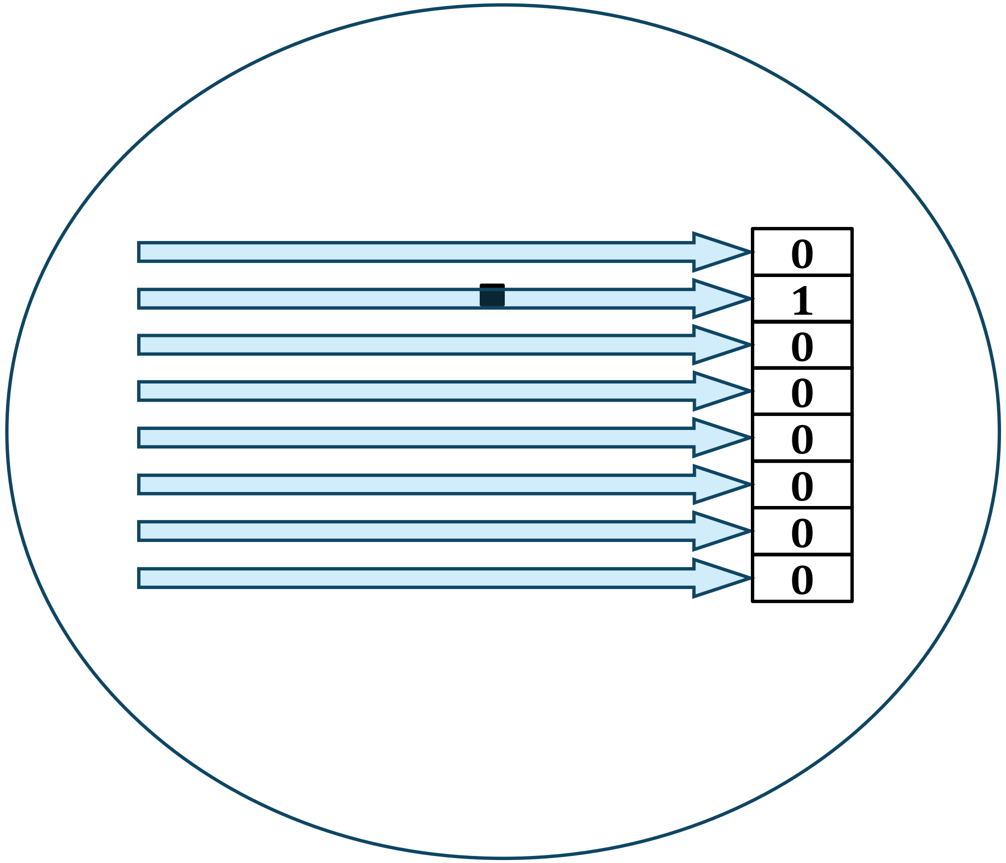
$$g(\ell, \theta) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} f(x, y) \delta(x \cos \theta + y \sin \theta - \ell) \, dx \, dy$$

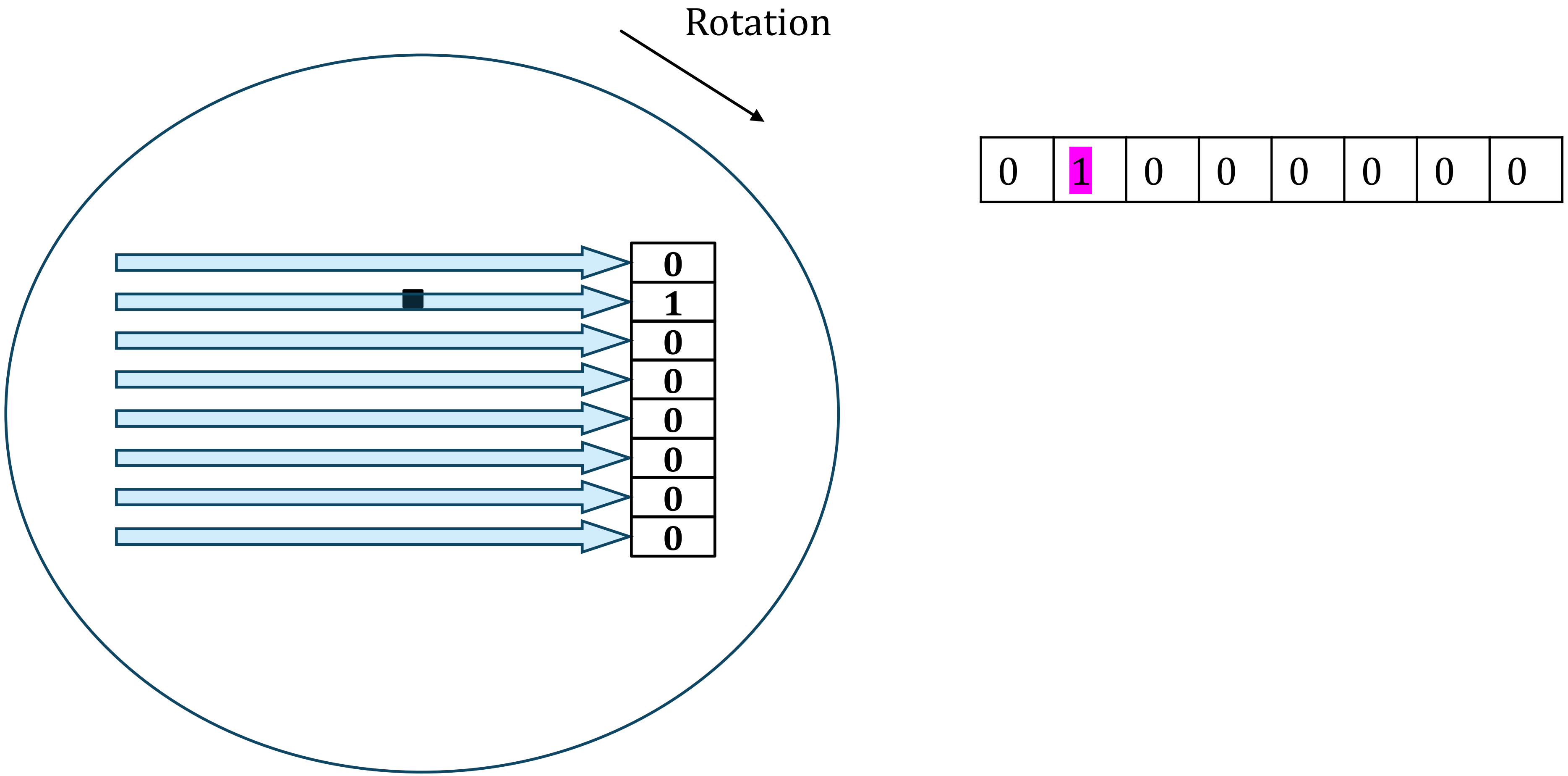
For all values of $\boldsymbol{l}$ and $\boldsymbol{\theta}$

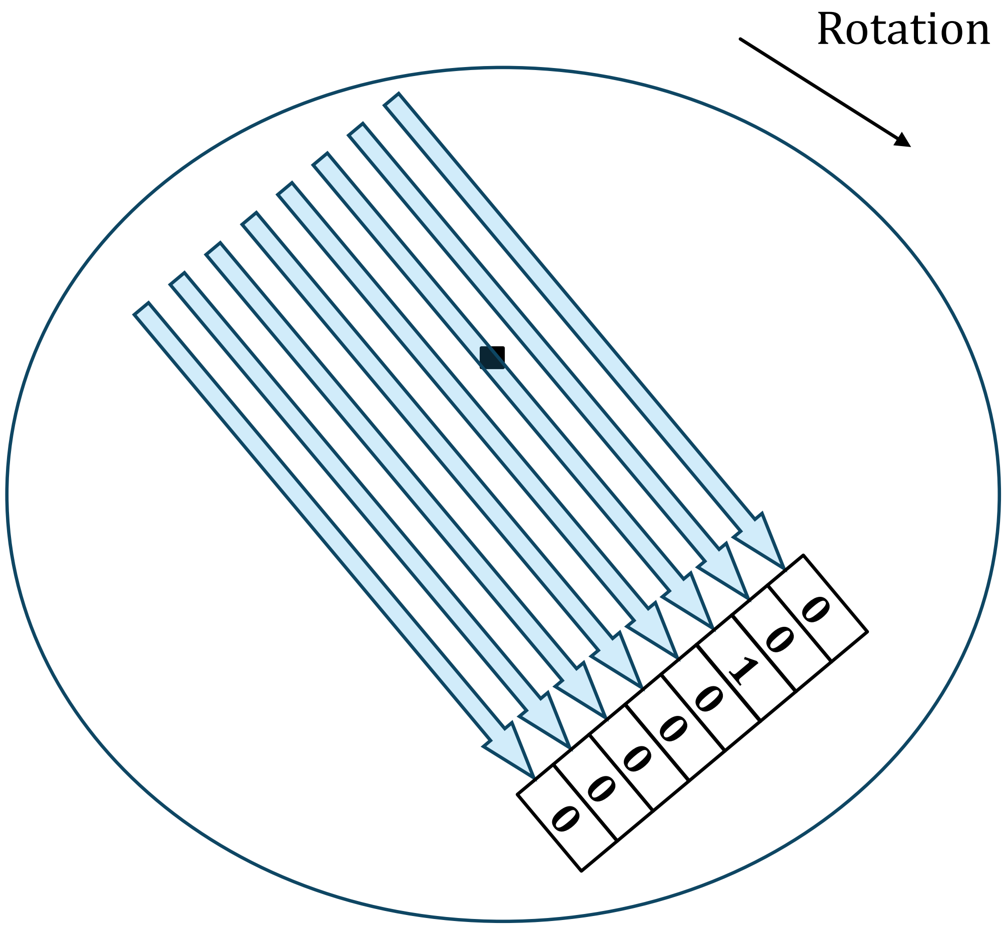
Visual Impact of Radon Transform


Detector
Object

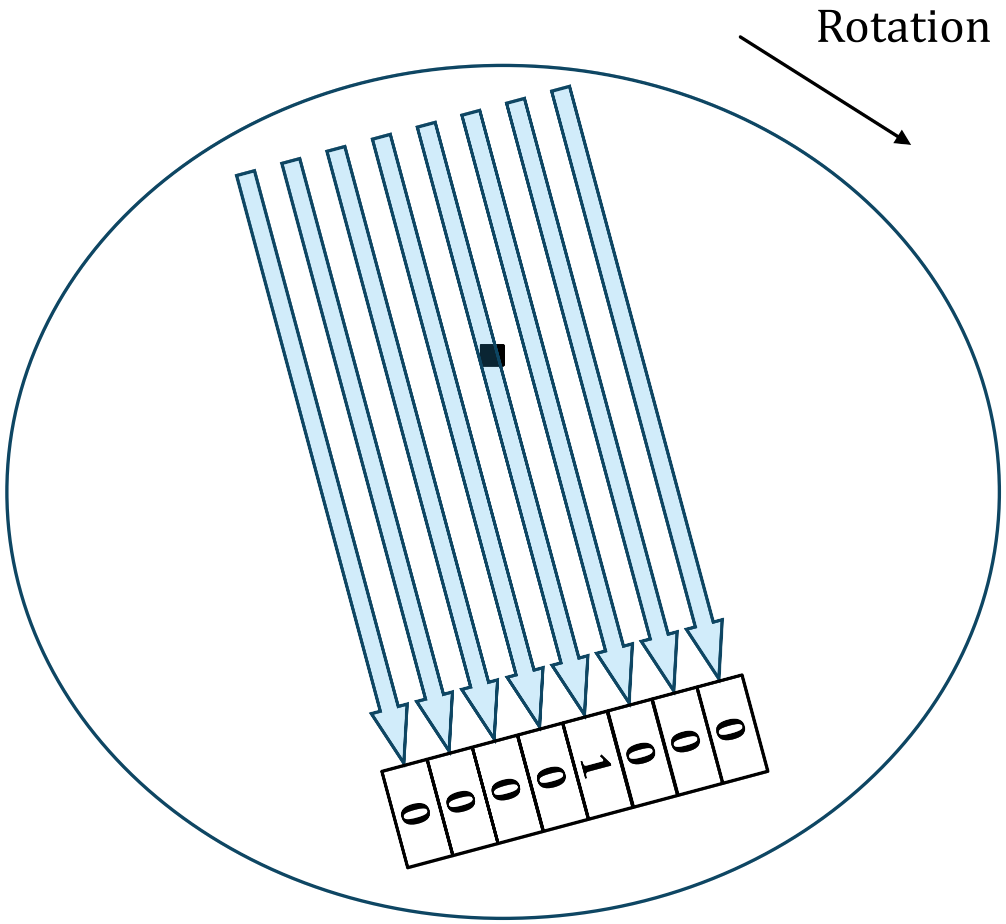

Detector
Object
X-ray
0
1
0
0
0
0
0
0


0
1
0
0
0
0
0
0

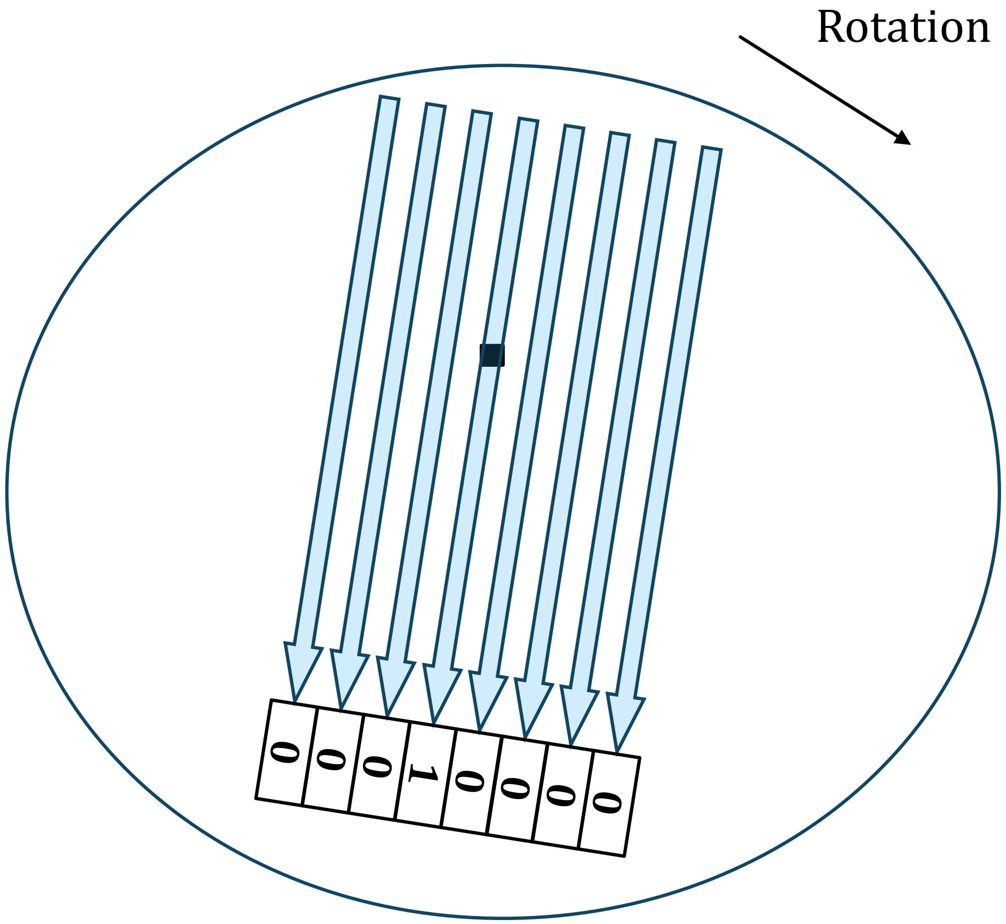

Rotation
0
1
0
0
0
0
0
0
0 1 0 0 0 0 0 0



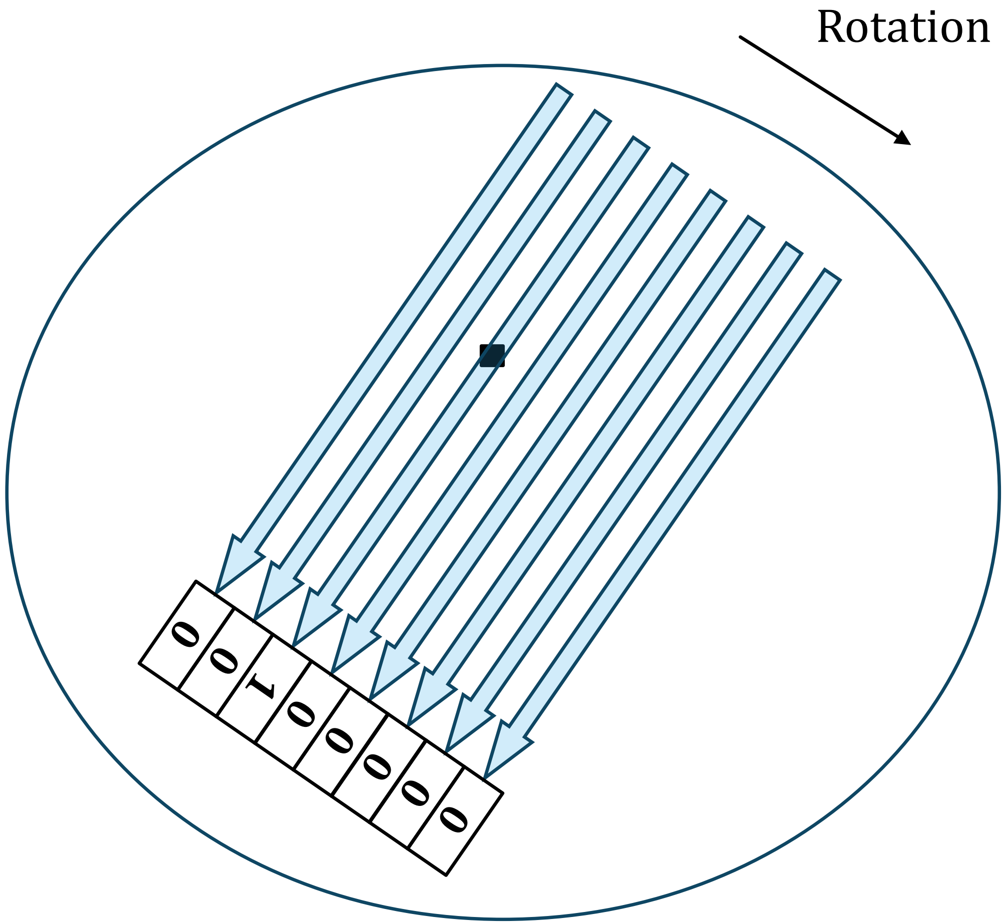
0	1	0	0	0	0	0	0
0	0	1	0	0	0	0	0



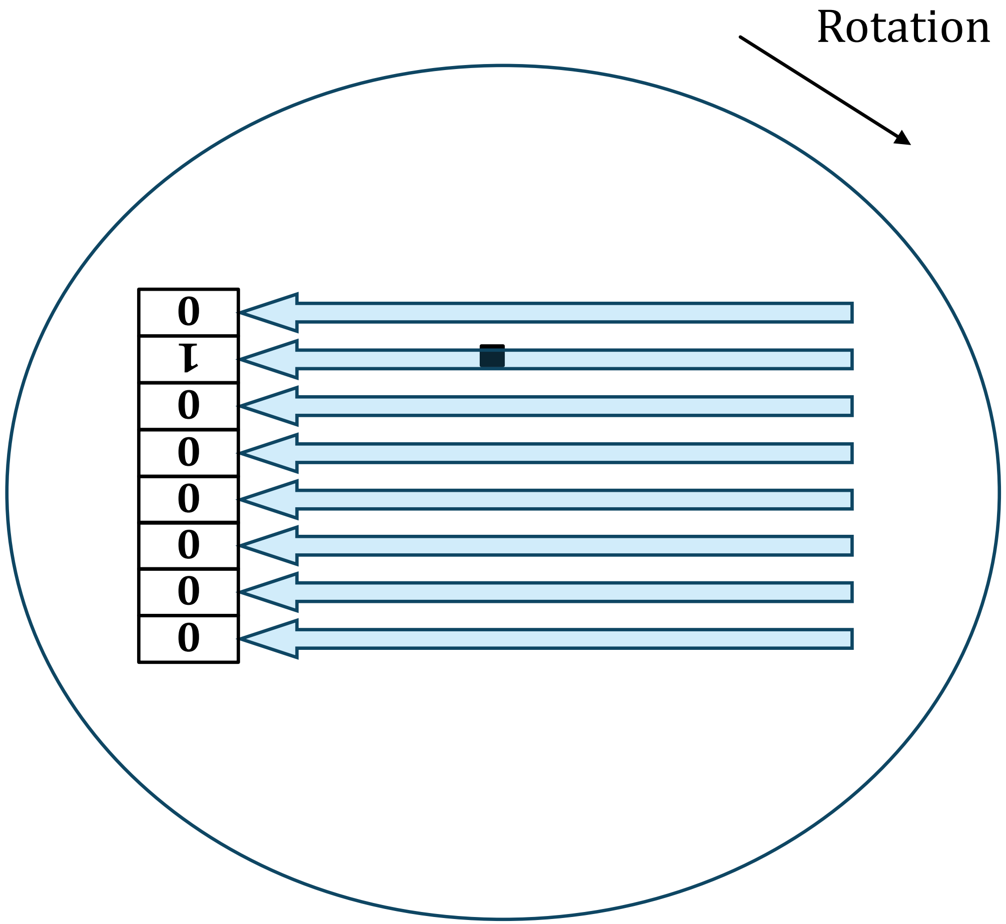
0	1	0	0	0	0	0	0
0	0	1	0	0	0	0	0
0	0	0	1	0	0	0	0



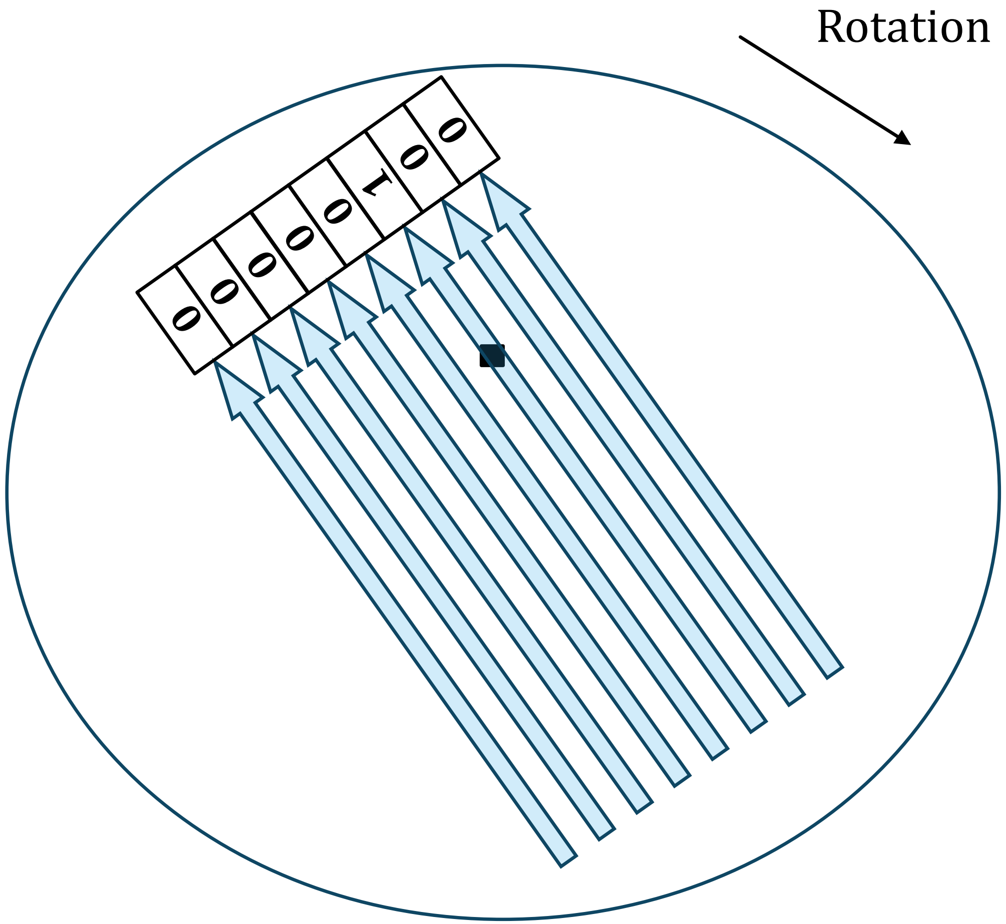
0	1	0	0	0	0	0	0
0	0	1	0	0	0	0	0
0	0	0	1	0	0	0	0
0	0	0	0	1	0	0	0



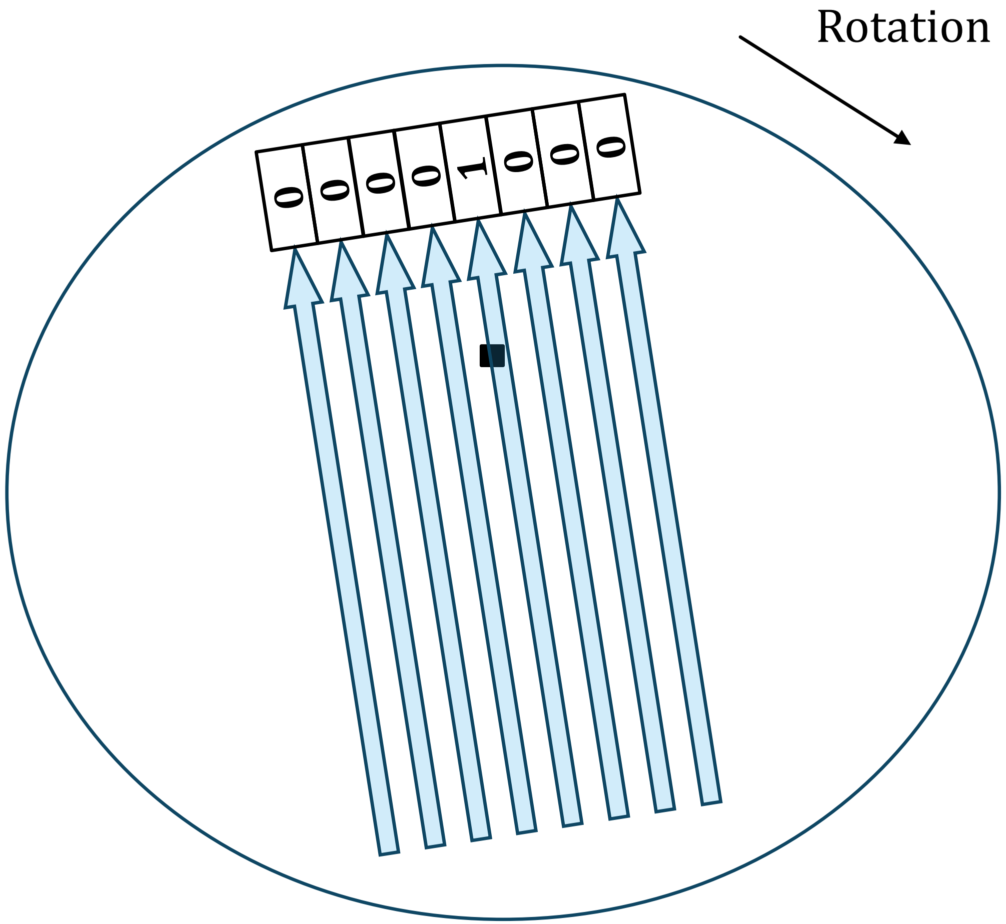
0	1	0	0	0	0	0	0
0	0	1	0	0	0	0	0
0	0	0	1	0	0	0	0
0	0	0	0	1	0	0	0
0	0	0	0	0	1	0	0



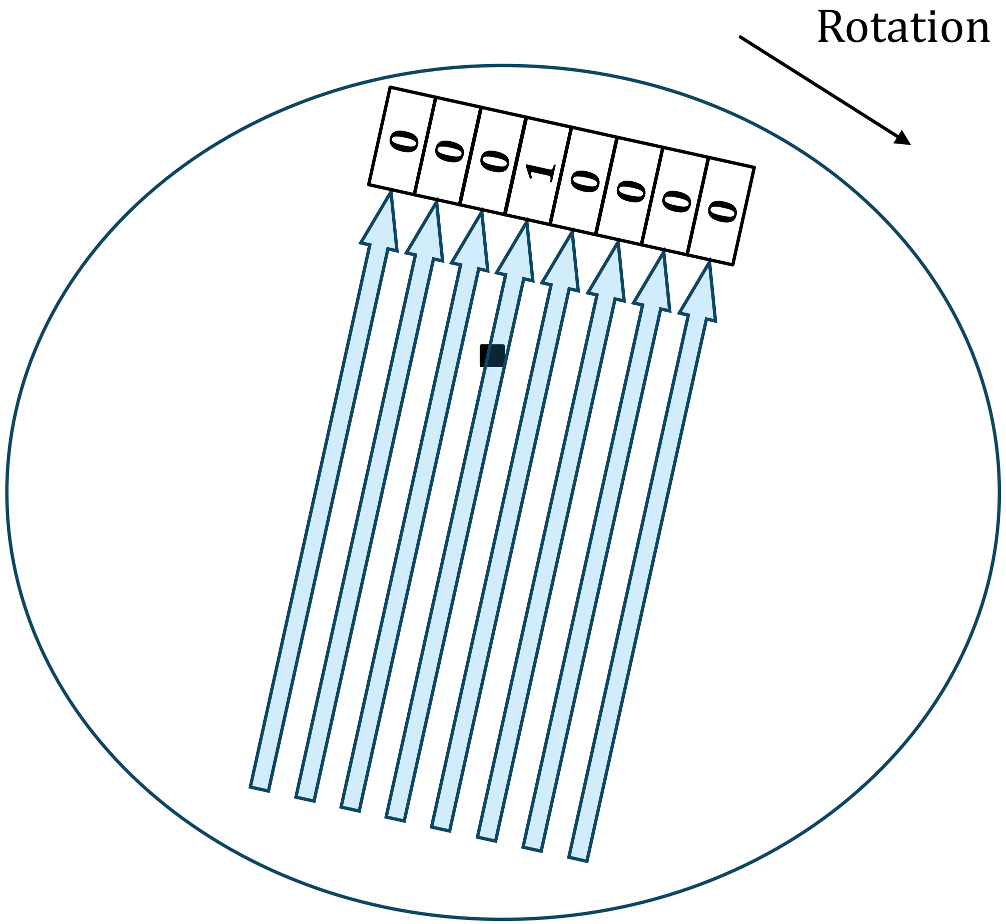
0	1	0	0	0	0	0	0
0	0	1	0	0	0	0	0
0	0	0	1	0	0	0	0
0	0	0	0	1	0	0	0
0	0	0	0	0	1	0	0
0	0	0	0	0	0	1	0



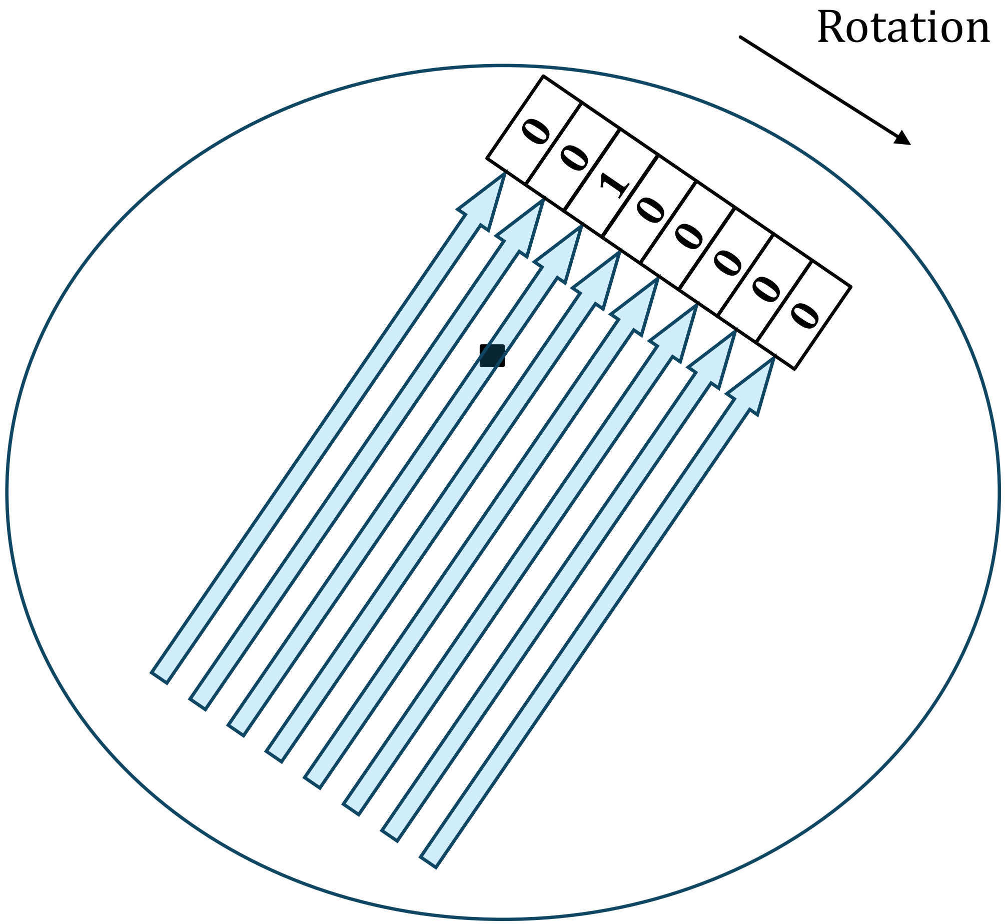
0	1	0	0	0	0	0	0
0	0	1	0	0	0	0	0
0	0	0	1	0	0	0	0
0	0	0	0	1	0	0	0
0	0	0	0	0	1	0	0
0	0	0	0	0	0	1	0
0	0	0	0	0	1	0	0



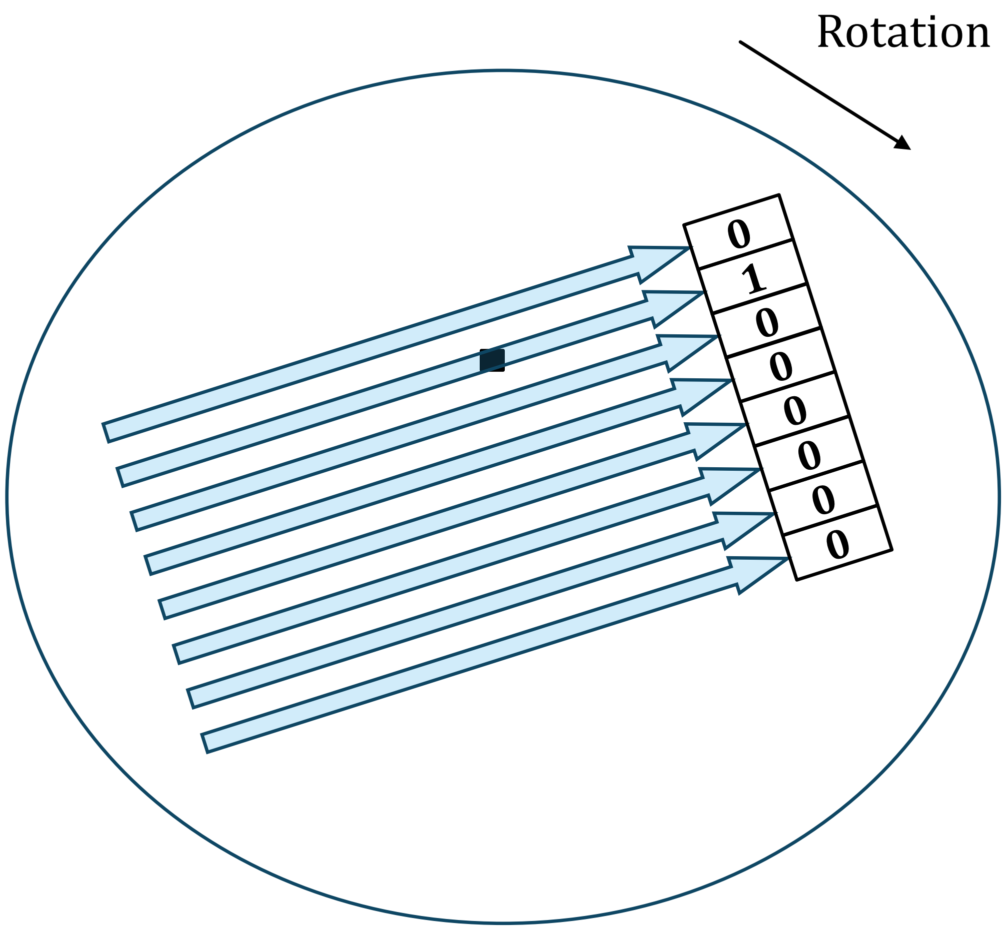
0	1	0	0	0	0	0	0
0	0	1	0	0	0	0	0
0	0	0	1	0	0	0	0
0	0	0	0	1	0	0	0
0	0	0	0	0	1	0	0
0	0	0	0	0	0	1	0
0	0	0	0	0	1	0	0
0	0	0	0	1	0	0	0



0	1	0	0	0	0	0	0
0	0	1	0	0	0	0	0
0	0	0	1	0	0	0	0
0	0	0	0	1	0	0	0
0	0	0	0	0	1	0	0
0	0	0	0	0	0	1	0
0	0	0	0	0	1	0	0
0	0	0	0	1	0	0	0
0	0	0	1	0	0	0	0

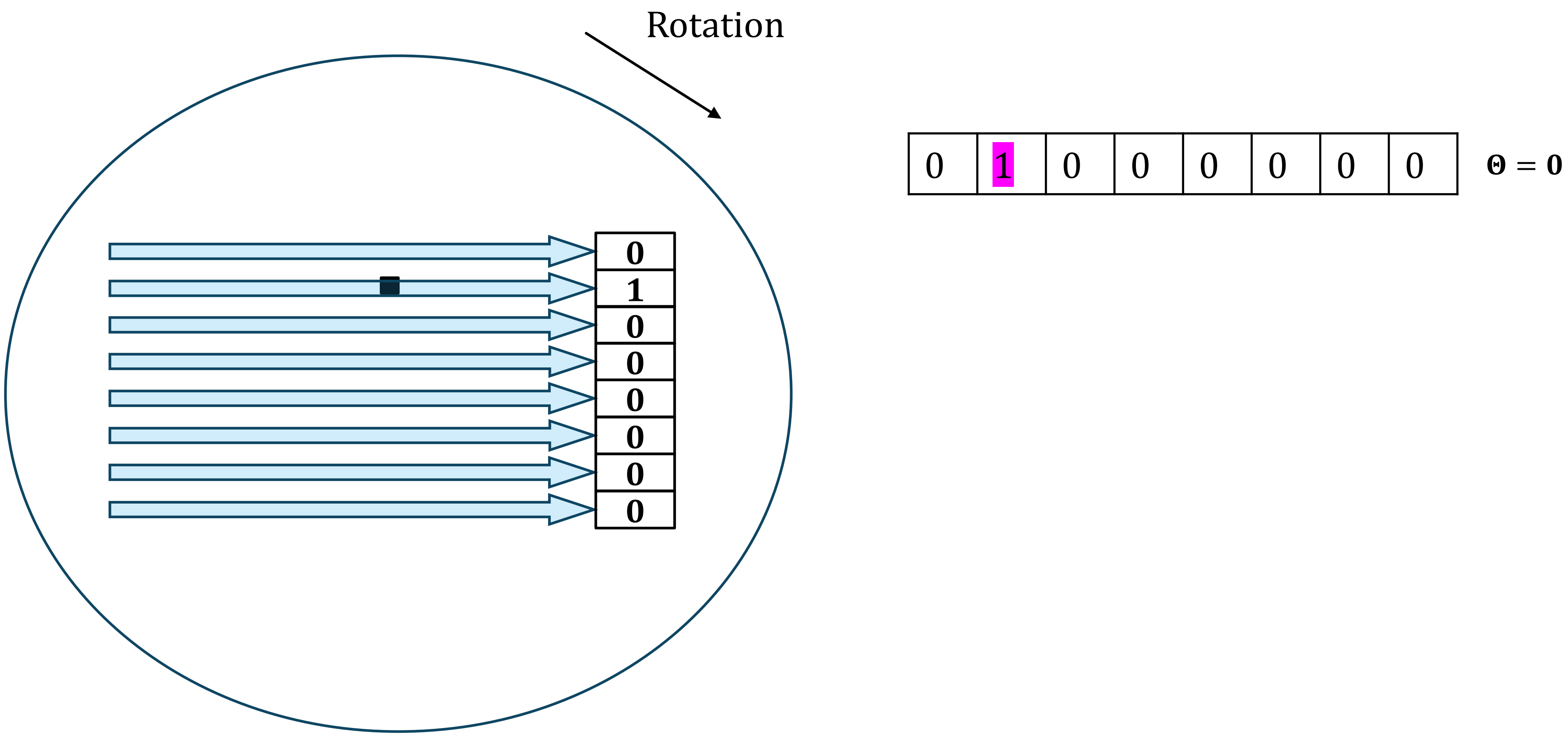


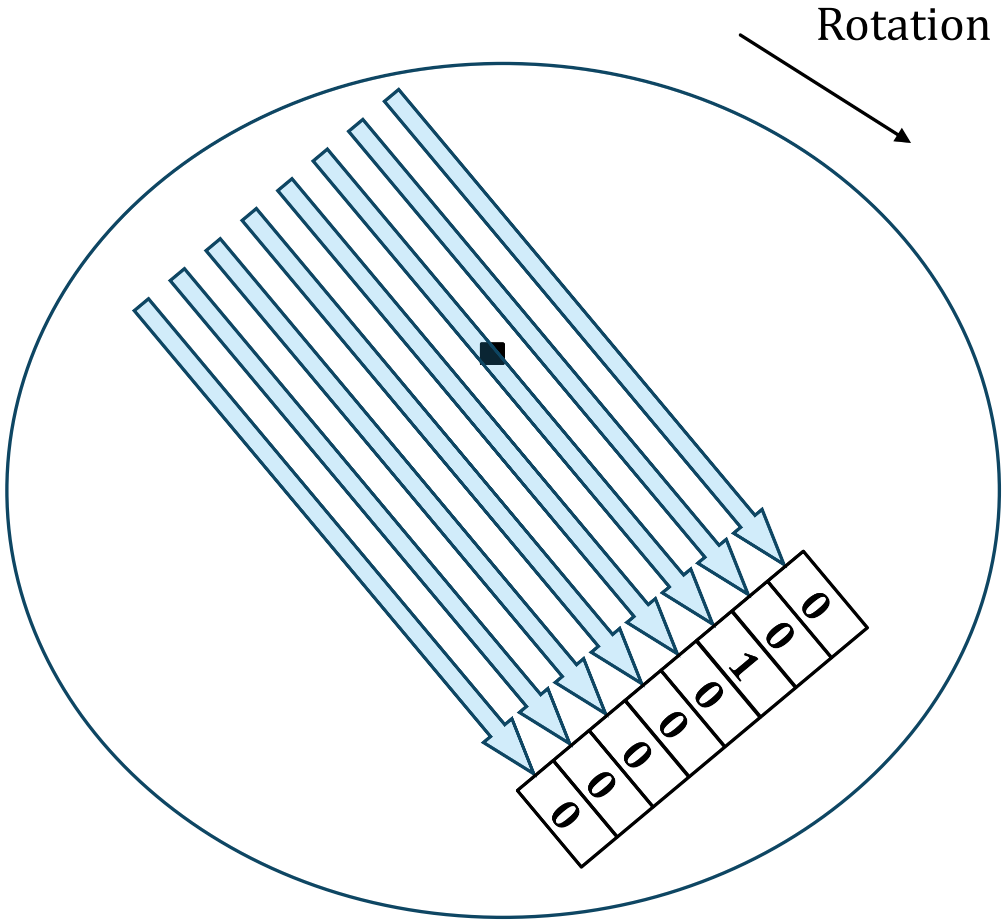
0	1	0	0	0	0	0	0
0	0	1	0	0	0	0	0
0	0	0	1	0	0	0	0
0	0	0	0	1	0	0	0
0	0	0	0	0	1	0	0
0	0	0	0	0	0	1	0
0	0	0	0	0	1	0	0
0	0	0	0	1	0	0	0
0	0	0	1	0	0	0	0
0	0	1	0	0	0	0	0



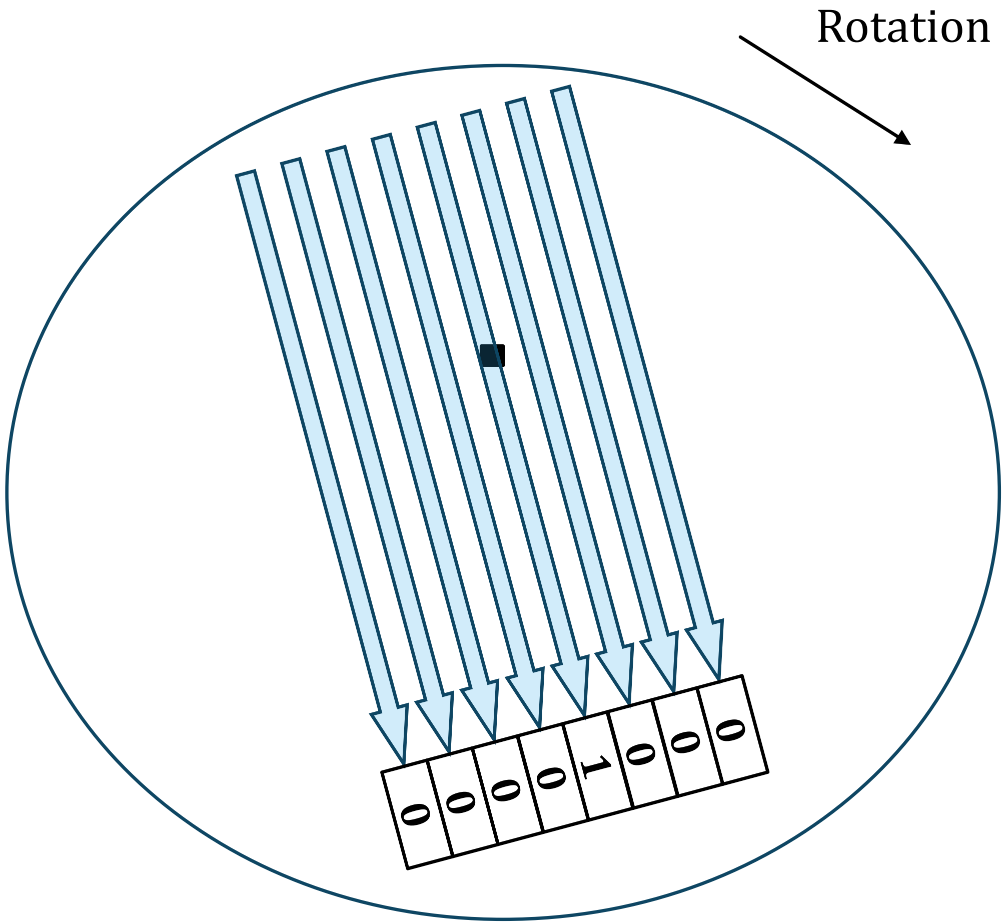
0	1	0	0	0	0	0	0
0	0	1	0	0	0	0	0
0	0	0	1	0	0	0	0
0	0	0	0	1	0	0	0
0	0	0	0	0	1	0	0
0	0	0	0	0	0	1	0
0	0	0	0	0	1	0	0
0	0	0	0	1	0	0	0
0	0	0	1	0	0	0	0
0	0	1	0	0	0	0	0
0	1	0	0	0	0	0	0

Let’s see once again

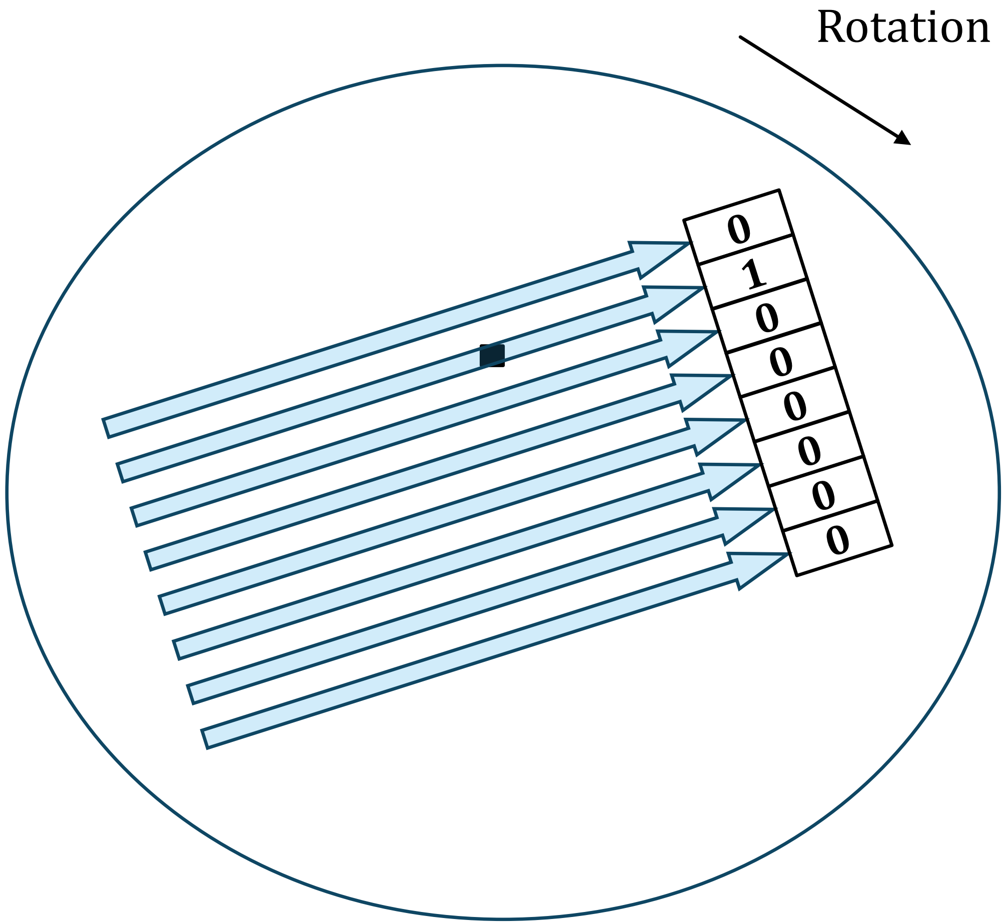

Rotation
0
1
0
0
0
0
0
0
0 1 0 0 0 0 0 0
Θ = 0



0	1	0	0	0	0	0	0	$\Theta = 0$
0	0	1	0	0	0	0	0	$\Theta = 30^0$

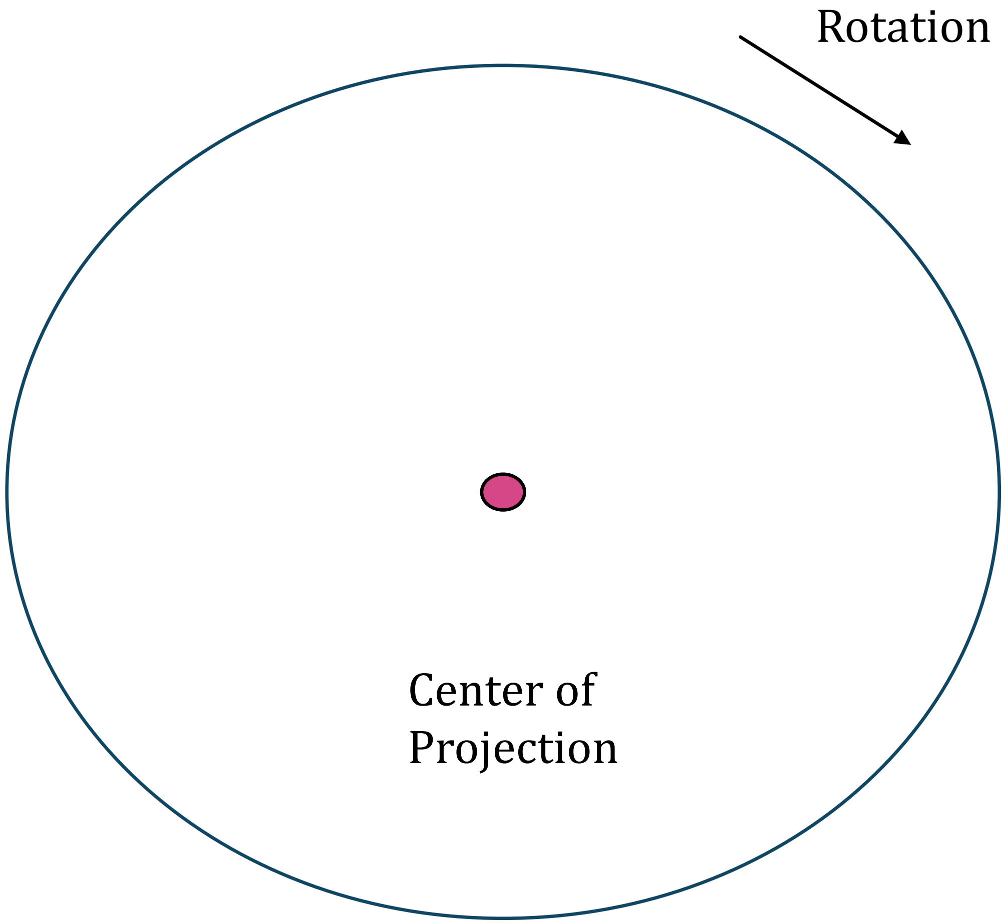


0	1	0	0	0	0	0	0	$\Theta = 0$
0	0	1	0	0	0	0	0	$\Theta = 30^0$
0	0	0	1	0	0	0	0	$\Theta = 45^0$



