

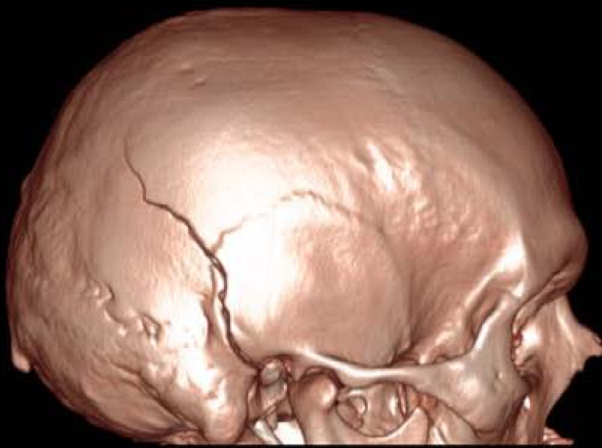

Principles and State of the Art of Medical Imaging Systems

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Motto:
One image is better than thousand words




All images were adopted from webpage http://www.medical.toshiba.com

How to start?

- Maybe by question(s) or quiz or test!
- By what question(s)?
- What does it mean imaging?
- What is the simplest imaging system?
- Why are the imaging systems so important?

Answers

- What does it mean imaging?

- Imaging is the representation or reproduction of an object's outward form; especially a visual representation.

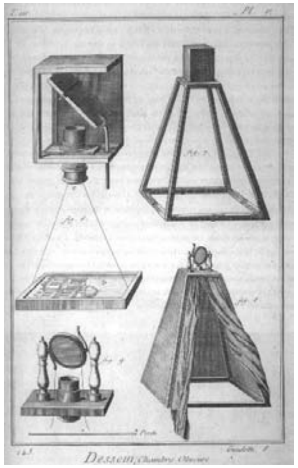
↓

the formation of an image

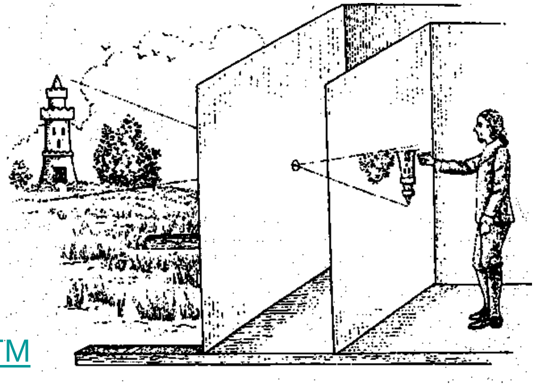
Answers

- What is the simplest imaging system?

- The camera obscura (Latin *veiled chamber*) is an optical device used, for example, in drawing or for entertainment.



the pinhole camera



From courses.essex.ac.uk/lt/lt204/GERMAN.HTM

From "Encyclopédie, ou dictionnaire raisonné des sciences, des arts et des métiers,,, 1772

Answers

- What are the imaging systems so important?
- Medical imaging systems have an important role from the point of view of the early diagnostics and the following treatment without invasive approach.

↓

early diagnostics

Lecture motto

- One sentence is better than thousand characters

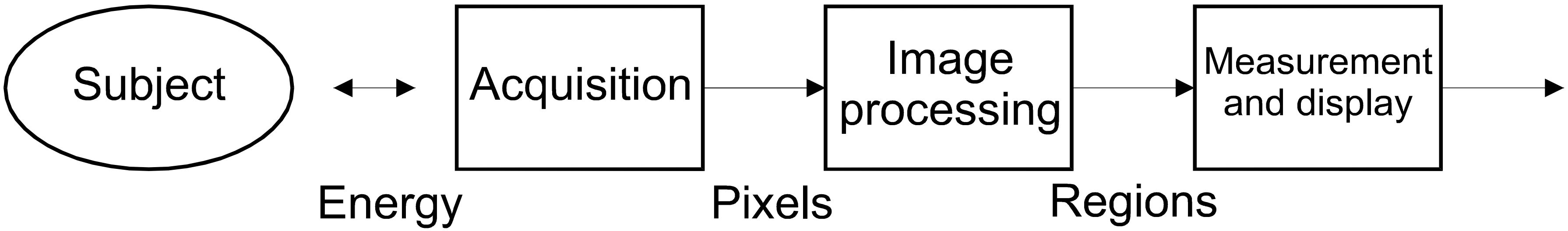
↓

- One image is better than thousand words

↓

- One videosequence is better than thousand images

Essential parts of a medical imaging system



Acquisition = building the image =
applying energy + sensing a response

reflection, transmission

Medical imaging systems

- conventional
  X-ray, X-ray TV, DSA, DR, (IR), NM

- tomographical (tomography)
  US

- tomographical (computed tomography)
  CT, MR, SPECT, PET, (EIT)

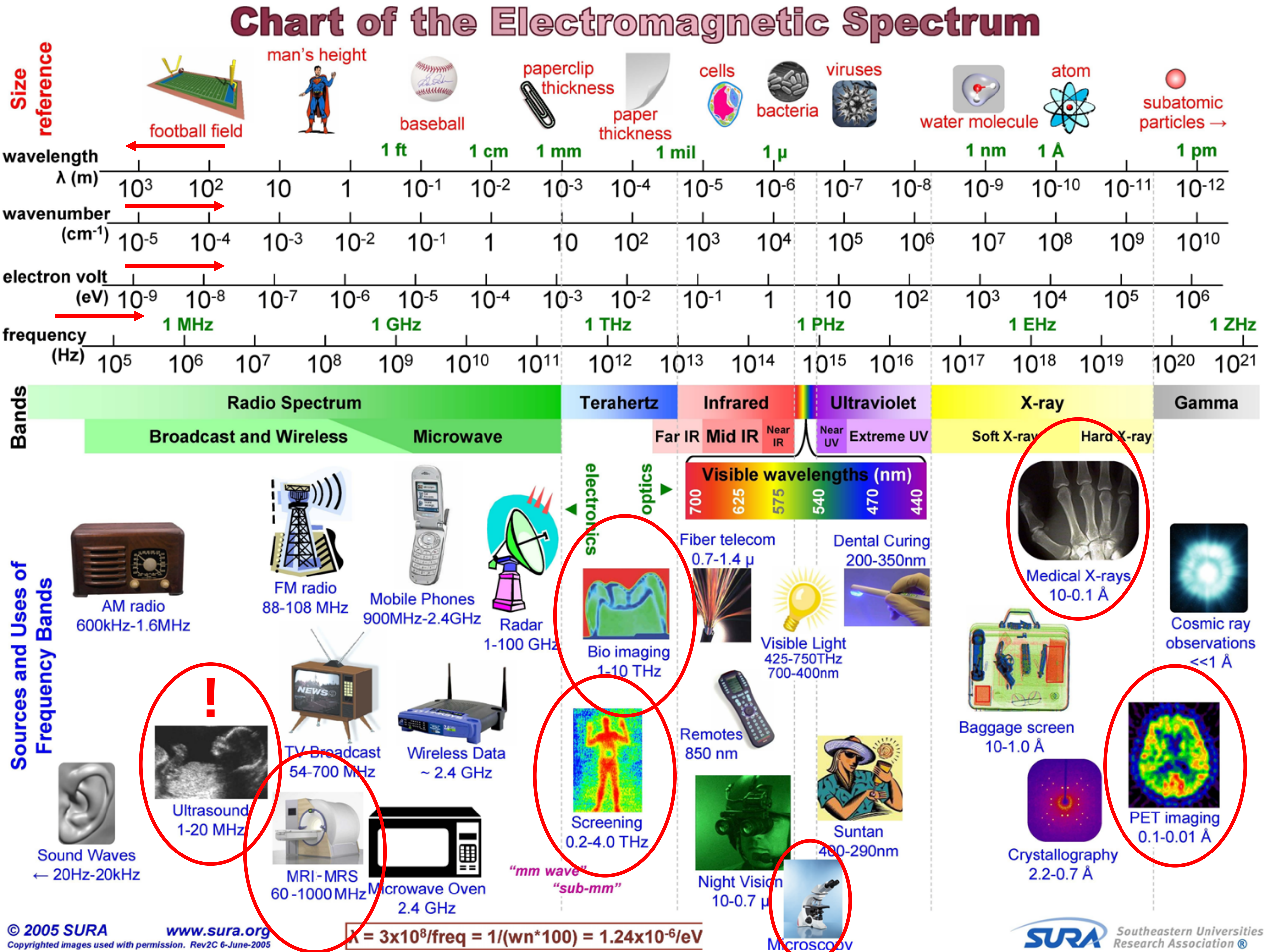


Chart of the Electromagnetic Spectrum
Size reference
football field
man's height
baseball
paperclip thickness
paper thickness
cells
bacteria
viruses
water molecule
atom
subatomic particles →
wavelength λ (m)
1 ft
1 cm
1 mm
1 mil
1 μ
1 nm
1 Å
1 pm
10³ 10² 10 1 10⁻¹ 10⁻² 10⁻³ 10⁻⁴ 10⁻⁵ 10⁻⁶ 10⁻⁷ 10⁻⁸ 10⁻⁹ 10⁻¹⁰ 10⁻¹¹ 10⁻¹²
wavenumber (cm⁻¹)
10⁻⁵ 10⁻⁴ 10⁻³ 10⁻² 10⁻¹ 1 10 10² 10³ 10⁴ 10⁵ 10⁶ 10⁷ 10⁸ 10⁹ 10¹⁰
electron volt (eV)
10⁻⁹ 10⁻⁸ 10⁻⁷ 10⁻⁶ 10⁻⁵ 10⁻⁴ 10⁻³ 10⁻² 10⁻¹ 1 10 10² 10³ 10⁴ 10⁵ 10⁶
frequency (Hz)
1 MHz
1 GHz
1 THz
1 PHz
1 EHz
1 ZHz
10⁵ 10⁶ 10⁷ 10⁸ 10⁹ 10¹⁰ 10¹¹ 10¹² 10¹³ 10¹⁴ 10¹⁵ 10¹⁶ 10¹⁷ 10¹⁸ 10¹⁹ 10²⁰ 10²¹
Bands
Radio Spectrum
Terahertz
Infrared
Ultraviolet
X-ray
Gamma
Broadcast and Wireless
Microwave
Far IR
Mid IR
Near IR
Near UV
Extreme UV
Soft X-ray
Hard X-ray
electronics
optics
Visible wavelengths (nm)
700 625 575 540 470 440
Sources and Uses of Frequency Bands
AM radio
600kHz-1.6MHz
FM radio
88-108 MHz
Mobile Phones
900MHz-2.4GHz
Radar
1-100 GHz
Bio imaging
1-10 THz
Fiber telecom
0.7-1.4 μ
Dental Curing
200-350nm
Medical X-rays
10-0.1 Å
Cosmic ray observations
<<1 Å
Visible Light
425-750THz
700-400nm
TV Broadcast
54-700 MHz
Wireless Data
~ 2.4 GHz
Remotes
850 nm
Baggage screen
10-1.0 Å
!
Ultrasound
1-20 MHz
Screening
0.2-4.0 THz
Suntan
400-290nm
Crystallography
2.2-0.7 Å
PET imaging
0.1-0.01 Å
Sound Waves
← 20Hz-20kHz
MRI-MRS
60-1000MHz
Microwave Oven
2.4 GHz
"mm wave"
"sub-mm"
Night Vision
10-0.7 μ
Microscopy
© 2005 SURA
www.sura.org
Copyrighted images used with permission. Rev2C 6-June-2005
λ = 3x10⁸/freq = 1/(wn*100) = 1.24x10⁻⁶/eV
SURA
Southeastern Universities Research Association ®

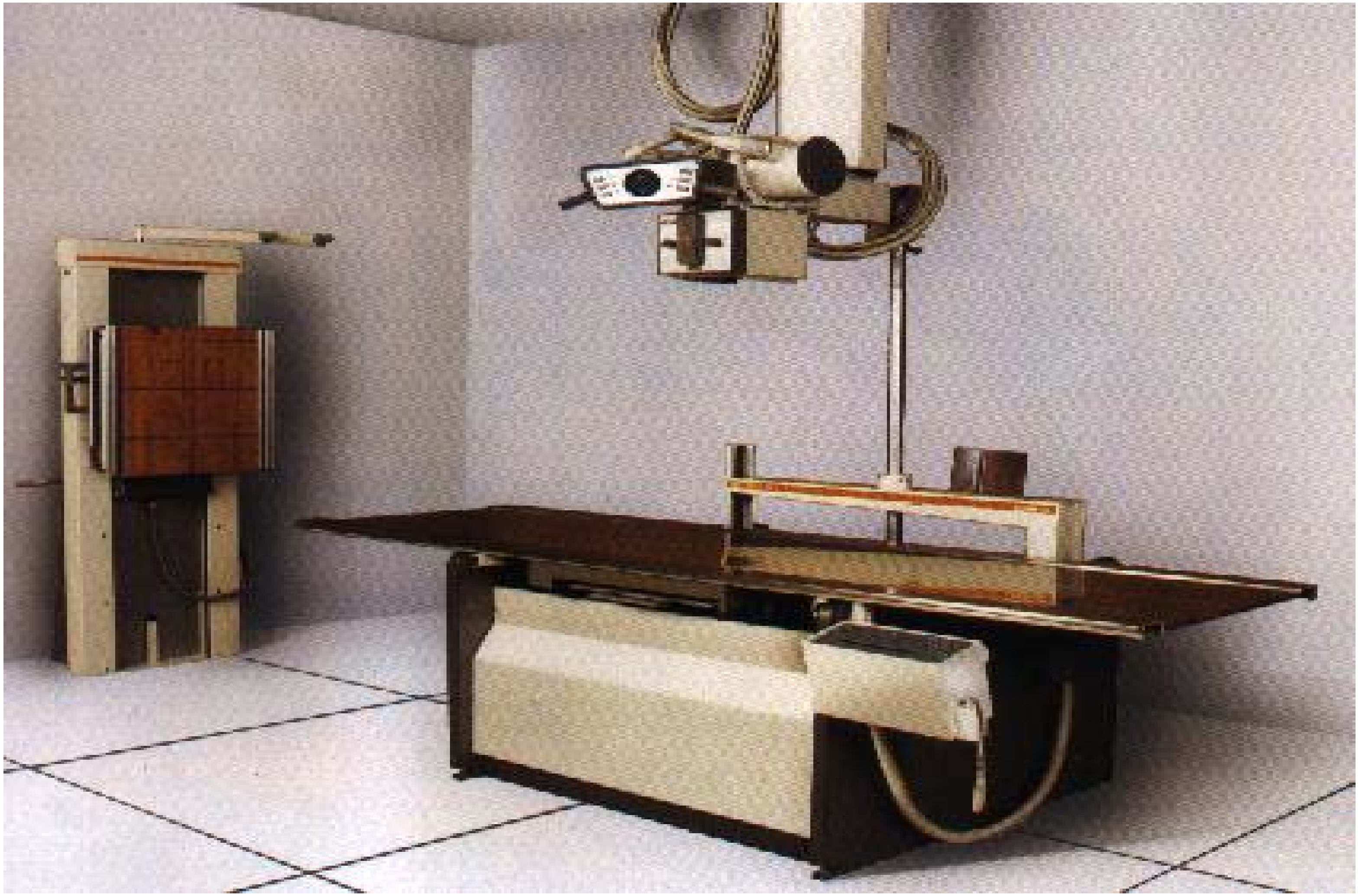
Image acquisition modalities

- the various technologies and protocols used to acquire image data

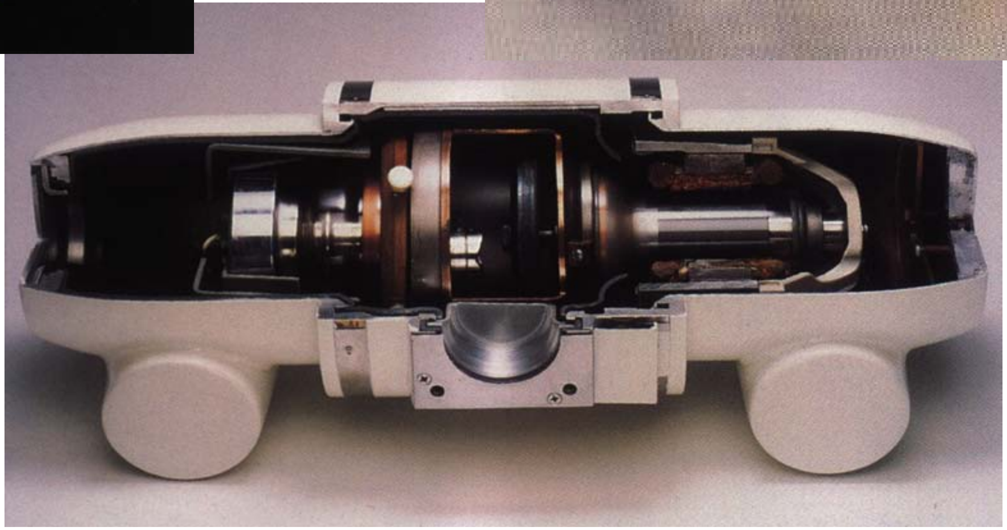
Projection X-ray (radiography)

- Different absorption chracteristics allow to distinguish different material (and provide contrast) in the image.
- X-ray attenuation is measured by the linear attenuation coefficient (μ).
- Projection X-rays (radiographs) are 2D projections of 3D data

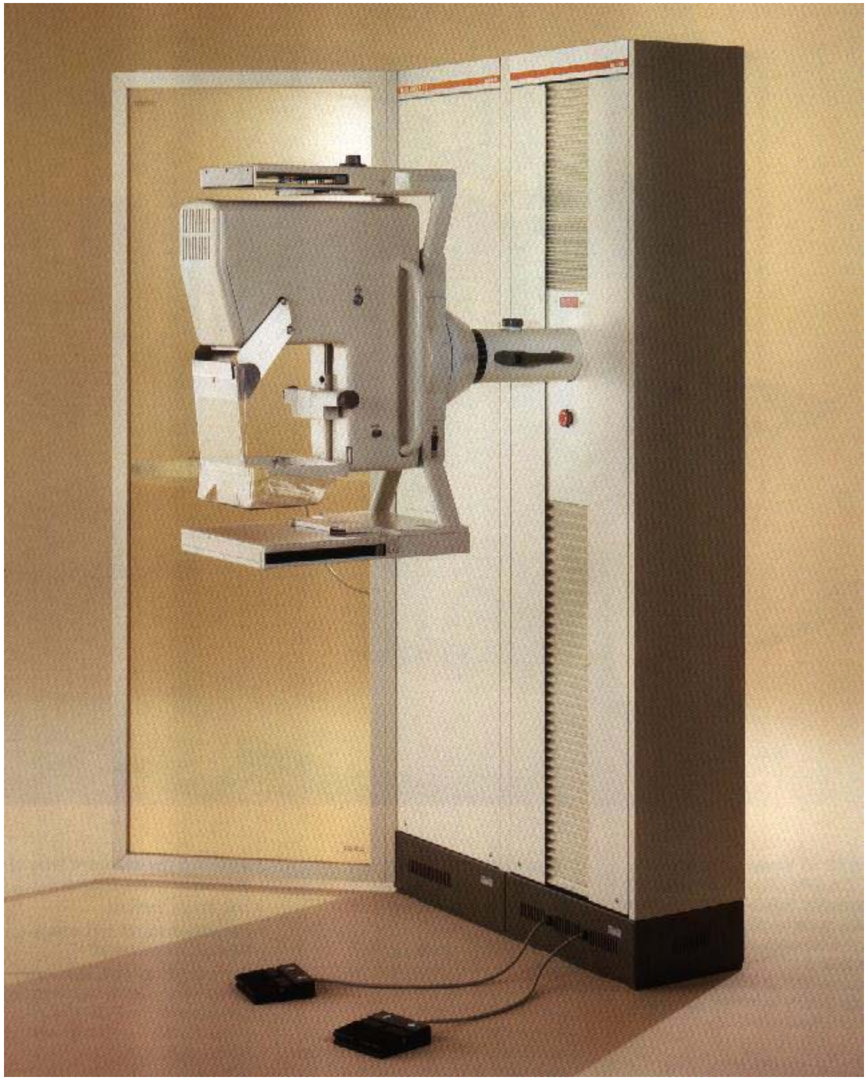
Conventional X-ray (projection radiography)



Conventional X-ray (X-ray tube)



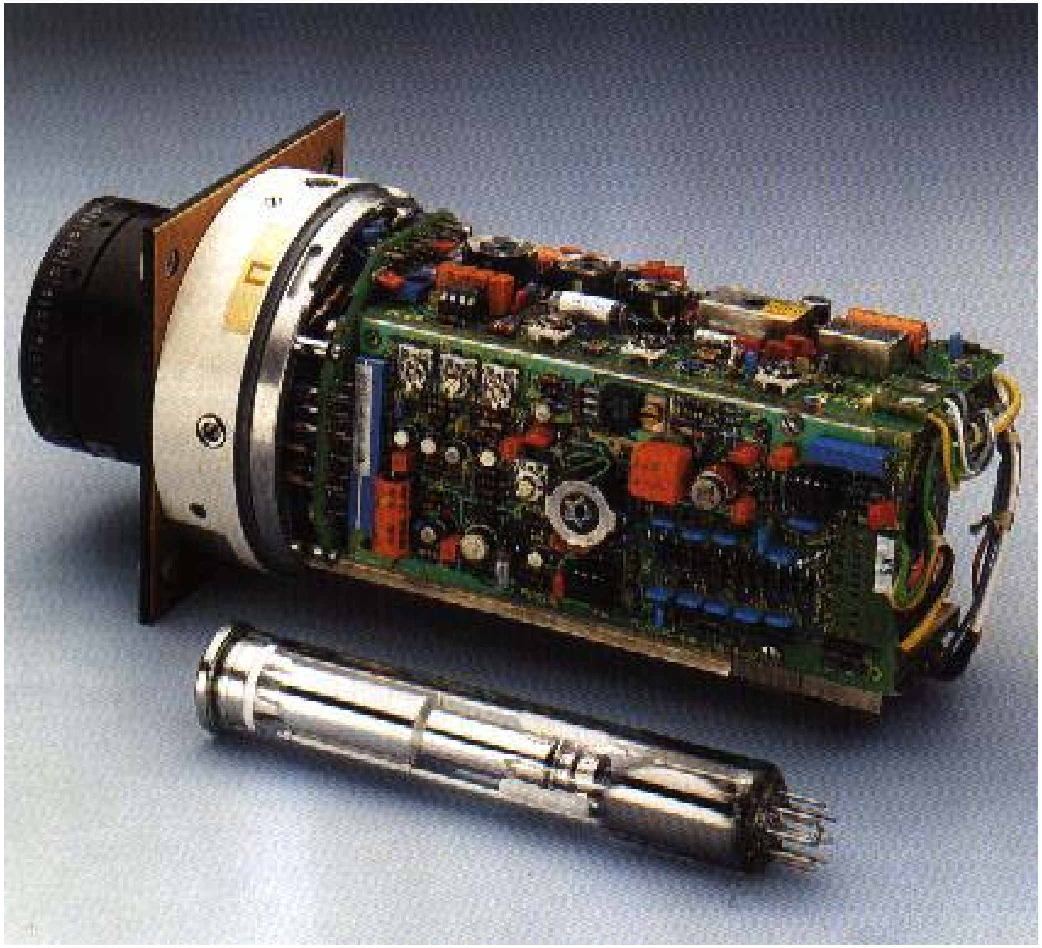
Conventional X-ray (mamograph)



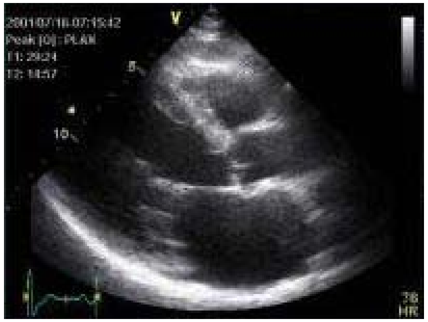
Conventional X-ray TV (C arm with II)

Conventional X-ray TV (image intensifier)

Conventional X-ray TV (TV pick-up tube)

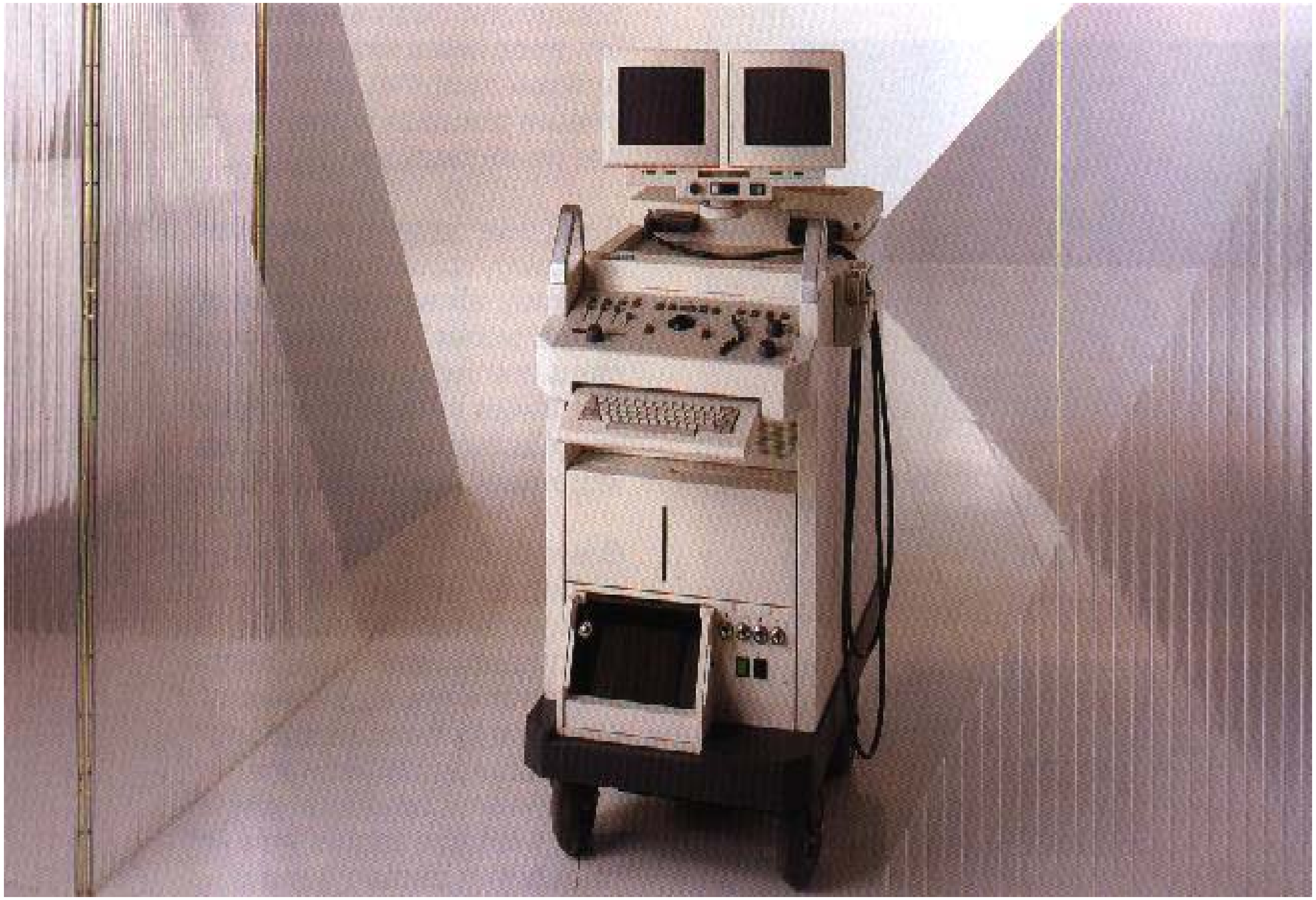


Ultrasound



- US imaging employs HF sound energy to image the interface between differing tissue types.
- When the sound wave strikes an interface, some energy moves across the interface and some energy is reflected backwards.
- The reflected energy is detected by a receiver and is used to form the image.

