MRI Physics II(A): Understanding Phase Encoding

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Gradient Fields

- The last magnetic field to be used in MRI are the gradient fields
  - 3 of them: G_x, G_y, G_z
  - These are for localization
  - Make the magnetic field different in different parts of the body, e.g. for the x-gradient:

$$B(x) = B_0 + G \cdot x$$

  - Observe the field points in the same direction as B_0 so it adds to B_0.

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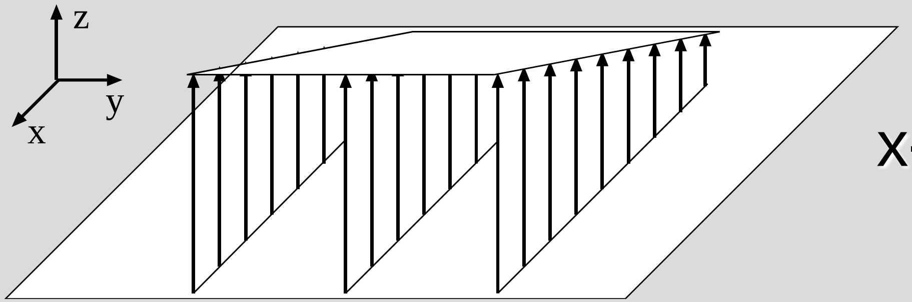
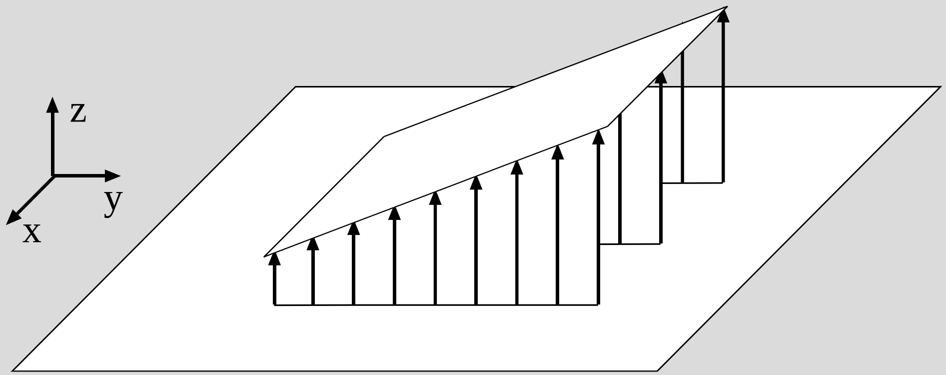
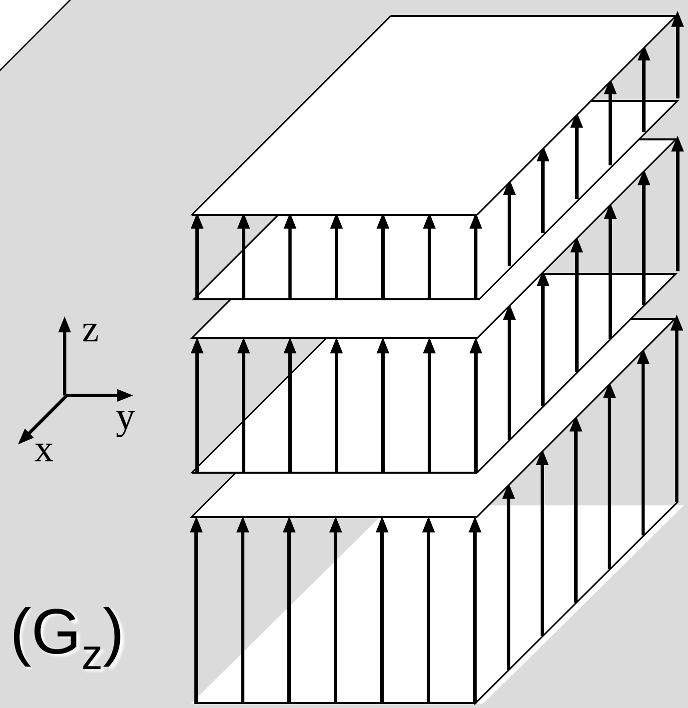


x-gradient (G_x)



y-gradient (G_y)



z-gradient (G_z)

Frequency Encoding

- A fundamental property of nuclear spins says that the frequency at which they precess (or emit signals) is proportional to the magnetic field strength:

$$\omega = \gamma B$$

- The Larmor Relationship

- This says that precession frequency now increases as we move along the x-direction (e.g. as we move rightwards).

$$\omega(x) = \gamma\,(B_0 + G \cdot x).$$

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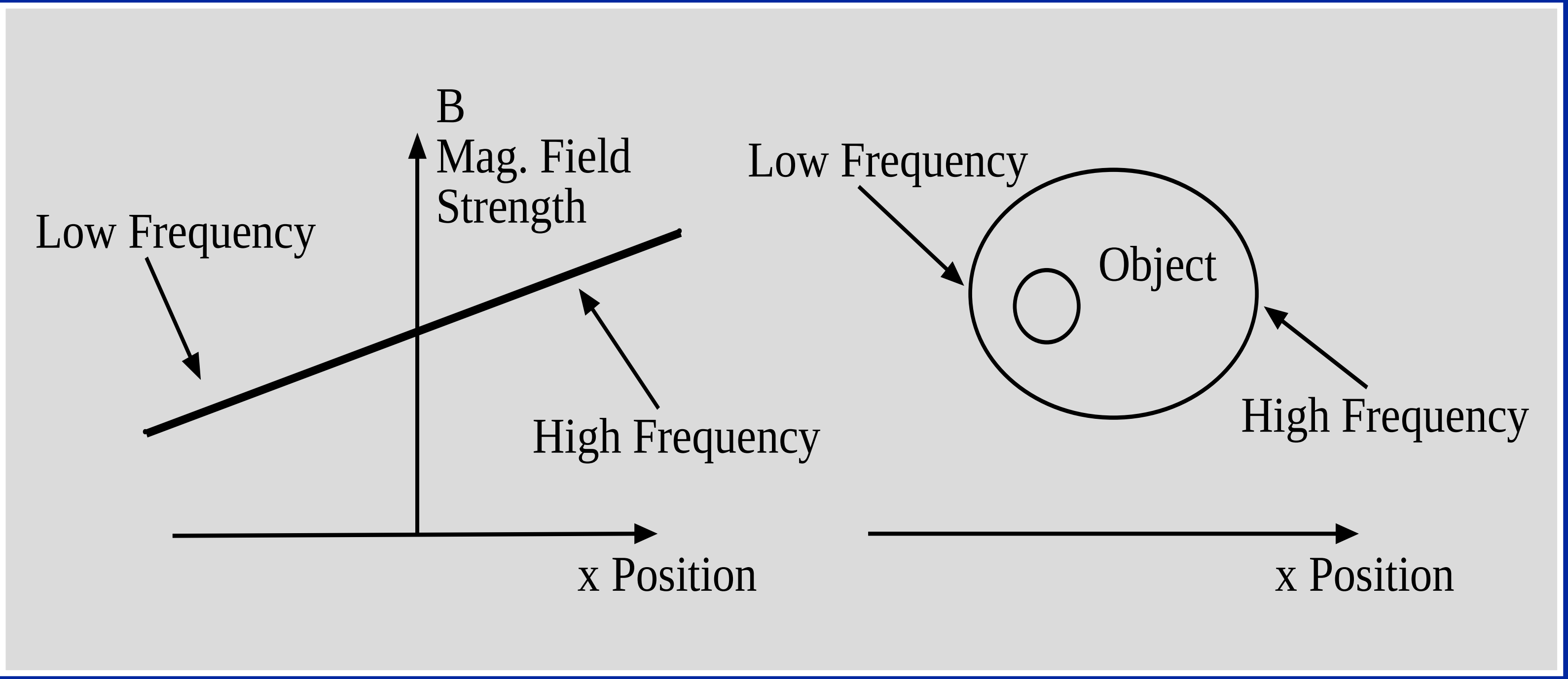
Frequency Encoding