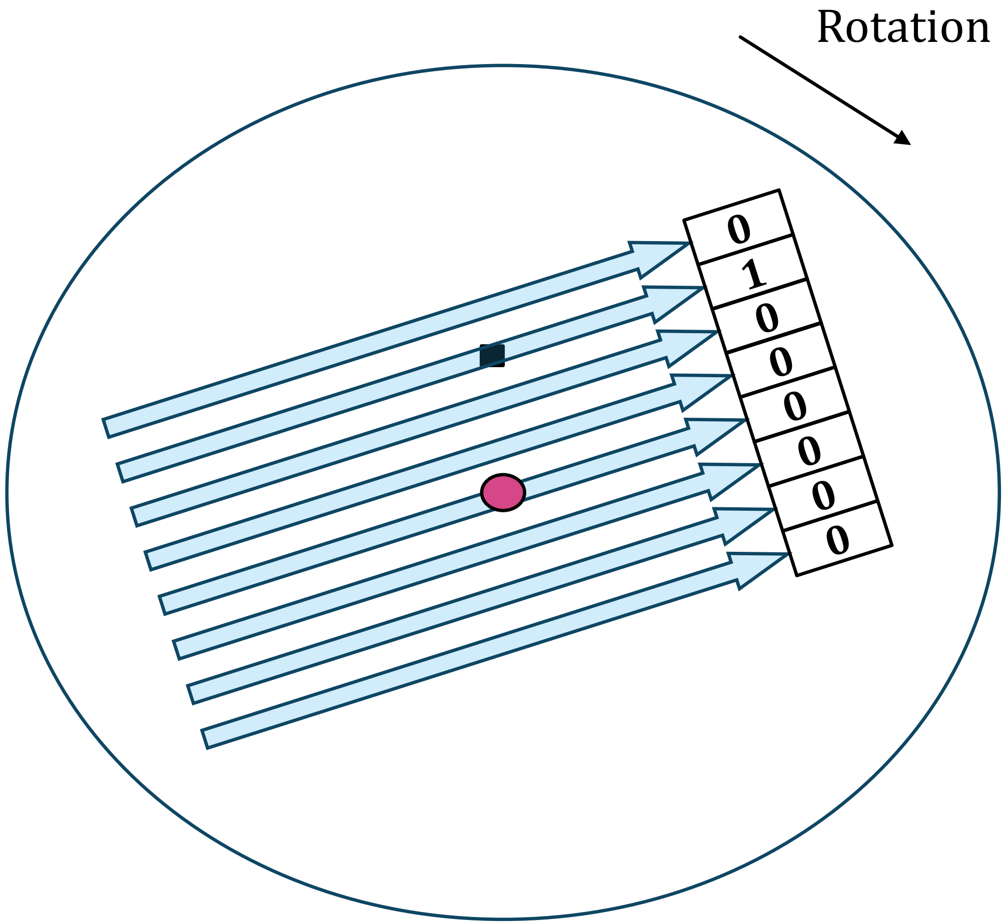
Θ

0	1	0	0	0	0	0	0
0	0	1	0	0	0	0	0
0	0	0	1	0	0	0	0
0	0	0	0	1	0	0	0
0	0	0	0	0	1	0	0
0	0	0	0	0	0	1	0
0	0	0	0	0	1	0	0
0	0	0	0	1	0	0	0
0	0	0	1	0	0	0	0
0	0	1	0	0	0	0	0
0	1	0	0	0	0	0	0



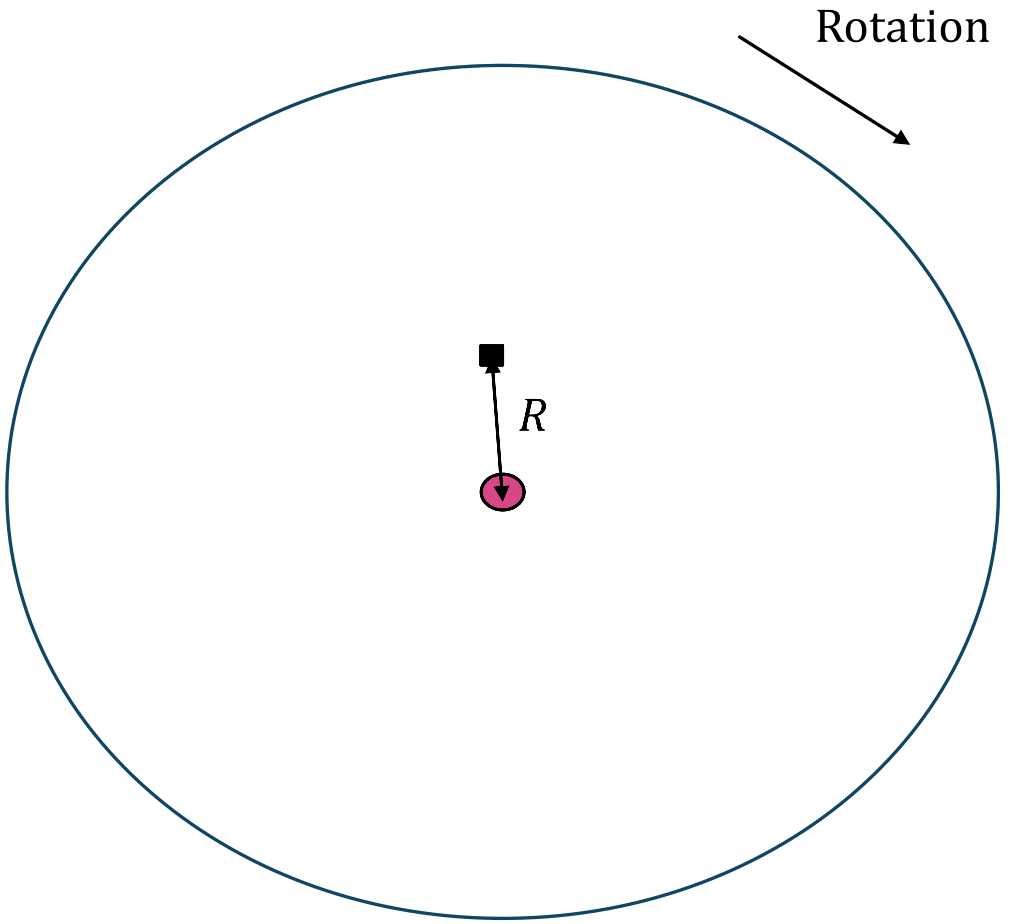
Θ

0	1	0	0	0	0	0	0
0	0	1	0	0	0	0	0
0	0	0	1	0	0	0	0
0	0	0	0	1	0	0	0
0	0	0	0	0	1	0	0
0	0	0	0	0	0	1	0
0	0	0	0	0	1	0	0
0	0	0	0	1	0	0	0
0	0	0	1	0	0	0	0
0	0	1	0	0	0	0	0
0	1	0	0	0	0	0	0



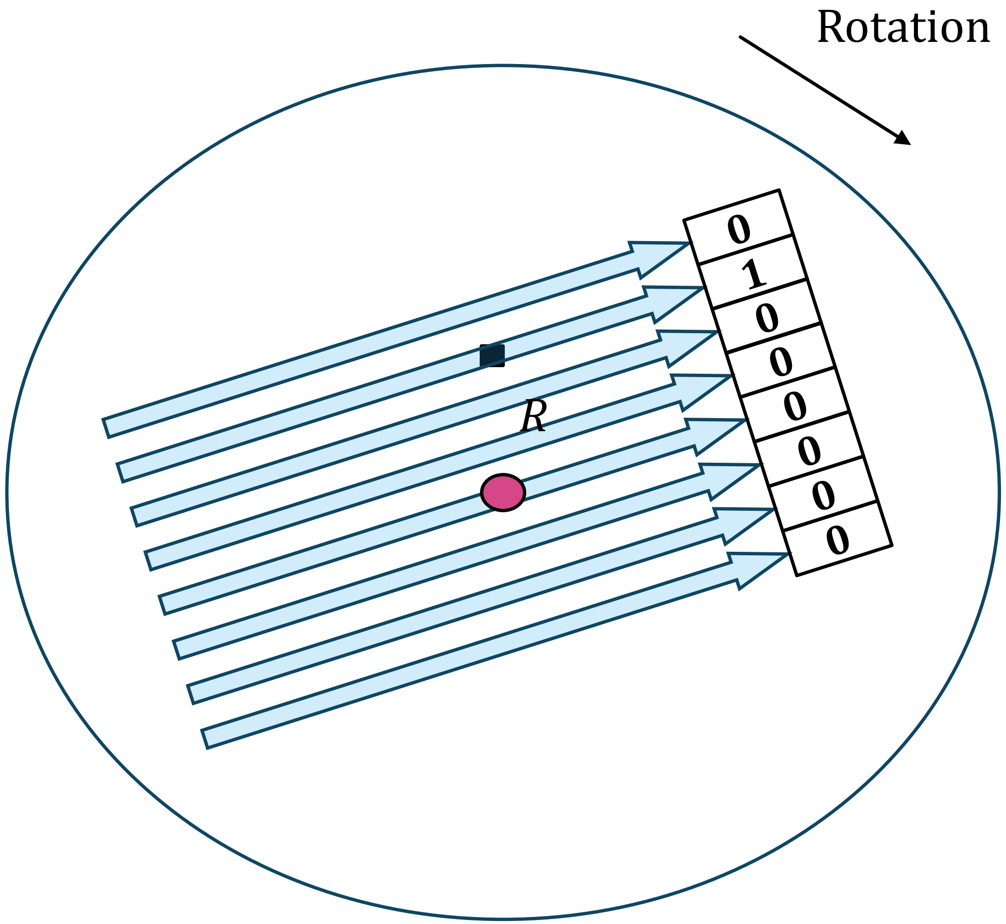
Θ

0	1	0	0	0	0	0	0
0	0	1	0	0	0	0	0
0	0	0	1	0	0	0	0
0	0	0	0	1	0	0	0
0	0	0	0	0	1	0	0
0	0	0	0	0	0	1	0
0	0	0	0	0	1	0	0
0	0	0	0	1	0	0	0
0	0	0	1	0	0	0	0
0	0	1	0	0	0	0	0
0	1	0	0	0	0	0	0



Θ

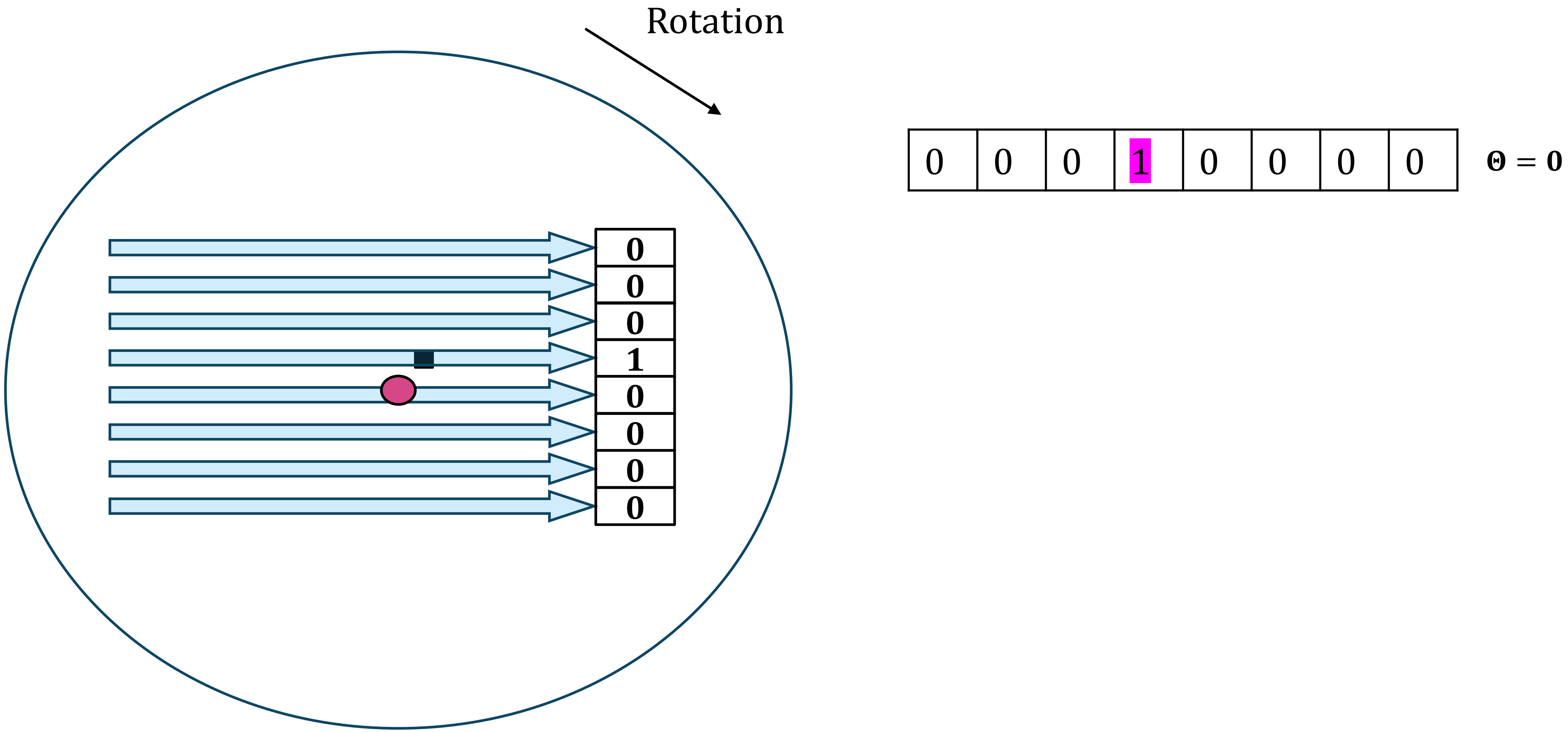
0	1	0	0	0	0	0	0
0	0	1	0	0	0	0	0
0	0	0	1	0	0	0	0
0	0	0	0	1	0	0	0
0	0	0	0	0	1	0	0
0	0	0	0	0	0	1	0
0	0	0	0	0	1	0	0
0	0	0	0	1	0	0	0
0	0	0	1	0	0	0	0
0	0	1	0	0	0	0	0
0	1	0	0	0	0	0	0

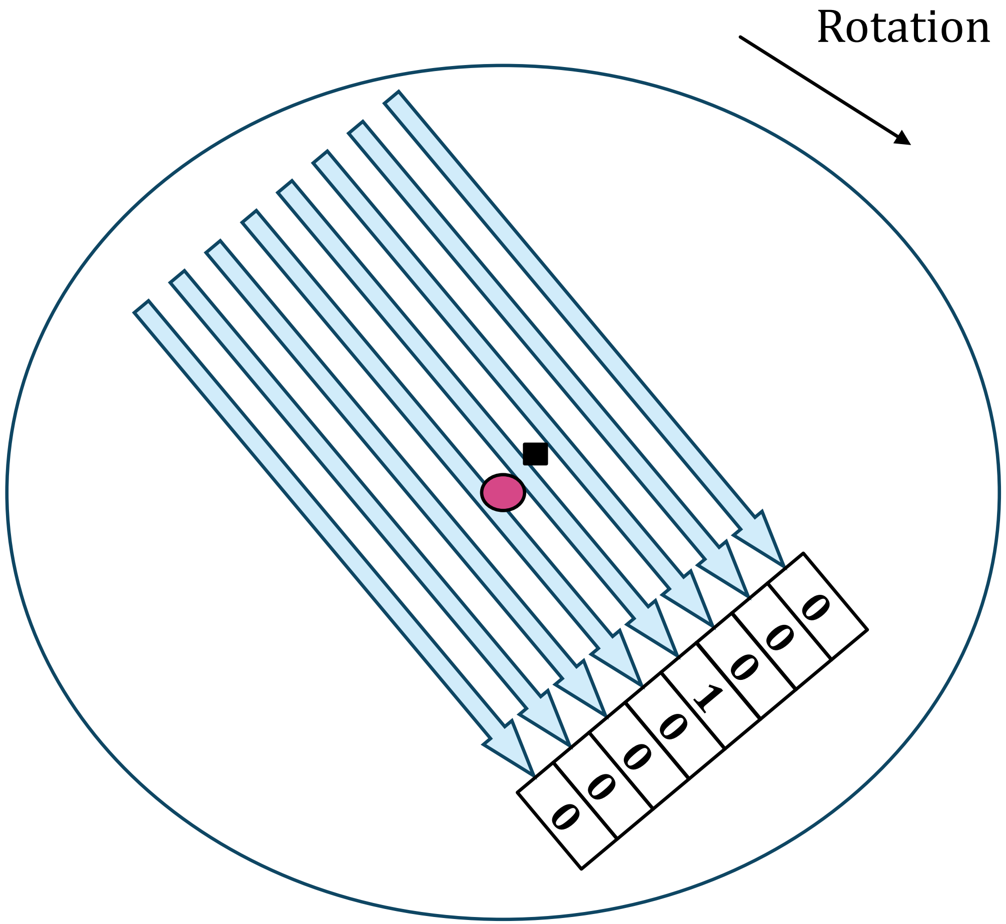


Θ

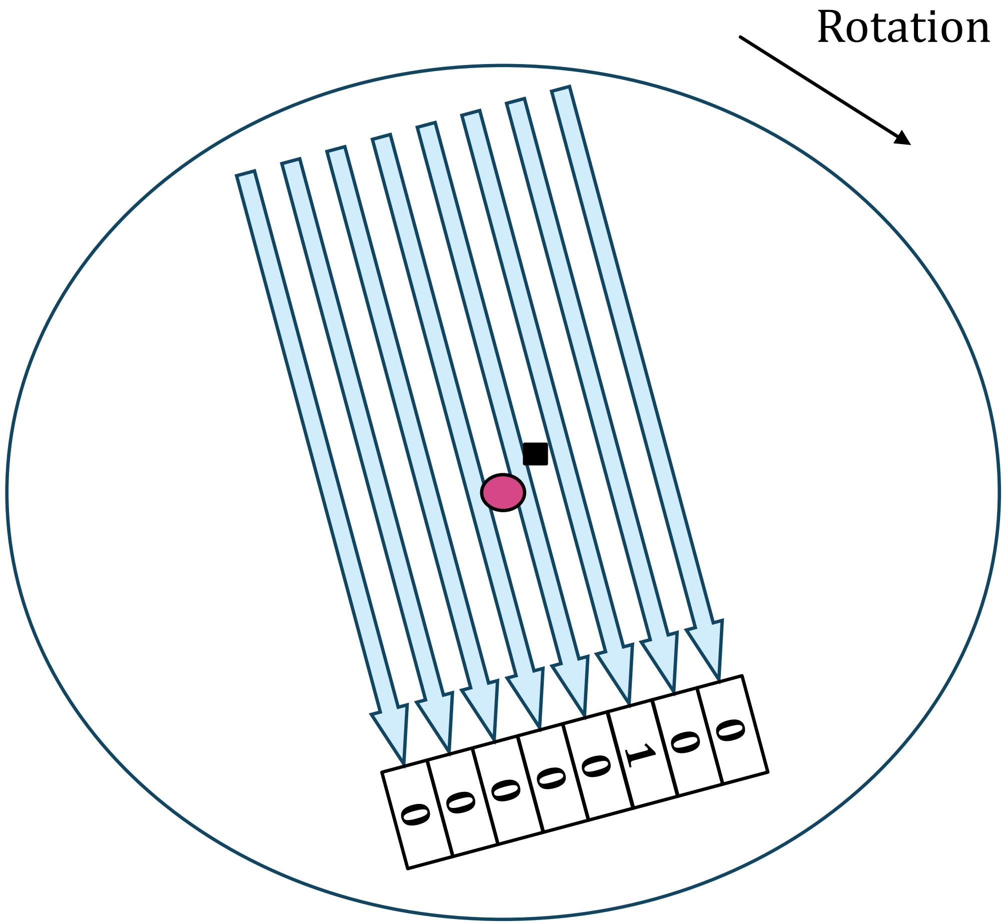
0	1	0	0	0	0	0	0
0	0	1	0	0	0	0	0
0	0	0	1	0	0	0	0
0	0	0	0	1	0	0	0
0	0	0	0	0	1	0	0
0	0	0	0	0	0	1	0
0	0	0	0	0	1	0	0
0	0	0	0	1	0	0	0
0	0	0	1	0	0	0	0
0	0	1	0	0	0	0	0
0	1	0	0	0	0	0	0

If distance is smaller

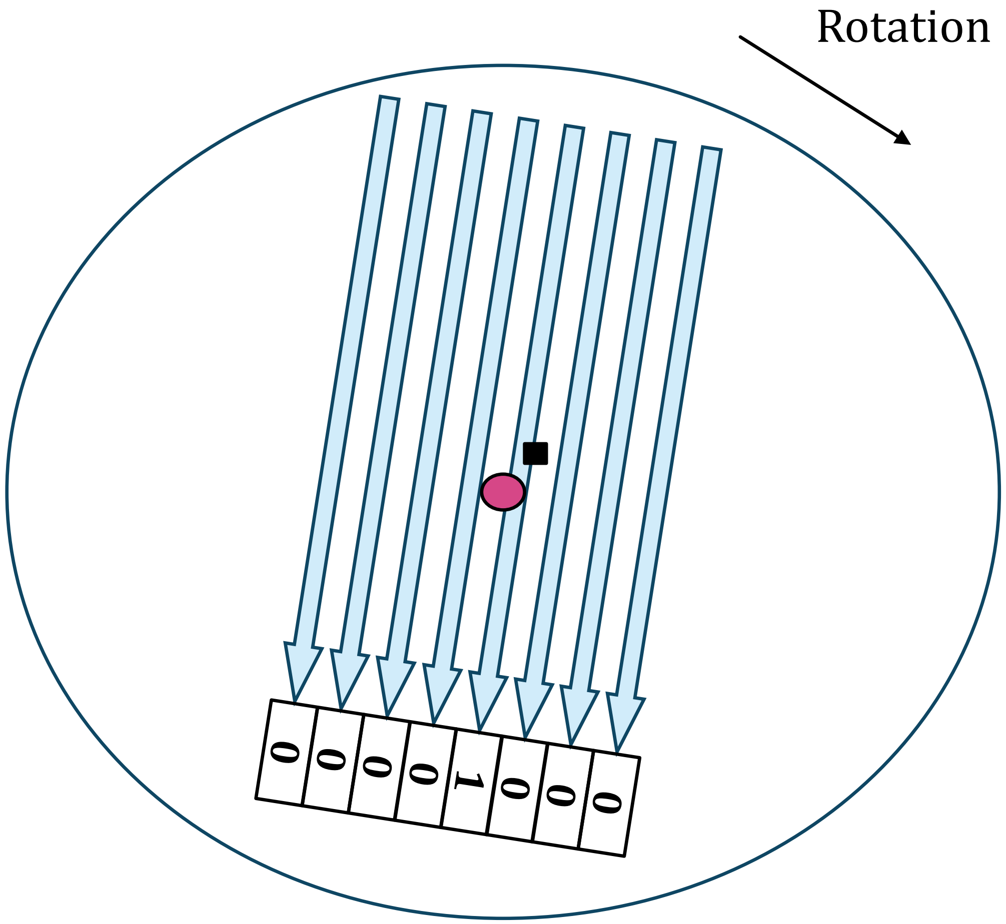




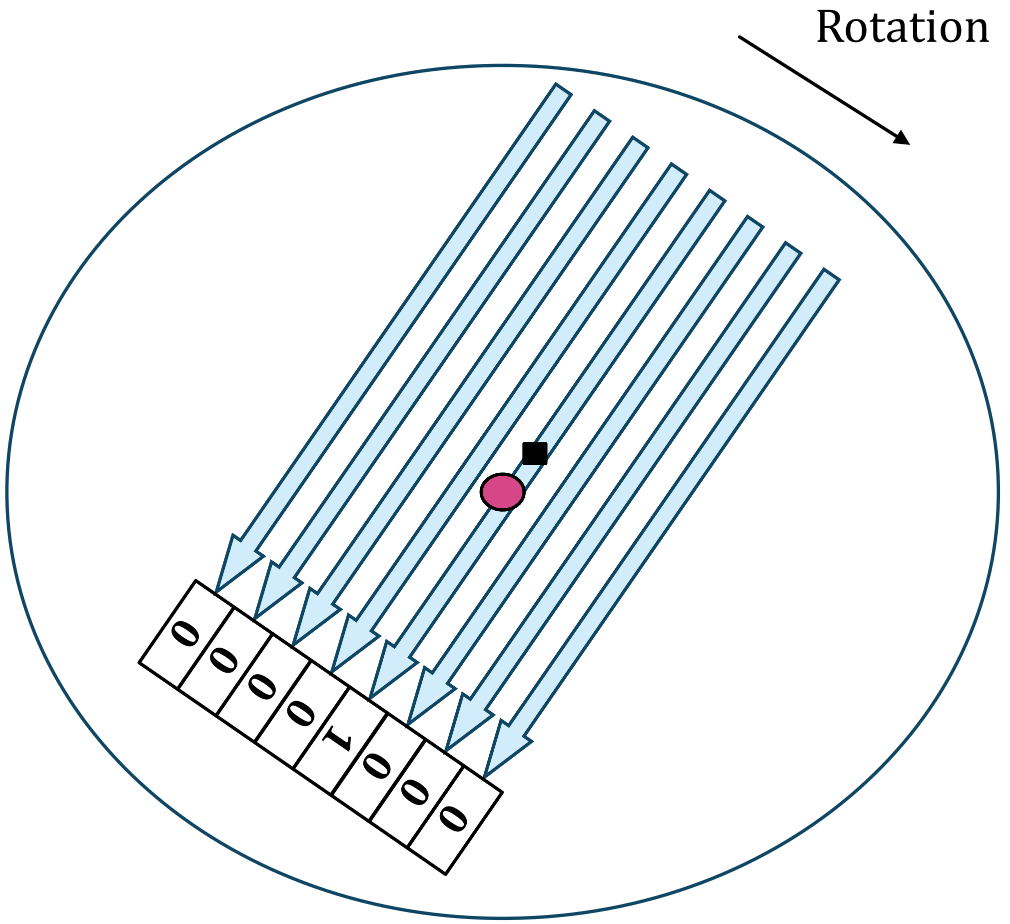
0	0	0	1	0	0	0	0
0	0	0	1	0	0	0	0



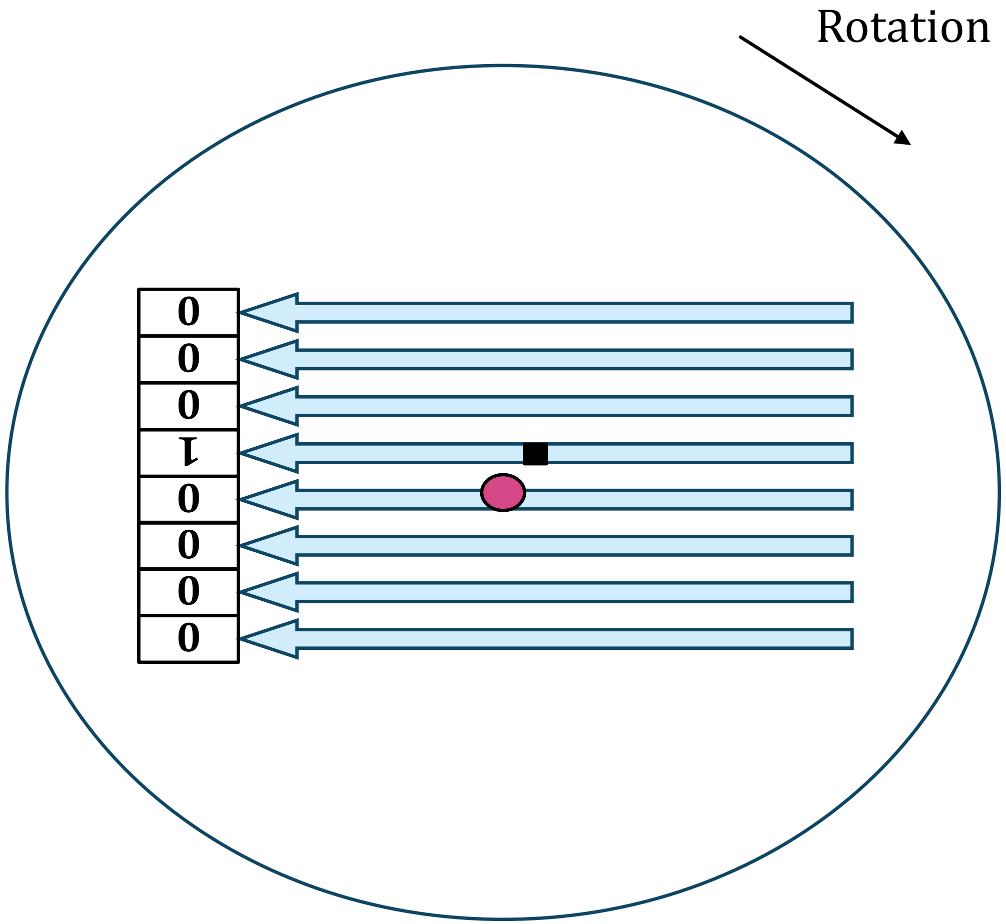
0	0	0	1	0	0	0	0
0	0	0	1	0	0	0	0
0	0	1	0	0	0	0	0



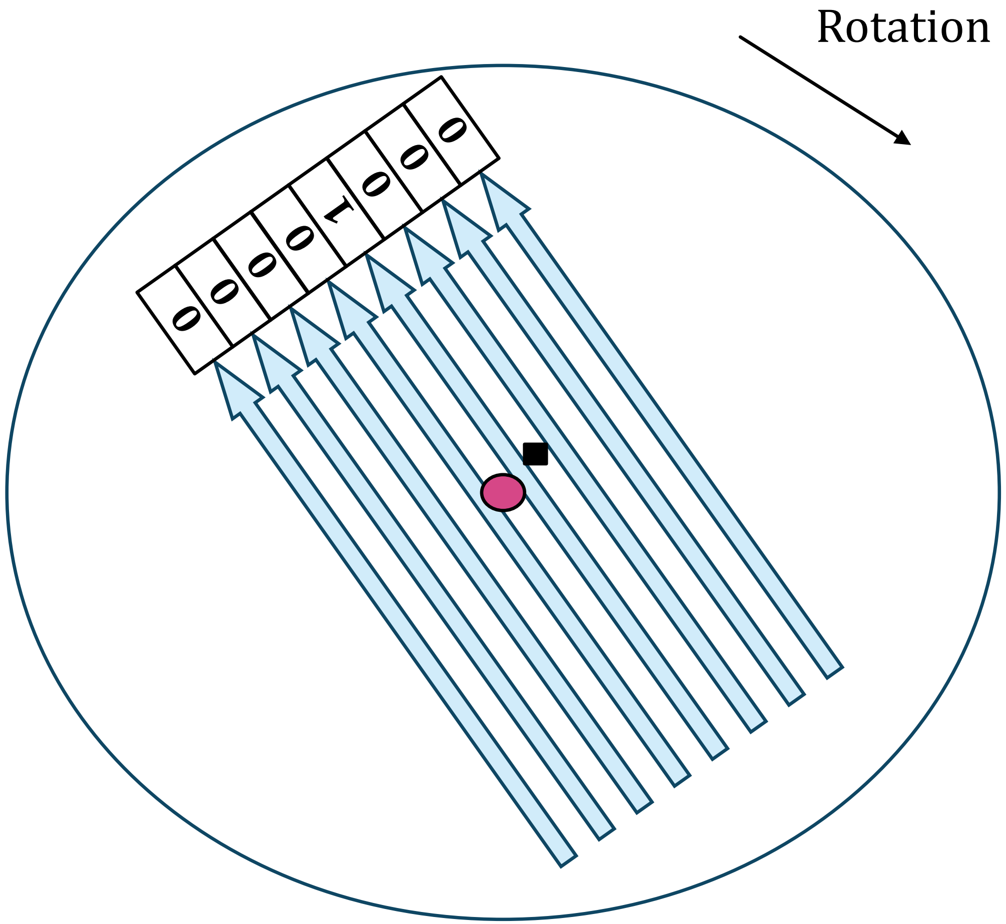
0	0	0	1	0	0	0	0
0	0	0	1	0	0	0	0
0	0	1	0	0	0	0	0
0	0	0	1	0	0	0	0



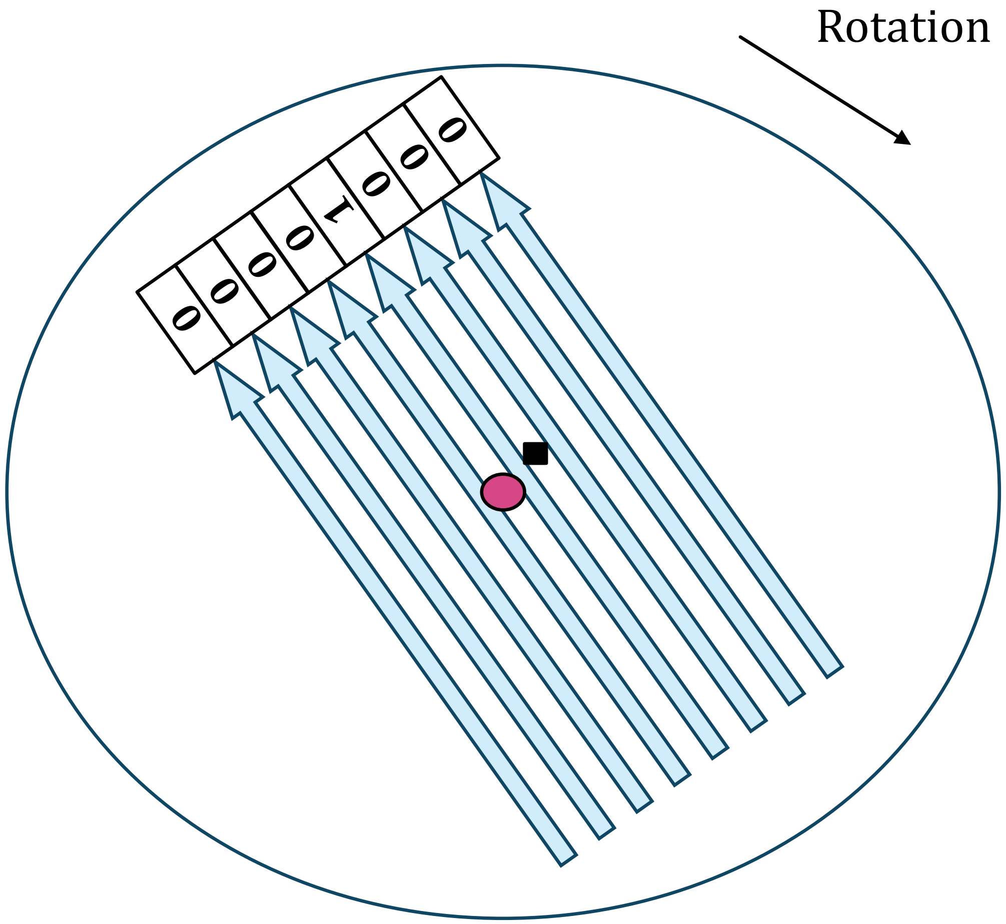
0	0	0	1	0	0	0	0
0	0	0	1	0	0	0	0
0	0	1	0	0	0	0	0
0	0	0	1	0	0	0	0
0	0	0	1	0	0	0	0



0	0	0	1	0	0	0	0
0	0	0	1	0	0	0	0
0	0	1	0	0	0	0	0
0	0	0	1	0	0	0	0
0	0	0	1	0	0	0	0
0	0	0	0	1	0	0	0

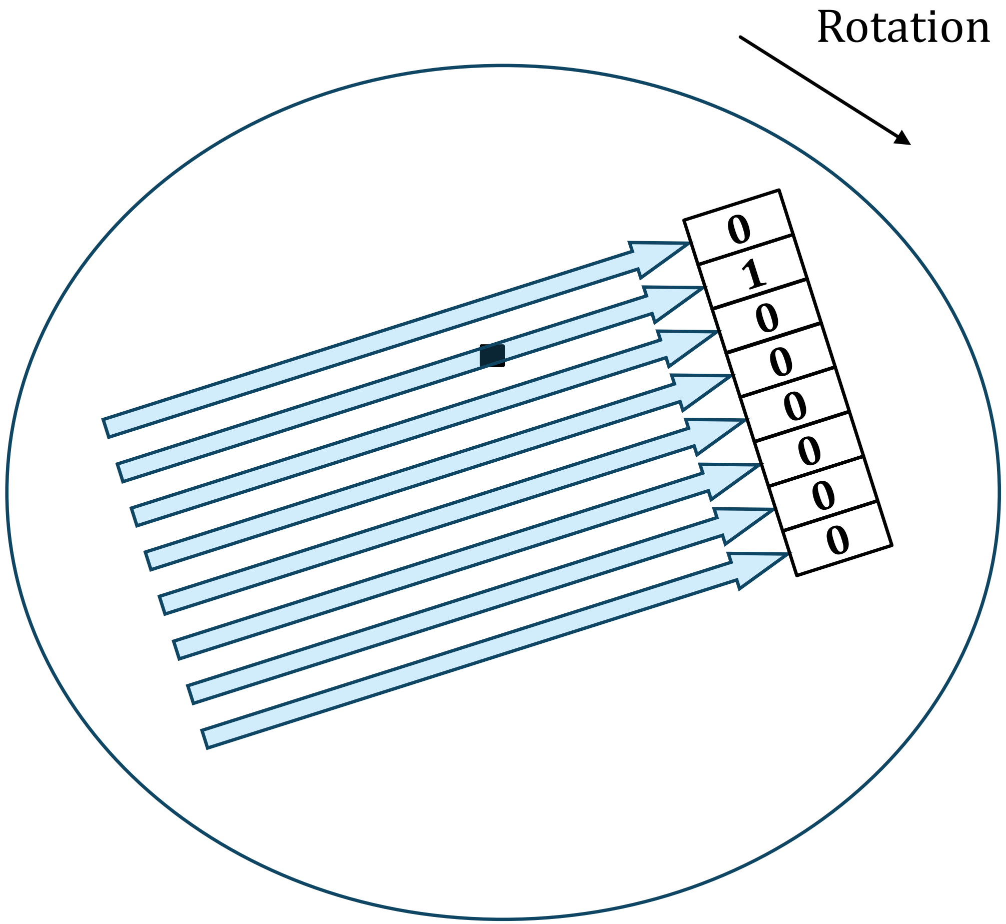


0	0	0	1	0	0	0	0
0	0	0	1	0	0	0	0
0	0	1	0	0	0	0	0
0	0	0	1	0	0	0	0
0	0	0	1	0	0	0	0
0	0	0	0	1	0	0	0
0	0	0	1	0	0	0	0



0	0	0	1	0	0	0	0
0	0	0	1	0	0	0	0
0	0	1	0	0	0	0	0
0	0	0	1	0	0	0	0
0	0	0	1	0	0	0	0
0	0	0	0	1	0	0	0
0	0	0	1	0	0	0	0

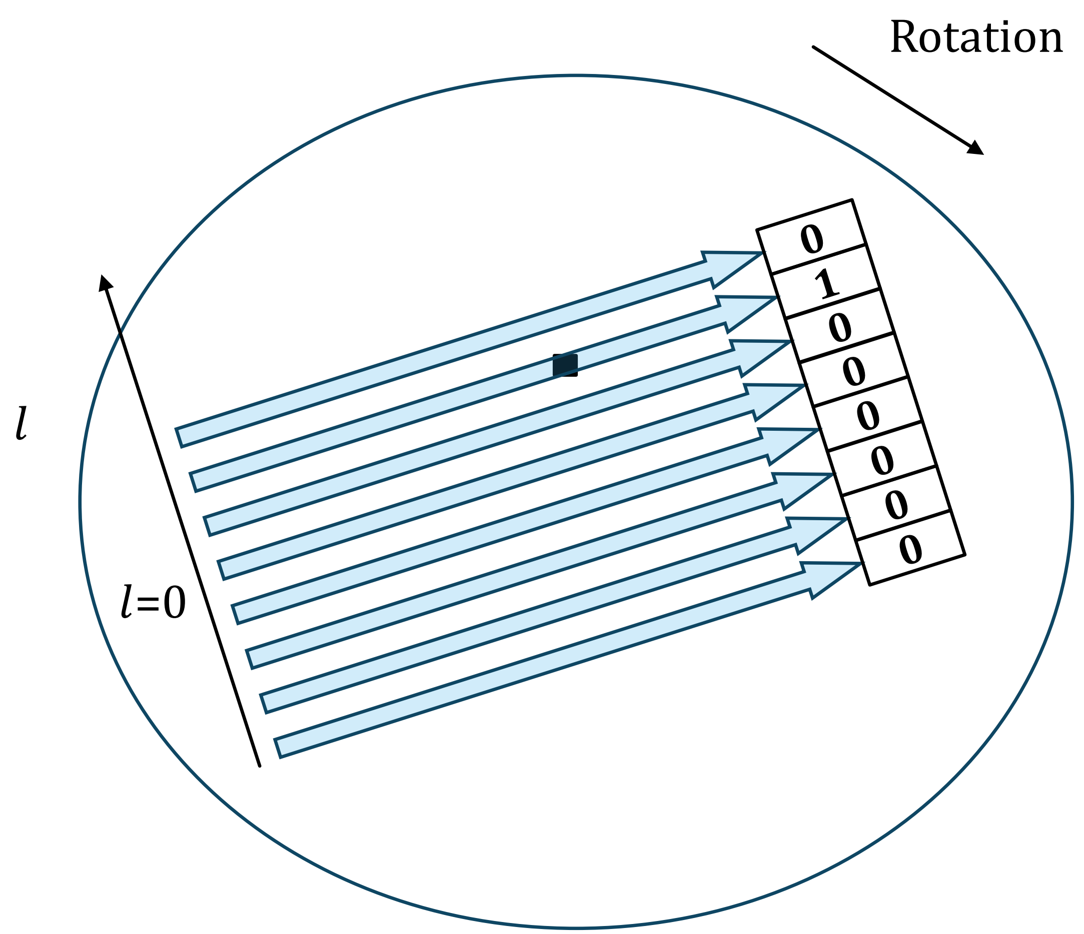
The closer an object from the center of rotation, the smaller is the amplitude



l

Θ

0	1	0	0	0	0	0	0
0	0	1	0	0	0	0	0
0	0	0	1	0	0	0	0
0	0	0	0	1	0	0	0
0	0	0	0	0	1	0	0
0	0	0	0	0	0	1	0
0	0	0	0	0	1	0	0
0	0	0	0	1	0	0	0
0	0	0	1	0	0	0	0
0	0	1	0	0	0	0	0
0	1	0	0	0	0	0	0

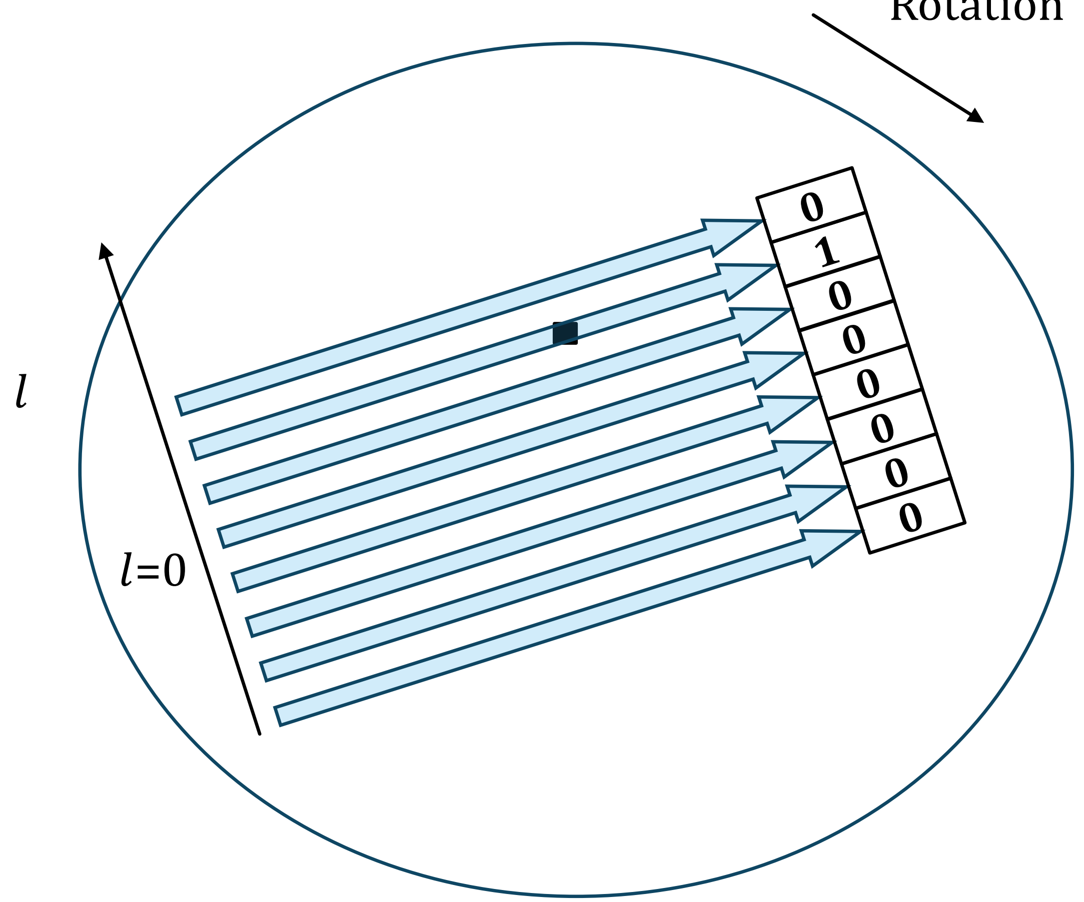


l=0 l

Θ

0	1	0	0	0	0	0	0
0	0	1	0	0	0	0	0
0	0	0	1	0	0	0	0
0	0	0	0	1	0	0	0
0	0	0	0	0	1	0	0
0	0	0	0	0	0	1	0
0	0	0	0	0	1	0	0
0	0	0	0	1	0	0	0
0	0	0	1	0	0	0	0
0	0	1	0	0	0	0	0
0	1	0	0	0	0	0	0

Sinogram



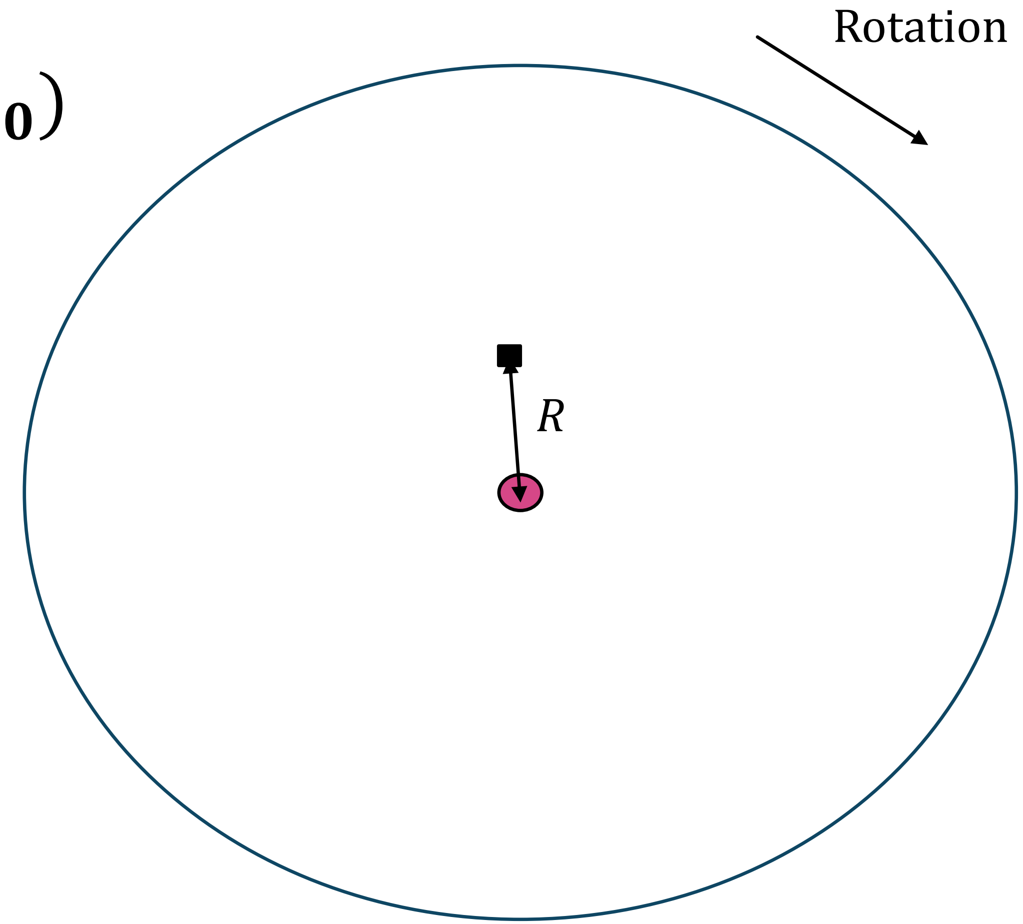
l=0 l

Θ

0	1	0	0	0	0	0	0
0	0	1	0	0	0	0	0
0	0	0	1	0	0	0	0
0	0	0	0	1	0	0	0
0	0	0	0	0	1	0	0
0	0	0	0	0	0	1	0
0	0	0	0	0	1	0	0
0	0	0	0	1	0	0	0
0	0	0	1	0	0	0	0
0	0	1	0	0	0	0	0
0	1	0	0	0	0	0	0

Sinogram

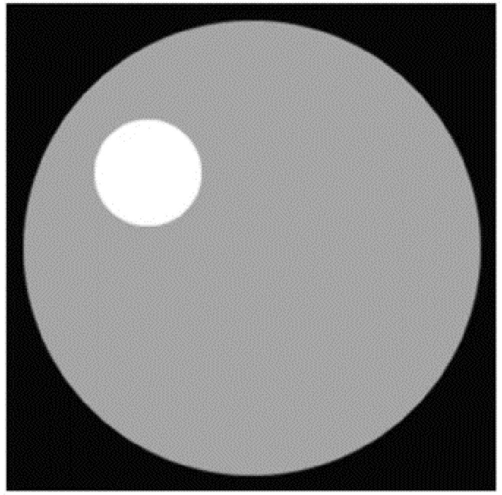
$$R\sin(\theta + \theta_0)$$



Θ

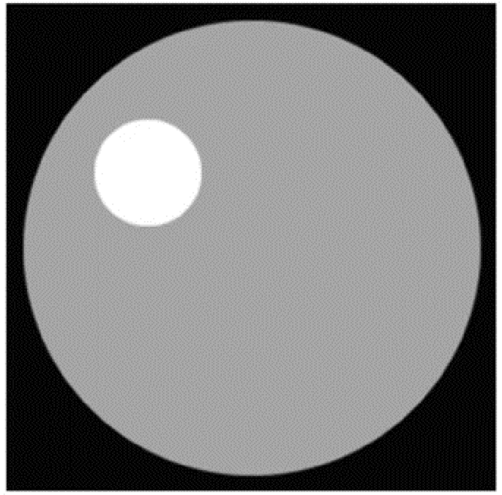
0	1	0	0	0	0	0	0
0	0	1	0	0	0	0	0
0	0	0	1	0	0	0	0
0	0	0	0	1	0	0	0
0	0	0	0	0	1	0	0
0	0	0	0	0	0	1	0
0	0	0	0	0	1	0	0
0	0	0	0	1	0	0	0
0	0	0	1	0	0	0	0
0	0	1	0	0	0	0	0
0	1	0	0	0	0	0	0

Sinogram



https://www.youtube.com/watch?v=gQUOBM5Hon4

Sinogram



Radom Transform is the transformation of any object into its sinogram

https://www.youtube.com/watch?v=gQUOBM5Hon4

Sinogram

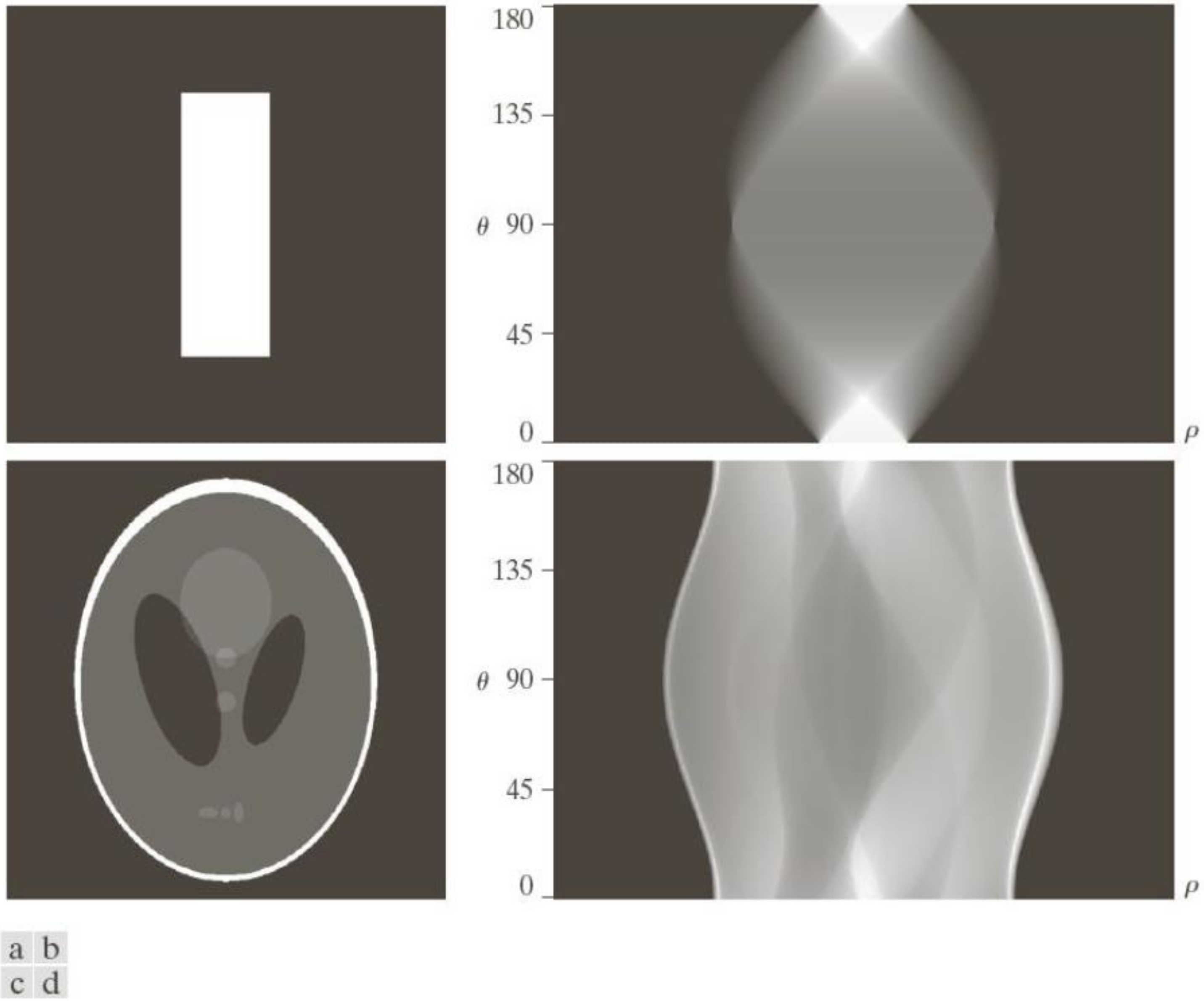


FIGURE 5.39 Two images and their sinograms (Radon transforms). Each row of a sinogram is a projection along the corresponding angle on the vertical axis. Image (c) is called the *Shepp-Logan phantom*. In its original form, the contrast of the phantom is quite low. It is shown enhanced here to facilitate viewing.

