

The basics of MRI: Image contrast, reconstruction, and hardware

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National Institute
of Mental Health



Outline

- Source of the MRI signal
 - Expanding the acronym
 - Magnetic ...
 - Resonance ...
 - Imaging ...
- Physics underlying contrast in MR images
- Random thoughts ...

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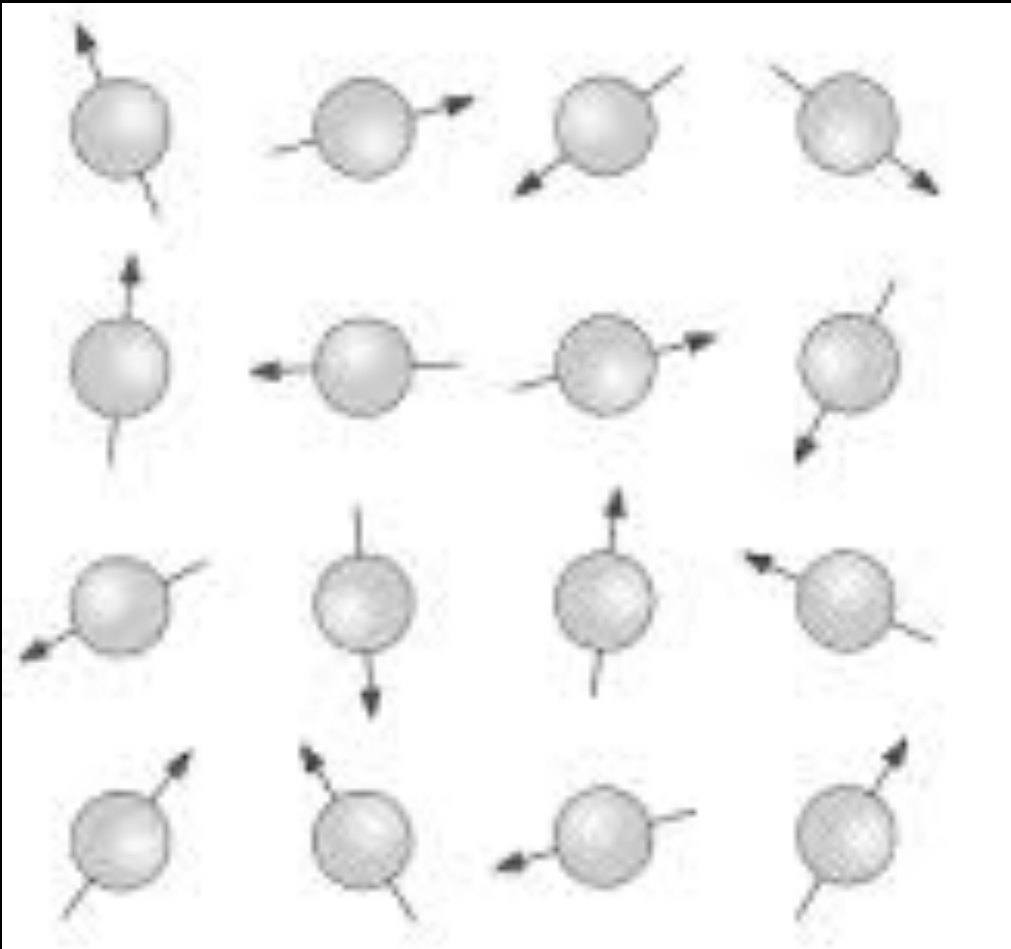
Magnets in atomic nuclei

- Certain nuclei (odd number of protons and/or neutrons) have magnetic properties (i.e. magnetic moment - 1952 Nobel Prize in Physics, to Bloch and Purcell).
- Include ^{13}C , ^{23}Na , ^{31}P , ^{129}Xe , and ...

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- ^1H !

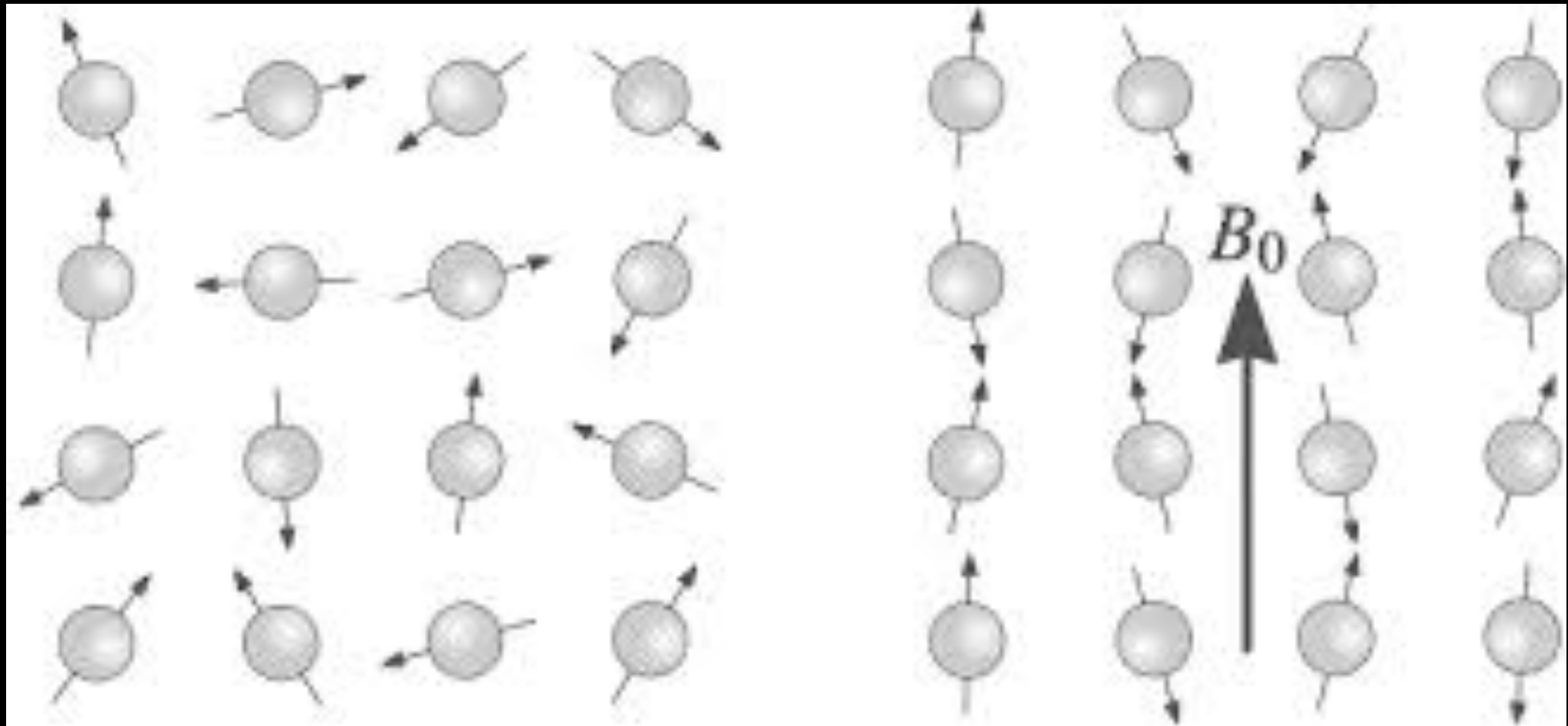
Magnets



- Protons randomly aligned naturally

http://wikidoc.org/index.php/Basic_MRI_Physics

Magnets



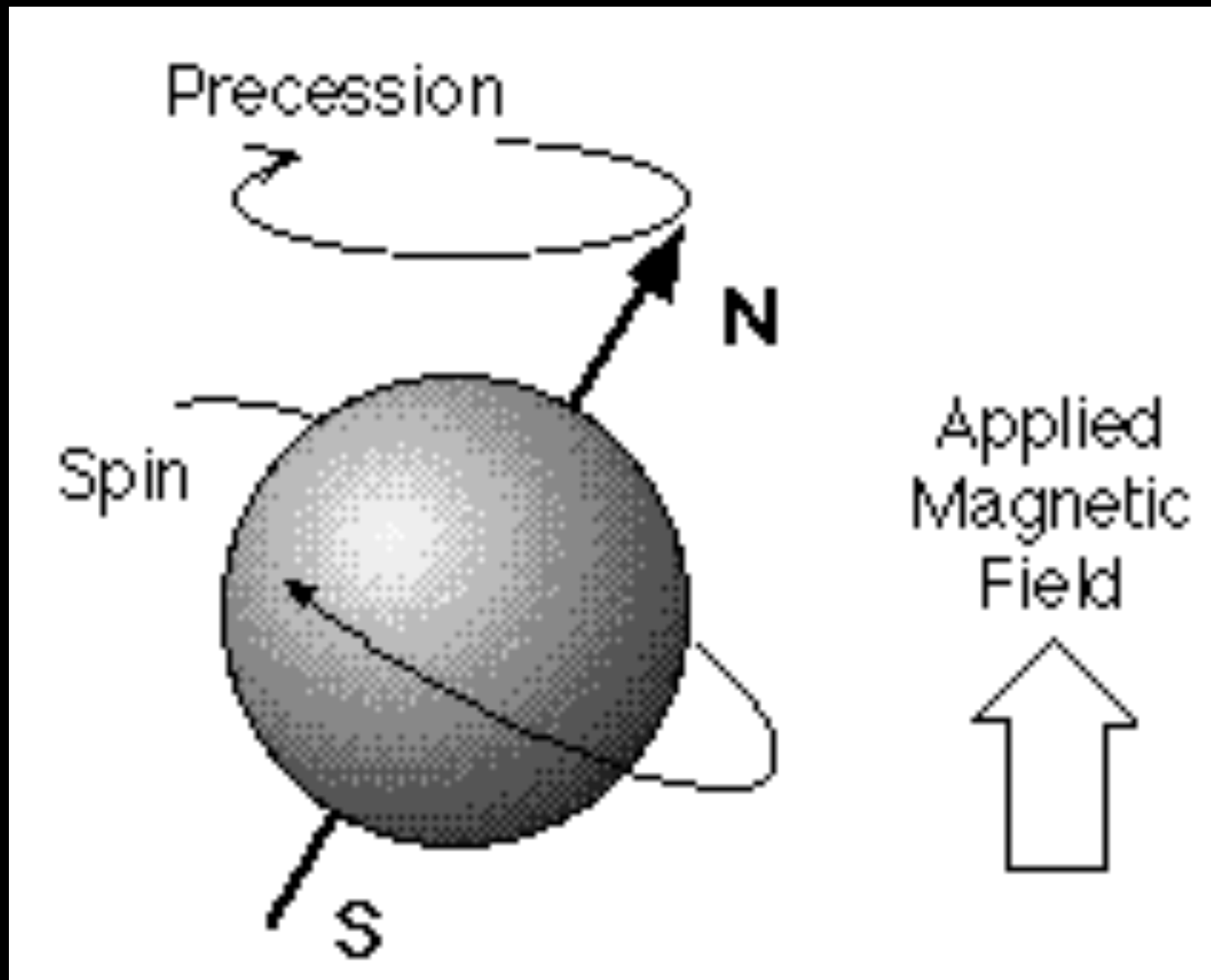
- Protons randomly aligned naturally
- But align when exposed to strong magnets —> M_0