Conventional US („tomography“)



Nuclear medicine

- Radio-isotopes are introduced into the body to „tag“ specifig physiologic functions.
- As the tracer accumulates in a particular anatomic location , it periodically emits a particle that can be observed and used to form an image.
- NM it can be used to form functional rather than structural images.

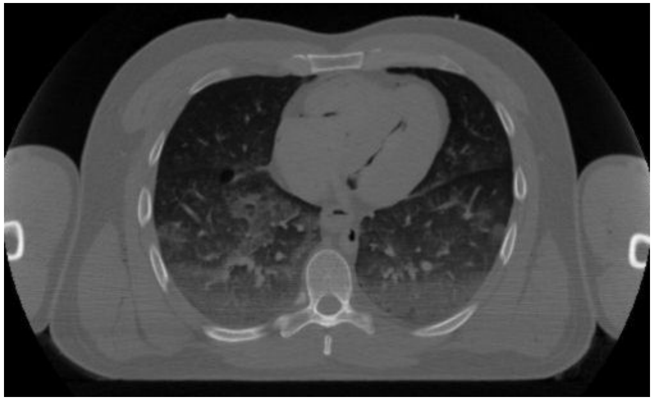
Conventional NM (Anger gama camera)

Computed tomography (CT)

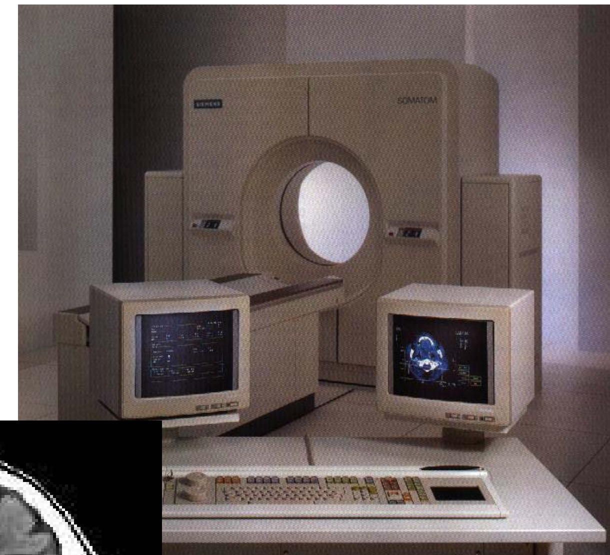
- CT is used to generate cross-sectional images (CT slices) from a set of projections images obtained at different angles.
- CT image pixels are reported in units called Hounsfield units (HU).
- The following reference points are useful to know:

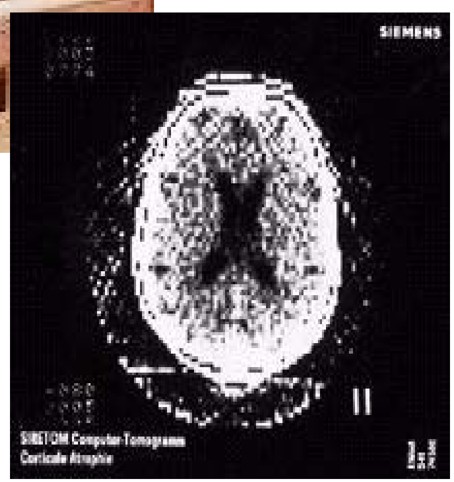
CT

Material	CT number	μ [cm^{-1}]
Bone	808	0.38
Muscle	0	0.21
Water	-48	0.20
Fat	-142	0.18
Air	-1000	0.00



CT (history vs. present)



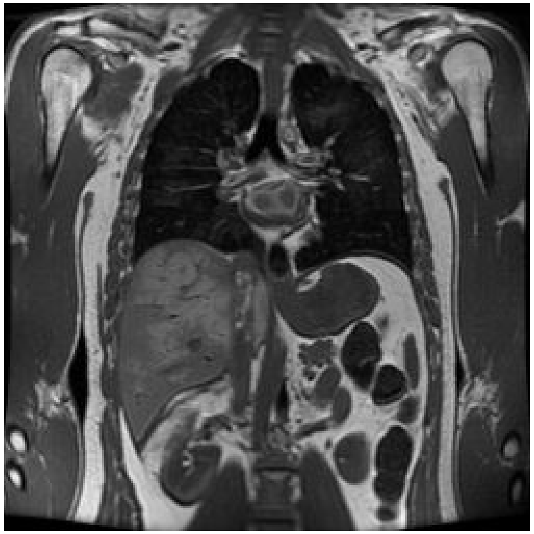


Magnetic resonance imaging

- MRI images proton density by using a permanent magnet with a pulsed radio frequency (RF) field.
- The RF field changes the spin orientation of protons (tilting them and causing them to precess as they spin) within the body.
- We form an image by listening to a signal emitted as the protons relax back to their original orientation.

MRI

- We apply energy to perturb the system, but the signal itself is generated from the tissue sample under study!
- This places some fundamental limitations on MR image acquisition.



Single photon emission computed tomography (SPECT)

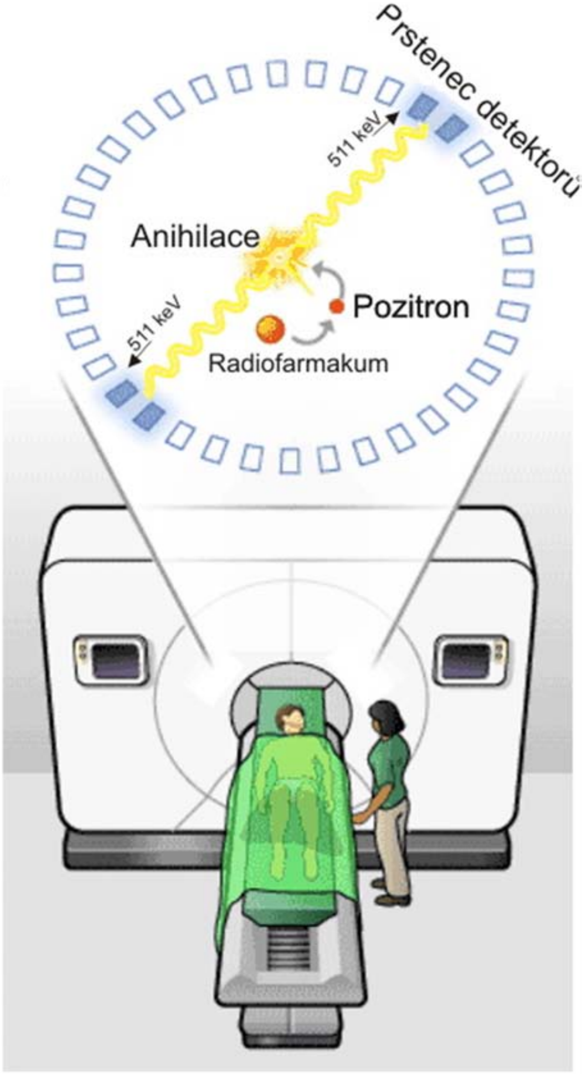
- SPECT camera acquire multiple planar views of the radioactivity in an organ
- the data are then processed mathematically (iterative reconstruction)
- SPECT utilizes the single photon emitted by gama-emitting radionuclides such as ^{99m}Tc, ^{67}Ga, ^{111}In, and ^{123}I
- this is in contrast to PET

SPECT

Positron emission tomography (PET)

- PET cameras are designed to detect the paired 511-keV photons generated from the anihilation event of a positron and electron
- following emission, any positron travels only a short distance before coliding with electrons in surrounding matter
- the paired 511-keV annihilation photons travel in opposite directions (180° apart) along a line

PET



Prstenec detektorů
511 keV
Anihilace
Pozitron
511 keV
Radiofarmakum

Ionizing vs. non-ionizing radiation

- Ionizing radiation – applied energy is sufficient to ionize atoms (ejects an electron from orbit, creating a positively charged ion). (e.g., X-ray, CT, PET, SPECT)
- Non-ionizing radiation – insufficient energy to ionize atoms (MRI, US, optical)

Imaging structure and function

- Structure: tissue density, region size, shape, and orientation.
- Function: Activity (metabolic rate) , perfusion, ventilation.
- Challenge: combining structural and functional information together in a synergistic presentation (ex. display blood flow distribution on top of a CT slice of lung).

Digital image processing

- What is an image?
- Formal definition: A digital image is a multi-dimensional signal that is sampled in space and/or time and quantized in amplitude. An image is often represented by a multi-dimensional matrix (array) of numbers.
- Looser definition: An image is a „picture“. The brightness value in the picture may represent distance, reflectivity, density, temperature, etc.

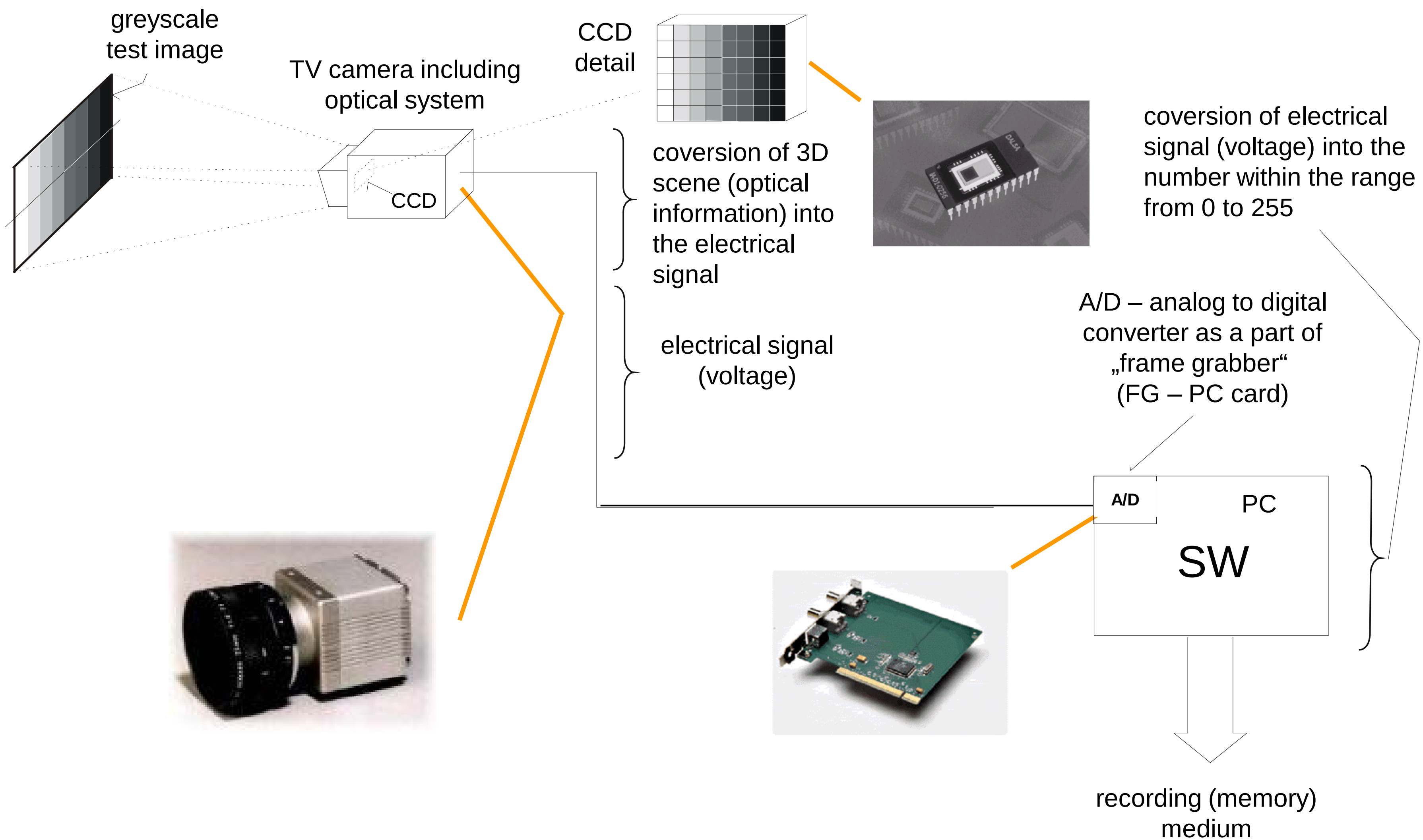
Digital image processing

- The image may be 2-D (planar), 3-D (volumetric), or N-D.
- Image elements: an image is composed of:

  2-D: pixels = picture x elements

  3-D: voxels = volume x elements

Analog image to digital image conversion



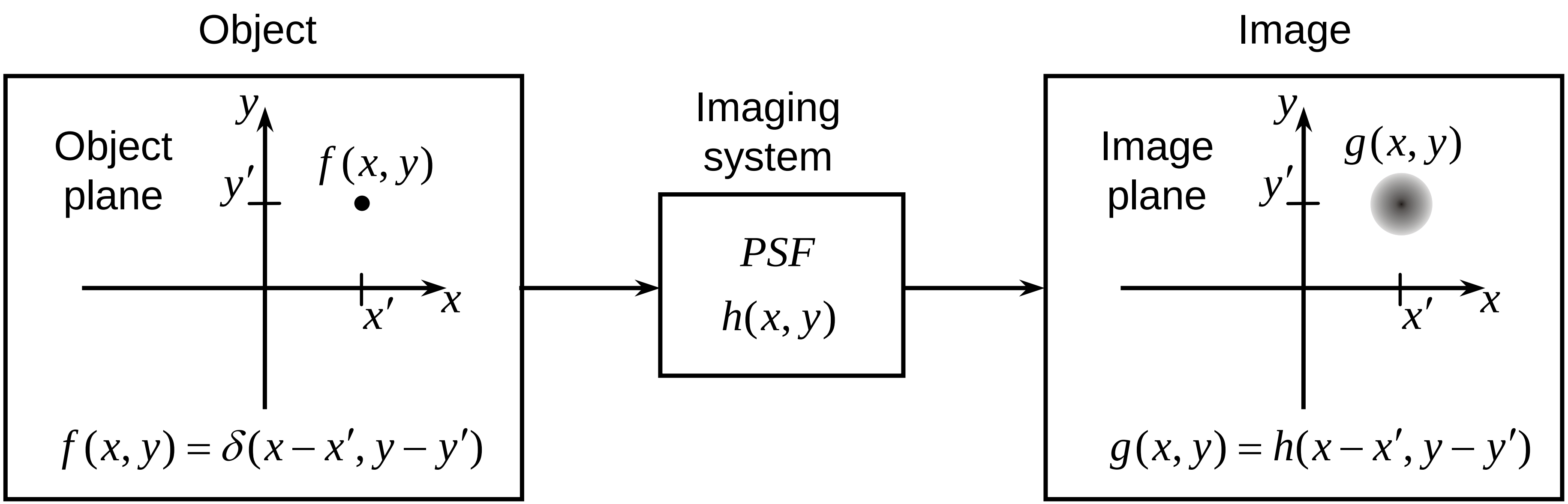
What do images represent?

- X-ray attenuation (density) X-ray, CT
- Water (proton) density, relaxation times MRI
- Acoustic impedance US
- Brightness TV
- Tracer uptake (distribution of radioactivity) NM
- Heat IR
- Electrical impedance EIT

Transfer properties of imaging systems

- Why?
- Analogy with 1D cases.
- Key point: spatial frequency, contrast transfer
- How to measure quality?
- Set of transfer functions

Impulse response of imaging system - PSF



$$g(x,y) = f(x,y) * h(x,y)$$

2D convolution

$$f(x,y)=\delta(x-x',y-y') \qquad g(x,y)=h(x-x',y-y')$$

$$g(x,y)=f(x,y)*h(x,y)$$

$$g(x,y)=f(x,y)*h(x,y)=\int_{\mathbb{R}^2} f(\alpha,\beta)\,h(x-\alpha,y-\beta)\,d\alpha\,d\beta$$

$$h_{ideal}(x,y)=\delta(x,y)$$

2D convolution – example 1

Video_1

2D convolution– example 2

Video_2

Transfer function of imaging system in frequency domain

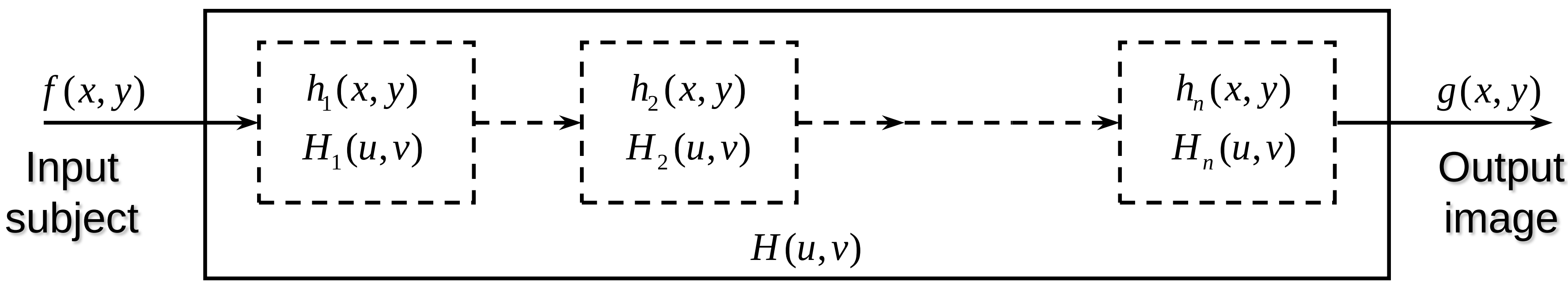
$$\mathcal{F}\{g(x,y)\} = \mathcal{F}\{f(x,y) * h(x,y)\}$$

$$G(u,v) = F(u,v)\,H(u,v)$$

The resulting transfer function of imaging system

$$h(x,y) = h_1(x,y) * h_2(x,y) * \ldots * h_n(x,y)$$

$$H(u,v) = H_1(u,v) \cdot H_2(u,v) \cdot \ldots \cdot H_n(u,v)$$



Spatial frequency

$$u = \frac{1}{X}, \quad v = \frac{1}{Y}$$

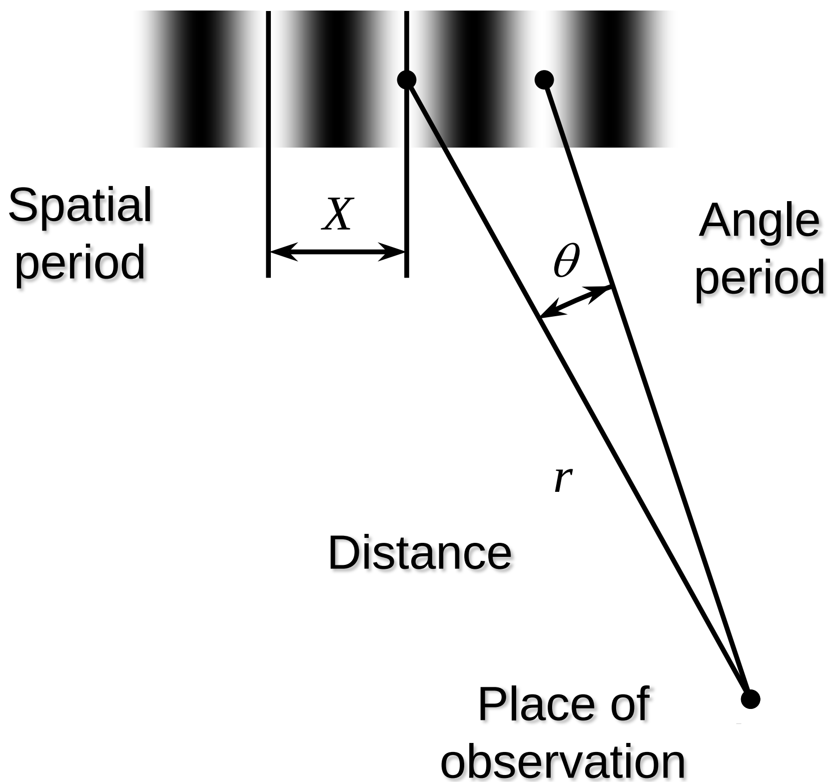
cy/mm

$Hz \equiv cy/s$

lp/mm

$cy/mrad$

$$u_a = \frac{r}{X} = r\,u$$



Spatial frequency

$$u = 1/X\ [cy/m]$$

Spatial angle frequency

$$u_a = r/X\ [cy/rad]$$

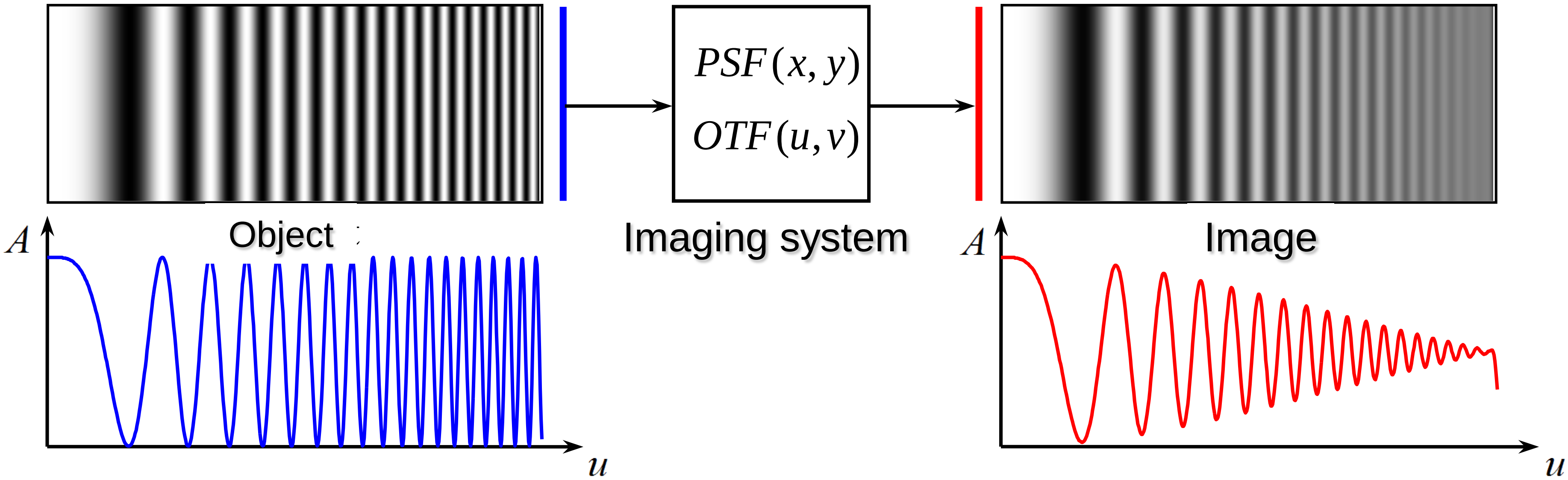
Relationships among transfer functions

$$OTF \equiv \mathcal{F}\{h(x,y)\} = |H(u,v)|\, e^{j\phi(u,v)}$$

$$MTF \equiv |H(u,v)|$$

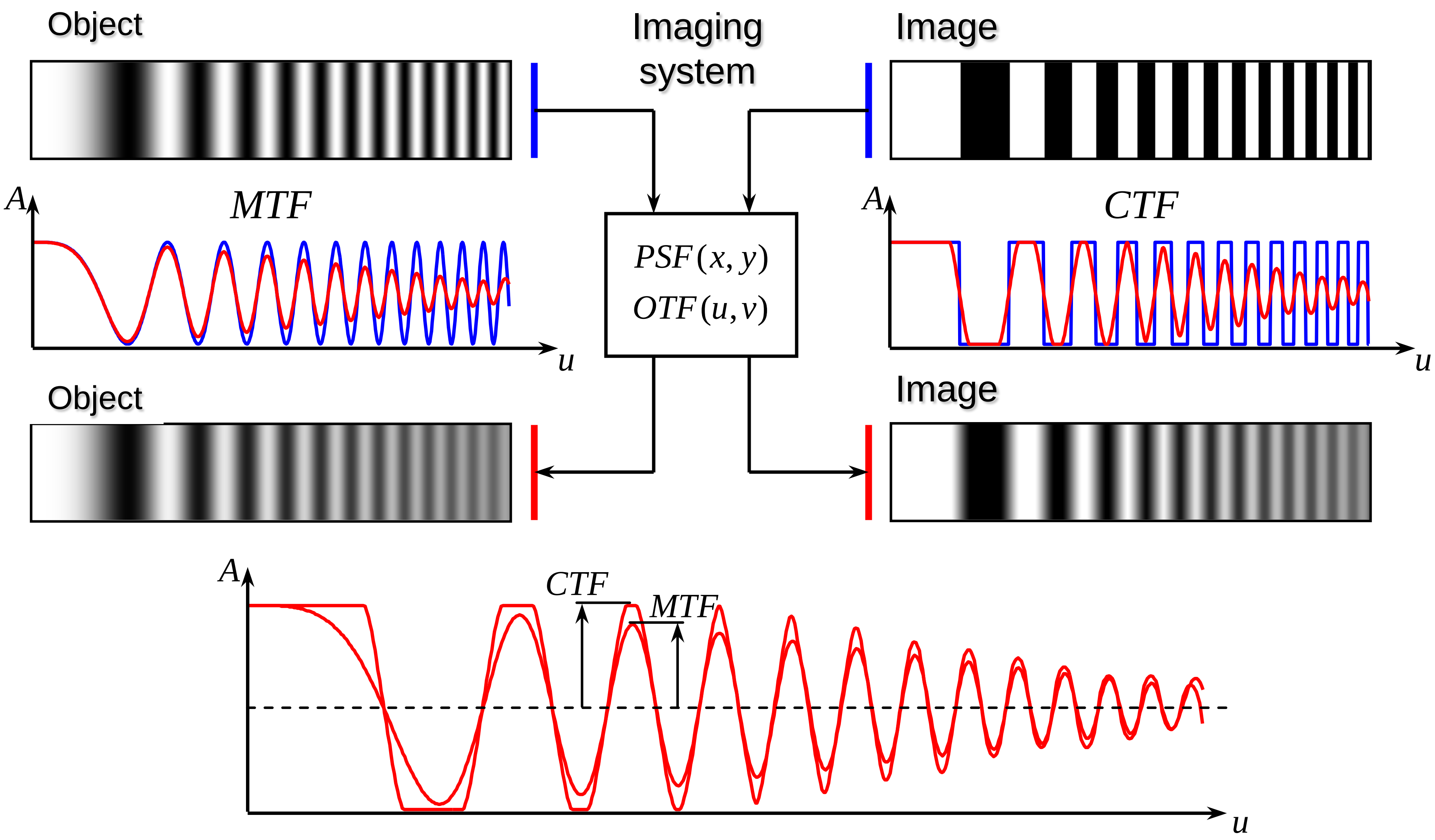
$$PTF \equiv \angle H(u,v) = \phi(u,v)$$

