Image Formation

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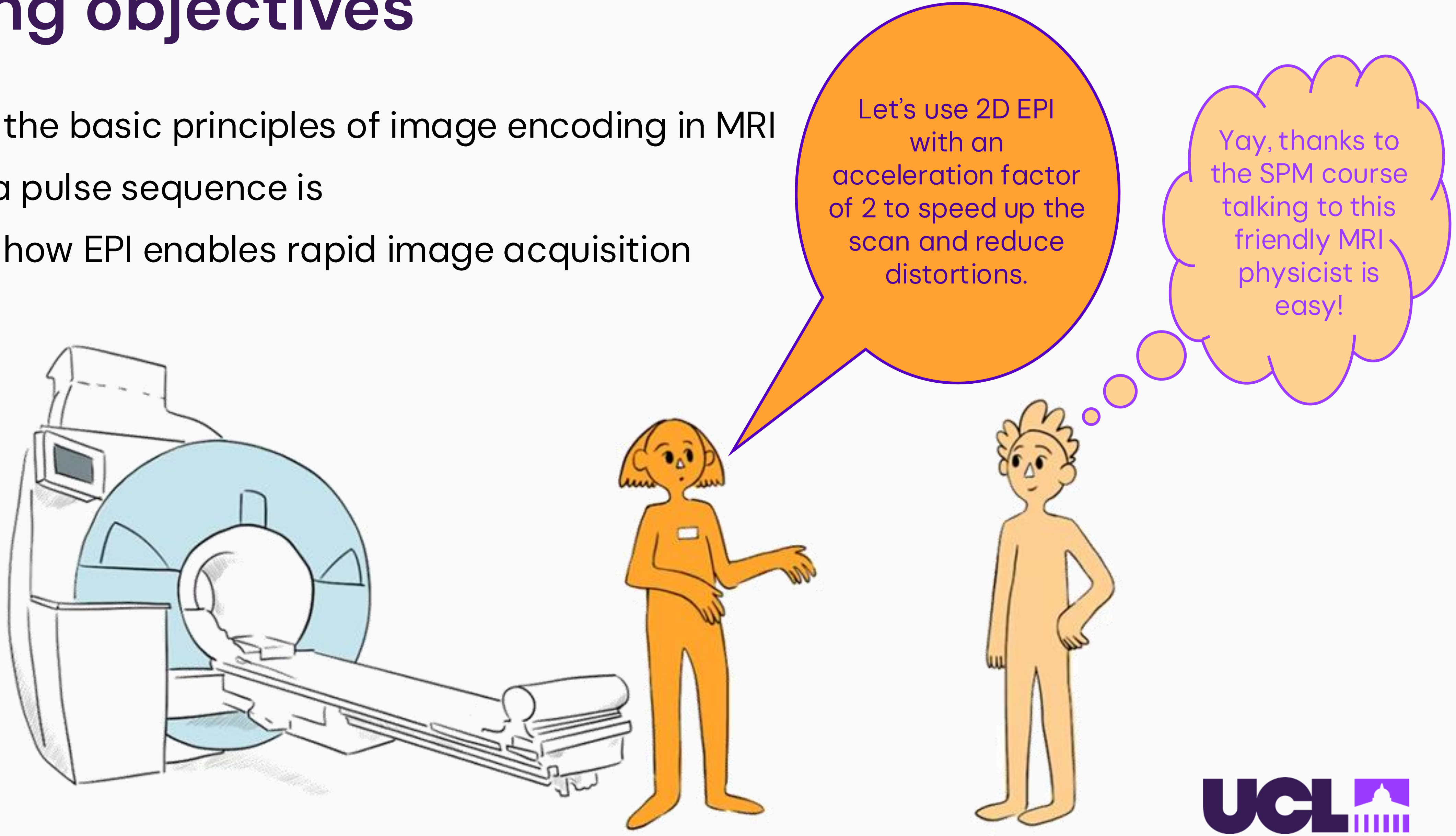
MR Physics for SPM – May 2026

Functional Imaging Laboratory
Department of Imaging Neuroscience

Learning objectives

- Understand the basic principles of image encoding in MRI
- Know what a pulse sequence is
- Understand how EPI enables rapid image acquisition



https://engagement.fil.ion.ucl.ac.uk/projects/understanding-mri/

Larmor Equation Revisited

The Larmor equation relates frequency ω to magnetic field B:

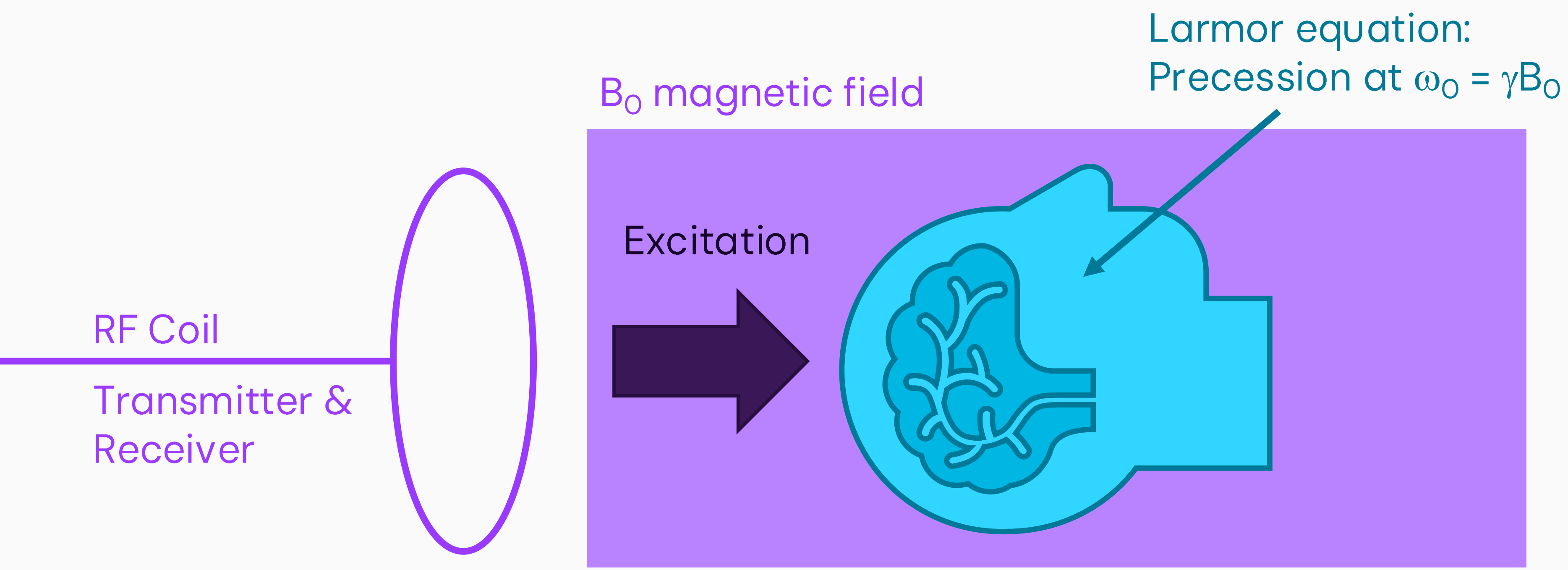
$$\boxed{\omega = \gamma B}$$

- γ is the gyromagnetic ratio

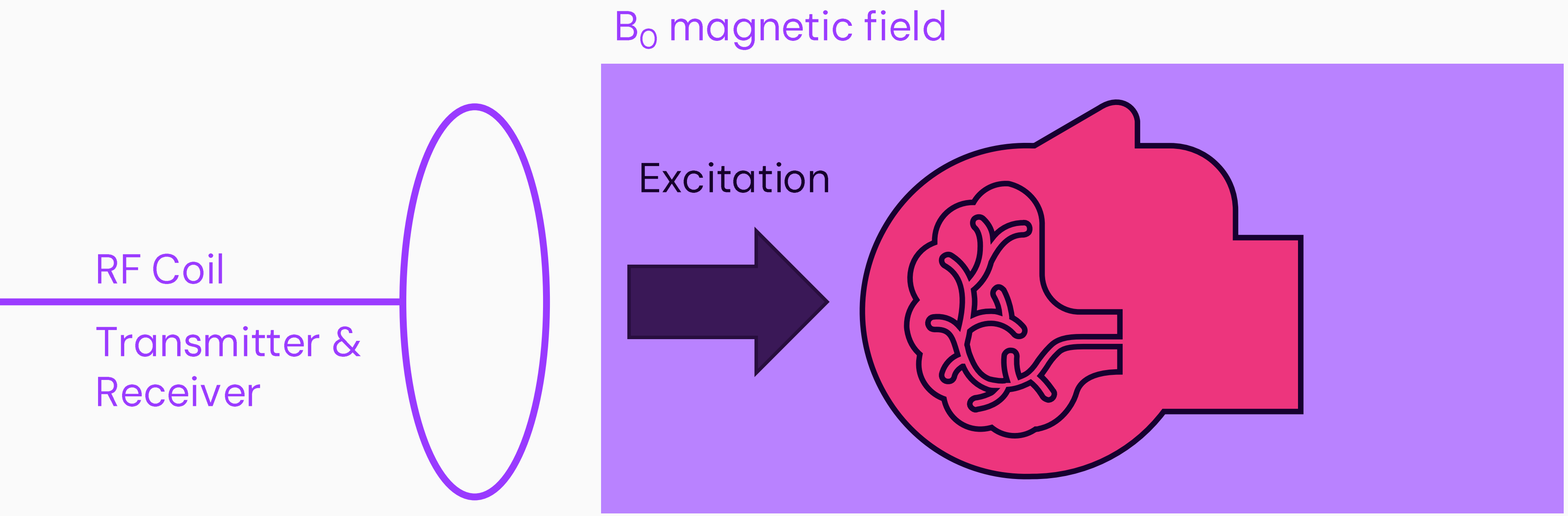
  $\gamma = 42.57$ MHz/T for Hydrogen Nuclei