http://wikidoc.org/index.php/Basic_MRI_Physics

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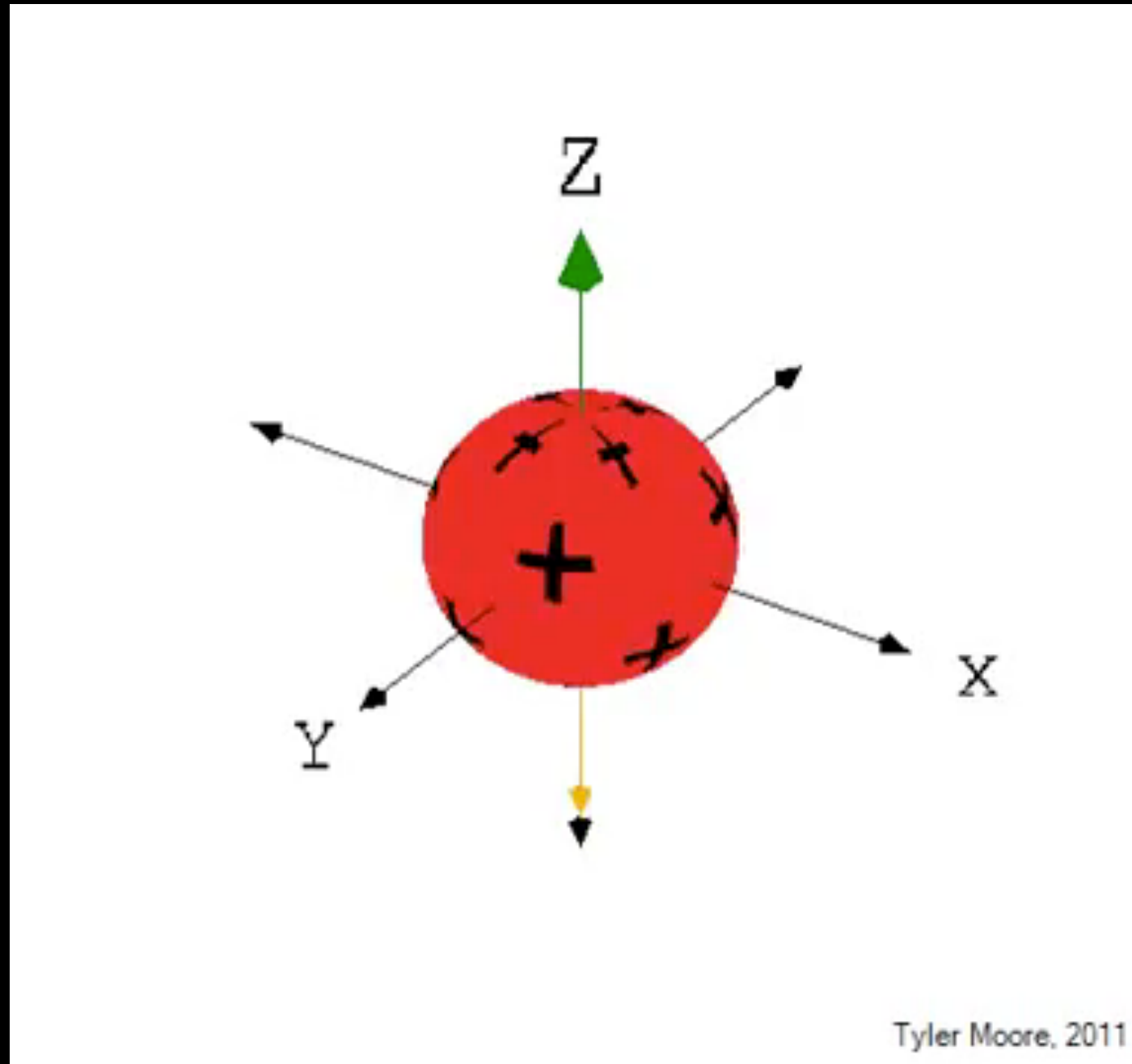
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Resonance



<http://ccn.ucla.edu/BMCweb/SharedCode/TINS/FMRI-TINS.html>

Resonance



<https://www.youtube.com/playlist?list=PLAE12114468910462>

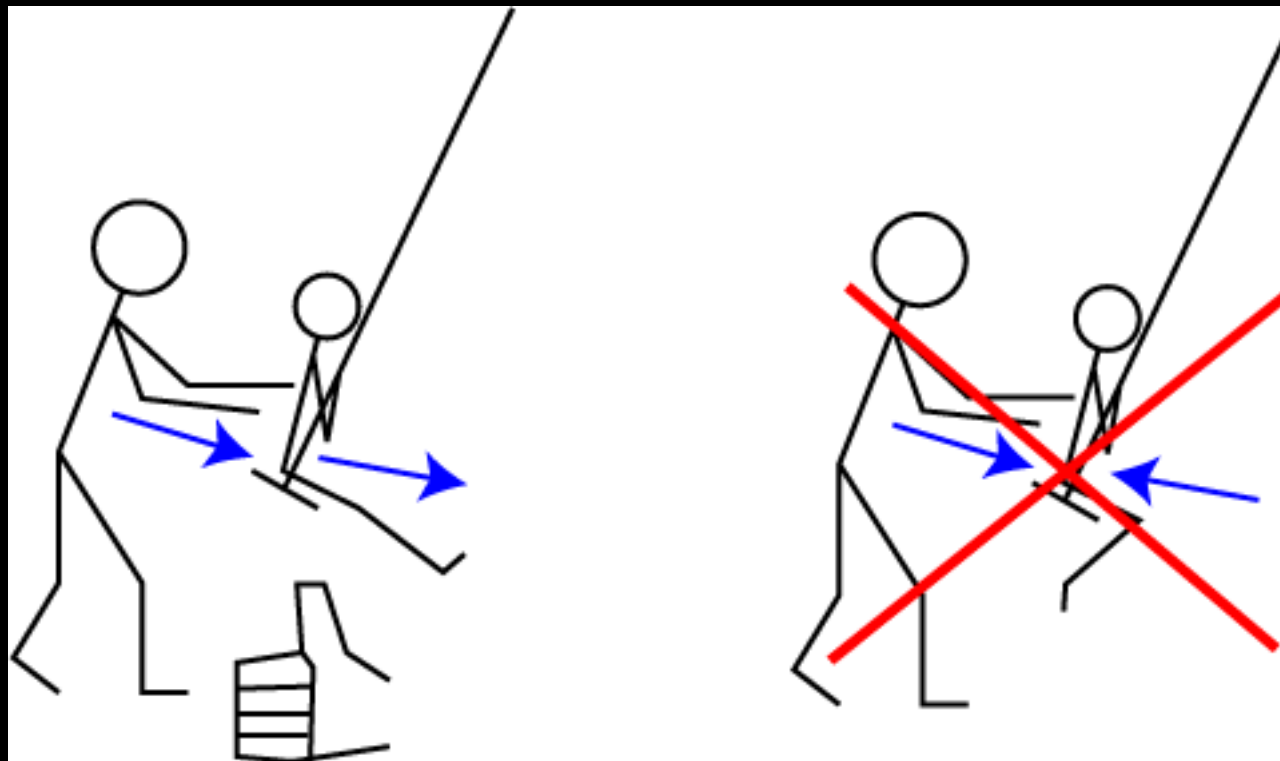
Resonance

$$\omega_0 = \gamma B_0$$

Resonance

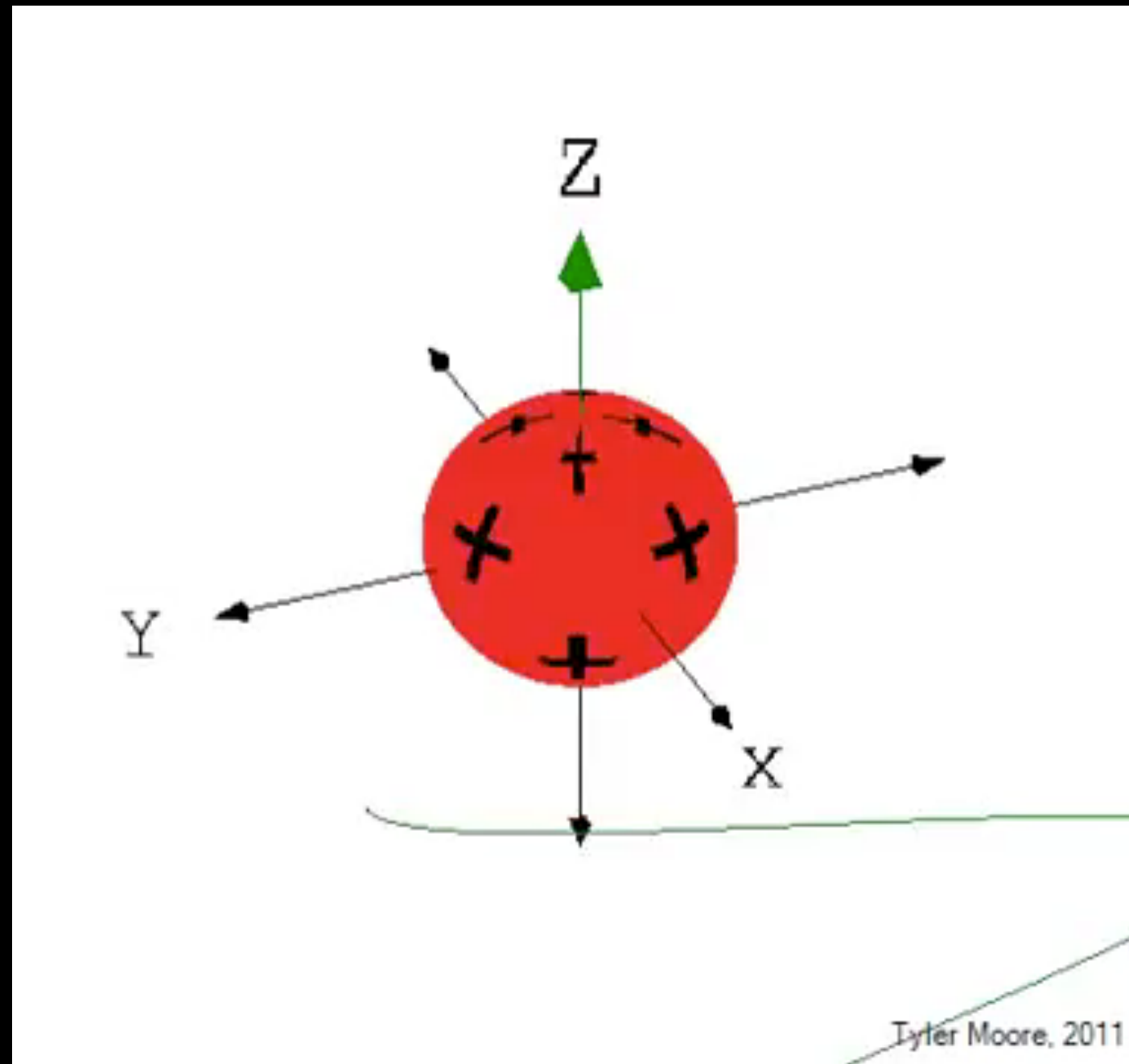
- Protons aligned with main magnetic field (B_0)
are not visible / detectable in MR imaging
- “Flip” / excite into visibility by applying energy
at the same frequency as precession ...
- == Resonance !

Resonance



<https://shapeofdata.wordpress.com/2013/12/03/case-study-4-resonance-and-robots/>

Resonance



<https://www.youtube.com/playlist?list=PLAE12114468910462>

Resonance

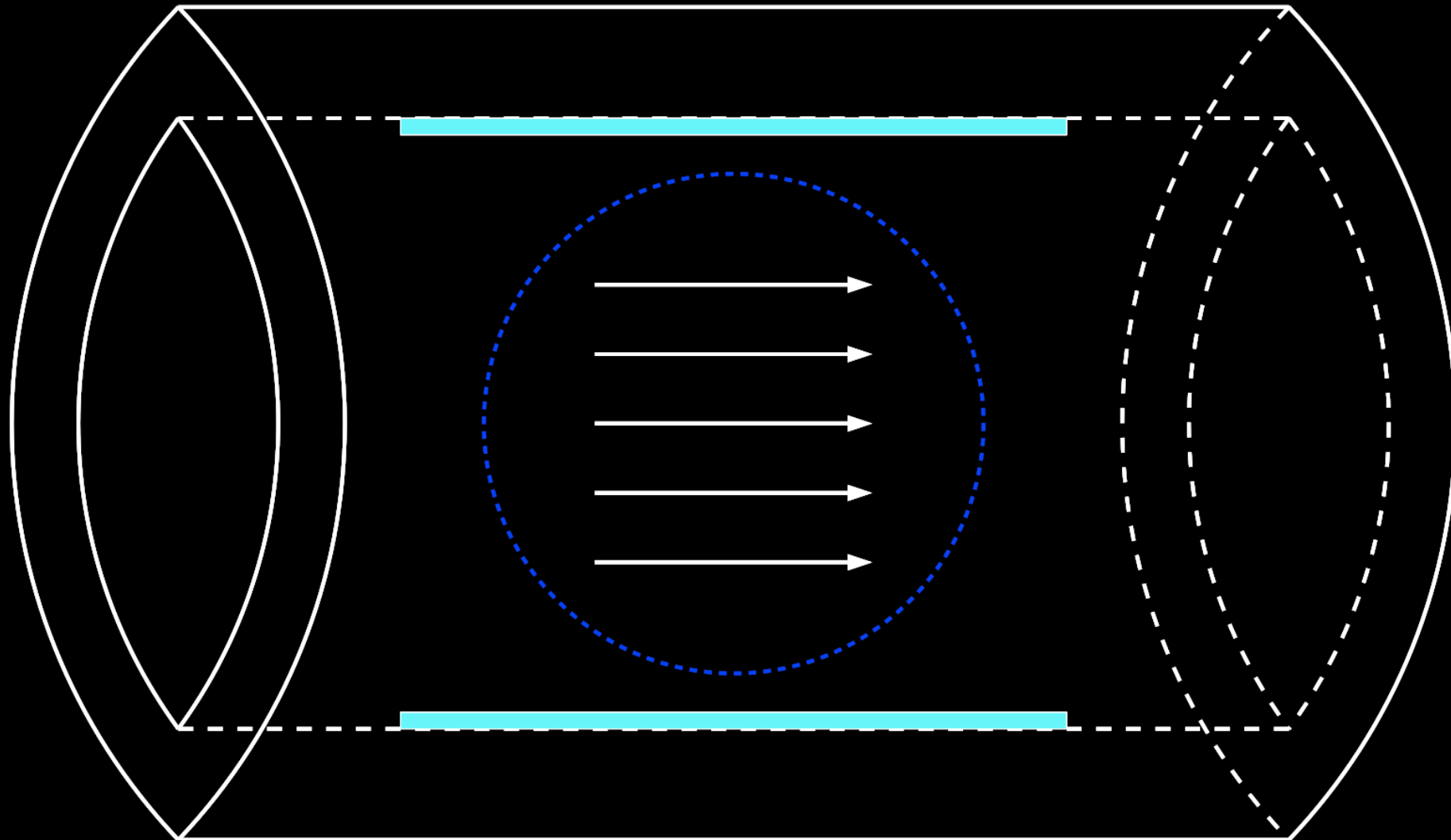
- Perpendicular protons (partially or completely) **are** visible in typical MR experiment.
- RF must be “on resonance” for efficient excitation
- Off resonance - power deposited in sample / no signal → high SAR.
- Uniform B_0 → uniform signal. Need additional info to localize signal to generate image.