Modulation transfer function

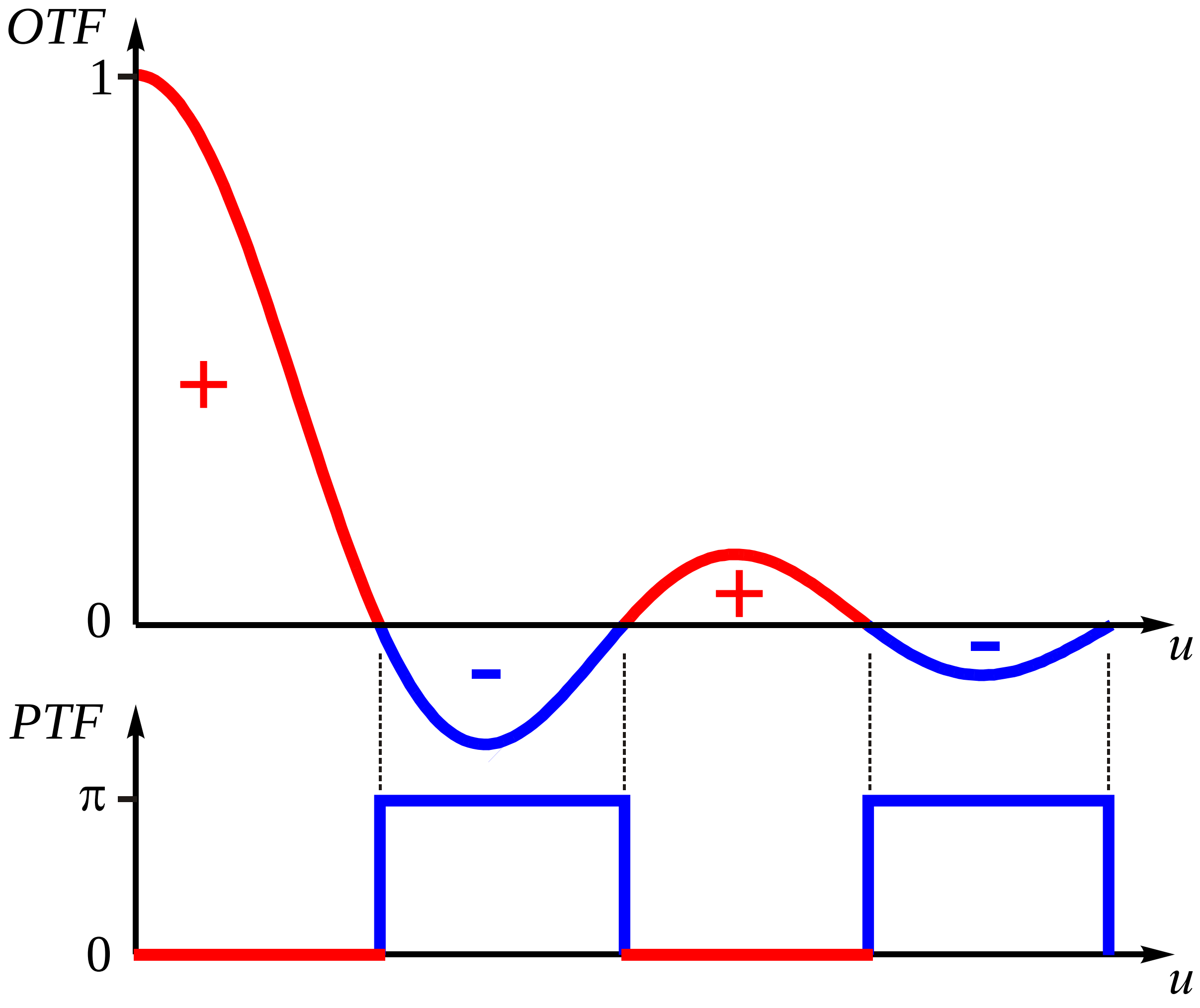


$$M = \frac{A_{max} - A_{min}}{A_{max} + A_{min}} = \frac{ac}{dc}$$

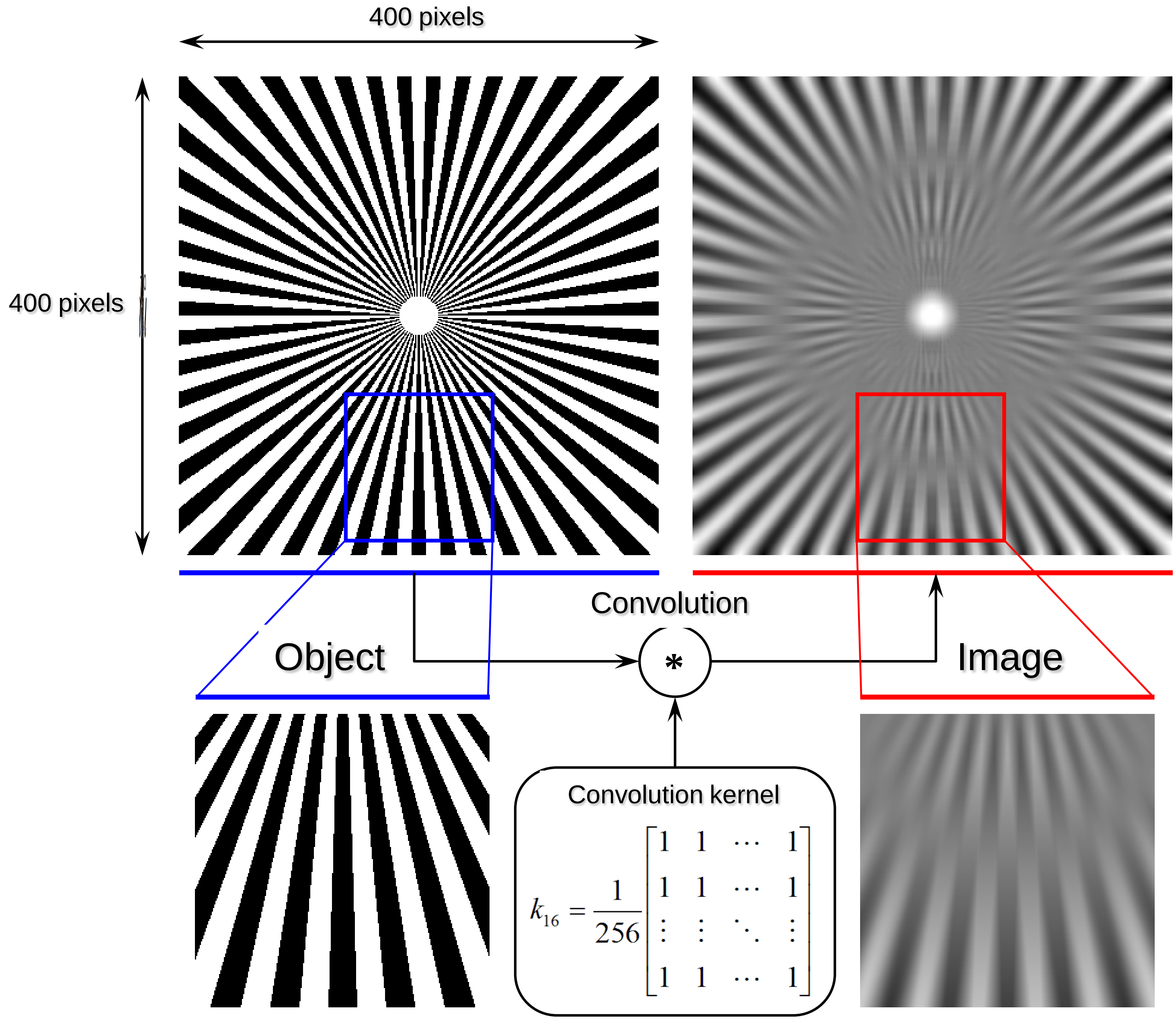
CTF and MTF relatioship



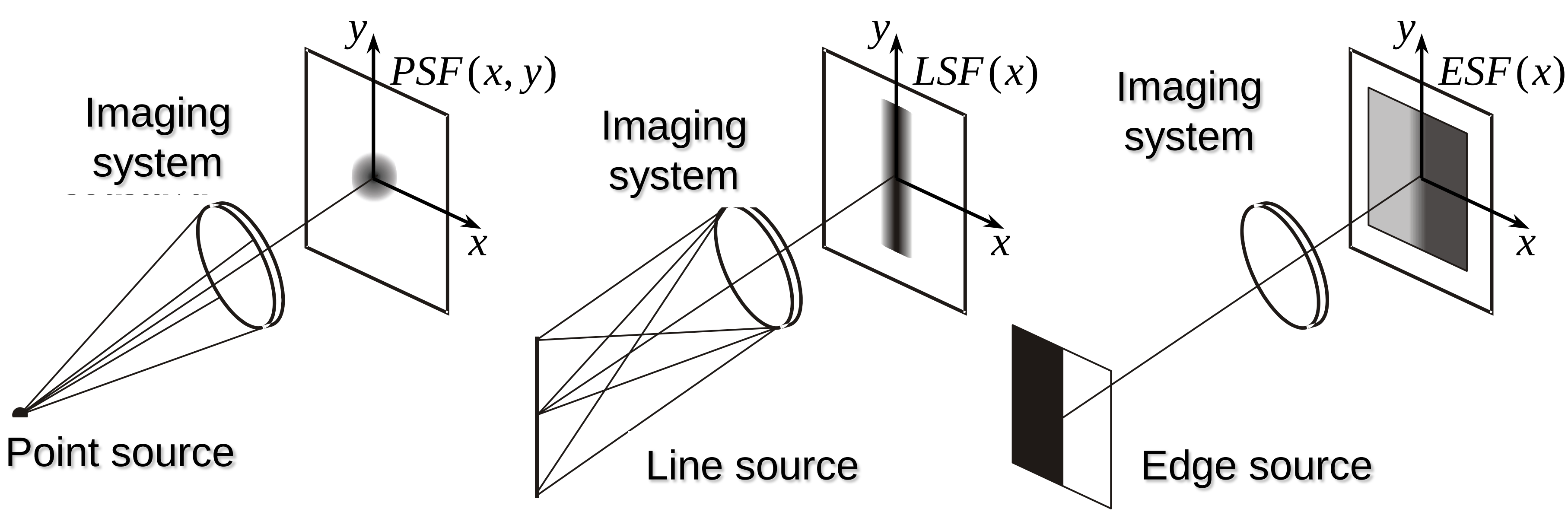
Phase transfer function (PTF)



Effect of PTF on distortion



Another transfer functions



Line spread function (LSF)

$$LSF(x) \equiv g(x,y) = f(x,y) * h(x,y) = \delta(x) * PSF(x,y)$$

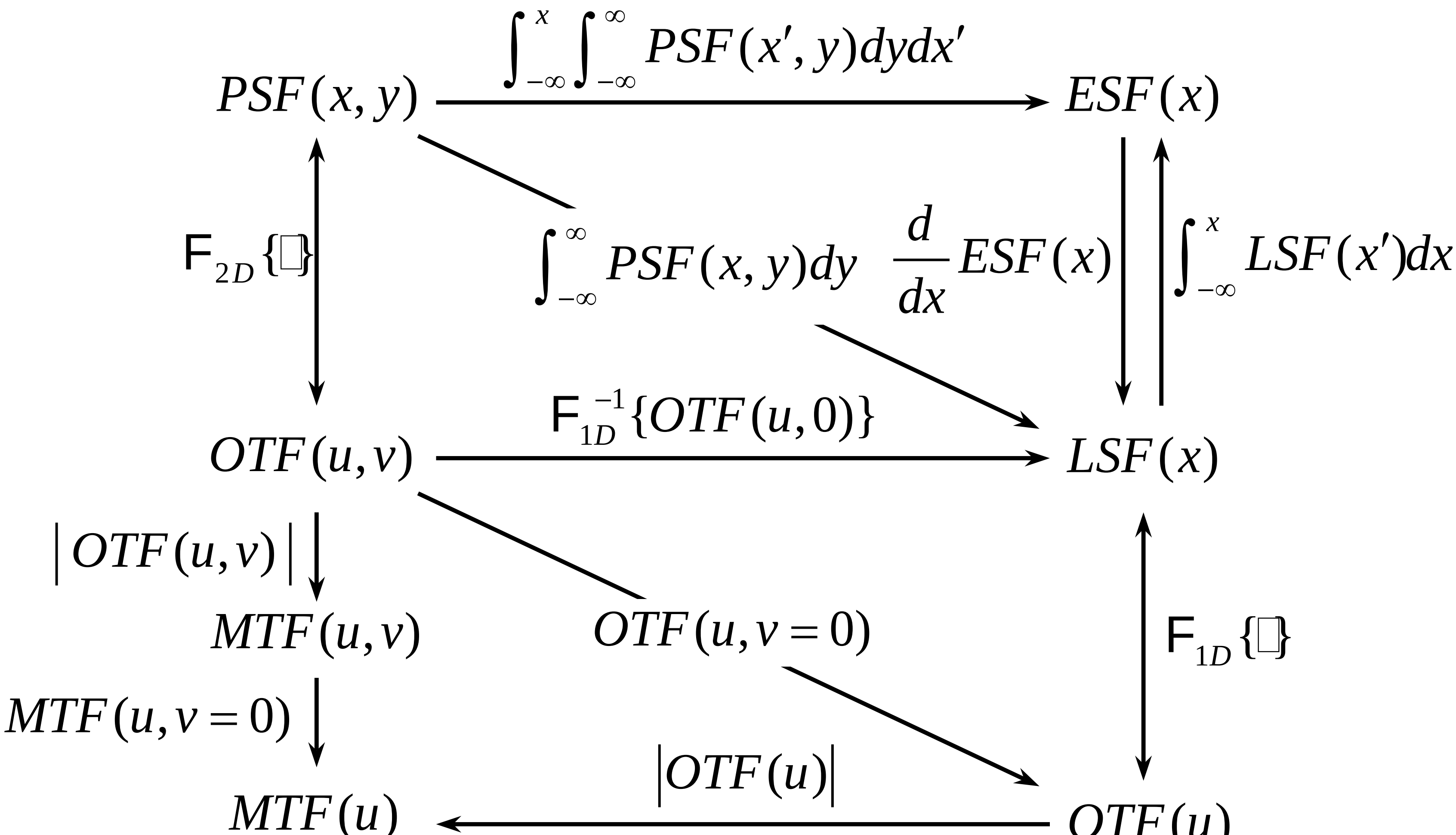
$$MTF(u,0) = \left|\mathcal{F}\{LSF(x)\}\right| \qquad f(x,y) = \delta(y) \qquad MTF(0,v) = \left|\mathcal{F}\{LSF(y)\}\right|$$

$$LSF(x) \neq PSF(x,0)$$

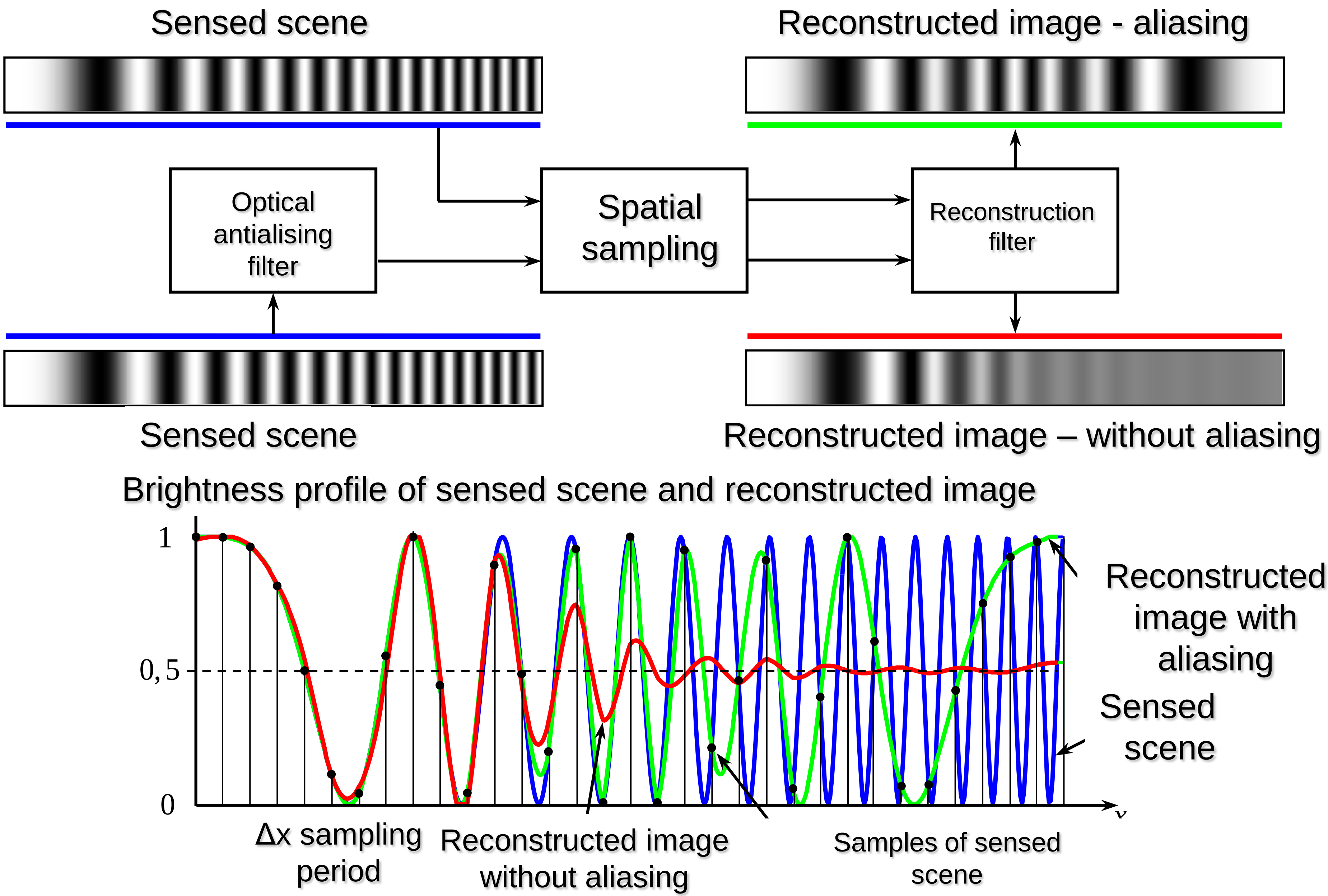
Edge spread function (ESF)

$$LSF(x) = \frac{d}{dx}\left(\int_{-\infty}^{x} LSF(x')dx'\right) = \frac{d}{dx}\left(ESF(x)\right)$$

Mathematical relatioships among PSF, OTF, MTF, LSF, ESF



Aliasing


Sensed scene
Reconstructed image - aliasing
Optical antialising filter
Spatial sampling
Reconstruction filter
Sensed scene
Reconstructed image – without aliasing
Brightness profile of sensed scene and reconstructed image
1
0,5
0
ν
Reconstructed image with aliasing
Sensed scene
Δx sampling period
Reconstructed image without aliasing
Samples of sensed scene

Magnetic resonance imaging

- MRI physics in brief

  - proton NMR physics

  - MR image formation

Basic NMR physics

- Magnetization
- Resonance
- Excitation and detection
- Rotating frame
- Dephasing
- T1 & T2 relaxation

Charge, mass and spin of the proton as nuclear particle

Video_1

NMR parameters of common nuclei

Nucleus	Gyromagnetic ratio [MHz/T]	Relative sensitivity
^{1}H	42.570	1.000
^{13}C	10.700	0.015
^{19}F	40.050	0.833
^{31}P	17.235	0.066
^{23}Na	11.230	0.092

Only isotopes with an odd number of protons or neutrons have a non zero spin.

Bulk magnetization

Video_2

Detection of magnetization (induction)

Video_3

RF pulses (spin excitation)

Video_4

NMR signal (spin-echo pulse sequence)

Video_5

The motions of the magnetization vector

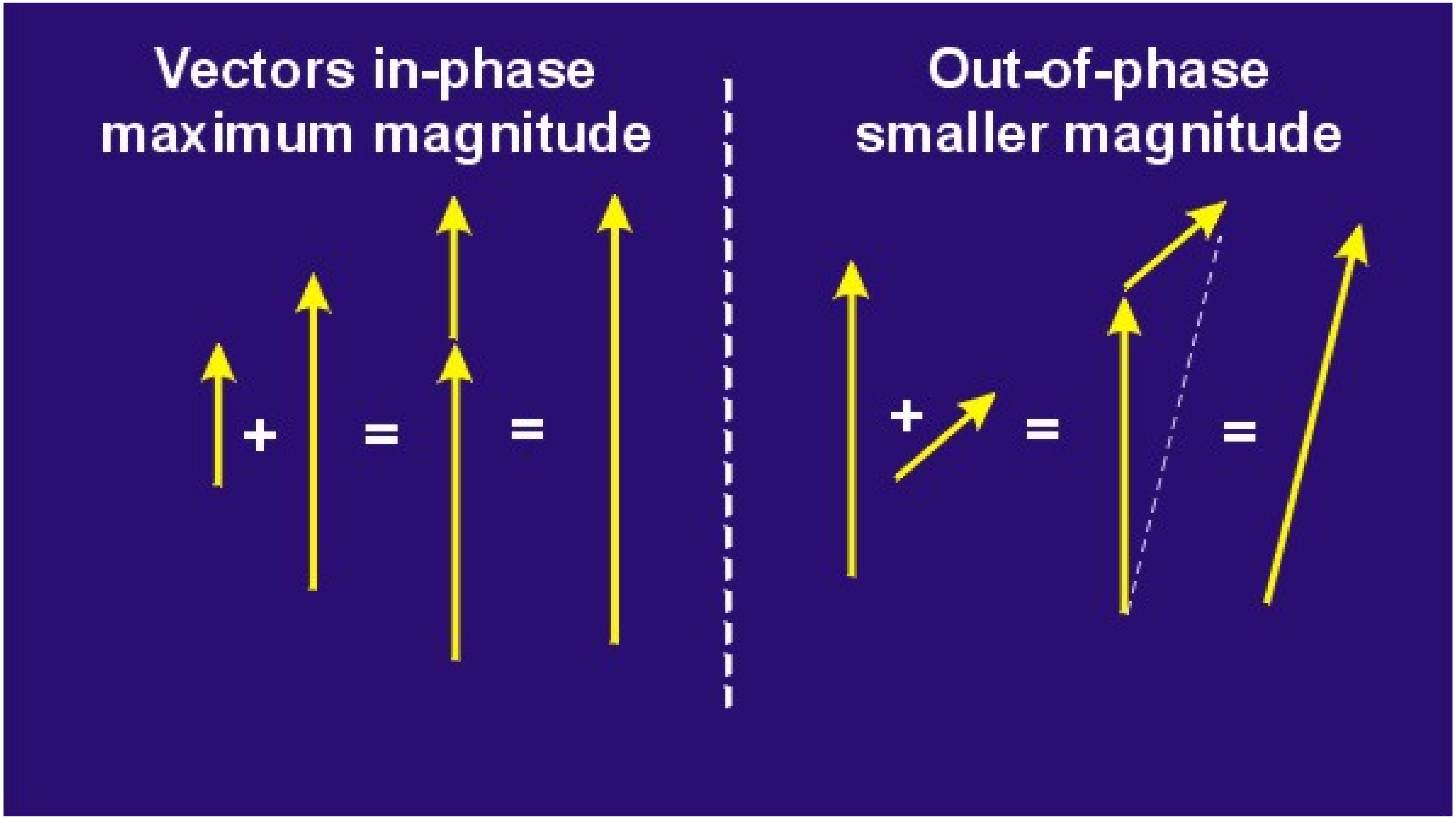
- part 1 – laboratory frame point of view
- part 2 – magnetization+turntable+camera in synchrony
- part 3 – view of the rotating frame camera

Video_6

Tissue MR properties

- Proton density (PD)
- Spin-lattice relaxation (T1)
- Spin-spin relaxation (T2)
- Susceptibility efects (T2*)
- Motion

Addition of magnetization vectors



The resulting magnetization vector

Video_7

The resulting magnetization vector for laboratory and rotating frame

Video_8

The MR system demodulation of the NMR signal

Video_9

Dephasing in laboratory and rotating frame

Video_10

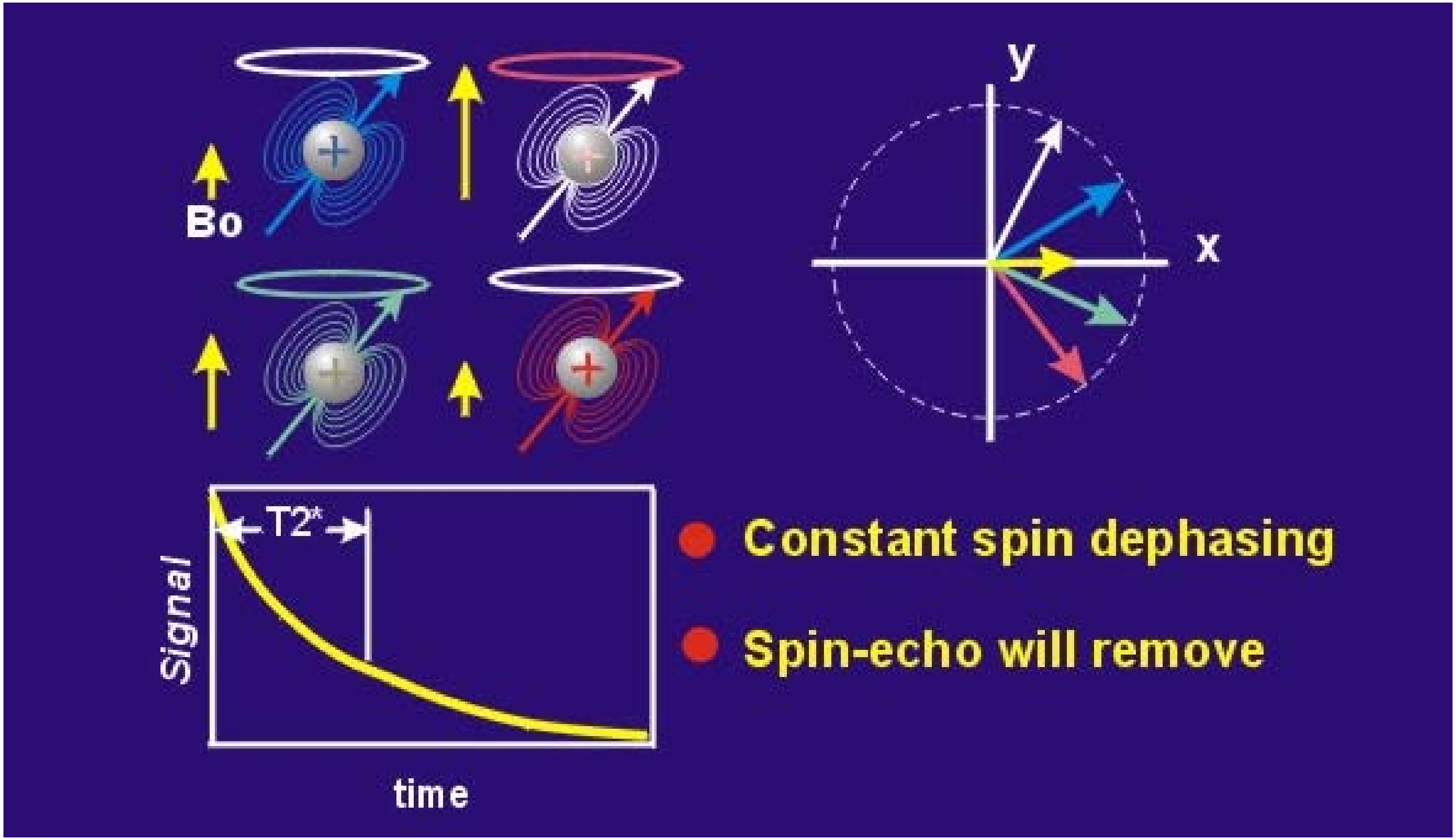
Total dephasing in laboratory and rotating frame