It is very difficult to interpret sinograms

https://acrobat.adobe.com/link/review?uri=urn%3Aaaid%3Ascds%3AUS%3A4c7fe4df-7964-38df-a818-ad12e21d4125

CT Scanner

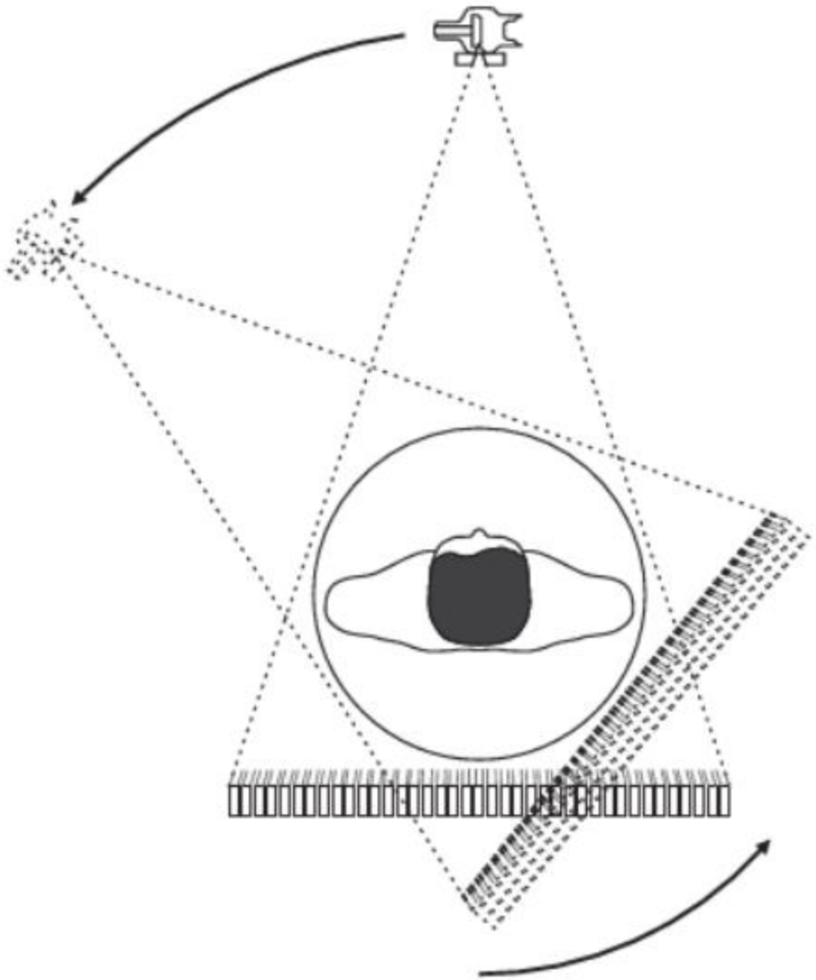
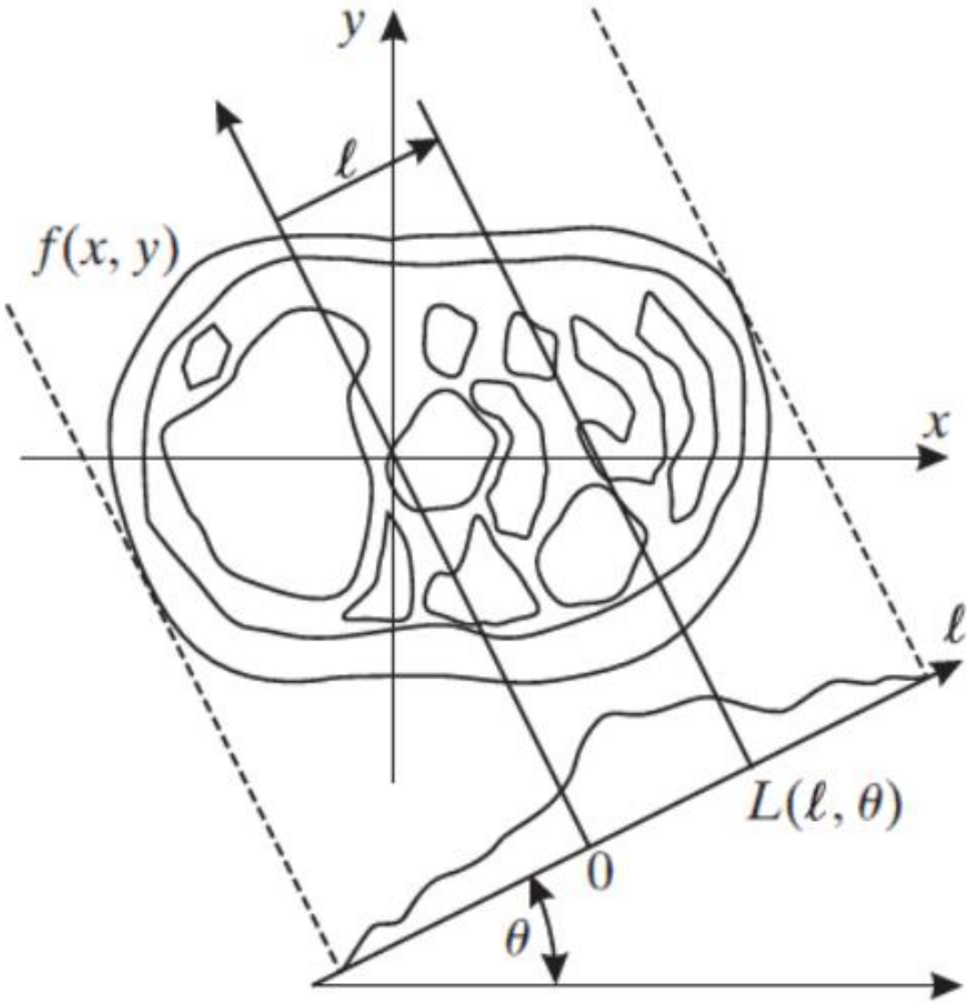


Figure 6.4
The geometry of a third-generation (3G) CT scanner.

Projection

Parallel rays



CT Scanner

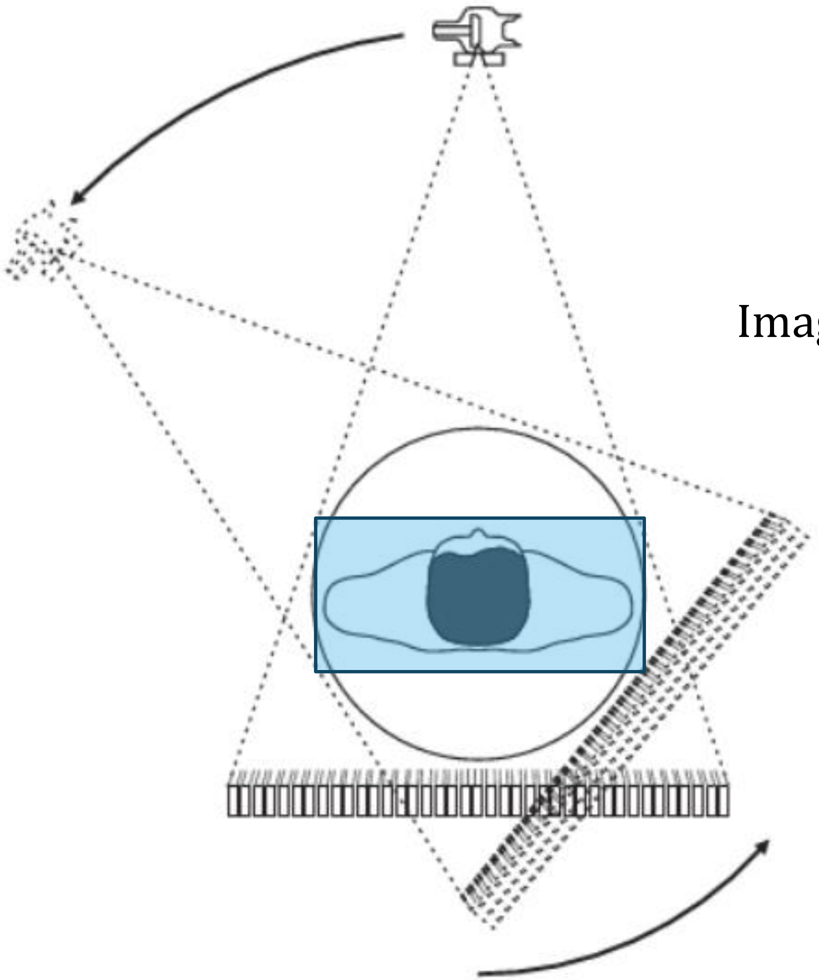
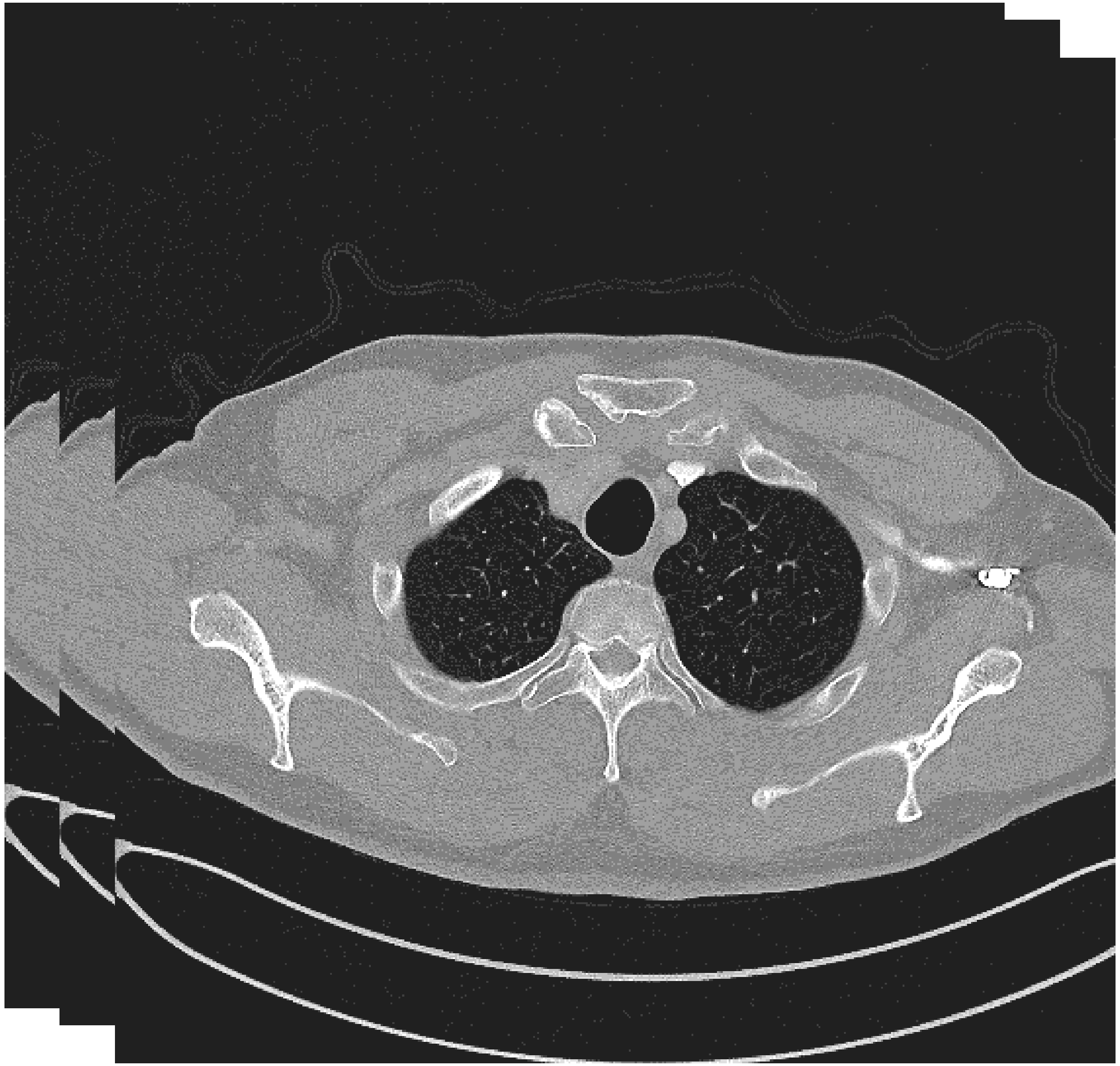


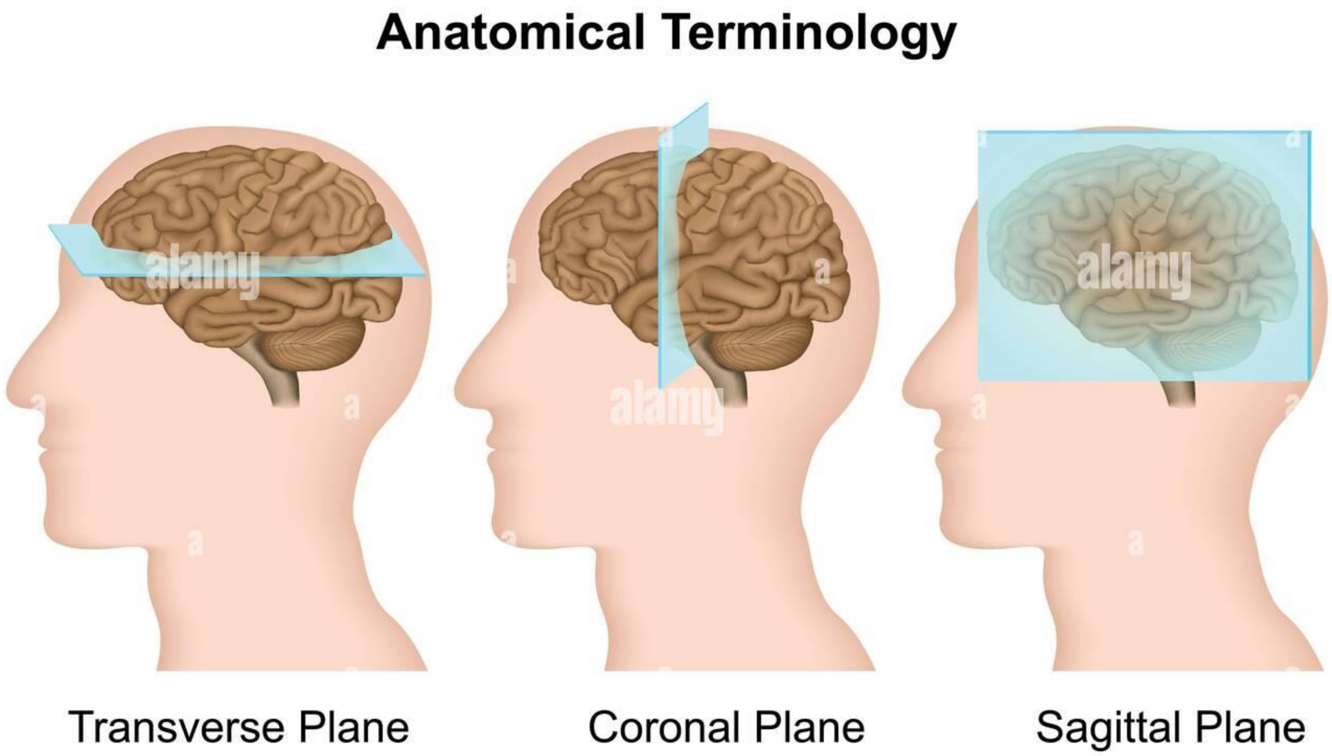
Image that we want to see

Figure 6.4
The geometry of a third-generation (3G) CT scanner.

Slices stacked together provides 3D information



Planes of Body



Axial Plane

CT Scanner

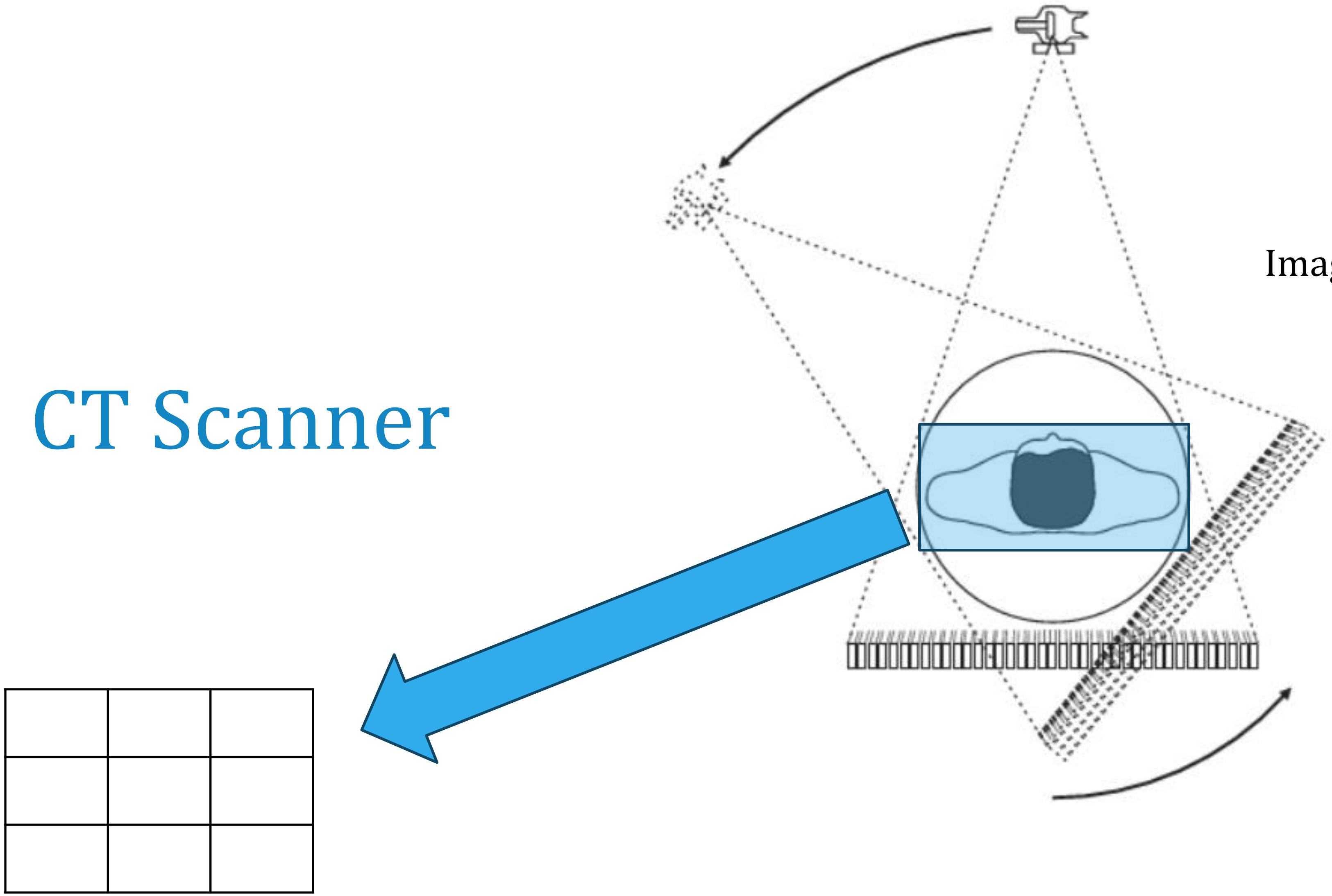
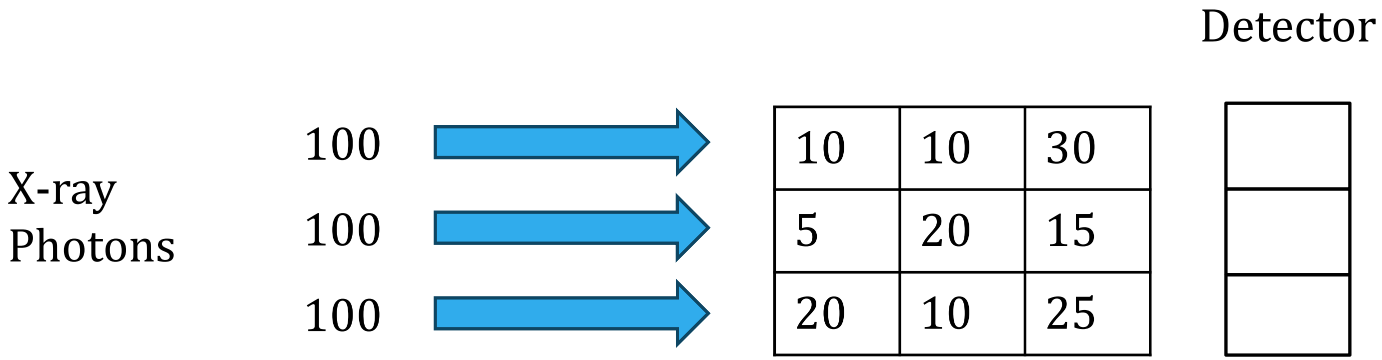


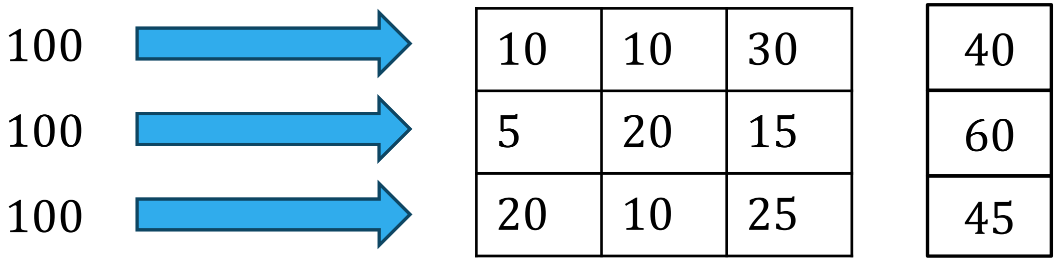
Image that we want to see

Figure 6.4
The geometry of a third-generation (3G) CT scanner.

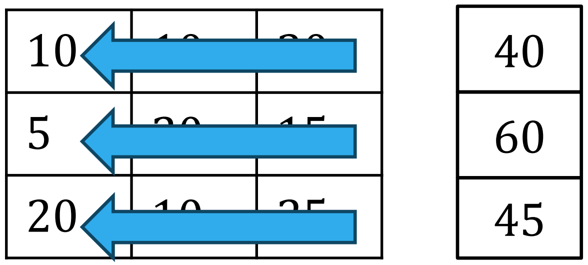
Projection



Forward Projection

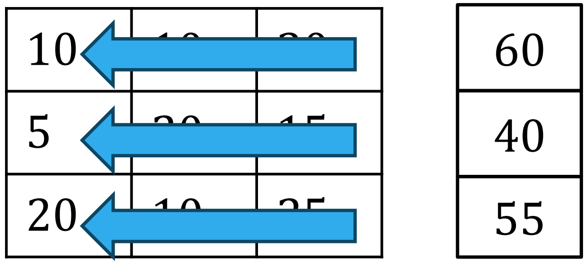


Back Projection



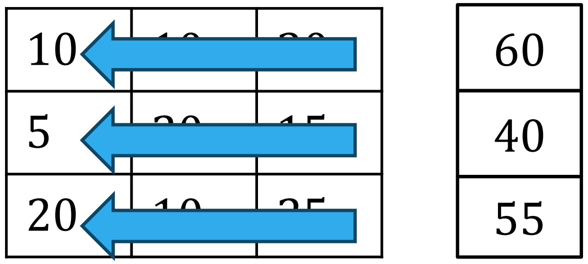
Back Projection

Photons absorbed
along the straight line
of the x-ray



Back Projection

Photons absorbed along the straight line of the x-ray



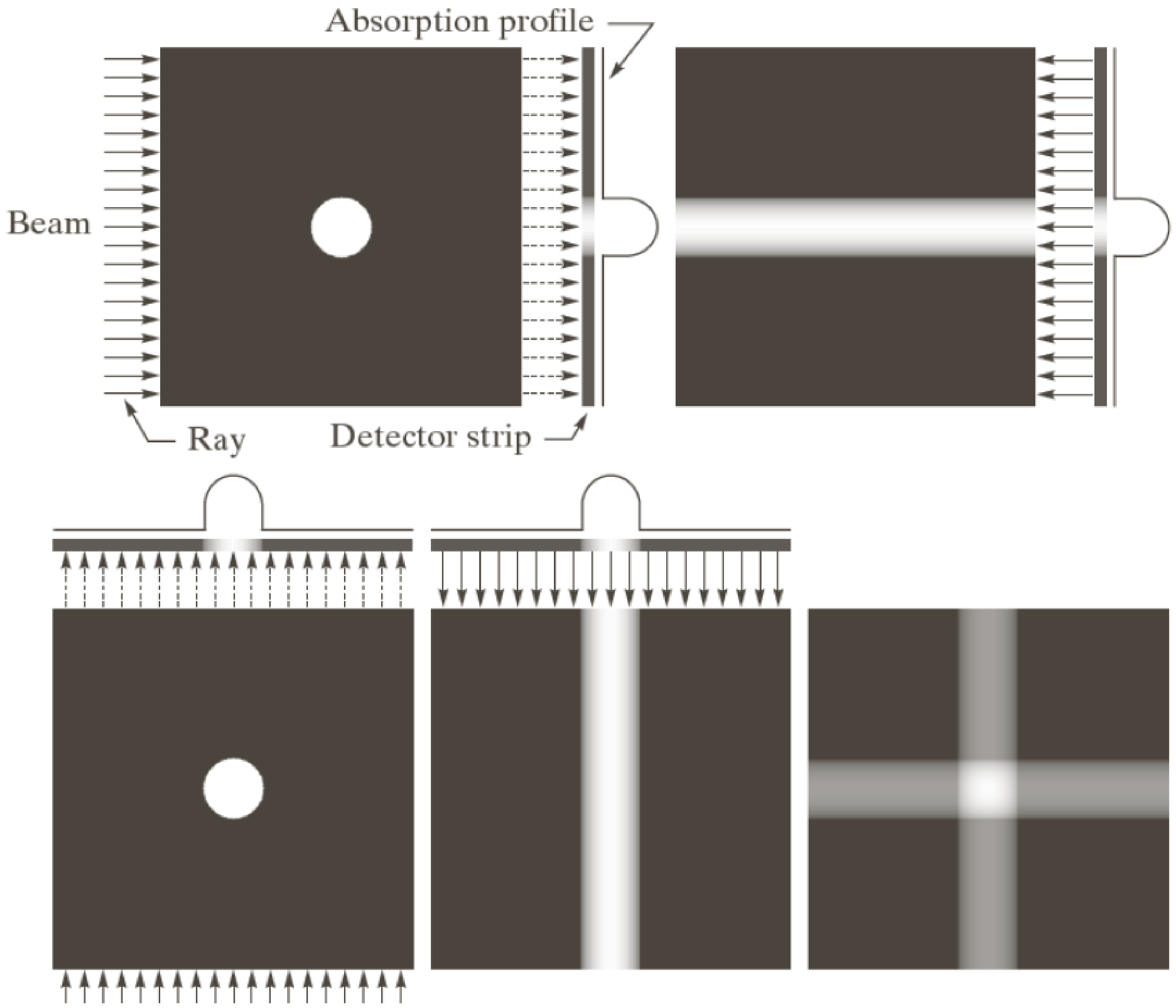
Fill all the pixels in a straight line along an x-ray with the number of photons absorbed in that line

Back Projection

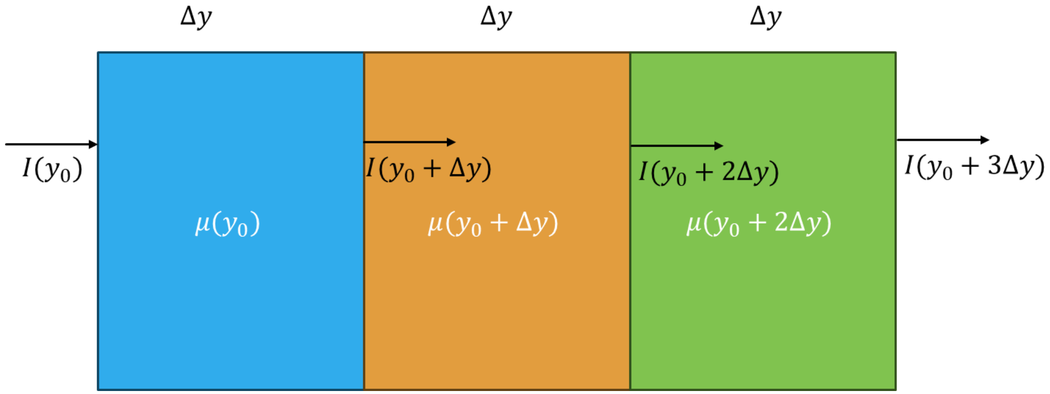
60	60	60
40	40	40
55	55	55

60
40
55

Back Projection



Radon Transform

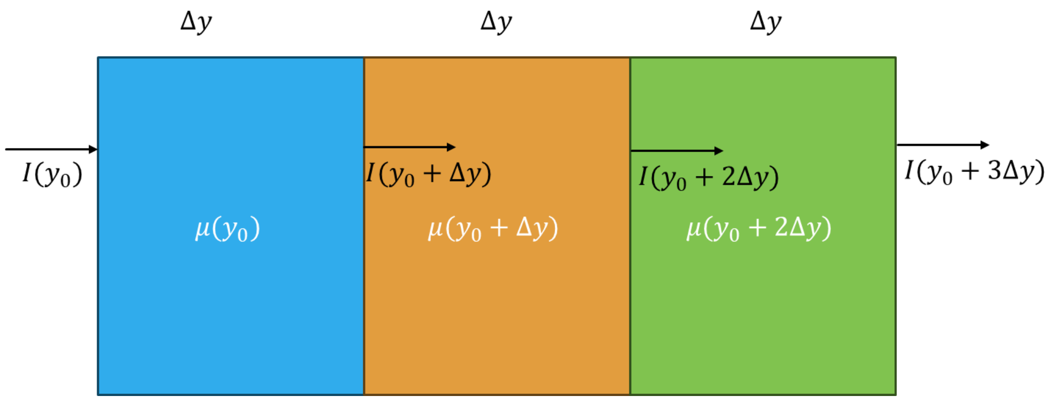


$$I_{out} = I(y_0)e^{-\int_{source}^{detector} \mu(x,y')dy'}$$

Line integral along the line $xcos\theta + ysin\theta = l$

$$g(\ell,\theta) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \mu(x,y)\delta(x\cos\theta + y\sin\theta - \ell)\, dx\, dy$$

Radon Transform



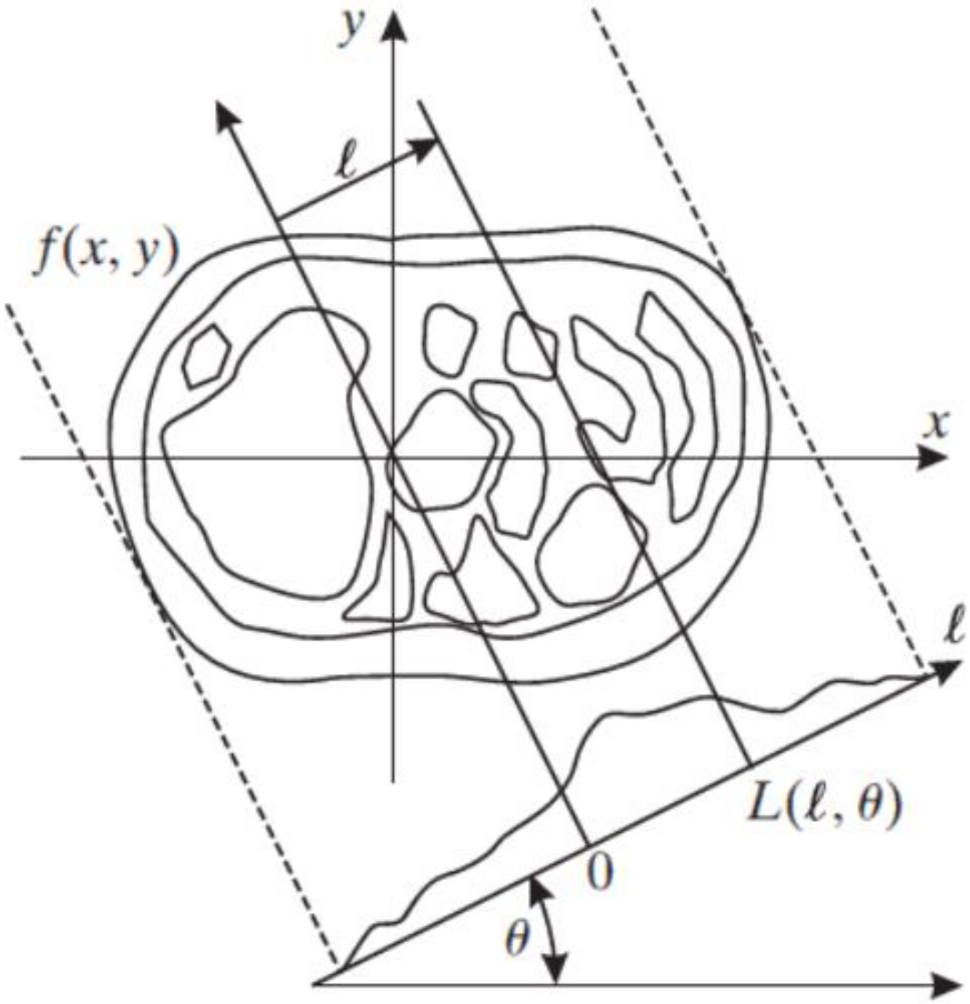
$$I_{out} = I(y_0)e^{-\int_{source}^{detector} \mu(x,y')dy'}$$

We want to get μ

$$g(\ell, \theta) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \mu(x, y)\delta(x\cos\theta + y\sin\theta - \ell)\, dx\, dy$$

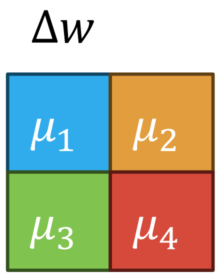
Projection

Parallel rays

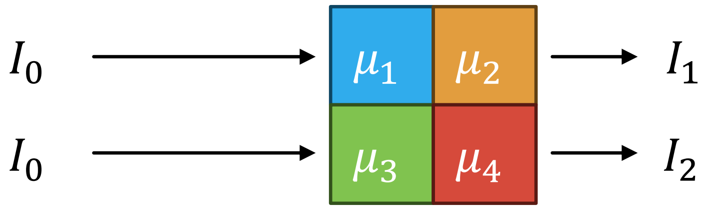


Reconstruction of Objects

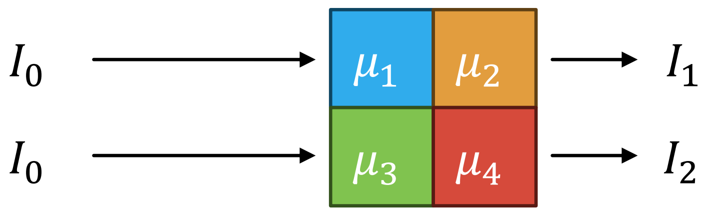
2D Objects



2D Objects



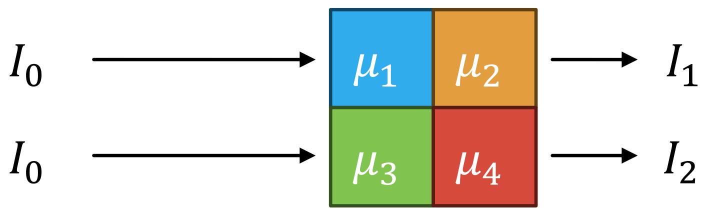
2D Objects



$$I_1 = I_0 e^{-(\mu_1 \Delta w + \mu_2 \Delta w)}$$

$$I_2 = I_0 e^{-(\mu_3 \Delta w + \mu_4 \Delta w)}$$

2D Objects

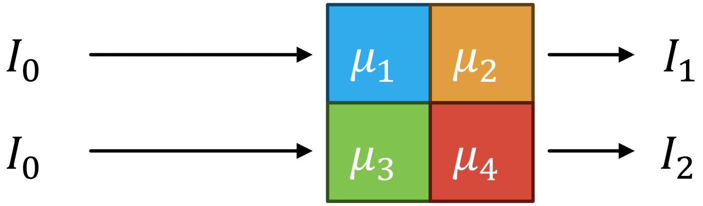


$$I_1 = I_0 e^{-(\mu_1 \Delta w + \mu_2 \Delta w)}$$

$$I_2 = I_0 e^{-(\mu_3 \Delta w + \mu_4 \Delta w)}$$

From this, can I find out the various components, the x-ray passing through?

2D Objects



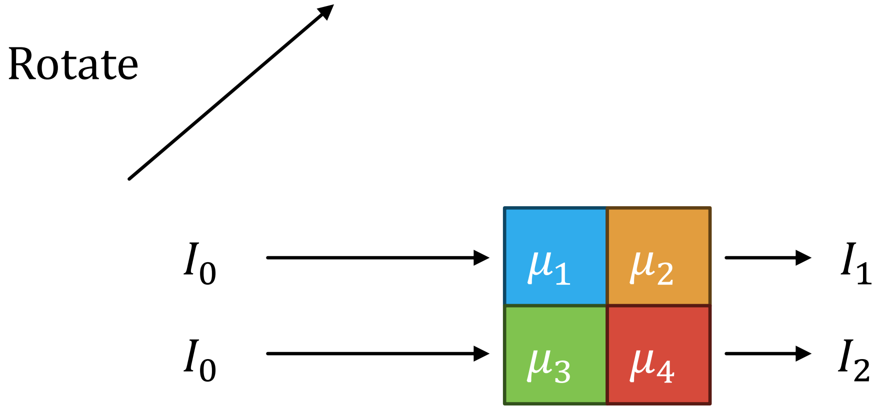
$$I_1 = I_0 e^{-(\mu_1 \Delta w + \mu_2 \Delta w)}$$

$$I_2 = I_0 e^{-(\mu_3 \Delta w + \mu_4 \Delta w)}$$

From this, can I find out the various components, the x-ray passing through?

No. Because I have two equations and four unknowns. So, infinite possibilities

2D Objects

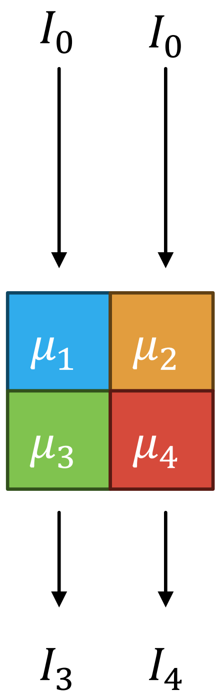


$$I_1 = I_0 e^{-(\mu_1 \Delta w + \mu_2 \Delta w)}$$

$$I_2 = I_0 e^{-(\mu_3 \Delta w + \mu_4 \Delta w)}$$

So, we take projections from another view

2D Objects



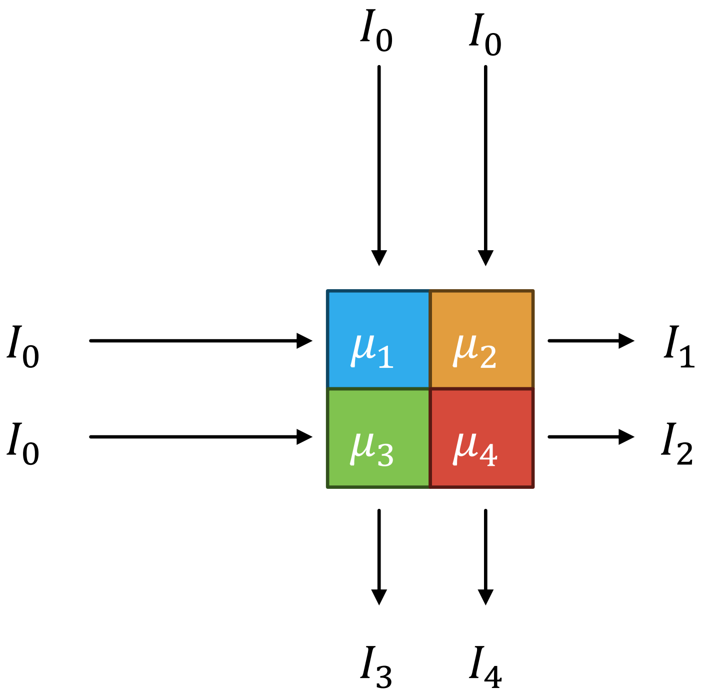
$$I_1 = I_0 e^{-(\mu_1 \Delta w + \mu_2 \Delta w)}$$

$$I_2 = I_0 e^{-(\mu_3 \Delta w + \mu_4 \Delta w)}$$

$$I_3 = I_0 e^{-(\mu_1 \Delta w + \mu_3 \Delta w)}$$

$$I_4 = I_0 e^{-(\mu_2 \Delta w + \mu_4 \Delta w)}$$

2D Objects



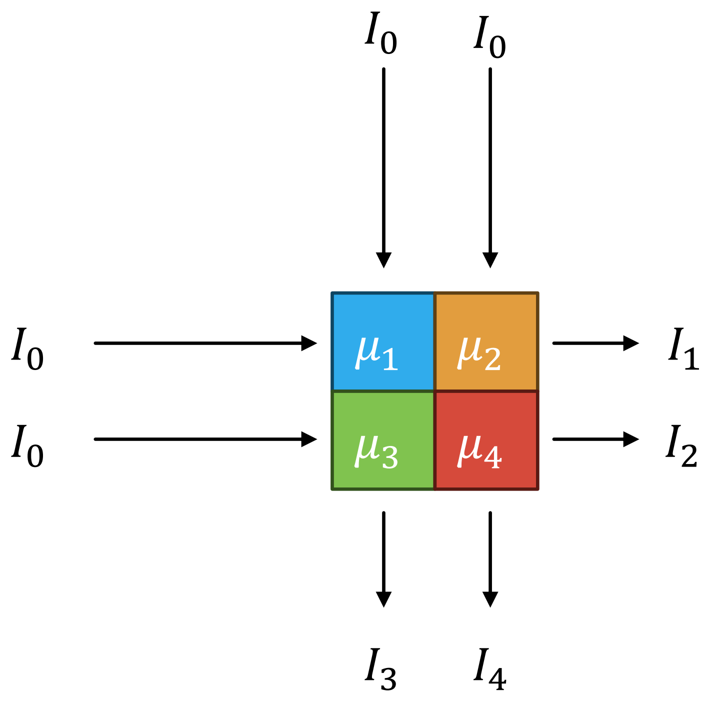
$$I_1 = I_0 e^{-(\mu_1 \Delta w + \mu_2 \Delta w)}$$

$$I_2 = I_0 e^{-(\mu_3 \Delta w + \mu_4 \Delta w)}$$

$$I_3 = I_0 e^{-(\mu_1 \Delta w + \mu_3 \Delta w)}$$

$$I_4 = I_0 e^{-(\mu_2 \Delta w + \mu_4 \Delta w)}$$

2D Objects



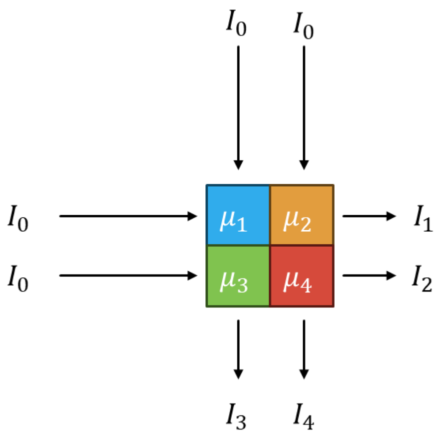
$$-\mu_1 \Delta w - \mu_2 \Delta w = \ln \frac{I_1}{I_0}$$

$$-\mu_3 \Delta w - \mu_4 \Delta w = \ln \frac{I_2}{I_0}$$

$$-\mu_1 \Delta w - \mu_3 \Delta w = \ln \frac{I_3}{I_0}$$

$$-\mu_2 \Delta w - \mu_4 \Delta w = \ln \frac{I_4}{I_0}$$

2D Objects



We can solve using matrix inversion. But too complex for larger objects

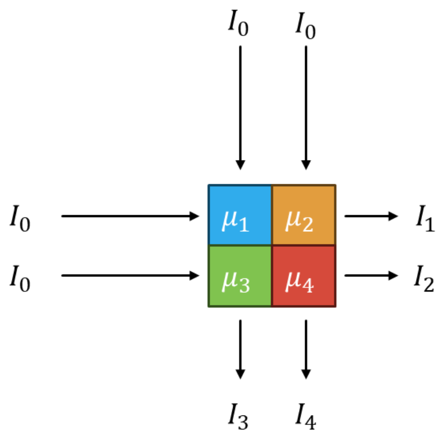
$$-\mu_1 \Delta w - \mu_2 \Delta w = \ln \frac{I_1}{I_0}$$

$$-\mu_3 \Delta w - \mu_4 \Delta w = \ln \frac{I_2}{I_0}$$

$$-\mu_1 \Delta w - \mu_3 \Delta w = \ln \frac{I_3}{I_0}$$

$$-\mu_2 \Delta w - \mu_4 \Delta w = \ln \frac{I_4}{I_0}$$

2D Objects



$$-\mu_1\Delta w - \mu_2\Delta w = \ln\frac{I_1}{I_0}$$

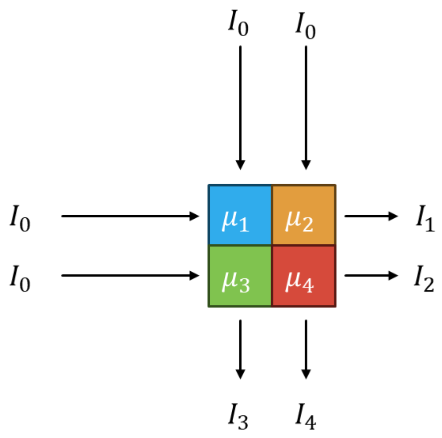
$$-\mu_3\Delta w - \mu_4\Delta w = \ln\frac{I_2}{I_0}$$

$$-\mu_1\Delta w - \mu_3\Delta w = \ln\frac{I_3}{I_0}$$

$$-\mu_2\Delta w - \mu_4\Delta w = \ln\frac{I_4}{I_0}$$

In general, we can solve for and $n \times n$ matrix if we have n^2 equations

2D Objects



$$-\mu_1\Delta w - \mu_2\Delta w = \ln\frac{I_1}{I_0}$$

$$-\mu_3\Delta w - \mu_4\Delta w = \ln\frac{I_2}{I_0}$$

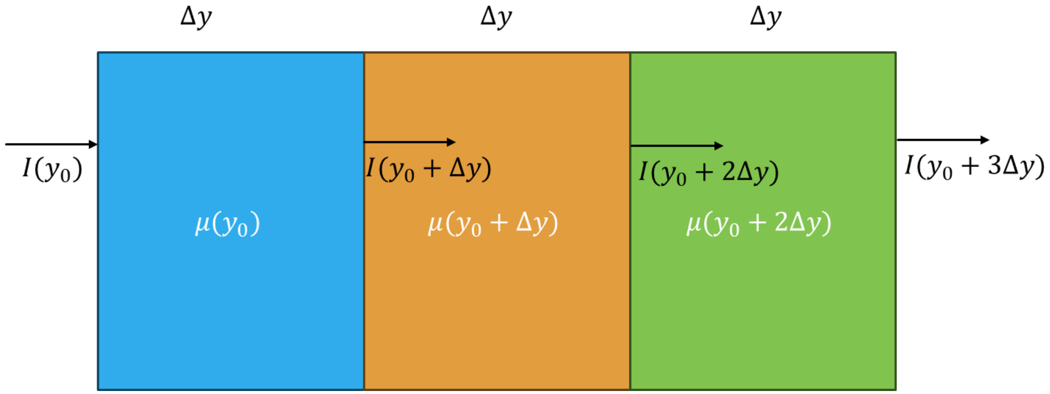
$$-\mu_1\Delta w - \mu_3\Delta w = \ln\frac{I_3}{I_0}$$

$$-\mu_2\Delta w - \mu_4\Delta w = \ln\frac{I_4}{I_0}$$

If I can find out the value of μ_is, I can understand the composition of the object

Computationally not efficient

Radon Transform



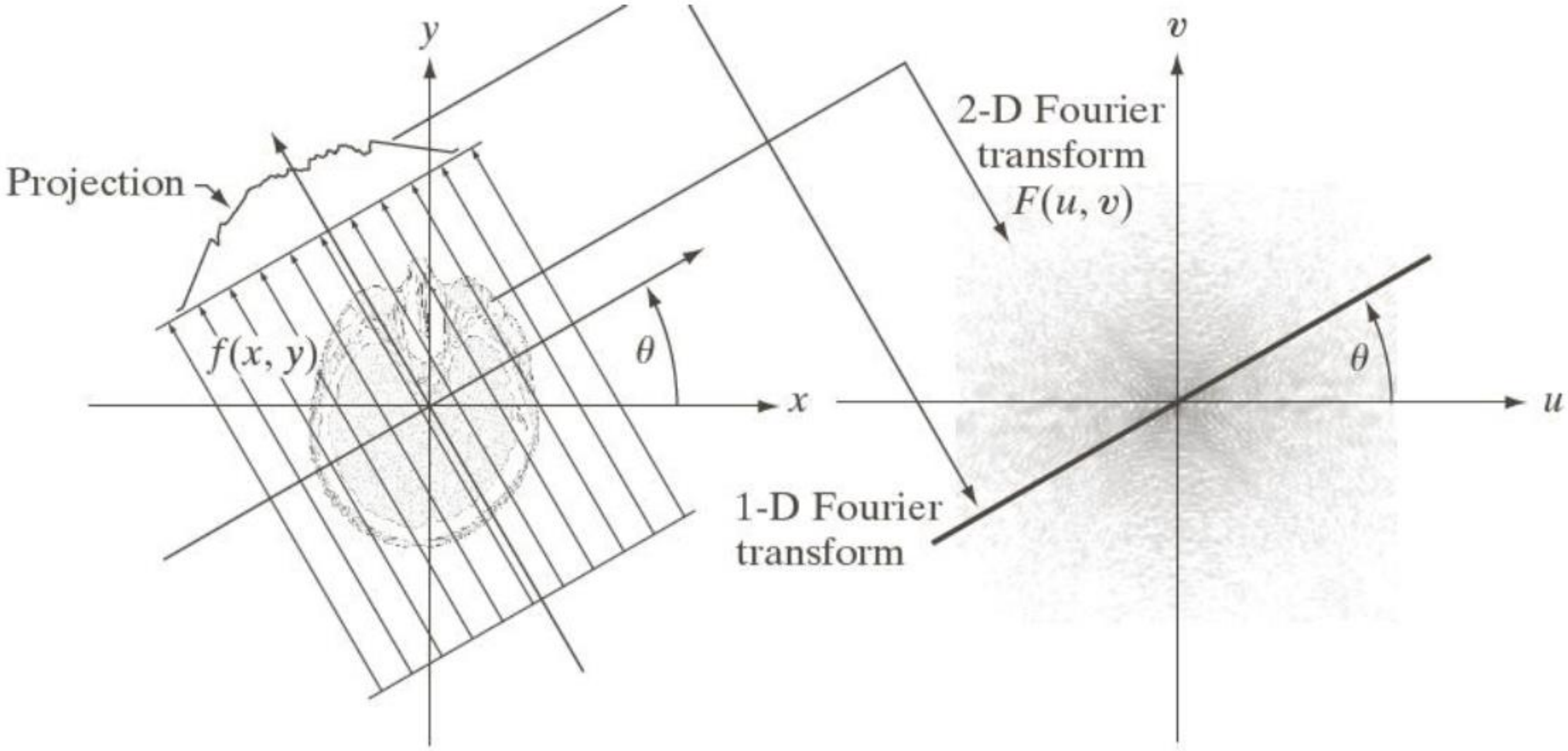
$$I_{out} = I(y_0)e^{-\int_{source}^{detector} \mu(x,y')dy'}$$