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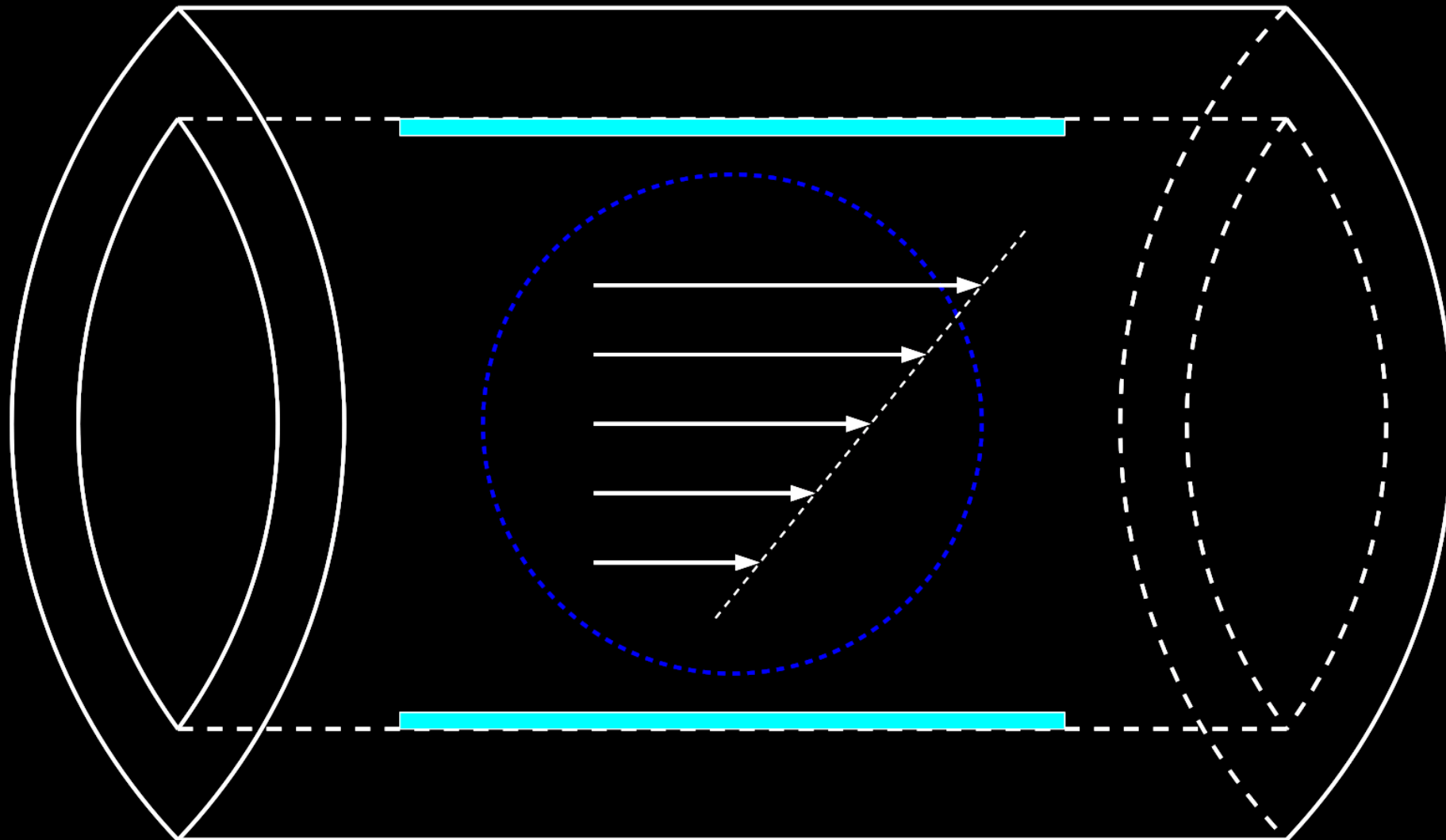
Imaging

- Uniform $B_0 \rightarrow$ uniform signal - cannot localize ...
so how to image?



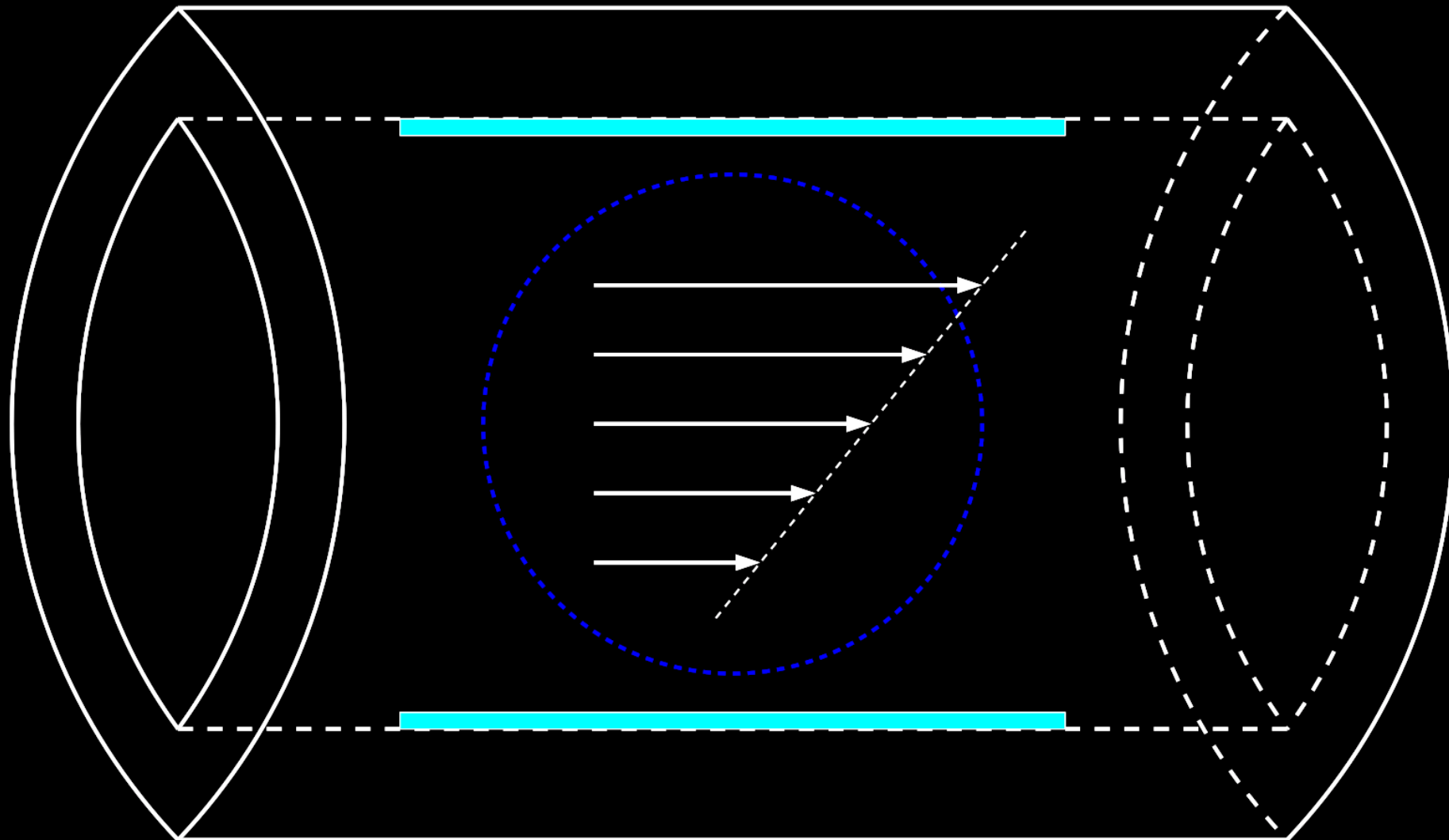
Imaging

- Apply controlled distortion to B_0



Imaging

- Apply controlled distortion to $B_0 \rightarrow \rightarrow \rightarrow$ Spatially varying frequency