Video_11

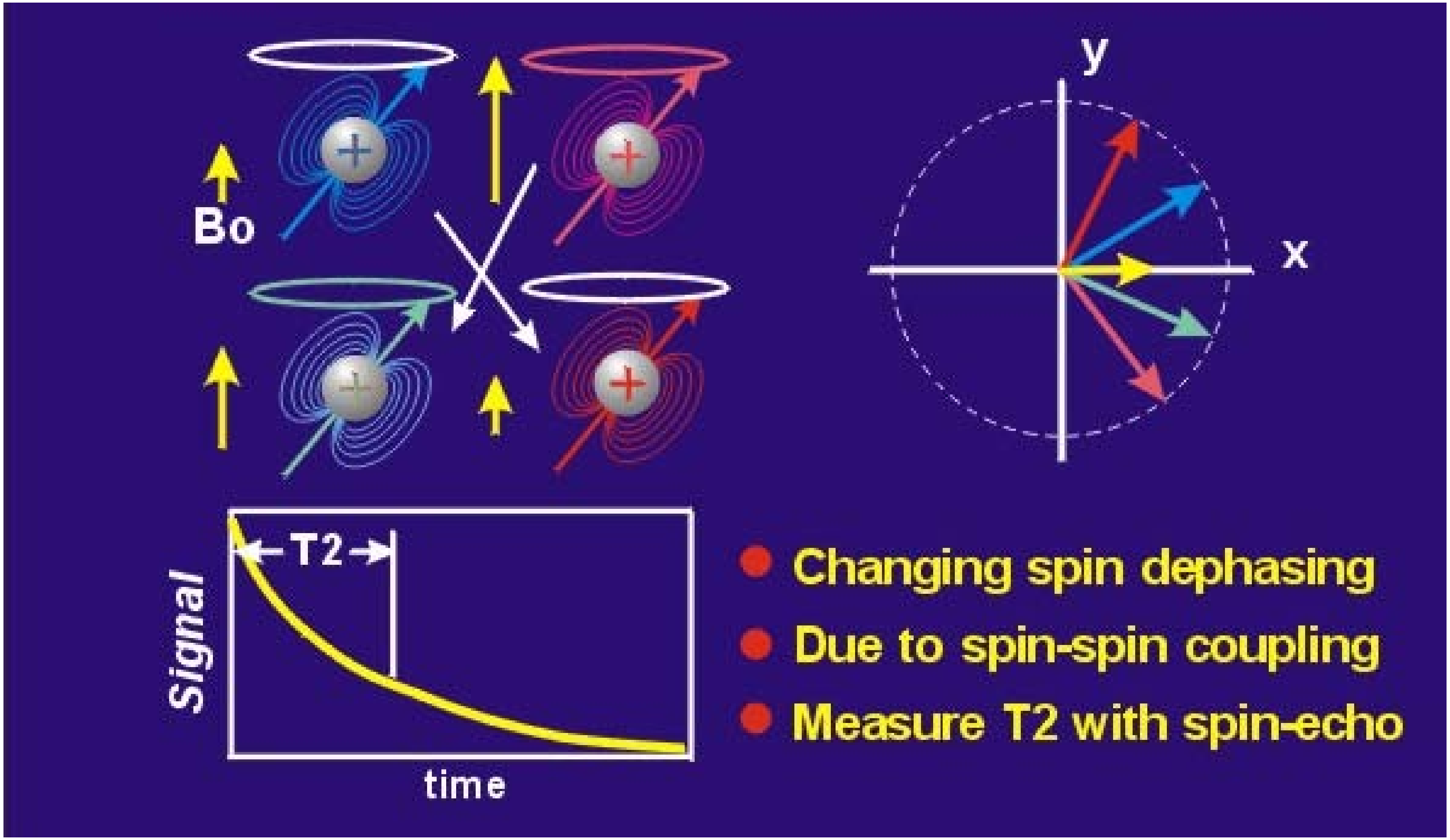
Total dephasing in laboratory and rotating frame – T2* decay time

Video_11_2

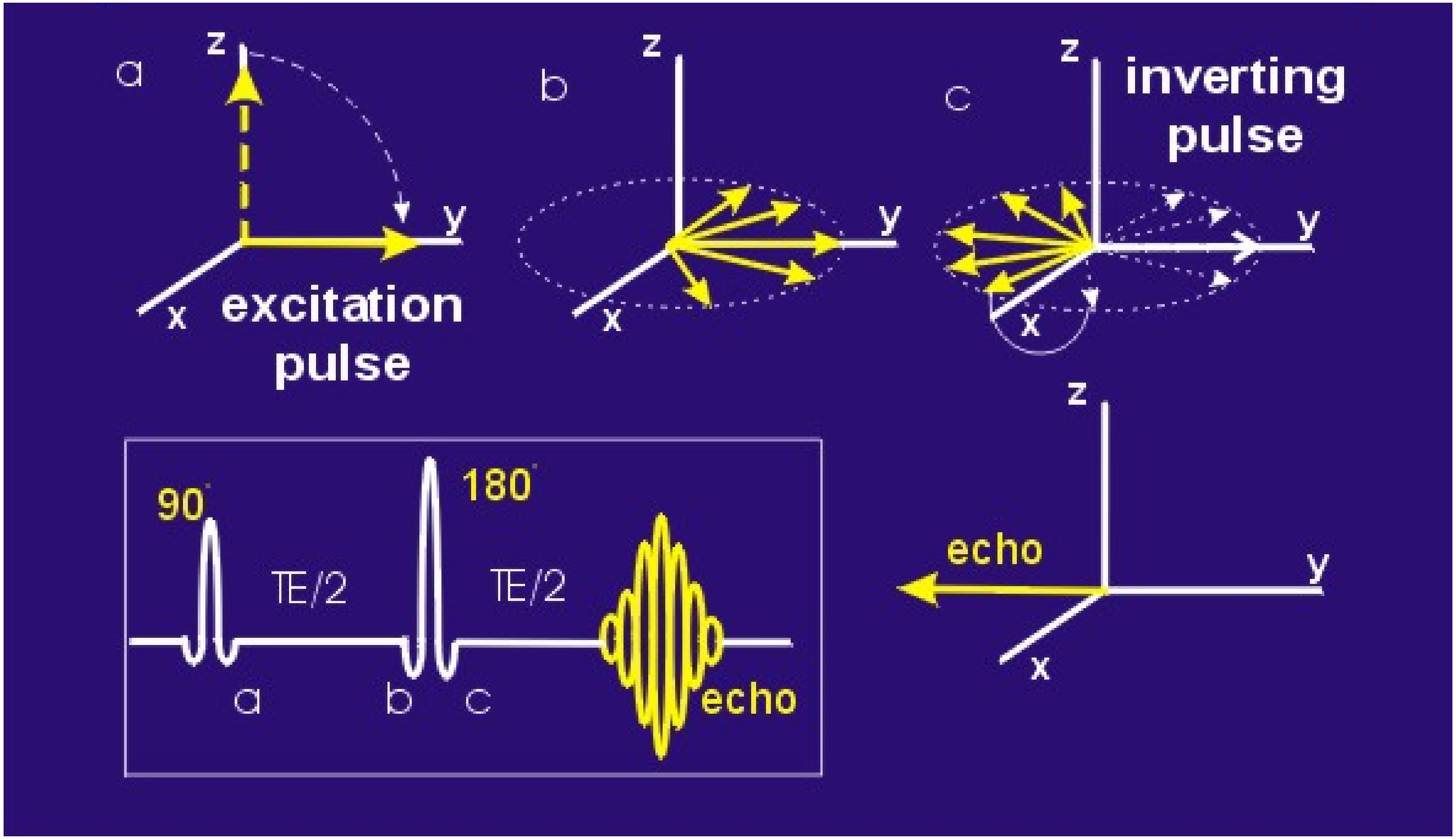
MNR signal decay (spin-echo)



Spin-spin interactions



Spin-echo



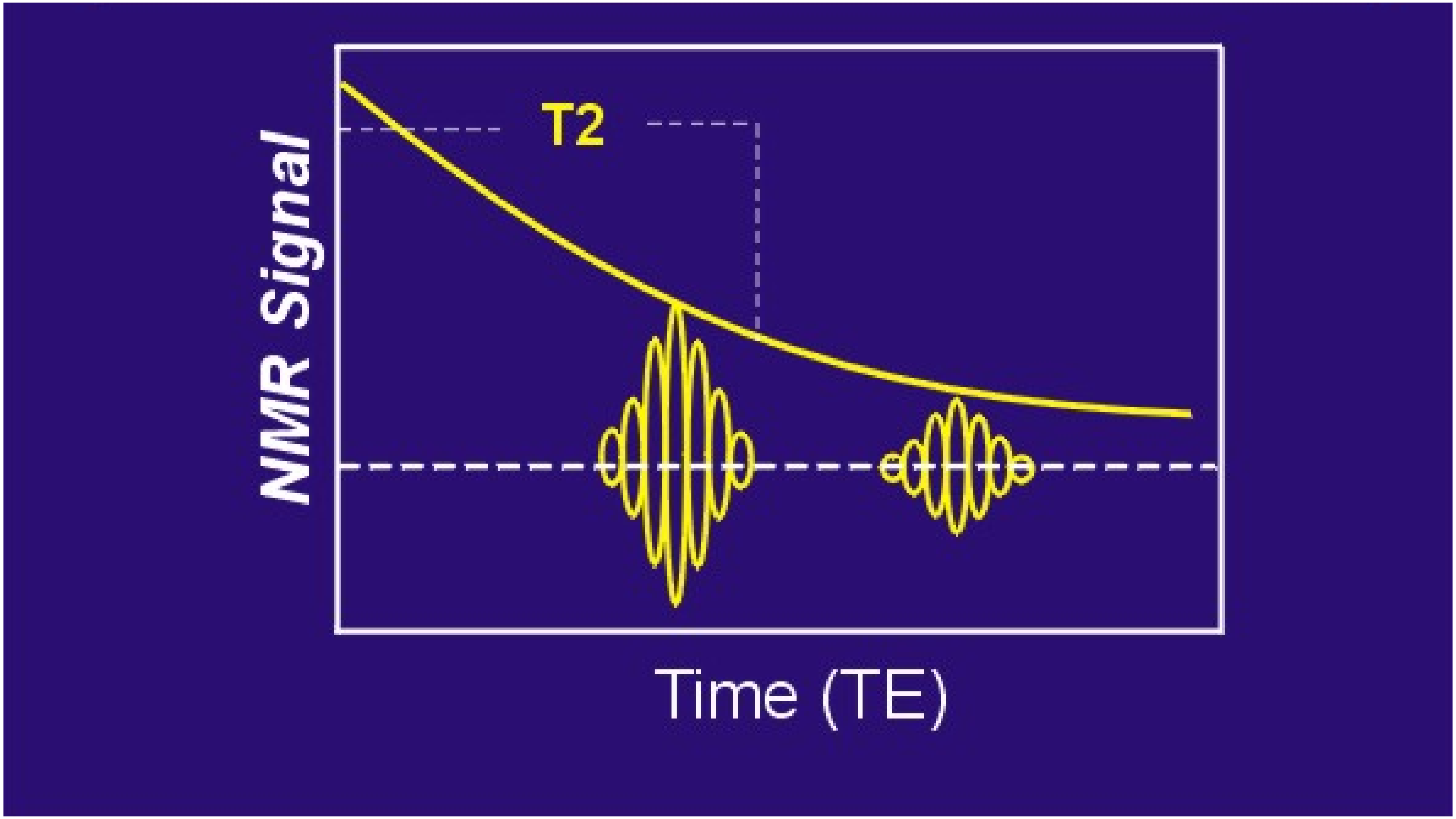
a
z
y
x
excitation pulse
b
z
y
x
c
z
inverting pulse
y
x
z
echo
y
x
90°
180°
TE/2
TE/2
a
b
c
echo

Details of the spin-echo sequence

- part 1 - the behavior of spin dephasing and RF pulses during the sequence
- part 2 - NMR signal for different echo times TE
- part 3 - detailed view of the transverse magnetization components alone

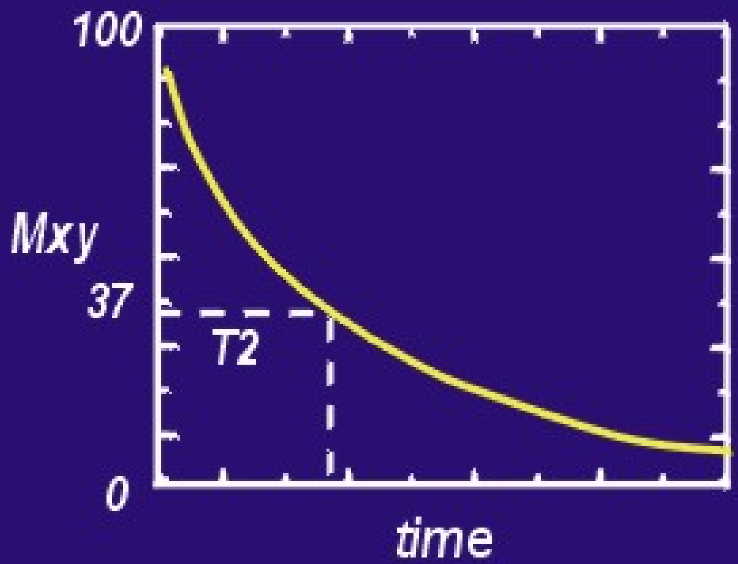
Video_12

The spin echo - T2 summary (MNR signal vs. the time TE)



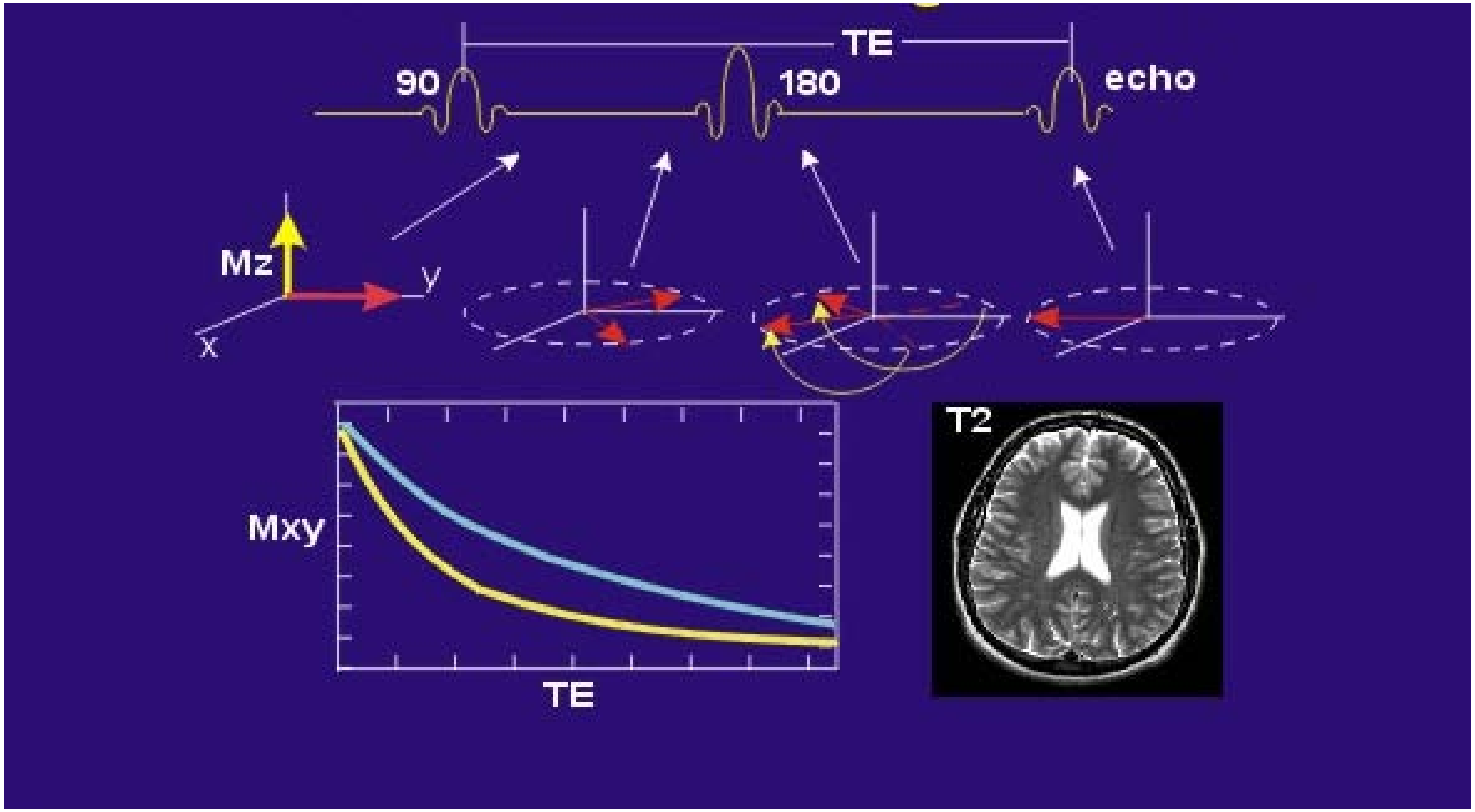
Typical T2 values in the head

SampleT2 Relaxation Times

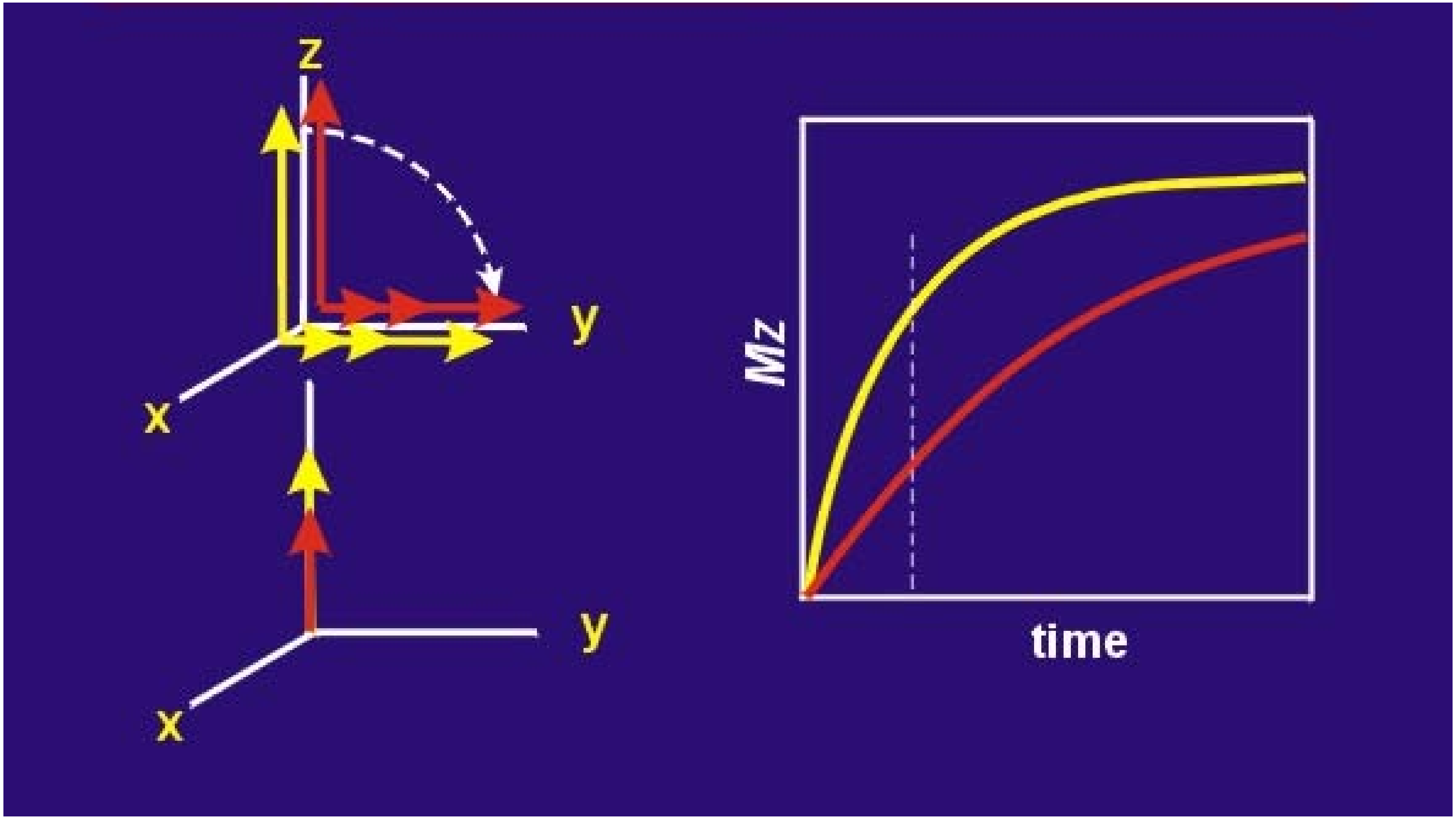


Tissue	T2 (ms)
Grey matter	87
White matter	74
CSF	250
Thalamus	75
Putamen	71
Internal capsule	67
Corpus callosum	69
Caudate nucleus	76

T2 modulation of image contrast



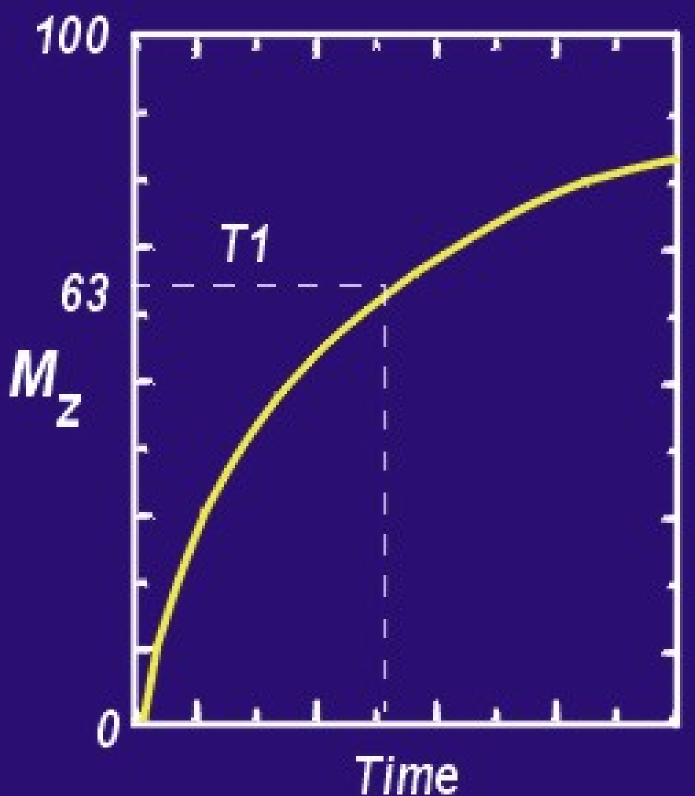
Spin-lattice (T1) relaxation



Spin-lattice (T1) relaxation - animation

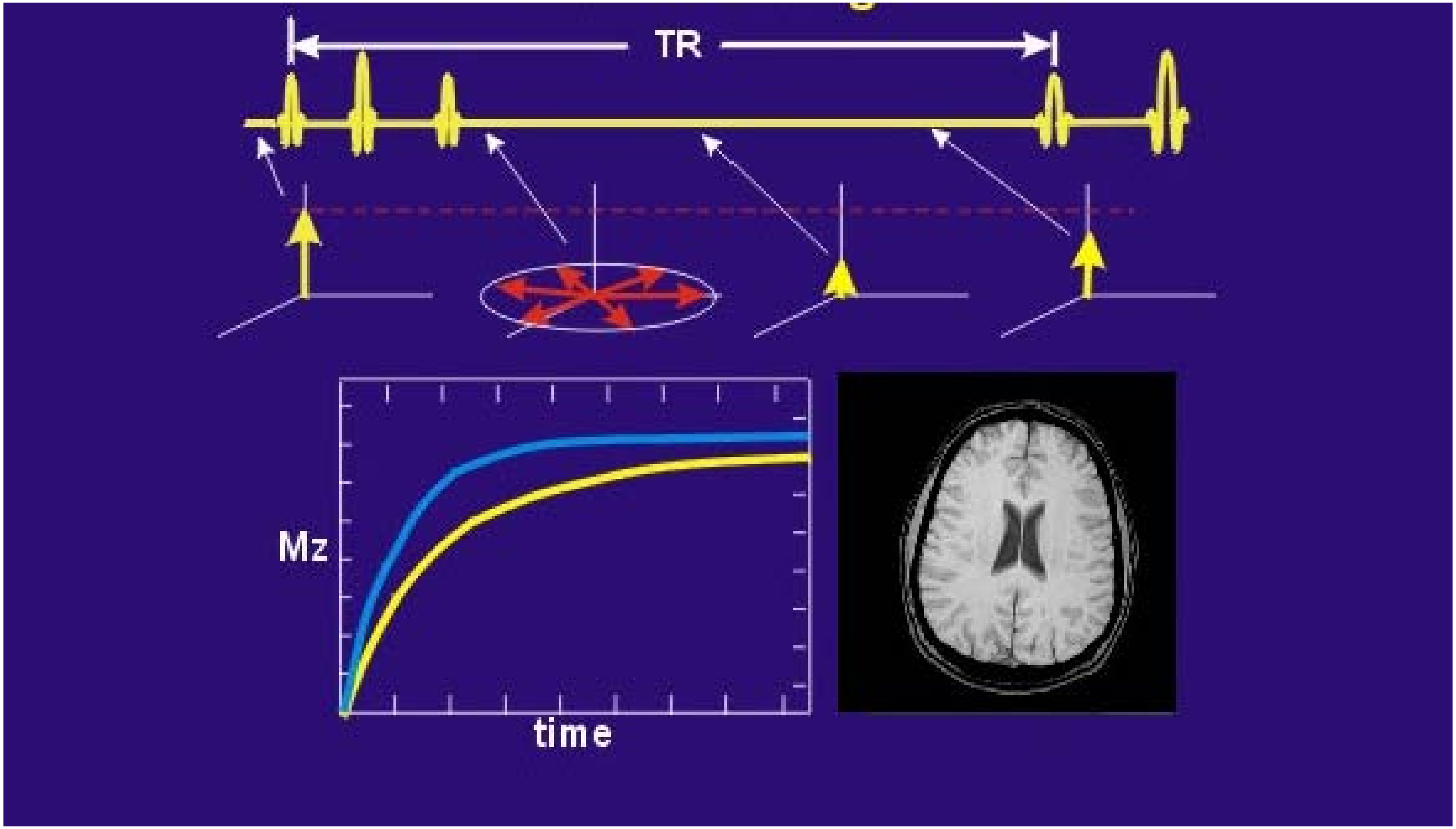
Video_13

Spin-lattice relaxation values for various tissues (sample T1 relaxation times)



Tissue	T1(ms)
Grey matter	871
White matter	515
CSF	1900
Thalamus	703
Putamen	747
Internal capsule	559
Corpus callosum	509
Caudate nucleus	822

T1 modulation on image contrast



Summary of T1 and T2 relaxation (relaxation effects)