We want to get μ

But from one projection, we can't solve through inverse transform since there would be infinite possibilities

$$g(\ell,\theta) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \mu(x,y)\delta(x\cos\theta + y\sin\theta - \ell)\,dx\,dy$$

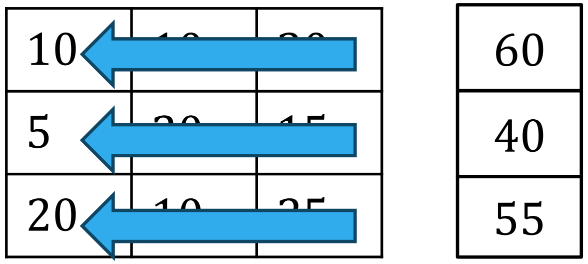
Fourier Slice Theorem



Computationally-efficient Reconstruction: Analytical Reconstruction

Back Projection

Photons absorbed along the straight line of the x-ray



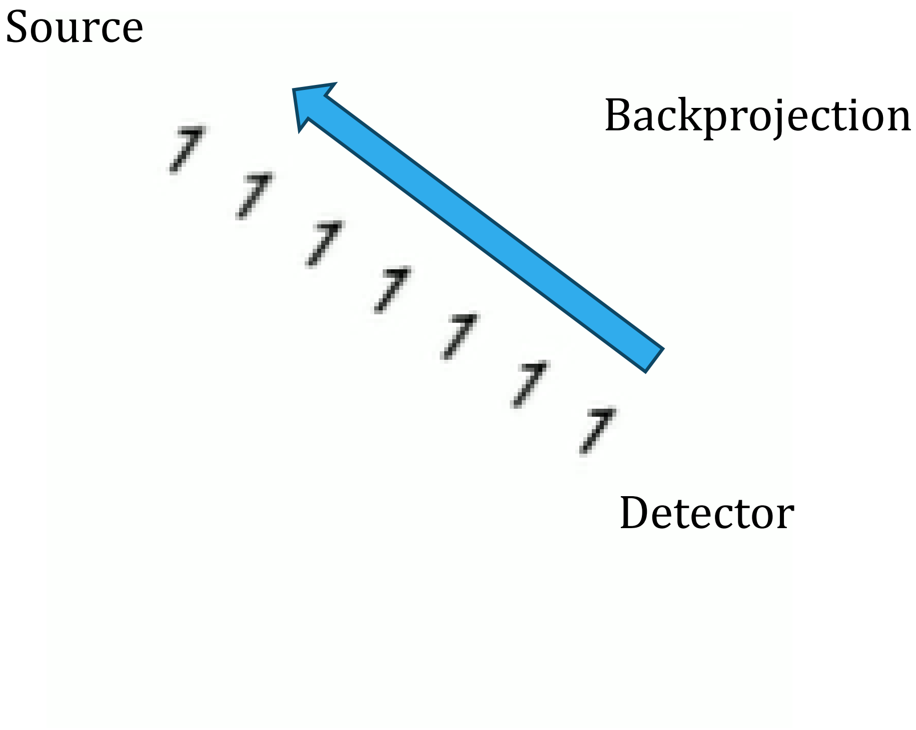
Fill all the pixels in a straight line along an x-ray with the number of photons absorbed in that line

Back Projection

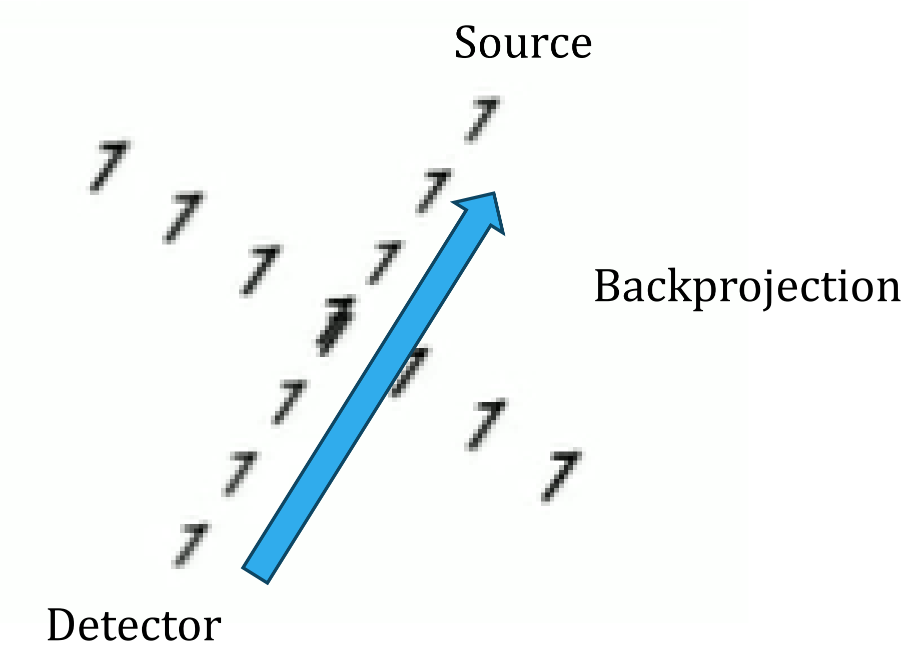
60	60	60
40	40	40
55	55	55

60
40
55

Backprojection Reconstruction



Backprojection Reconstruction



Backprojection Reconstruction

Backprojection Reconstruction

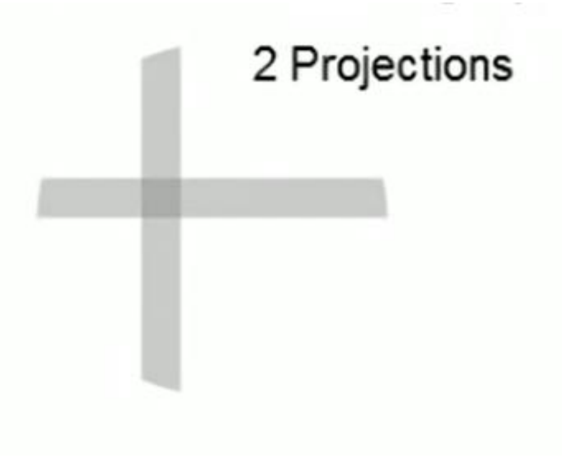
Backprojection

$$b_\theta(x, y) = g(x\cos\theta + y\sin\theta, \theta)$$

Backprojection summation image

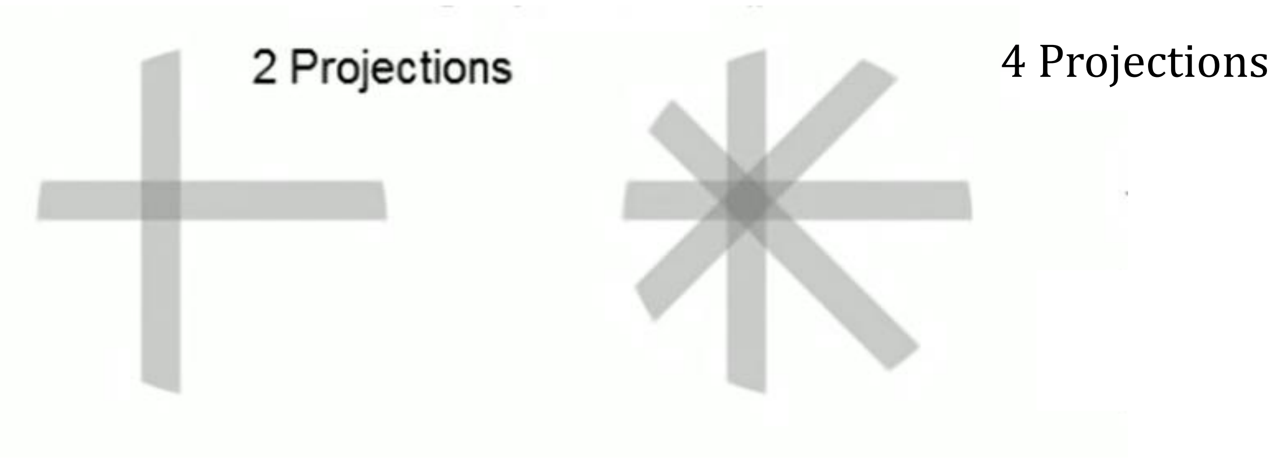
$$f_b(x, y) = \int_0^\pi b_\theta(x, y)\, d\theta$$

Backprojection Reconstruction

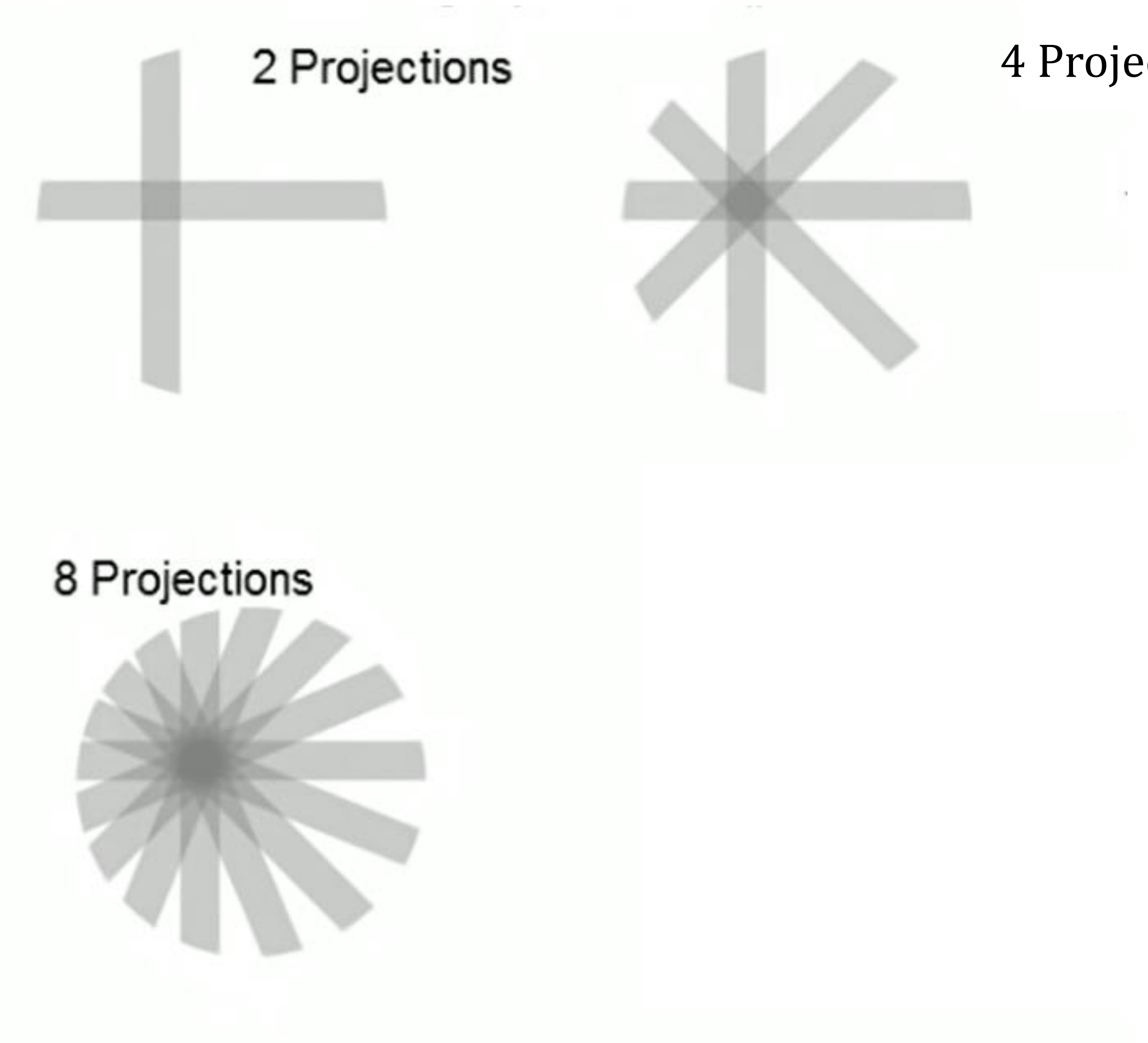


of a point

Backprojection Reconstruction

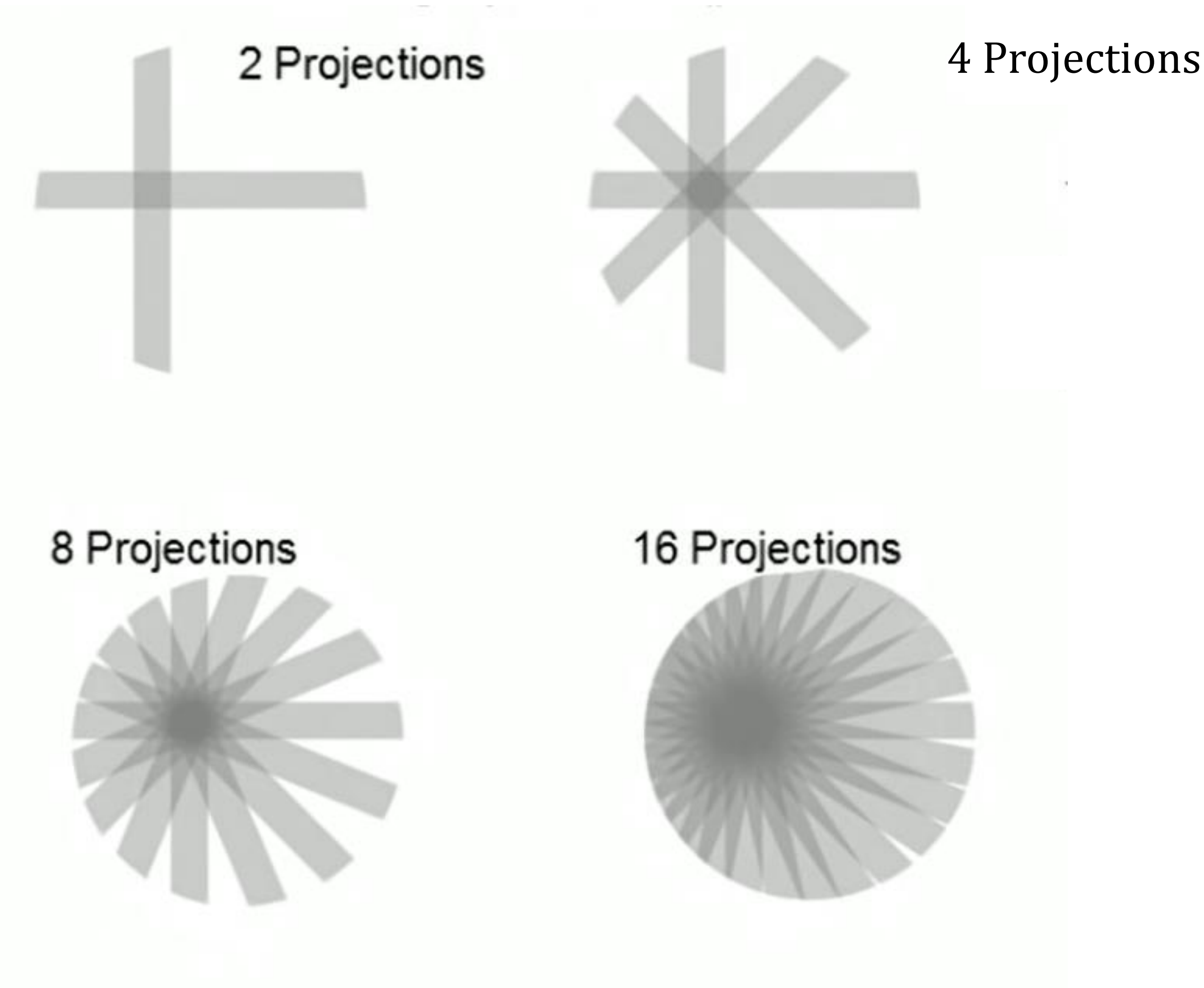


Backprojection Reconstruction



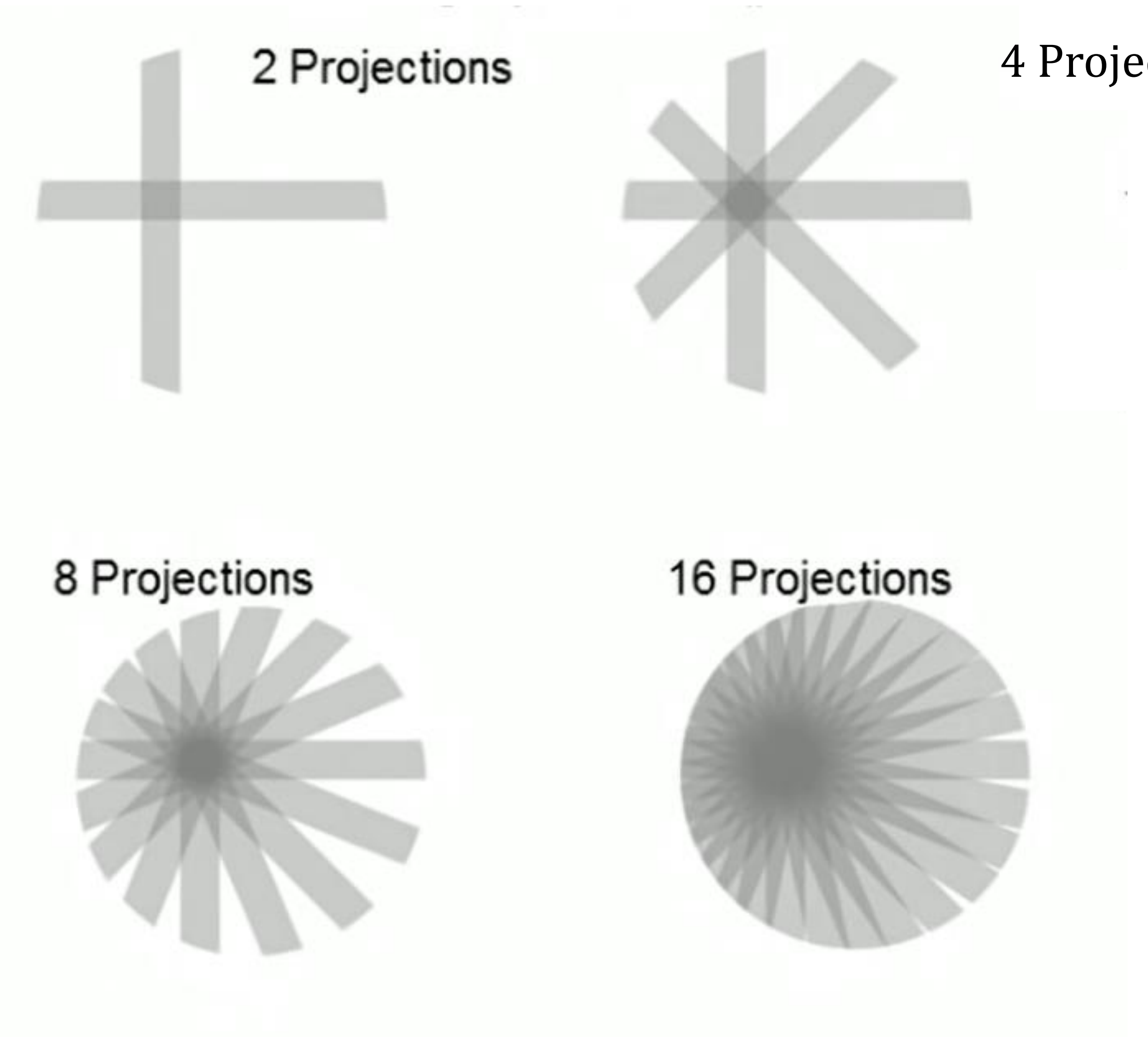
4 Projections

Backprojection Reconstruction



Backprojection Reconstruction

4 Projections



Does not preserve the shape

Blurring effect due to under-represented high frequencies

Backprojection Reconstruction

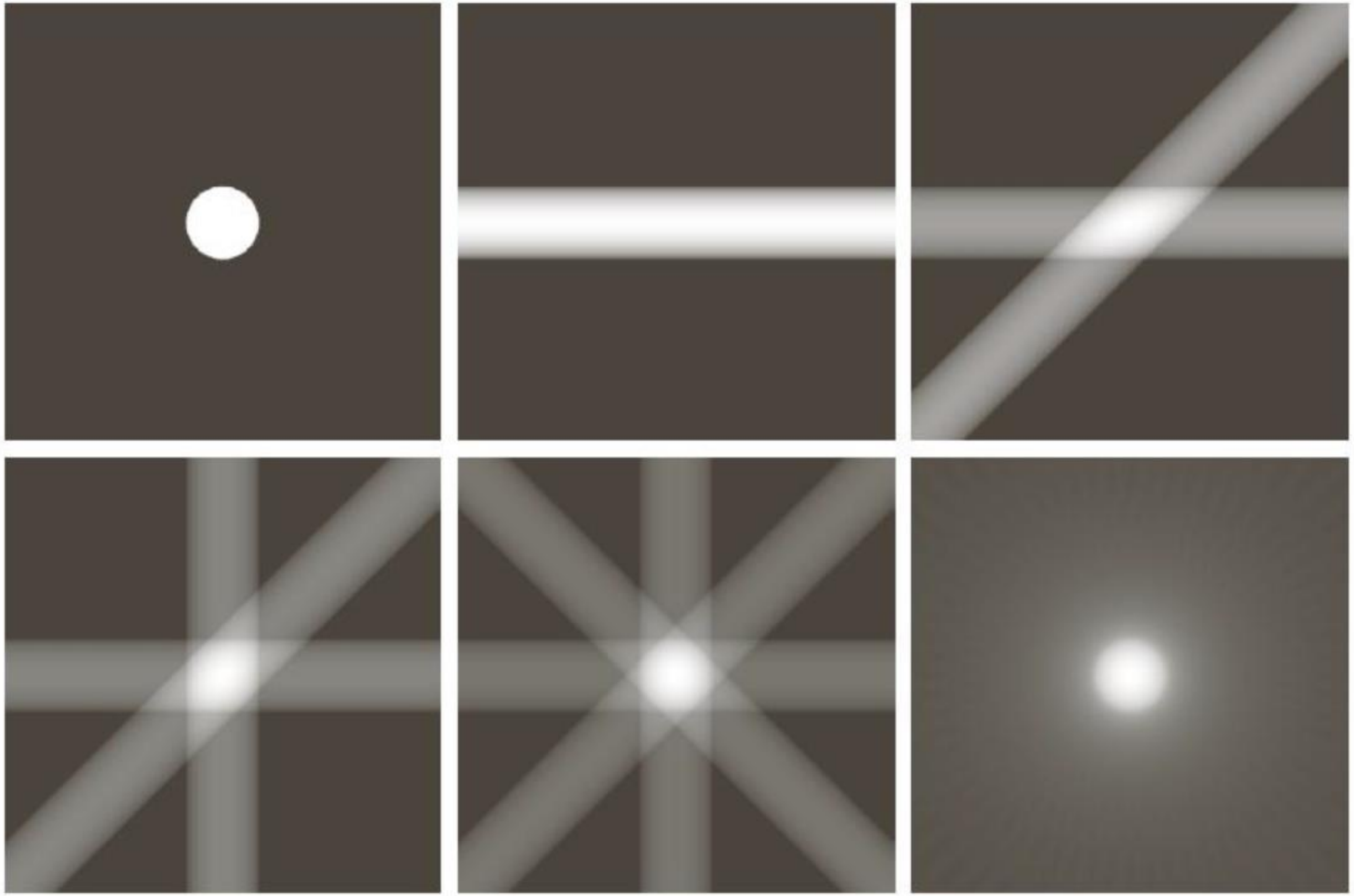


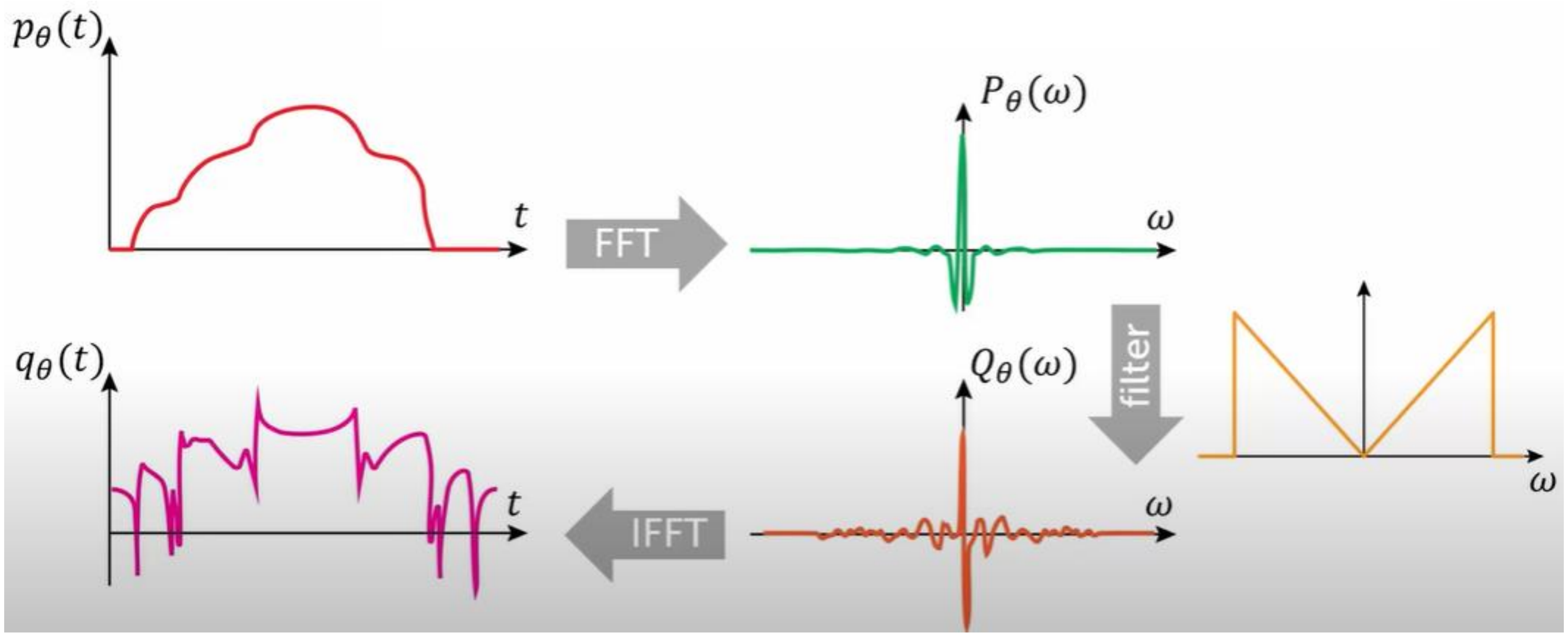
FIGURE 5.33 (a) Same as Fig. 5.32(a). (b)–(e) Reconstruction using 1, 2, 3, and 4 backprojections 45° apart. (f) Reconstruction with 32 backprojections 5.625° apart (note the blurring).

Filtered Backprojection

- Filter the low frequencies
    - High pass filter

- Detected signal -> FFT -> HPF -> IFFT -> Reconstruction

Filtered Backprojection



https://www.youtube.com/watch?v=pZ7JlXagT0w

CT Scanner

CT Scanner

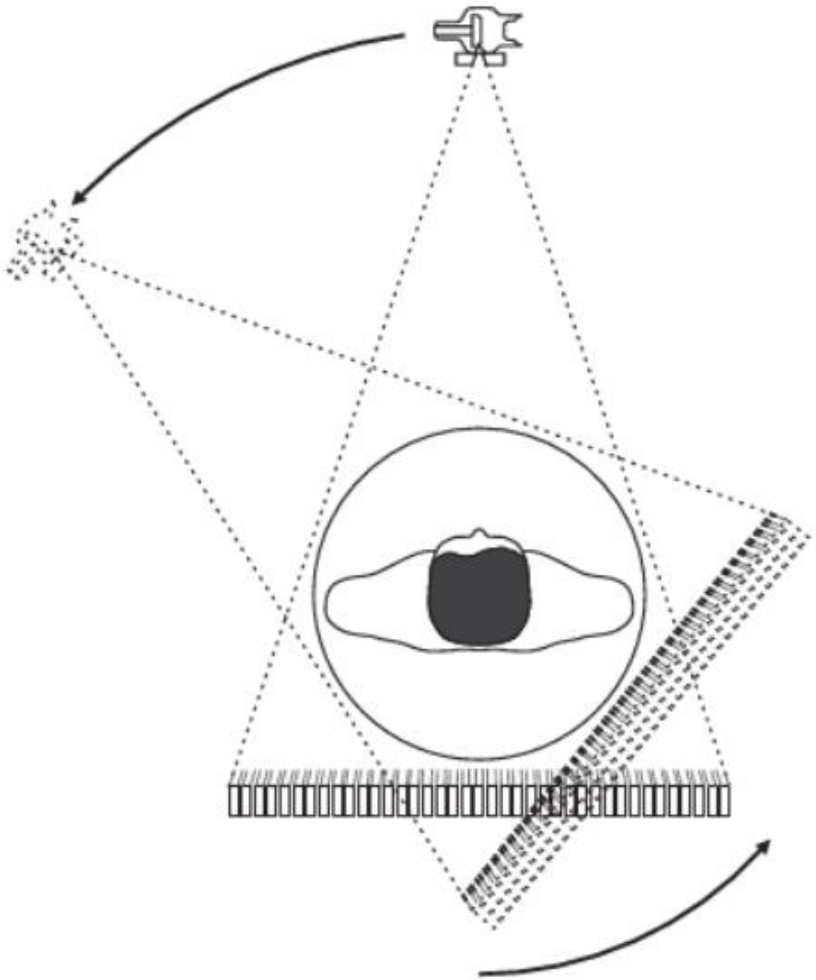


Figure 6.4
The geometry of a third-generation (3G) CT scanner.

CT Slices

Beam Type

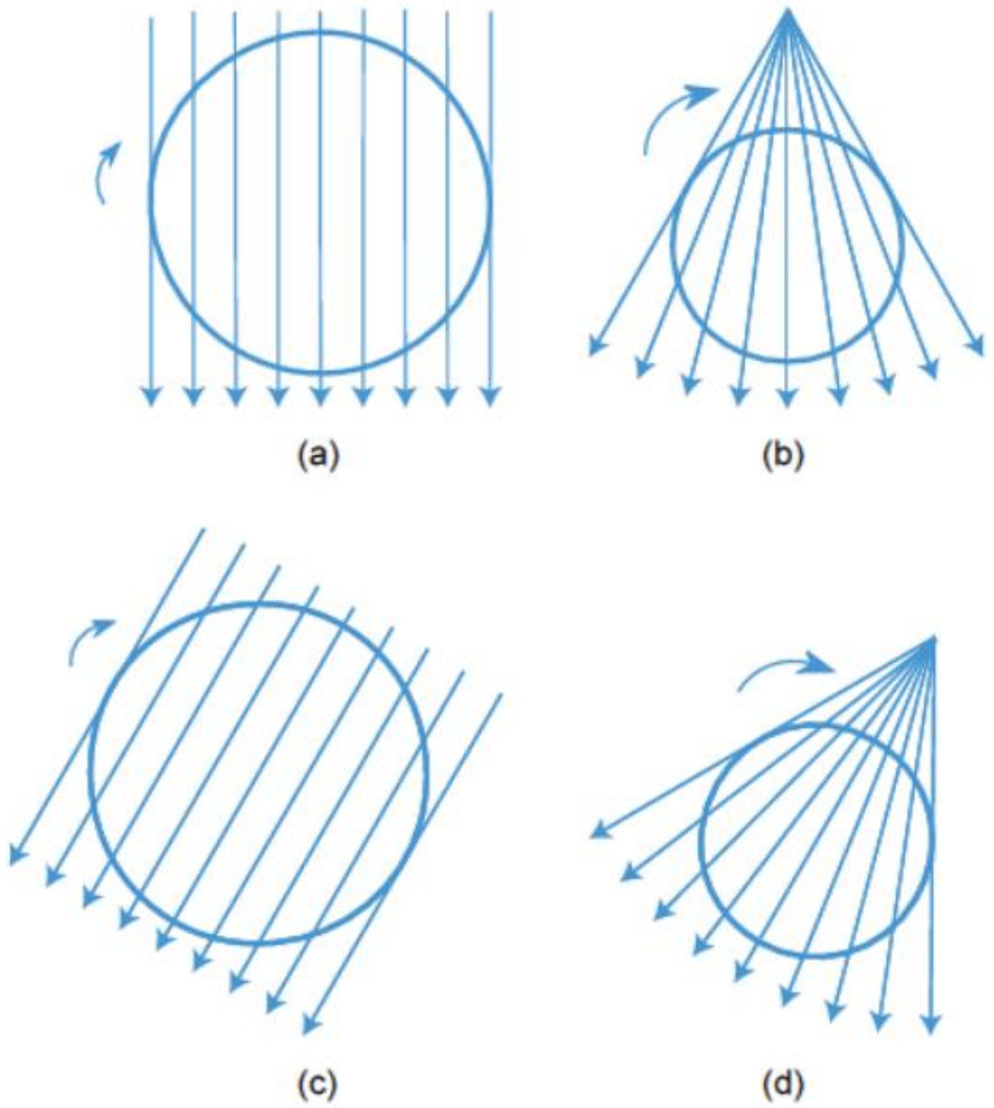
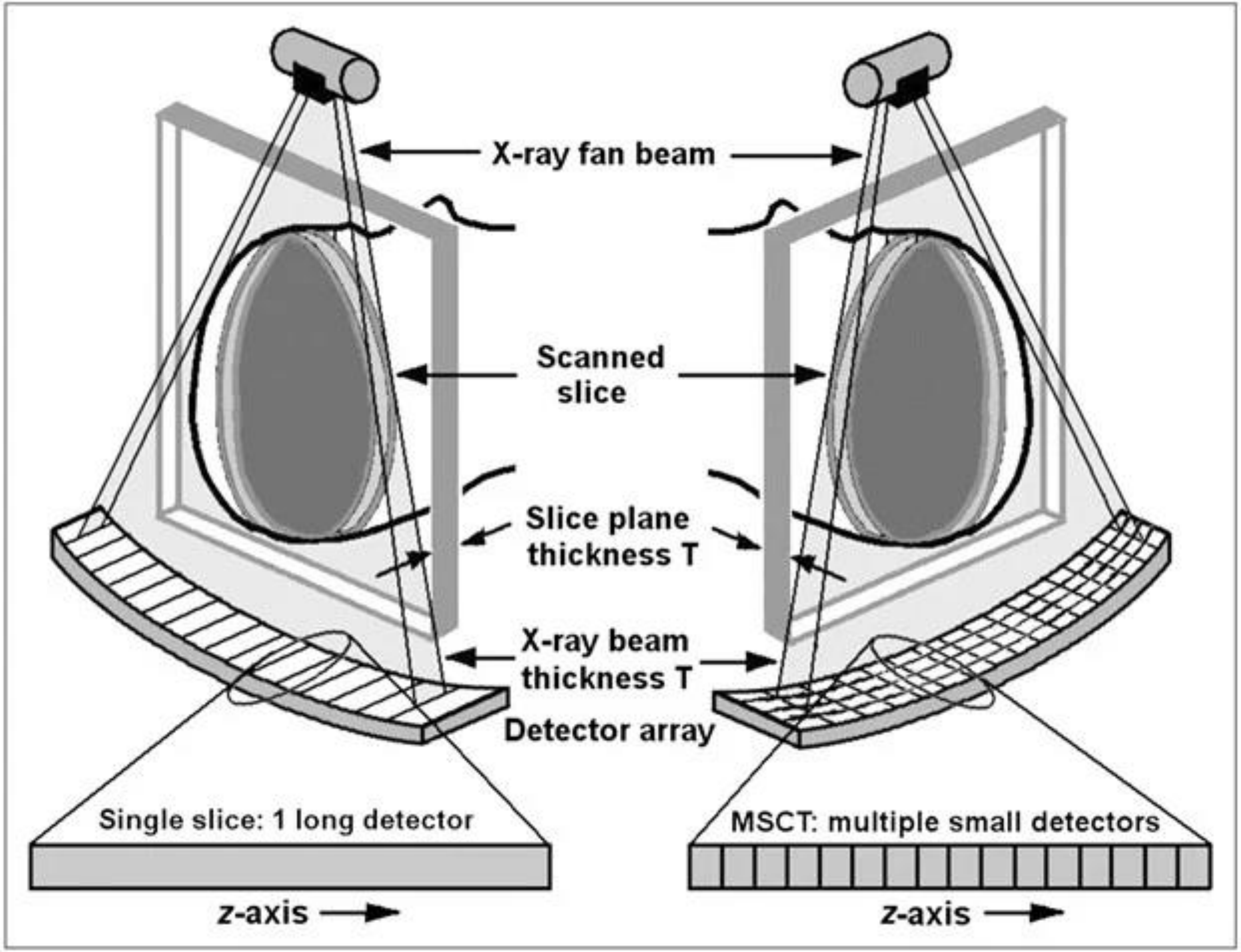


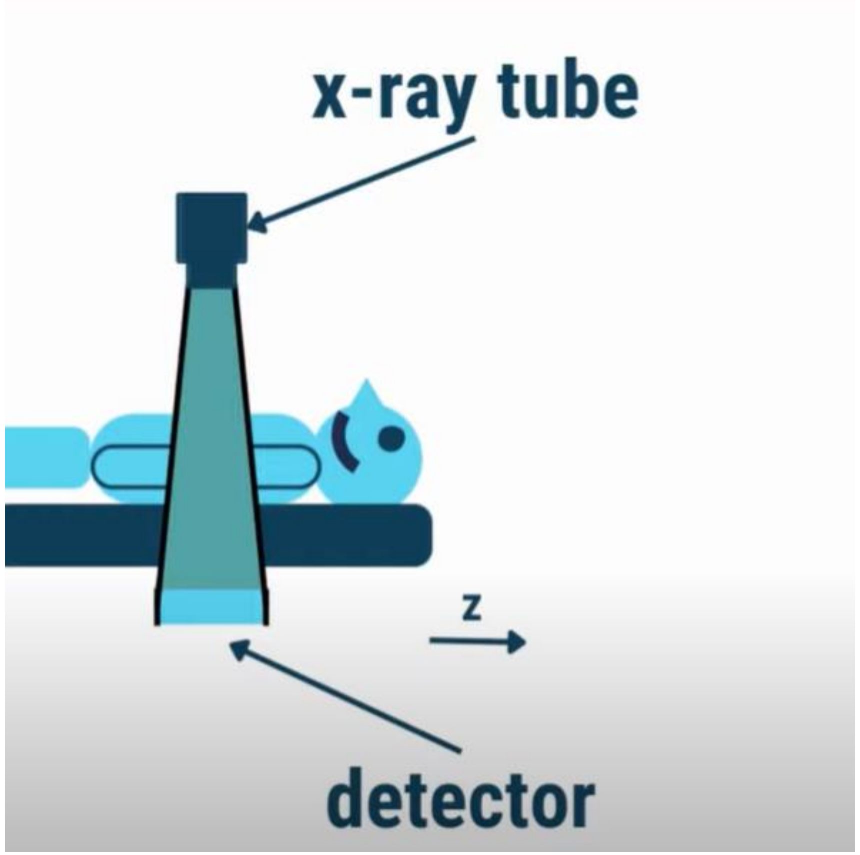
Figure 3.2 Basic scanning procedure in CT. A set of lines is scanned covering the entire field of view: **(a)** parallel-beam geometry and **(b)** fan-beam geometry. This process is repeated for a large number of angles (**c** and **d**).

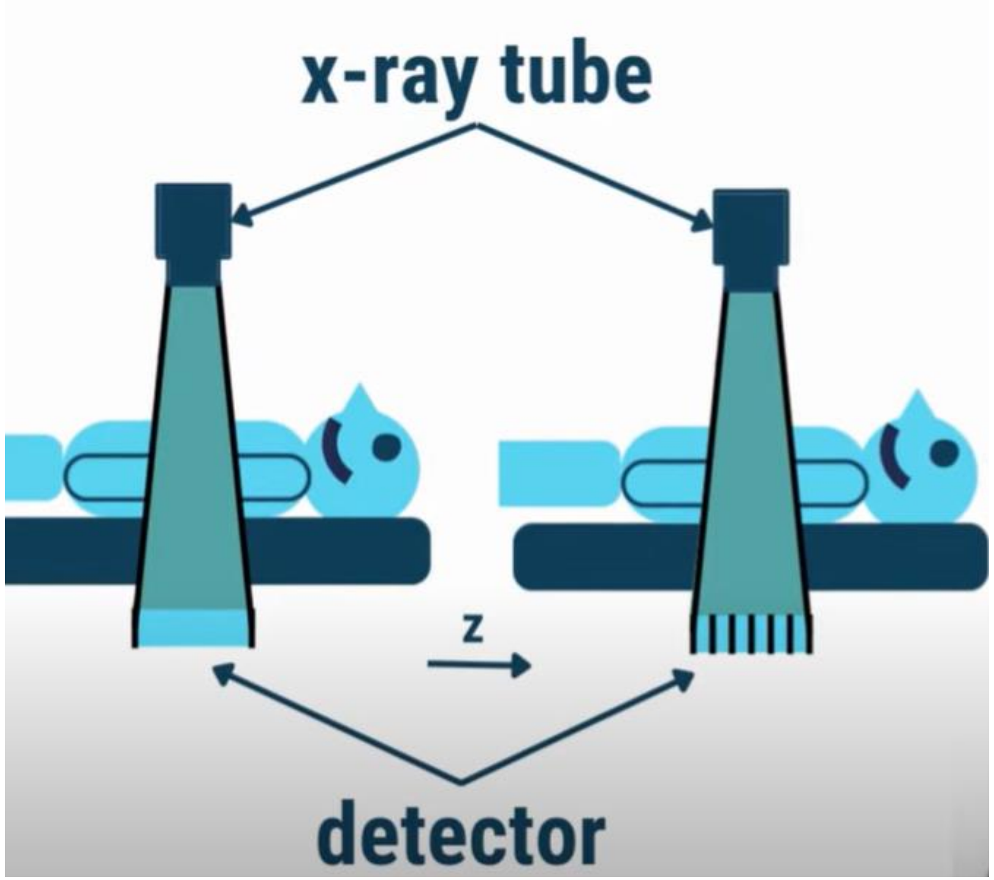
CT Slices



https://www.neurologica.com/blog/slice-of-ct-scanners

Single Slice vs Multi Slice CT





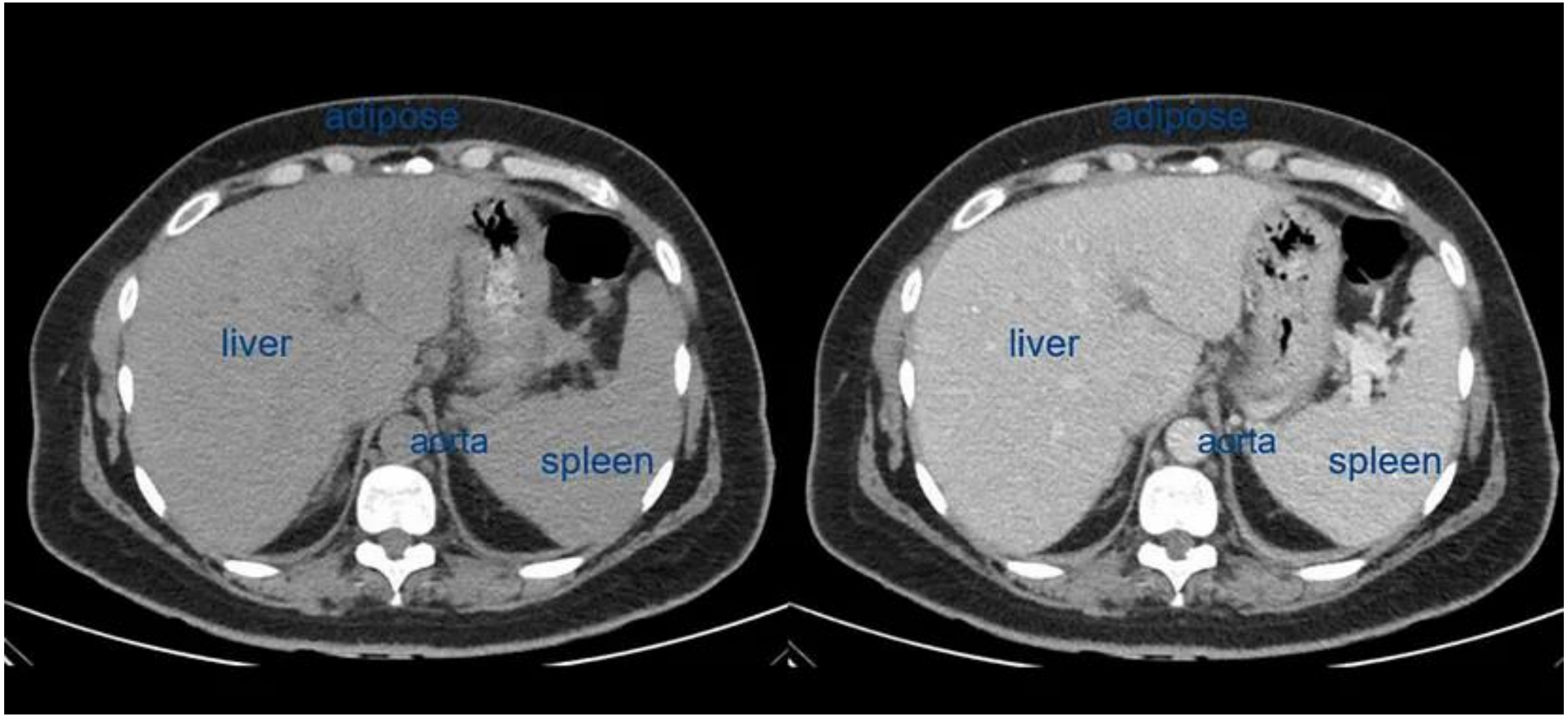
https://www.youtube.com/watch?v=Dz418O3KpPs

CT Slices

Generations of CT

https://howradiologyworks.com/ctgenerations/

Contrast Enhanced CT



Contrast agent: Iodine or Barium (heavy metal)

https://towardsdatascience.com/the-basics-of-contrast-enhanced-ct-eba2ab7f3c78

Use of CT

- A CT scan is a diagnostic imaging: images of the inside of the body
- Detailed images of any part of the body: bones, muscles, organs and blood vessels
- CT scans can also be used for fluid or tissue biopsies, or as part of preparation for surgery or treatment
- CT scans are frequently done with and without contrast agent to improve the radiologist’s ability to find any abnormalities

Magnetic Resonance Imaging

- Based on the principle of nuclear magnetic resonance (NMR)
  - Discovered in 1945
  - First NMR image: Paul C. Lauterbur (1973)
  - Mathematical theory of fast scanning and reconstruction: Peter Mansfield (1974)

- Non-ionizing

- Suitable for soft tissue and functional imaging

Spin of Elementary Particles

- An intrinsic property
- Actually does not spin around their axes
  - But shows properties which is equivalent to that of spinning charge
- Elementary particles have spin
  - Quarks, electrons
- Due to the spin property, elementary particles have spin angular momentum

Spin of Elementary Particles

- Spin of the nucleus
  - Vector sum of spins of constituent proton and neutron

- Inside nucleus
  - Proton-proton pair cancels each other's spin
  - Neutron-neutron pair cancels each other's spin

- If there is any unpaired proton or neutron
  - Contributes to the spin of the nucleus
    - Vector sum of spins of constituent unpaired proton and neutron

Spin of Nucleus

- If there is any unpaired proton or neutron
  - Nucleus will have some net spin and net angular momentum
- Even proton, even neutron
  - Spin=0, spin angular momentum=0
- Odd proton, even neutron (or opposite)
  - Spin=non zero, spin angular momentum: non-zero
  - Due to the unpaired proton or neutron (whichever is odd in number)
- Odd proton, odd neutron (or opposite)
  - Spin=non zero, spin angular momentum: non-zero
  - Due to the unpaired protons and neutrons

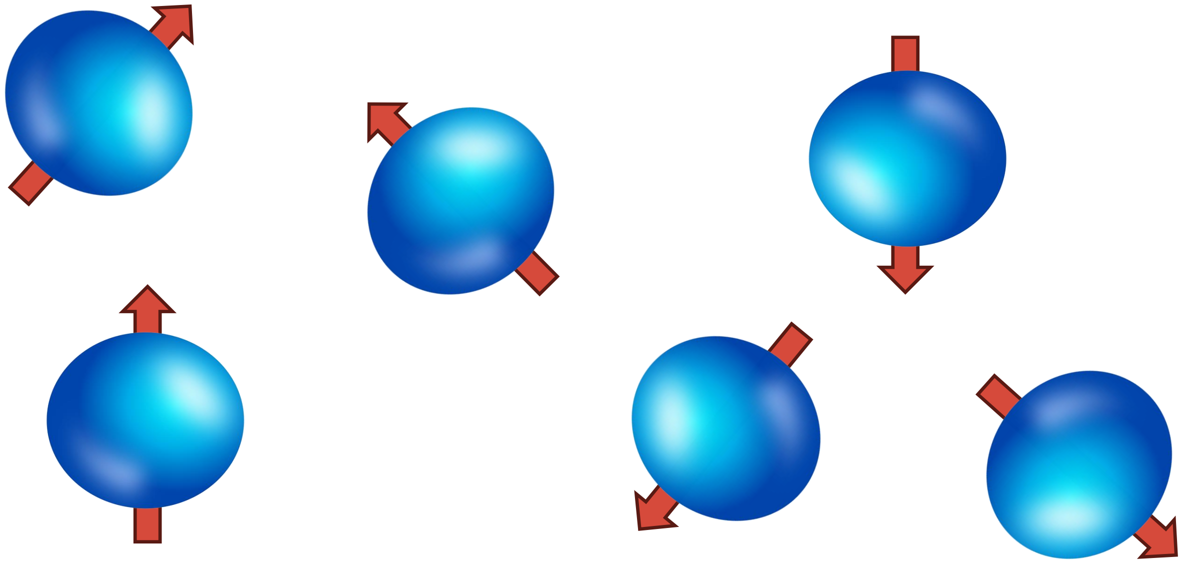
Spin of Nucleus

Nucleus	Spin	$\frac{\gamma}{2\pi}$ (MHz/T)
$^{1}_{1}H$	$\frac{1}{2}$	42.57
$^{2}_{1}H$	1	6.54
$^{12}_{6}C$	0	
$^{13}_{6}C$	$\frac{1}{2}$	10.71
$^{14}_{7}N$	1	3.08
$^{15}_{7}N$	$\frac{1}{2}$	−4.31
$^{16}_{8}O$	0	
$^{17}_{8}O$	$\frac{5}{2}$	−5.77
$^{31}_{15}P$	$\frac{1}{2}$	17.23
$^{33}_{16}S$	$\frac{3}{2}$	3.27
$^{43}_{21}Ca$	$\frac{7}{2}$	−2.86