- E.g. $B_0 = 3T \rightarrow \omega_0 = \gamma B_0 = 128$ MHz

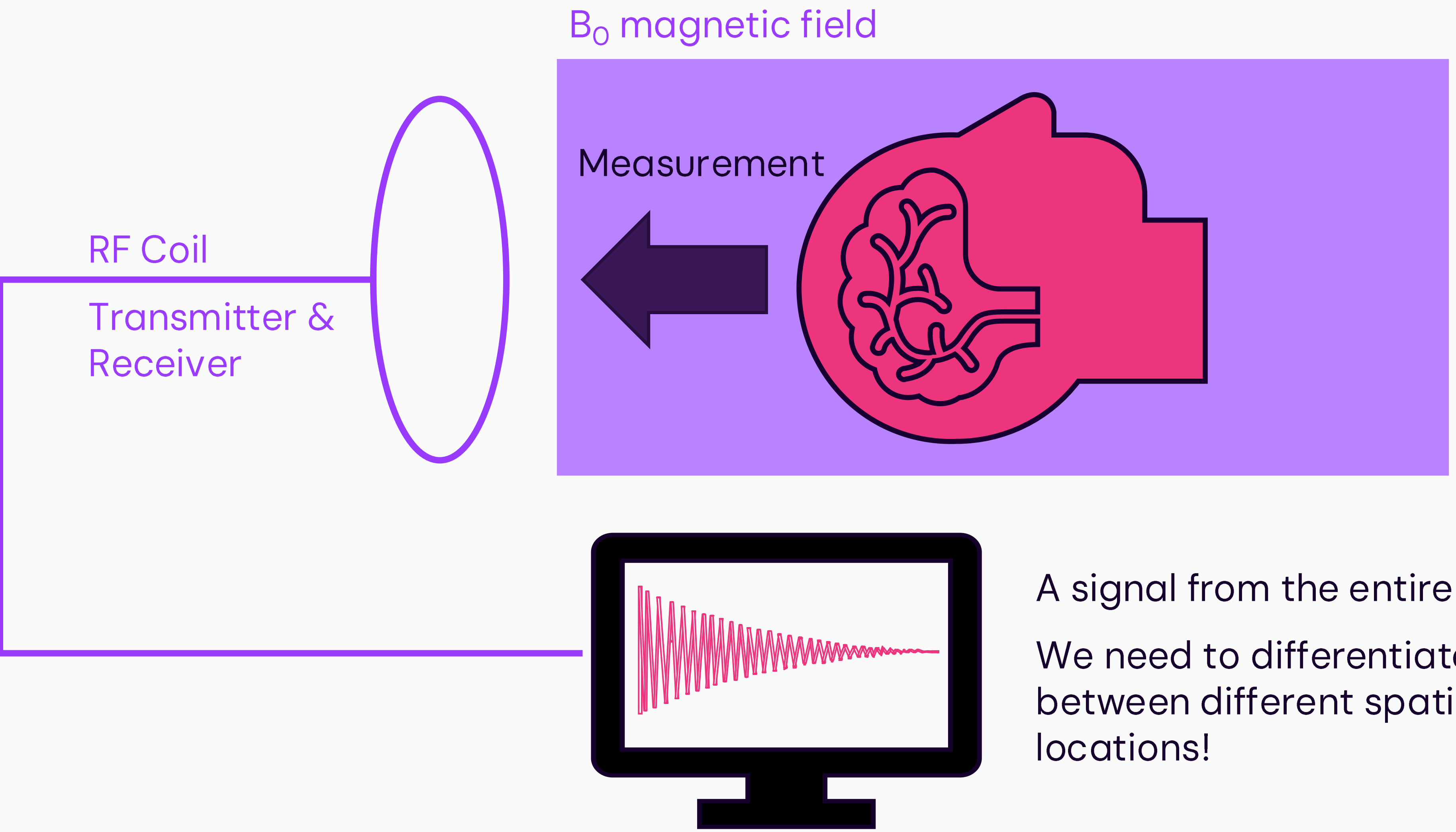
Spatial Encoding in MRI



Spatial Encoding in MRI



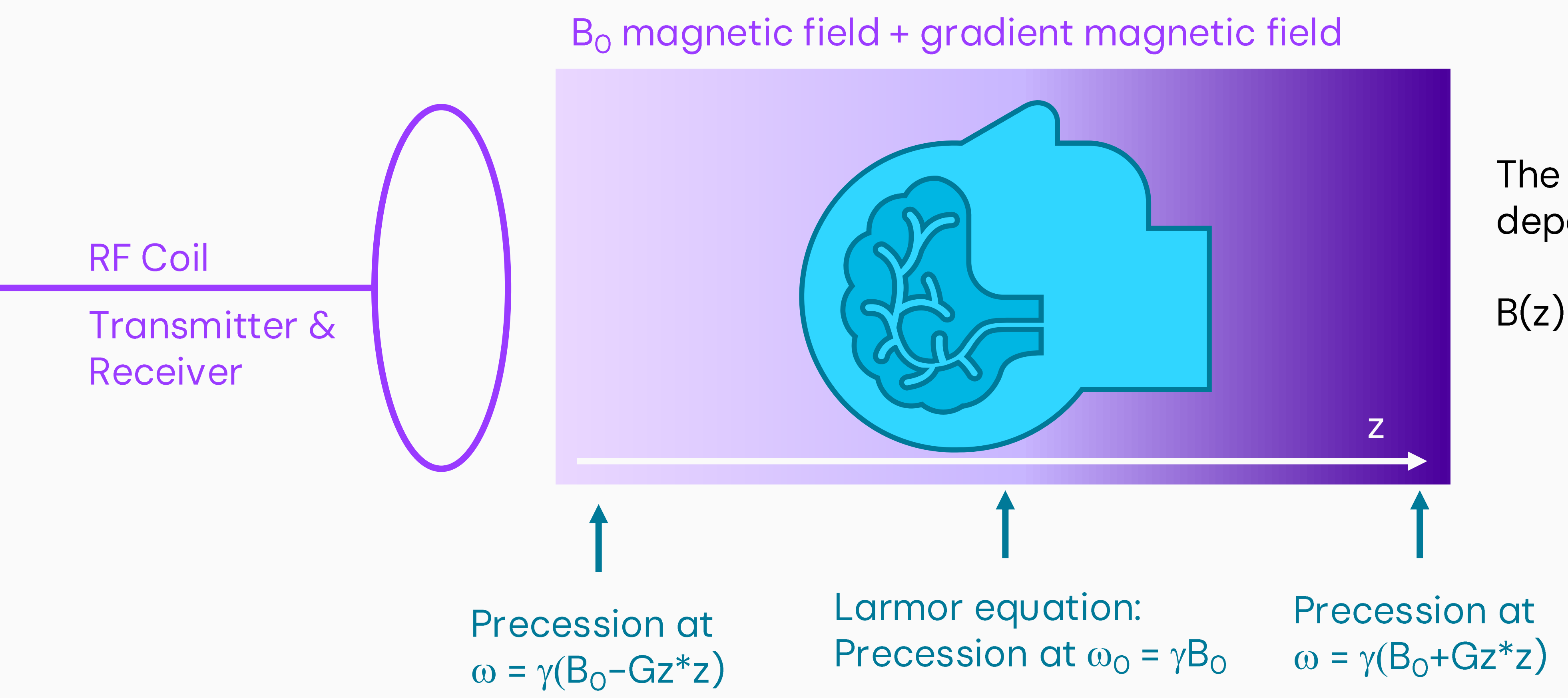
Spatial Encoding in MRI



A signal from the entire head

We need to differentiate between different spatial locations!

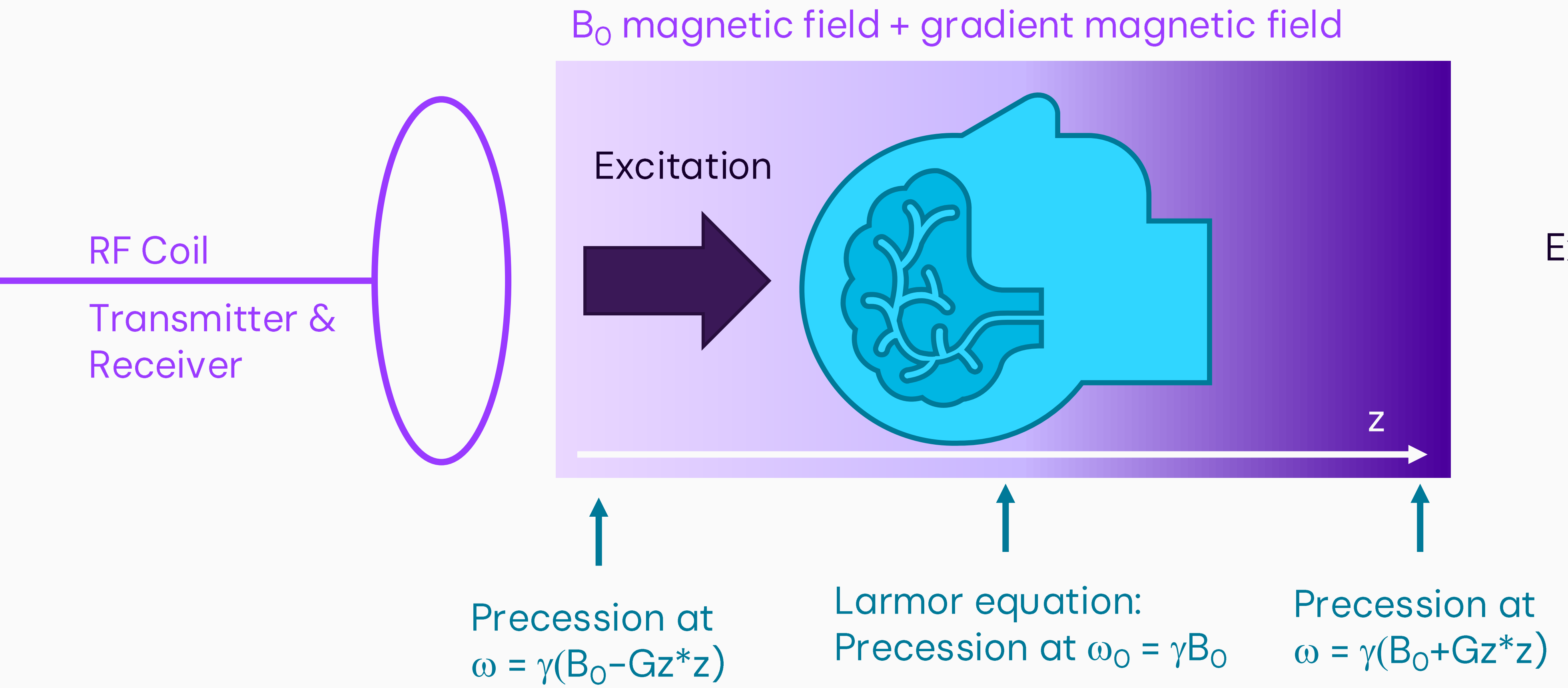
Spatial Encoding in MRI – Gradients



The magnetic field now depends on location:

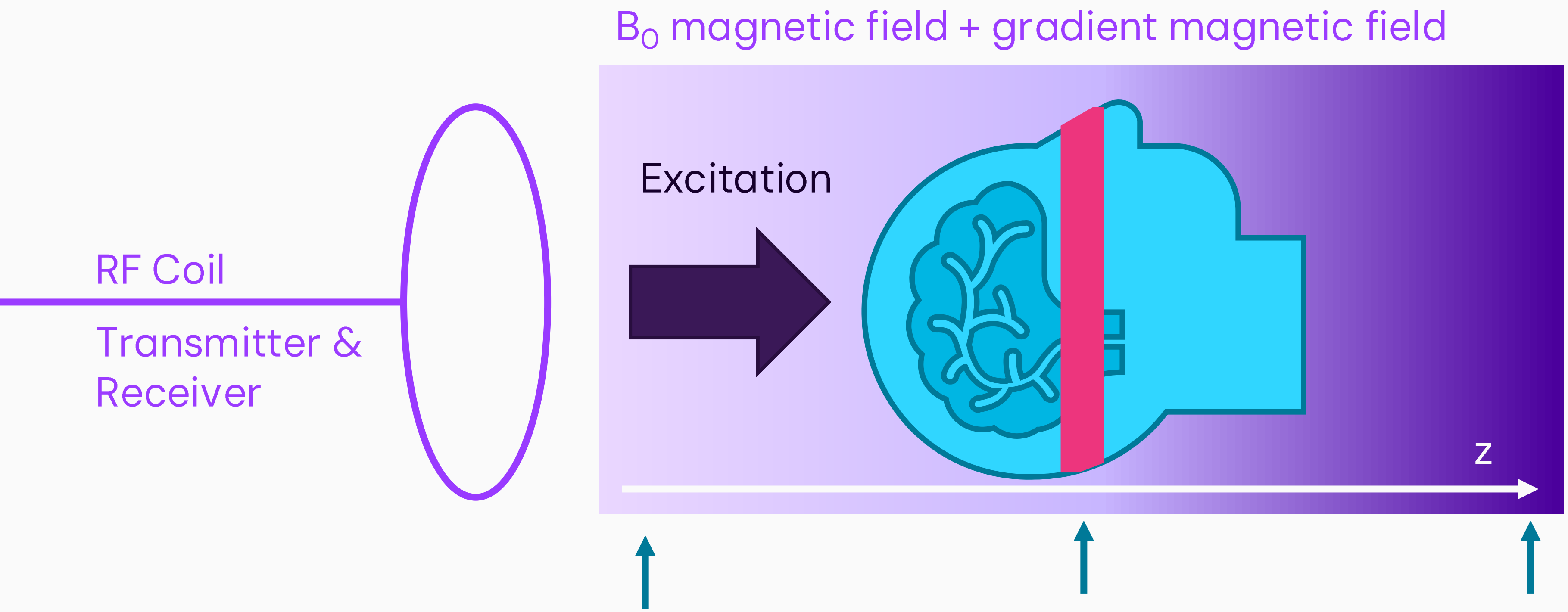
$B(z) = B_0+G_z*z$

Spatial Encoding in MRI – Gradients



Remember:
Excitation is tuned to excite spins on resonance

Spatial Encoding in MRI – Gradients



Precession at
$\omega = \gamma(B_0 - Gz*z)$

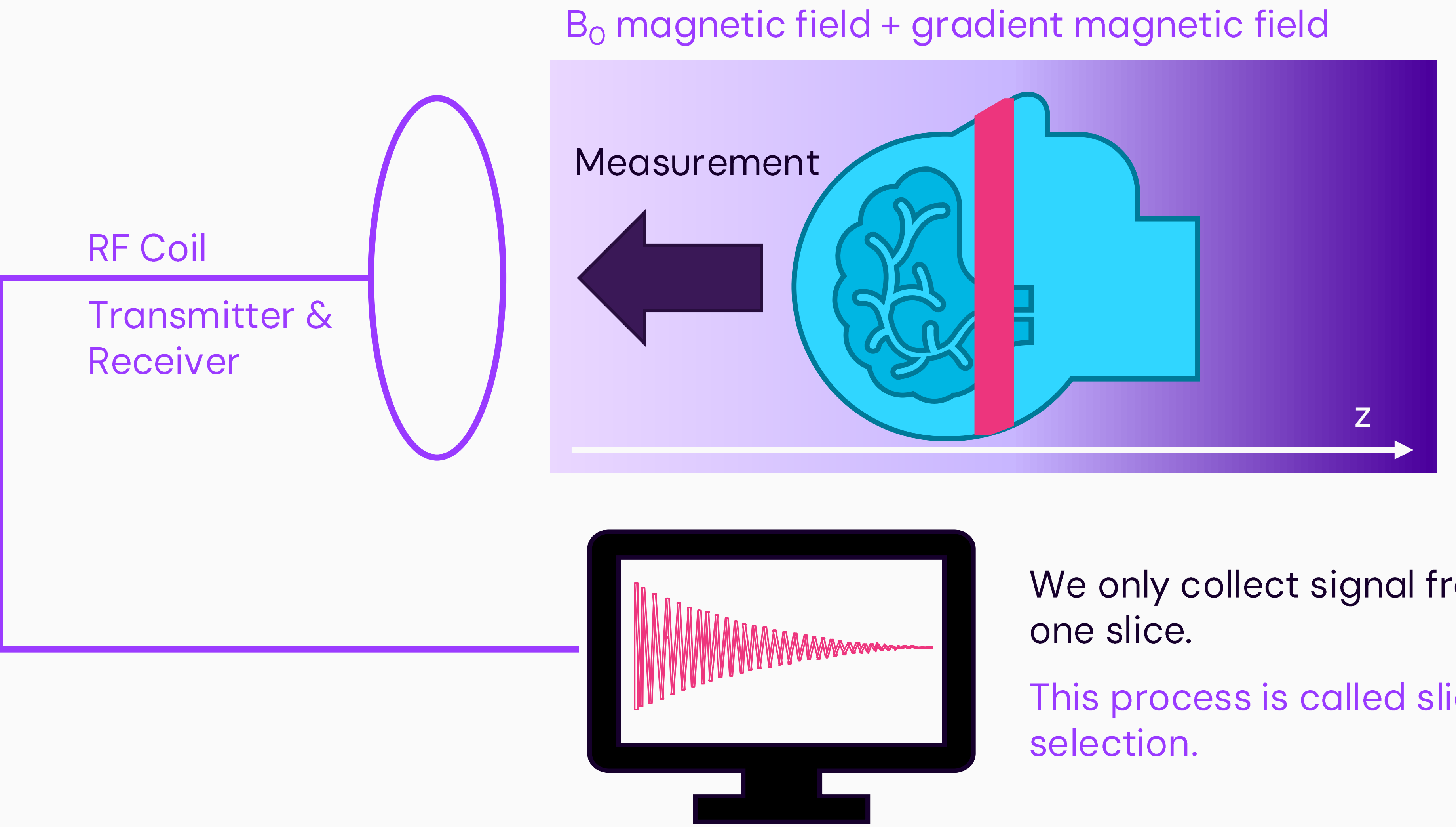
Larmor equation:
Precession at $\omega_0 = \gamma B_0$

Precession at
$\omega = \gamma(B_0 + Gz*z)$

Remember:
Excitation is tuned to excite spins on resonance

UCL

Spatial Encoding in MRI – Gradients

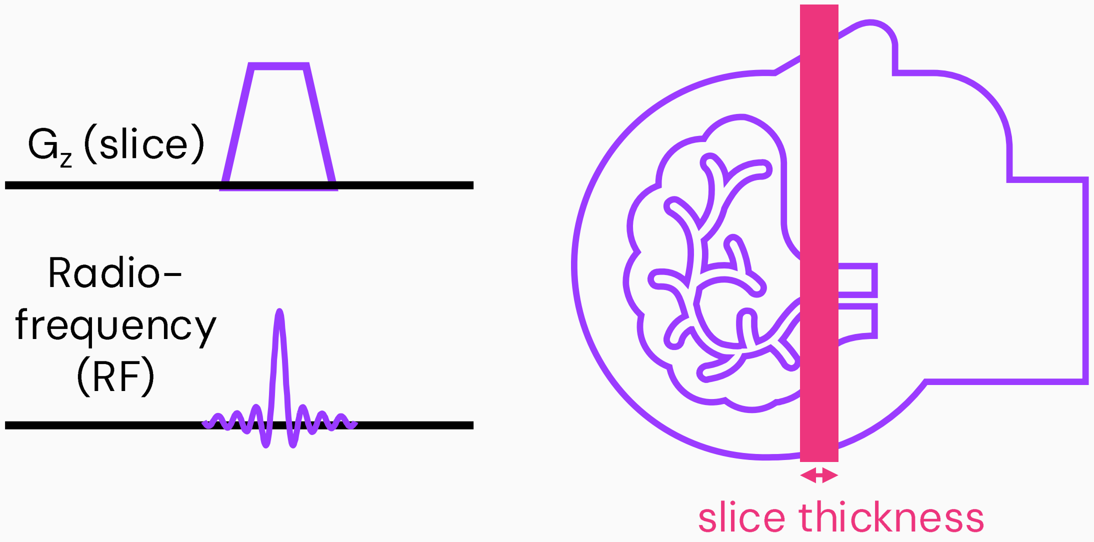


We only collect signal from one slice.