Imaging

$$\omega_0 = \gamma B_0$$

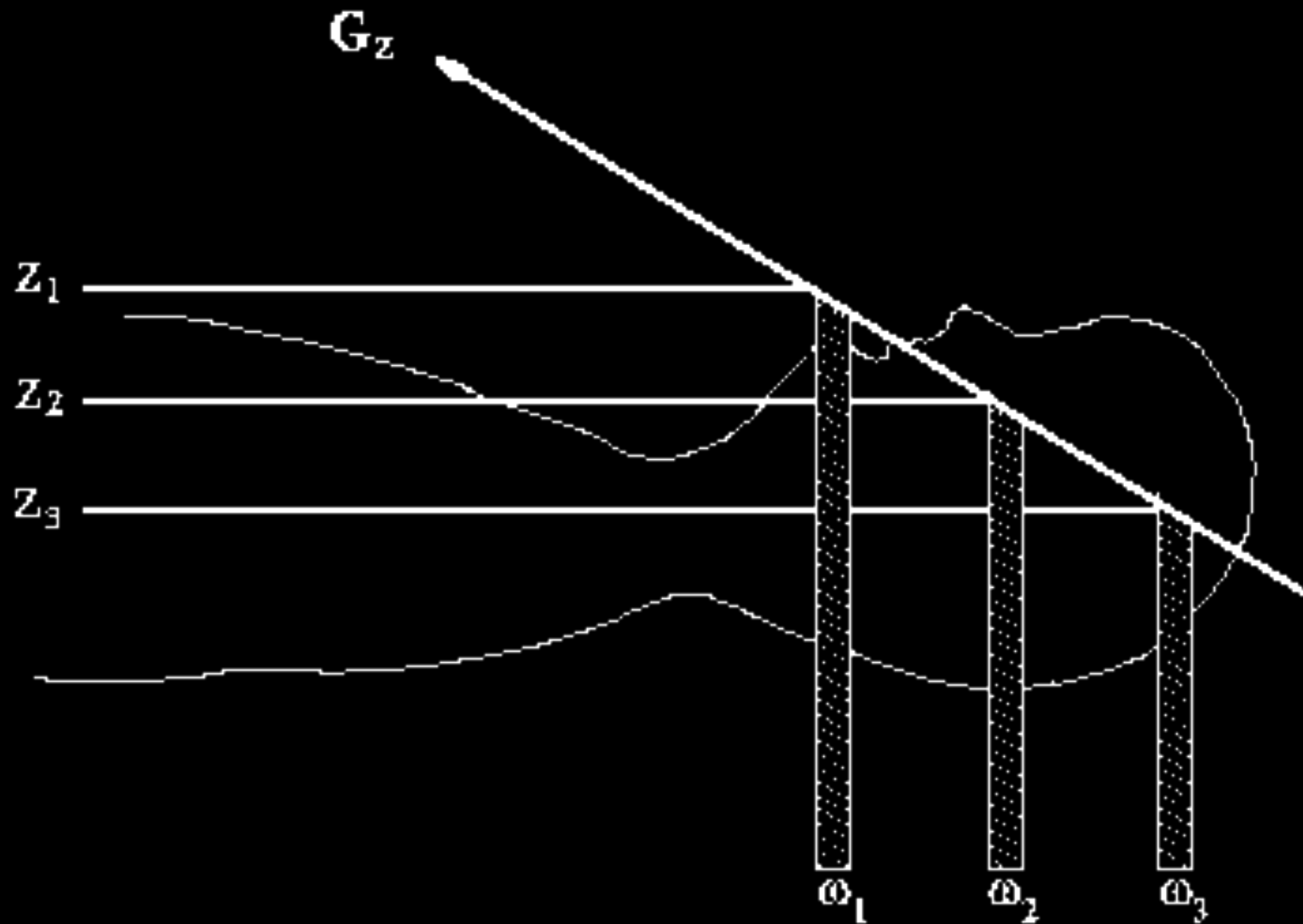
Imaging

$$\omega_x = \oint B_x$$

Imaging

$$\omega_x = \gamma (B_0 + G_x)$$

Imaging

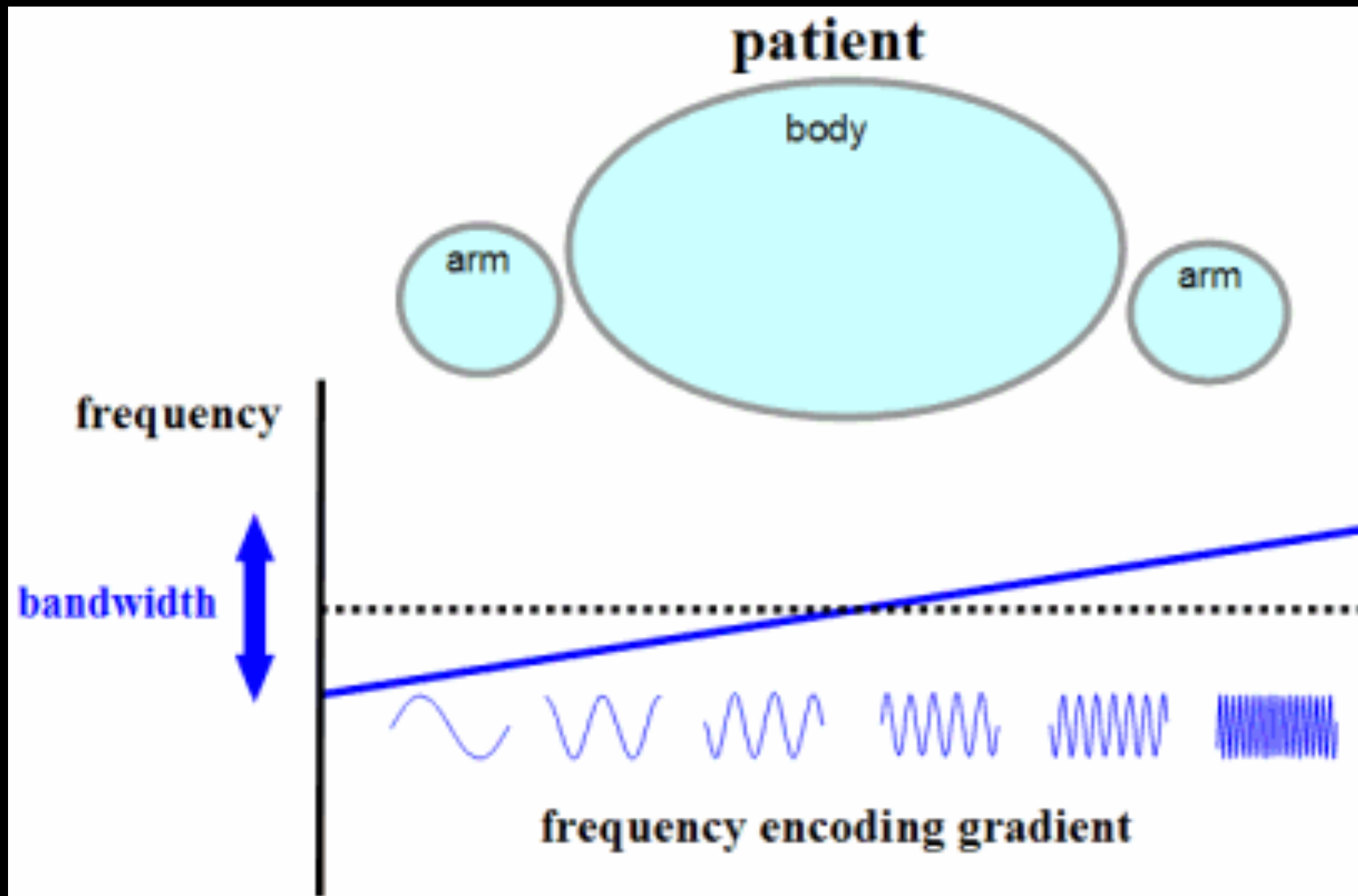


http://sfb649.wiwi.hu-berlin.de/fedc_homepage/xplore/ebooks/html/csa/node255.html

Imaging

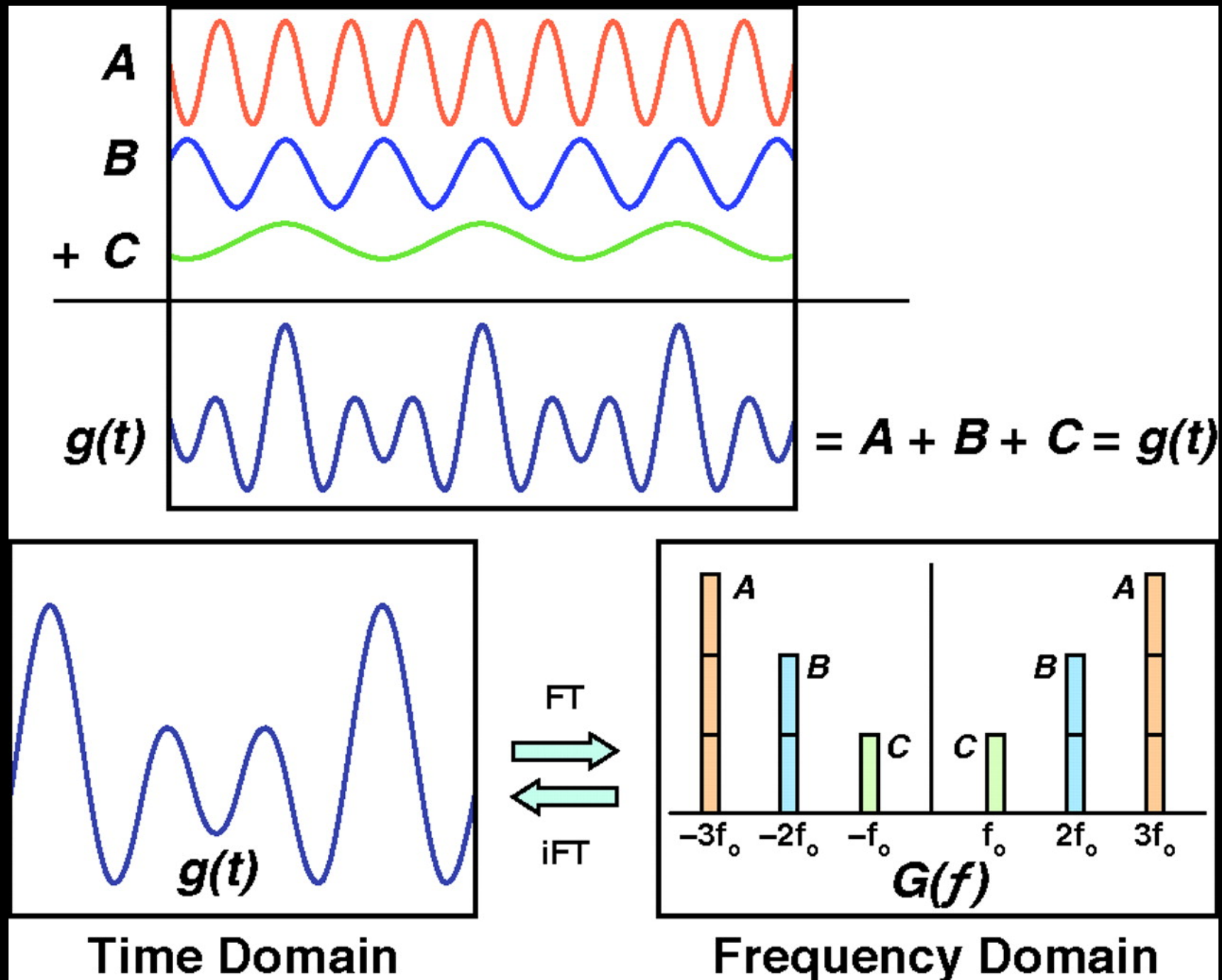
- Extend frequency change to other dimensions (x, y) for image encoding.
- 1st dimension → frequency encoding
- 2nd dimension → phase encoding