Effect of External Magnetic Field

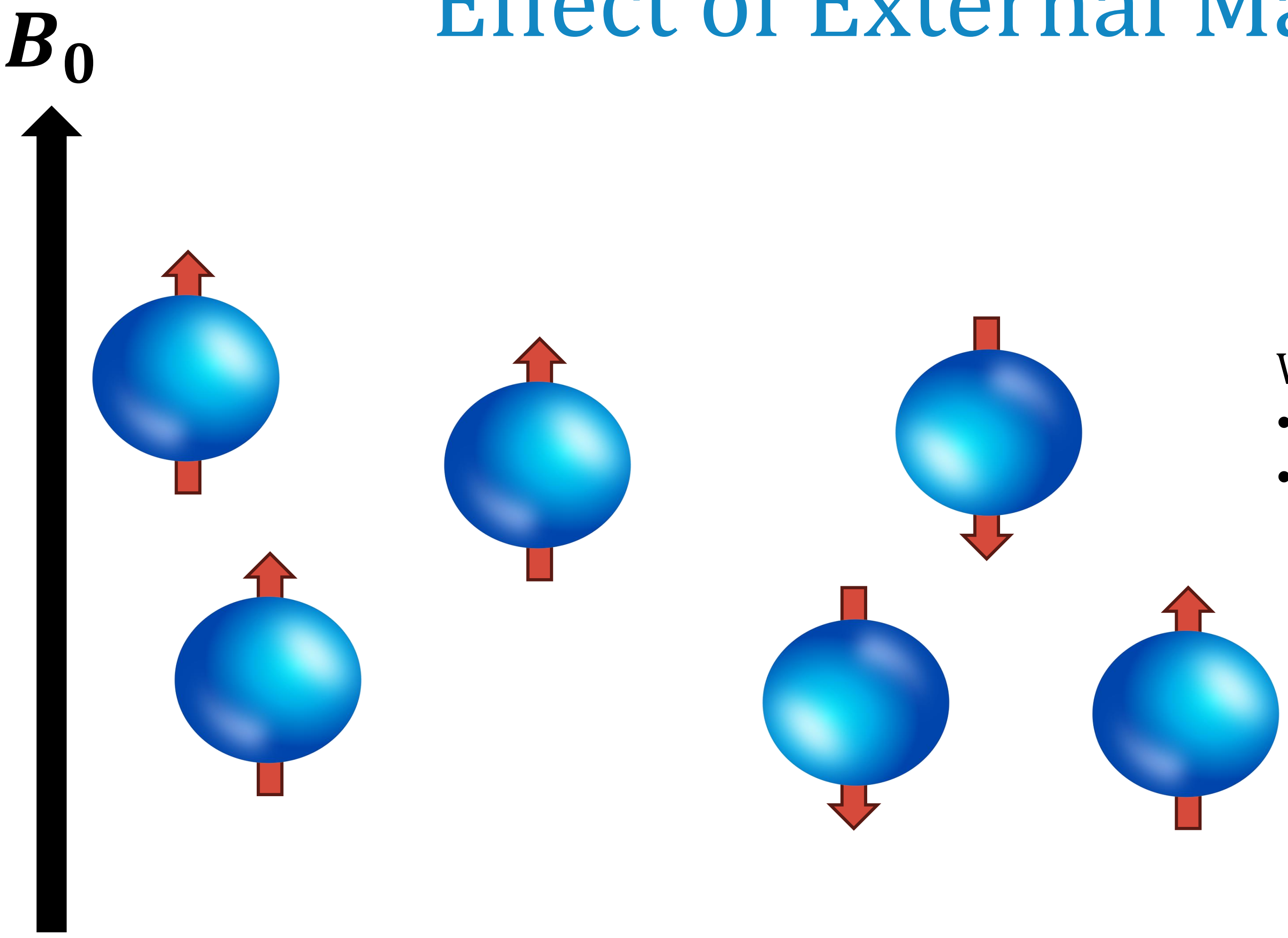
A nucleus may act like a magnet

Effect of External Magnetic Field



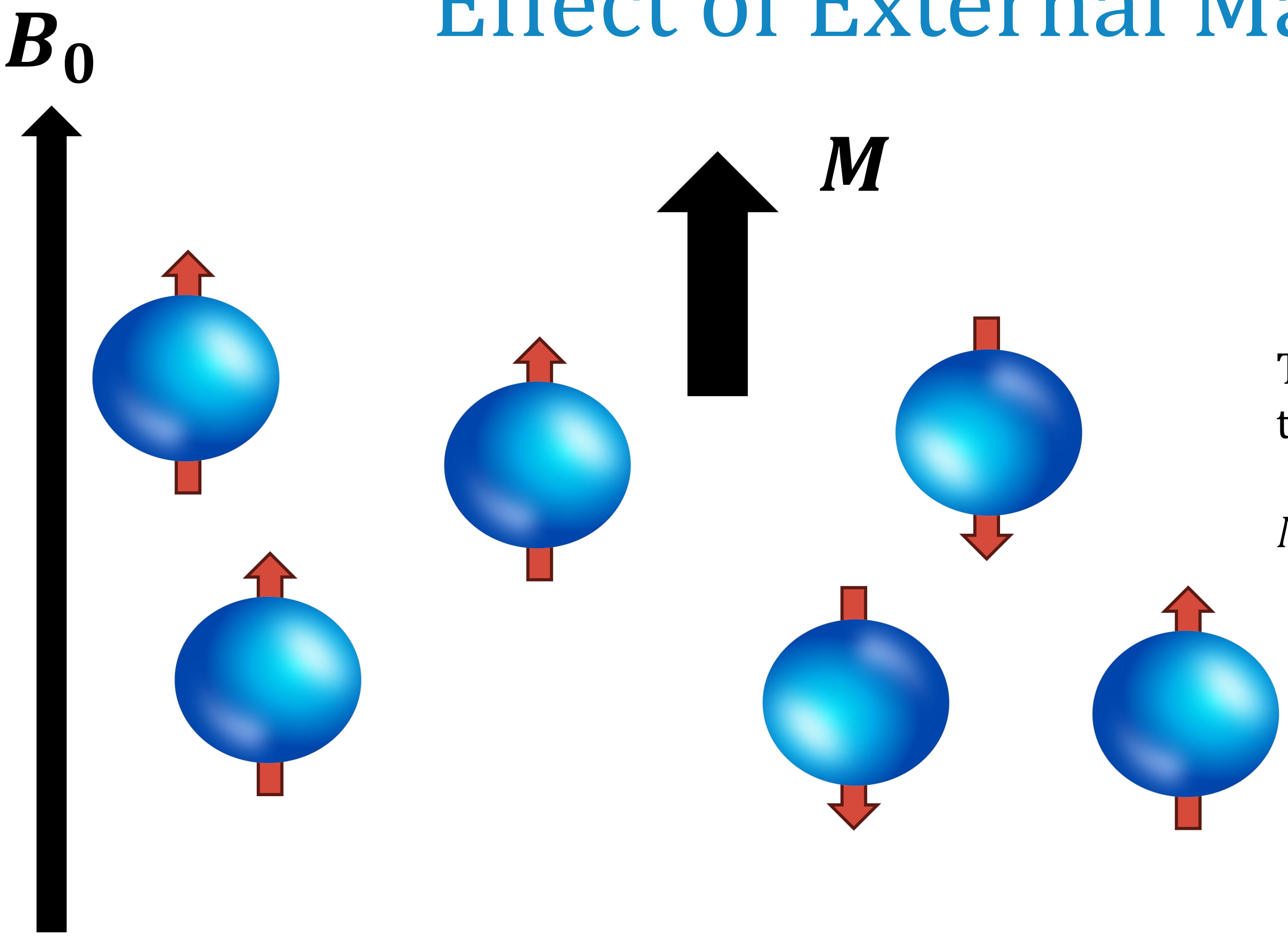
Usually, they are randomly oriented, cancelling each other's spins

Effect of External Magnetic Field



When an external magnetic field is applied
- Most nuclei align towards the field (up)
- Some (with higher energy) aligns opposite to the field

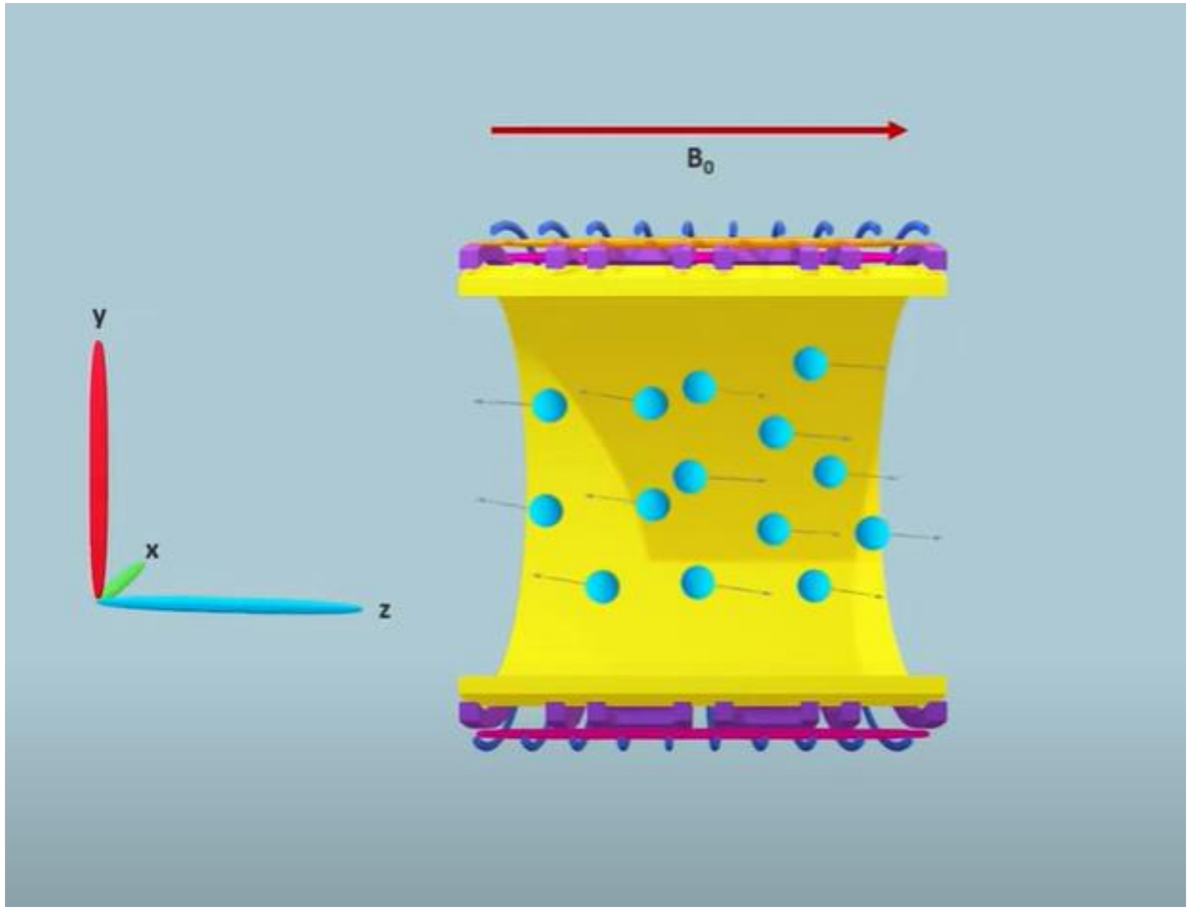
Effect of External Magnetic Field



There will be a net magnetization vector M towards B_0

M depends on number of spins (in a voxel)

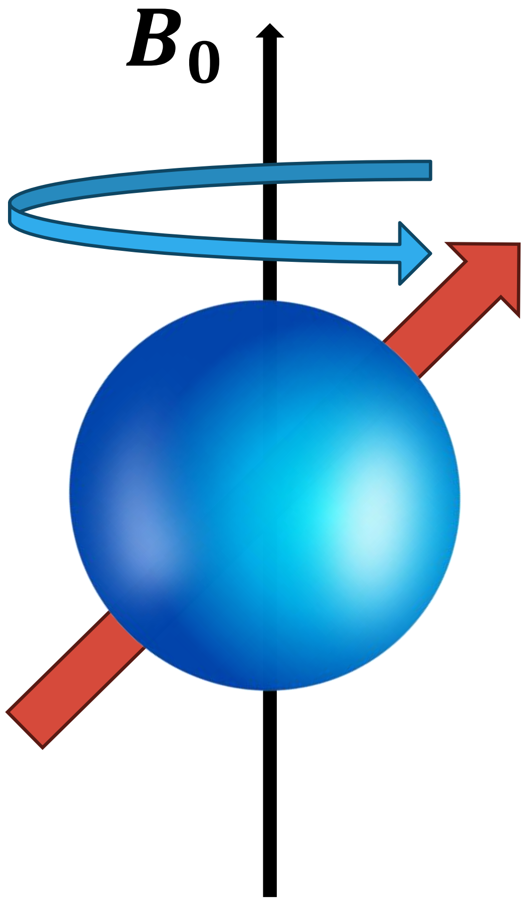
Effect of External Magnetic Field



There will be a net magnetization vector M towards B_0

https://www.youtube.com/watch?v=gtn0lotFgUY

Effect of External Magnetic Field



The nuclei will spin wrt B_0 axis at an angle θ

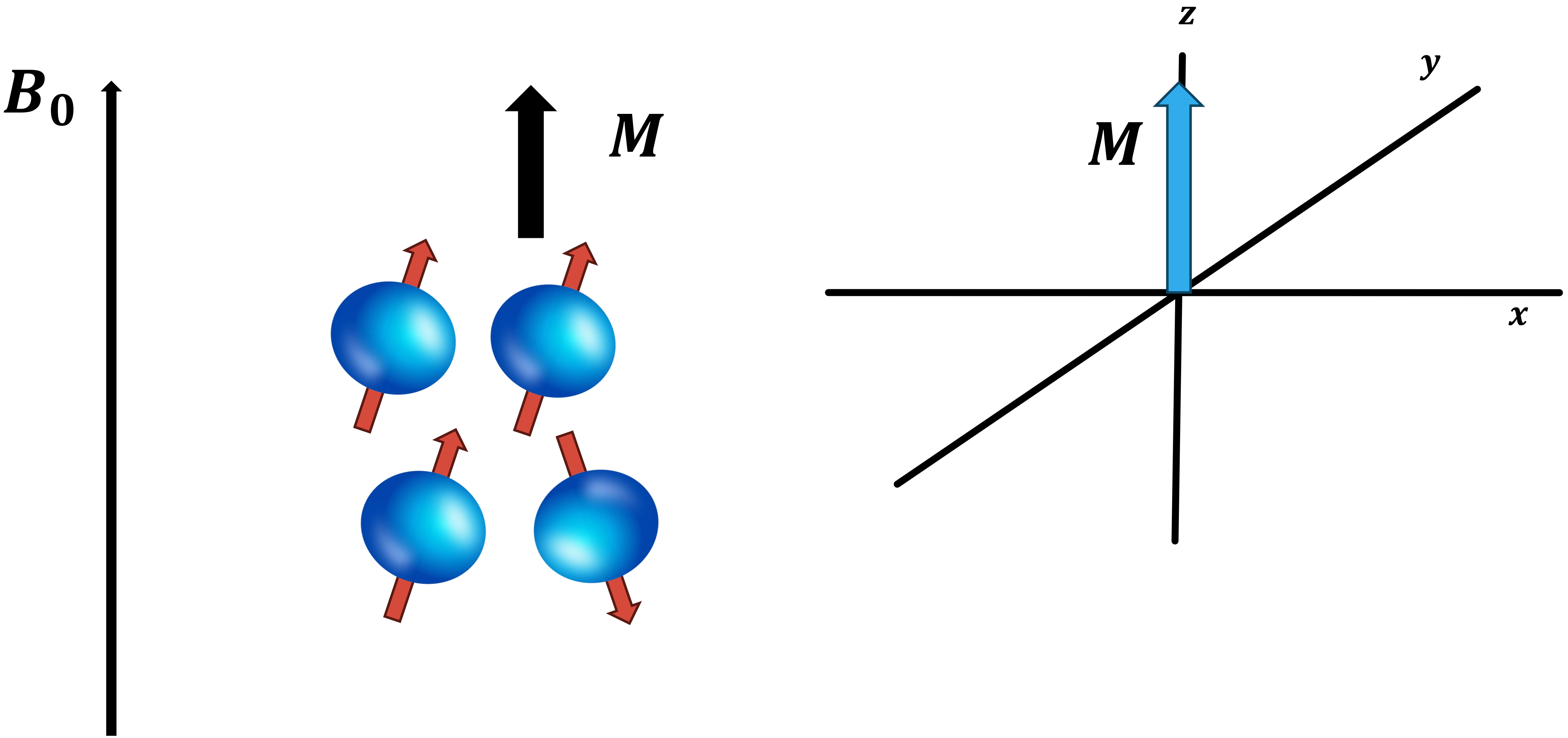
This is called precession

Larmor frequency -> precession rate

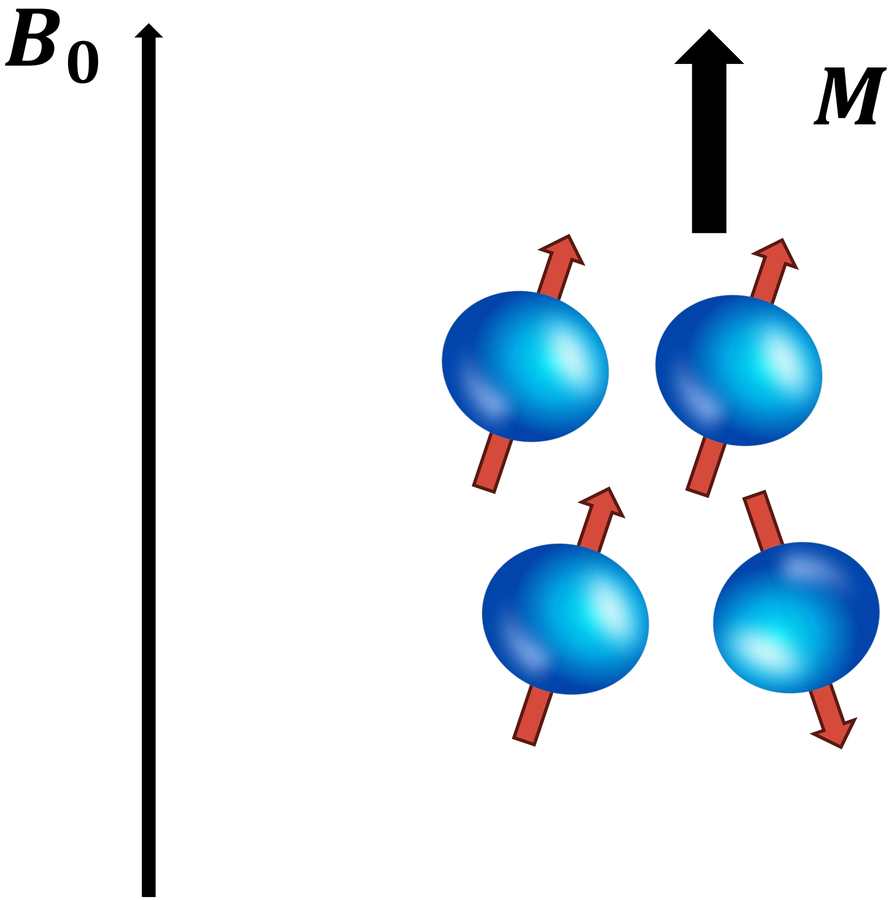
$$\omega_0 = \gamma B_0$$

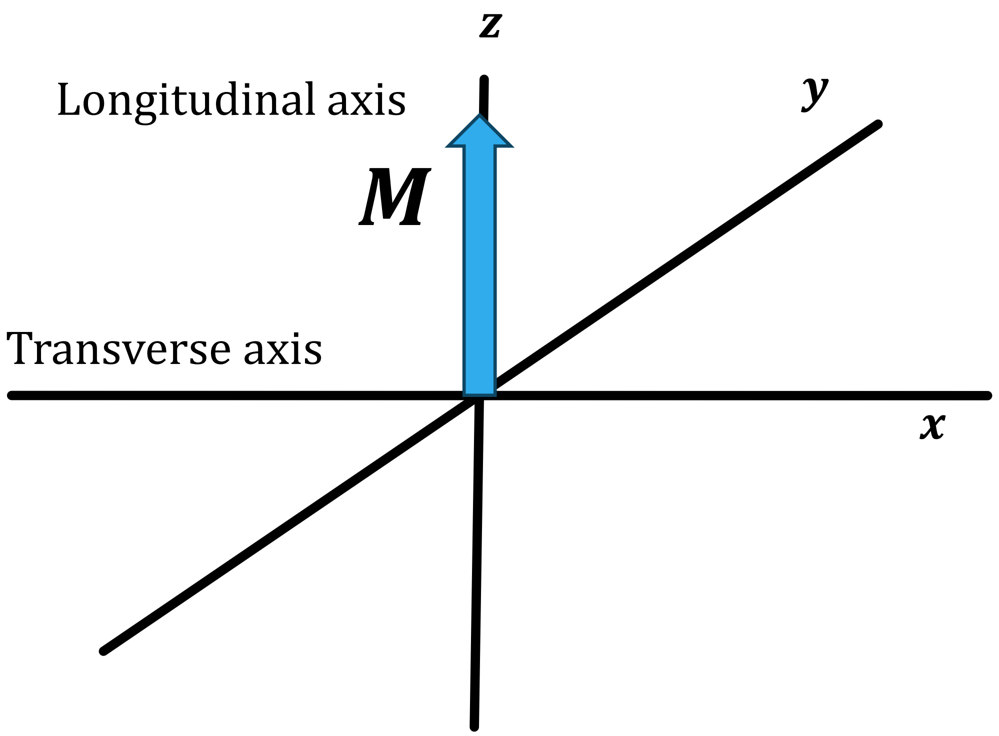
γ: Gyromagnetic ratio

The Initial Situation

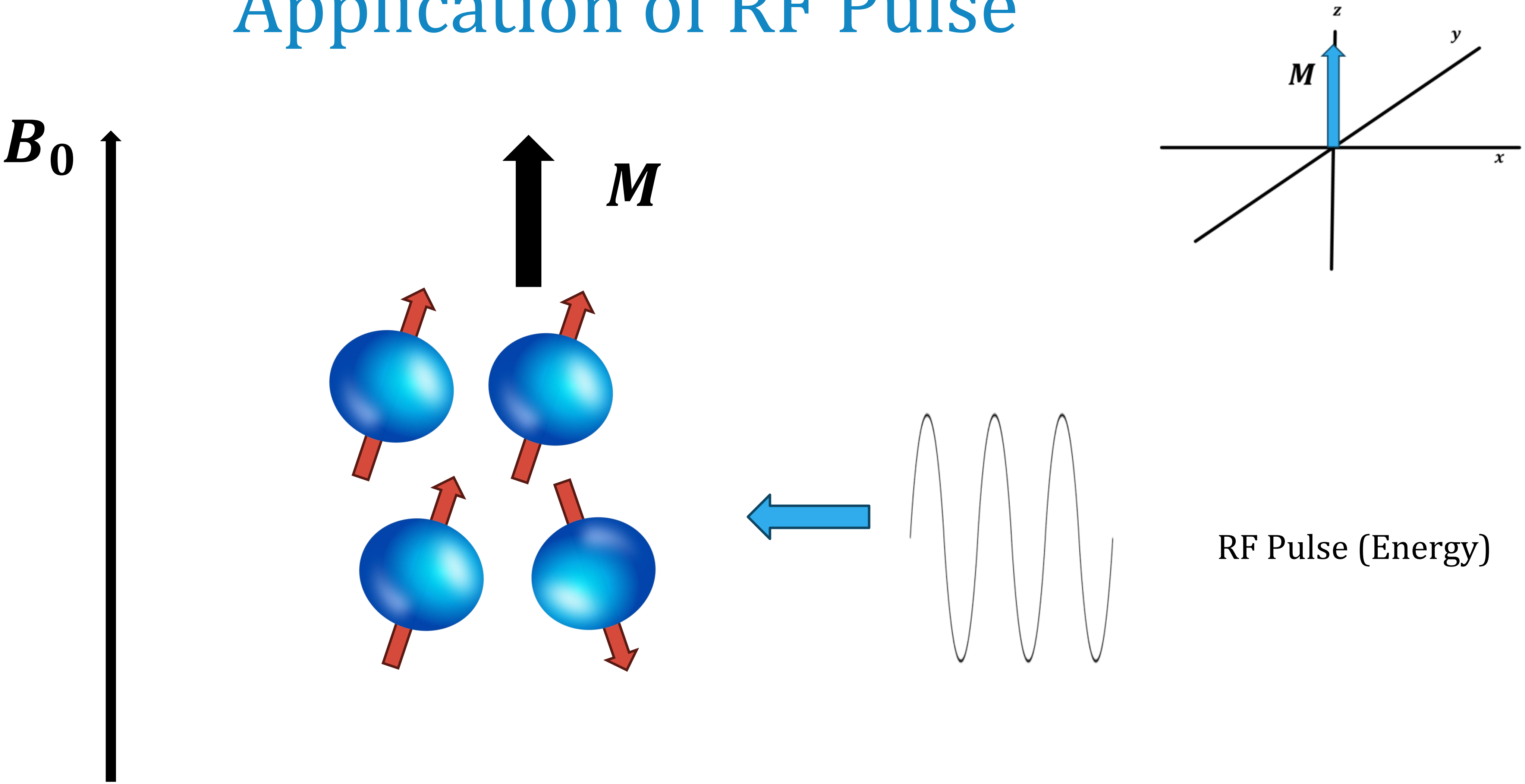


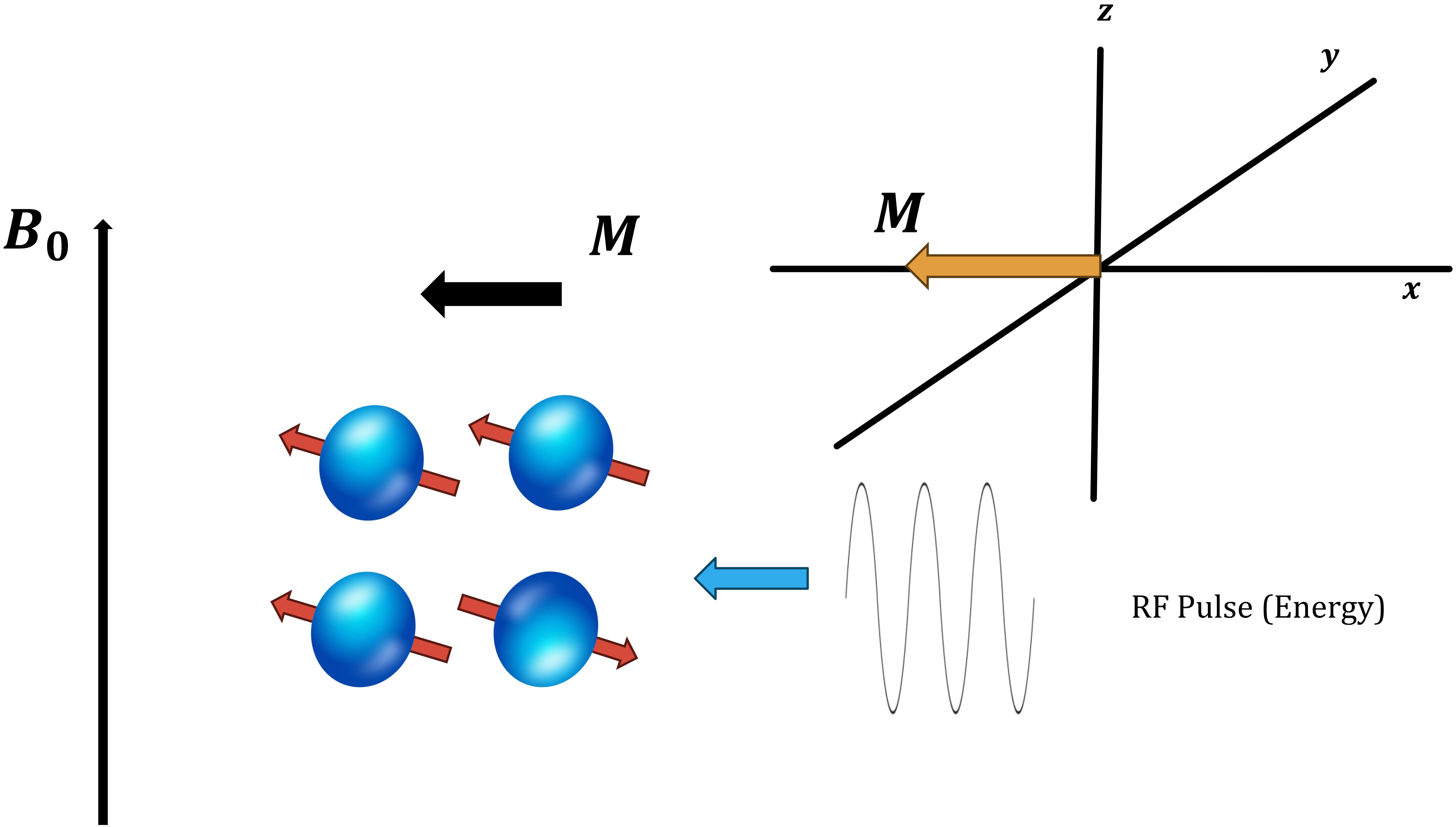
The Initial Situation



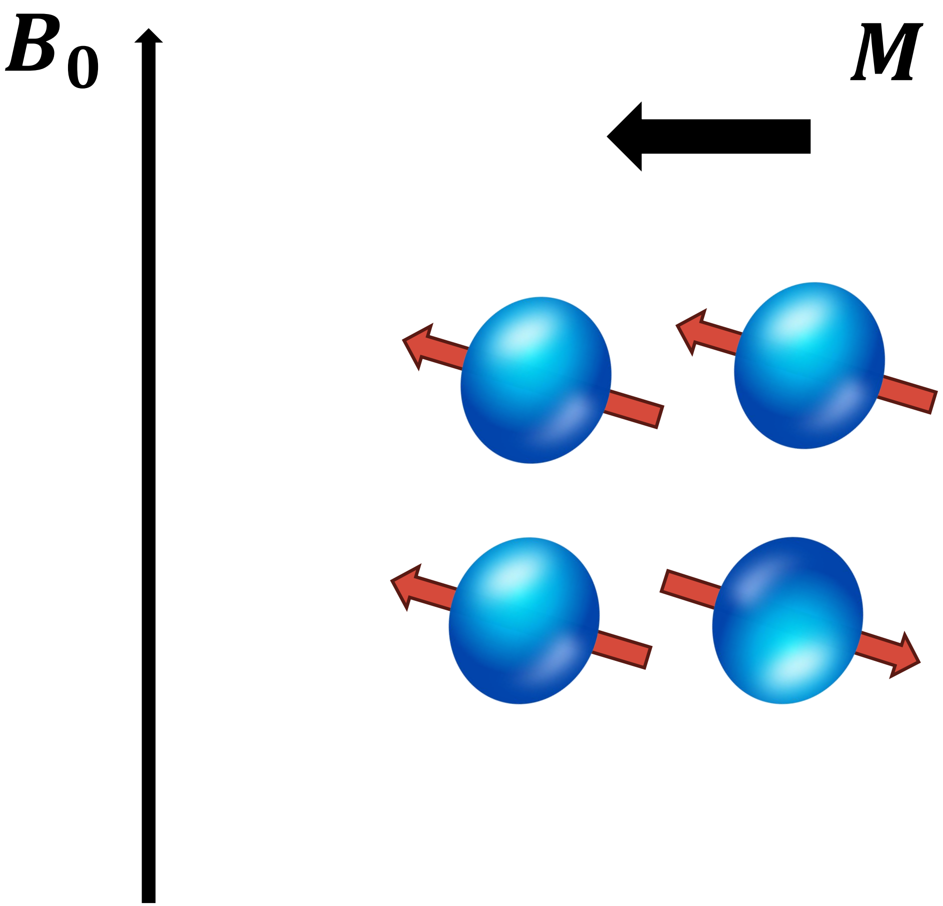


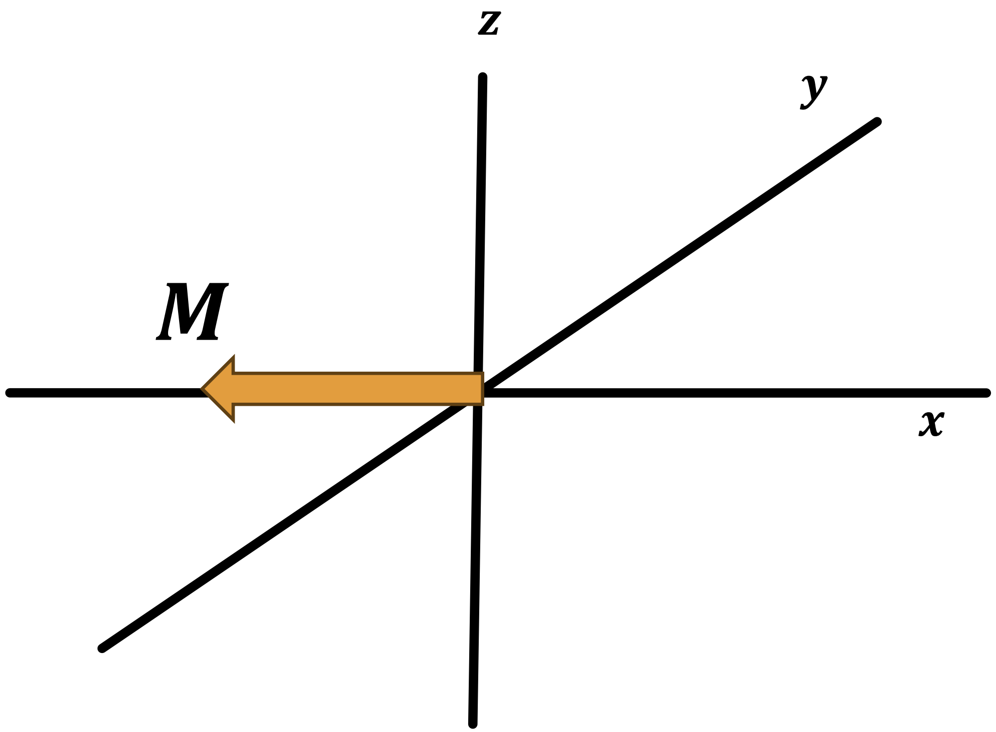
Application of RF Pulse



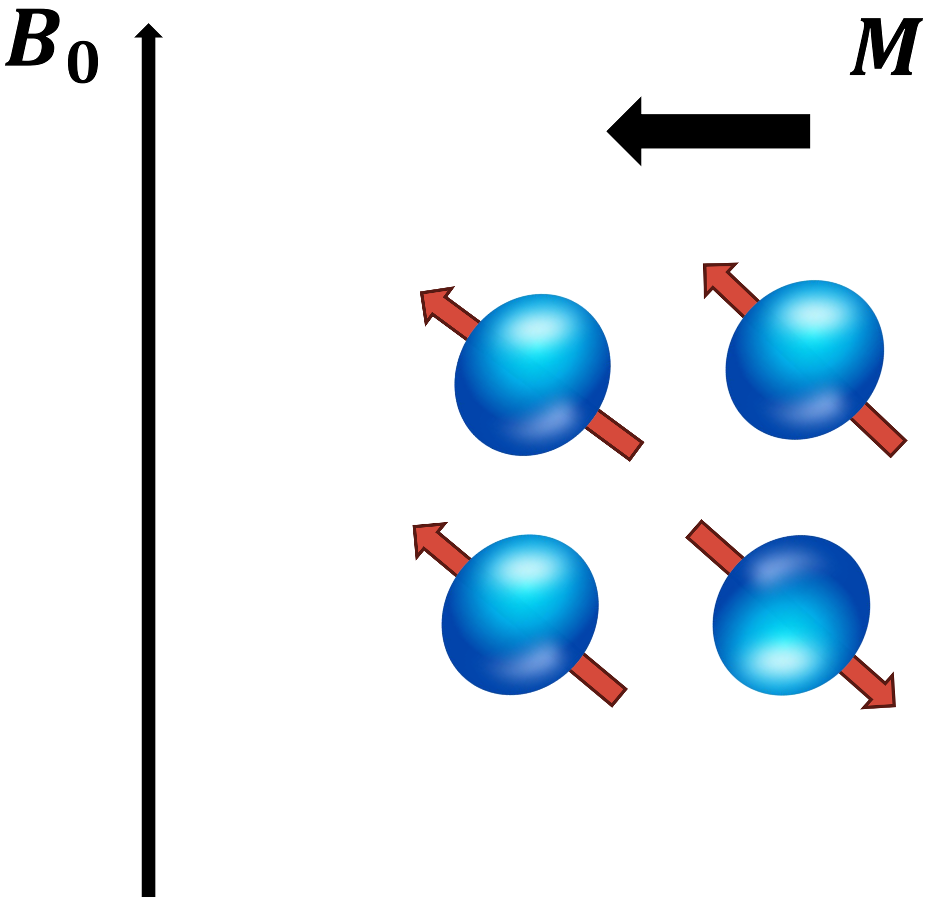


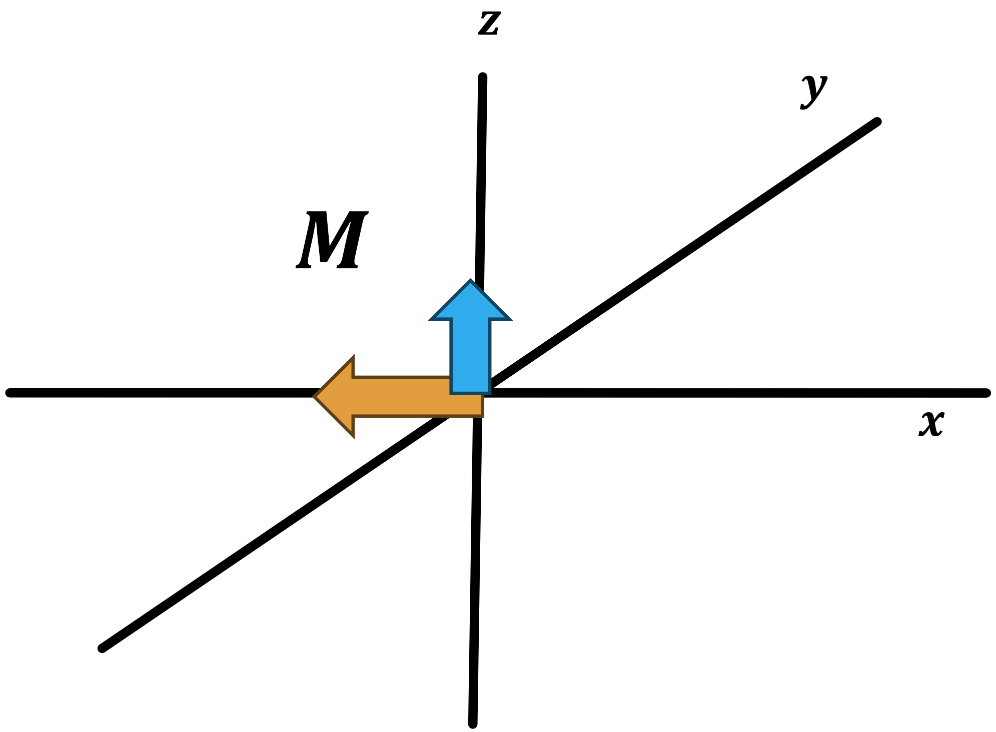
B_0
M
M
z
y
x
RF Pulse (Energy)



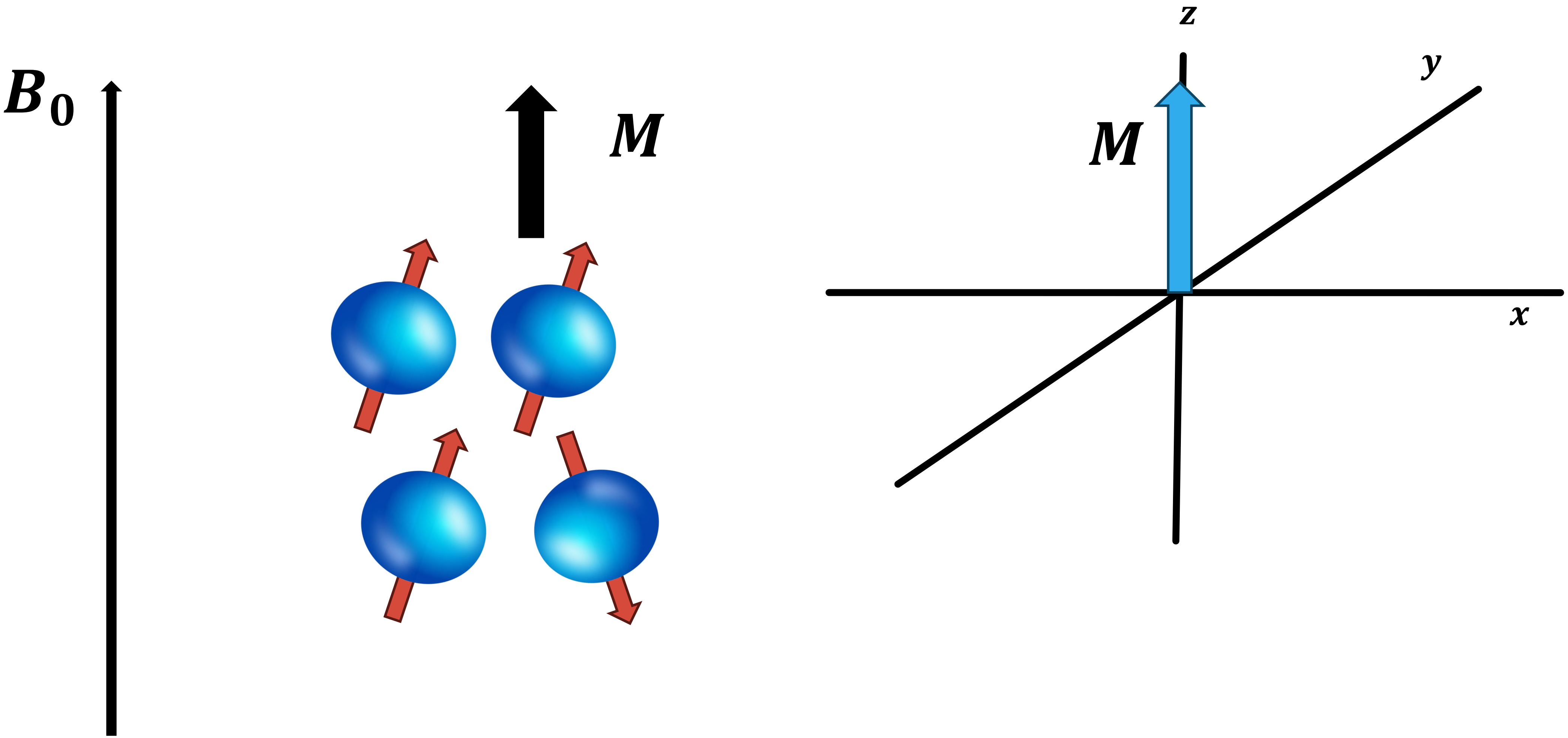


After the RF Pulse is removed, nuclei will start coming back to the original orientation

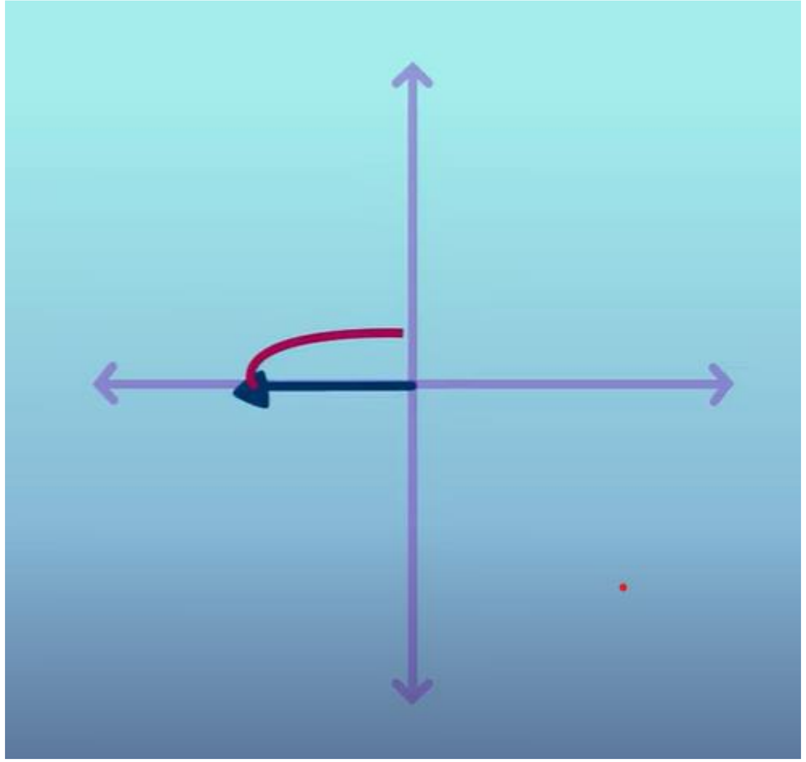


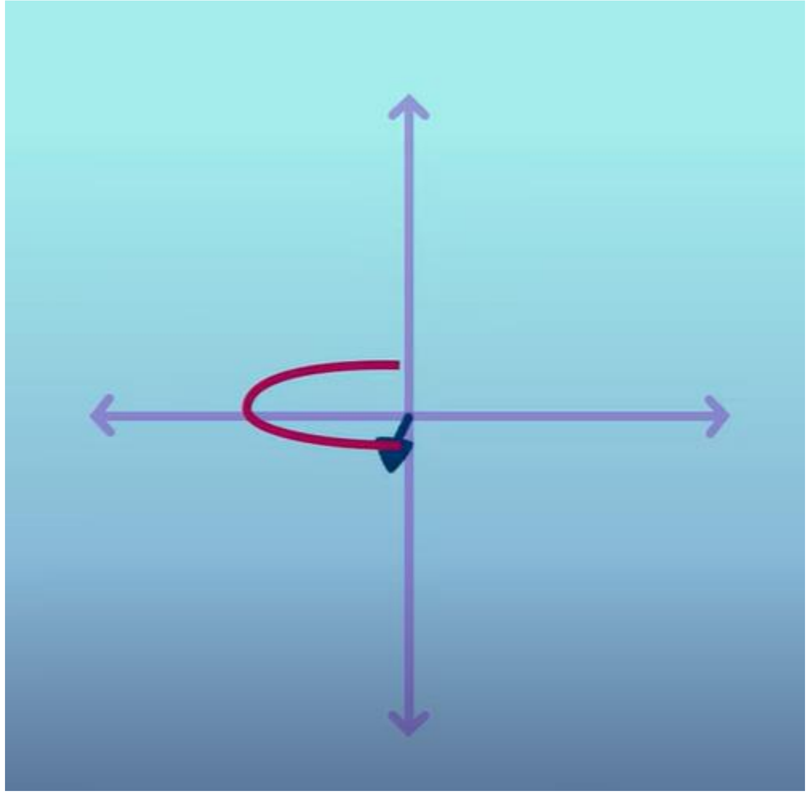


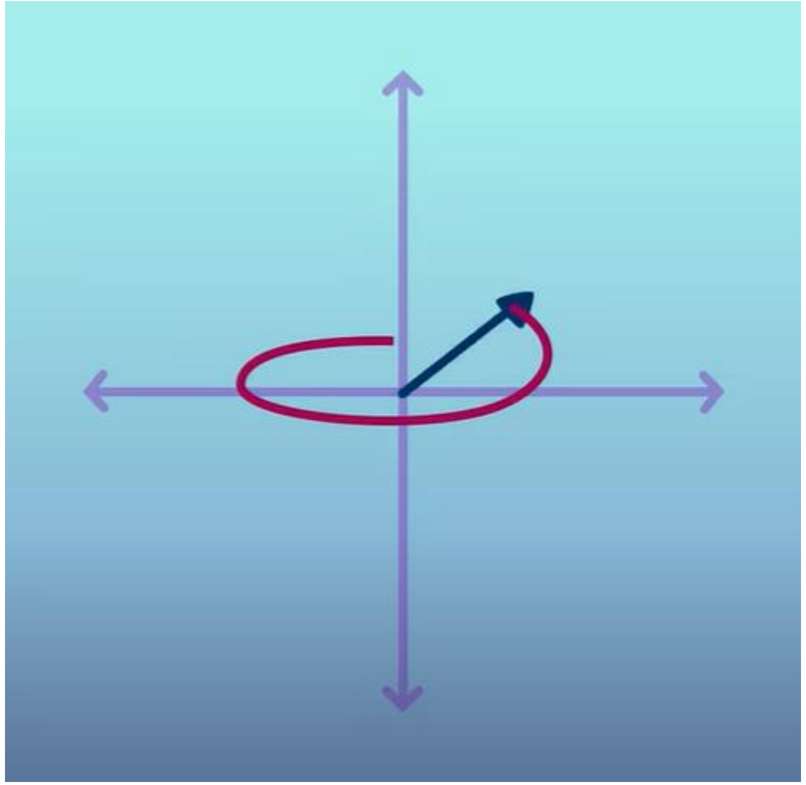
After the RF Pulse is removed, nuclei will start coming back to the original orientation

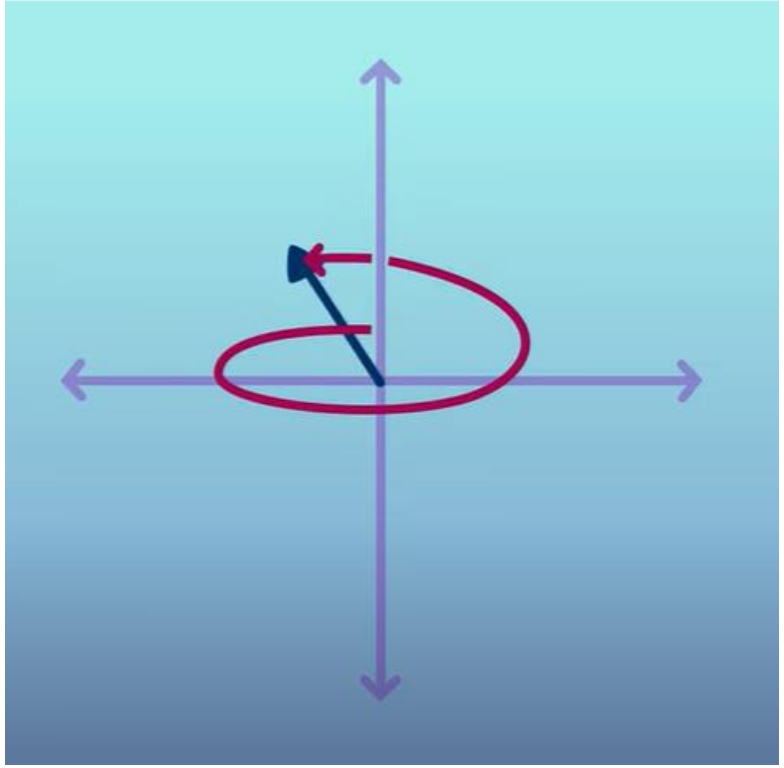


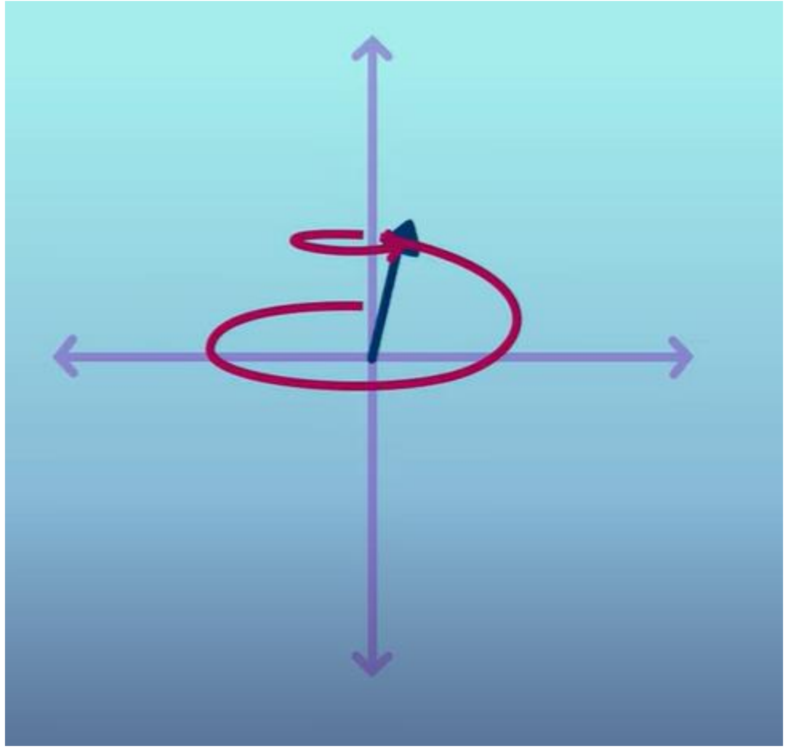
B_0
M
M
z
y
x

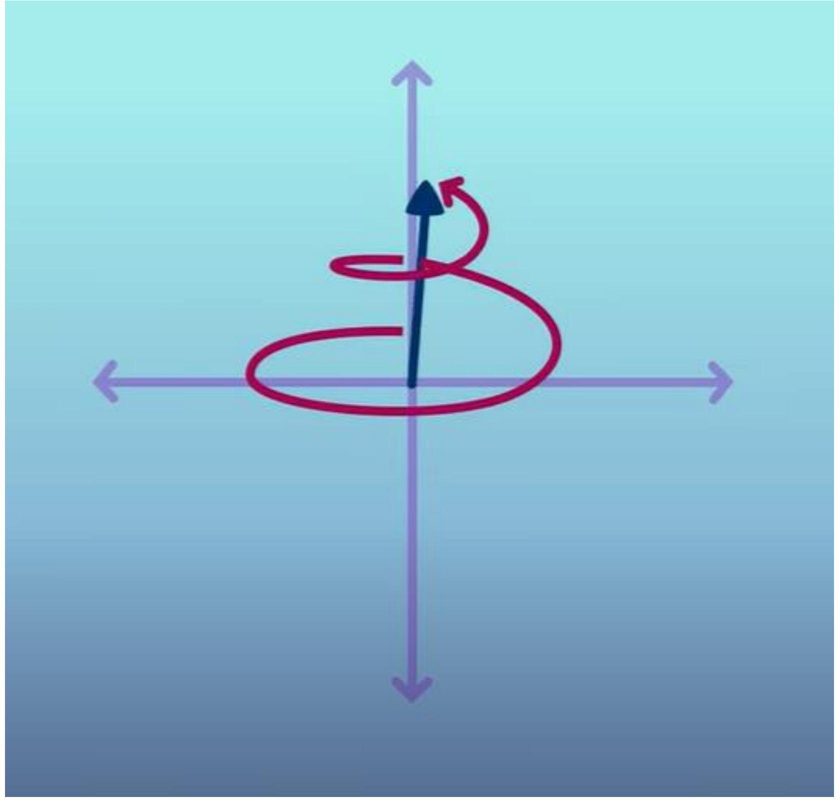




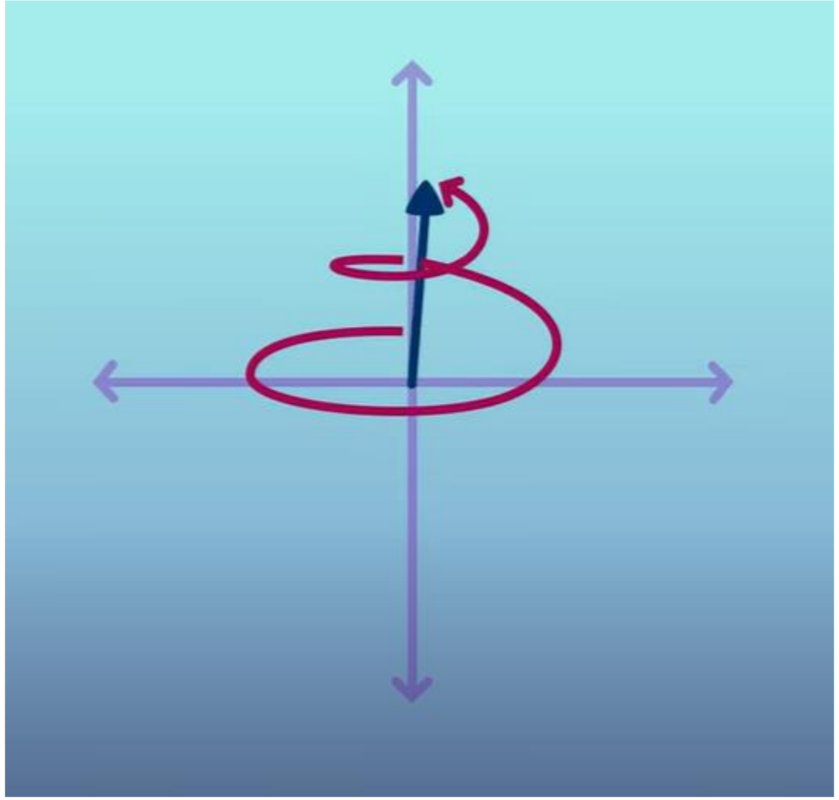








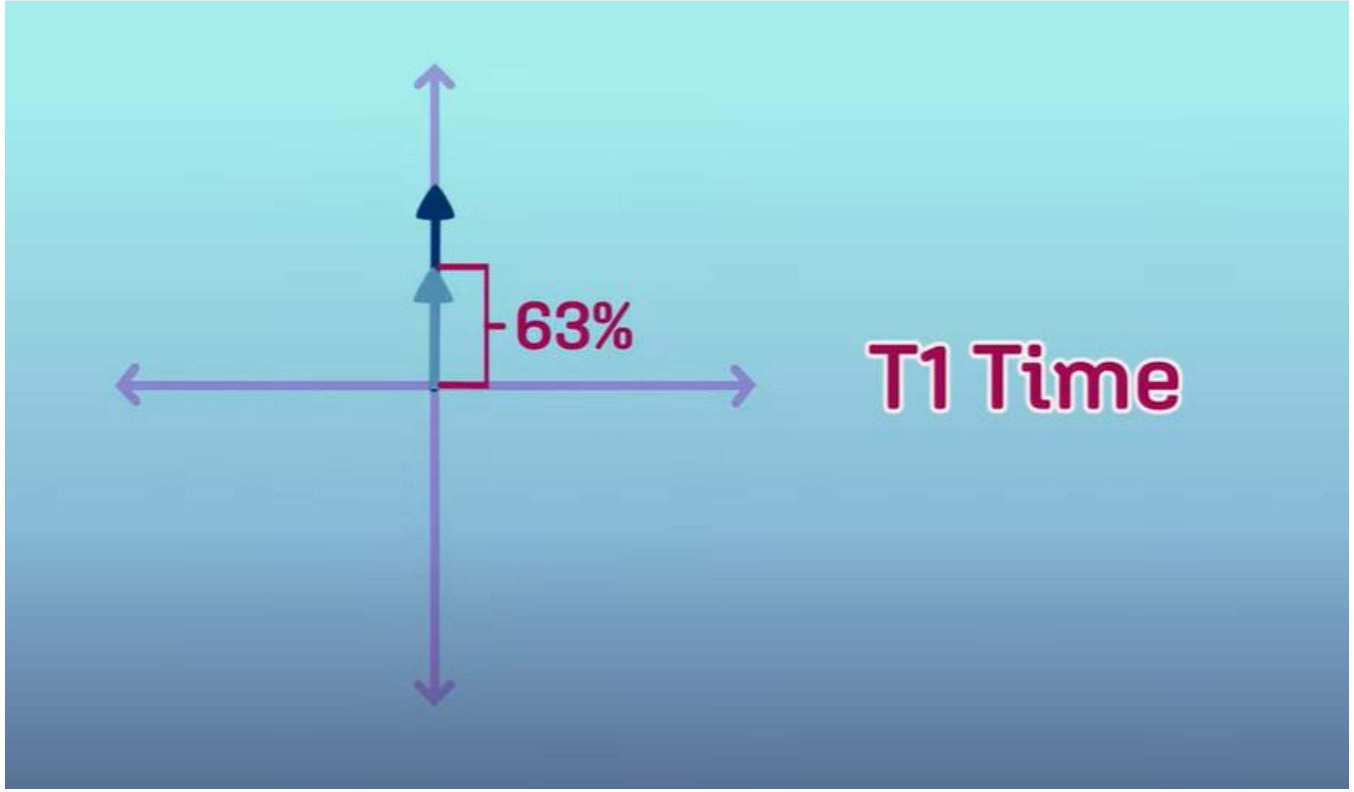
https://www.youtube.com/watch?v=jLnuPKhKXVM