This process is called slice-selection.

Spatial Encoding in MRI – Slice Selection

- **Slice selection:** applying a magnetic field gradient during an RF pulse to only excite a limited amount of space



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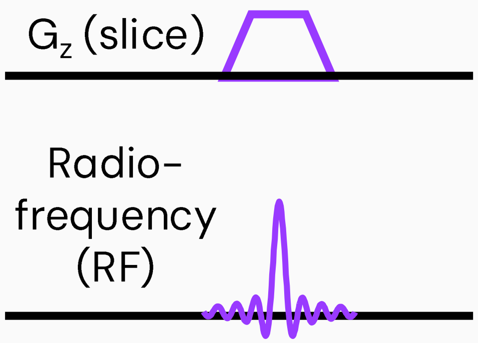
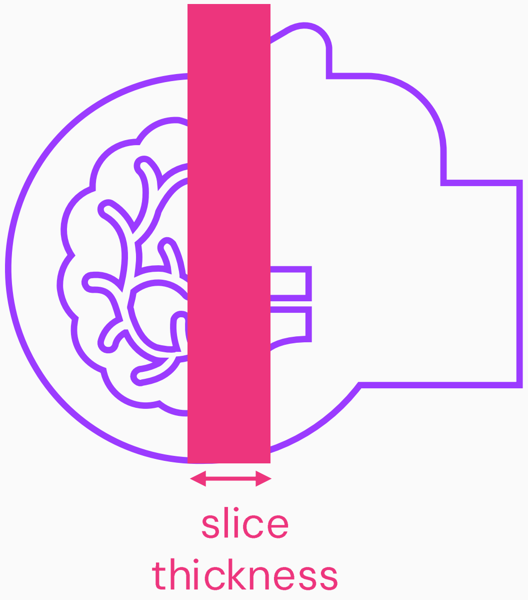


RF bandwidth and gradient strength determines slice thickness



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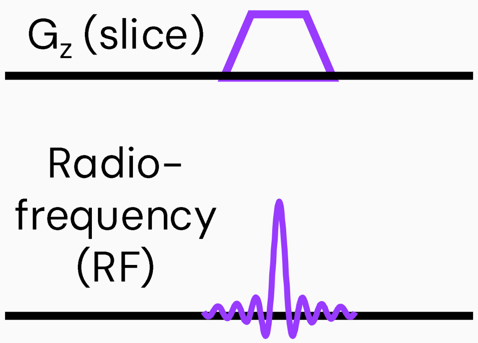

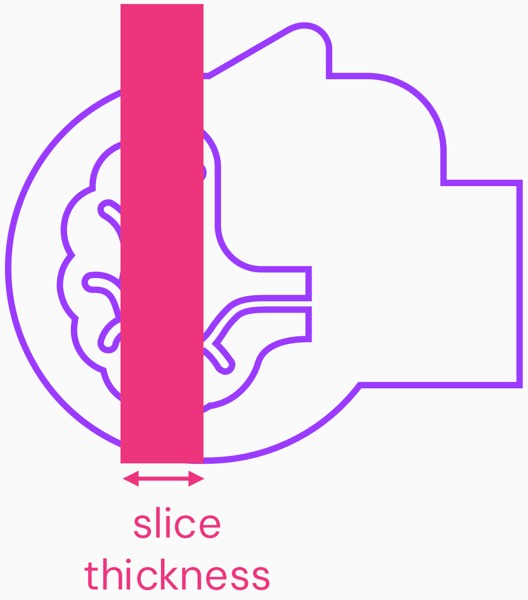

RF bandwidth and gradient strength determines slice thickness

RF centre frequency of pulse determines slice position

Spatial Encoding in MRI – Slice Selection

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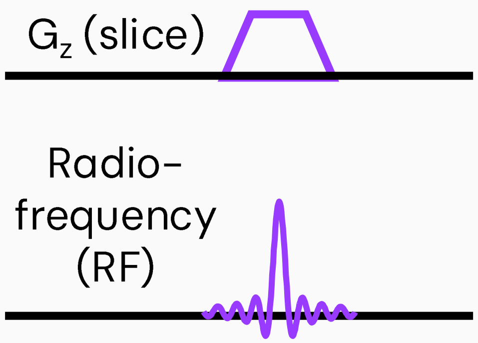

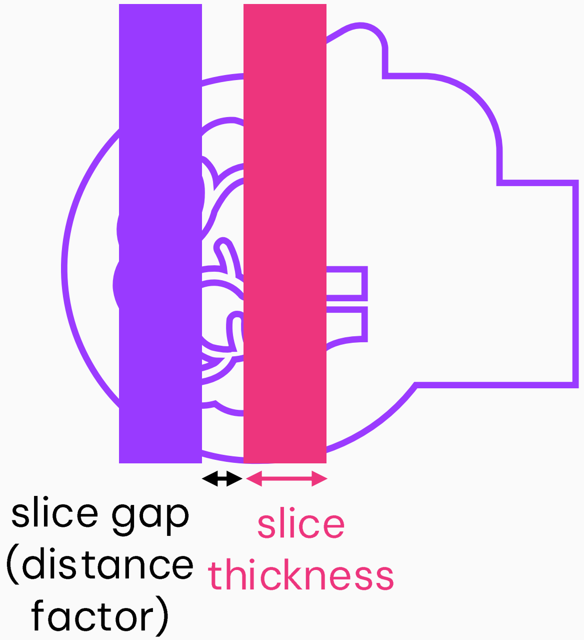

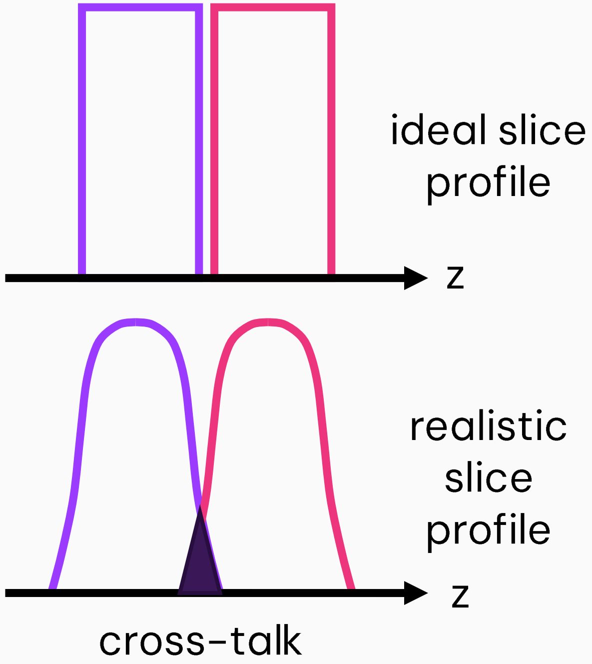

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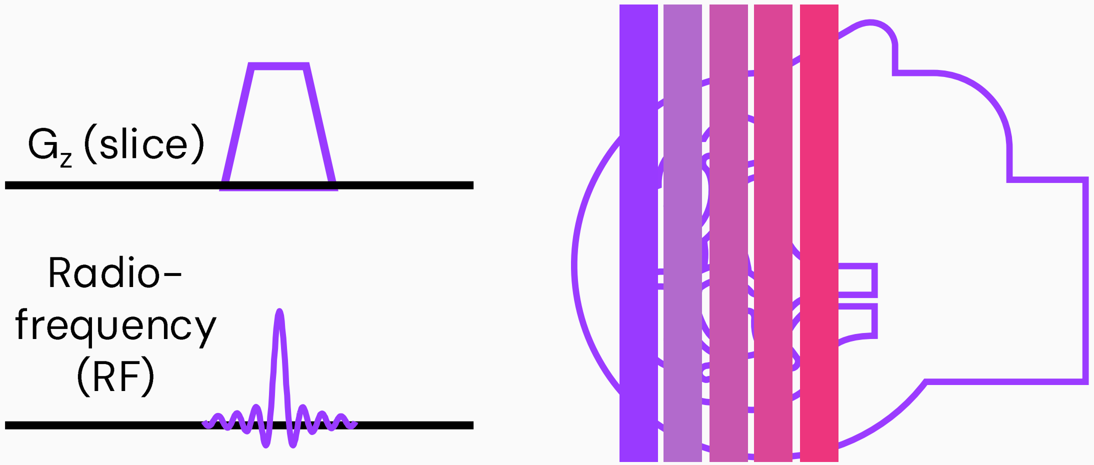

Spatial Encoding in MRI – Slice Selection

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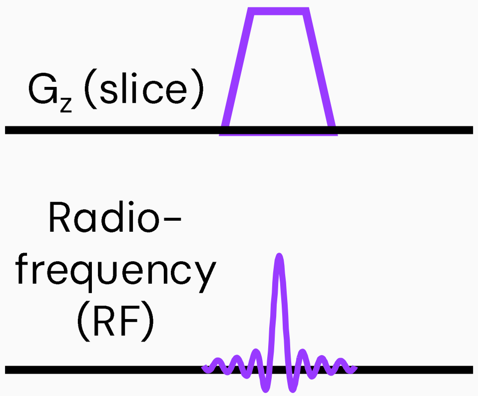
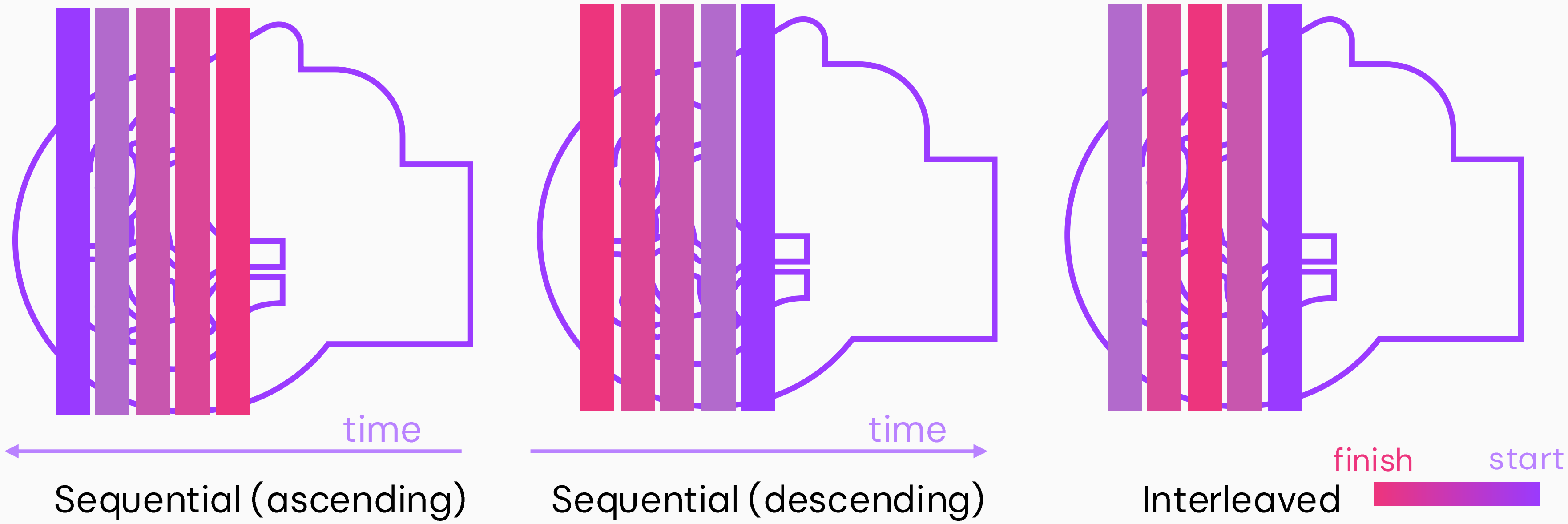
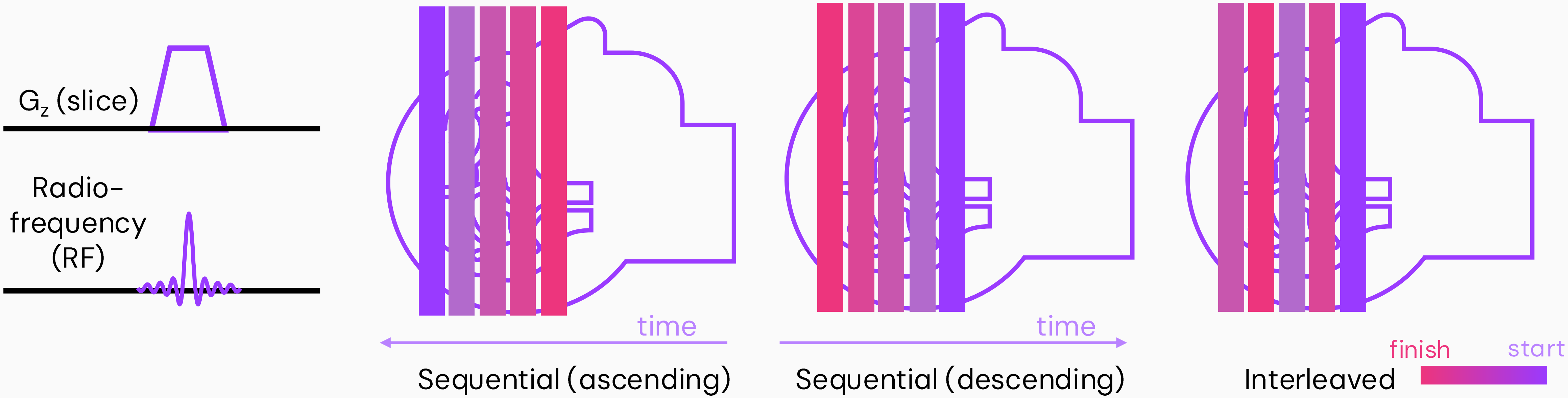