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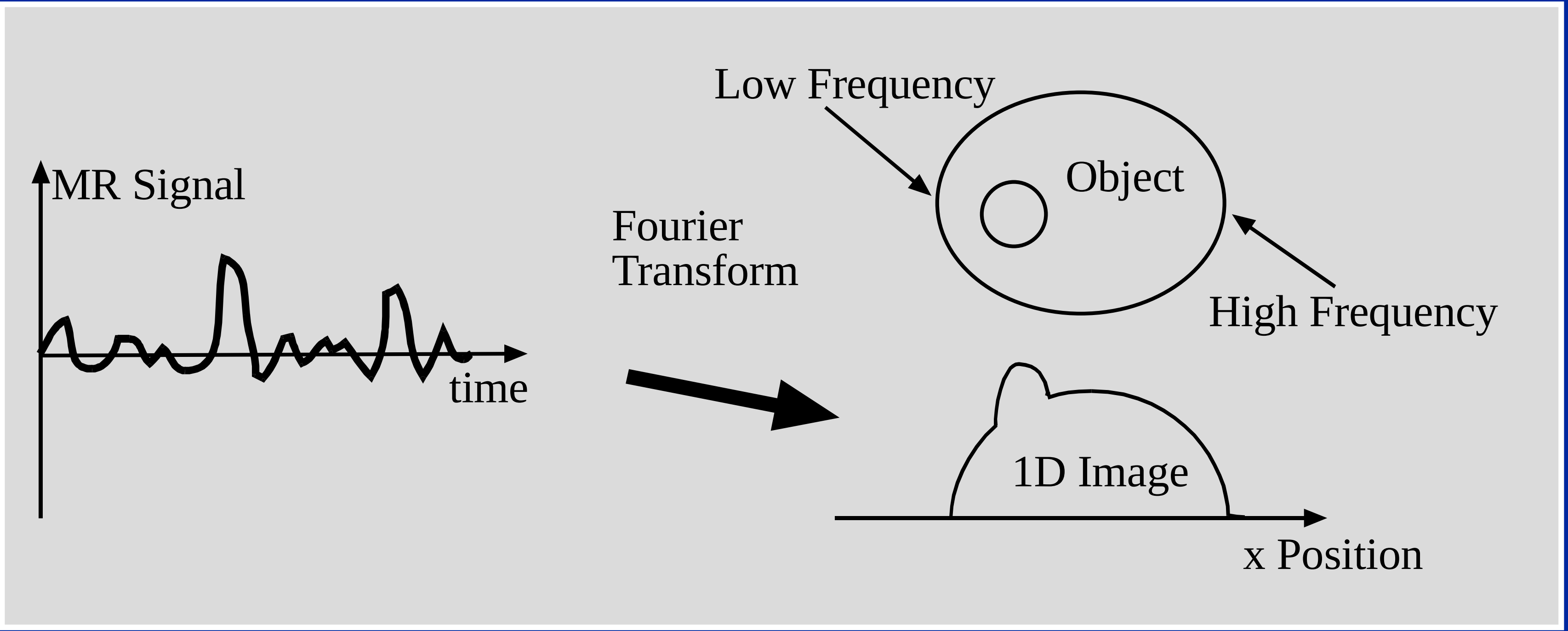
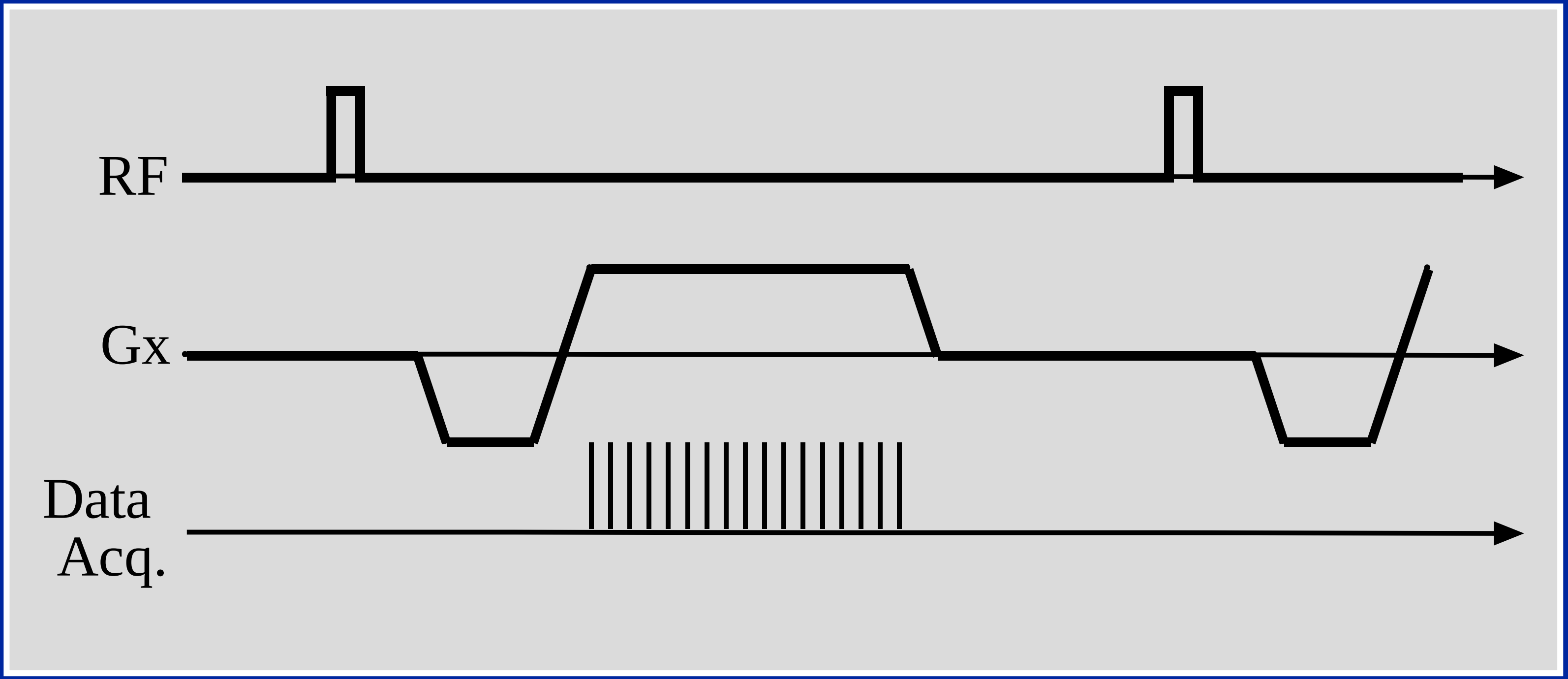
Fourier Transforms



1D Pulse Sequence

Now we put this together with excitation:

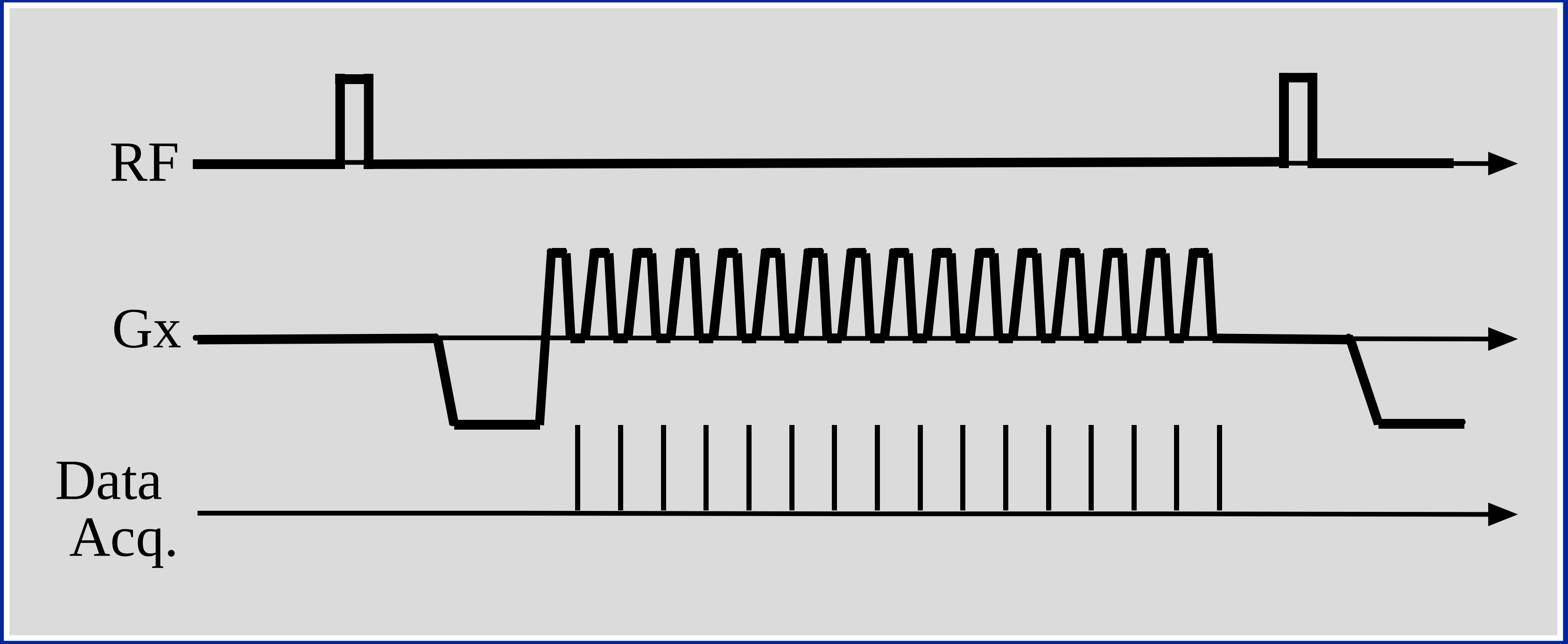


Alternate Method for 1D Localization

- In the case just described, the “frequency encoding” gradient was constant.
  - At different locations spins precessed at different frequencies.
  - This was true as long as the gradient was “on.”