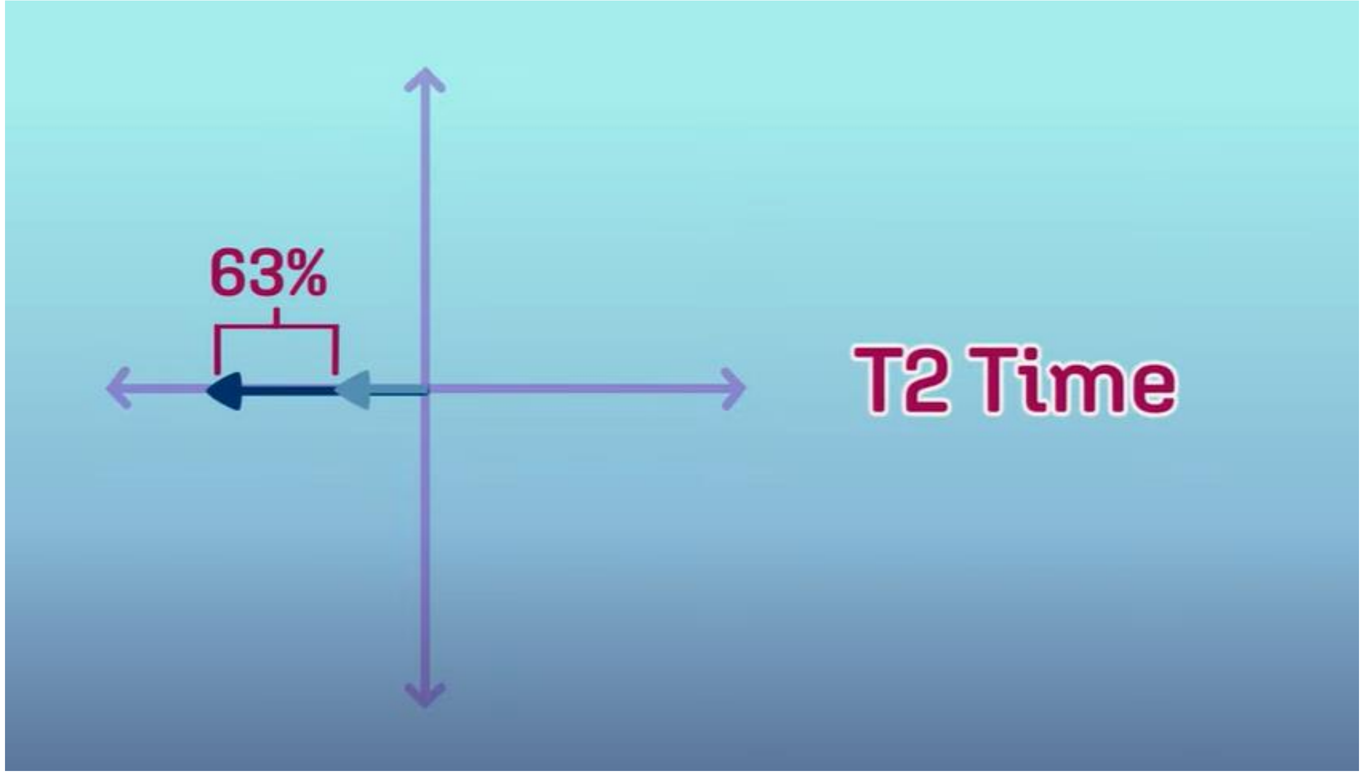
Spin relaxation

https://www.youtube.com/watch?v=jLnuPKhKXVM

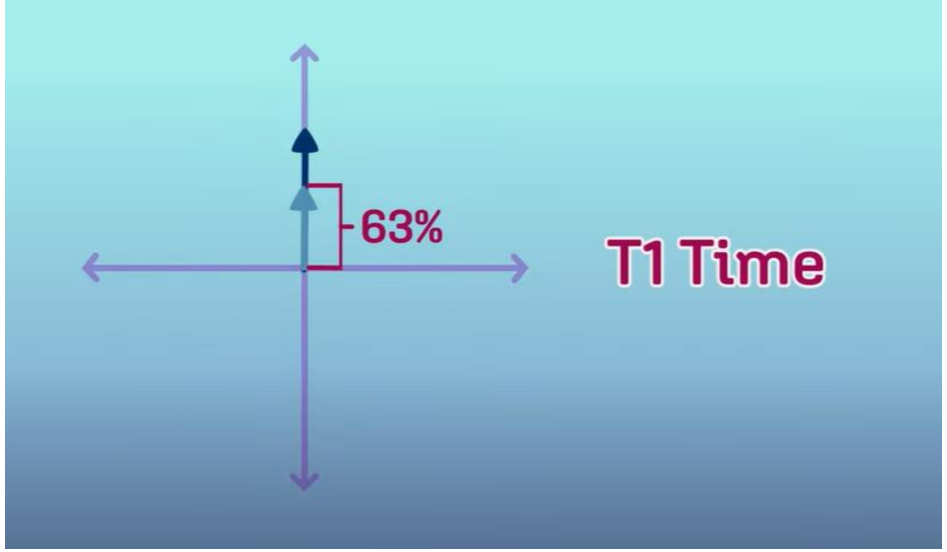
T1 and T2 Time

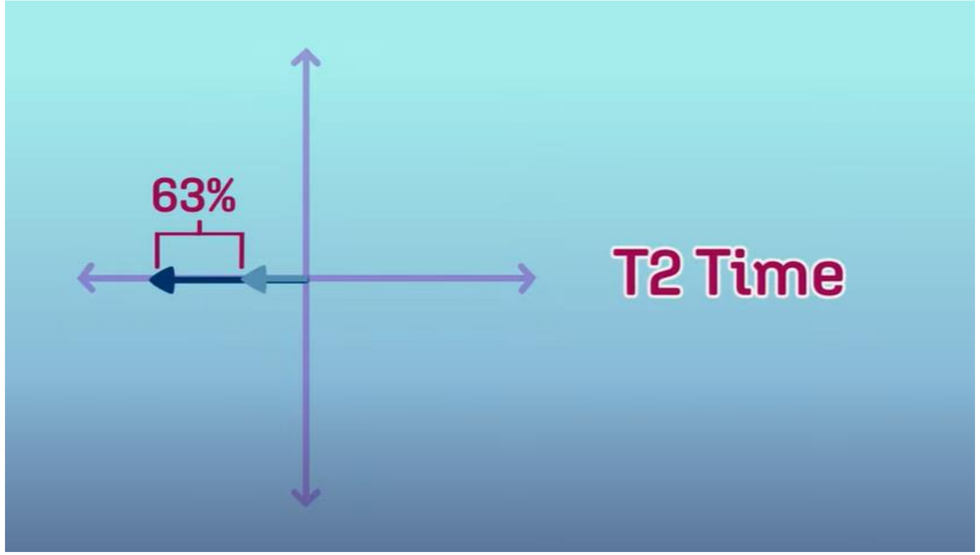


T1 and T2 Time



T1 and T2 Time





Net magnetization vector andT1 and T2 times
are unique for each tissue type

Spin Relaxation Times

Tissue	T1 (msec)	T2 (msec)
Water/CSF	4000	2000
Gray matter	900	90
Muscle	900	50
Liver	500	40
Fat	250	70
Tendon	400	5
Proteins	250	0.1- 1.0
Ice	5000	0.001

Approximate values for 1.5T

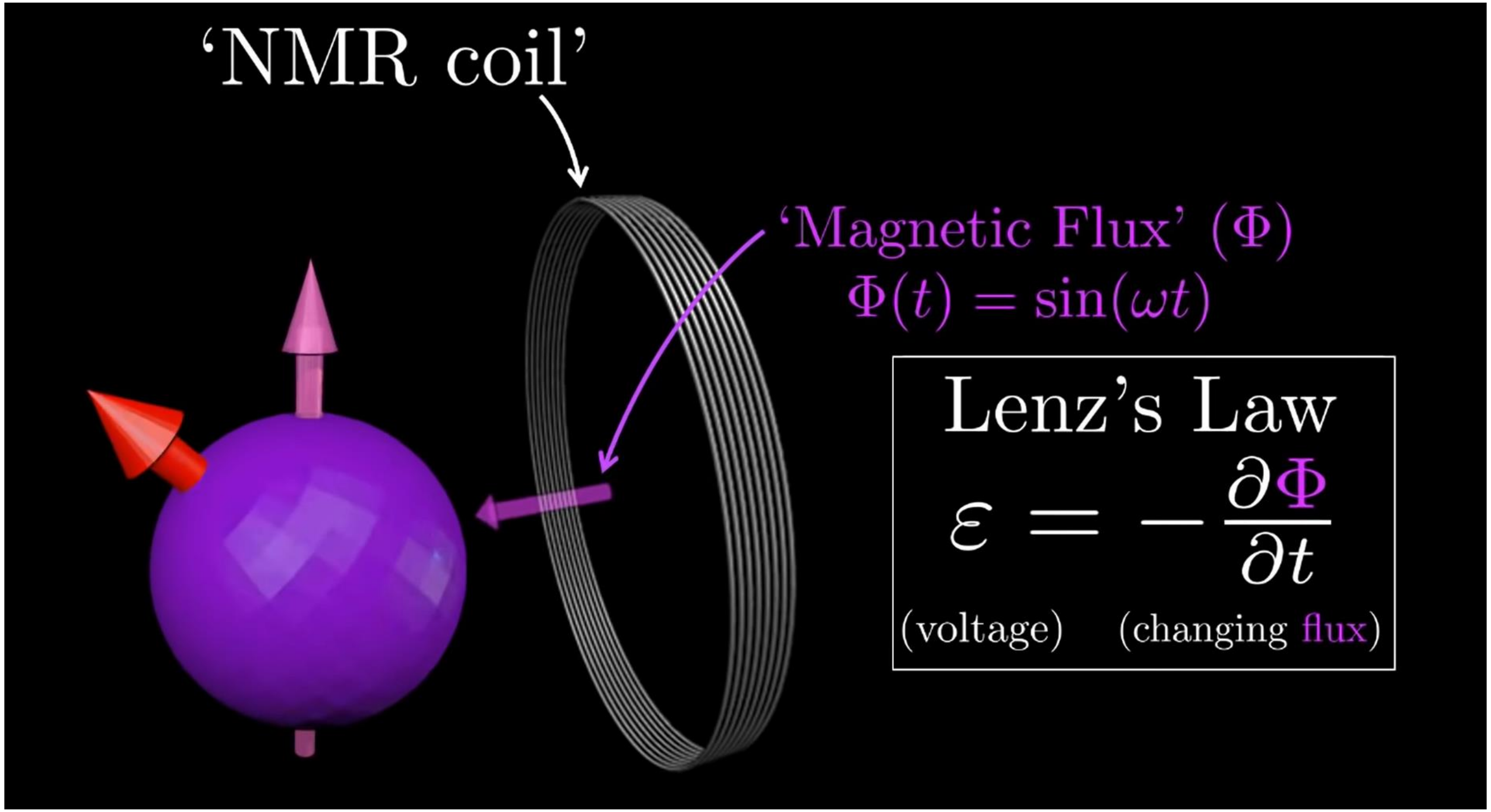
Spin Relaxation Times

Tissue	T1 (msec)	T2 (msec)
Water/CSF	4000	2000
Gray matter	900	90
Muscle	900	50
Liver	500	40
Fat	250	70
Tendon	400	5
Proteins	250	0.1- 1.0
Ice	5000	0.001

The entire process is repeated several times

Approximate values for 1.5T

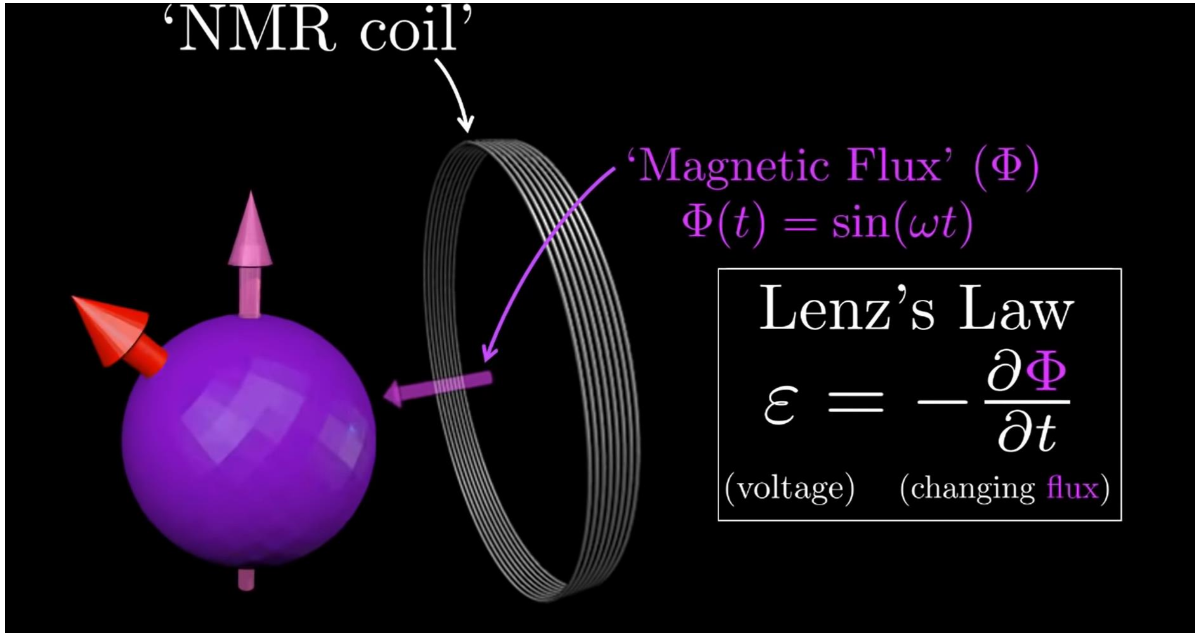
Detection of Signal



https://www.youtube.com/watch?v=TQegSF4ZiIQ&list=PLFs-r3e2iBRGyVlYqFHbtdutrPtQXPdPc&index=13&t=2177s

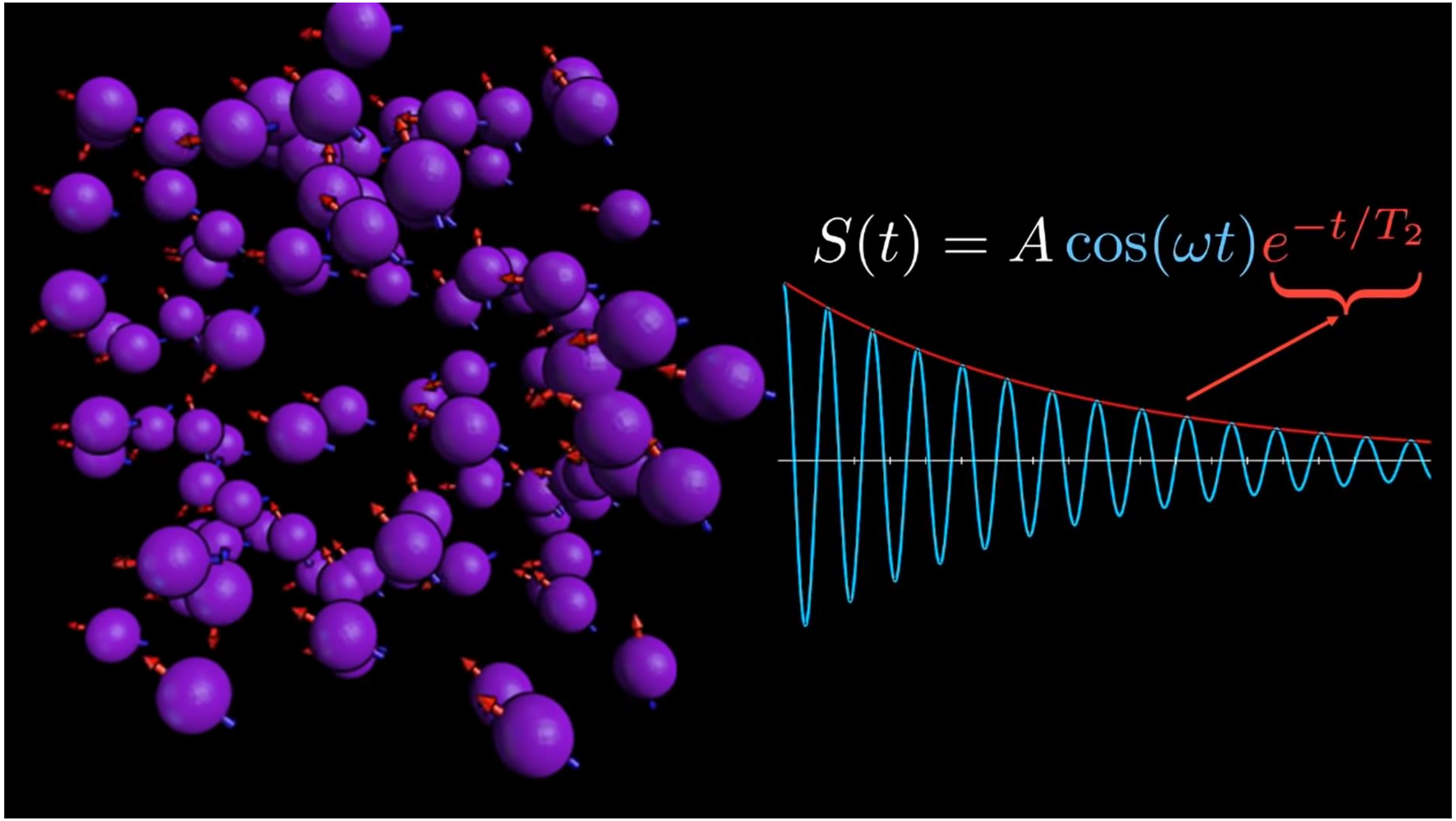
Detection of Signal

$$s(t) = M_0 \left(1 - e^{-TR/T_1}\right) e^{-t/T_2}$$



https://www.youtube.com/watch?v=TQegSF4ZiIQ&list=PLFs-r3e2iBRGyVlYqFHbtdutrPtQXPdPc&index=13&t=2177s

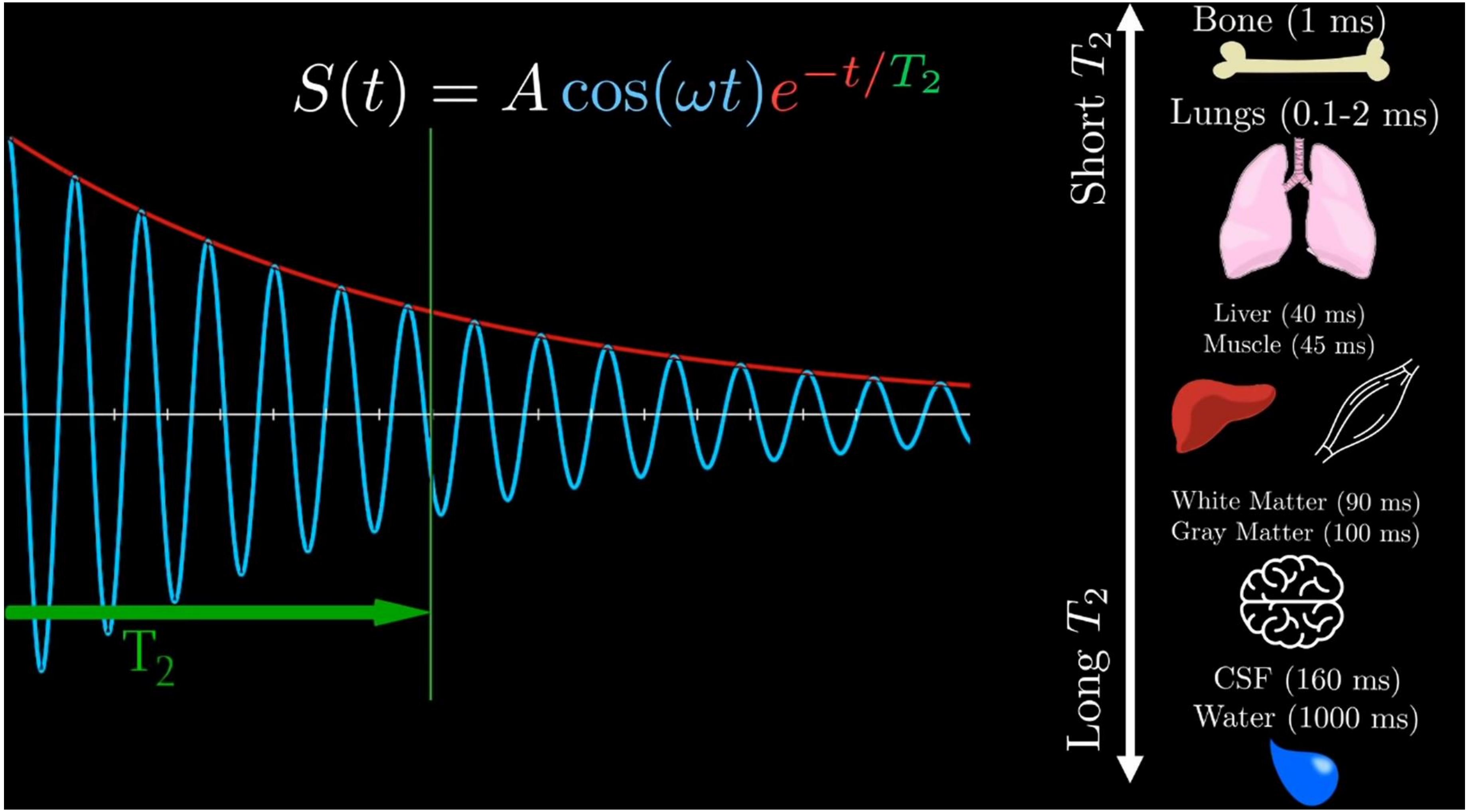
Detection of Signal



Signal decay

https://www.youtube.com/watch?v=TQegSF4ZiIQ&list=PLFs-r3e2iBRGyVlYqFHbtdutrPtQXPdPc&index=13&t=2177s

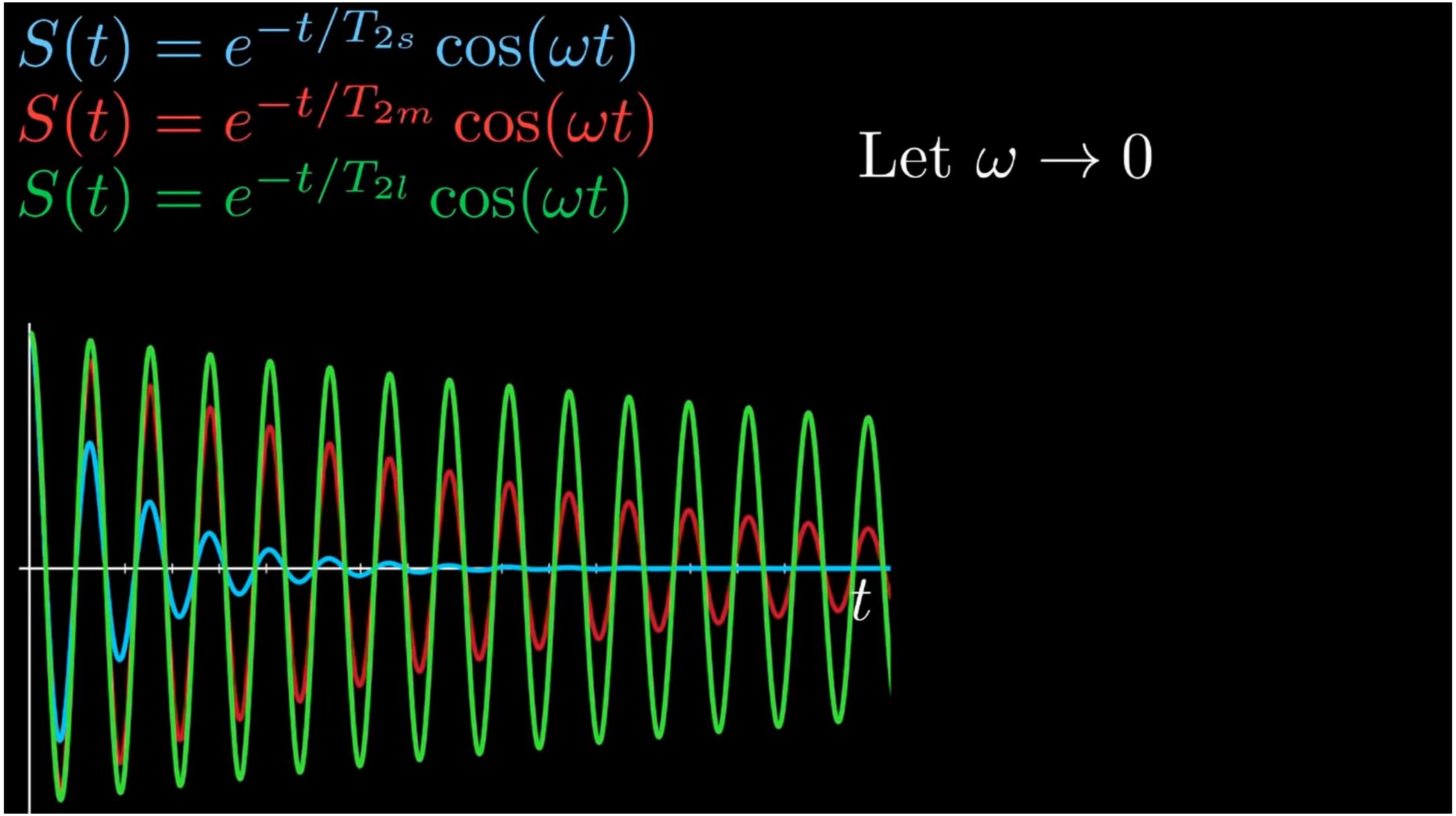
Detection of Signal



Signal decay

https://www.youtube.com/watch?v=TQegSF4ZiIQ&list=PLFs-r3e2iBRGyVlYqFHbtdutrPtQXPdPc&index=13&t=2177s

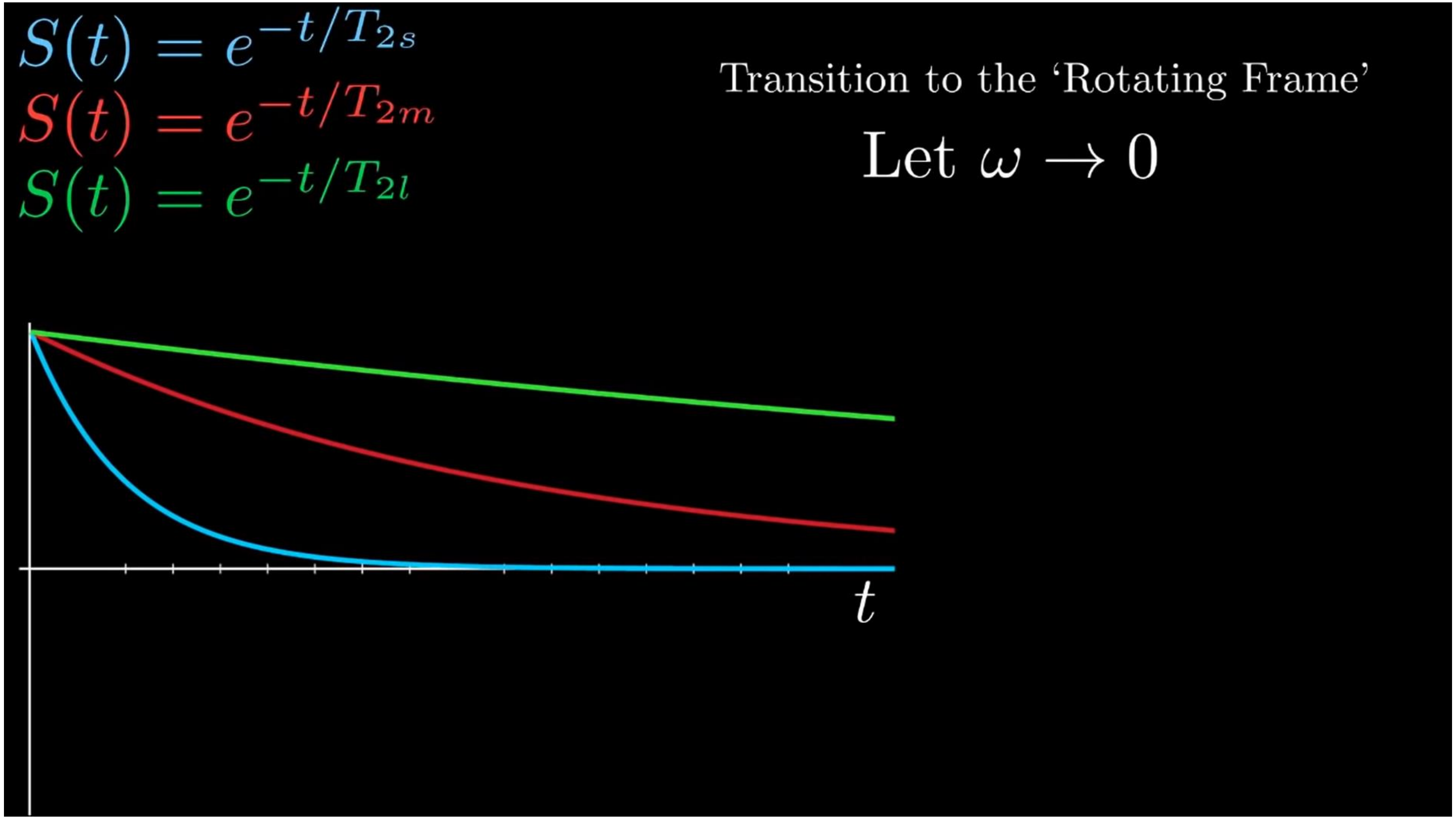
Detection of Signal



Transitioning to the rotating frame

https://www.youtube.com/watch?v=TQegSF4ZiIQ&list=PLFs-r3e2iBRGyVlYqFHbtdutrPtQXPdPc&index=13&t=2177s

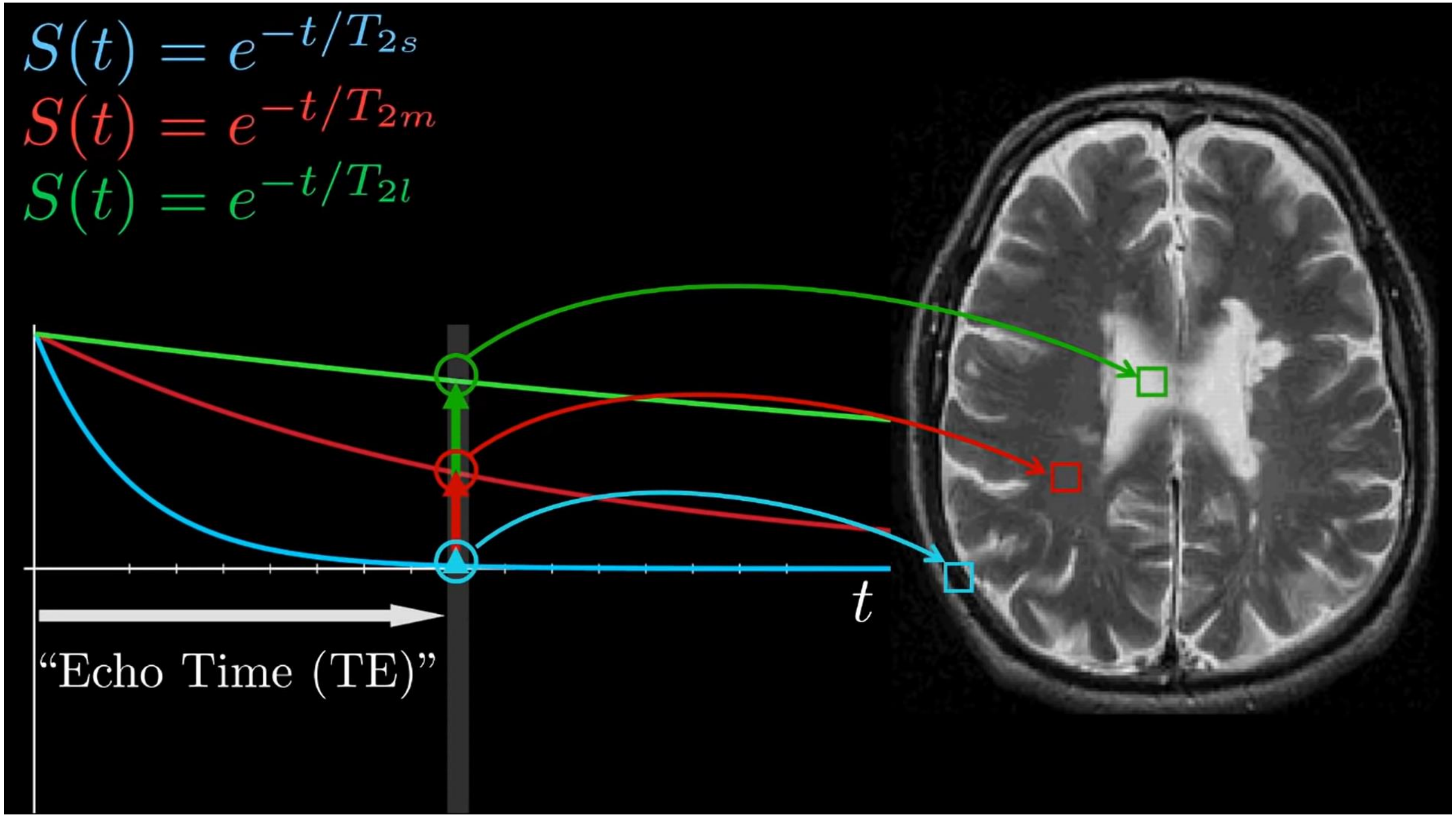
Detection of Signal



Transitioning to the rotating frame

https://www.youtube.com/watch?v=TQegSF4ZiIQ&list=PLFs-r3e2iBRGyVlYqFHbtdutrPtQXPdPc&index=13&t=2177s

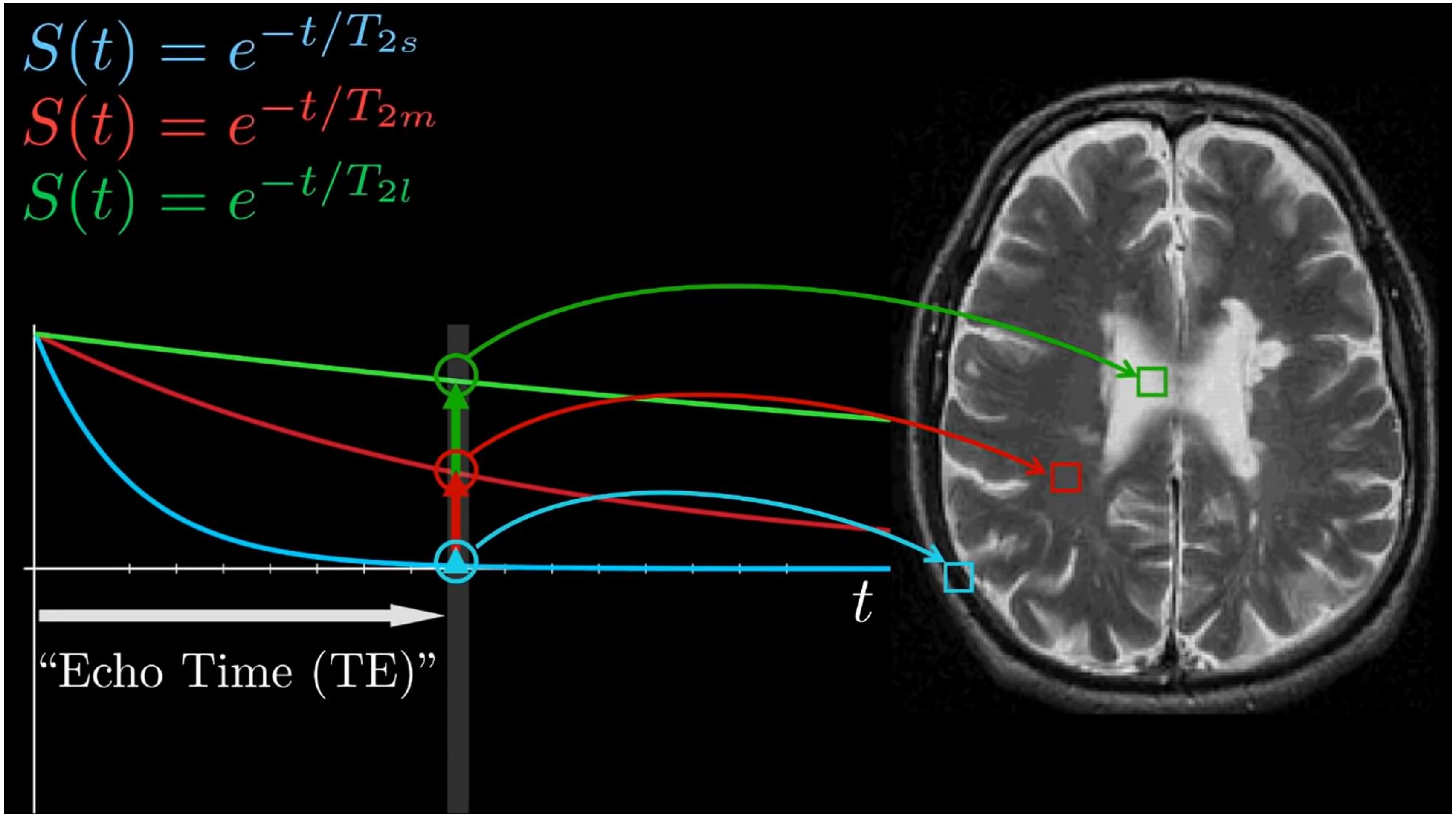
Detection of Signal



Echo time: Chosen by MRI technician to differentiate between the tissue the radiologist wants to see

https://www.youtube.com/watch?v=TQegSF4ZiIQ&list=PLFs-r3e2iBRGyVlYqFHbtdutrPtQXPdPc&index=13&t=2177s

Detection of Signal



Echo time: Chosen by MRI technician to differentiate between the tissue the radiologist wants to see

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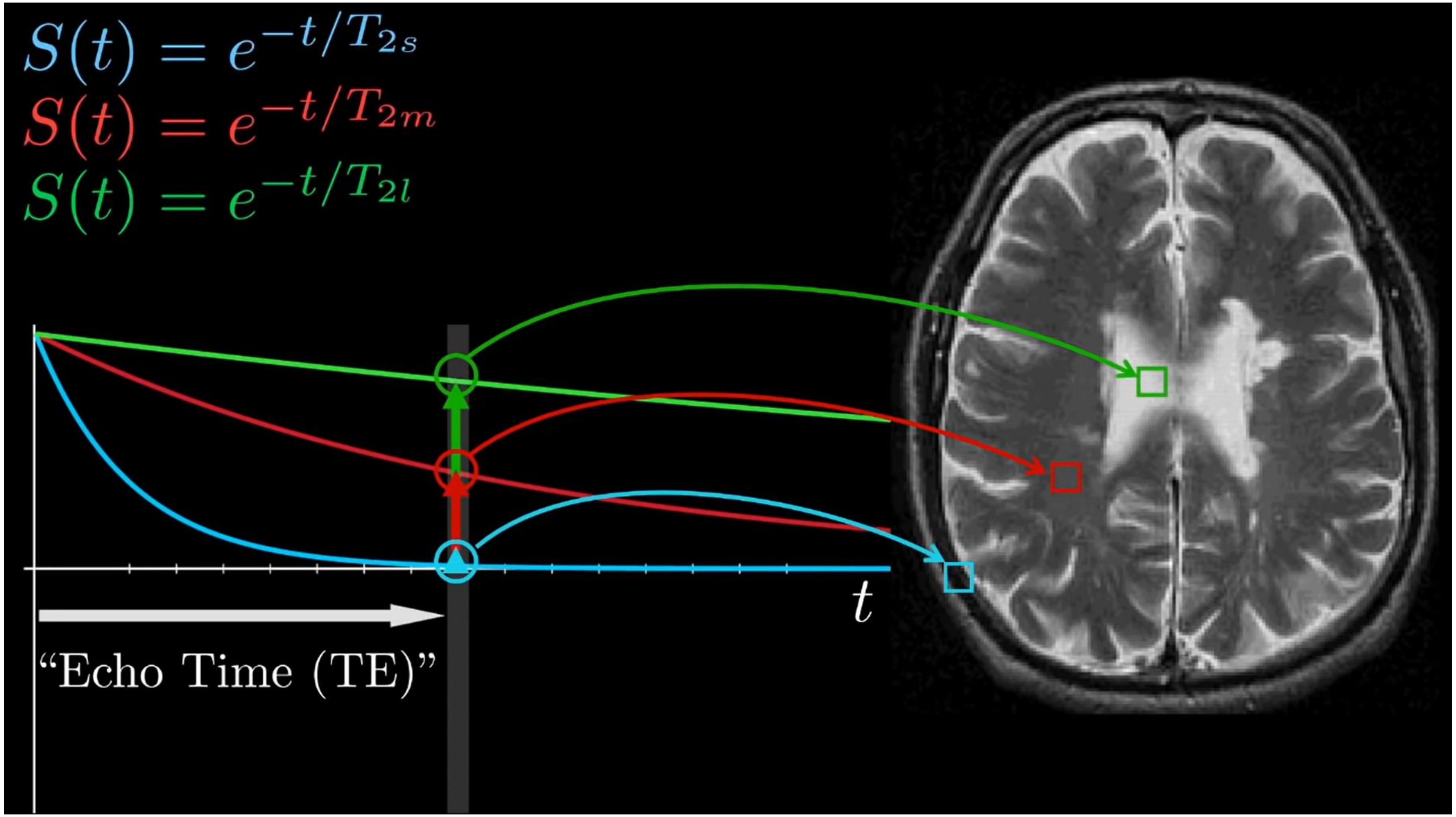
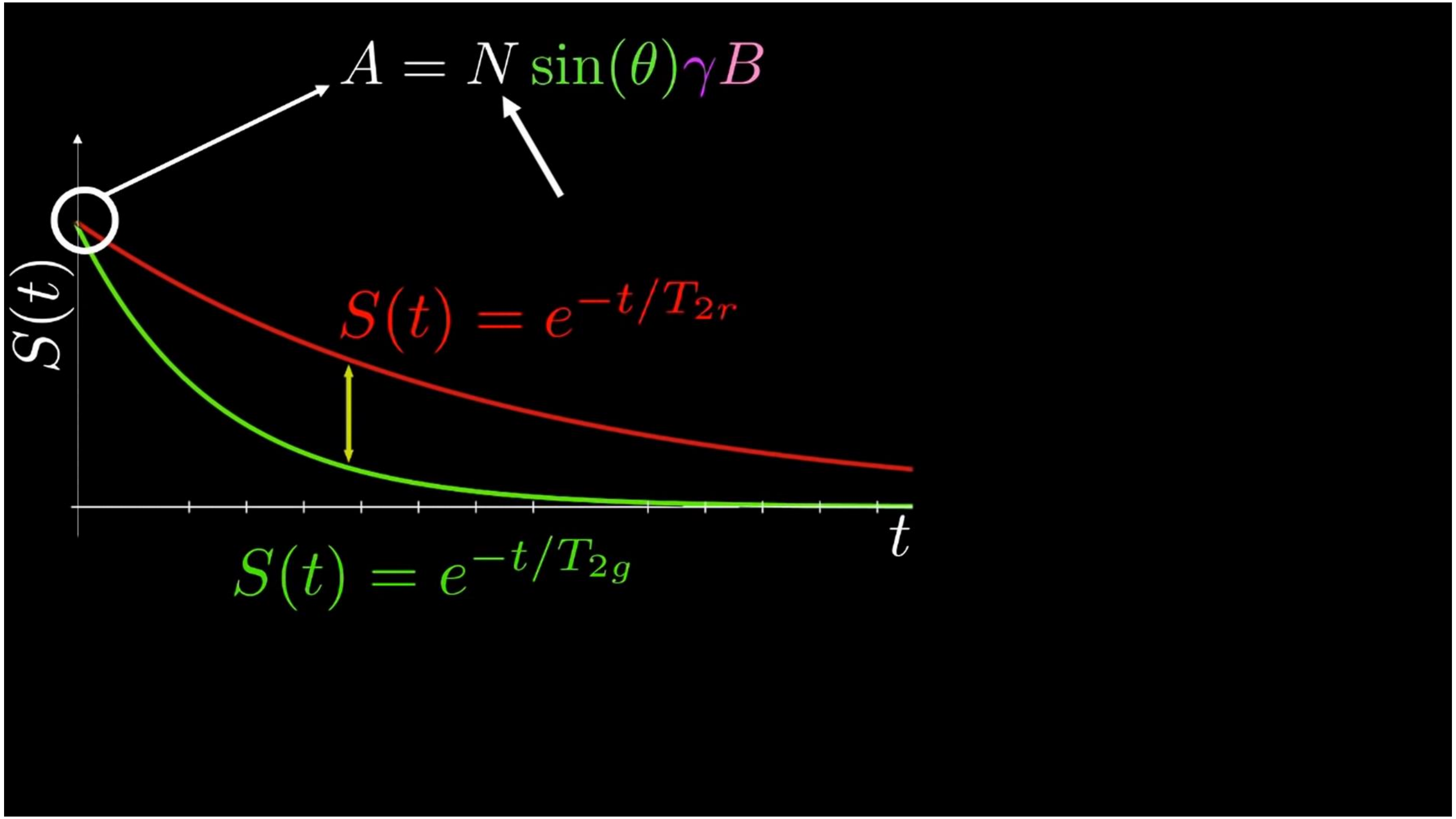
Detection of Signal



T2 weighted image

https://www.youtube.com/watch?v=TQegSF4ZiIQ&list=PLFs-r3e2iBRGyVlYqFHbtdutrPtQXPdPc&index=13&t=2177s