T1 Relaxation

- spin-lattice interactions
- dissipation of energy
- 200-2000 ms time constant

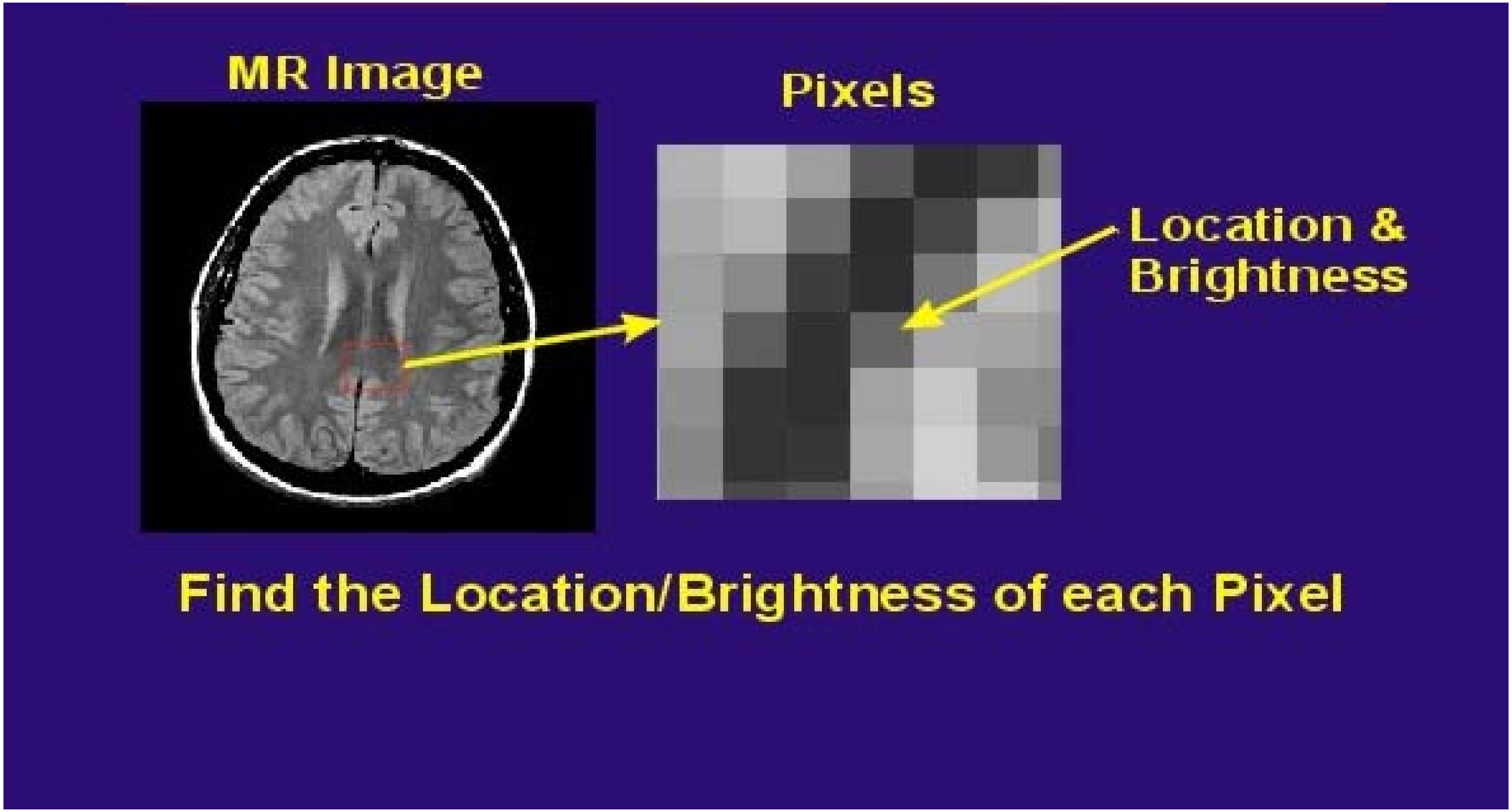
T2 Relaxation

- spin-spin interactions
- loss of spin phase (order)
- 25-250 ms time constant

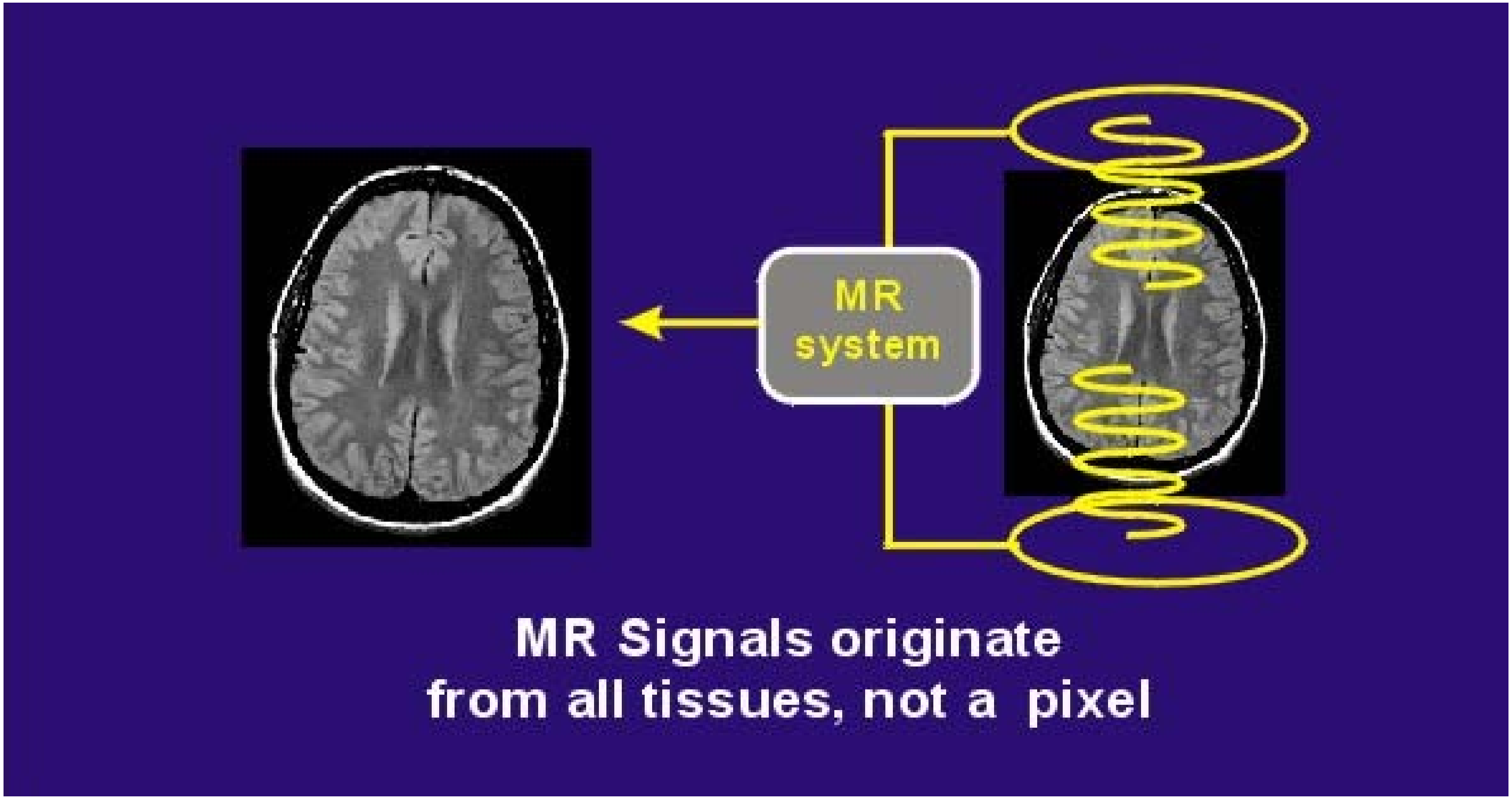
Overview of lecture on the physics of image formation (MR imaging)

- Image structure
- Fourier representation
- Magnetic field gradients
- Moving through K-space
- Collecting K-space data
- MRI sequence summary

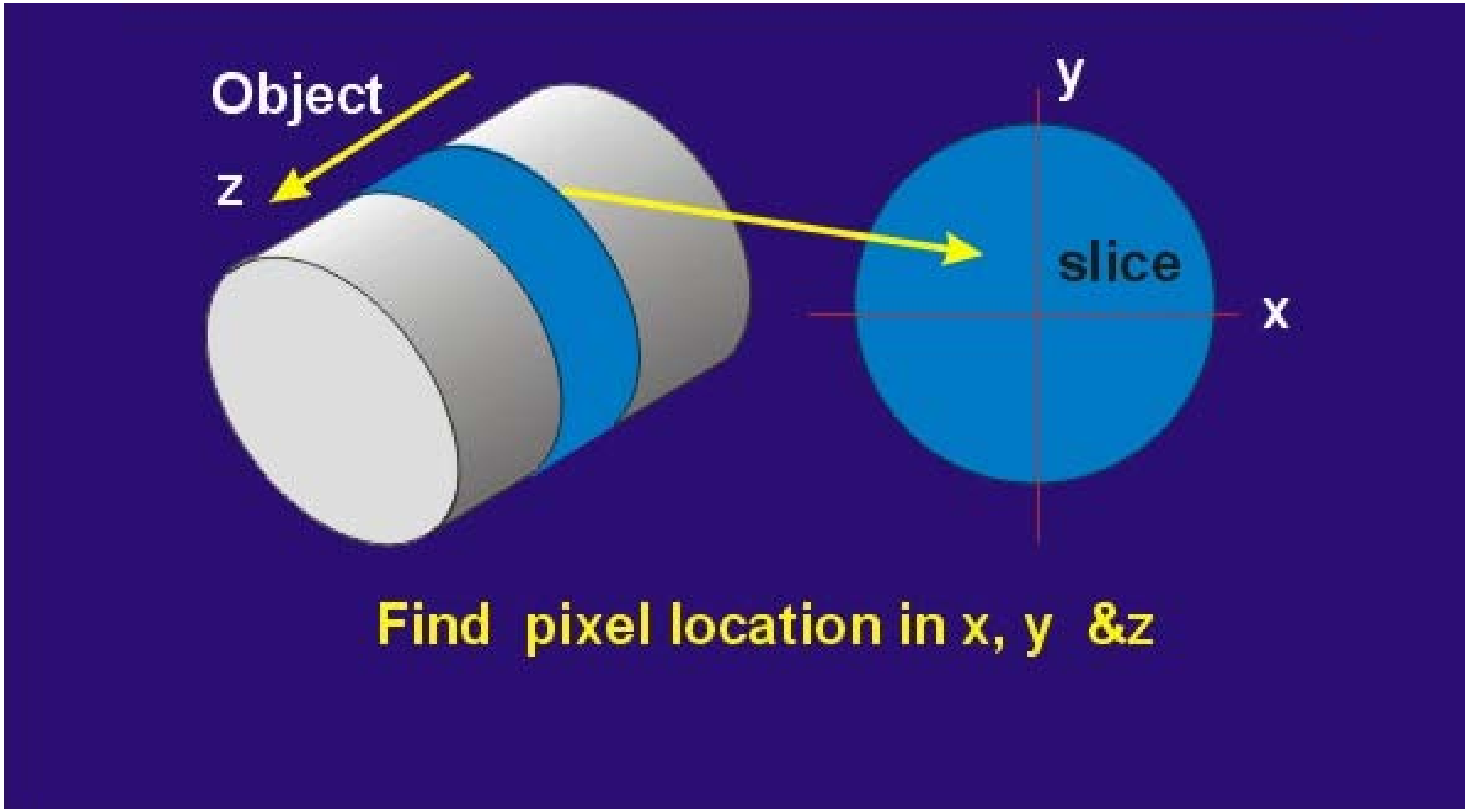
Structure of MR images



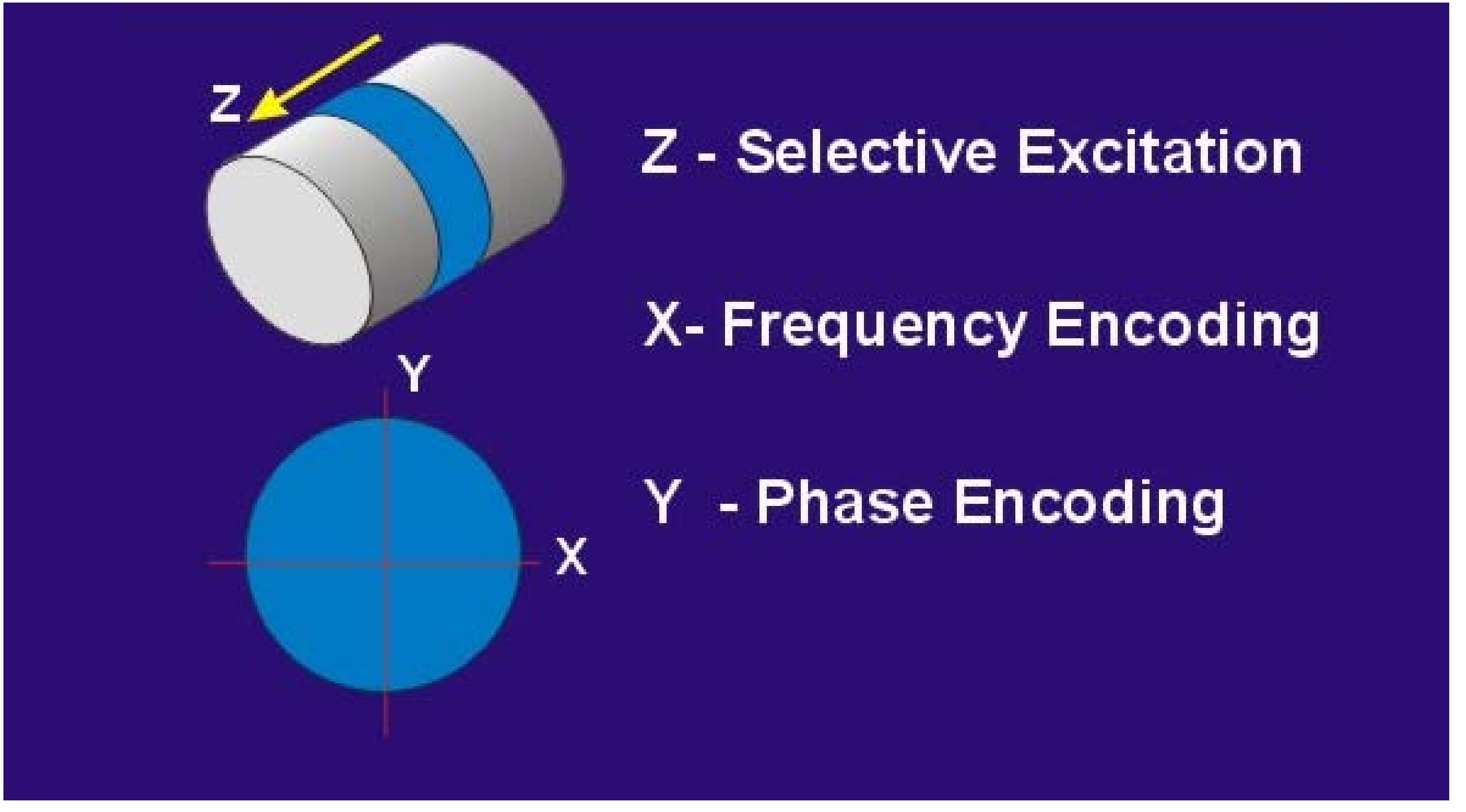
The question of localization (How do we localize the signal?)



The spatial location task



Techniques for spatial localization

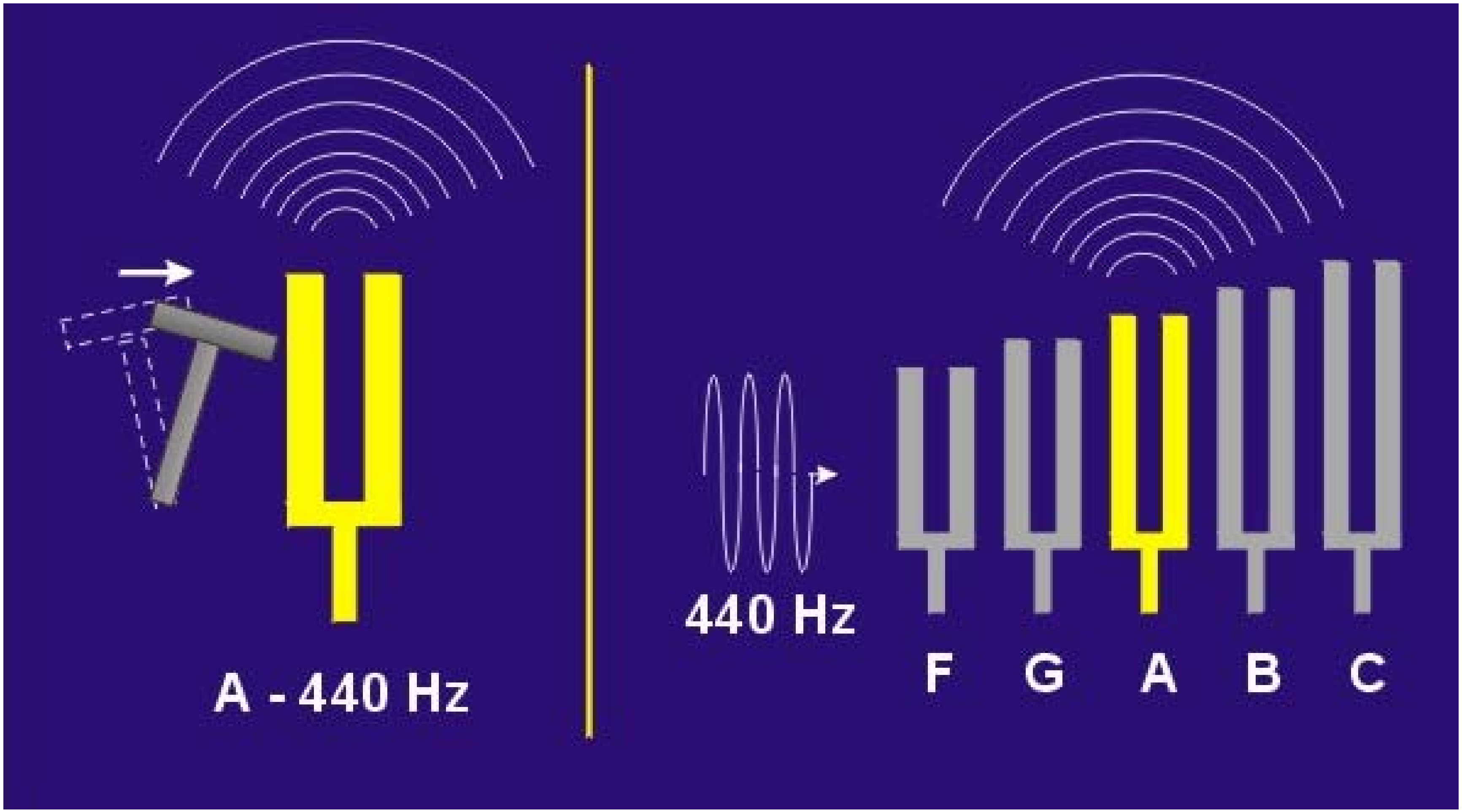


Selective excitation: The ingredients

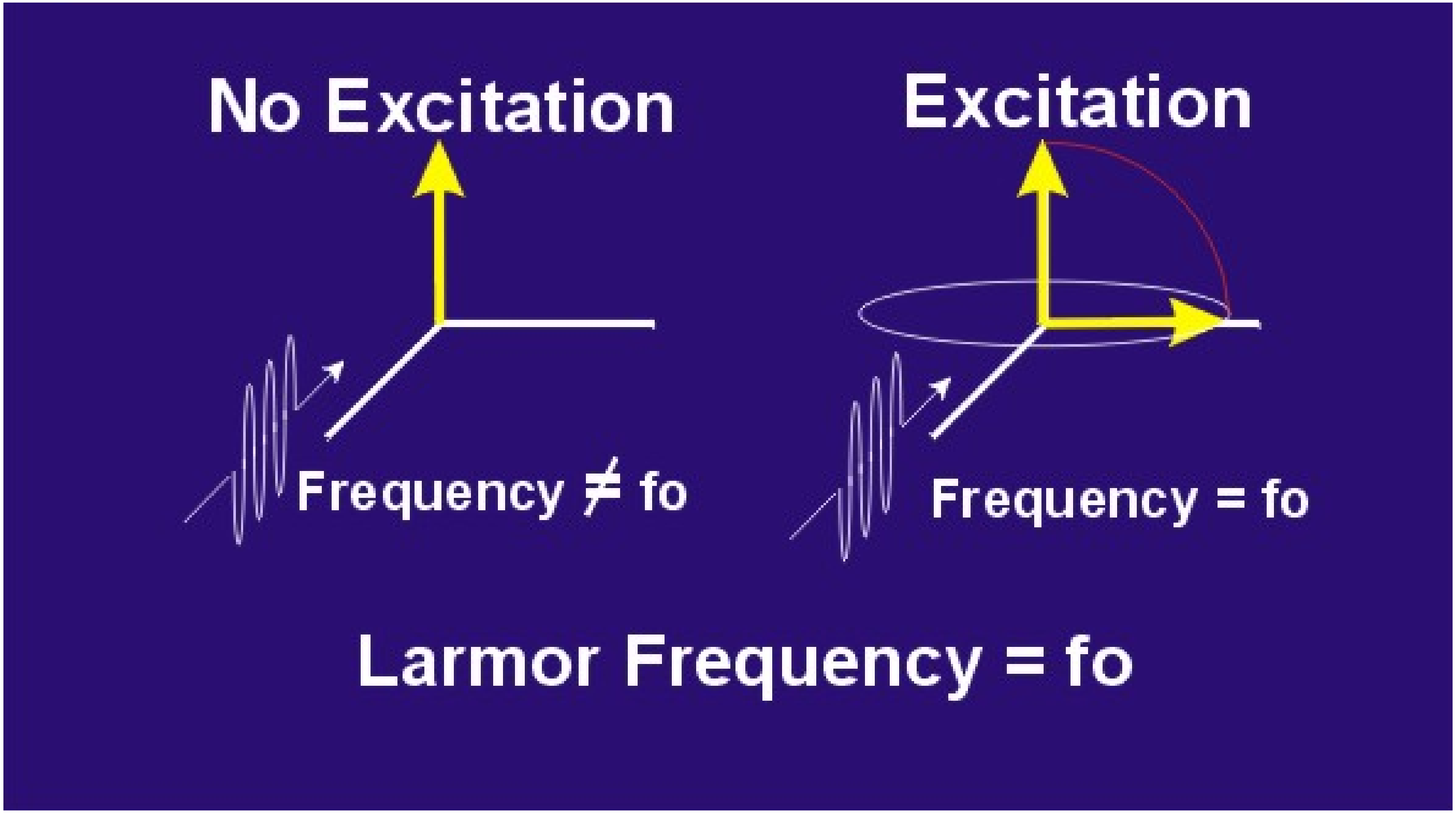
Combines effects of:

- **NMR resonance**
- **Magnetic Field Gradient**
- **RF excitation frequency**

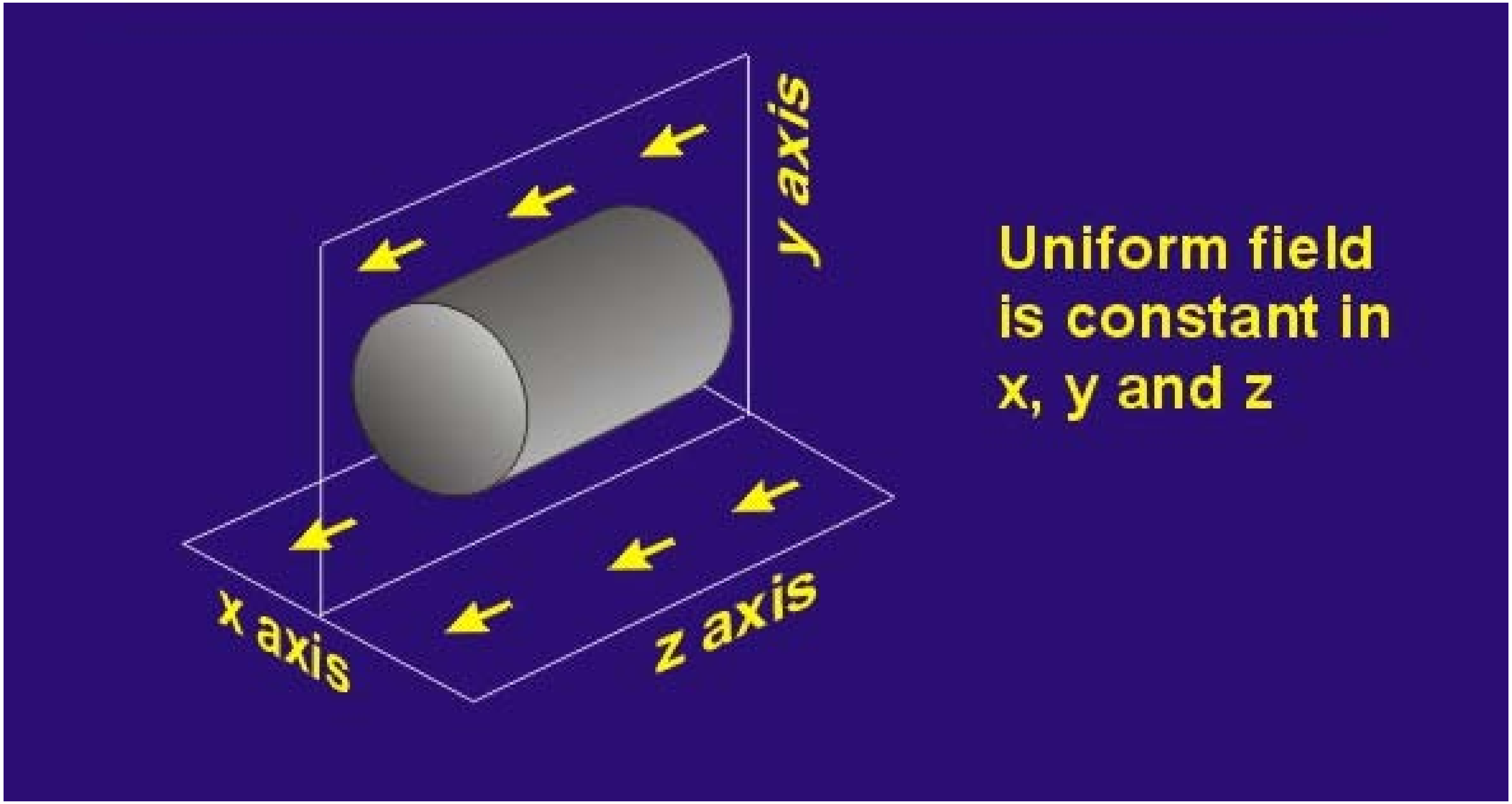
Selective excitations: An analogy - resonance