Imaging



http://www.revisemri.com/questions/creating_an_image/frequency_encoding_gradient

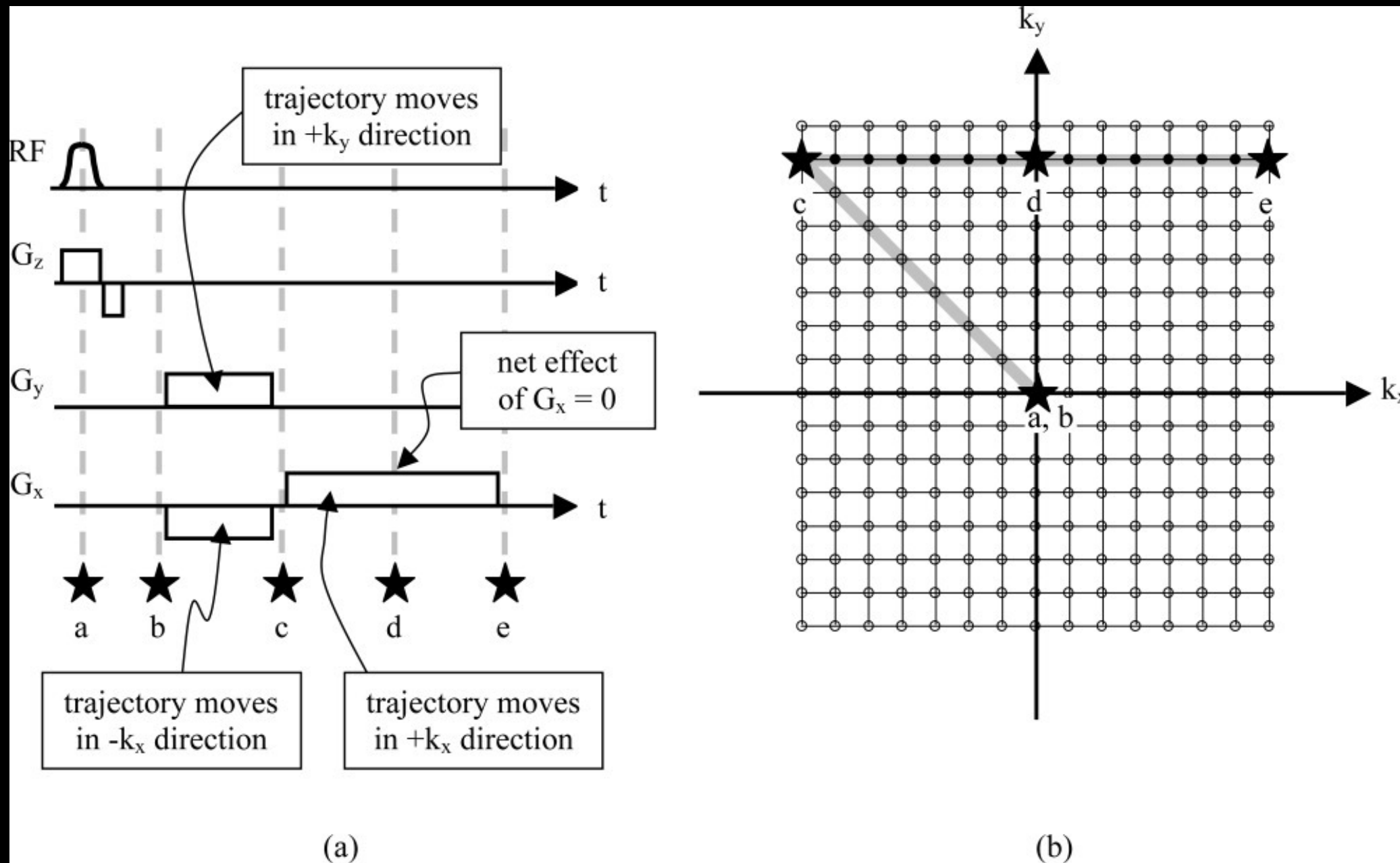
Imaging



Imaging

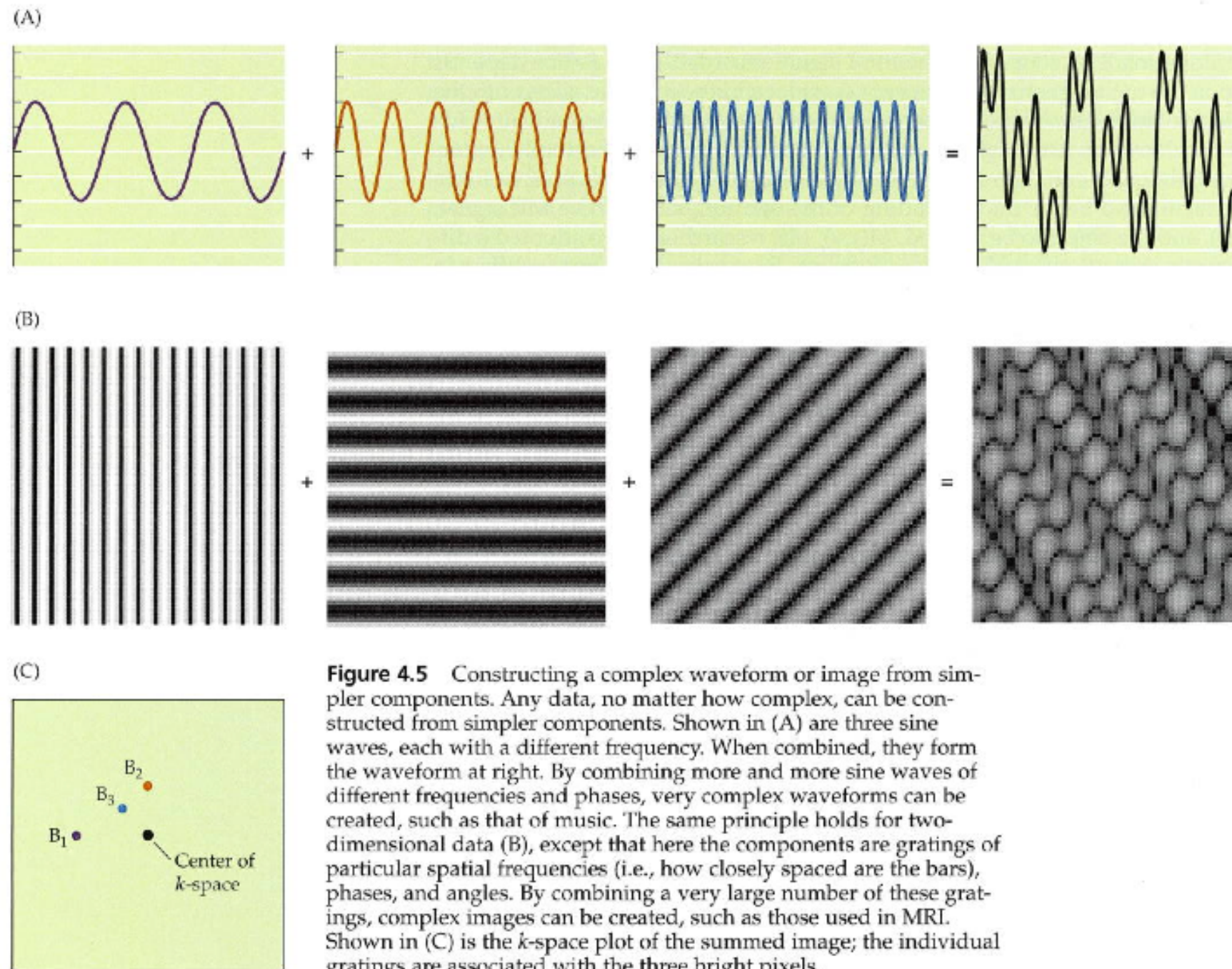
- Extend frequency change to other dimensions (x, y) for image encoding.
- 1st dimension → frequency encoding
- 2nd dimension → phase encoding
- Effects of gradients encodes “*k*-space”

Imaging



Paschal and Morris, DOI: 10.1002/jmri.10451

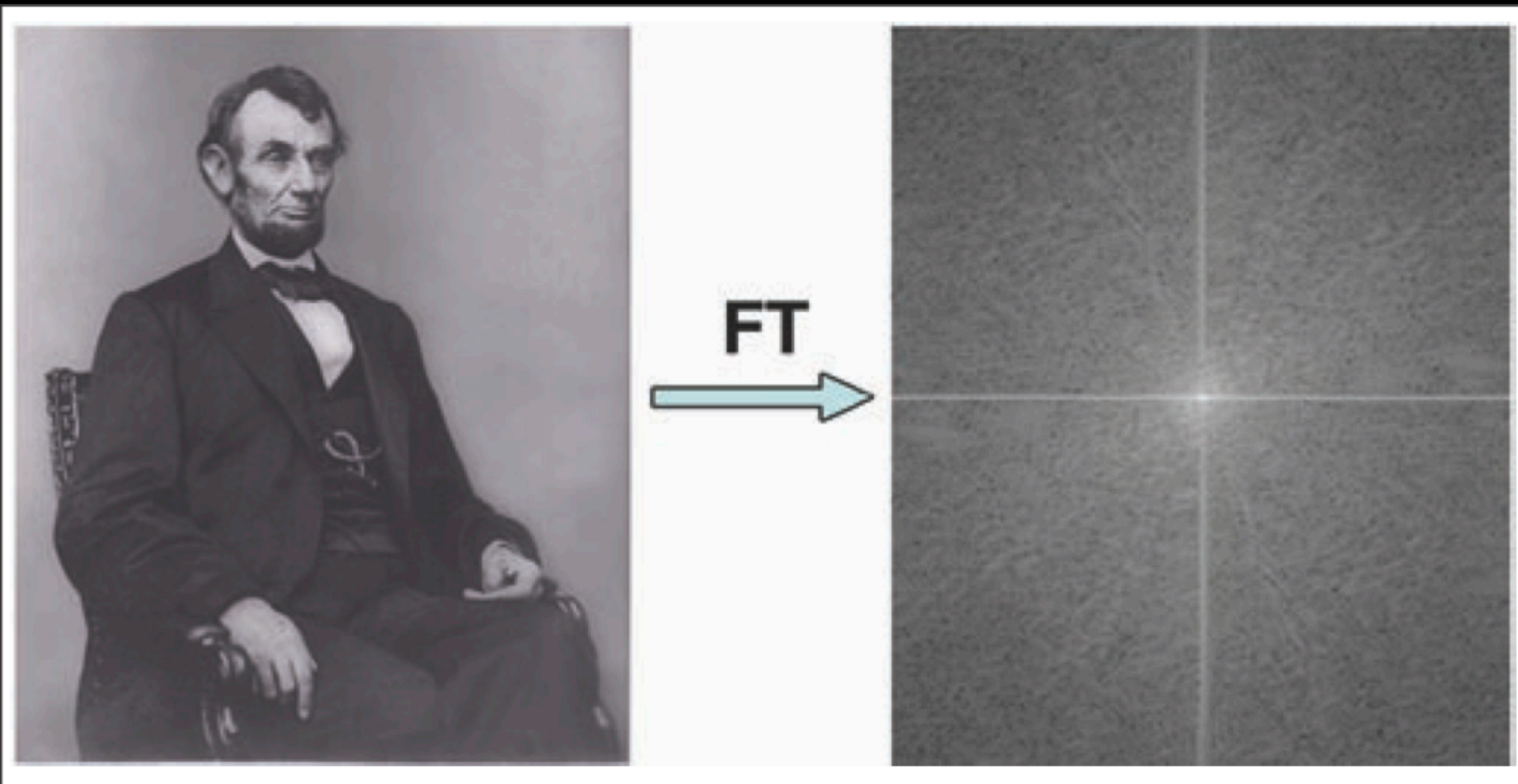
Imaging



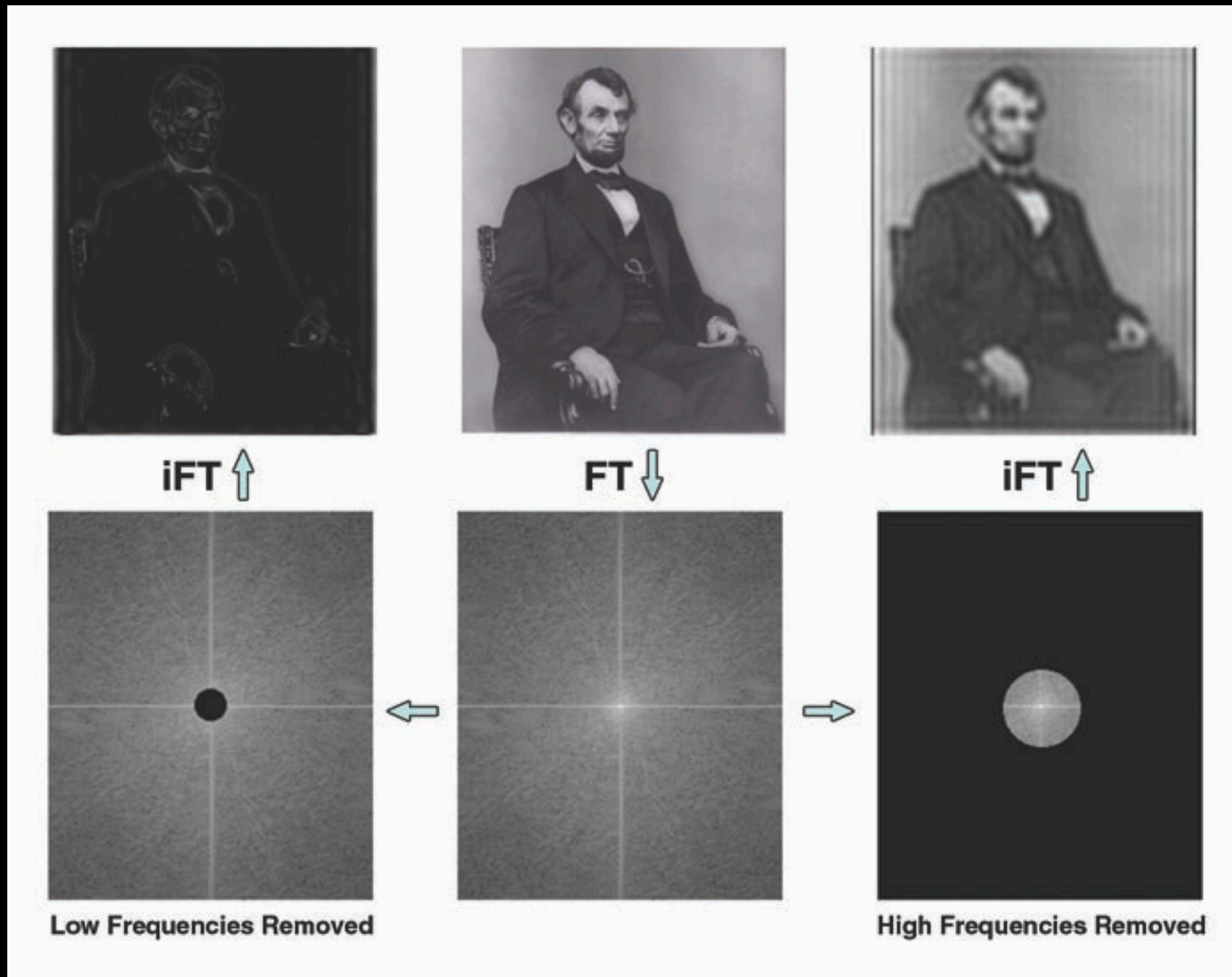
Signal (Fourier Transform) Equation in MRI

$$s(t) = \int_{\vec{r}} M_{xy}(\vec{r}, 0) e^{-i2\pi \vec{k}(t) \cdot \vec{r}} d\vec{r}$$