- **Slice order options:** Important to know for slice timing correction

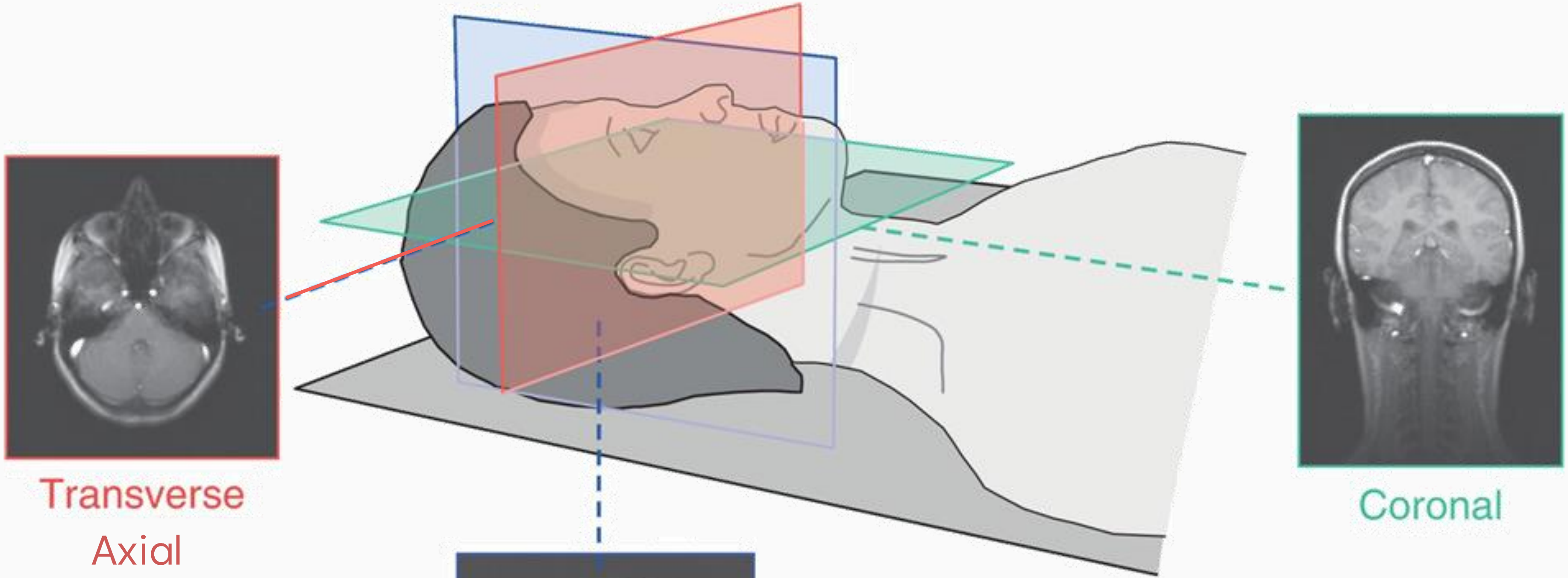
Spatial Encoding in MRI – Slice Selection

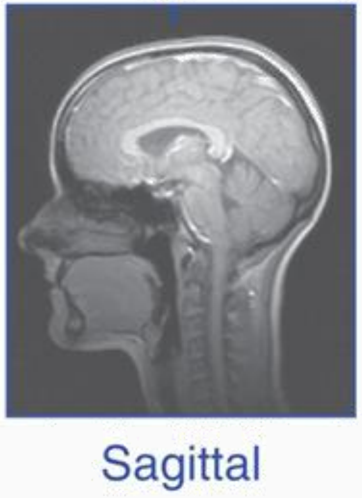
- **Slice selection:** applying a magnetic field gradient during an RF pulse to only excite a limited amount of space

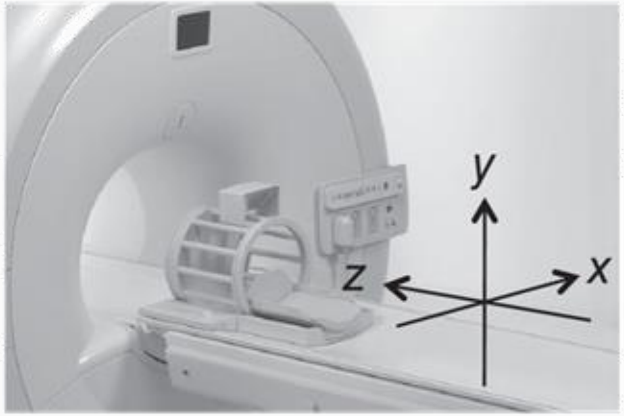


- **Slice order options:** Important to know for slice timing correction
- **Simultaneous-Multi-Slice SMS** (also called multi-band) allows to accelerate imaging by acquiring multiple slices at once

Spatial Encoding in MRI – Slice Orientation

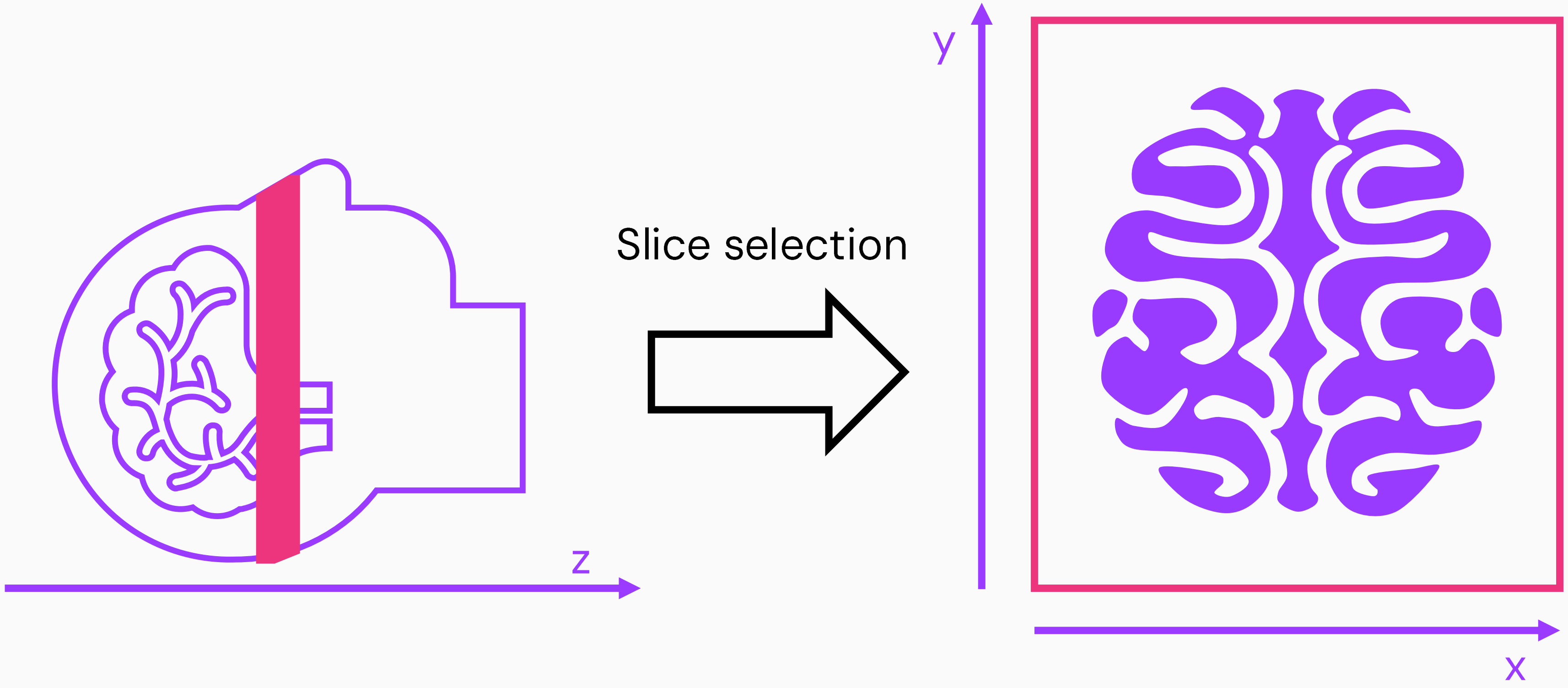






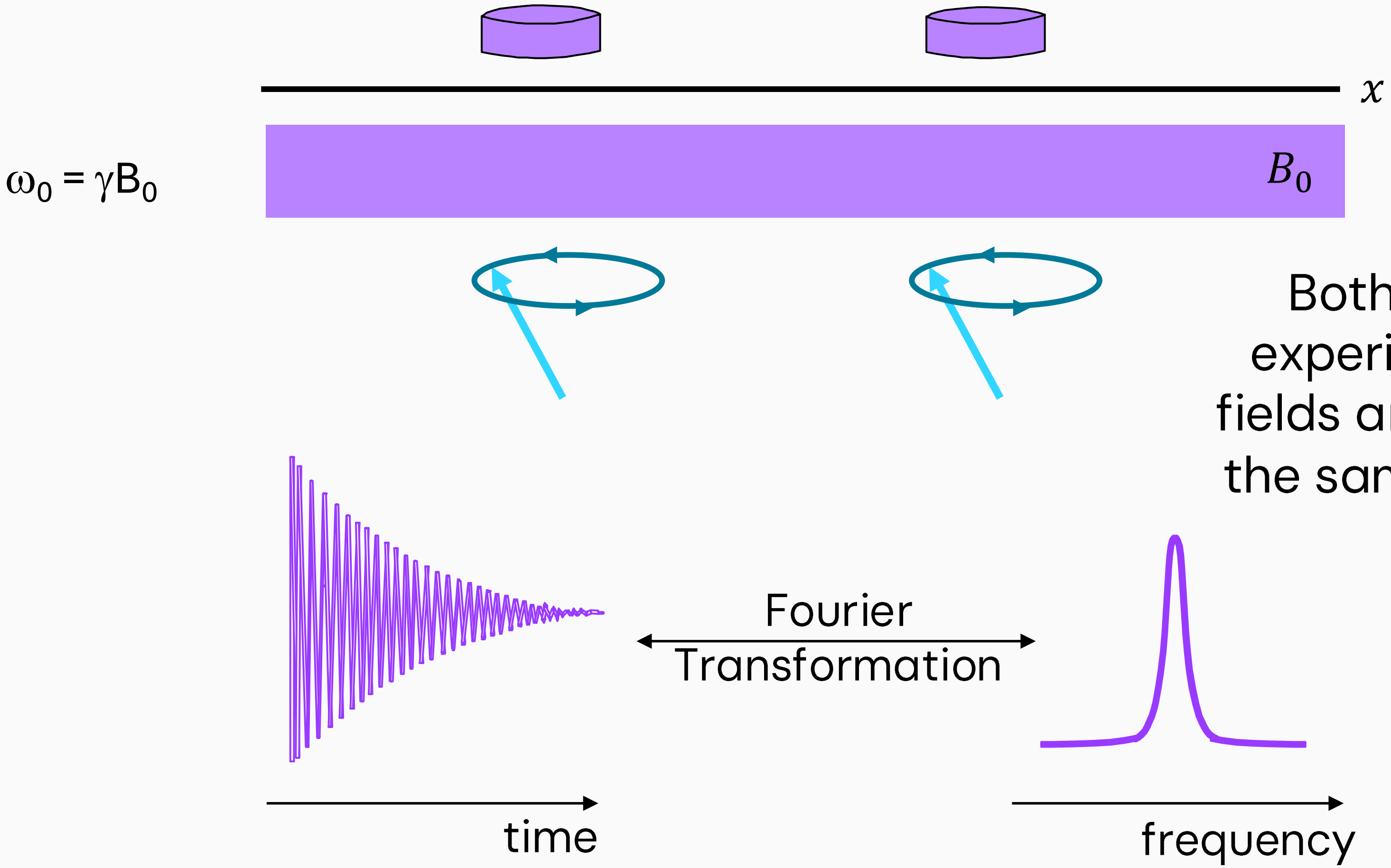
Slightly modified from: MRI: from Picture to Proton Cambridge University Press 2017

Image encoding using spatial gradients



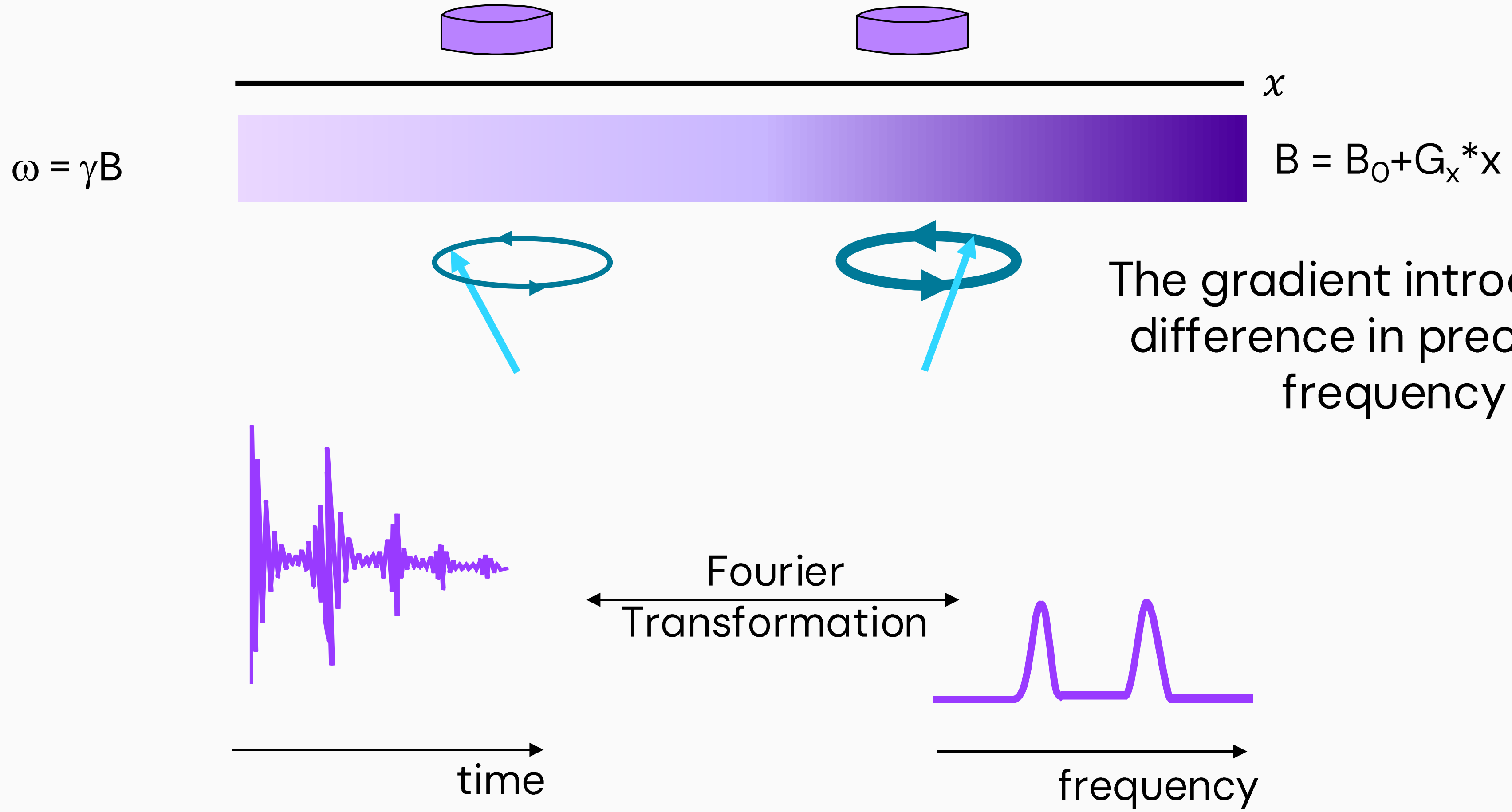
We can use gradient magnetic fields in the x & y directions to achieve image encoding in-plane.