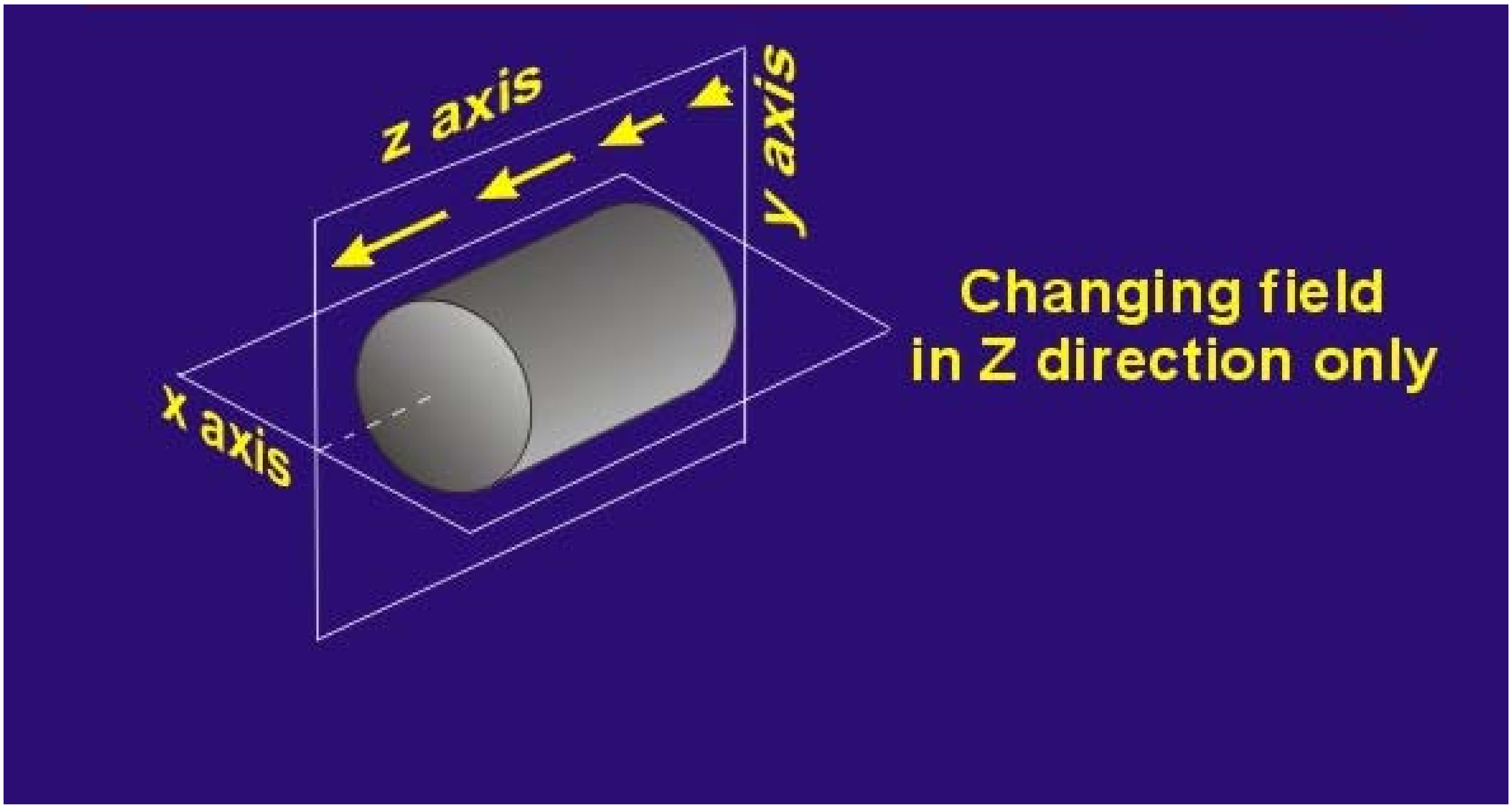
Selective excitations and NMR resonance



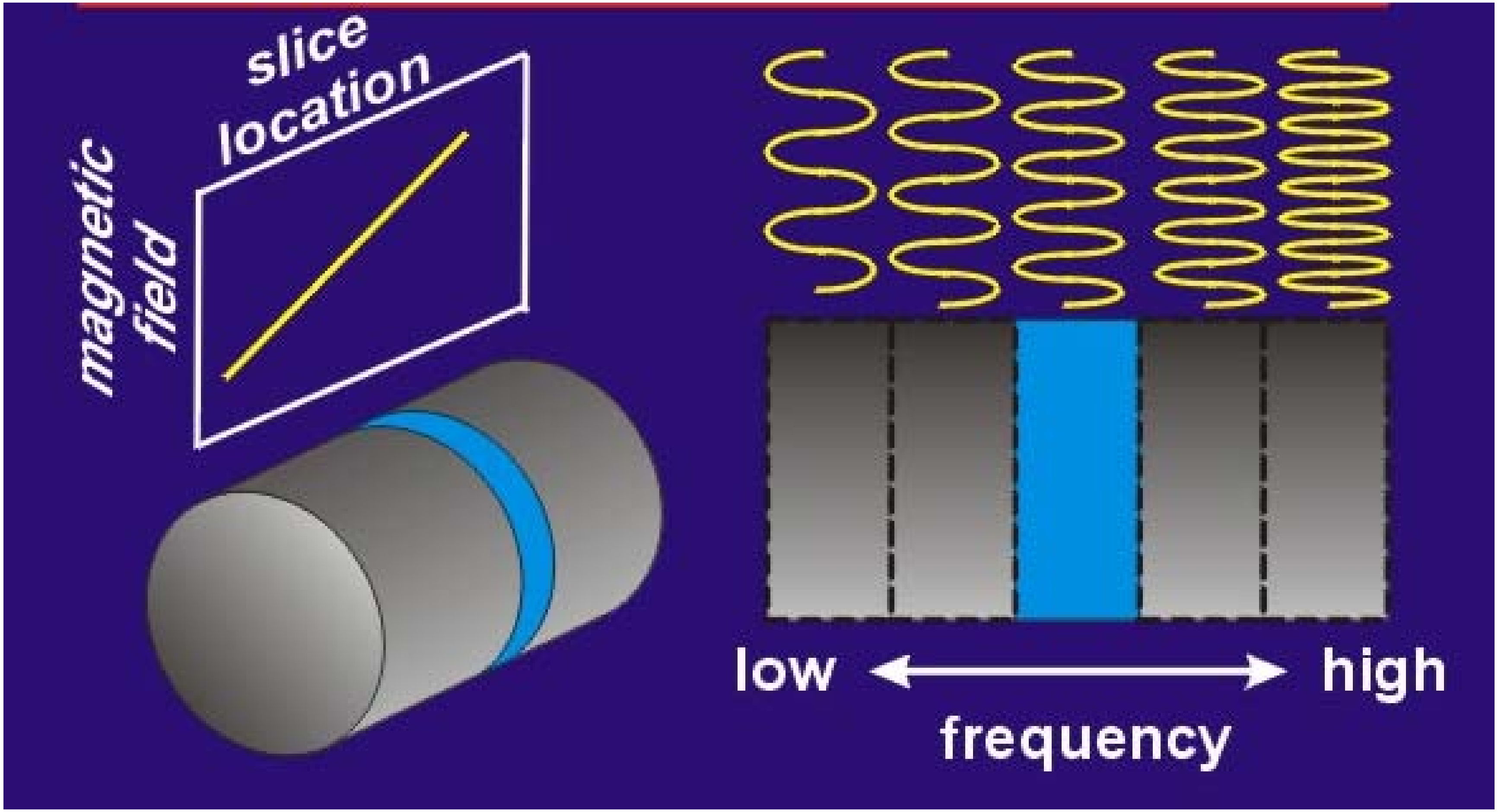
A uniform magnetic field (magnetic field gradients)



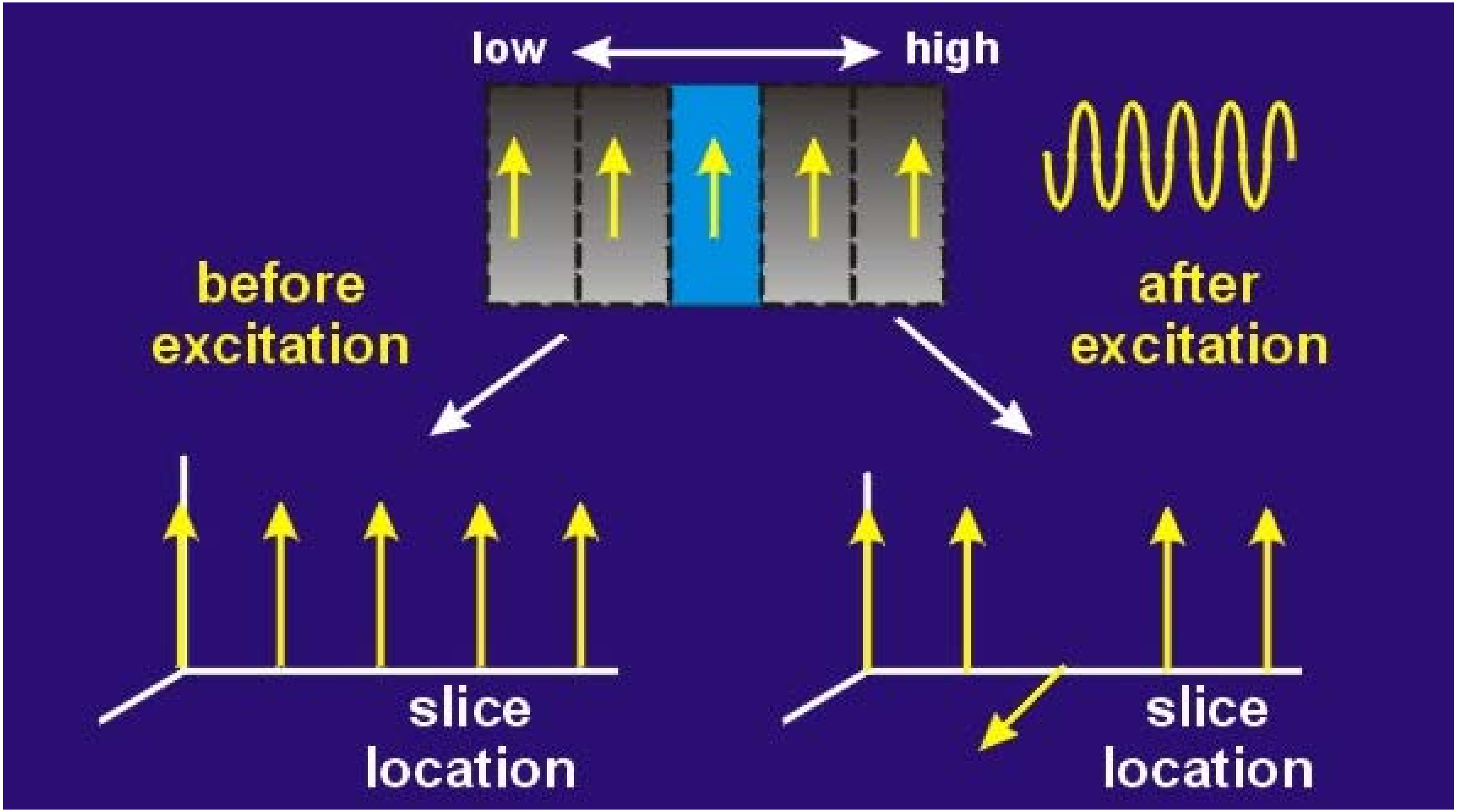
A magnetic field gradient (Gz - in Z direction)



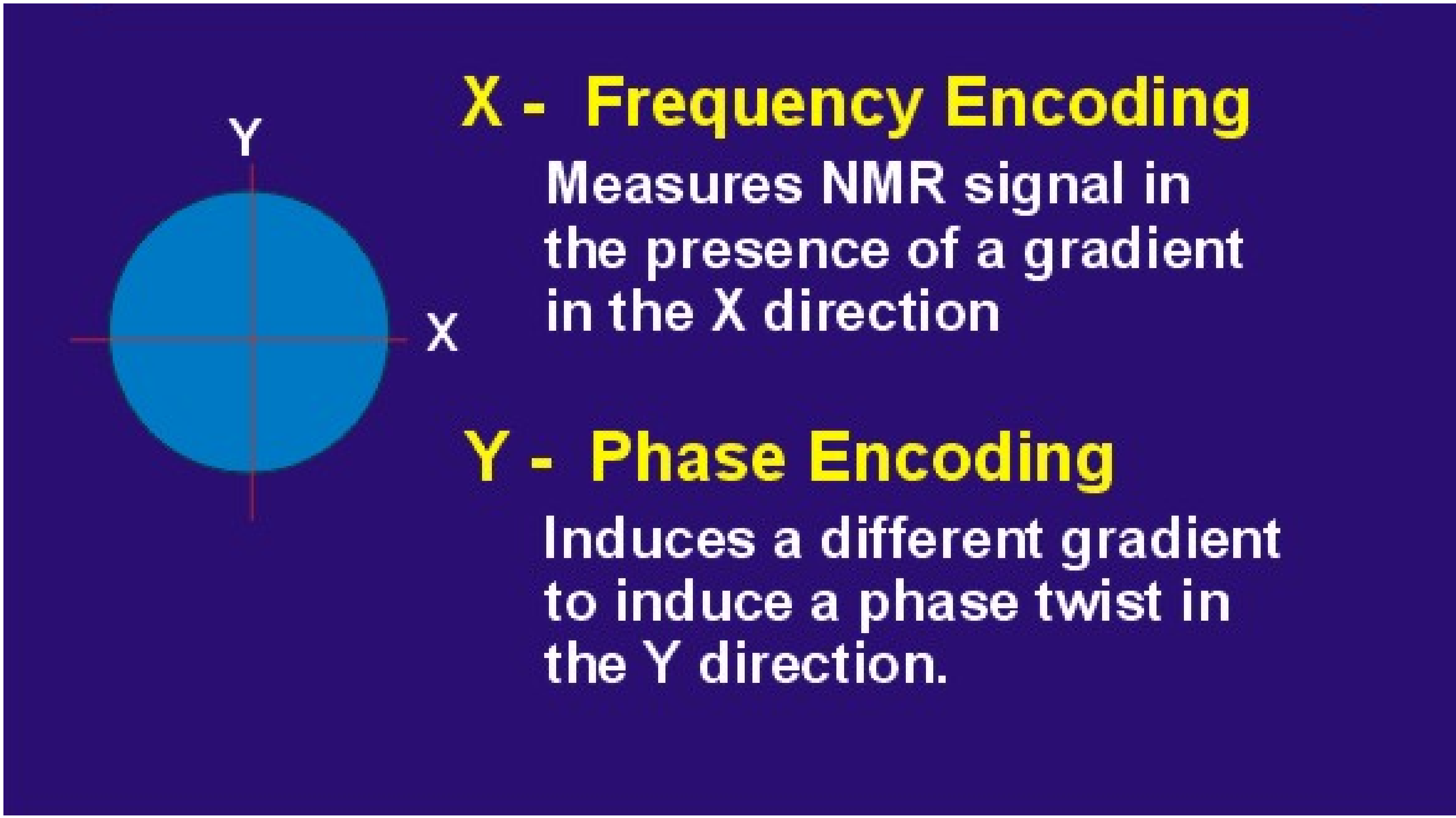
Selective excitation and a Gx gradient



The effect of RF pulses in selective excitation



In plane localization



The relation between the MR system and image formation

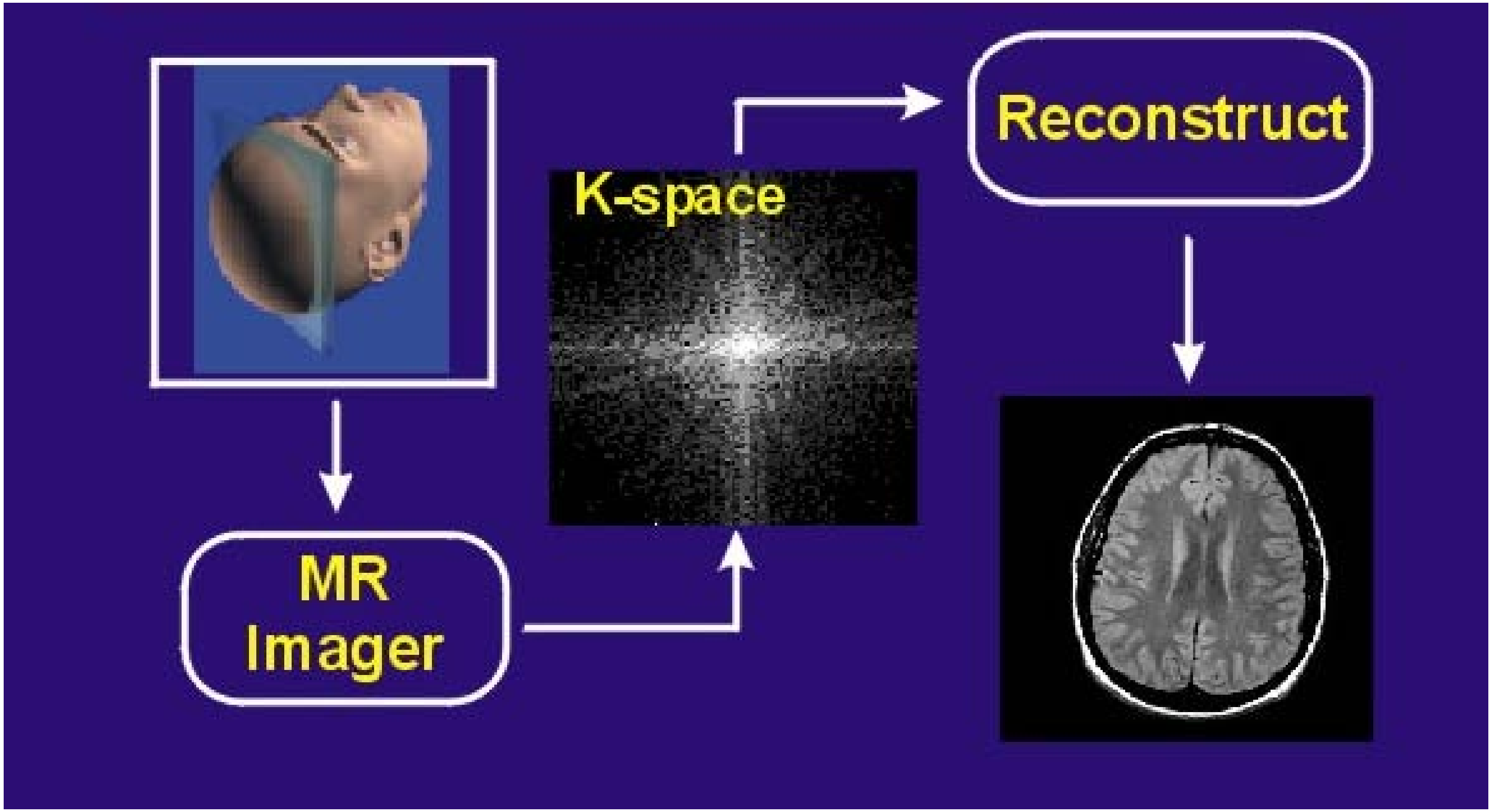
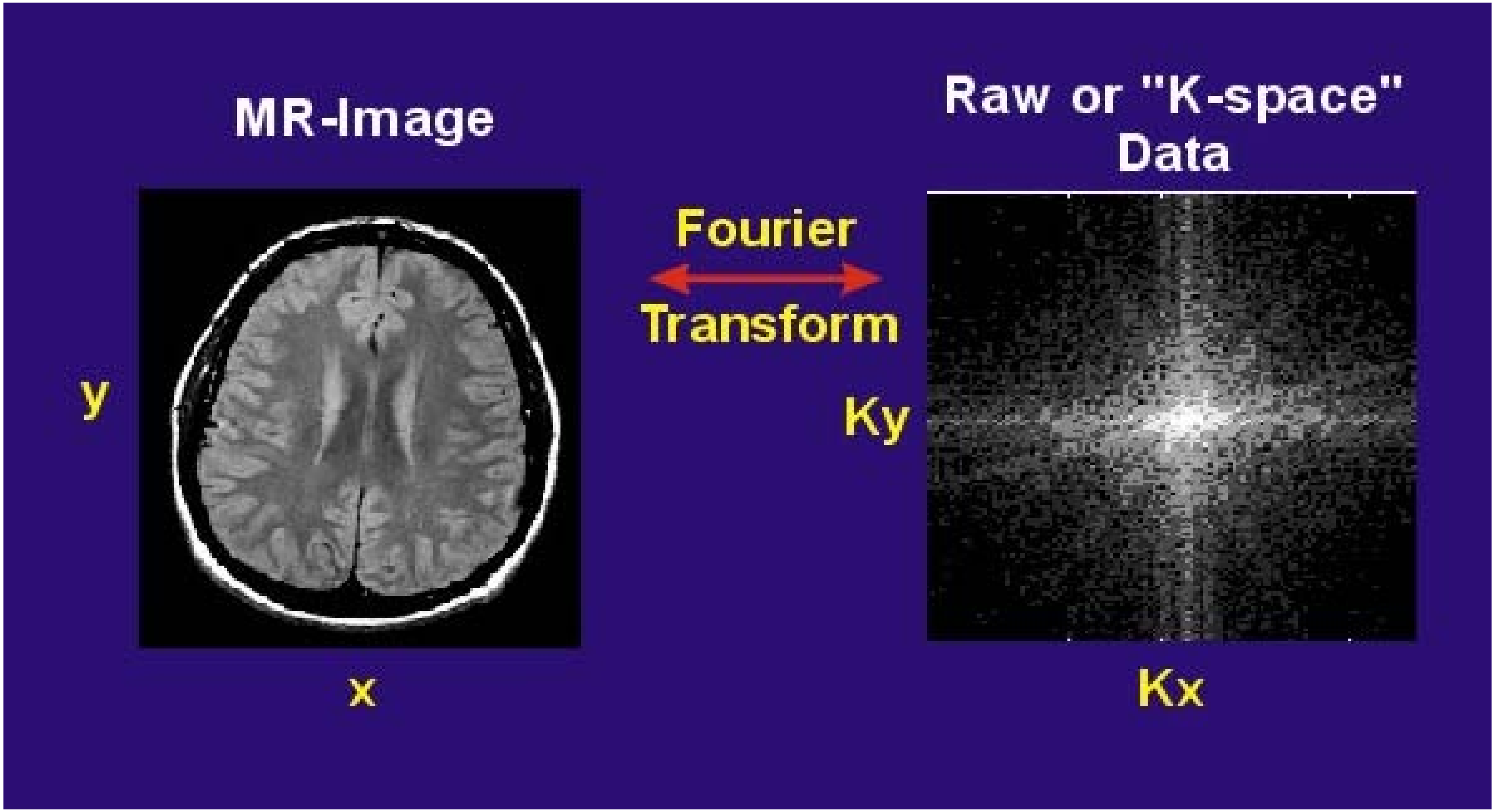
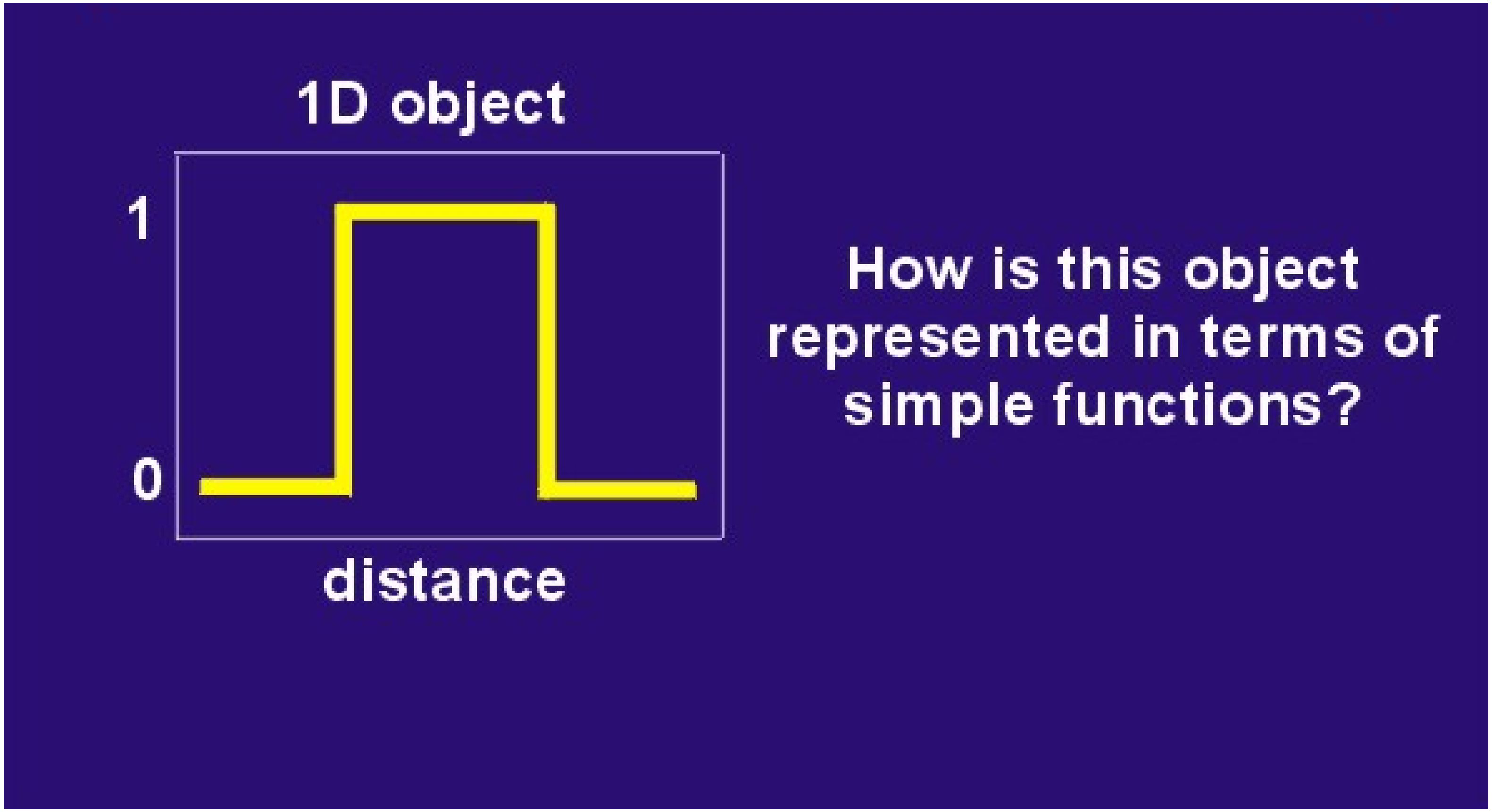