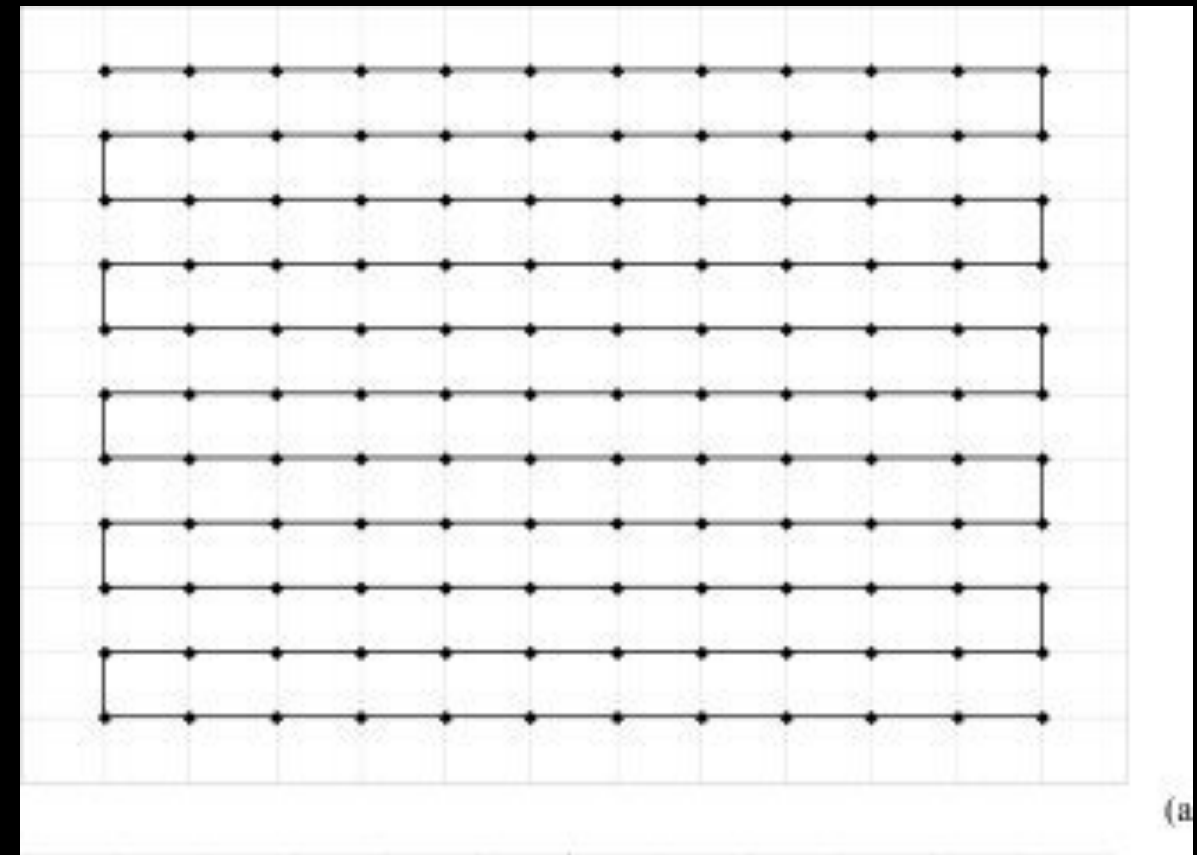
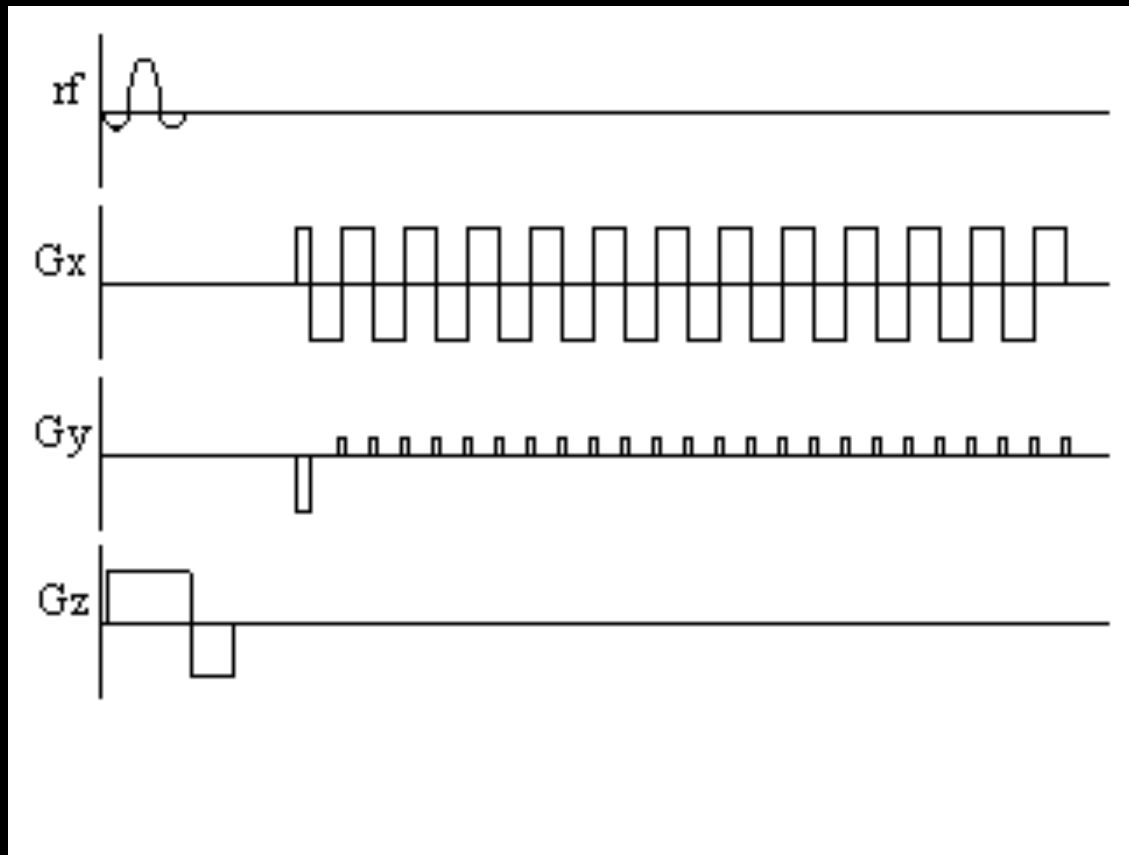
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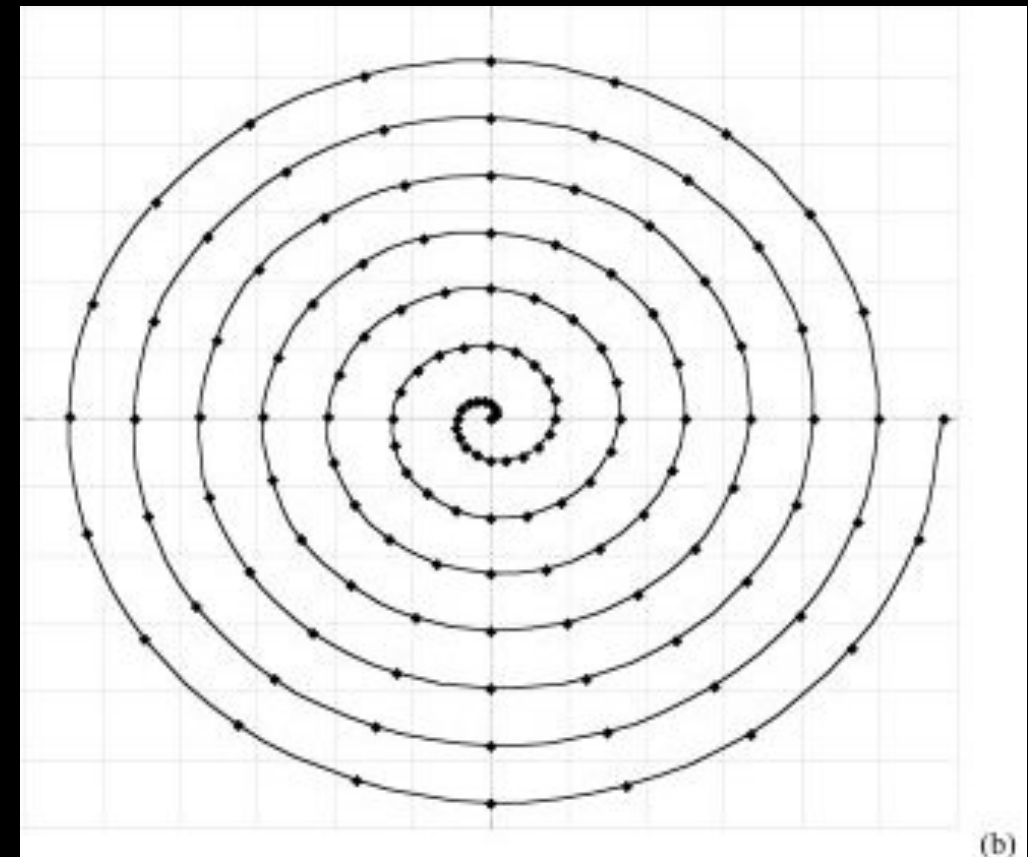
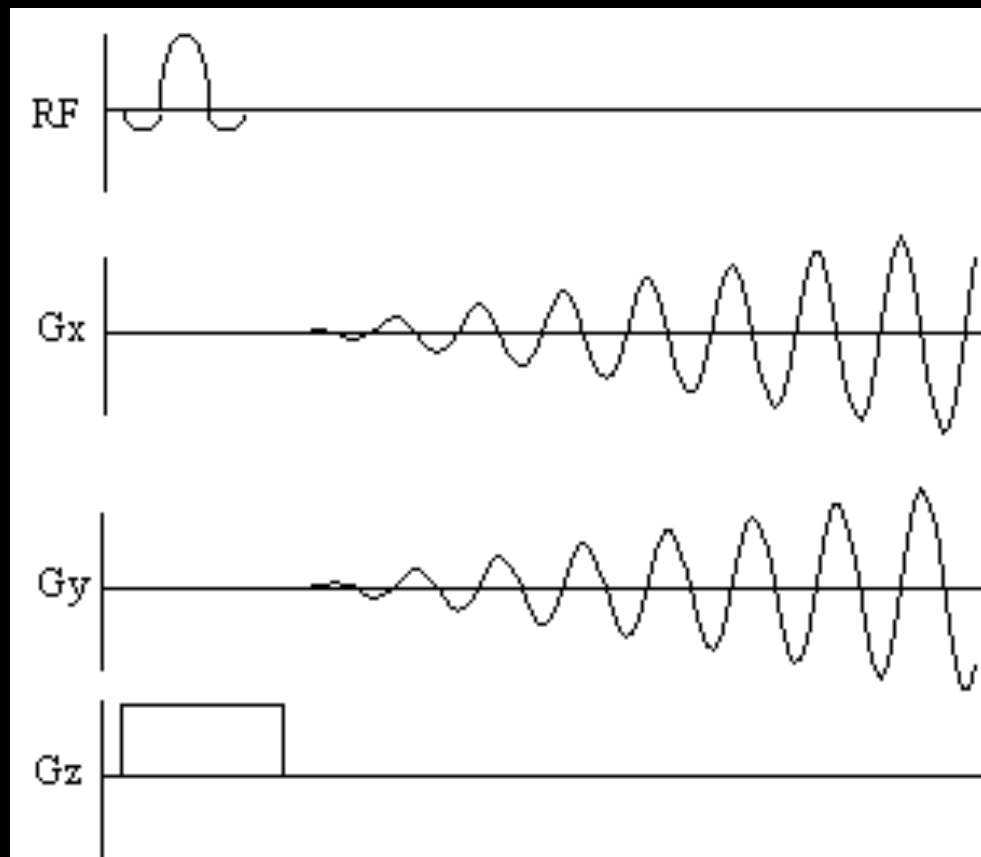
Imaging