Image encoding using spatial gradients



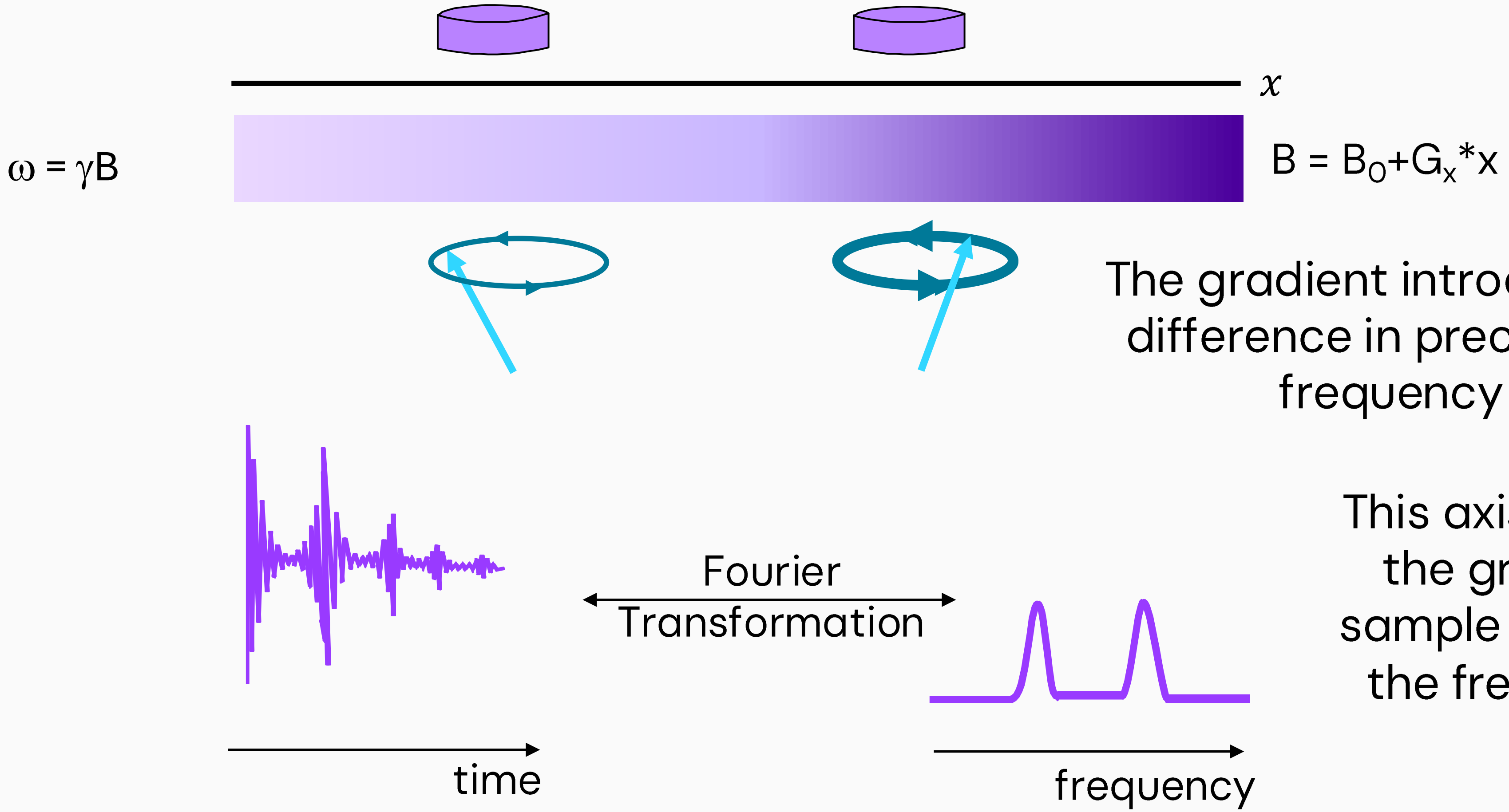
Both samples have experienced the same fields and therefore have the same frequency and phase

Image encoding using spatial gradients



The gradient introduces a difference in precession frequency

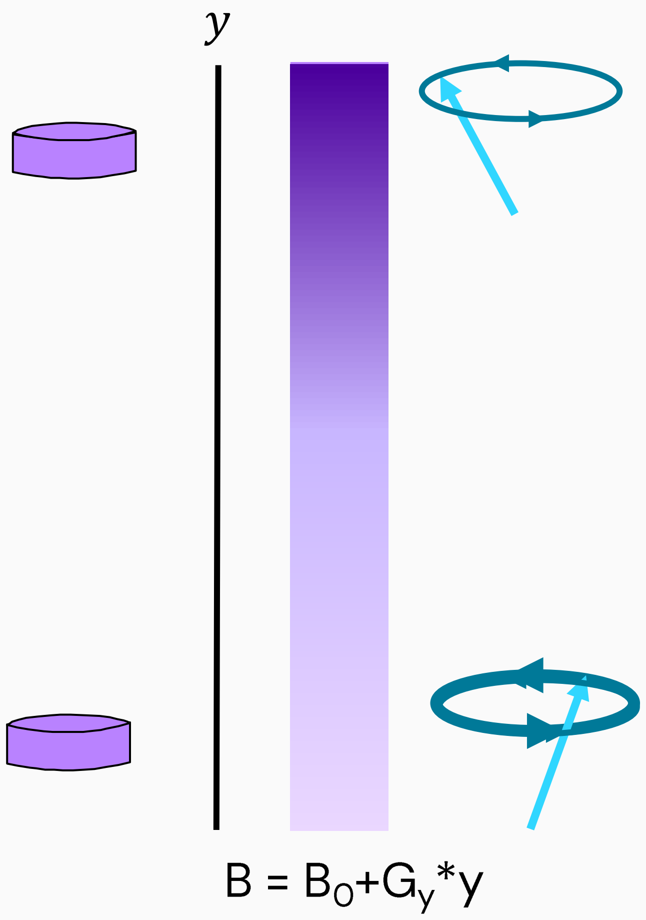
Image encoding using spatial gradients



The gradient introduces a difference in precession frequency

This axis where we turn on the gradients while we sample the signal is called the frequency encoding direction.

Image encoding using spatial gradients

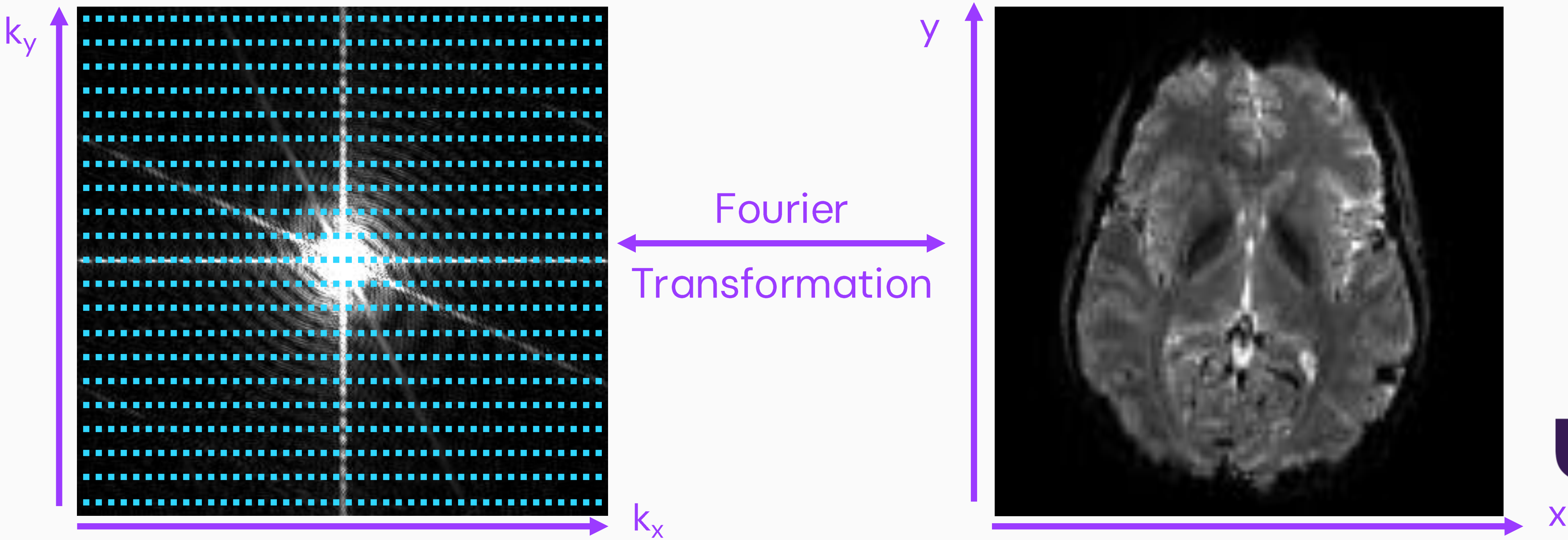


- Phase encoding : Gradient ON before acquisition
- The gradient introduces a difference in frequency
- After the y direction gradient is turned off the frequency is the same everywhere in y but the accrued phase difference persists
- This process is repeated multiple times (each time with a different y gradient) until we have enough samples

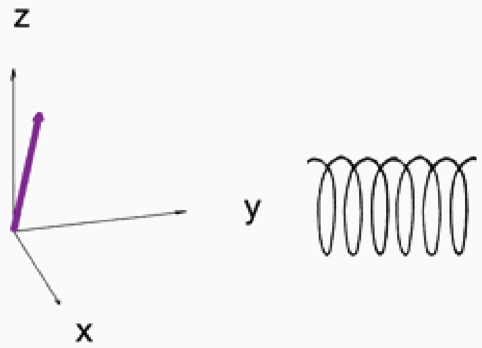
What is k-space?

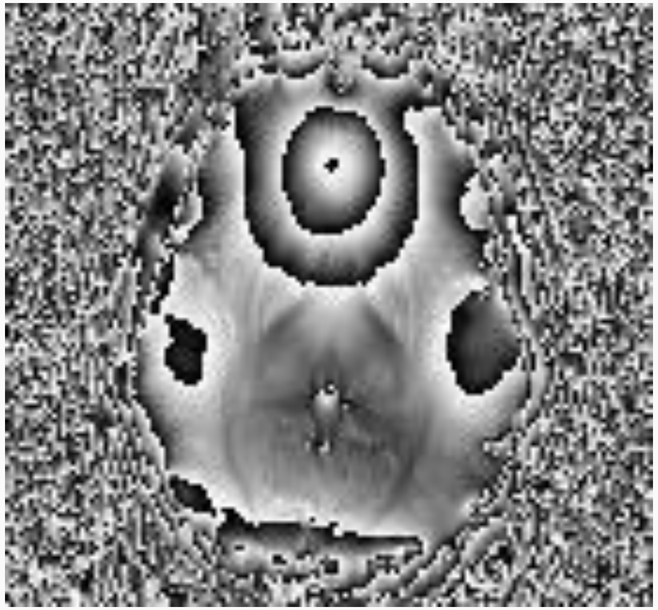
- k-space is the domain where MRI data are collected, gradients move us through k-space
- Each readout samples one trajectory (usually a line) in k-space
- Phase-encoding gradients step between lines
- The image is obtained by applying a Fourier transform to k-space