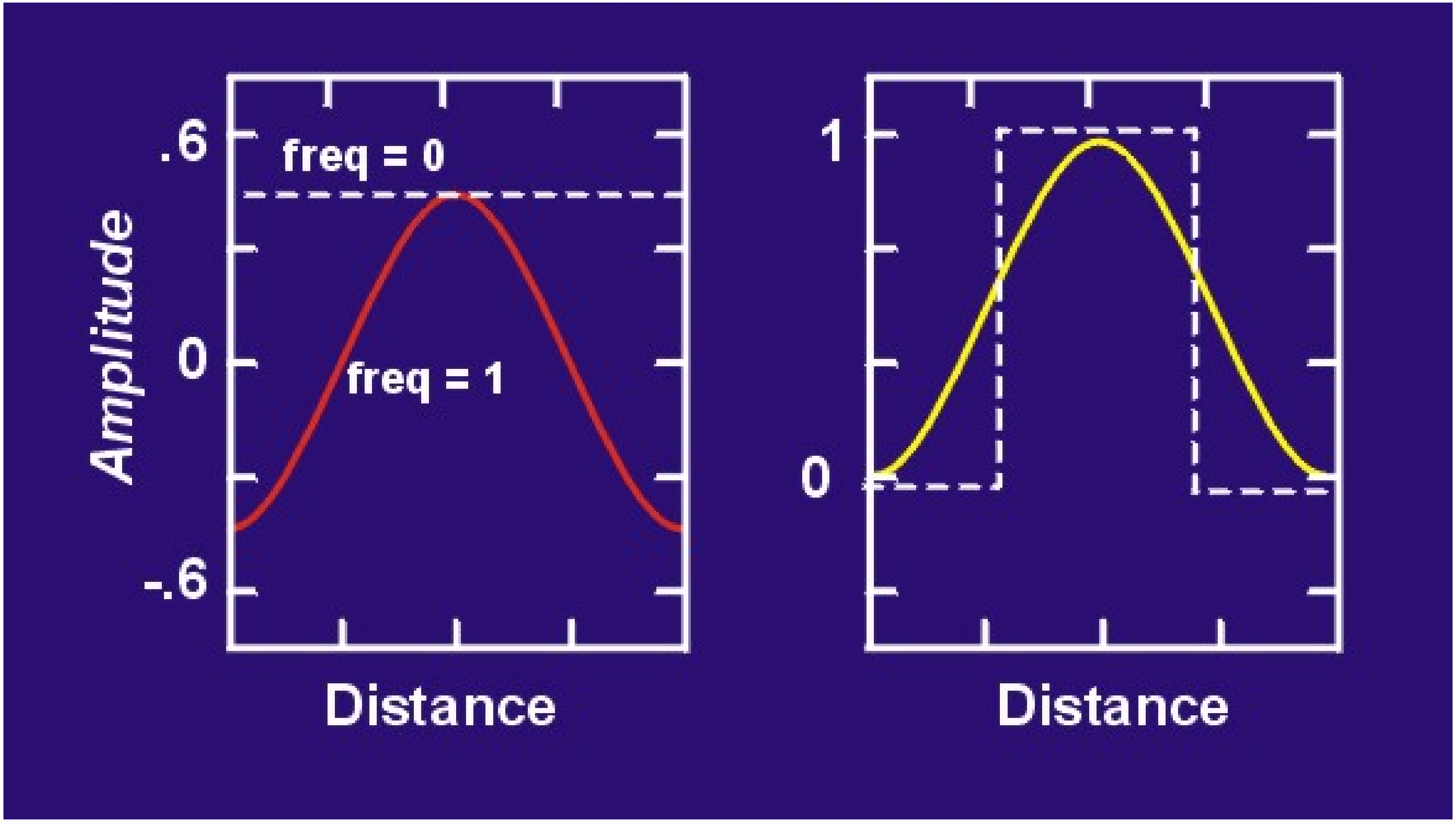
Image space vs. K-space



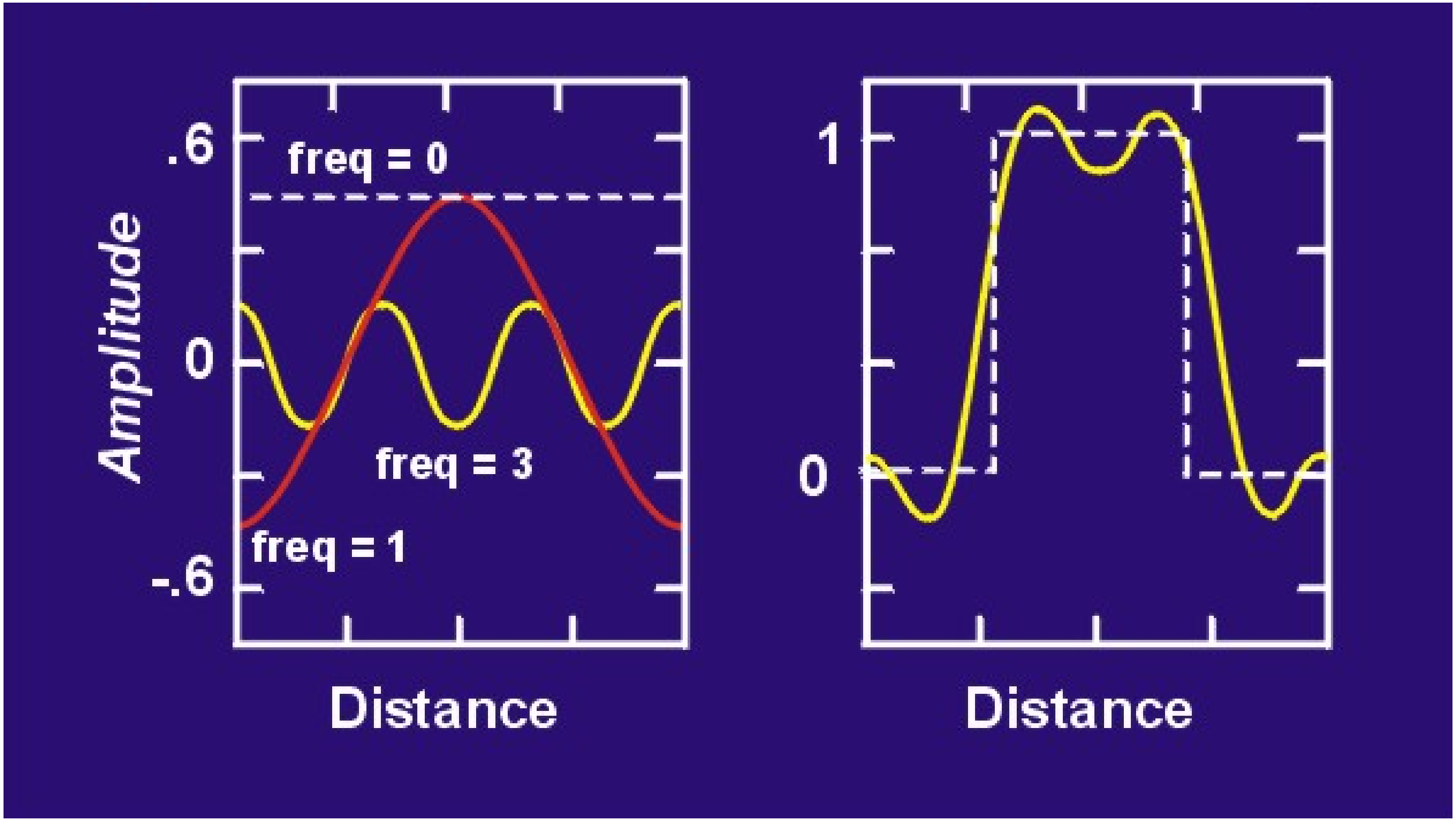
A one dimensional problem (Fourier transform)



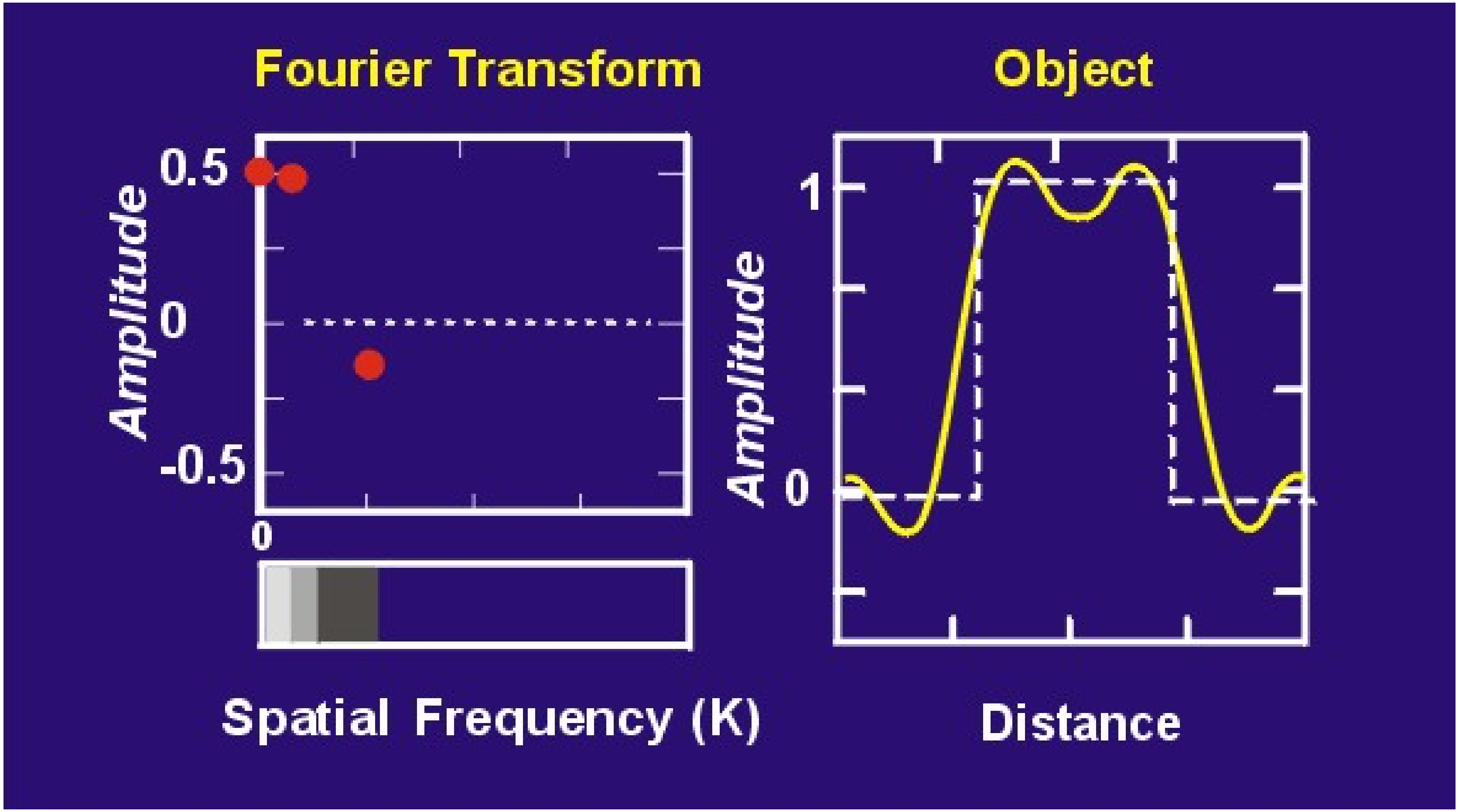
A crude Fourier approximation



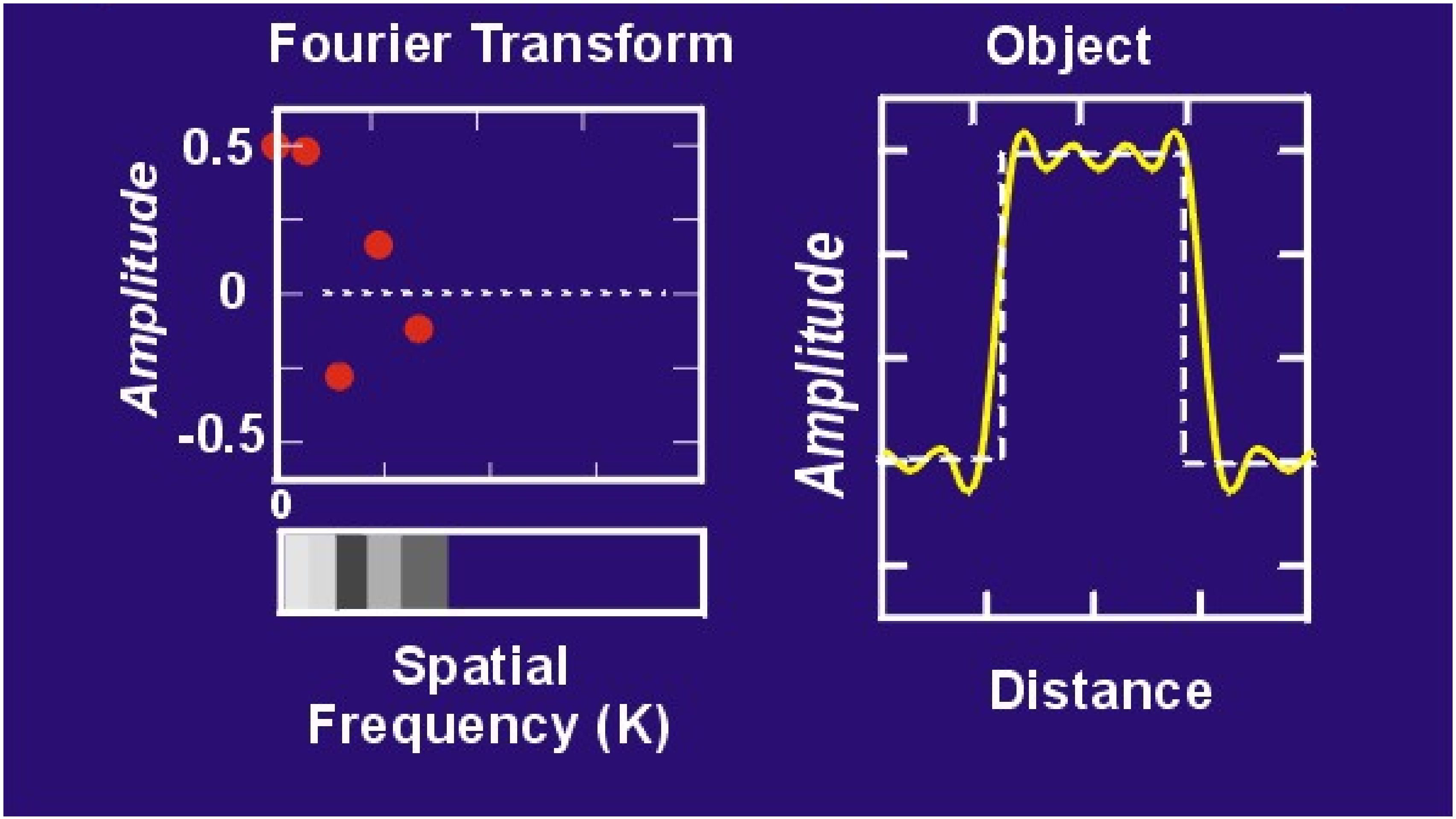
A better Fourier approximation



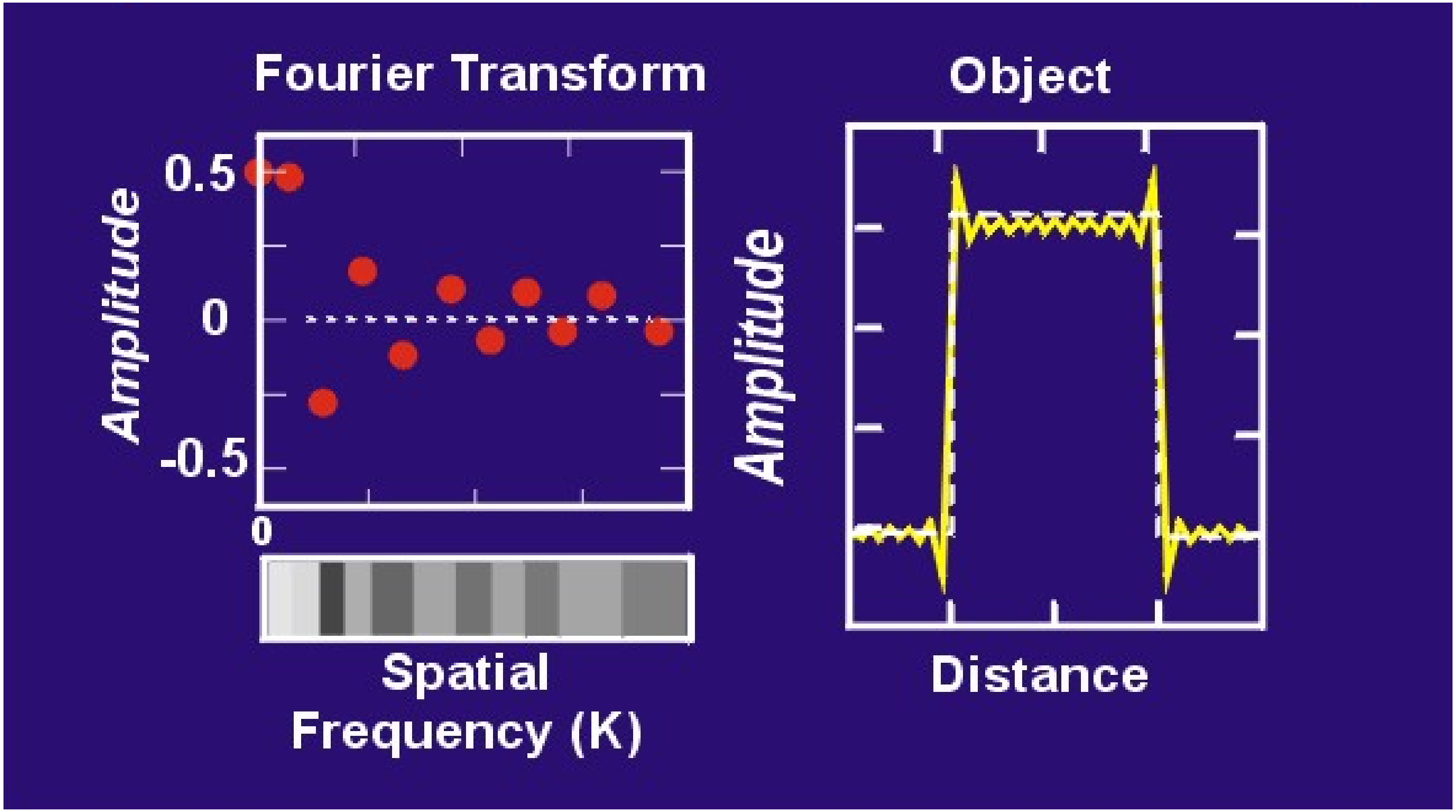
The definition of K-space



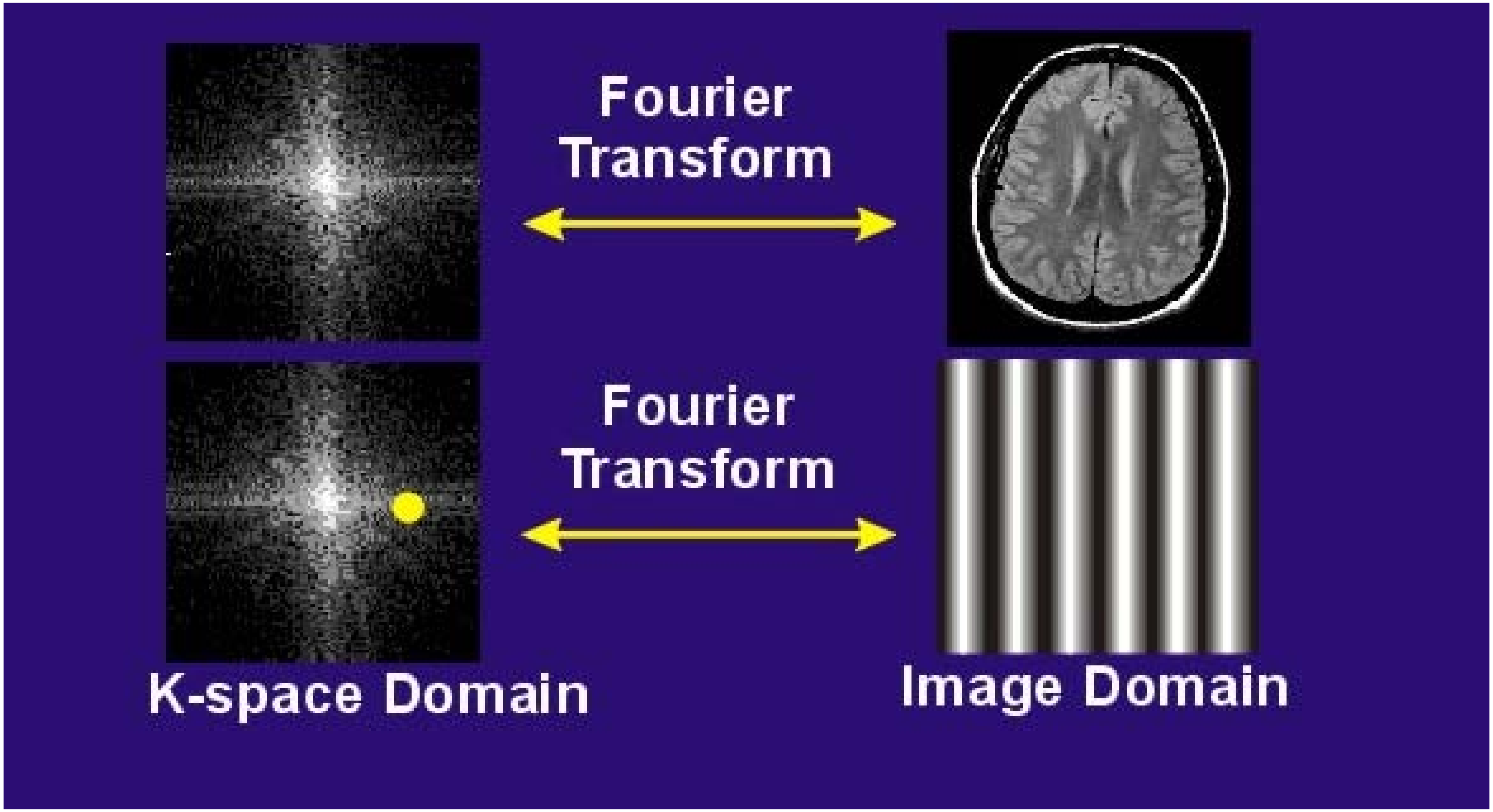
Successively better approximation



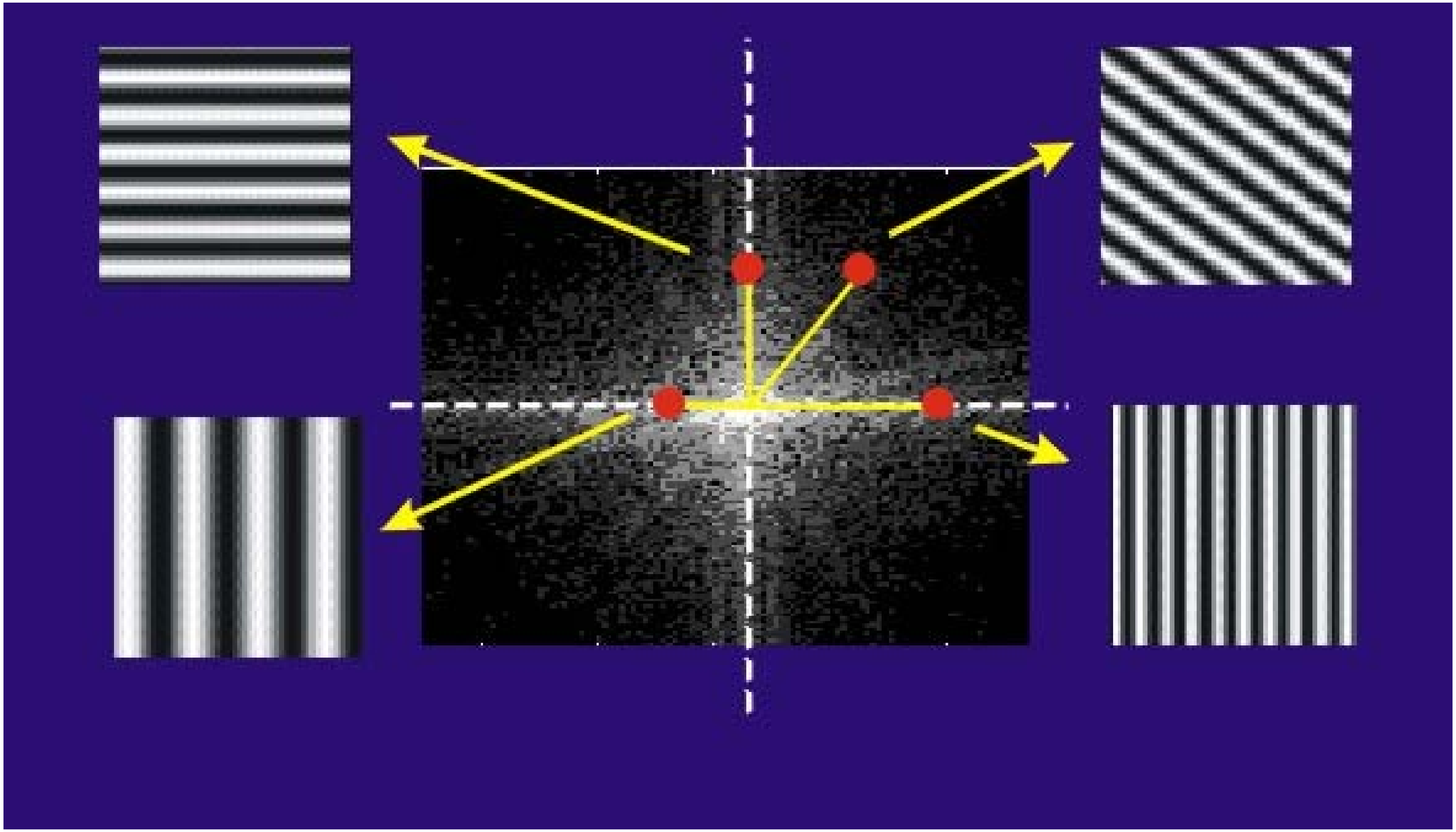
Successively better approximation



Two dimensional K-space and image space (space and image domains)



The meaning of various points on K-space (Fourier transform representation)

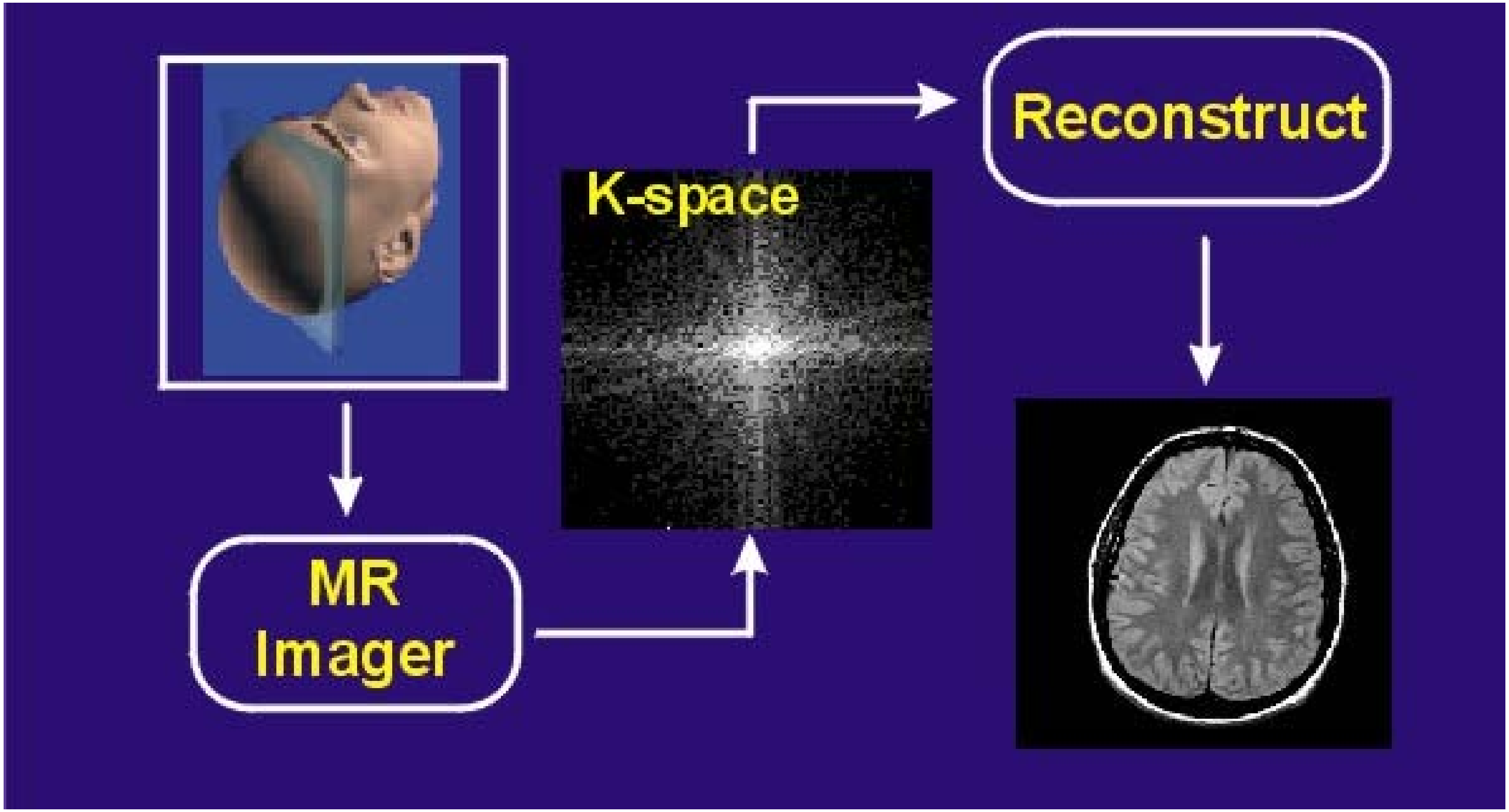


The question of How stripes are made in MRI ? (MR image formation)

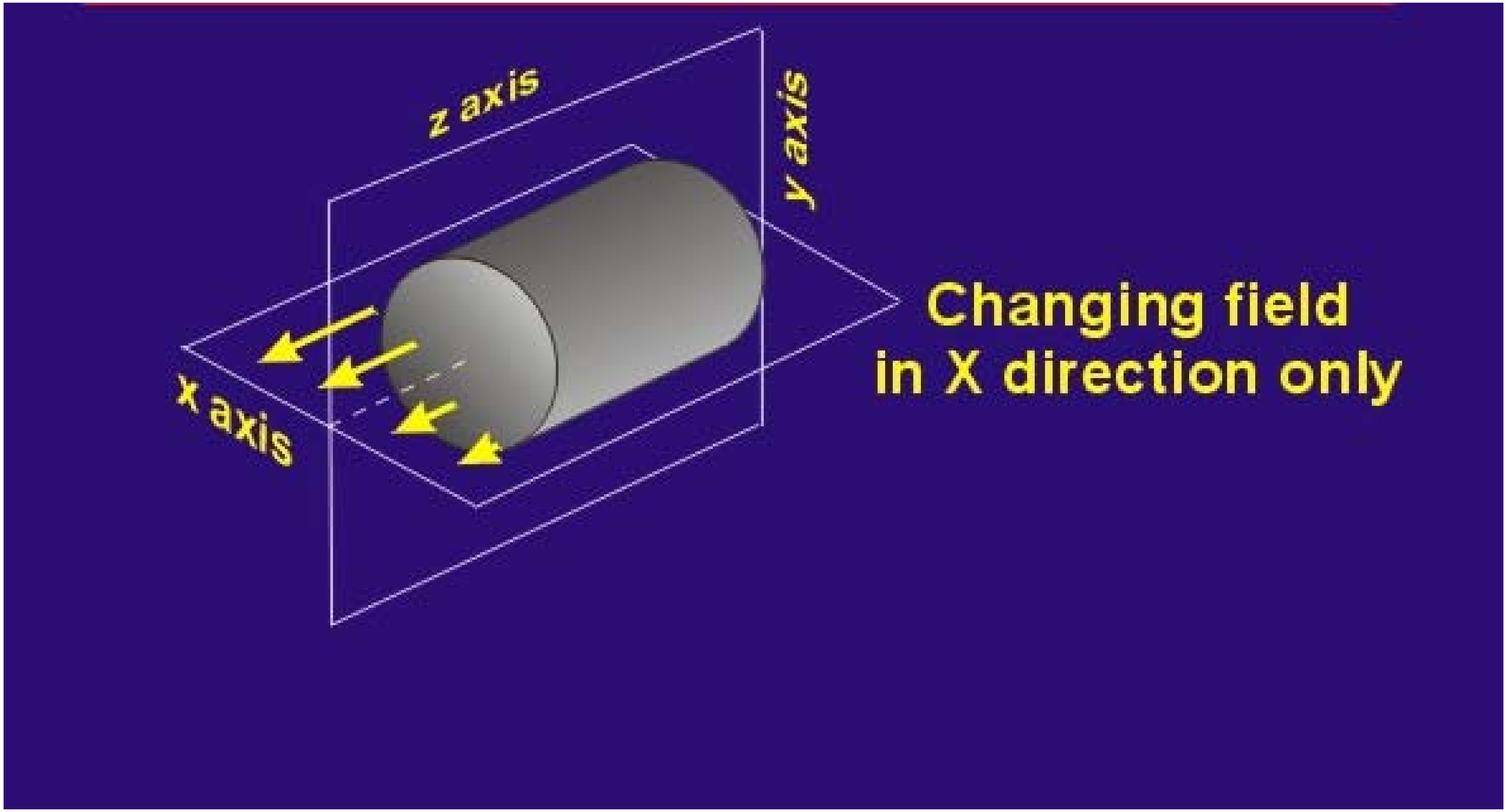
How does MR imaging make

- stripes?
- variable spatial frequency?
- variable orientation?