- We now look at an alternate situation where the gradient is turned “on” and “off” rapidly.
  - At different locations spins will precess at different frequencies, but only during the times that the gradient is “on.”

Alternate Method for 1D Localization



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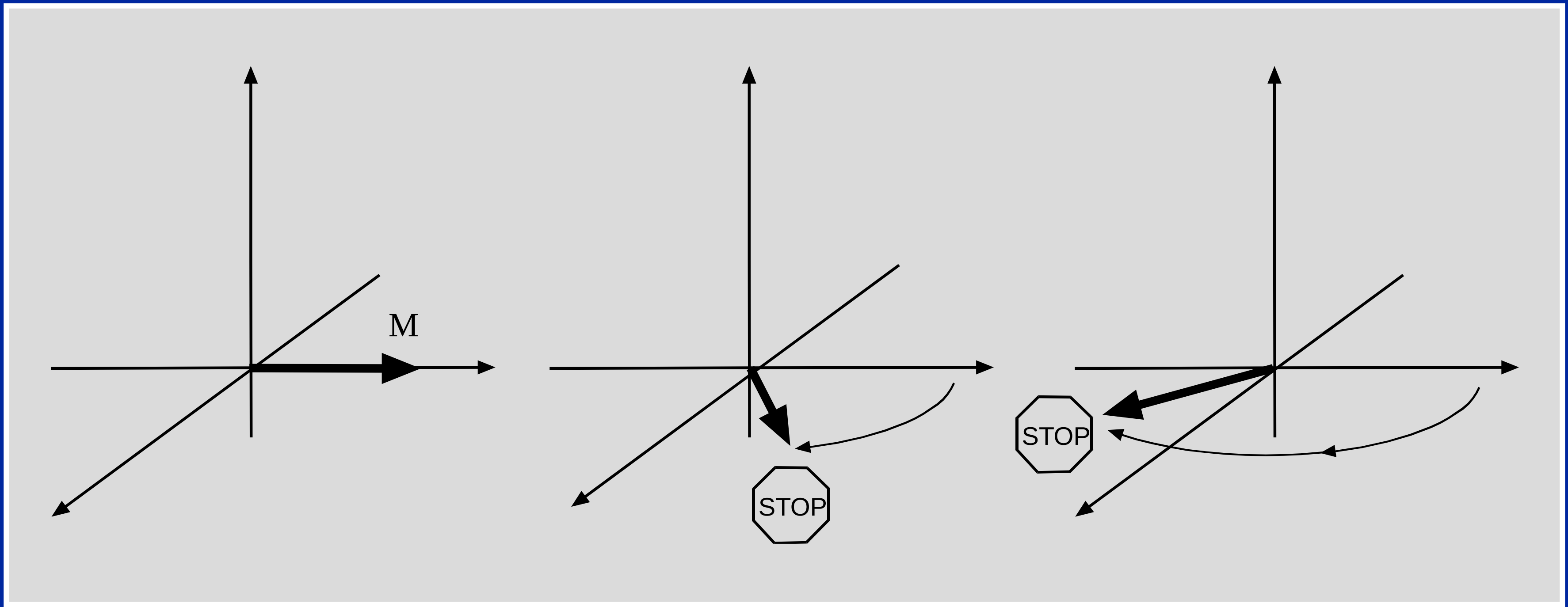
Stop-Action Movement of Magnetization



Sample 1 Sample 2 Sample 3

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On/Off Gradients in 1D Localization

- In the case previously described, the spins precessed smoothly.
- In this case, the spins precess in a “stop-action” or jerky motion.
- What is different here is that we sample the MR signal while it has stopped precessing.
  - At each step, the spatial information has been encoded into the phase.
  - This is a form of “phase encoding.”

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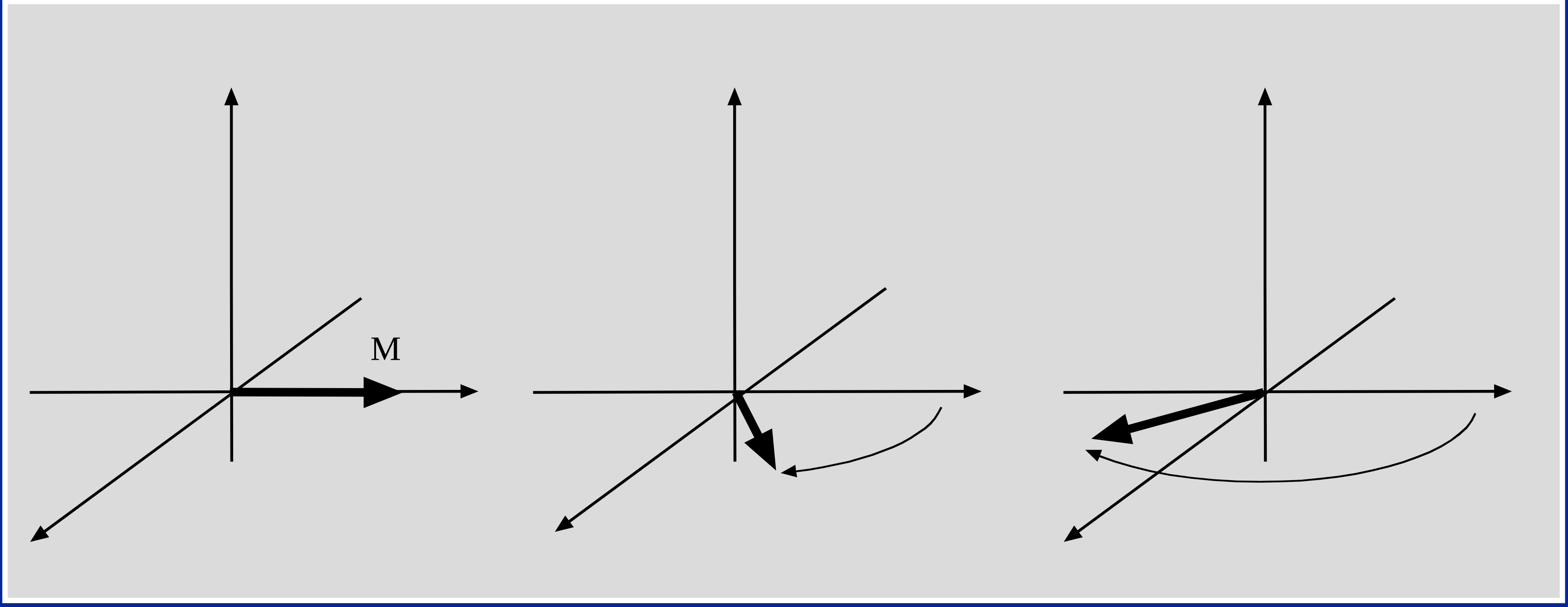
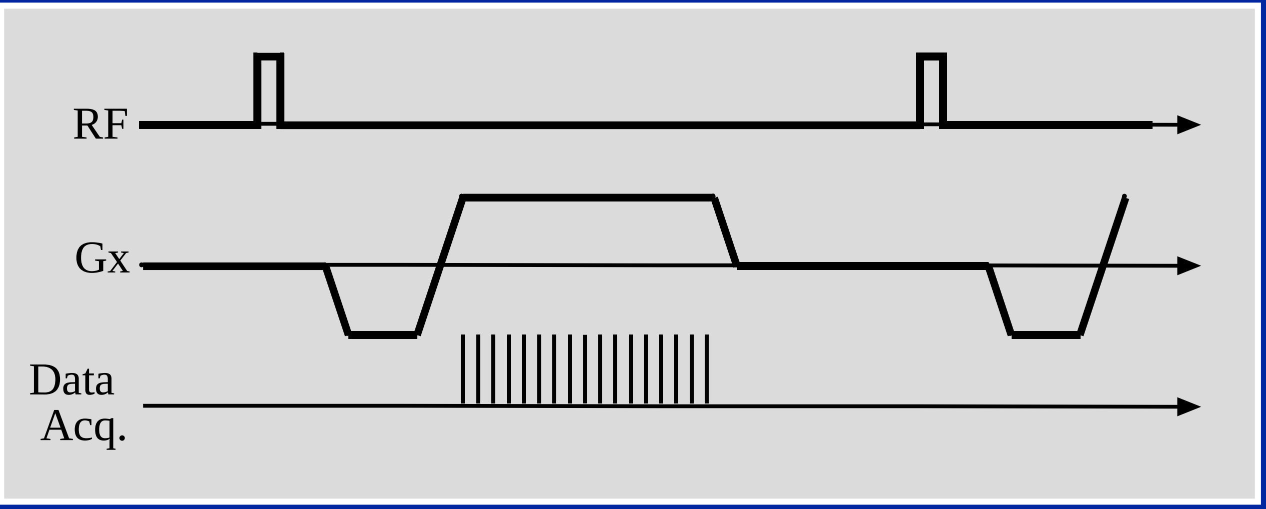
Movement of Magnetization with Constant Gradient