$$\boxed{k = \frac{\gamma}{2\pi}\int_0^t G(\tau)d\tau}$$

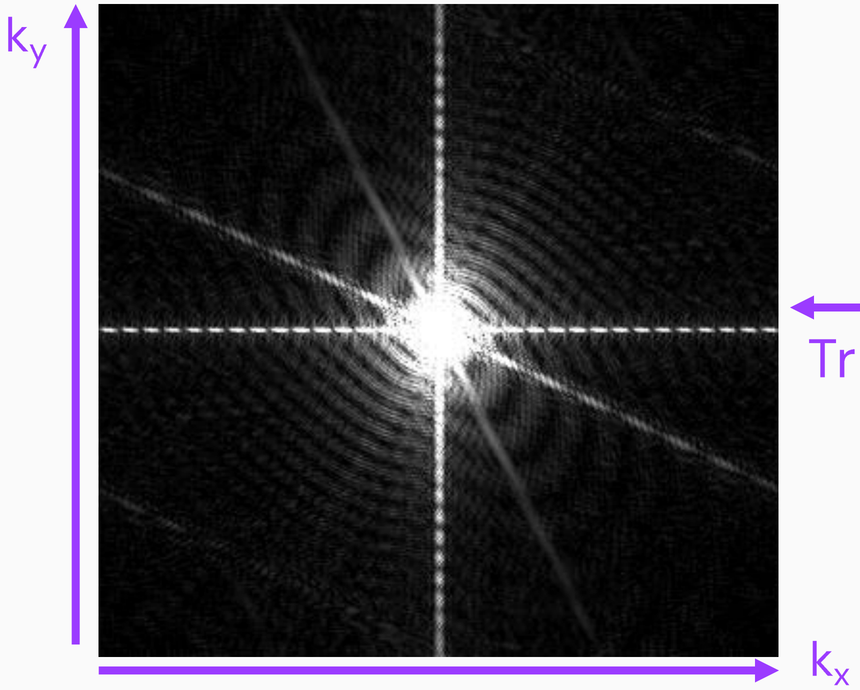


k-space is complex

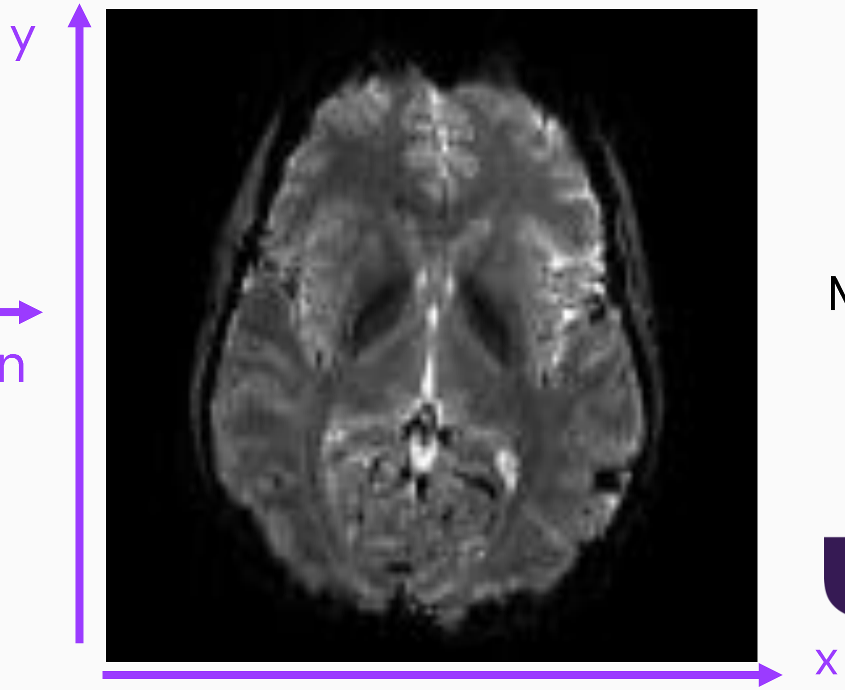




Phase
Image
$[-\pi \; \pi]$



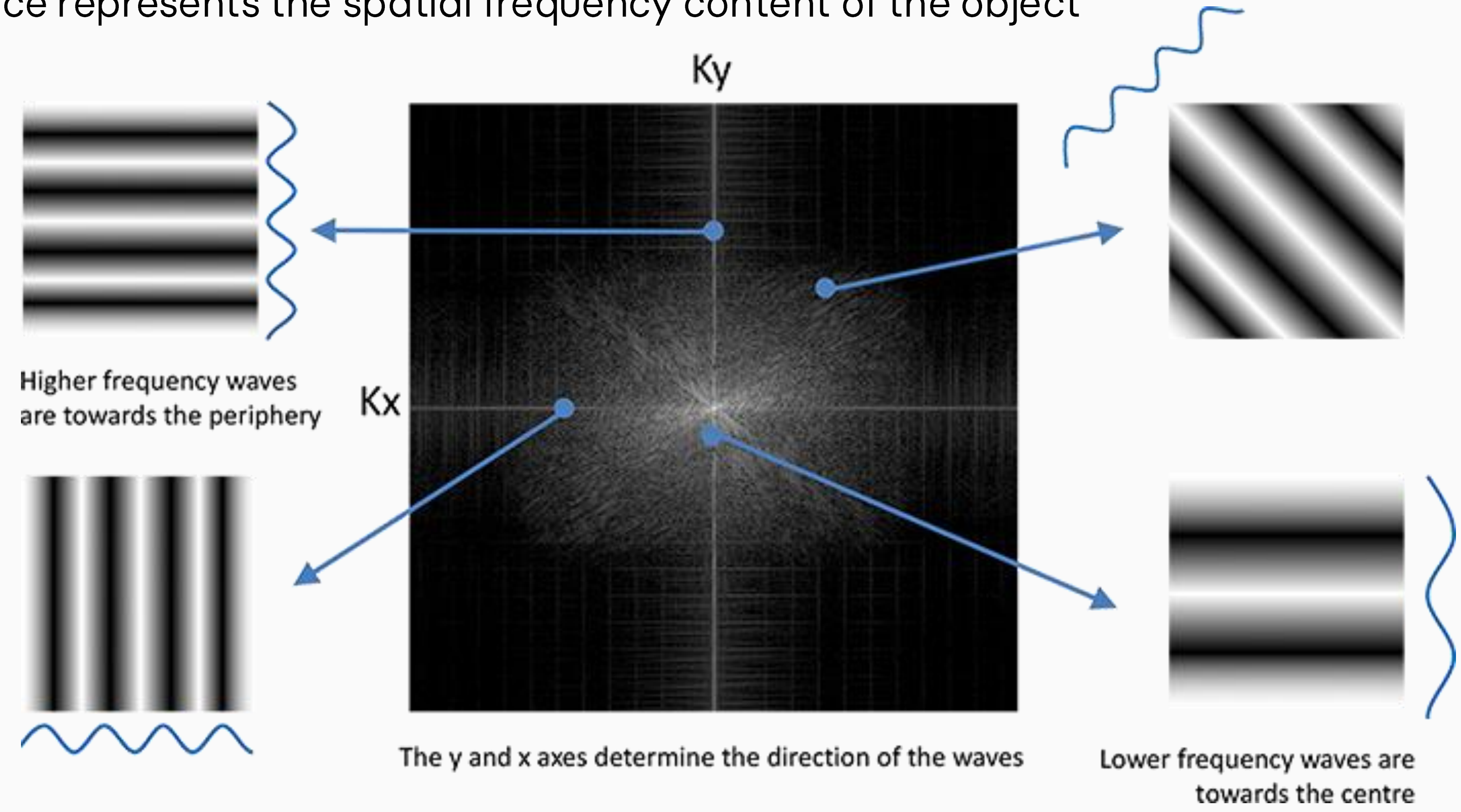
Fourier
Transformation



Magnitude
image

Properties of k-space

- k-space represents the spatial frequency content of the object

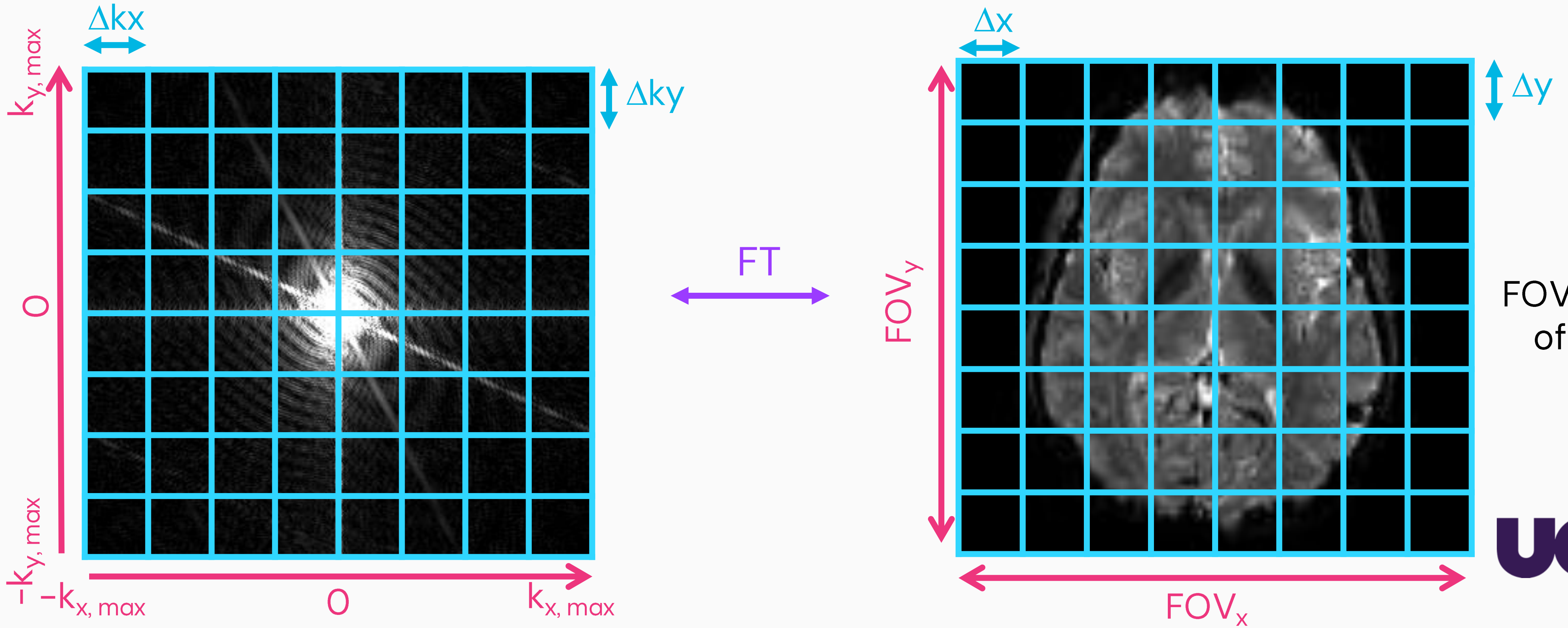


Source: https://www.radiologycafe.com/frcr-physics-notes/mr-imaging/k-space/

Properties of k-space

- The extent of k-space determines image resolution

- Denser sampling of k-space (smaller Δk) gives a larger image FOV



FOV = field of view

Summary: Image encoding using spatial gradients

- We encode spatial position into the phase of the MR signal using magnetic field gradients.

- The signal we measure corresponds to samples of the object in k-space (a spatial frequency domain), and the image is recovered via a Fourier transform

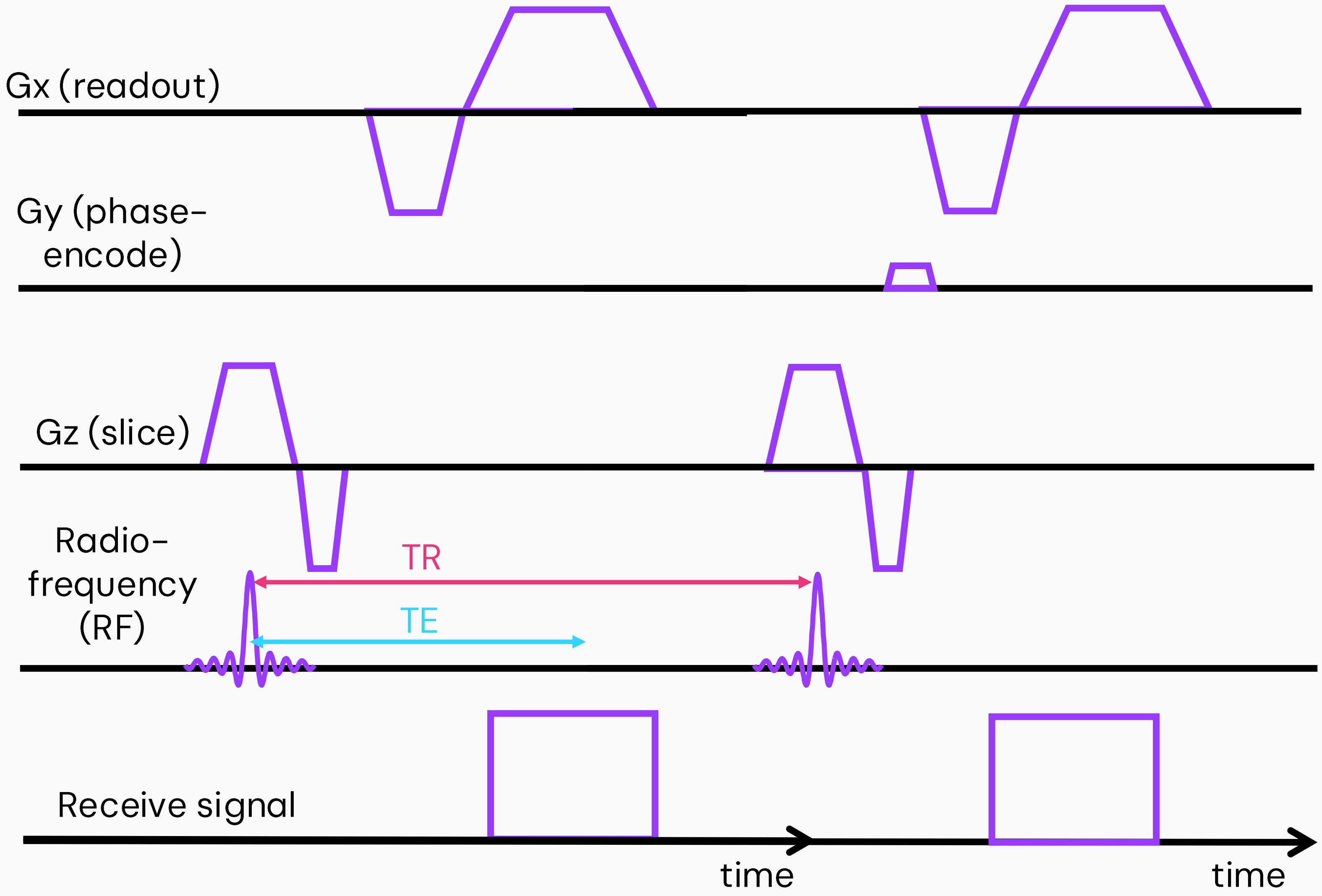
- “Frequency encoding” is rapid since the gradient is left on and samples are taken continuously.

- “Phase encoding” is slow since the gradient application needs to be repeated changing the duration or strength each time.

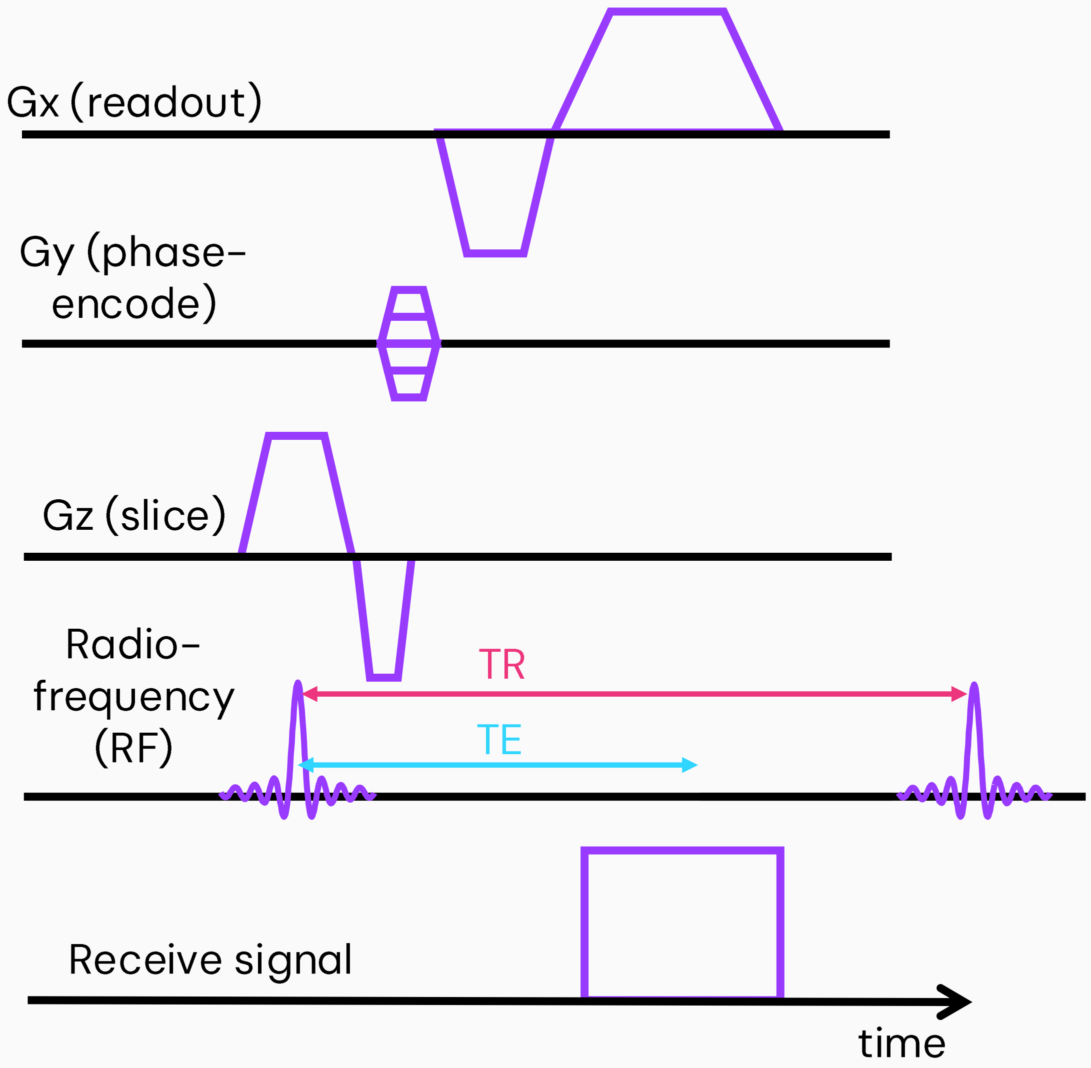
What is a pulse sequence?