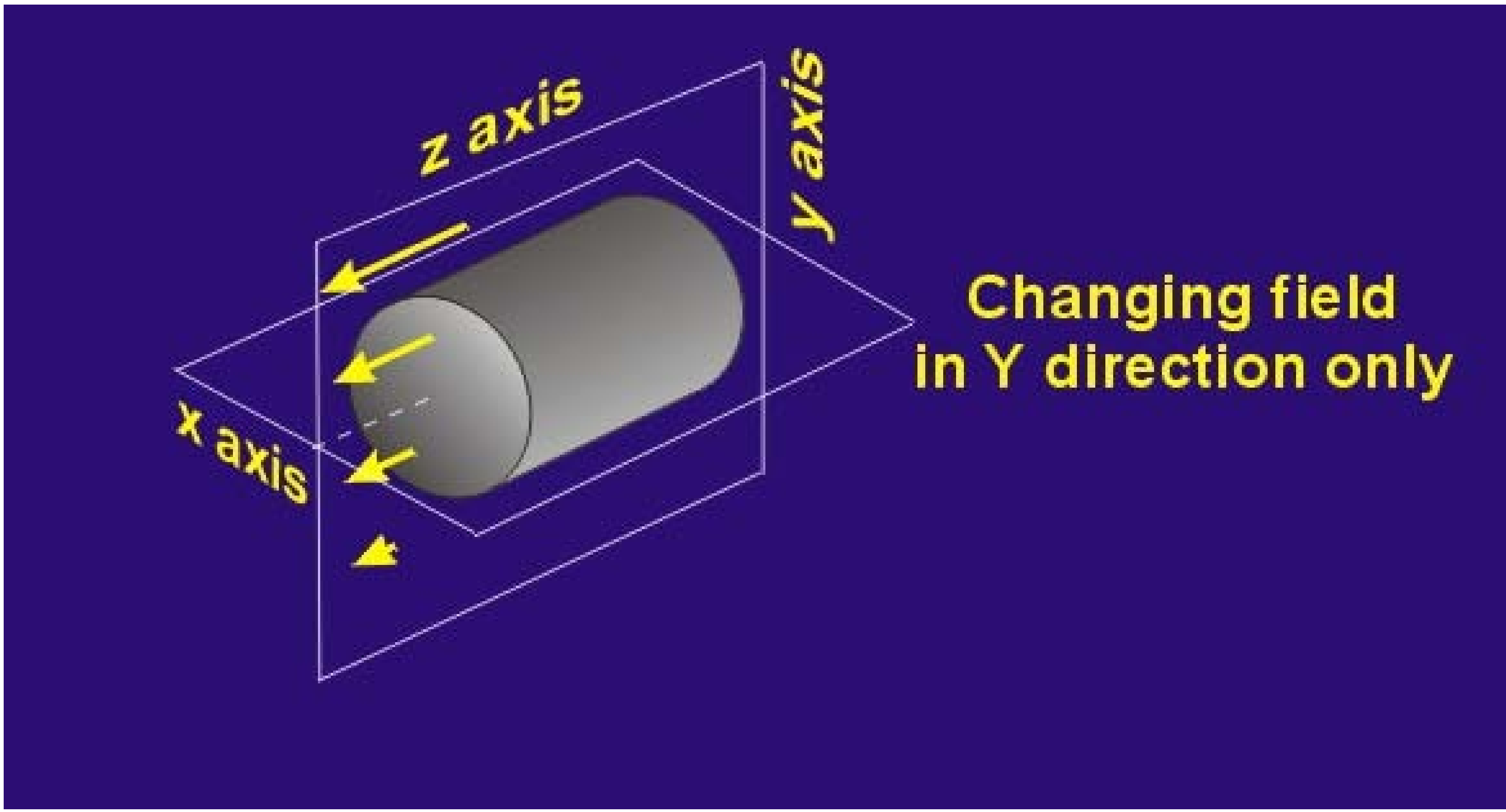
Return to the relation of the MR system and image formation



Gradient in X (gradient X direction)



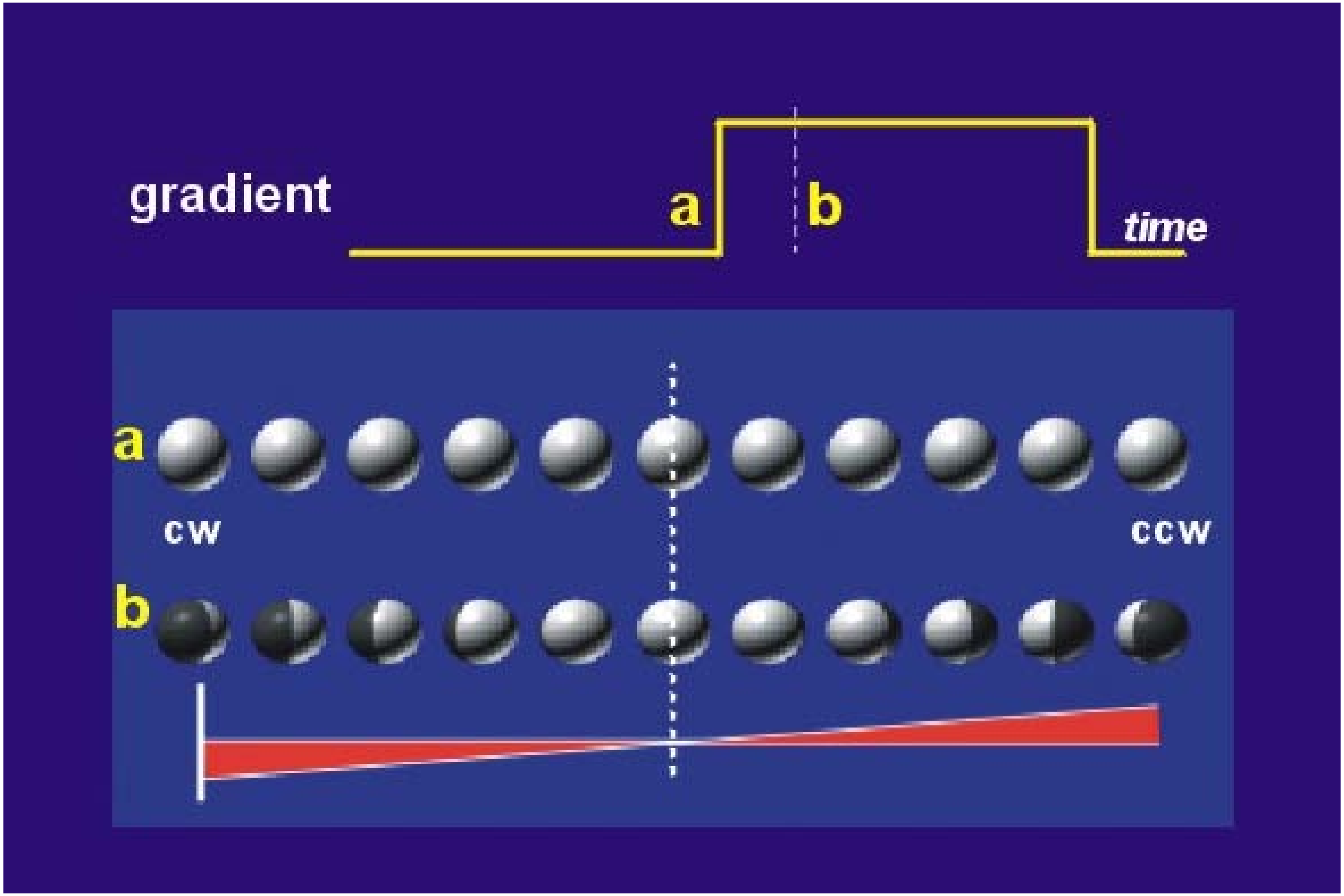
Gradient in Y (gradient Y direction)



An alternative representation for magnetization

Video_14

The effect of a gradient on an array of magnetization balls



The effect of a gradient on an array of magnetization balls (animation)

[Video_15]

Creating vertical stripes

Video_16

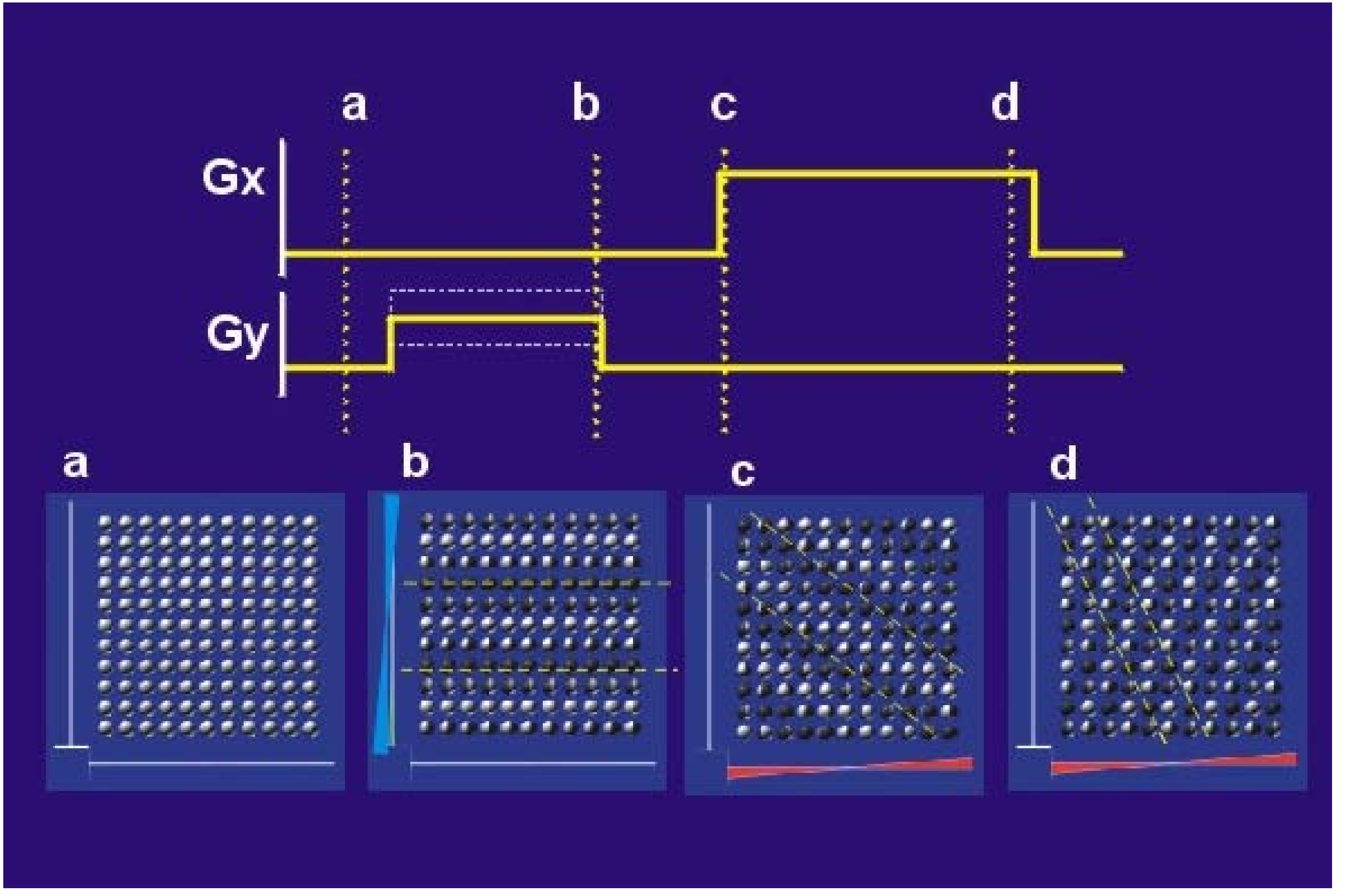
Creating horizontal stripes

Video_17

Creating blique stripes and K-space

Video_18

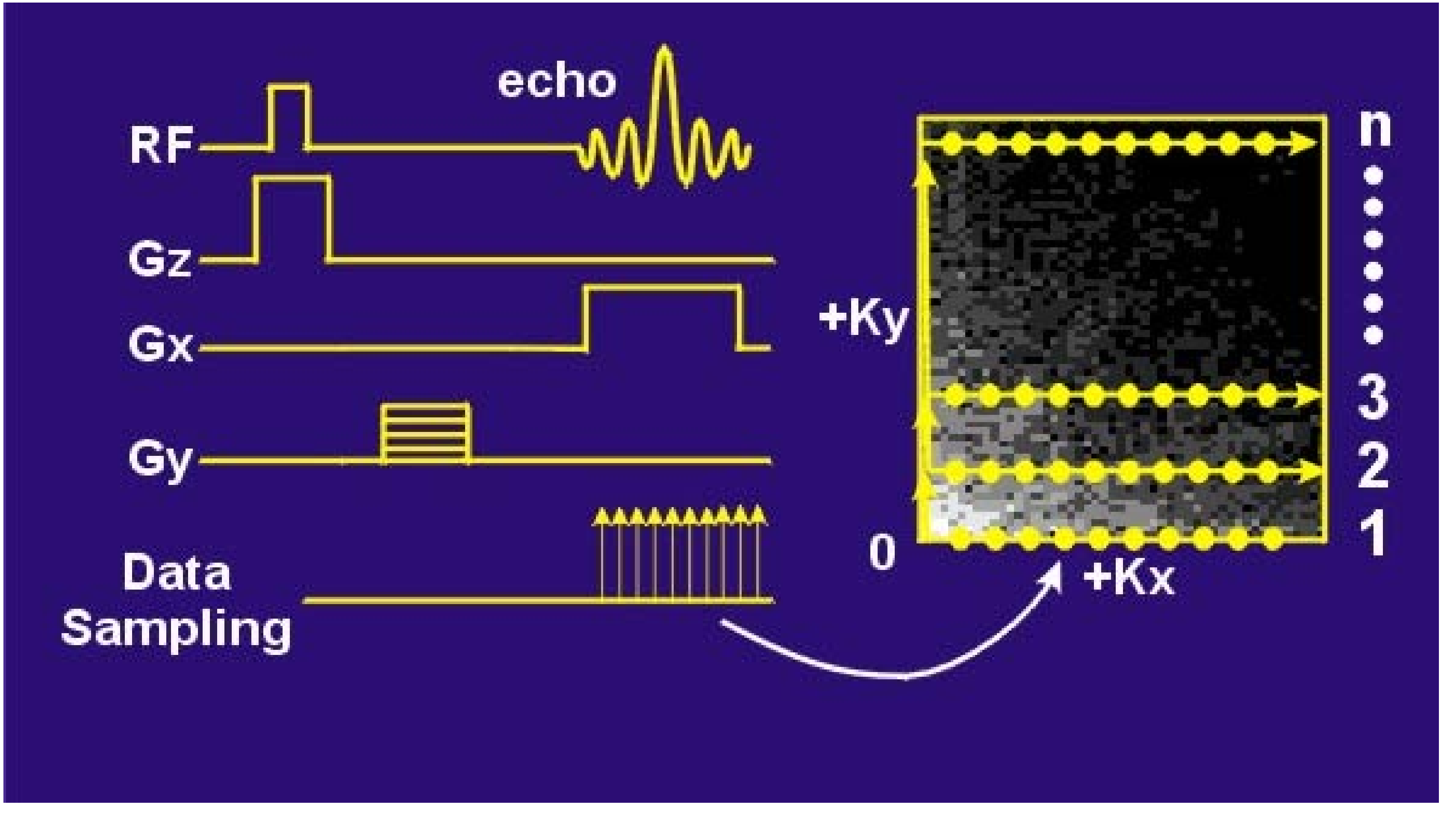
Oblique stripes: A summary



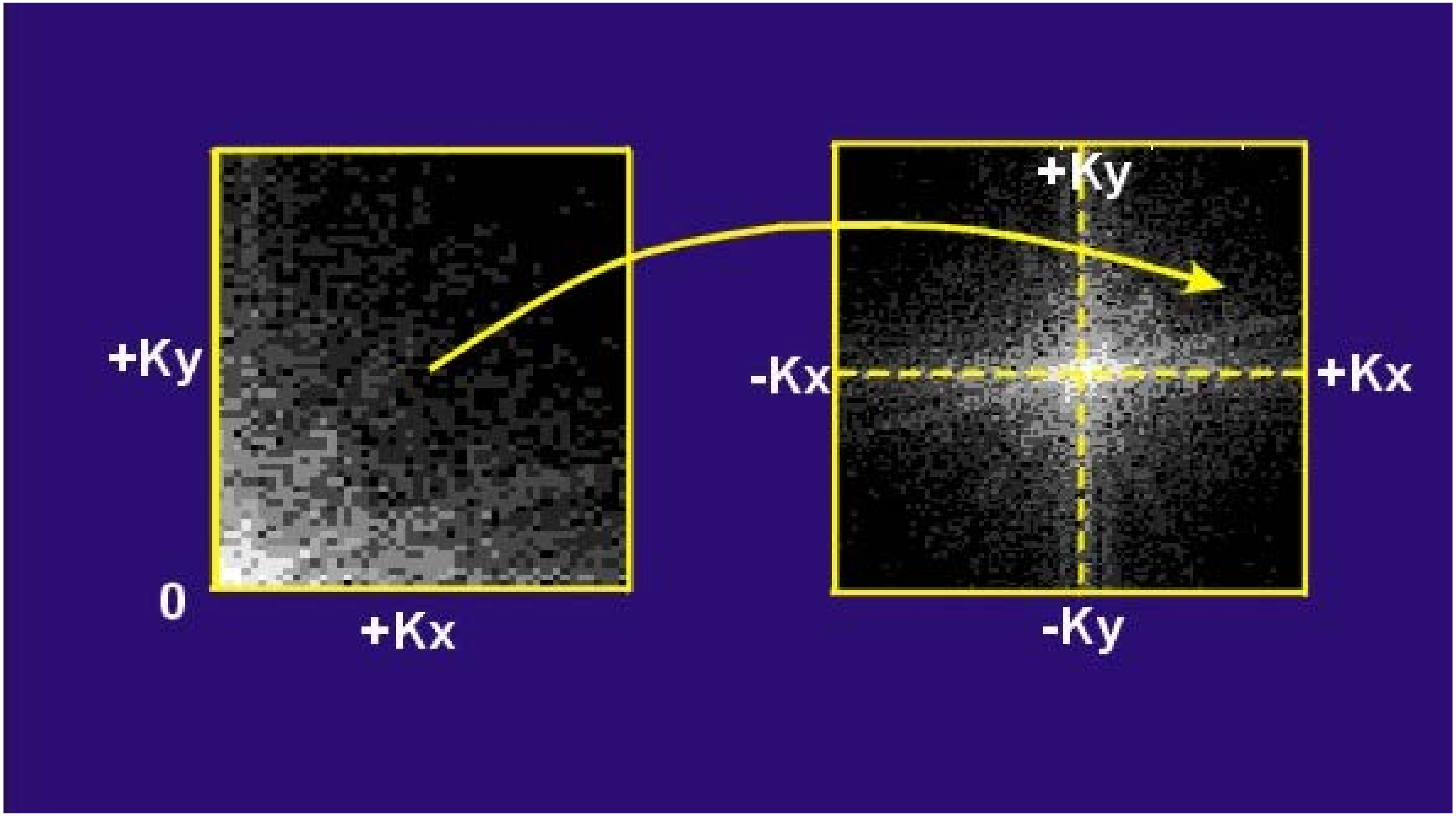
How does the MRI system measure the K-space signals?

Video_19

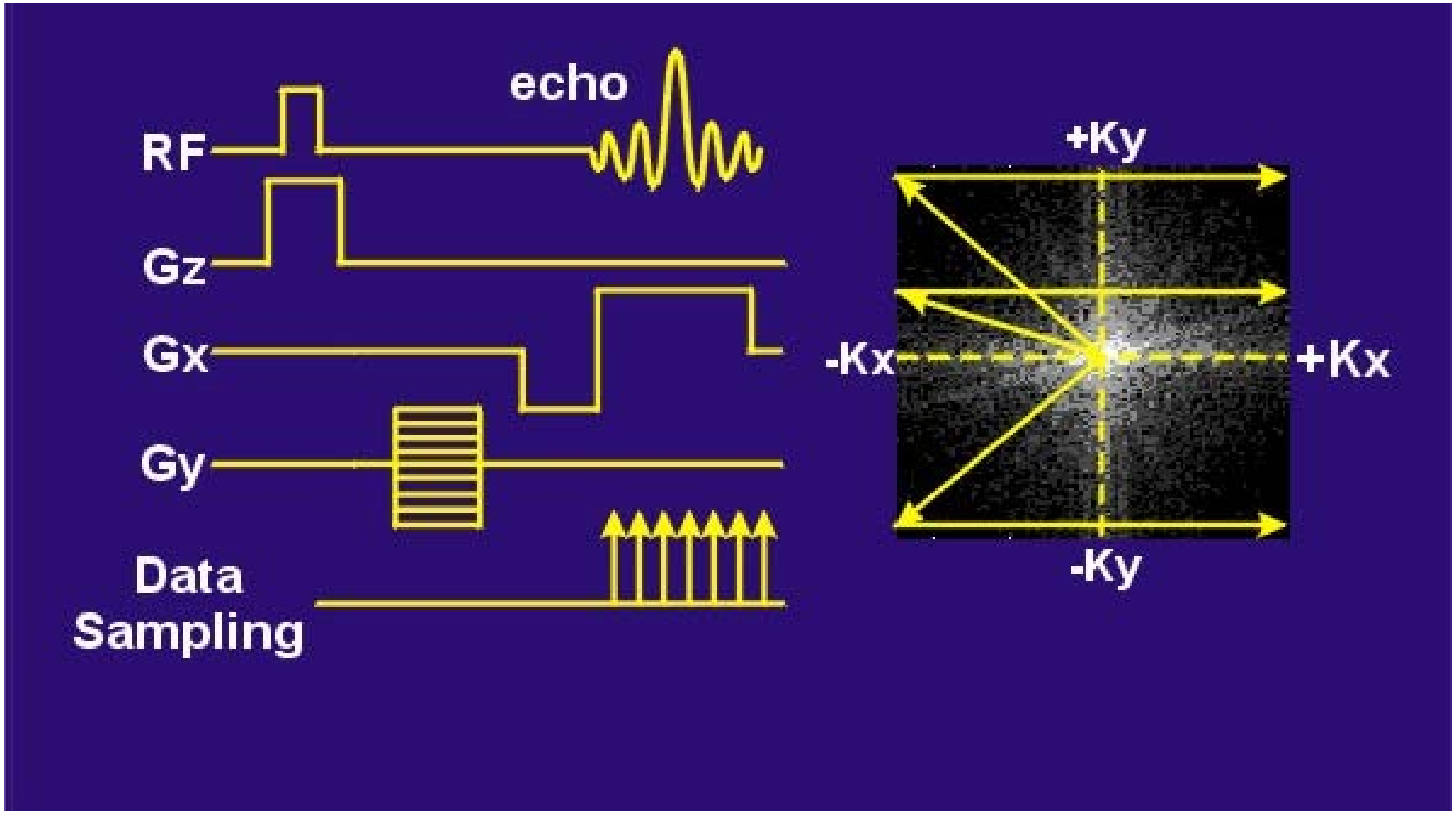
A simple (but incomplete) MRI pulse sequence



The four quadrants of K-space (symmetric 2D K-space)



A more complete MRI pulse sequence



Fourier reconstruction of K-space: part A

Video_20

Fourier reconstruction of K-space: part B

Video_20_2

Conclusion I (MR image formation)

- Spatial location by application of three orthogonal gradients
- Selection excitation defines slice location and width
- In-plane locations done by:
  - Frequency Encoding
  - Phase Encoding

Conclusion II (MR image formation)

Frequency Encoding

- Measures location in one direction
- MR signal measured with gradient on
- MR signal vs time measures the K-space data

Conclusion III (MR image formation)

- **Phase-encoding** defines Y position
- Incremented phase-encoding gradient generates Ky data
- Combined phase/frequency encoding defines all K-space data
- Requires many RF/gradient pulses to fill all K-space