https://users.fmrib.ox.ac.uk/~stuart/thesis/chapter_2/section2_3.html

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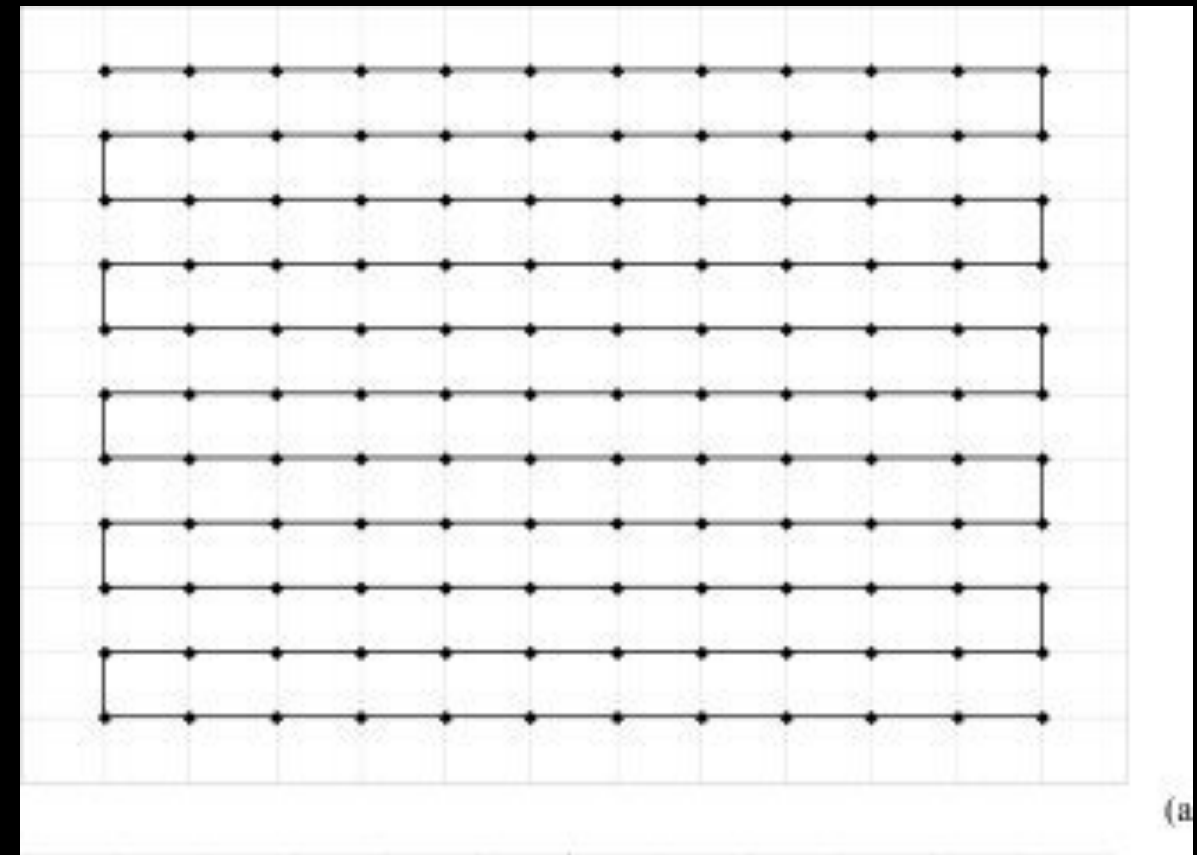
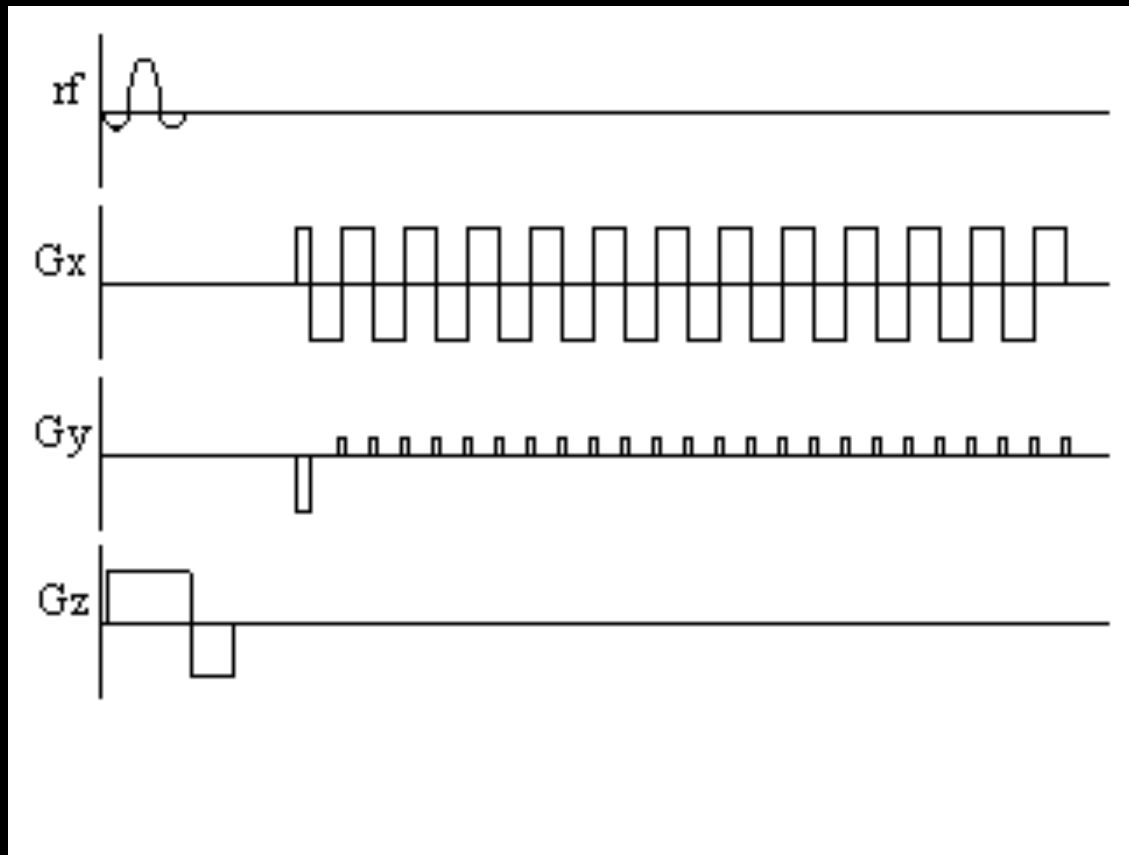
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Gradients Nuts and Bolts

- Space / step size in k -space is inversely proportional to FOV.
- Extent in k -space is inversely proportional to voxel size.
- Covering k -space requires strong **and** fast gradients.
- Gradient switching rate FDA limited (200 mT/m/ms).
Detectable below this threshold - subject comfort issues.
- “Local” gradient coils present a possible solution to address FDA limits and power requirements.

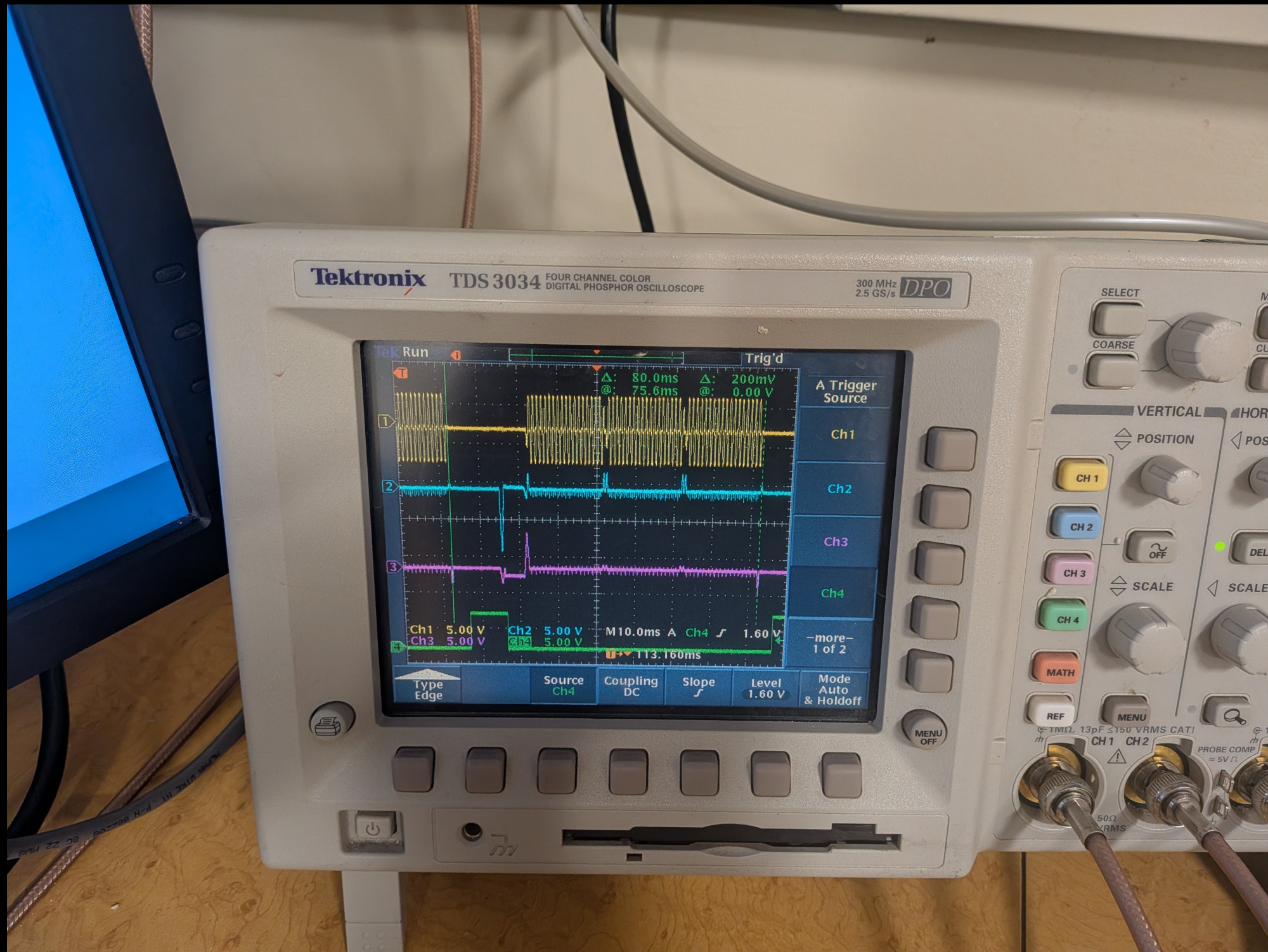
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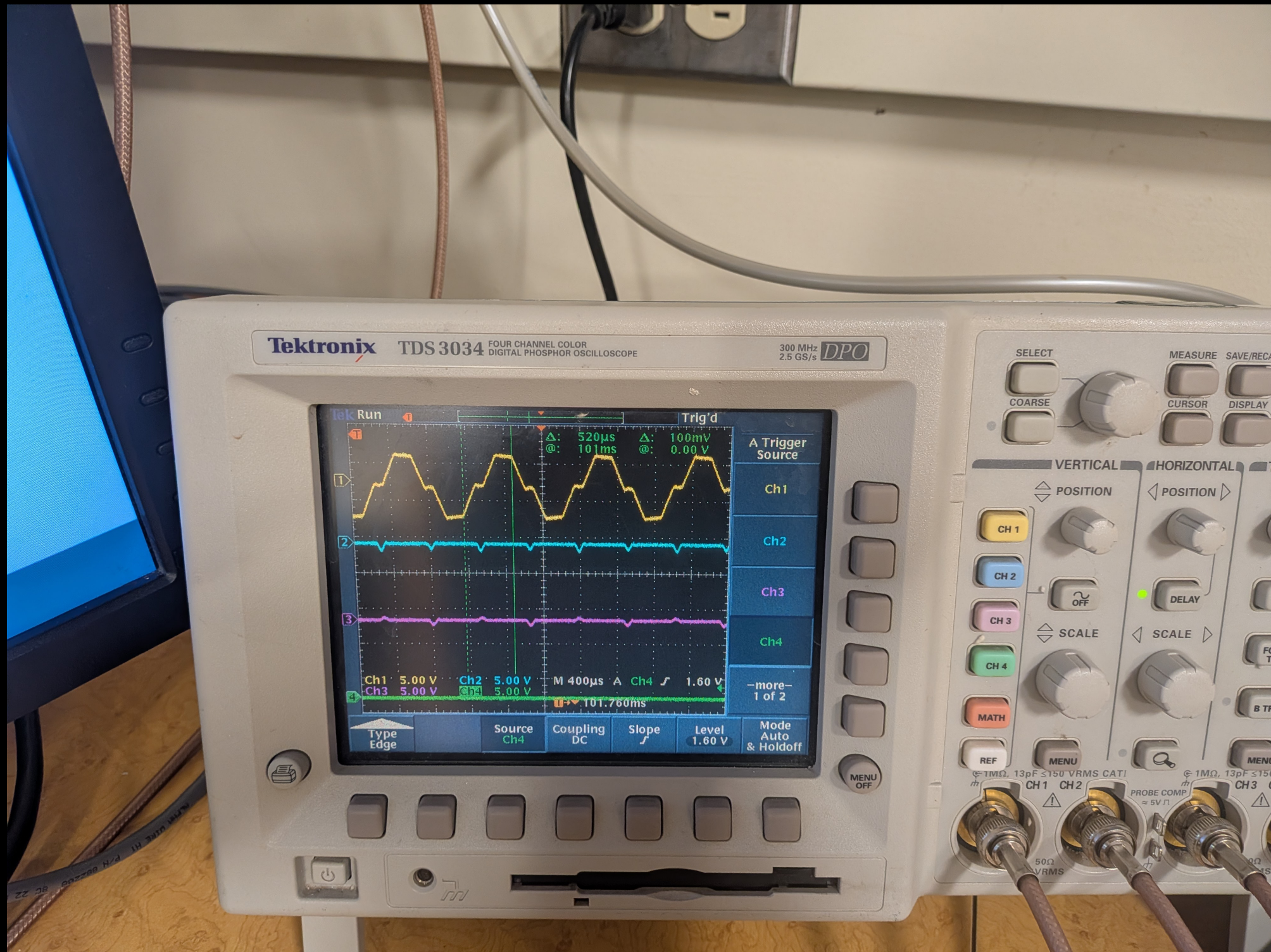
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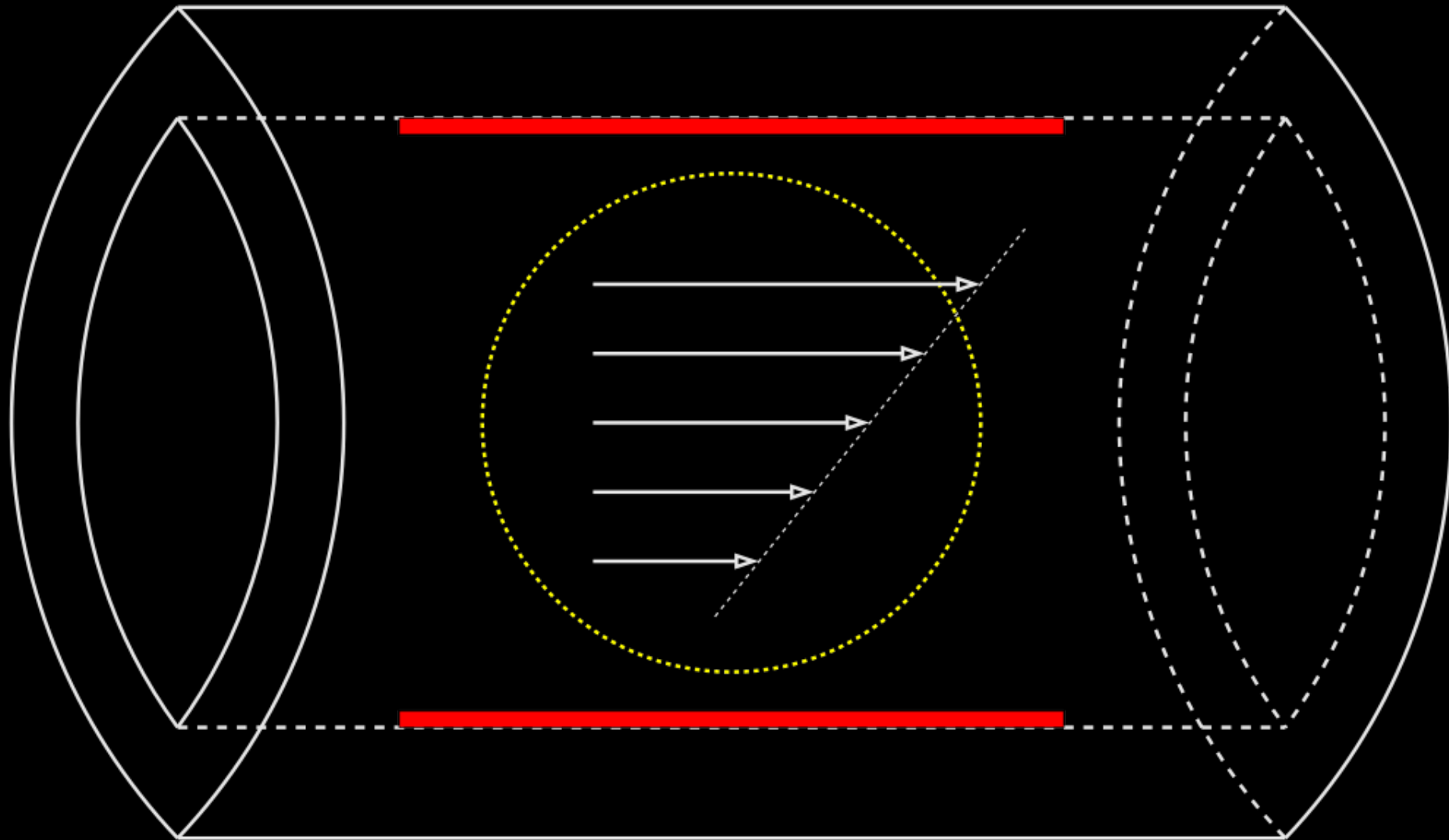