- A pulse sequence specifies how MRI hardware is coordinated to generate contrast and spatially encode the signal.
- It defines the timing and shape of RF pulses and the application of gradients along all three axes.
- It determines key contrast parameters such as repetition time (TR) and echo time (TE).
- These elements control how the signal is formed and how it is mapped into k-space.

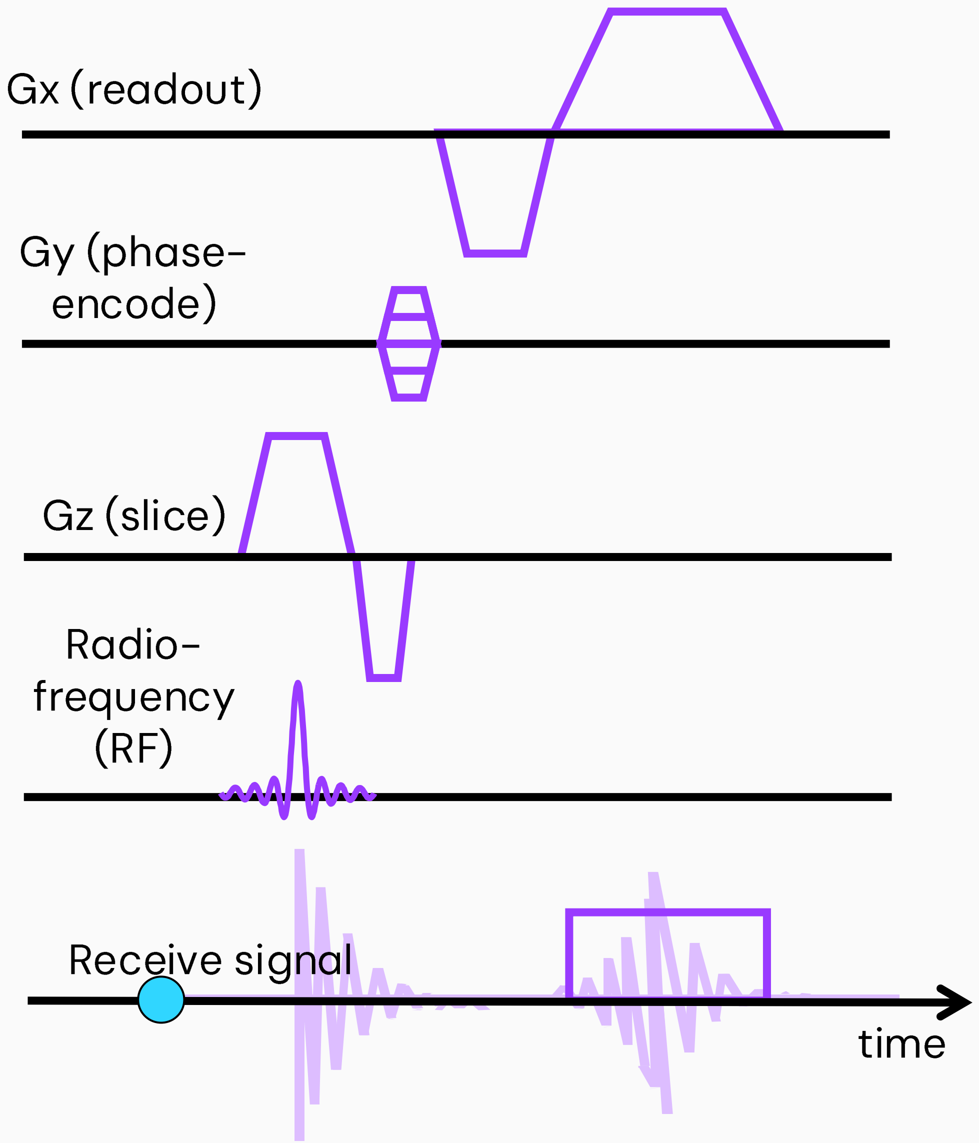
Gradient-echo sequence

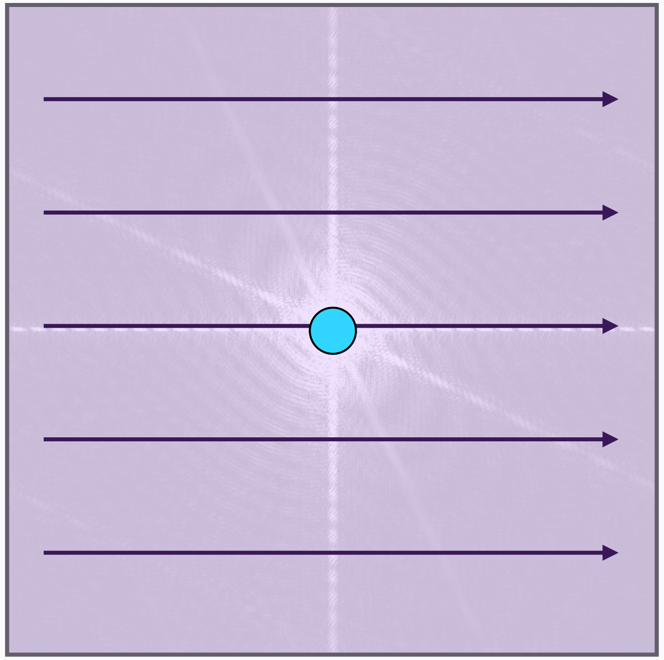


Gradient-echo sequence



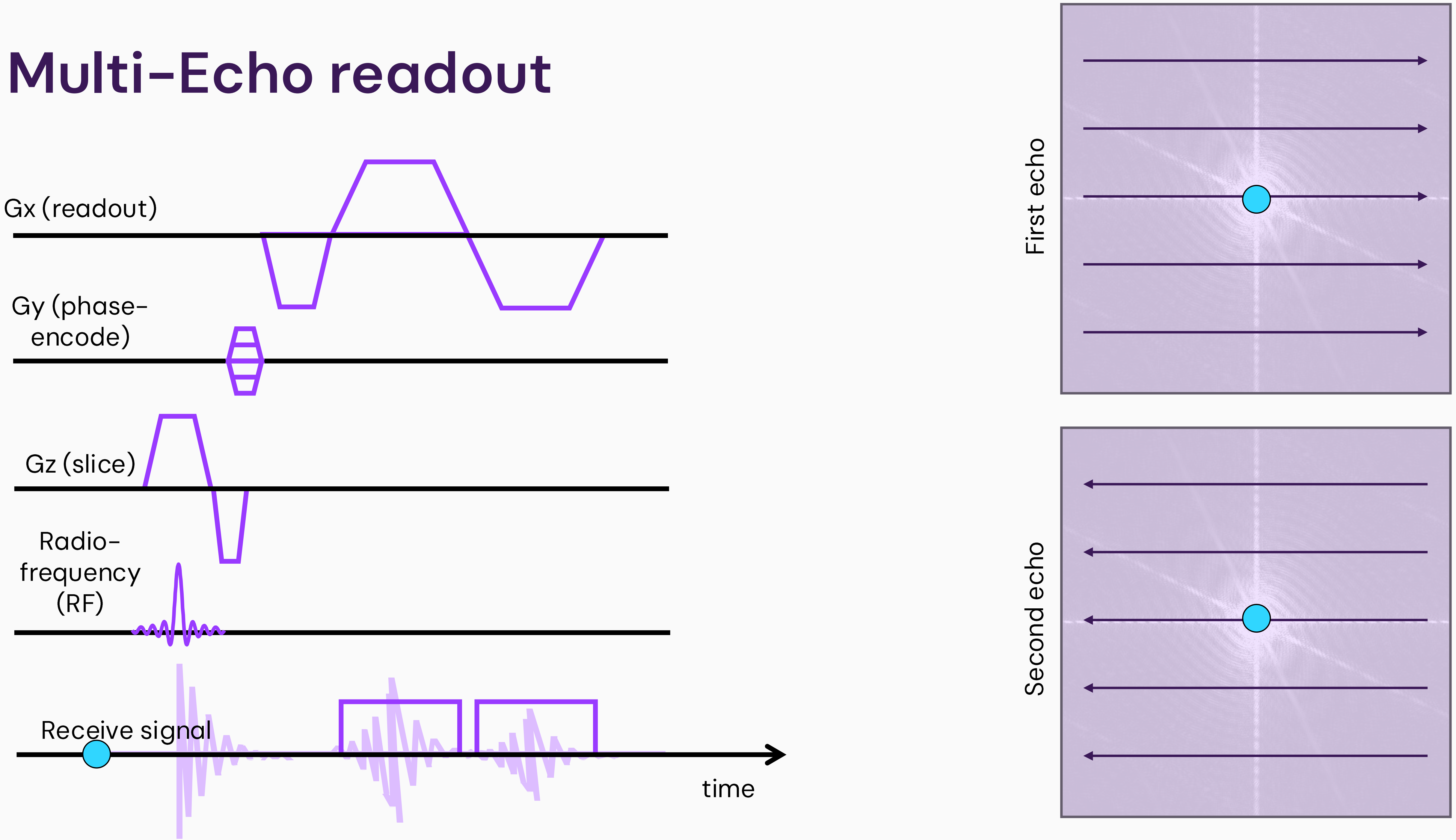
Gradient-Echo readout



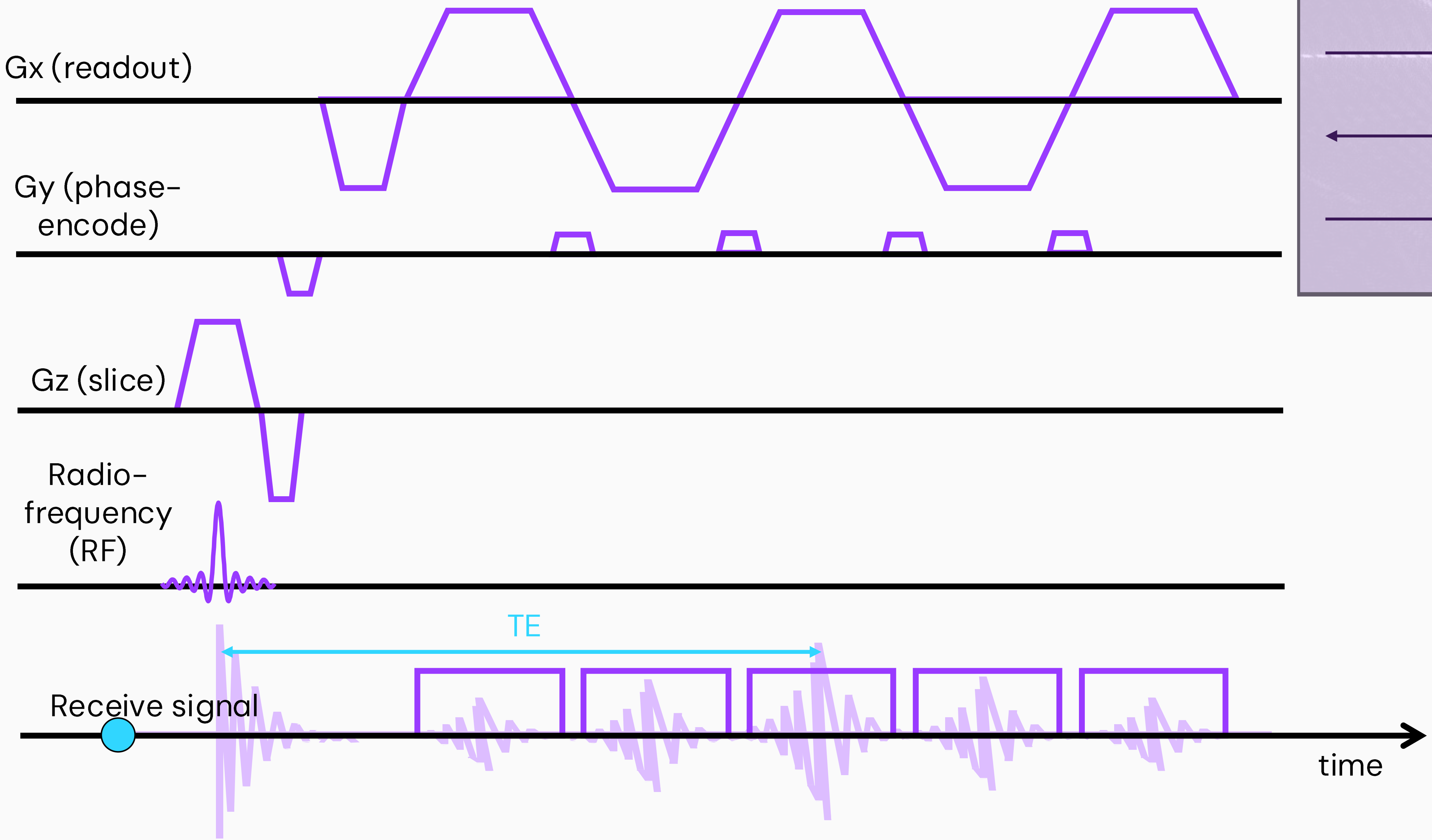


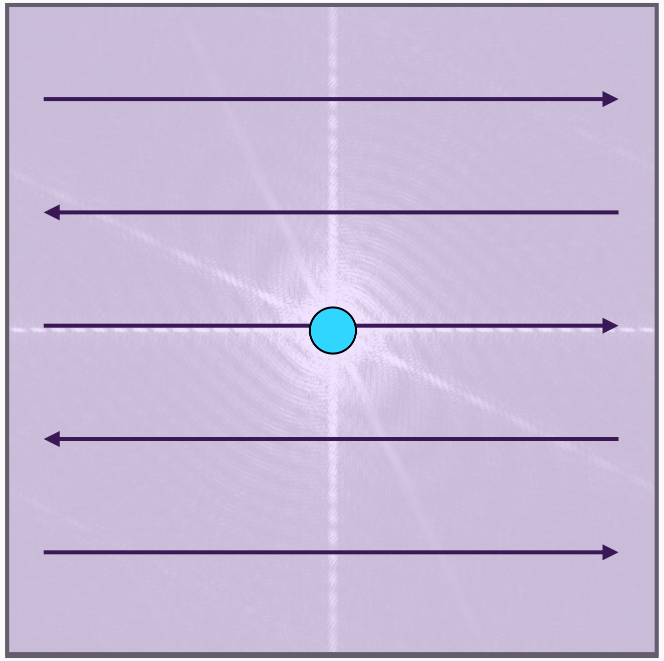
Very robust but not fast enough for dynamic imaging e.g. for fMRI