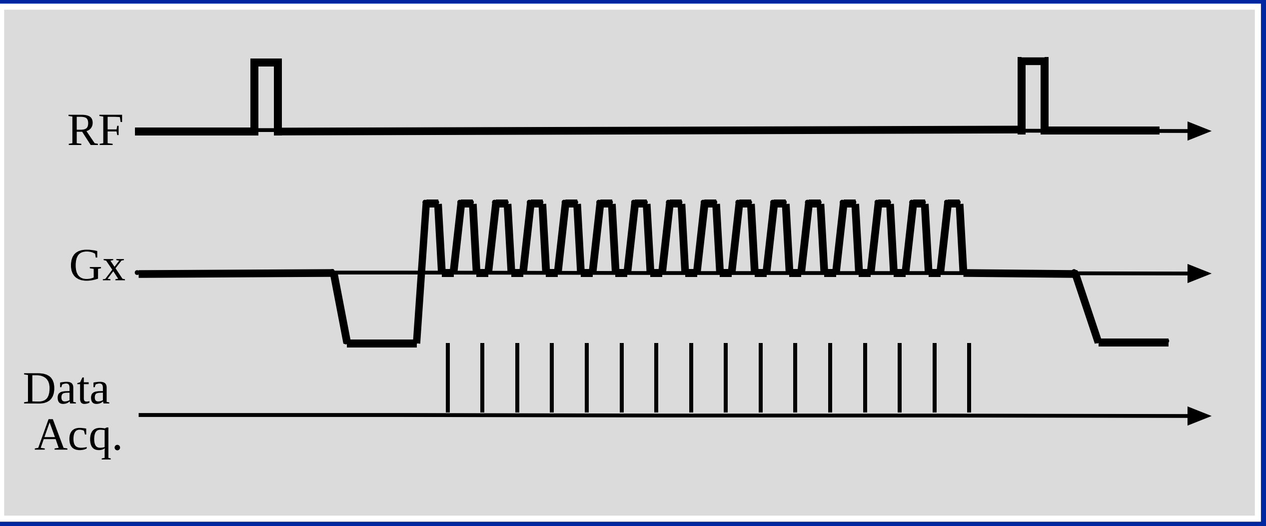


Smooth precession of magnetization

Different 1D Localization Methods

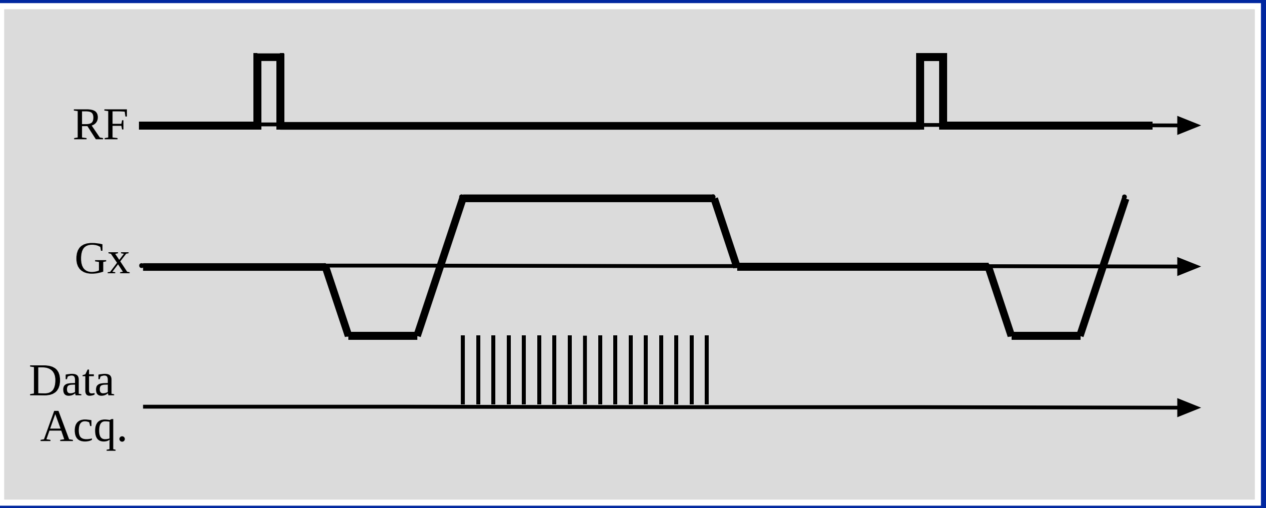


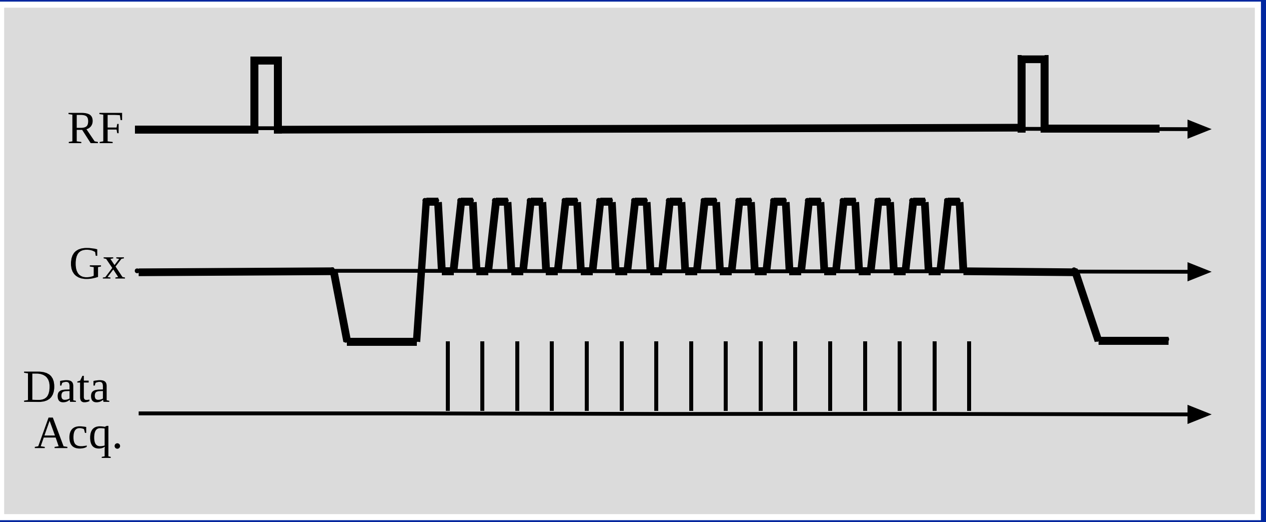
Upper - smooth precession at different frequencies. (frequency encoding)



Lower - precession in small steps, phase contains location info. (phase encoding).

Different 1D Localization Methods





Are the sampled data the same?

Yes, if we neglect T2.

In both cases, the Fourier transform creates the 1D image.

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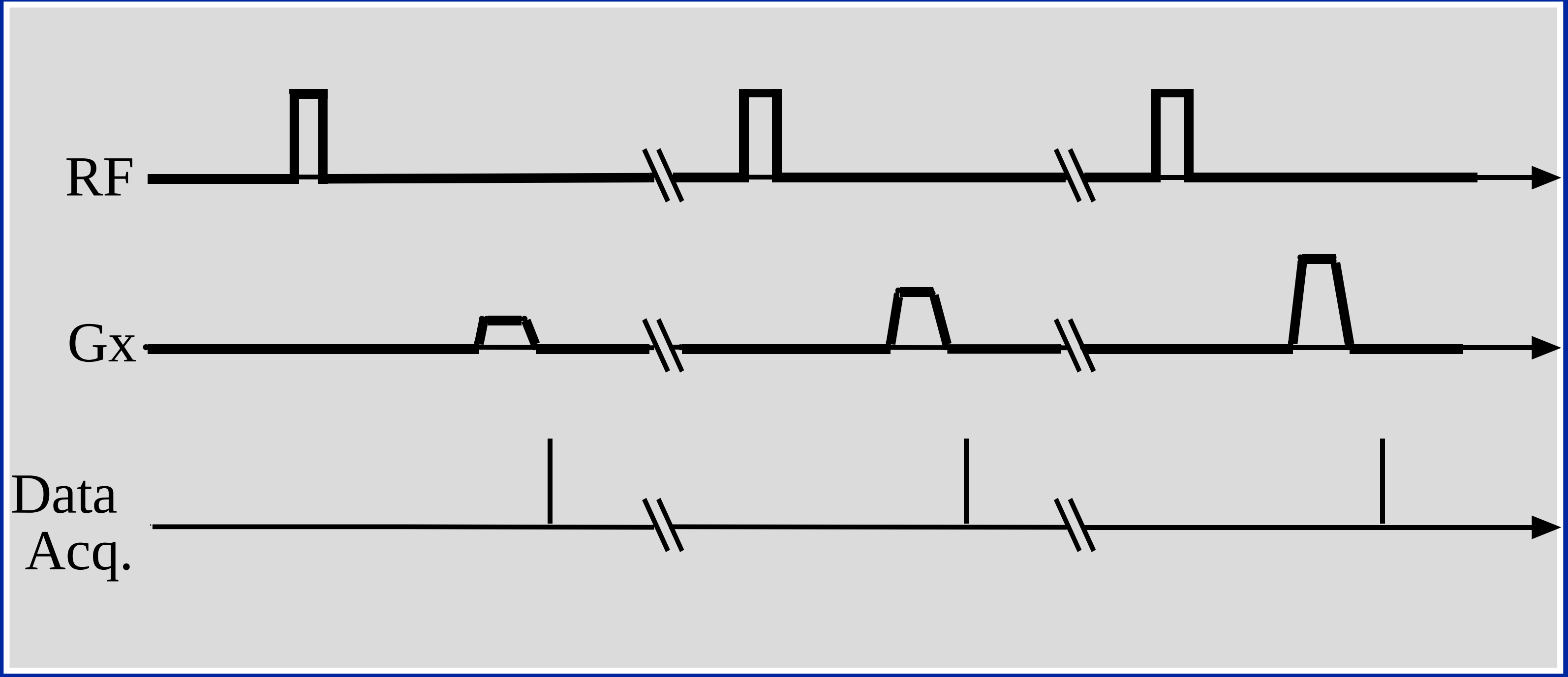
Alternate Method #2 for 1D Localization