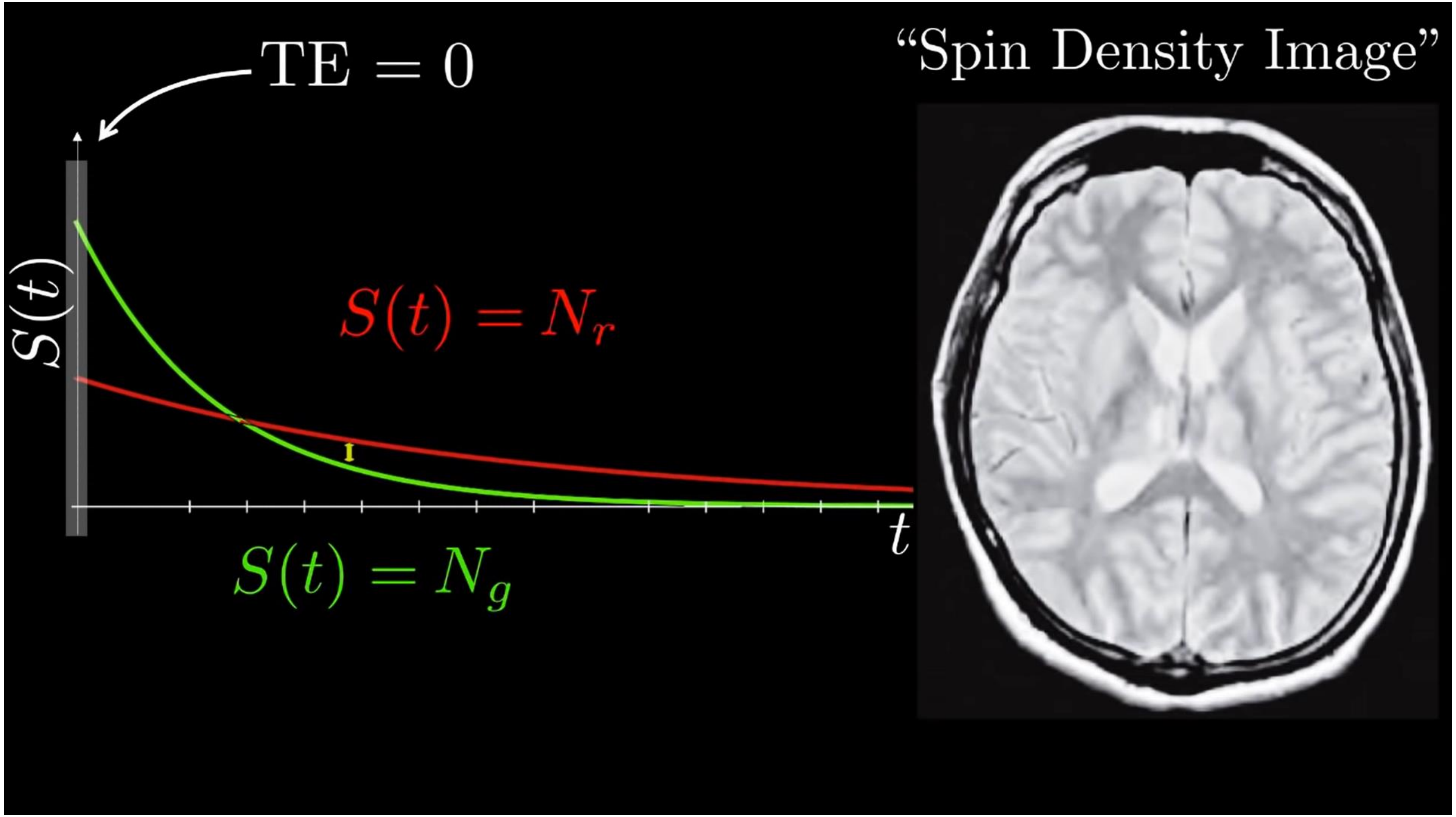
Detection of Signal



N will actually be different for different tissues

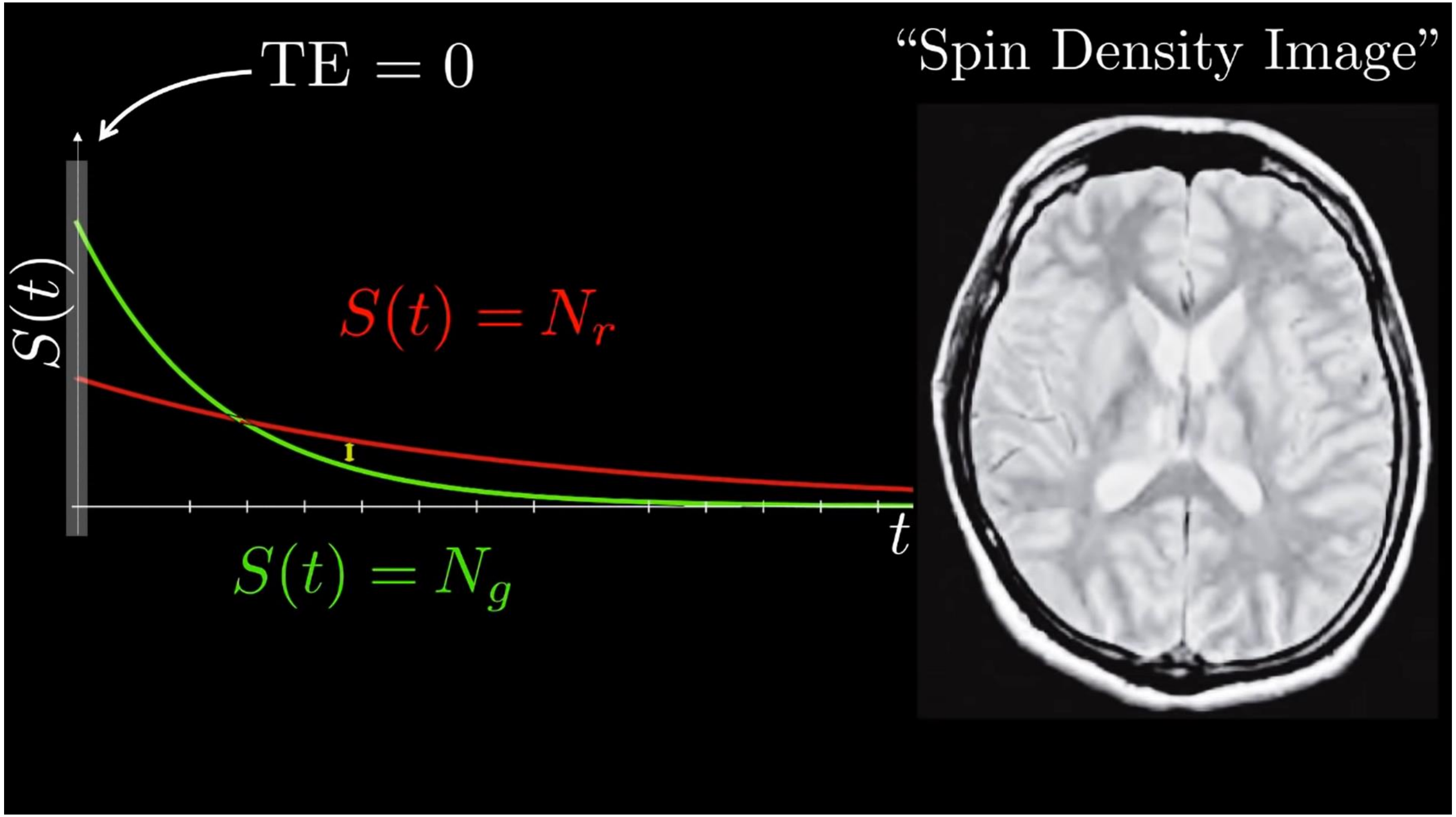
https://www.youtube.com/watch?v=TQegSF4ZiIQ&list=PLFs-r3e2iBRGyVlYqFHbtdutrPtQXPdPc&index=13&t=2177s

Detection of Signal



https://www.youtube.com/watch?v=TQegSF4ZiIQ&list=PLFs-r3e2iBRGyVlYqFHbtdutrPtQXPdPc&index=13&t=2177s

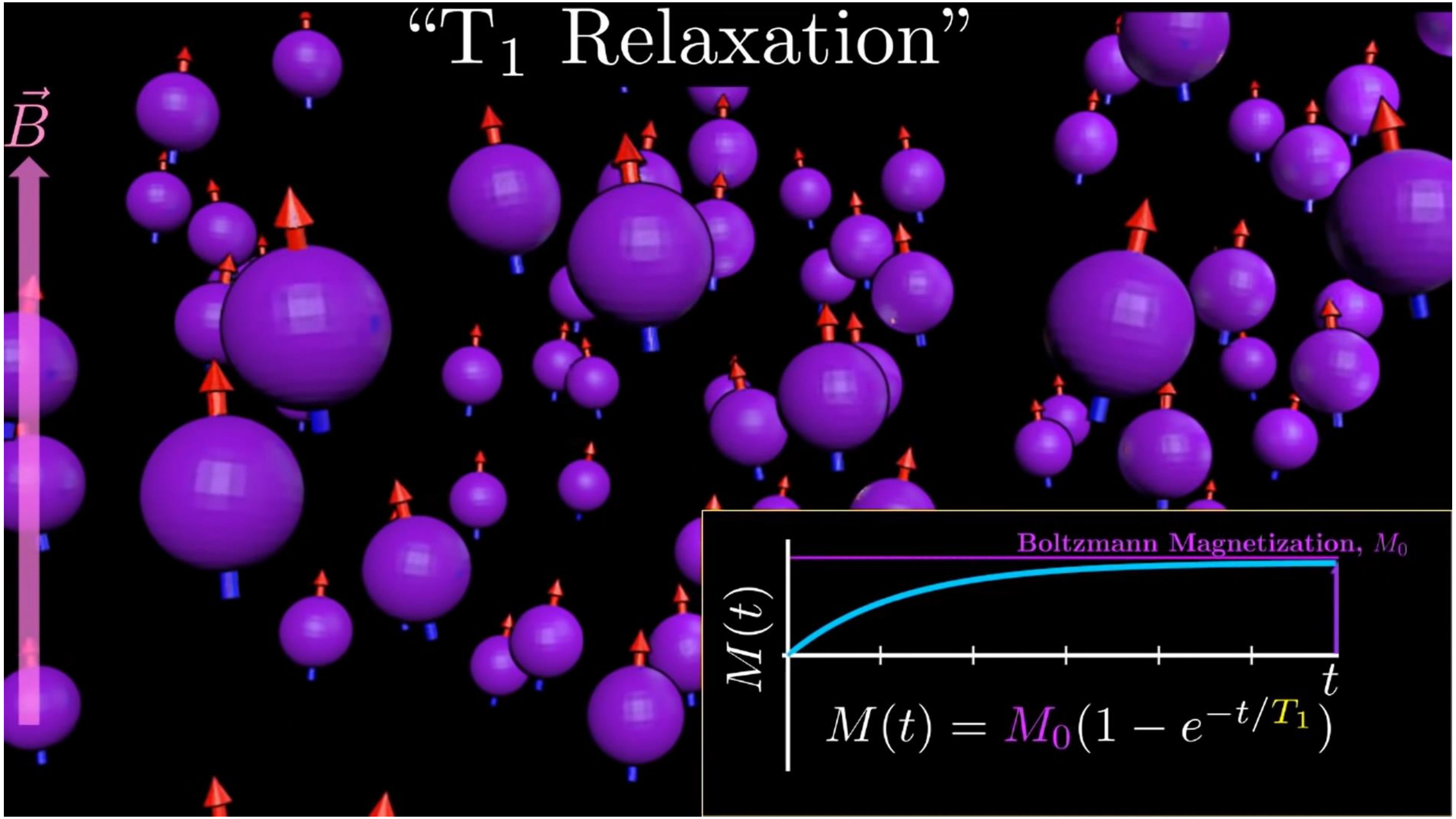
Detection of Signal



Usually does not provide very good contrast

https://www.youtube.com/watch?v=TQegSF4ZiIQ&list=PLFs-r3e2iBRGyVlYqFHbtdutrPtQXPdPc&index=13&t=2177s

Detection of Signal



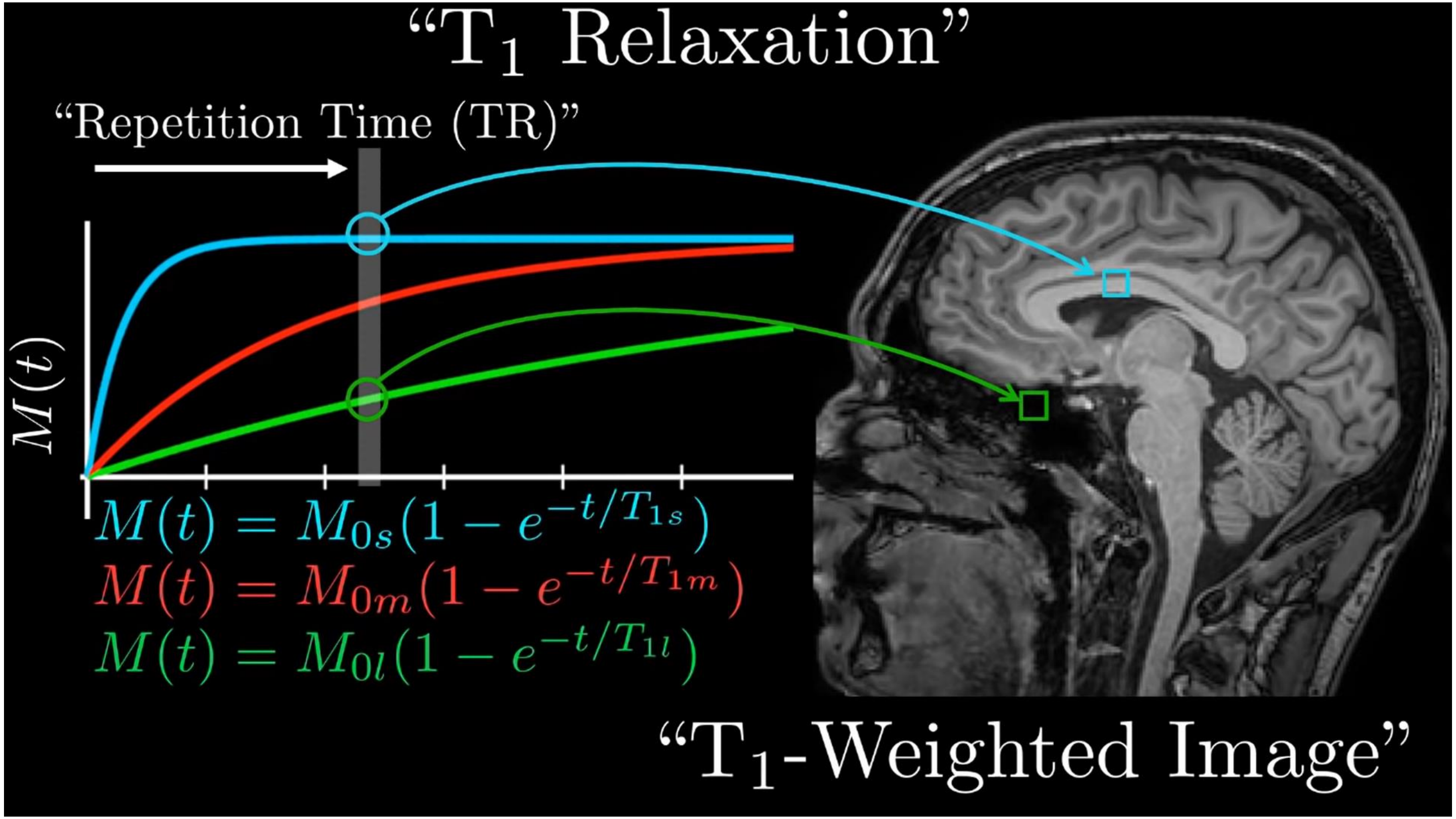
T_1 weighting

Different tissues exhibit different T_1

So, this can be another source of contrast

https://www.youtube.com/watch?v=TQegSF4ZiIQ&list=PLFs-r3e2iBRGyVlYqFHbtdutrPtQXPdPc&index=13&t=2177s

Detection of Signal

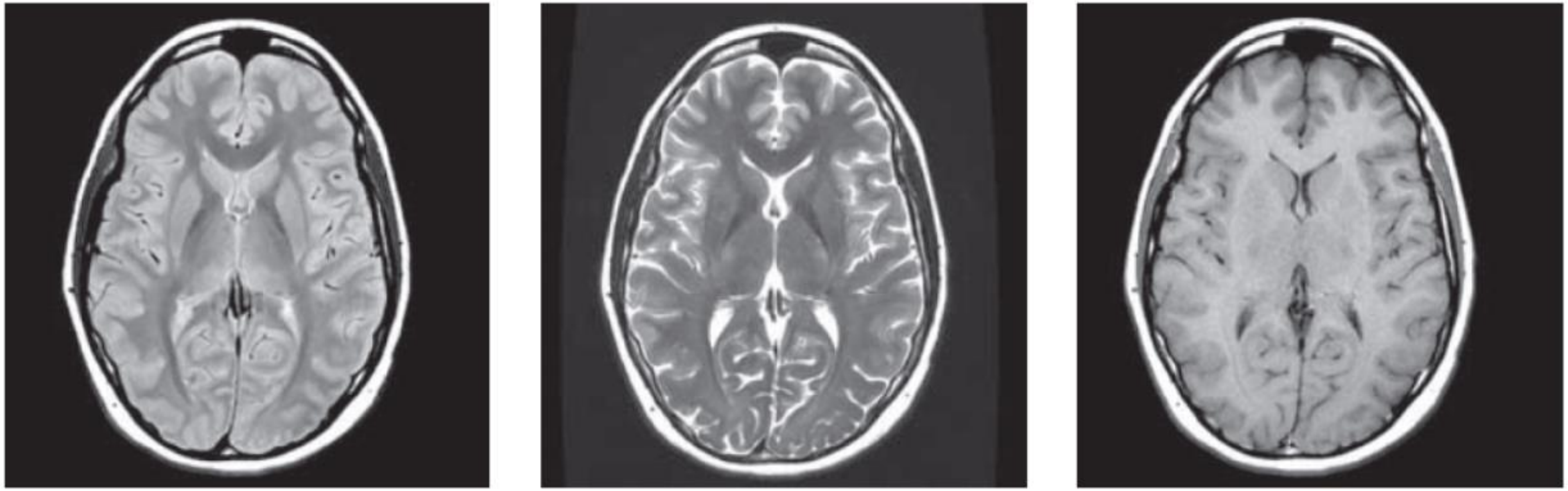


T_R: Repetition time

Chosen by MRI technician to provide the required contrast

https://www.youtube.com/watch?v=TQegSF4ZiIQ&list=PLFs-r3e2iBRGyVlYqFHbtdutrPtQXPdPc&index=13&t=2177s

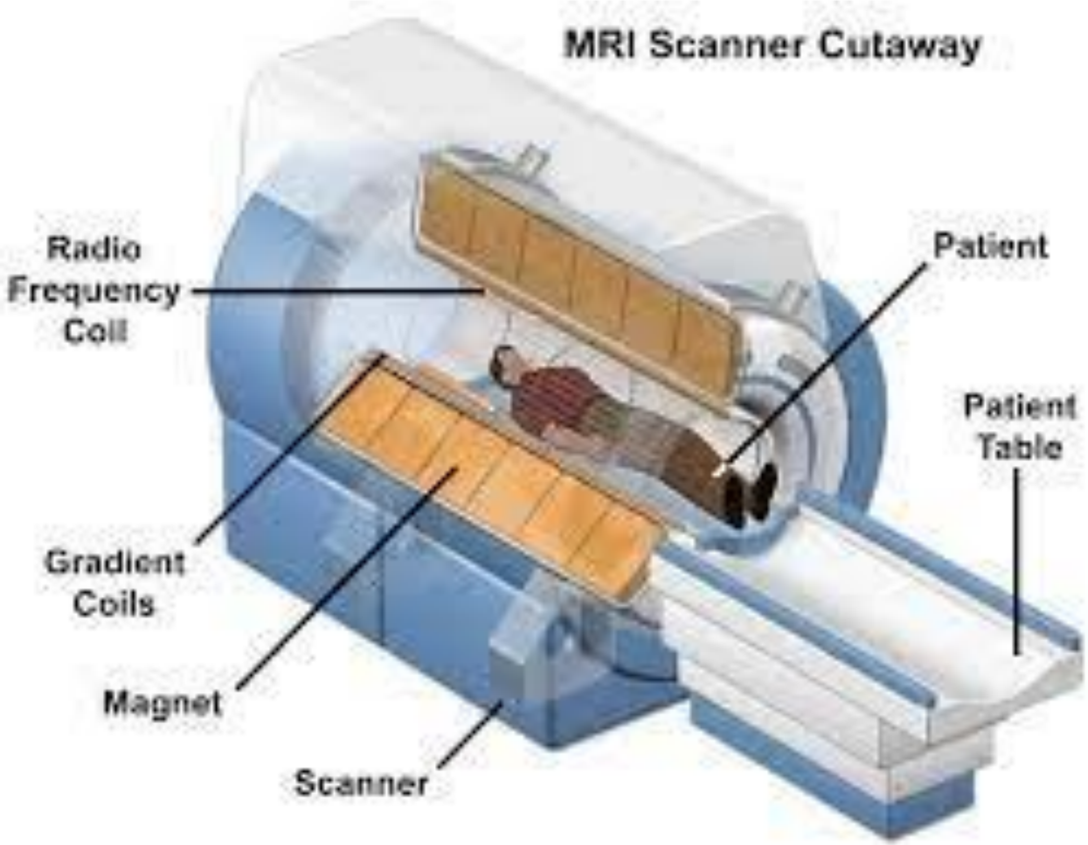
PD, T1 and T2 Weighted Images



(a) (b) (c)

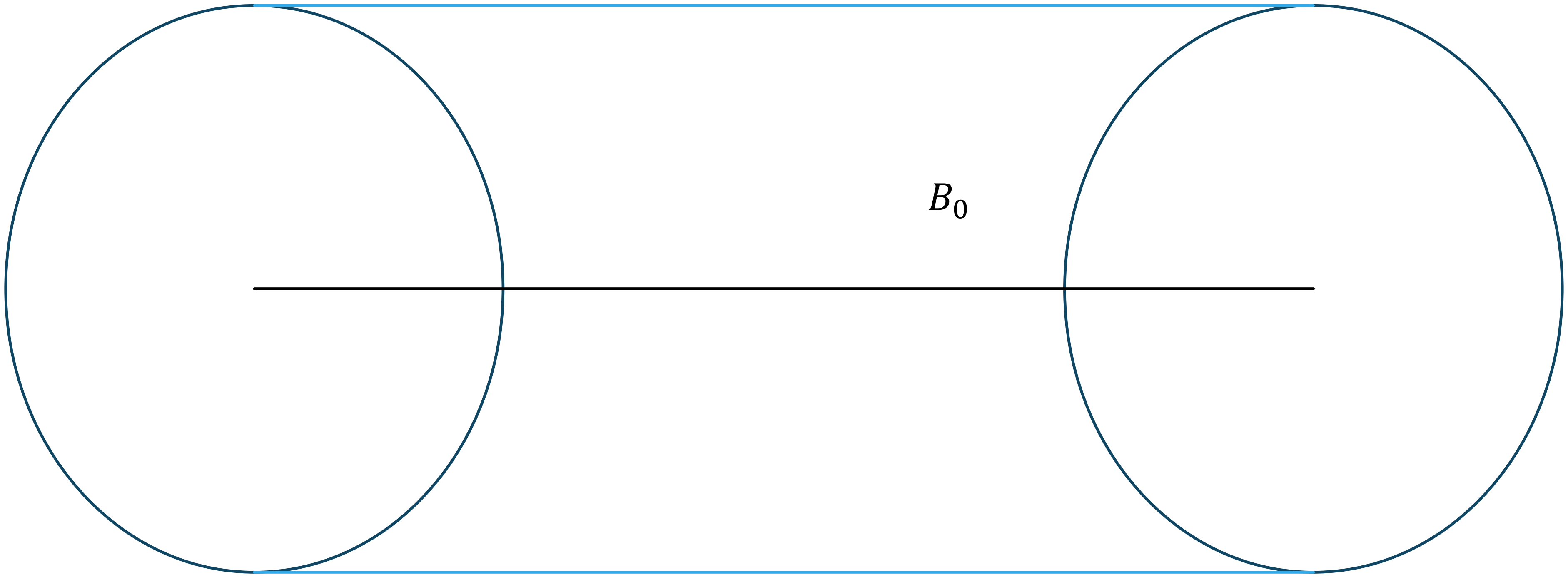
Figure 12.10
Three images of the same slice through the skull. Contrast between the tissue types are classified as (a) P_D-weighted, (b) T_2-weighted, and (c) T_1-weighted. Courtesy of GE Healthcare.

MRI Scanner

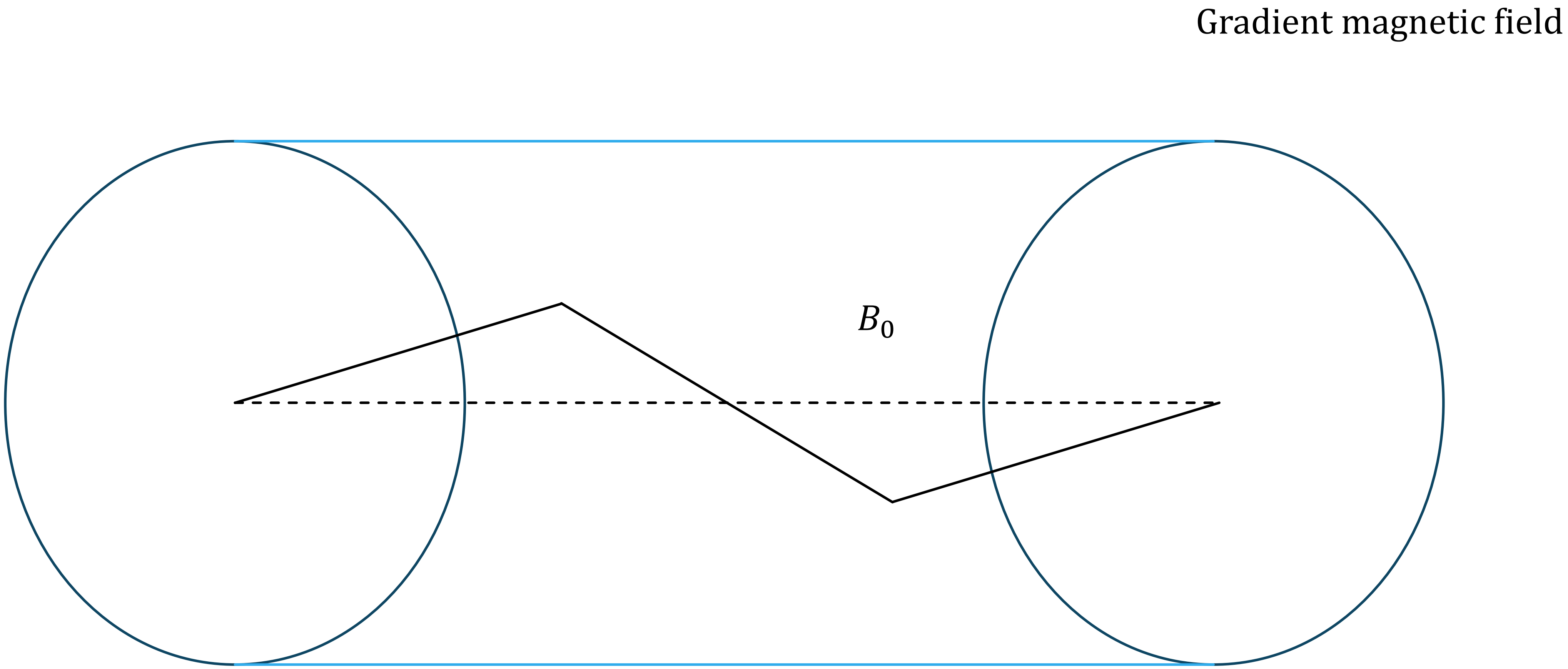


MRI Scanner Cutaway
Radio
Frequency
Coil
Patient
Patient
Table
Gradient
Coils
Magnet
Scanner

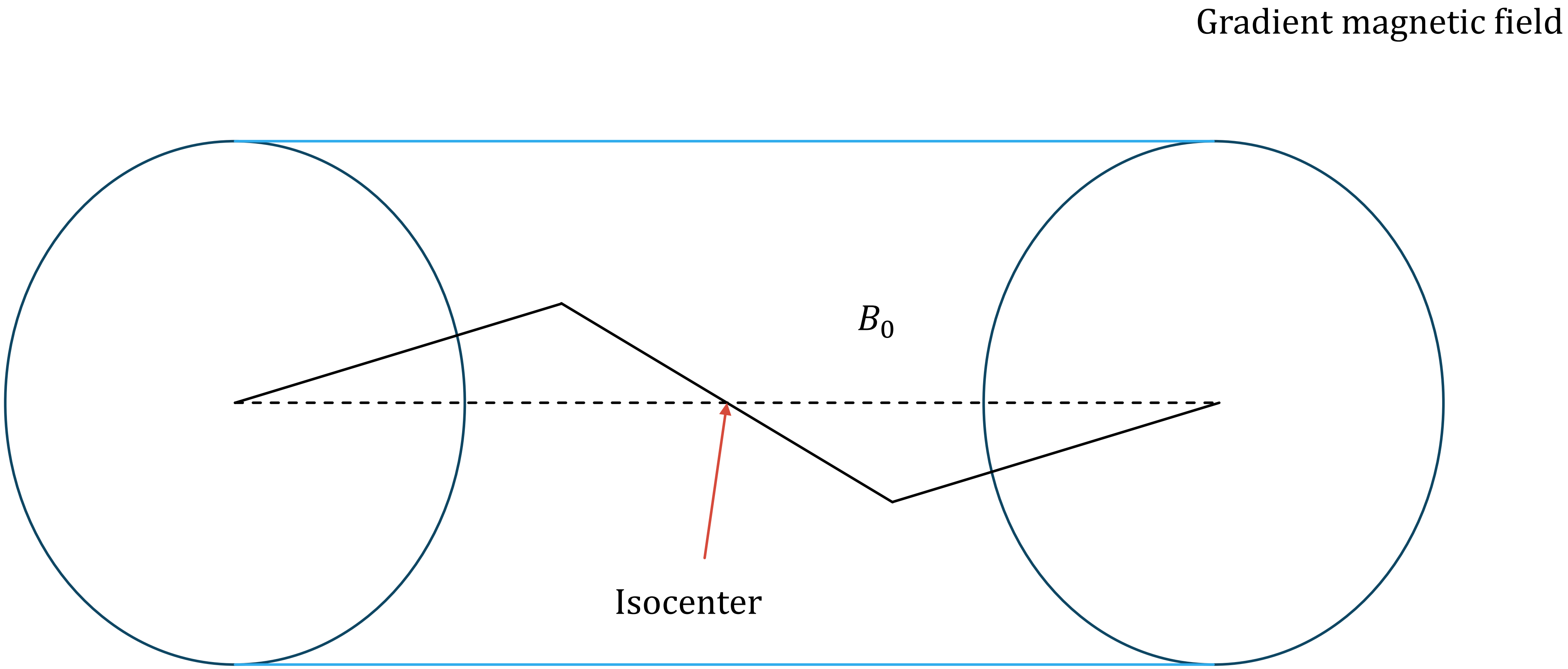
Slice Selection



Slice Selection

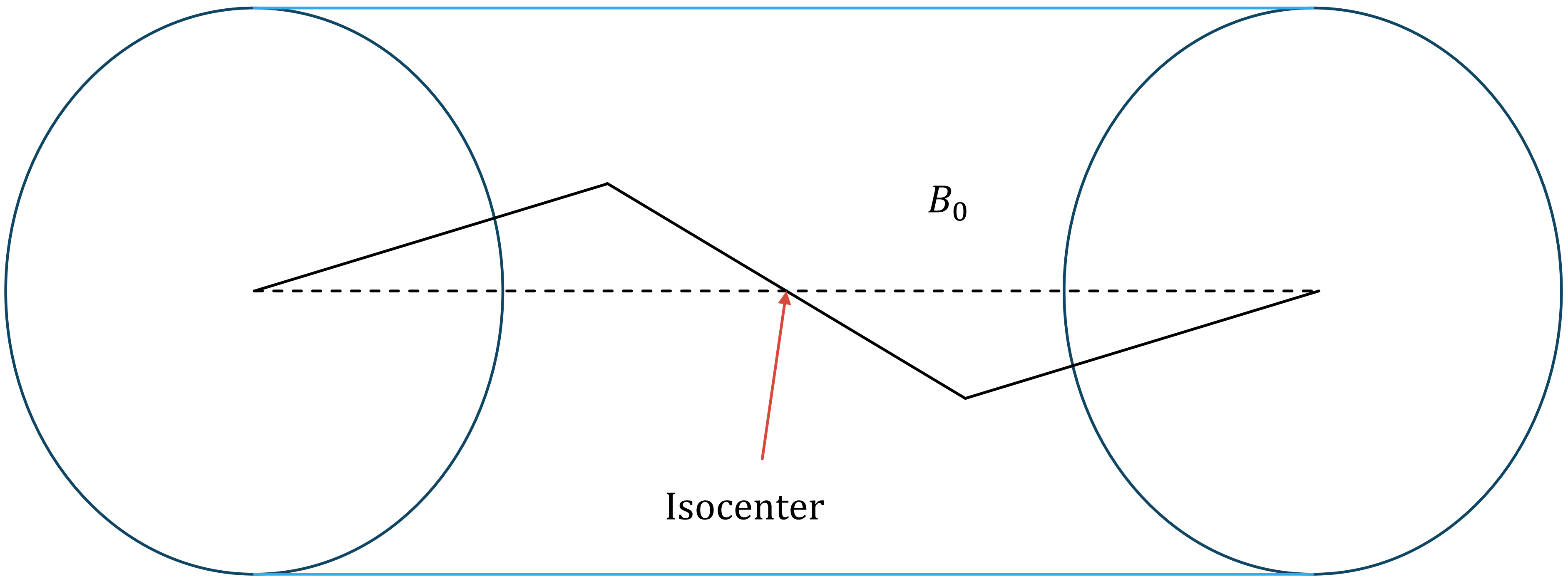


Slice Selection

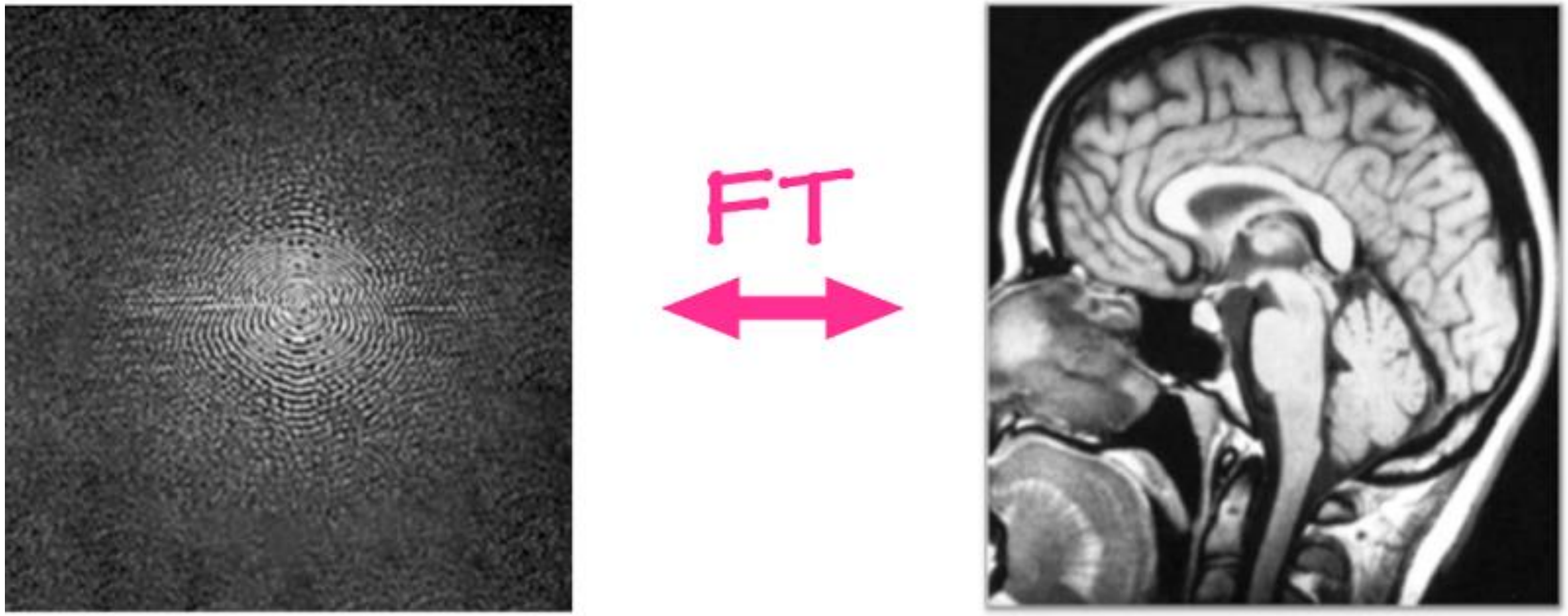


Slice Selection

Slice thickness is dependent on BW of RF pulse



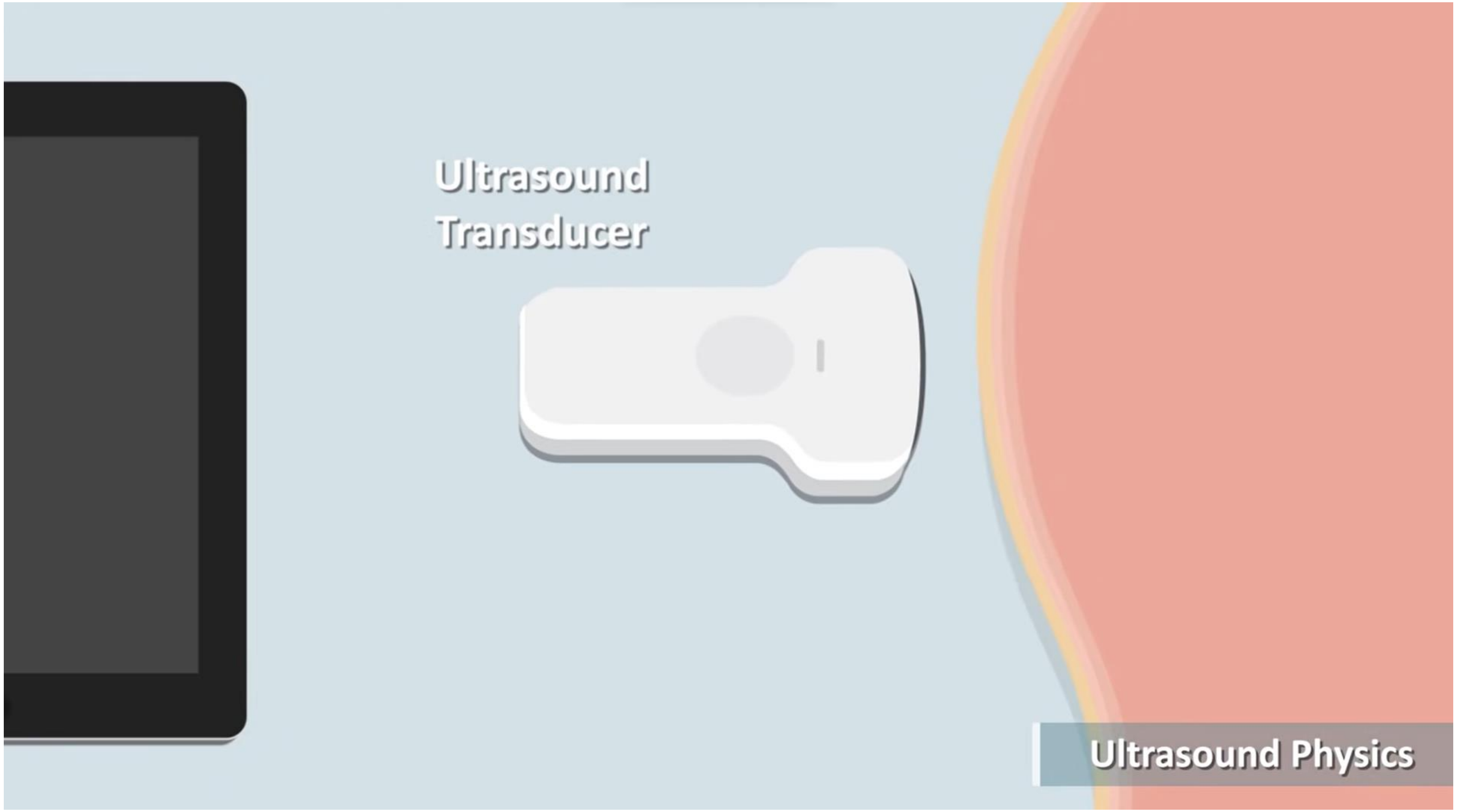
k-Space



K-space if the Fourier Transform of MR images

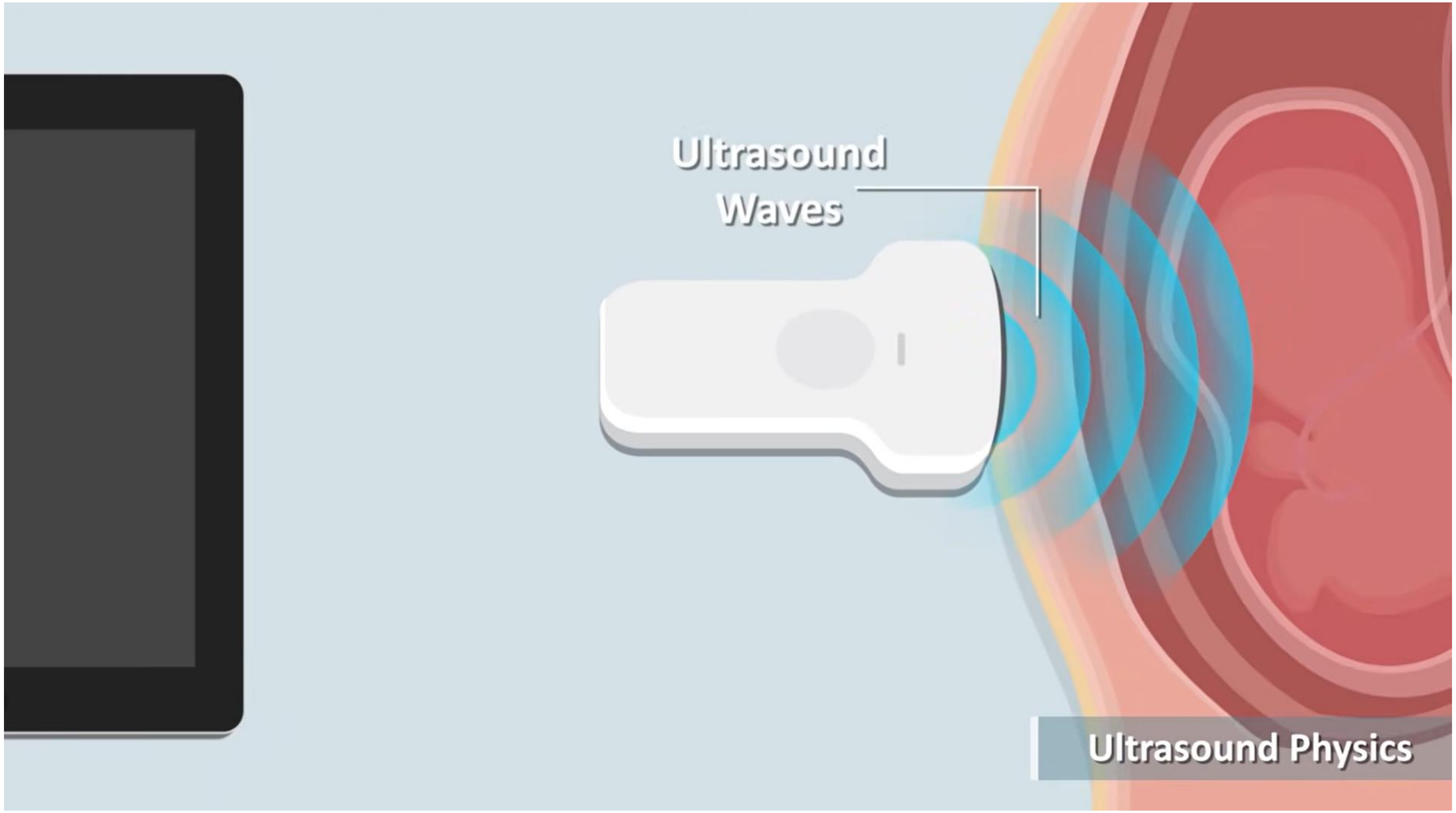
Ultrasound

Ultrasound

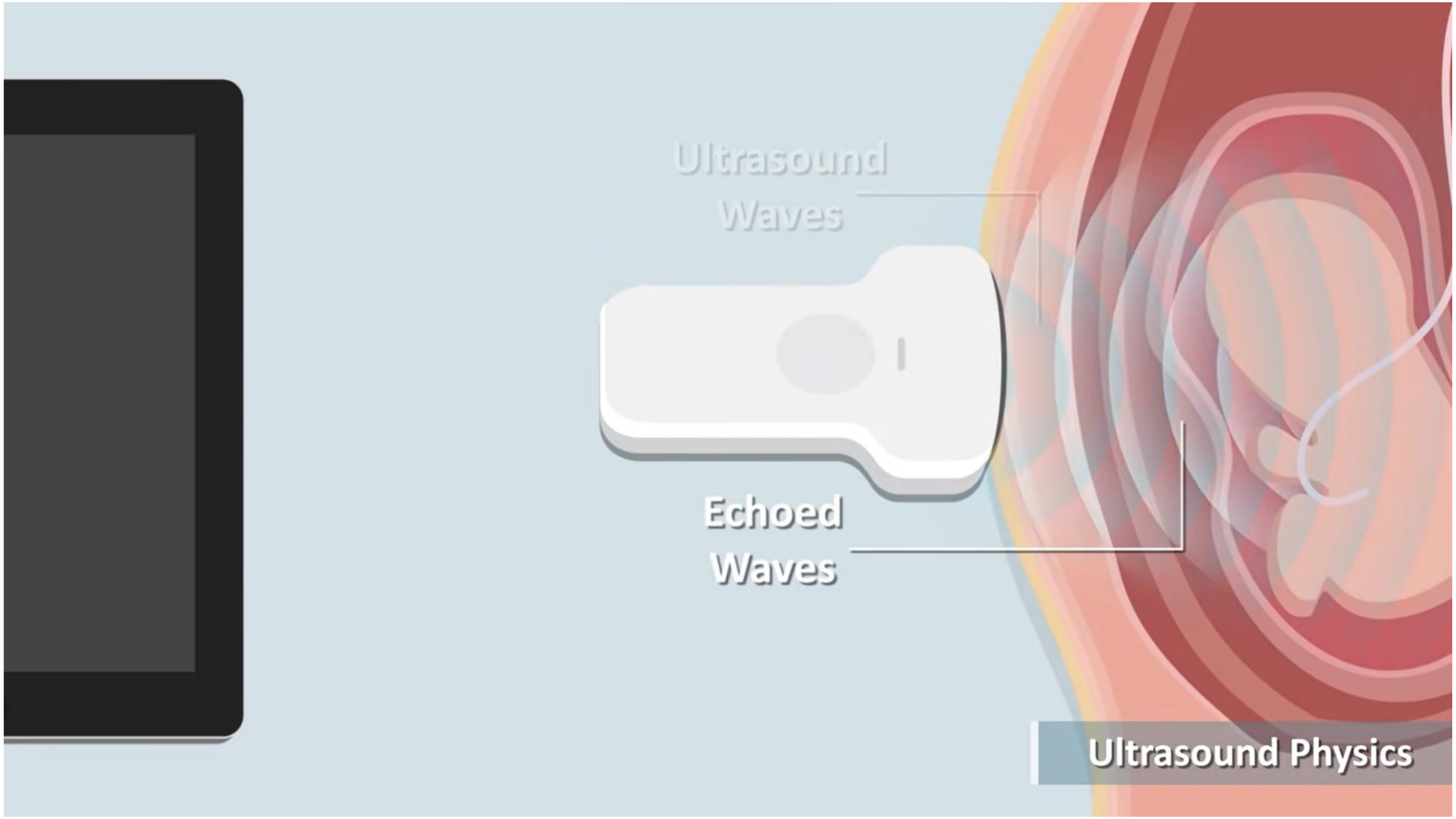


https://www.youtube.com/watch?v=cI7ULKNhVcw

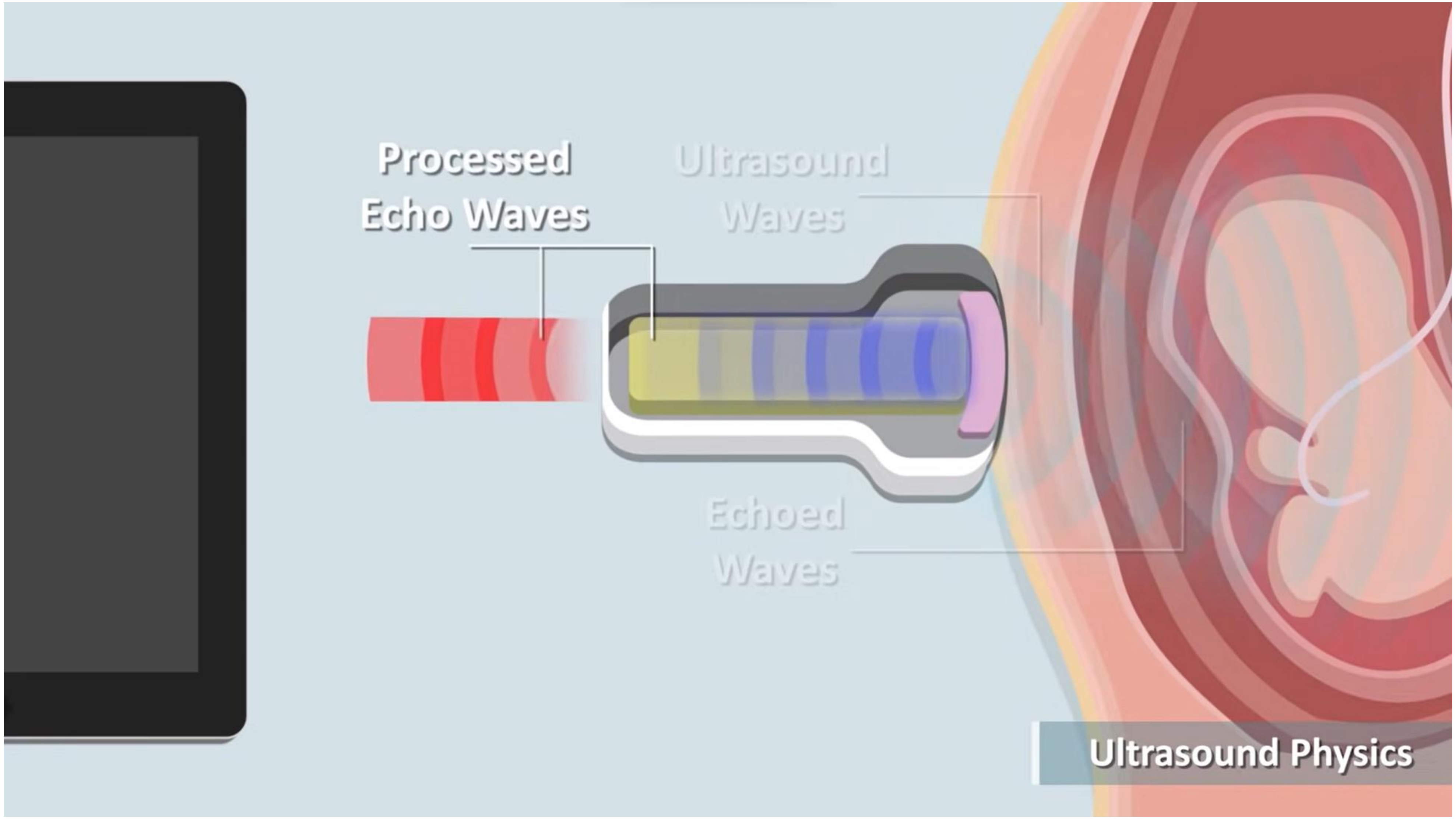
Ultrasound



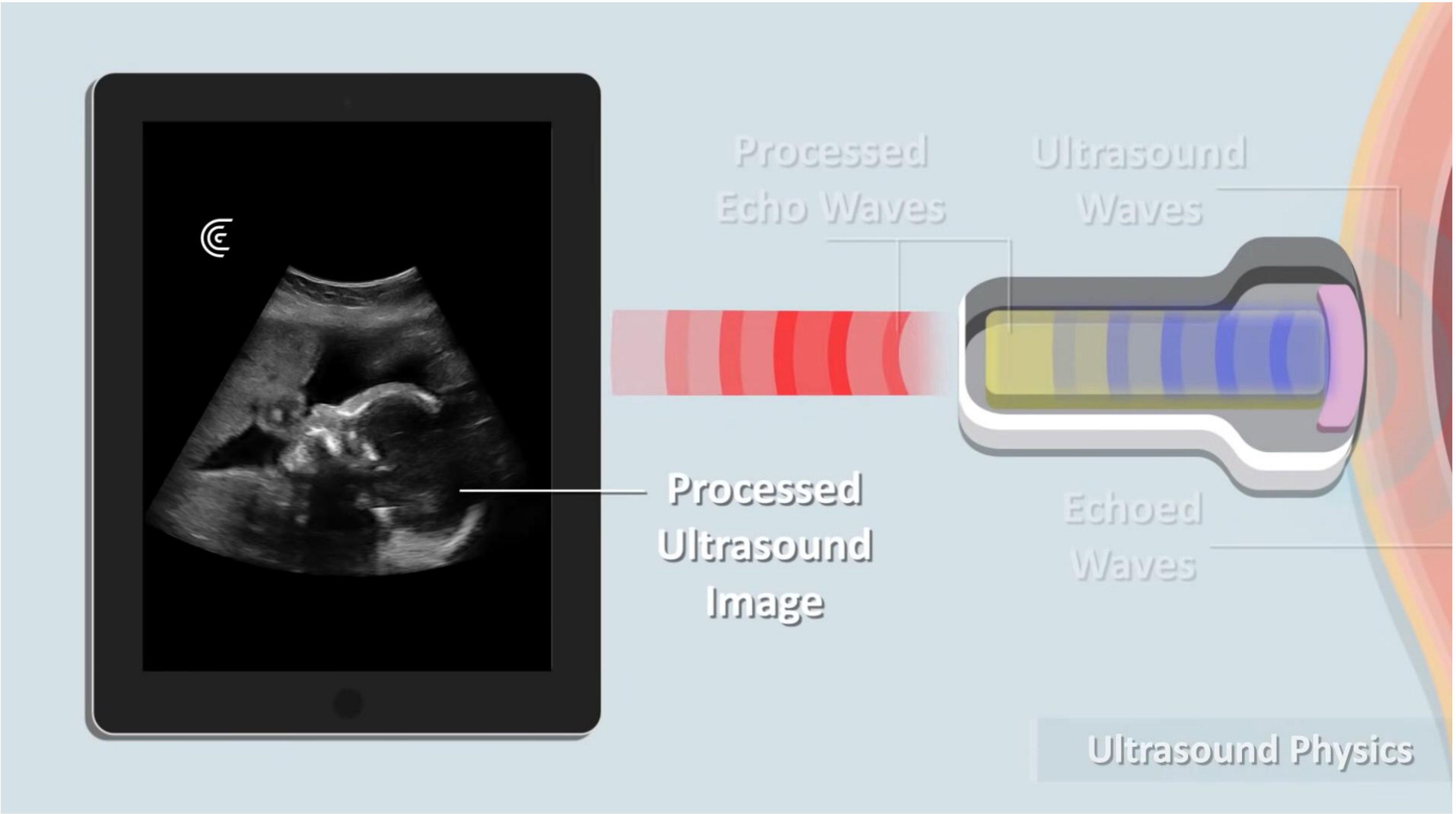
Ultrasound



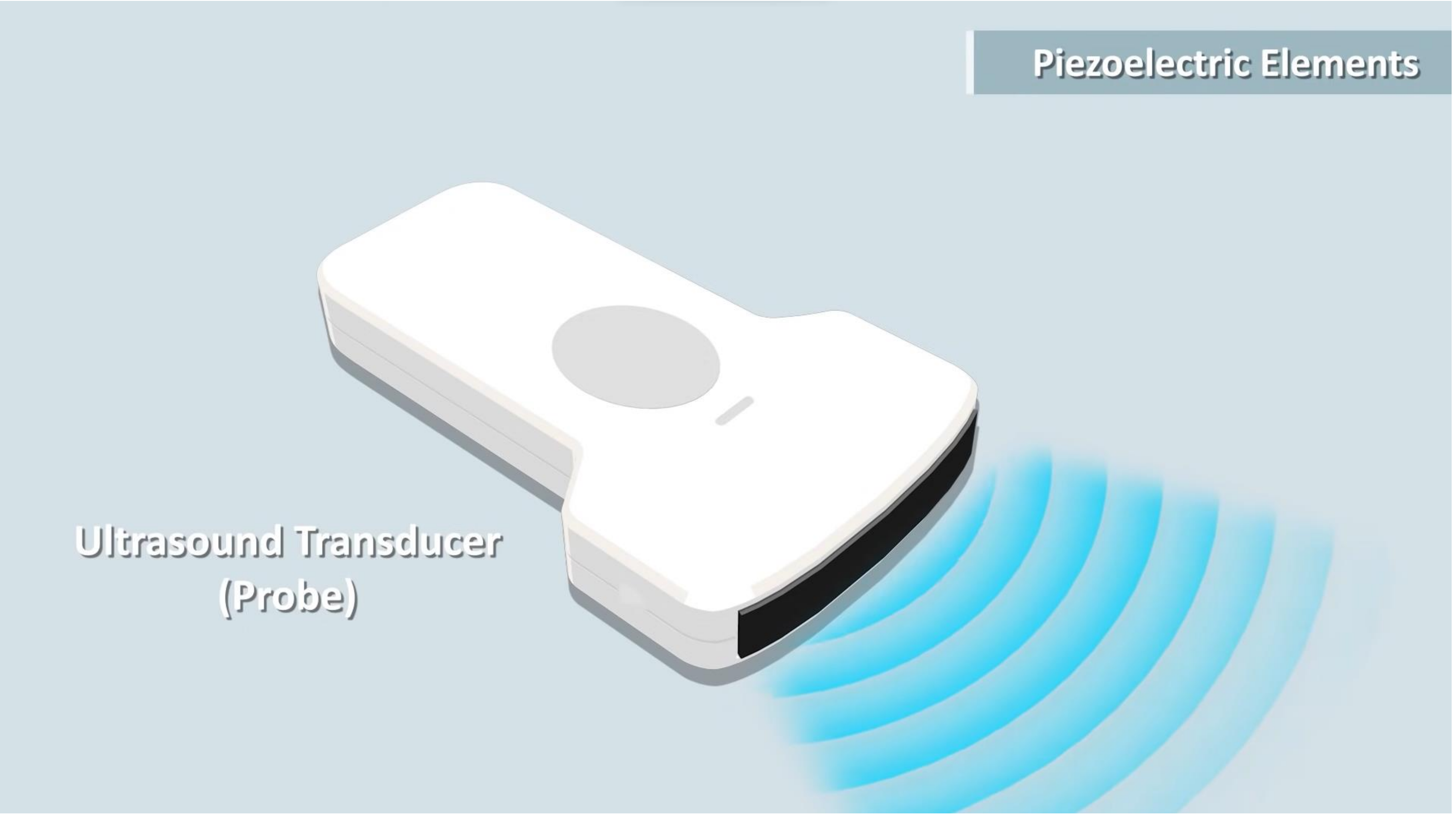
Ultrasound


Processed
Echo Waves
Ultrasound
Waves
Echoed
Waves
Ultrasound Physics

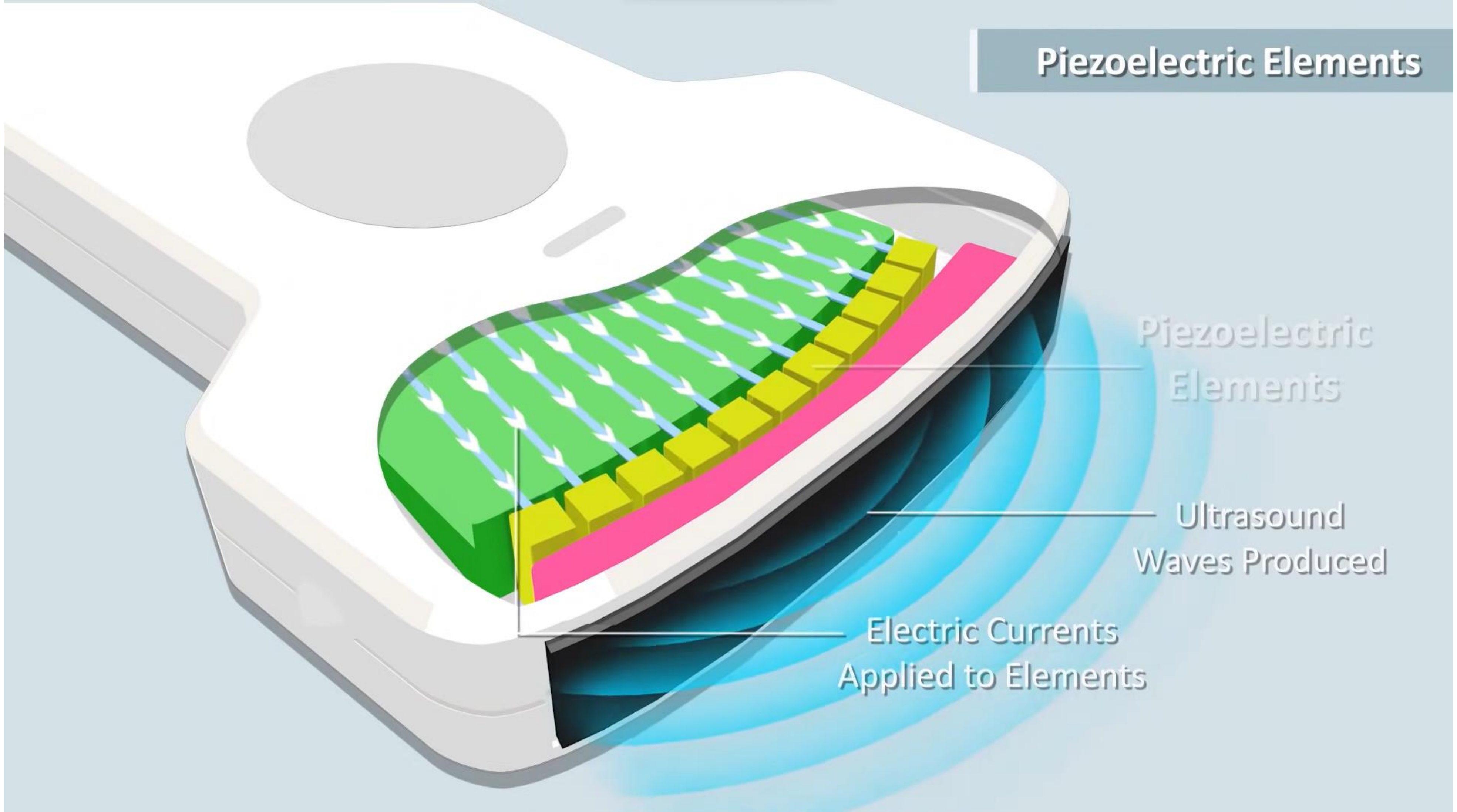
Ultrasound


Processed
Echo Waves
Ultrasound
Waves
Processed
Ultrasound
Image
Echoed
Waves
Ultrasound Physics