Multi-Echo readout

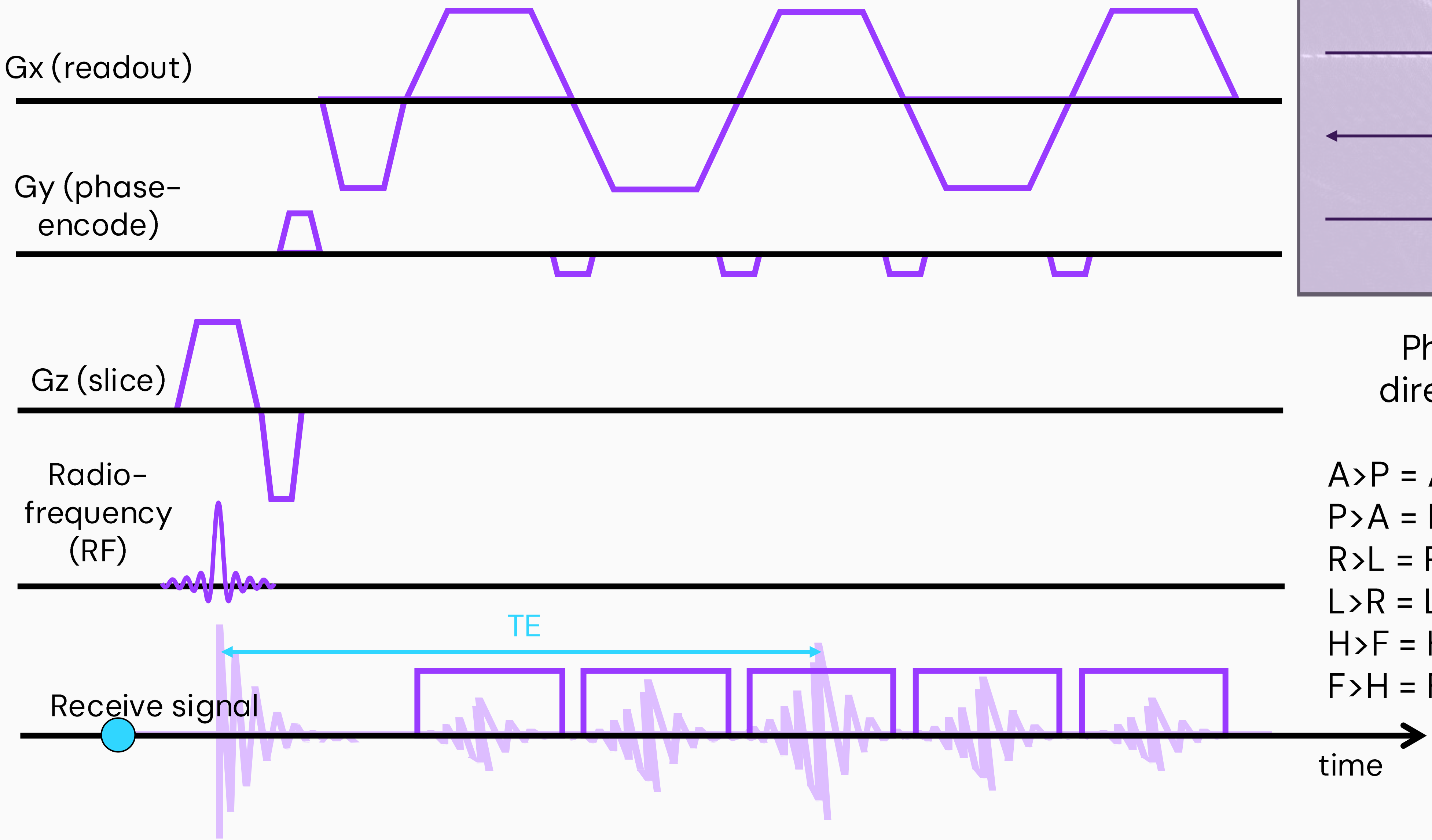


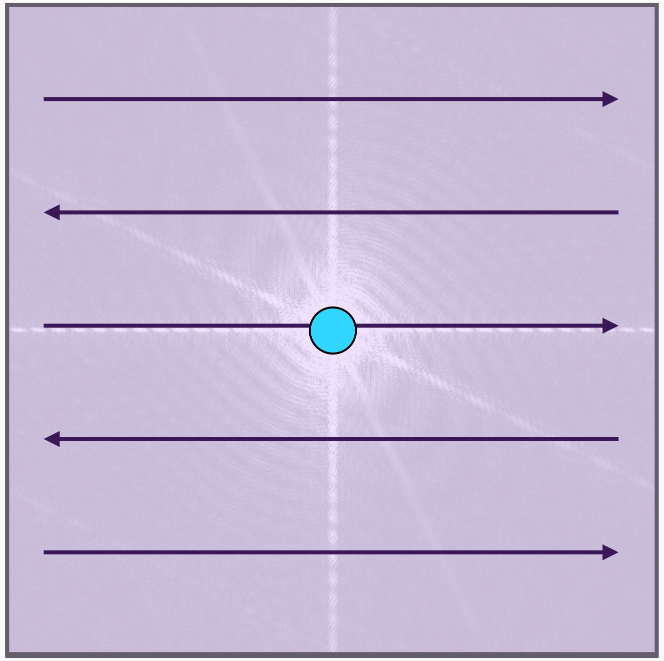
EPI: Echo-Planar Imaging





EPI: phase-encoding direction





Phase encoding direction reversed!

A>P = Anterior-Posterior
P>A = Posterior-Anterior
R>L = Right-Left
L>R = Left-Right
H>F = Head-Foot
F>H = Foot-Head

EPI – Echo Planar Imaging

- Conventional Gradient Echo Imaging acquires k-space line-by-line, requiring one excitation per line → relatively slow (minutes per image).

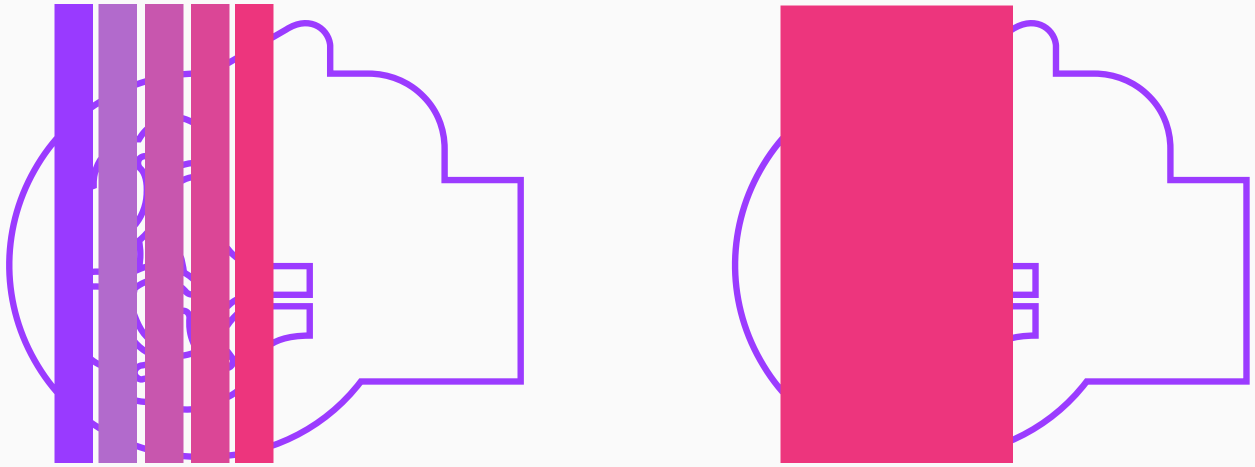
- Functional MRI requires much higher temporal resolution to capture dynamic signal changes.

- Echo Planar Imaging addresses this by rapidly traversing k-space after a single excitation.

- In EPI, an entire 2D slice of k-space is typically acquired in one shot (or a small number of shots), enabling image acquisition in tens of milliseconds.

2D versus 3D imaging

- 2D MRI: RF pulse excites a single slice, and gradients are used to sample a 2D k-space within that slice. Volume is built by repeating the acquisition across multiple slice locations.



- 3D MRI: The entire volume is excited at once, and spatial encoding is performed in all three dimensions using phase encoding in two directions.
- Trade-offs: 3D imaging is more SNR-efficient and enables higher spatial resolution, but is more sensitive to motion.
- Typical use: Structural imaging is often 3D, while most fMRI uses 2D acquisitions

Artifact and challenges

How you do image encoding impacts the type of artifacts you get!

- Slice selection: thinner slices need larger gradients → can be limited by hardware
- Slow sampling means more vulnerable to motion over long duration
- EPI is particularly artifact-vulnerable because the phase evolves continuously over the EPI-train → many artifacts appear in the EPI phase encoding direction

Back to the Methods section…

Pulse sequence

ELSEVIER

NeuroImage

www.elsevier.com/locate/ynimg
NeuroImage 31 (2006) 818 – 831

Task-induced deactivations during successful paired associates learning: An effect of age but not Alzheimer's disease

Rebecca L. Gould,[a,*] Richard G. Brown,[b] Adrian M. Owen,[c]
Edward T. Bullmore,[d] and Robert J. Howard [a]

Image acquisition

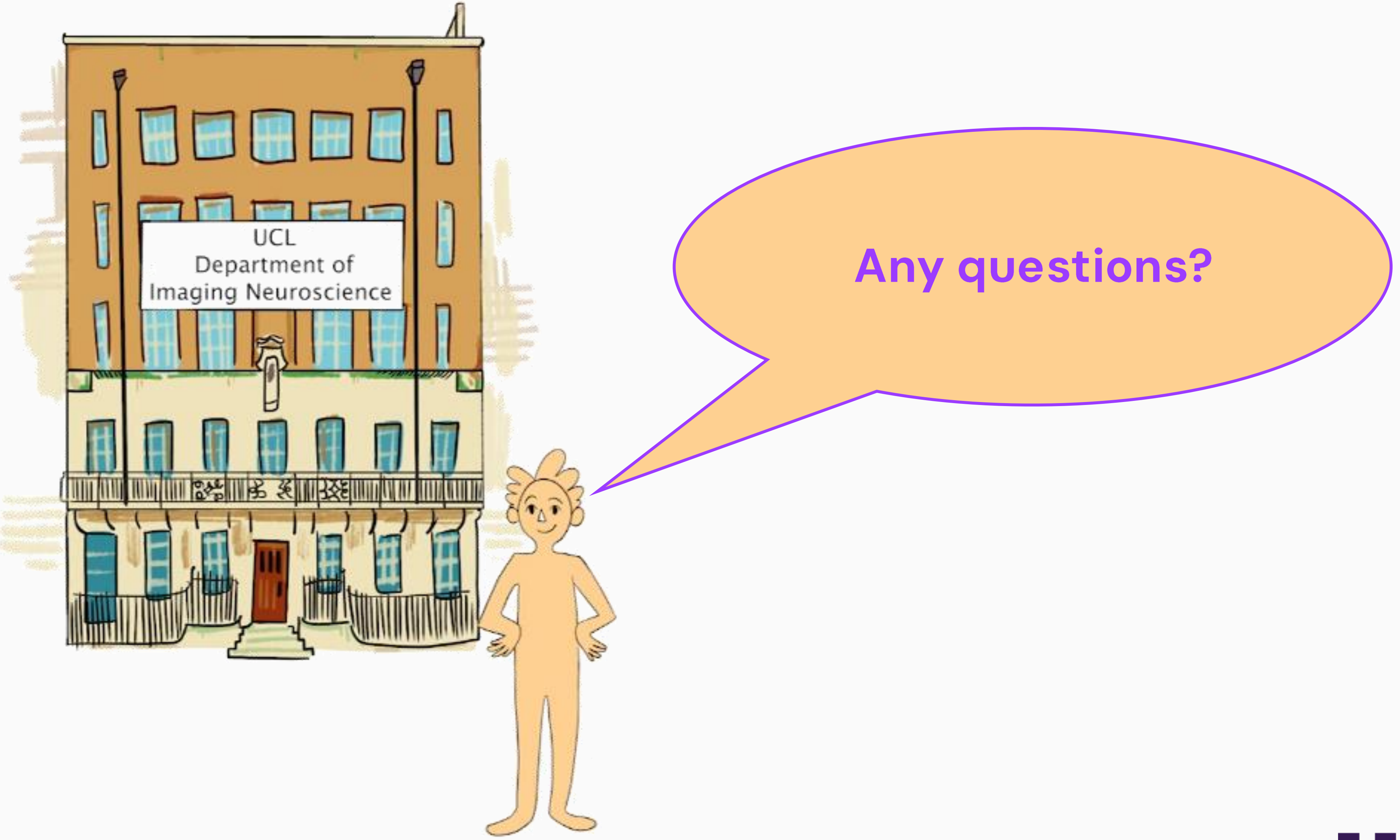
Functional and structural data were acquired on the 3 T Bruker scanner at the Wolfson Brain Imaging Centre, Cambridge. In each functional time series, T2*-weighted images depicting BOLD contrast were acquired using an interleaved echo planar (EPI) sequence at 21 whole-brain axial slices (TR = 3020 ms, TE = 27 ms, flip angle = 90°, matrix = 128 × 128, field of view = 25 cm^2, interslice distance = 5 mm, slice thickness = 5 mm). Seven initial EPI volumes were discarded to allow for magnetic stabilization in each functional time series. Each scan run lasted a maximum of 8 min or until 4 problems at each of the 3 levels of difficulty had been successfully completed. All participants received 3 scanning runs apart from 2 participants who only received 2 scanning runs due to technical difficulties. Imaging data from one younger adult had to be discarded due to problems with fMRI data acquisition. Three-dimensional, high resolution whole-brain axial images were also acquired for each participant.

Slice ordering

No slices & slice orientation

In-plane encoding

Slice thickness and


UCL
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Imaging Neuroscience
Any questions?

Time for coffee!