- In the above cases, gradients were turned on and samples were acquired following a single RF excitation pulse.
  - At different locations spins precessed at different frequencies.
  - Motion was either smooth or “stop-action.”
- We now look at a situation where a single sample is acquired after each RF pulse.
  - Spins precess for a particular length of time and then a single sample is acquired.

Alternate Method #2 for 1D Localization



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Phase Encoding in 1D

- Again, spins precess only as long as gradient is turned "on."
- If we look spins after each step (sample location), the precession will again appear as "stop-action" motion.
- Again, spatial information has been encoded into the phase of spin.
  - Another form of "phase encoding."

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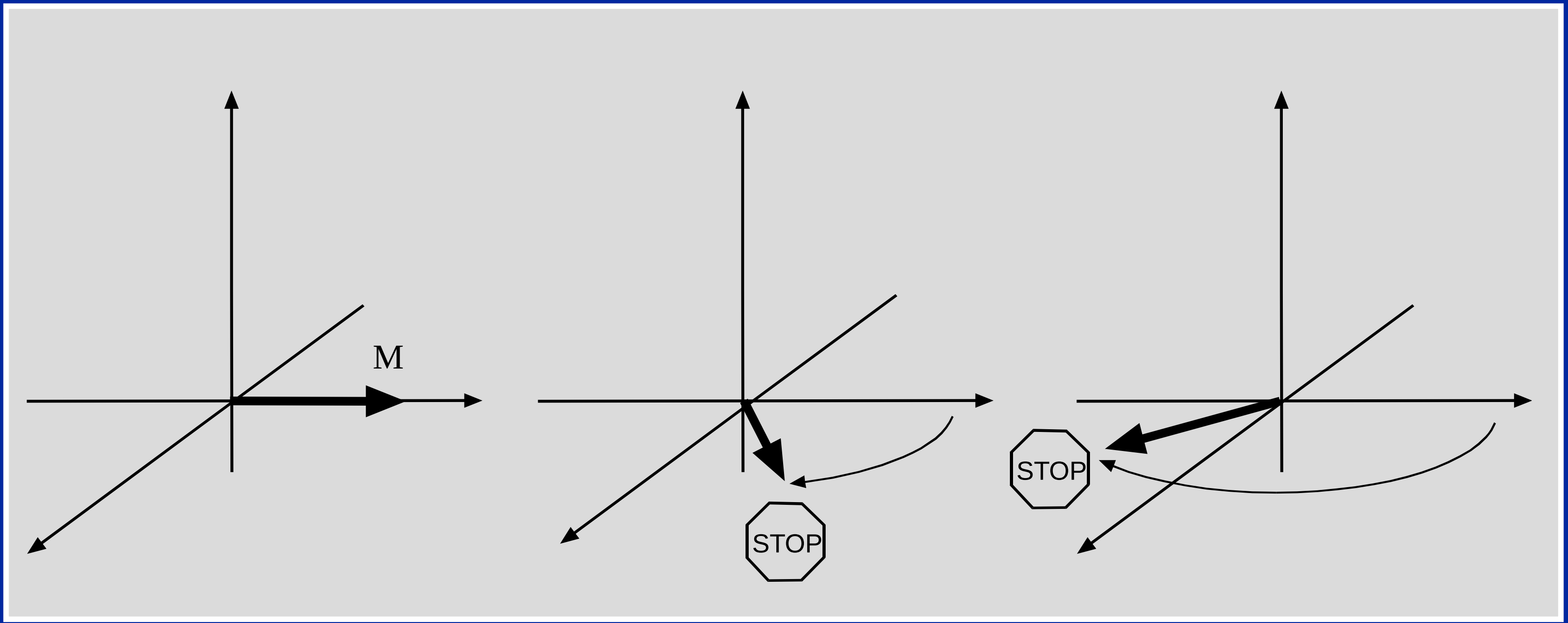
Phase Encoding in 1D



Phase Encode 0

Phase Encode 1

Phase Encode 2

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Three Methods for 1D Localization

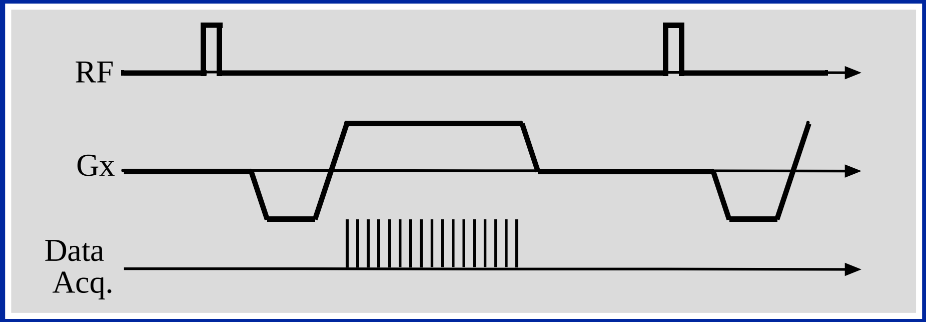
- 1D Localization:
  - Frequency encoding
  - Phase encoding following a single RF pulse
  - A single phase encode following each of many RF pulses

- Sampled data is the same (if we neglect T2).

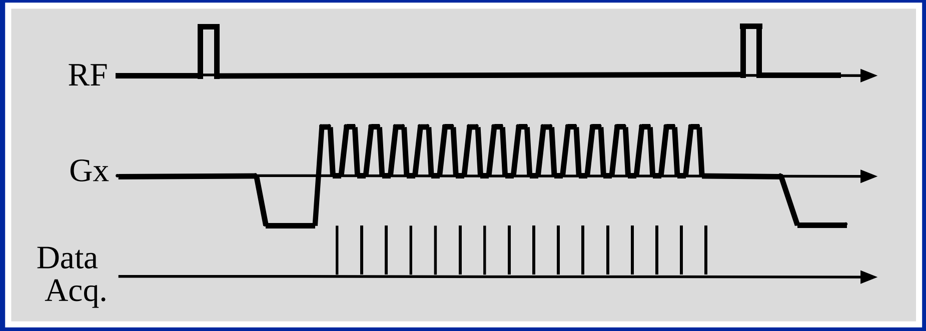
- The Fourier transform creates the 1D image.