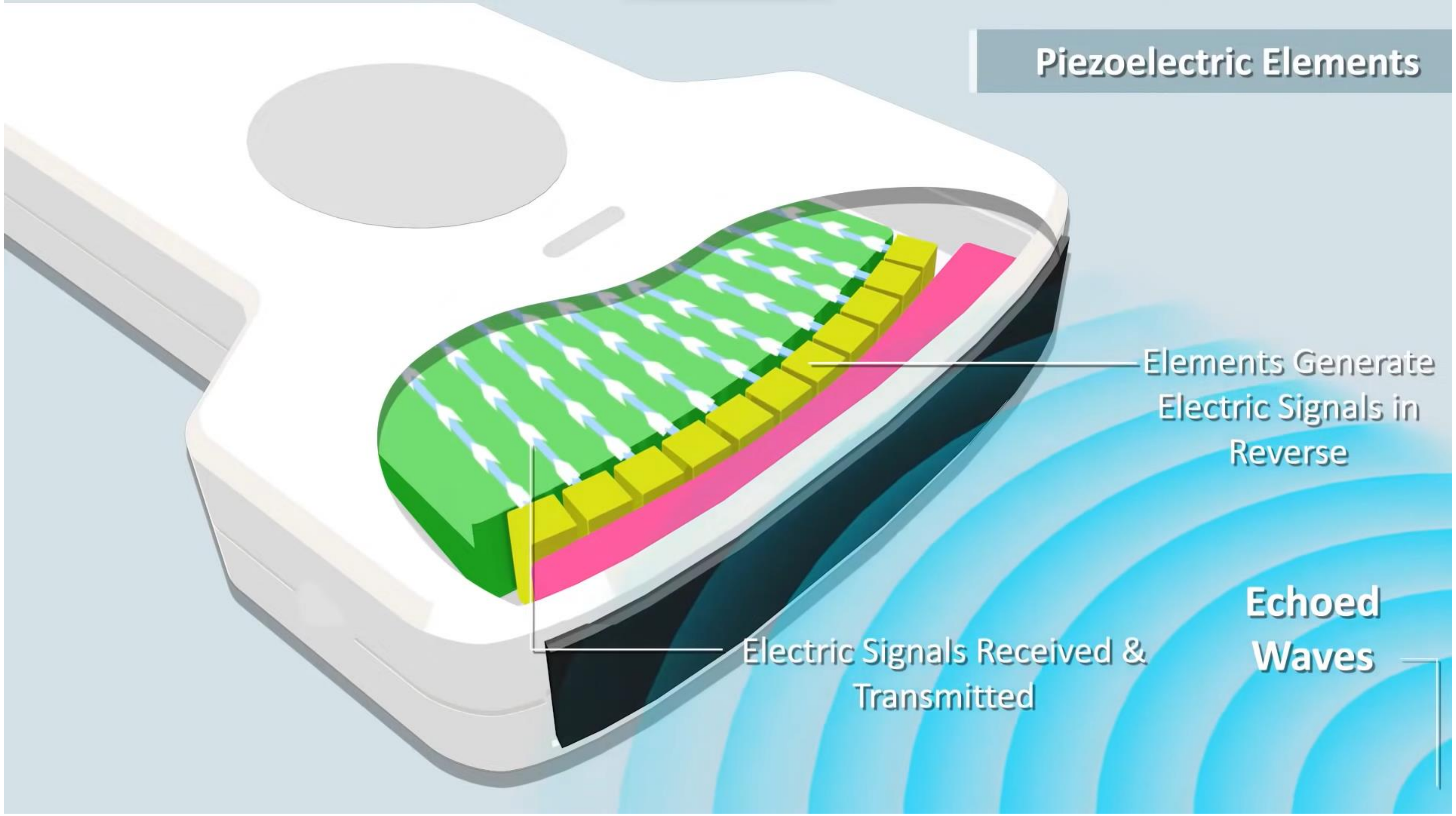
Ultrasound



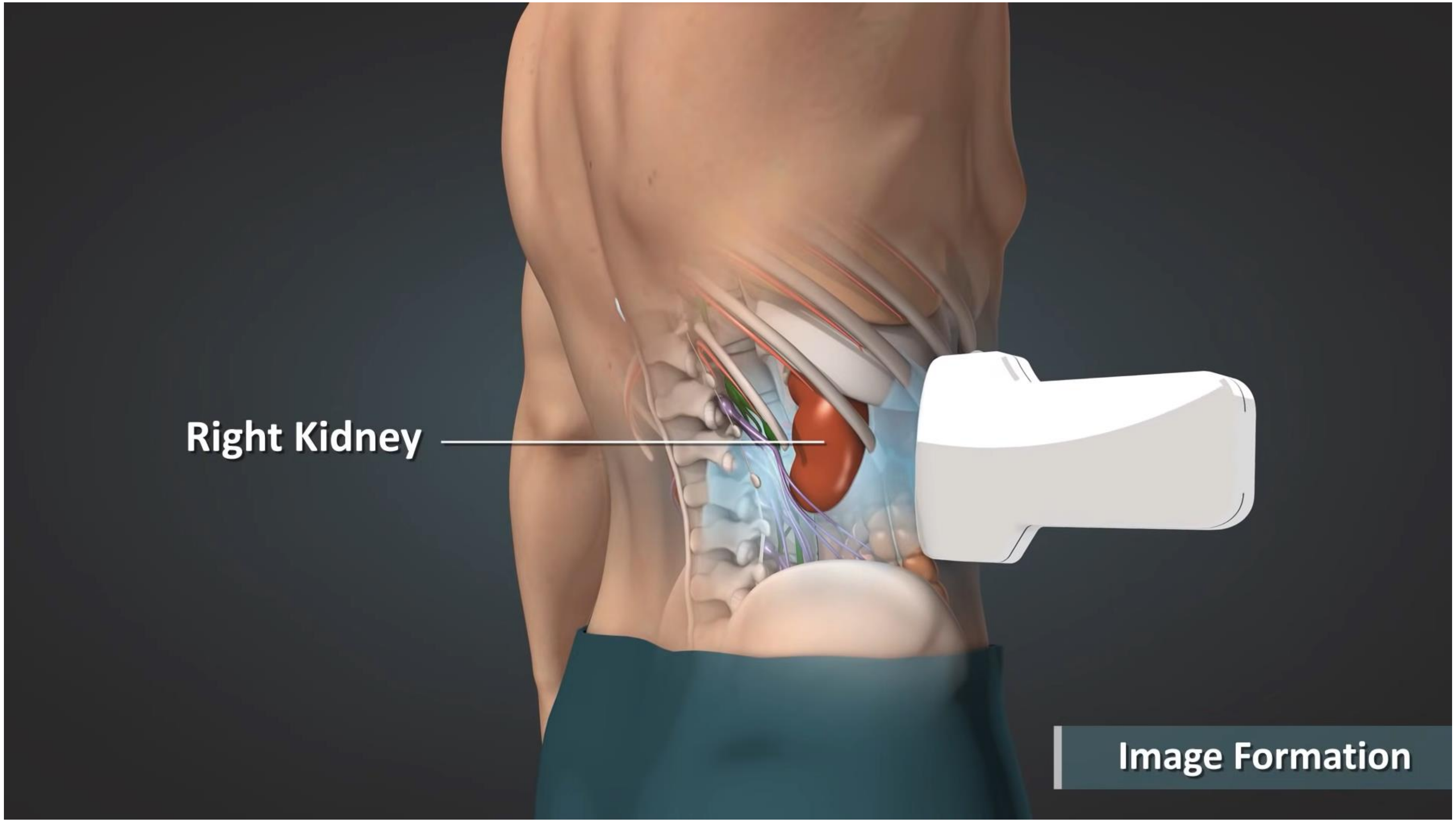
Ultrasound


Piezoelectric Elements
Piezoelectric
Elements
Ultrasound
Waves Produced
Electric Currents
Applied to Elements

Ultrasound


Piezoelectric Elements
Elements Generate Electric Signals in Reverse
Echoed Waves
Electric Signals Received & Transmitted

Ultrasound Image Formation



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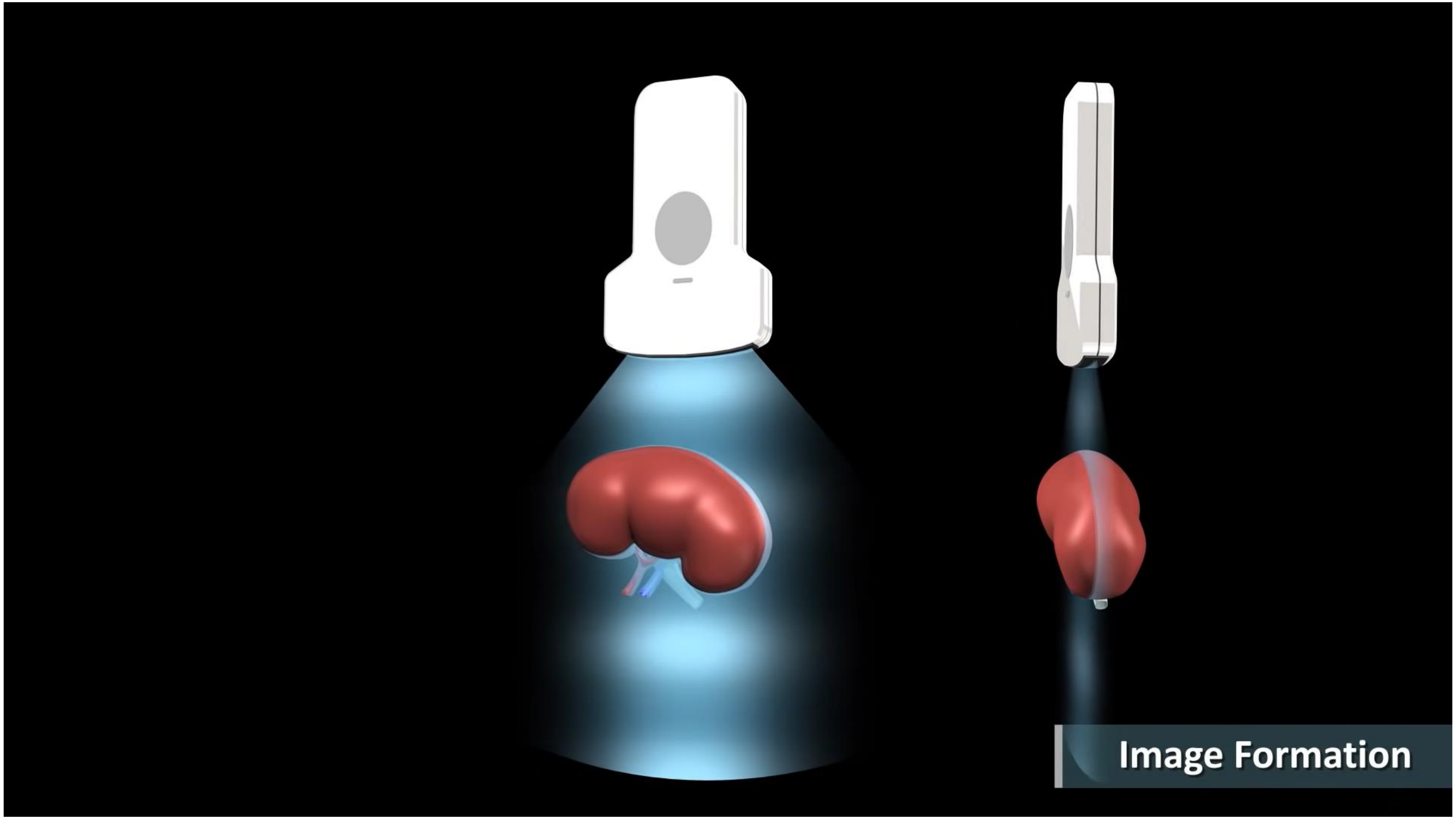

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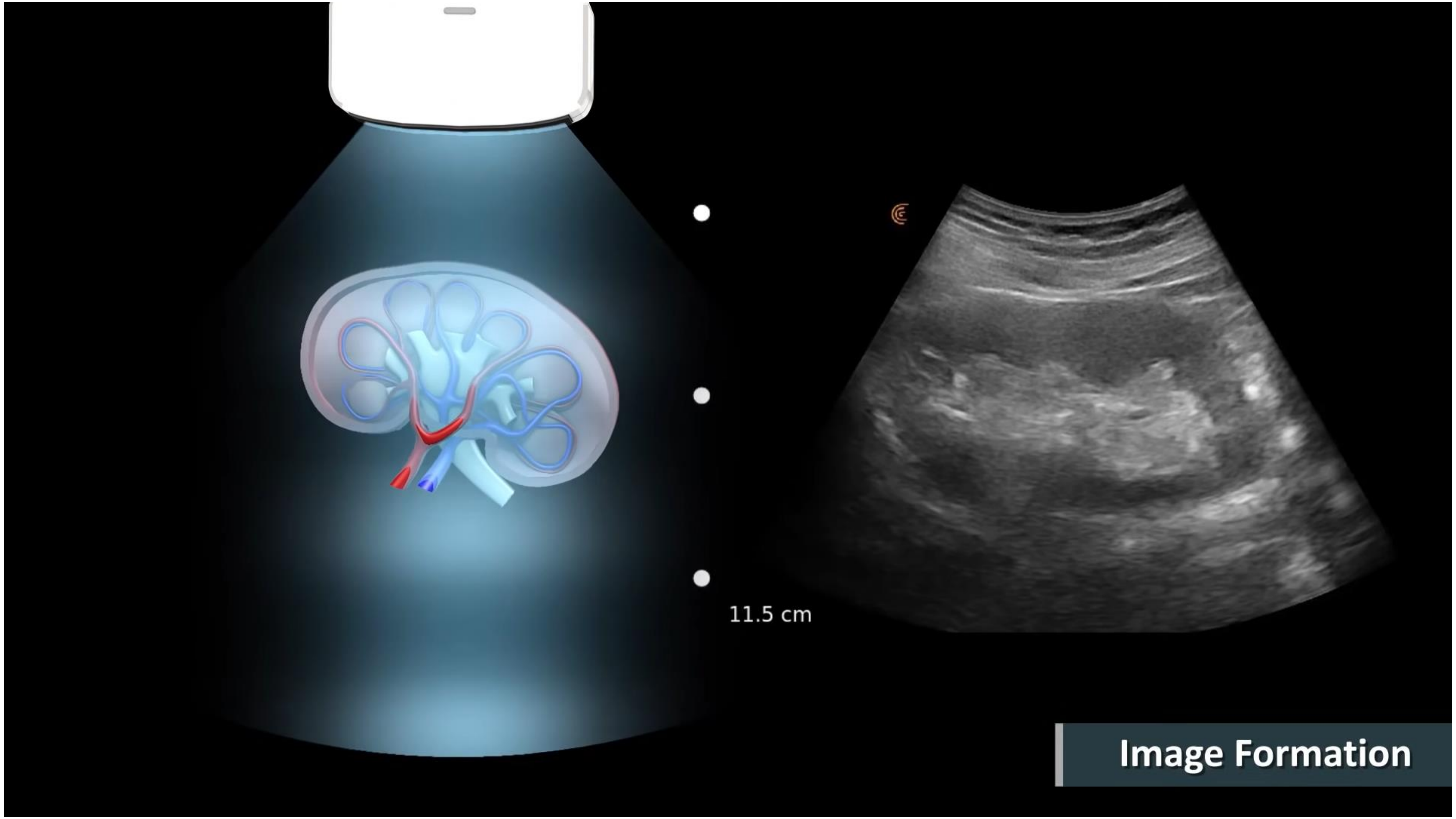

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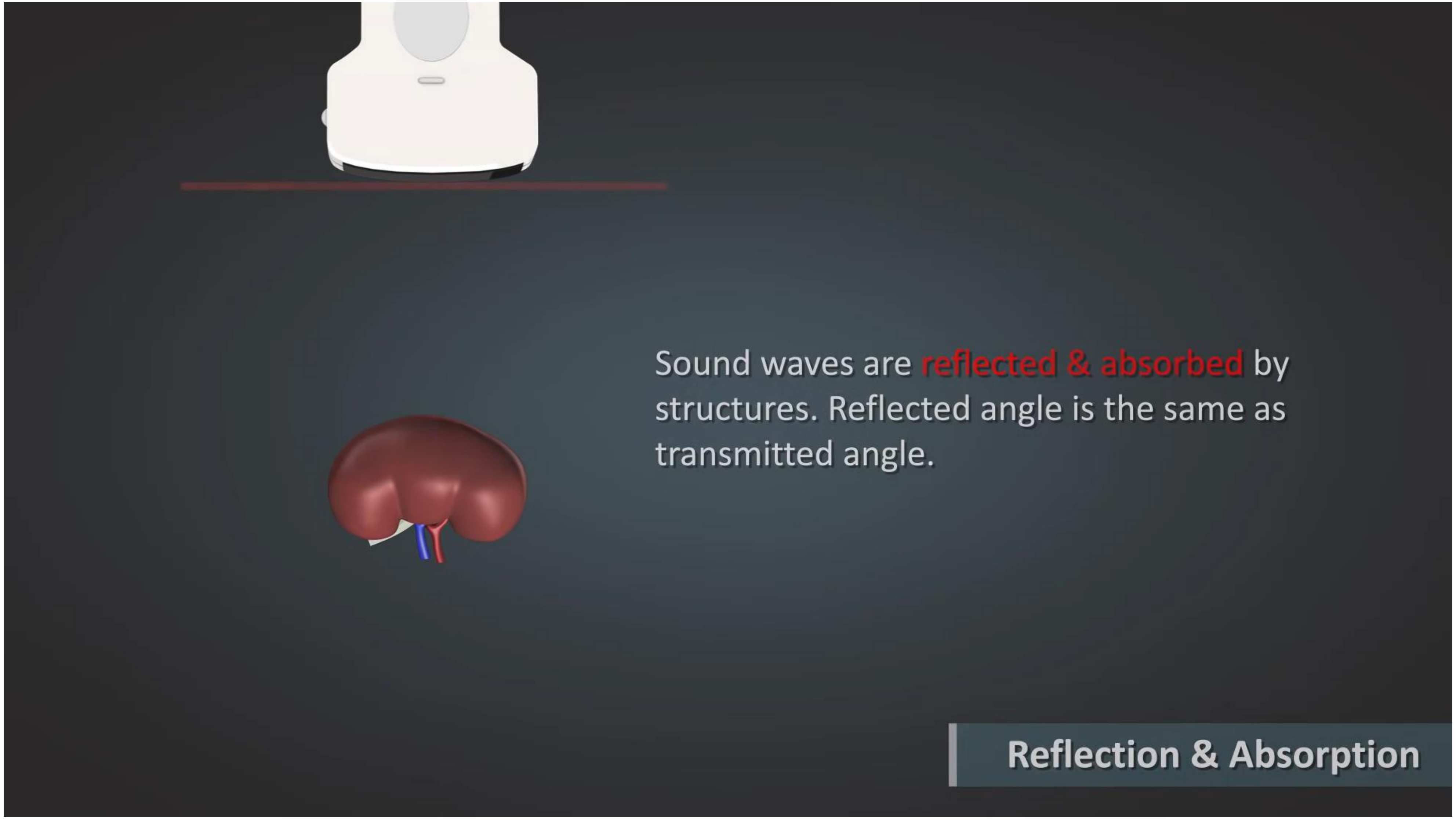

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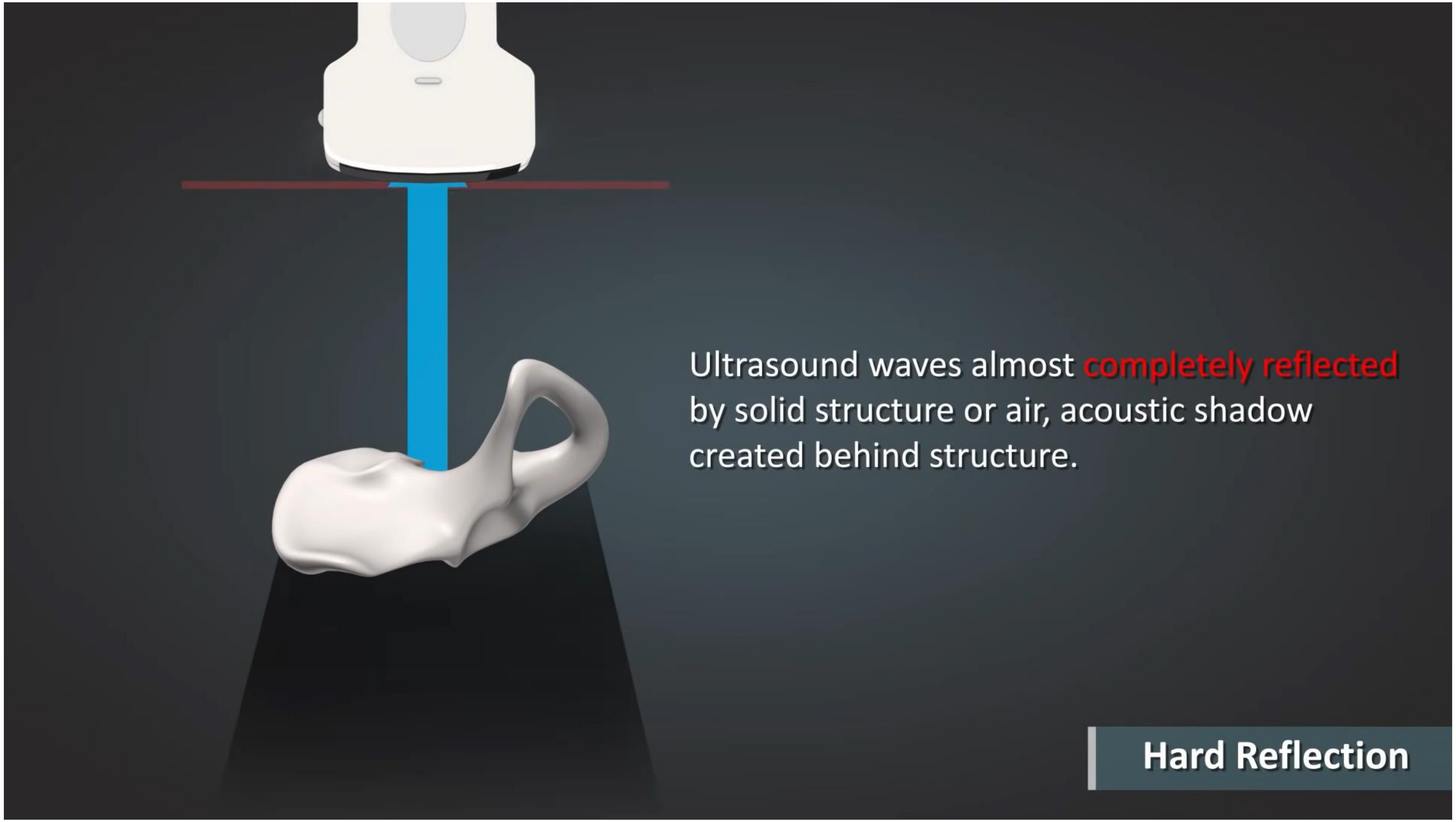

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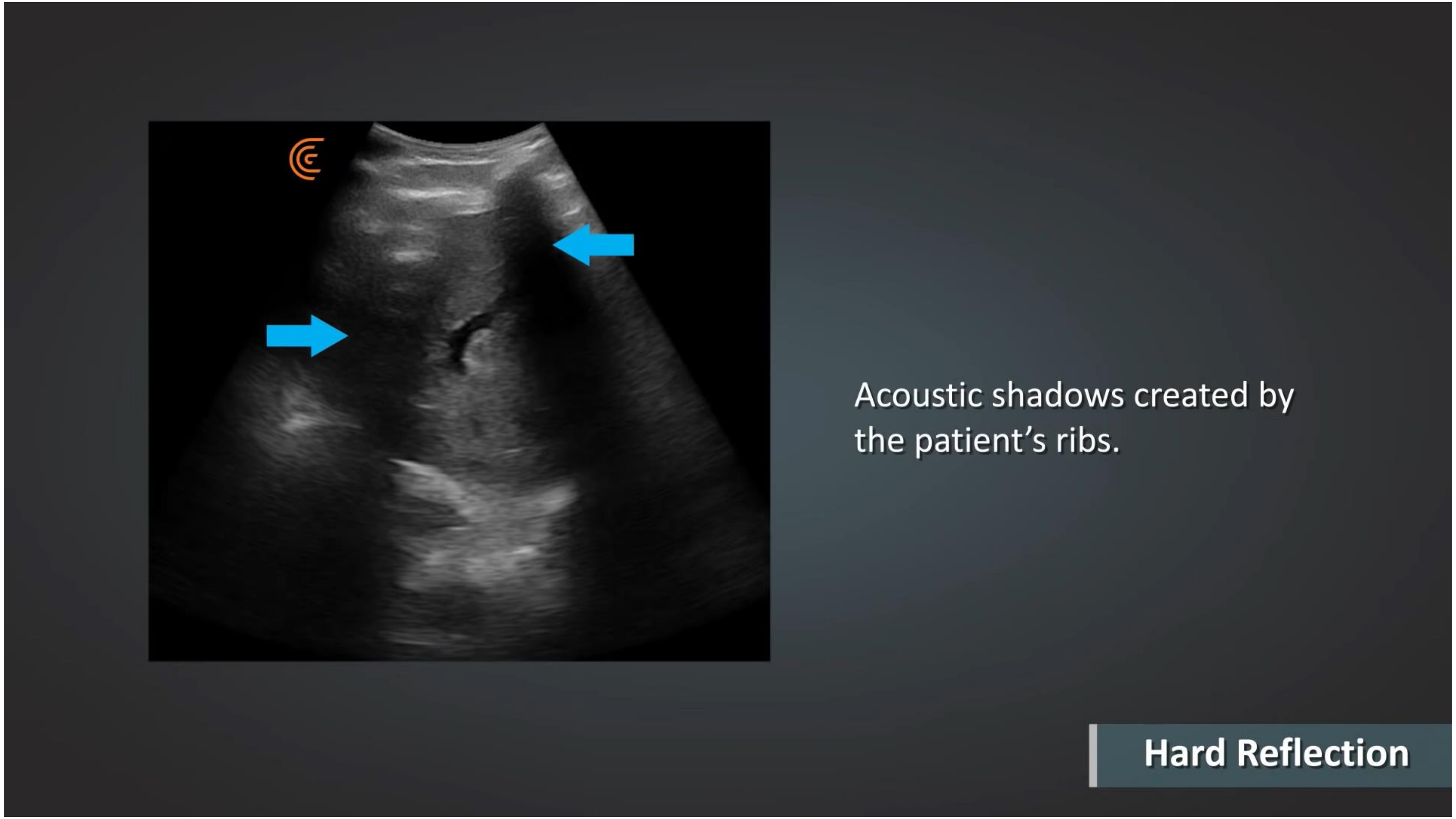

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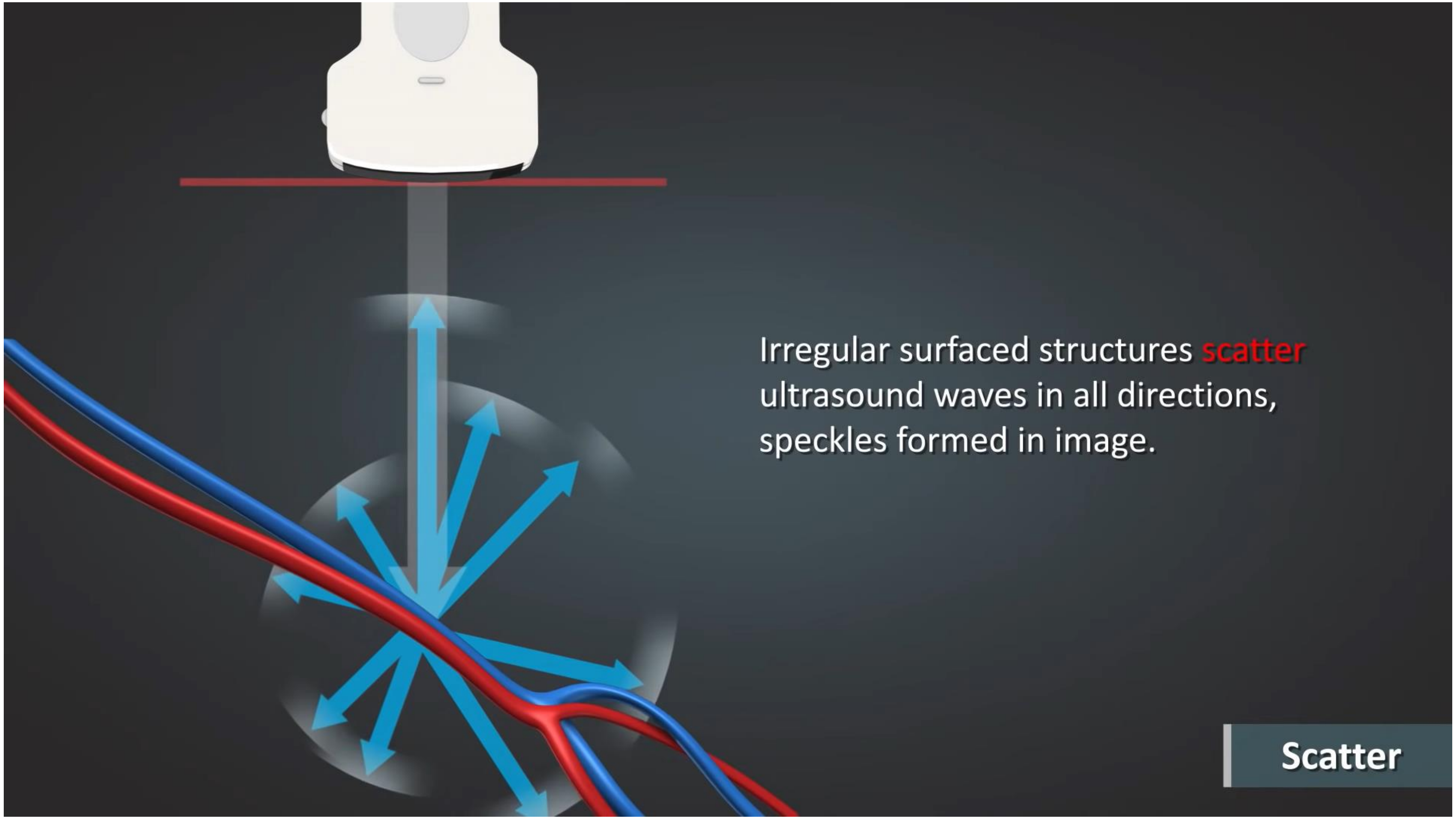

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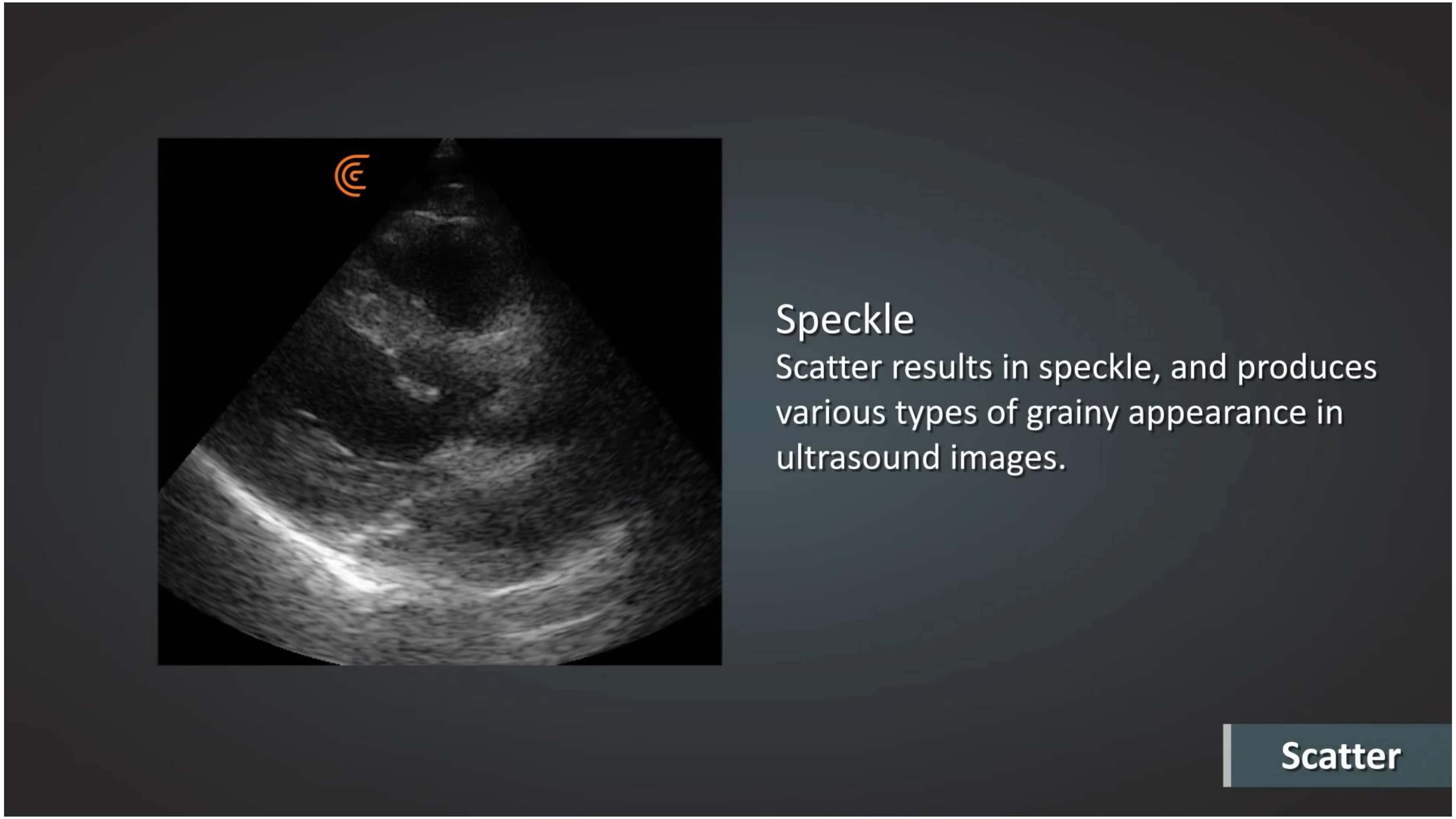

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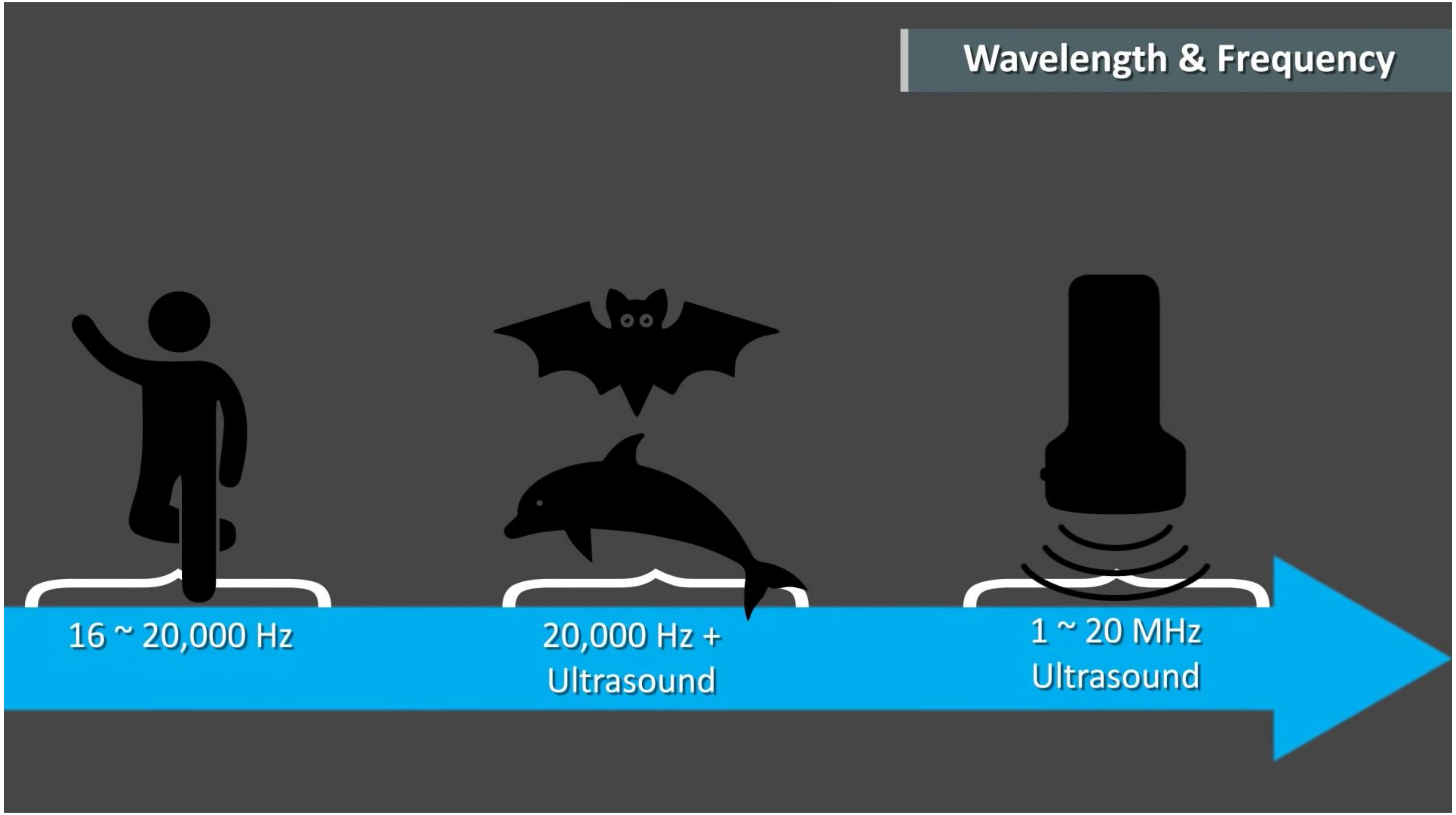

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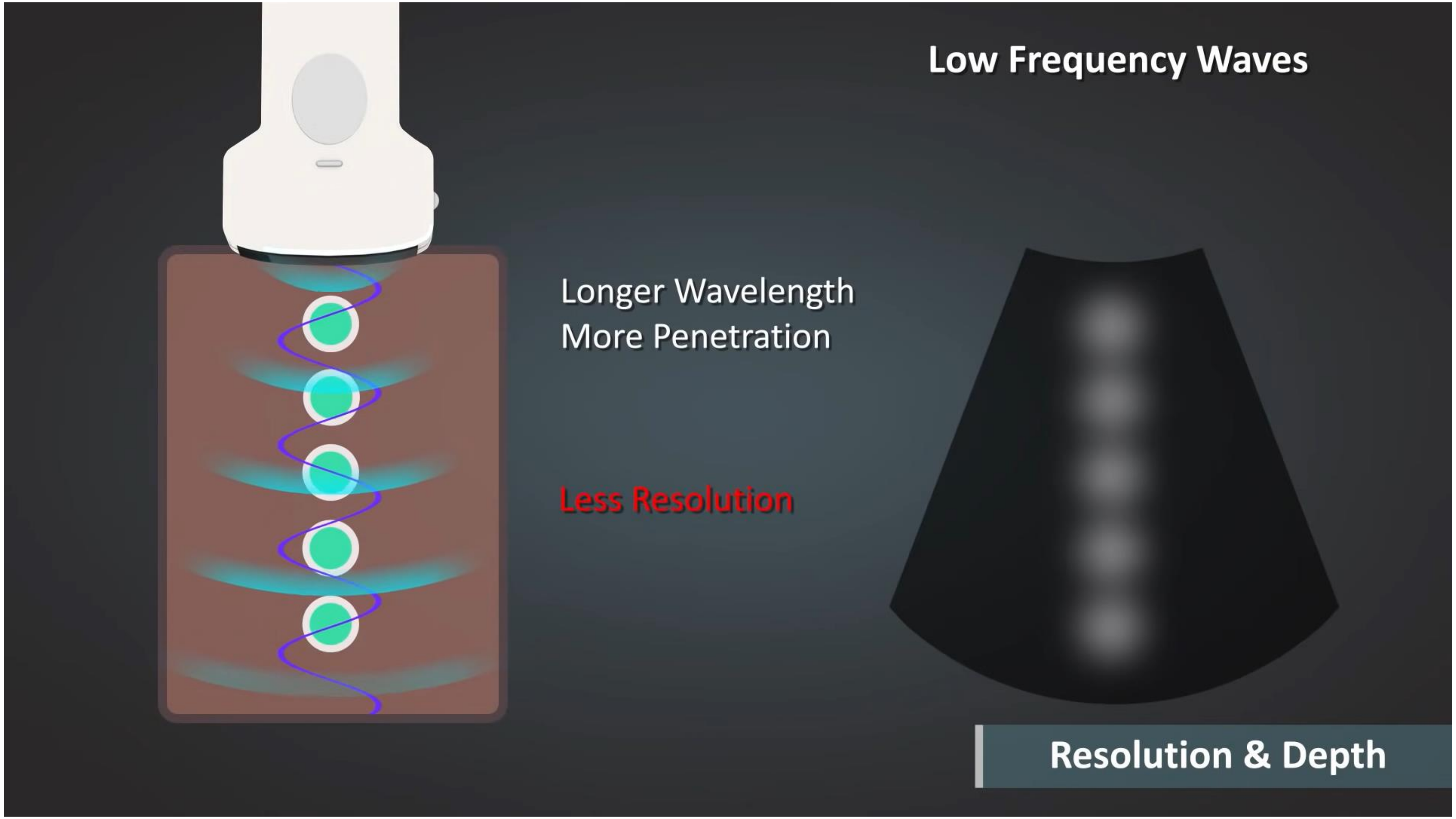

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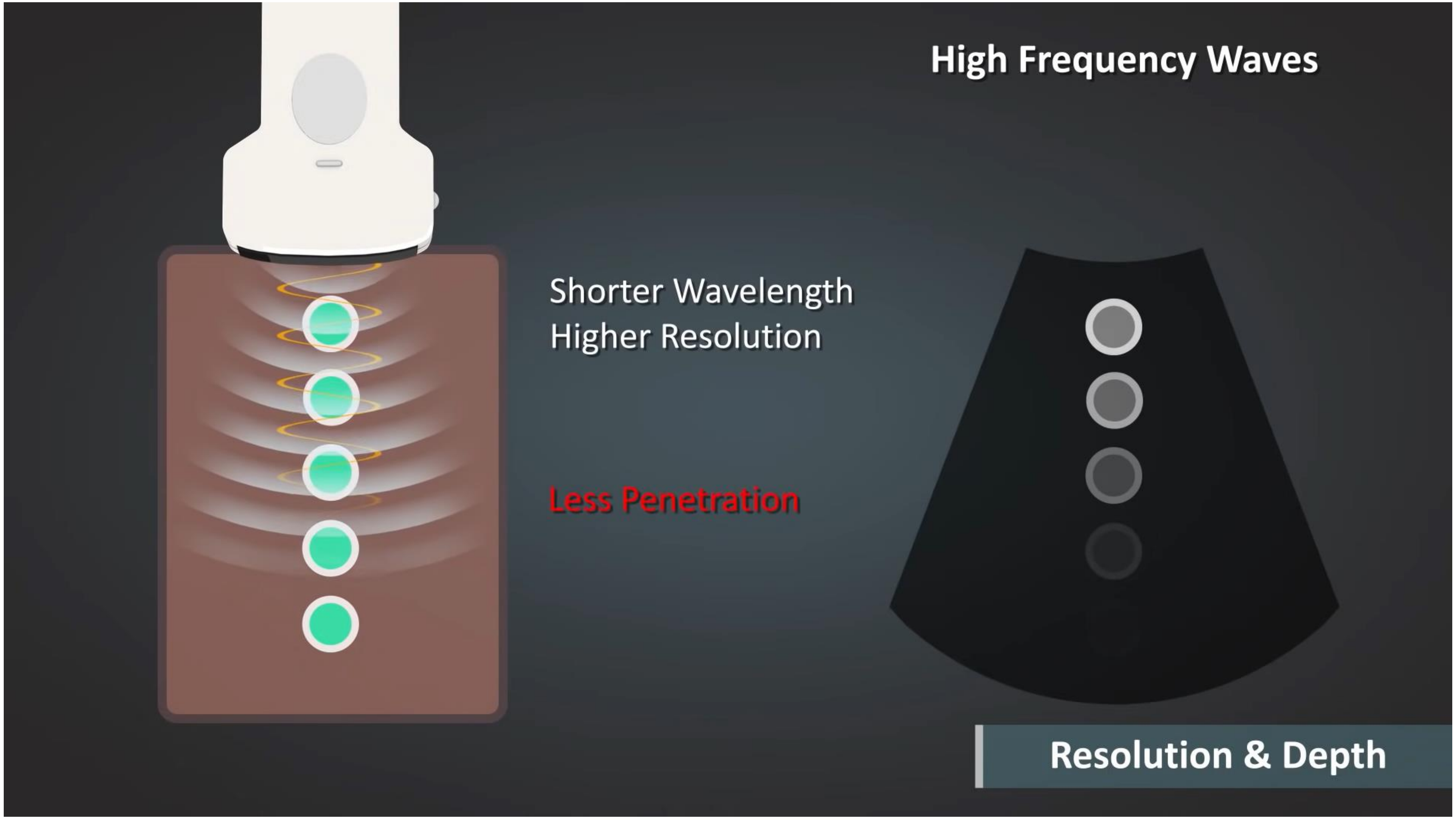

Ultrasound Image Formation