Three Methods for 1D Localization

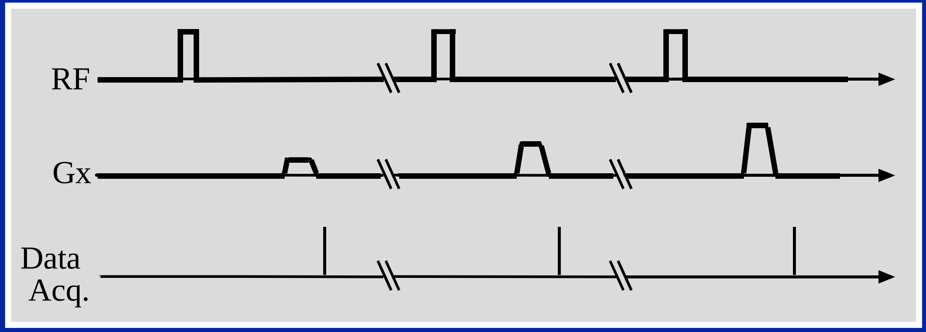
Frequency Encoding



Phase Encoding Method #1



Phase Encoding Method #2



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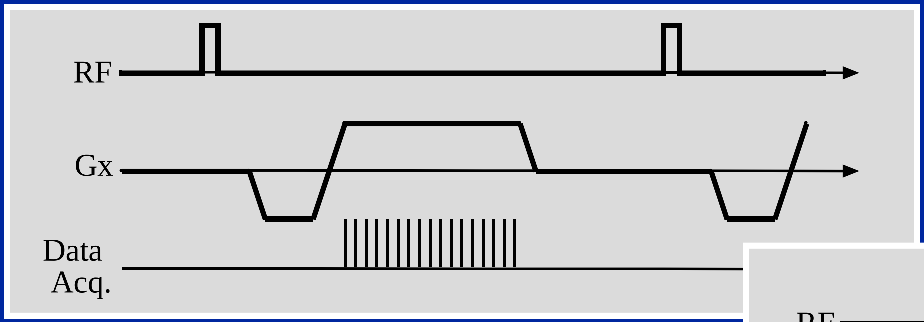
2D Localization

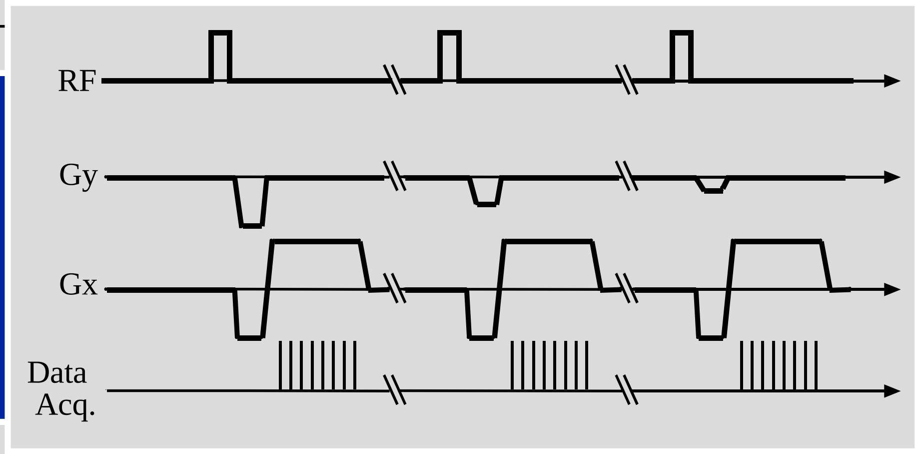
- In general, we will combine two 1D localization methods to create localization in two dimensions (2D).

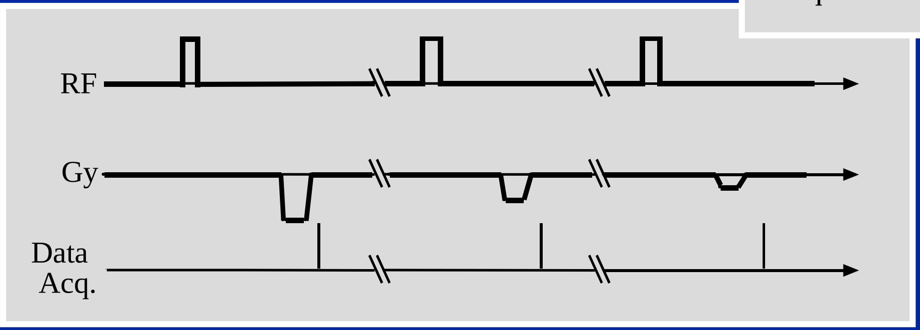
- The spin-warp method (used in almost all anatomical MRI) is a combination of :
  – Frequency encoding in one direction (e.g. Left-Right)
  – Phase encoding in the other direction (e.g. Anterior-Posterior)

2D Localization - Spin Warp



Frequency Encoding
(in x direction)





Phase Encoding
Method #2
(in y direction)

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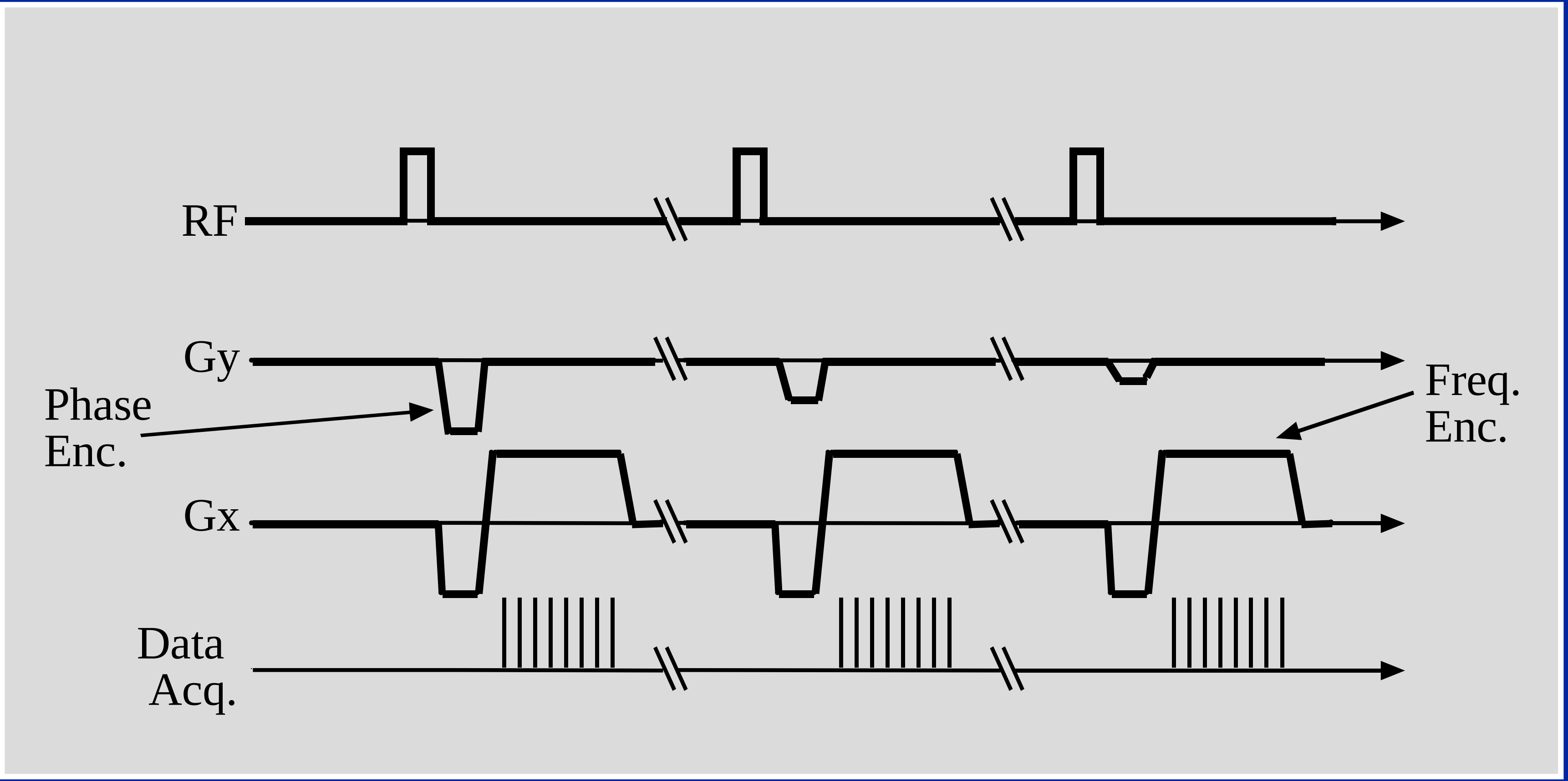
Spin-Warp Imaging

- For each RF pulse:
  - Frequency encoding is performed in one direction
  - A single phase encoding value is obtained
- With each additional RF pulse:
  - The phase encoding value is incremented
  - The phase encoding steps still has the appearance of "stop-action" motion

Spin-Warp Pulse Sequence



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Spin-Warp Data Acquisition

- In 1D, the Fourier transform produced a 1D image.
- In 2D, the Fourier transform is applied in both the frequency and phase encoding directions.
  - This is called the 2D Fourier transform.
- Commonly we structure the samples in a 2D grid that we call “k-space.”
  - One line of k-space is acquired at a time.

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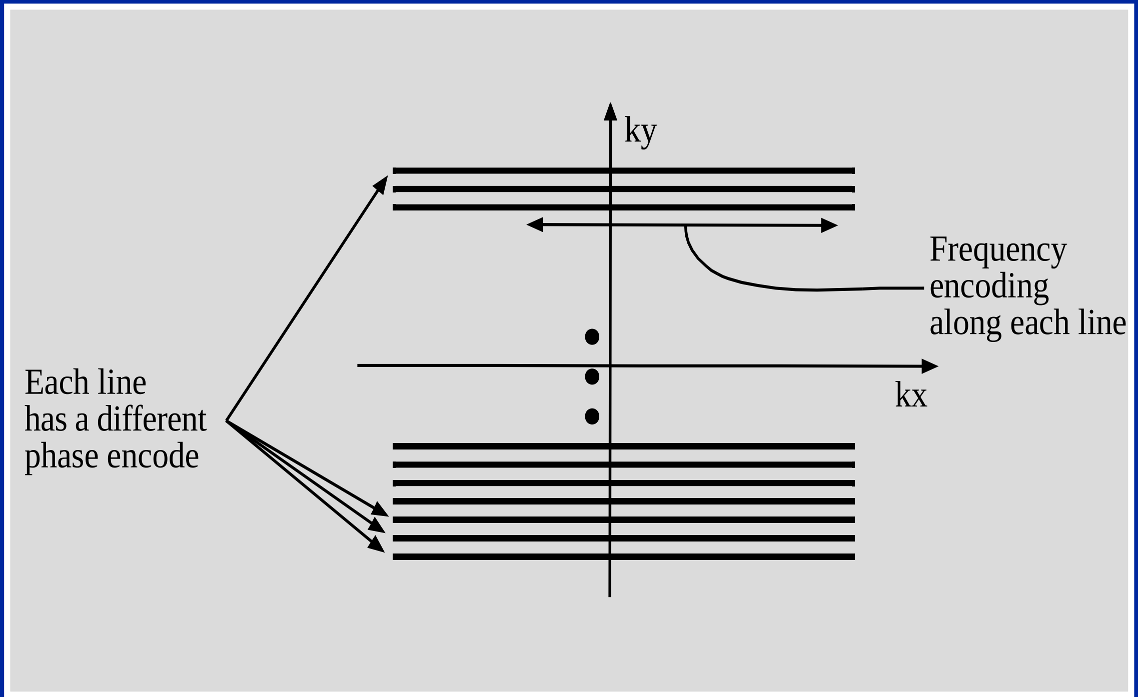
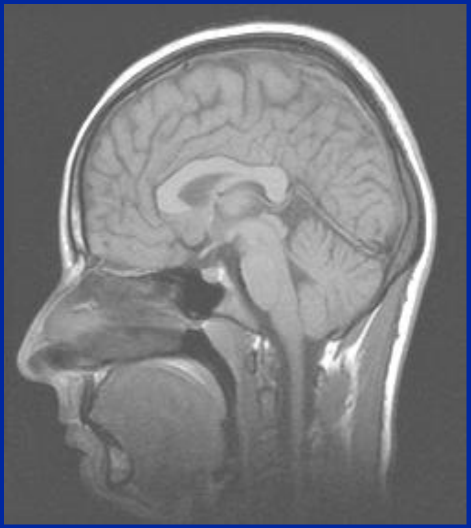
Spin-Warp Data Acquisition



2D Fourier Transform



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Echo-Planar Imaging

- As with spin-warp imaging, echo-planar imaging (EPI) is just the combination of two 1D localization methods

- EPI is also a combination of :
  – Frequency encoding in one direction (e.g. Left-Right)
  – Phase encoding in the other direction (e.g. Anterior-Posterior)

- EPI uses a different phase encoding method.

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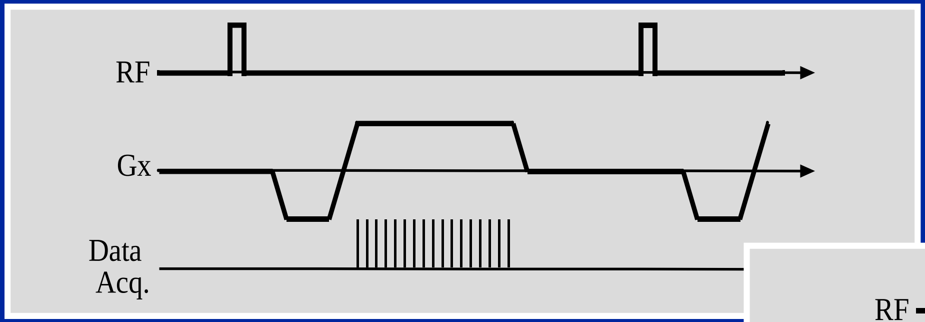
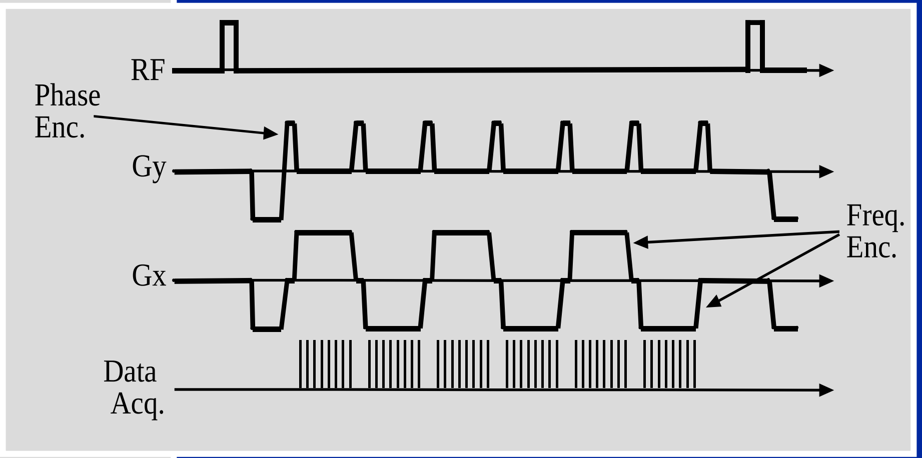
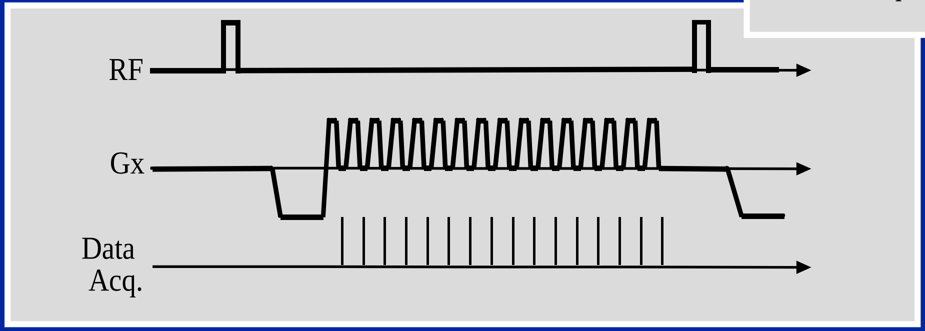
Echo-Planar Imaging



Frequency Encoding
(in x direction)





Phase Encoding
Method #1
(in y direction)

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Echo-Planar Imaging

- For each RF pulse:
  - Frequency encoding is performed many times
  - All phase encoding steps are obtained
  - The entire image is acquired
- With each additional frequency encoding (each additional line in the k-space grid):
  - The phase encoding value is incremented
  - The phase encoding steps still has the appearance of “stop-action” motion

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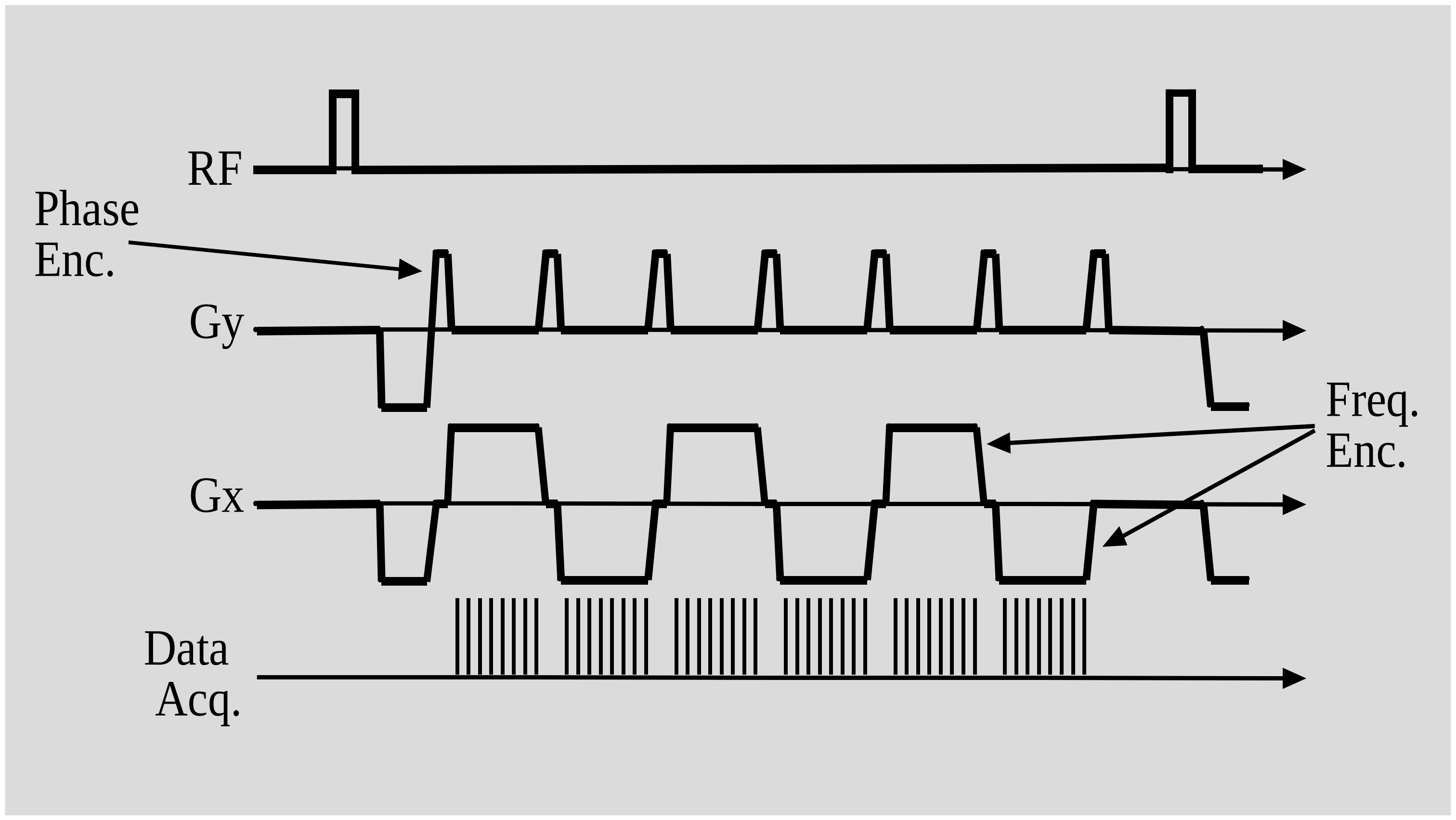
EPI Pulse Sequence



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EPI Data Acquisition

- As with Spin-Warp imaging, we put the acquired data for the frequency and phase encoding into the 2D grid called "k-space.
- Also, the 2D Fourier transform is used to create the image.
- In EPI, the data is filled into k-space in a rectangular "zig-zag"-like pattern.

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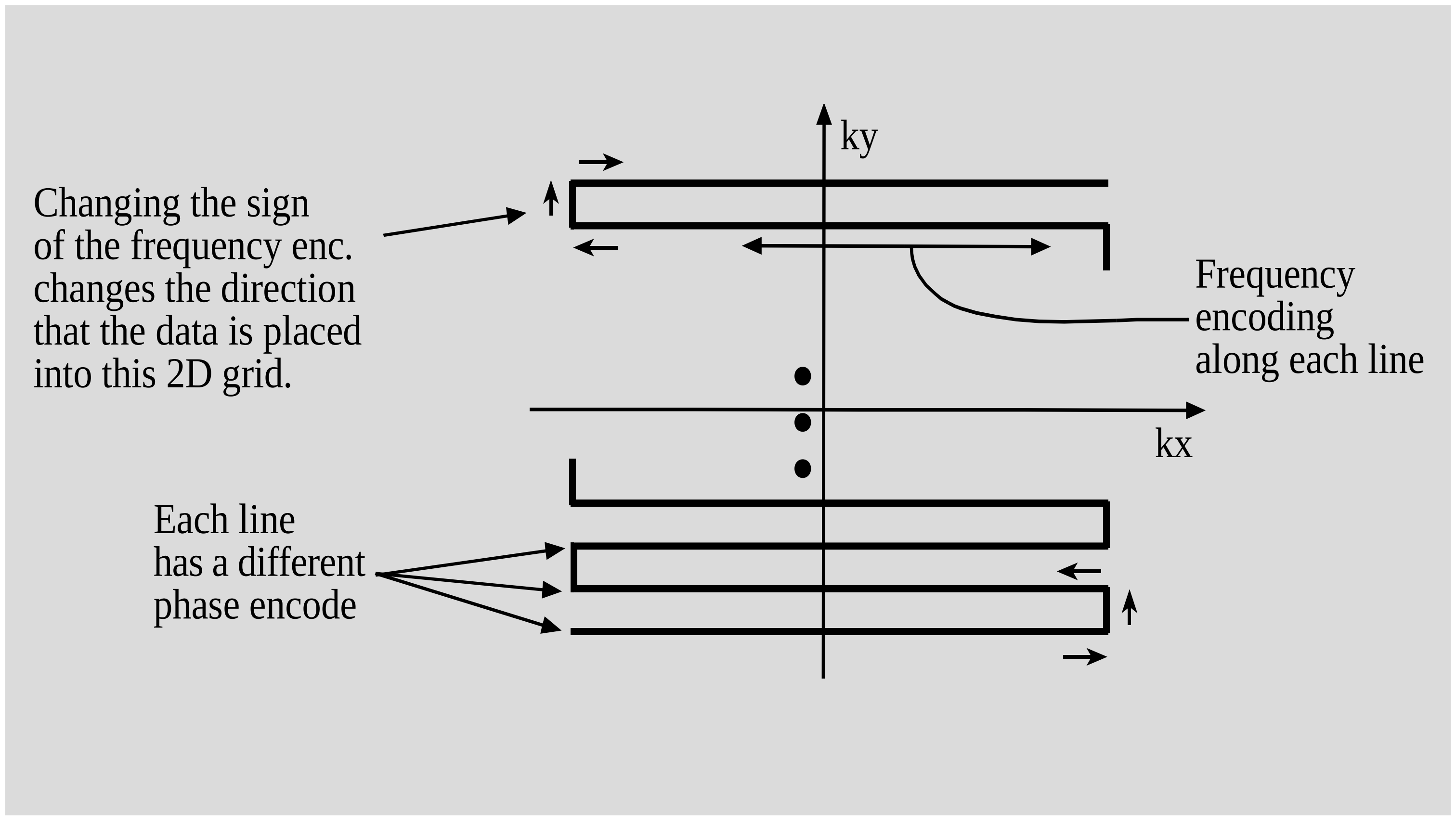
EPI Data Acquisition



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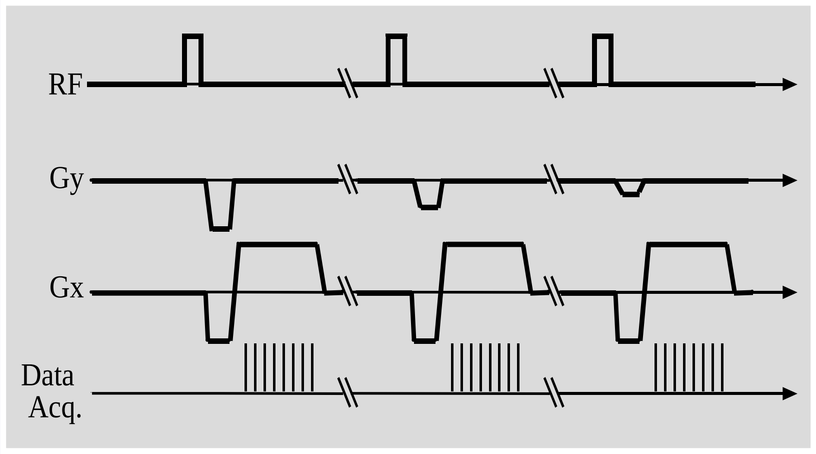
EPI Imaging

- In summary, EPI data is in many ways like Spin-Warp imaging:
  - They are combinations of two kinds of 1D localization.
  - They have both frequency and phase encoding.
  - Data are acquired on a 2D grid called k-space.
  - Images are reconstructed by a 2D Fourier transform.

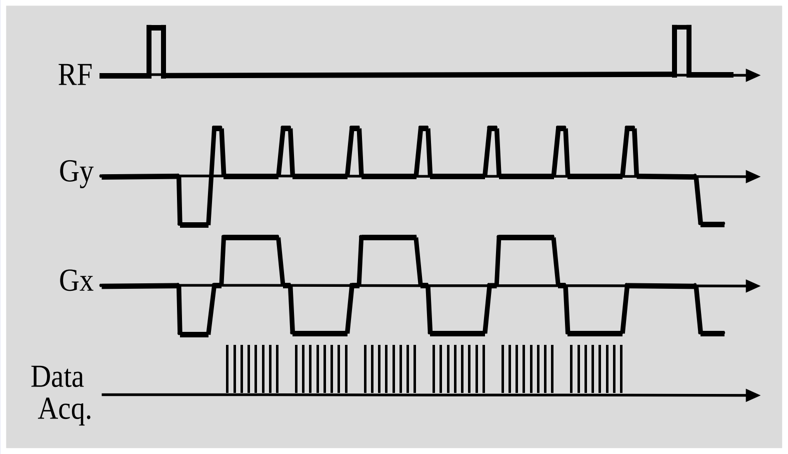
Spin-Warp vs. EPI Pulse Sequences

Spin-Warp



Many acquisitions
to make a one image.

EPI



One acquisition
to make one image.

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