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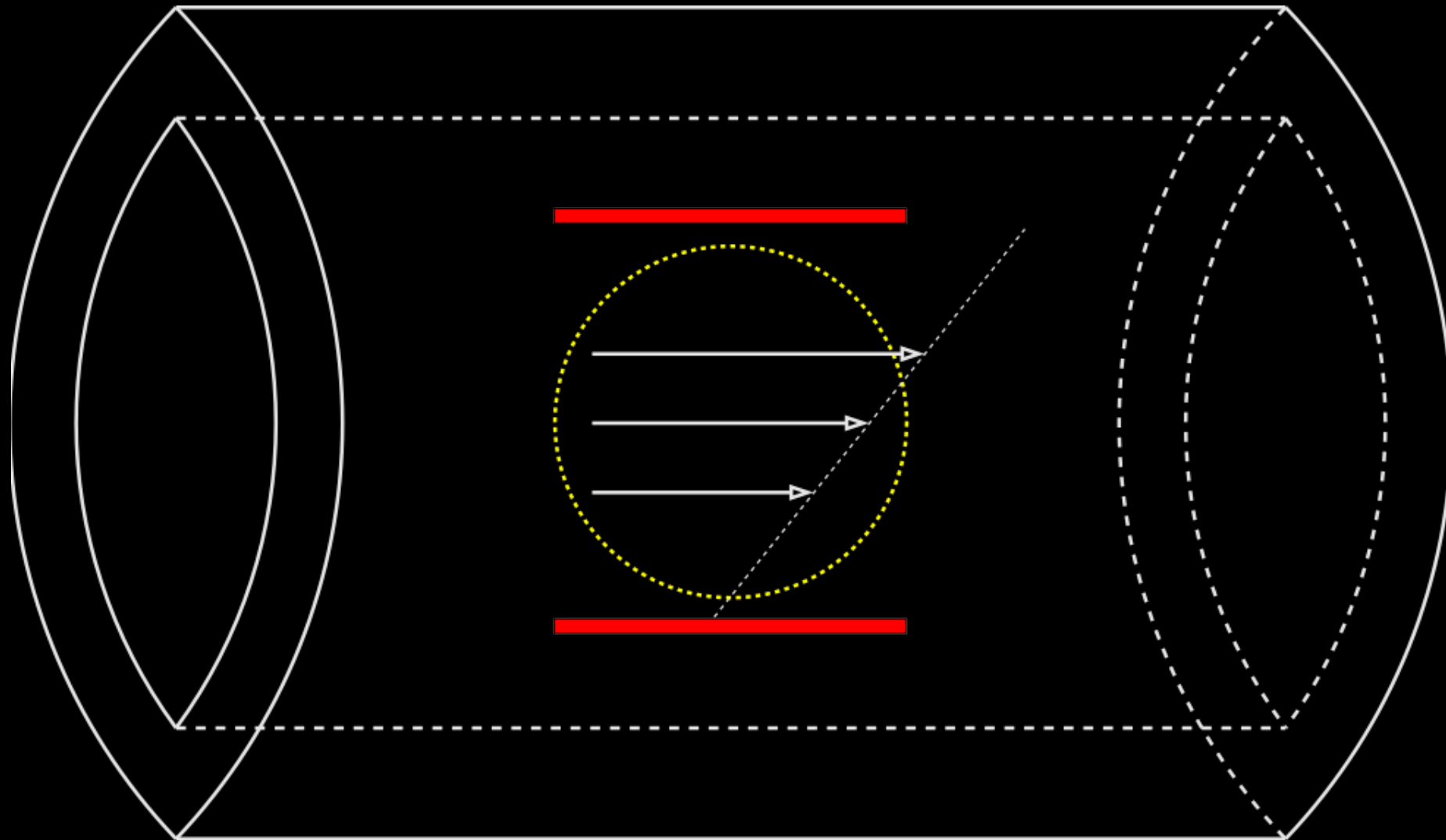
Imaging

- Conventional (a.k.a. 'body') gradients: ~ 500 mm diameter imaging volume. 50 - 300 mT/m amplitude and up to **200 - 250** mT/m/ms slew rate.



Imaging

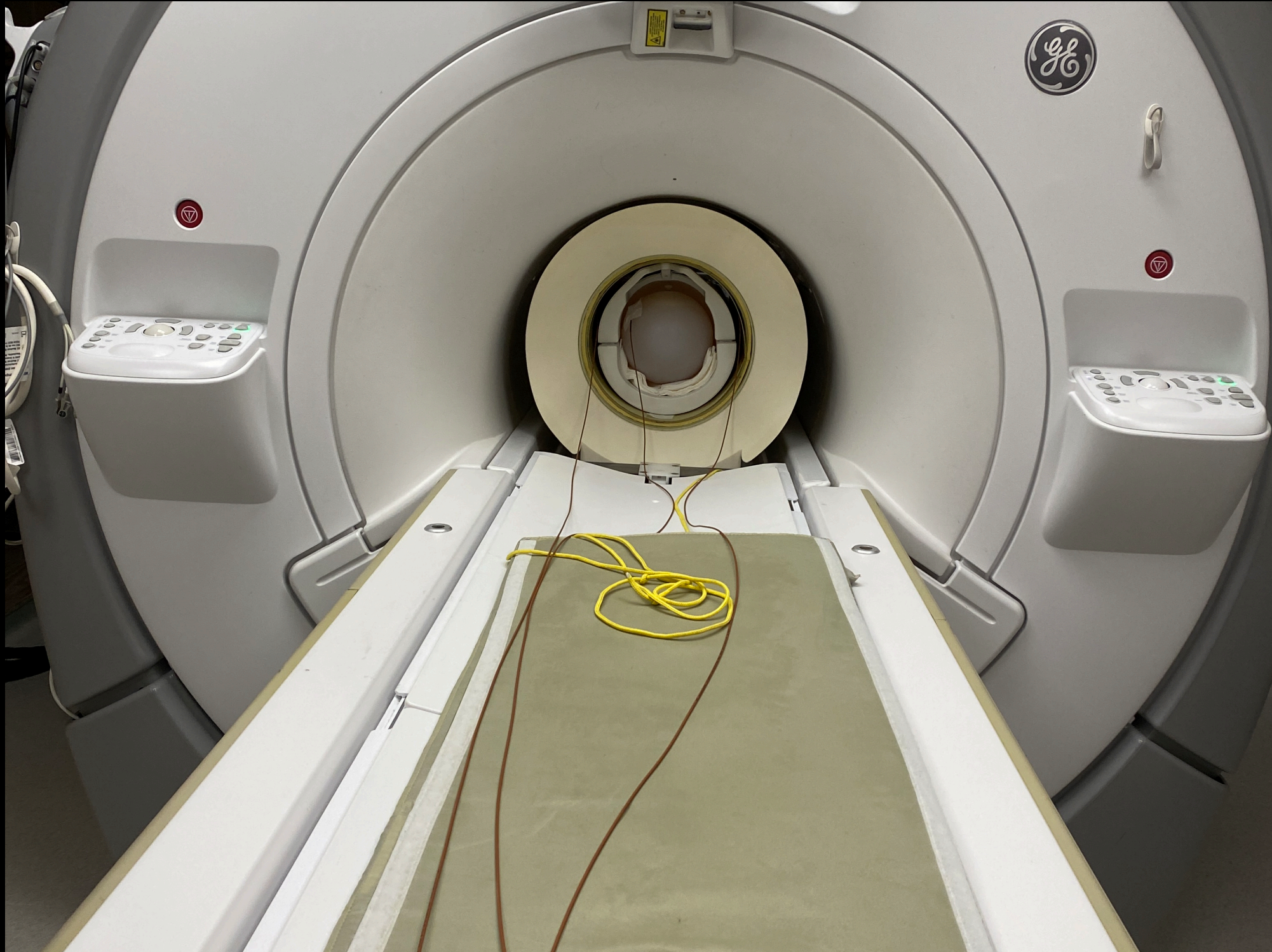
- High-performance / local gradients: ~ 300 mm diameter imaging volume. 100 - 500 mT/m amplitude and up to 600 - 1200 mT/m/ms slew rate.



Imaging



Imaging



Imaging

MRI systems' gradient performance

[gradients.csv](#) Raw

Search this file...

1	System/gradient-coil	G_max (mT/m)	G_slew (mT/m/ms)
2	GE MR-750 (FMRIF 3TA and 3TB)	50	200
3	Siemens 3T Skyra (FMRIF 3TD)	45	200
4	GE compact 3T (HG2) (Niskayna-NY then Mayo Clinic)	80	700
5	GE UHP (Duke +)	100 sustained/113 burst	250
6	Rutt/SH4 (UWO)	120	1200
7	GE Premier 3T	80	200
8	Siemens 3T Prisma (NIAAA 3T)	80	200
9	Siemens 7T Terra (FMRIF 7TB and NMRF 7T) standard/T60 gradient option	80	200
10	Siemens 7T Terra.X advanced/W60 gradient option	135	250
11	Siemens 7T Terra.X Impulse (Feinberg/Berkeley)	200	900
12	GE Magnus 3T (Waukesha-WI)	300	750
13	Rutt/SH7 (UWO then NIH@FMRIF 3TB)	140	1000
14	Siemens 3T Cima.X	200	200
15	Siemens 3T Connectom.X (MGH)	500	600
16	GE compact 7T (Niskayuna-NY)	140	820
17			
18	UWO == University of Western Ontario		

<https://gist.github.com/roopchansinghv/96bd7ee465308c7ea04f2dcf5cffeaa23>

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gradients.csv Raw

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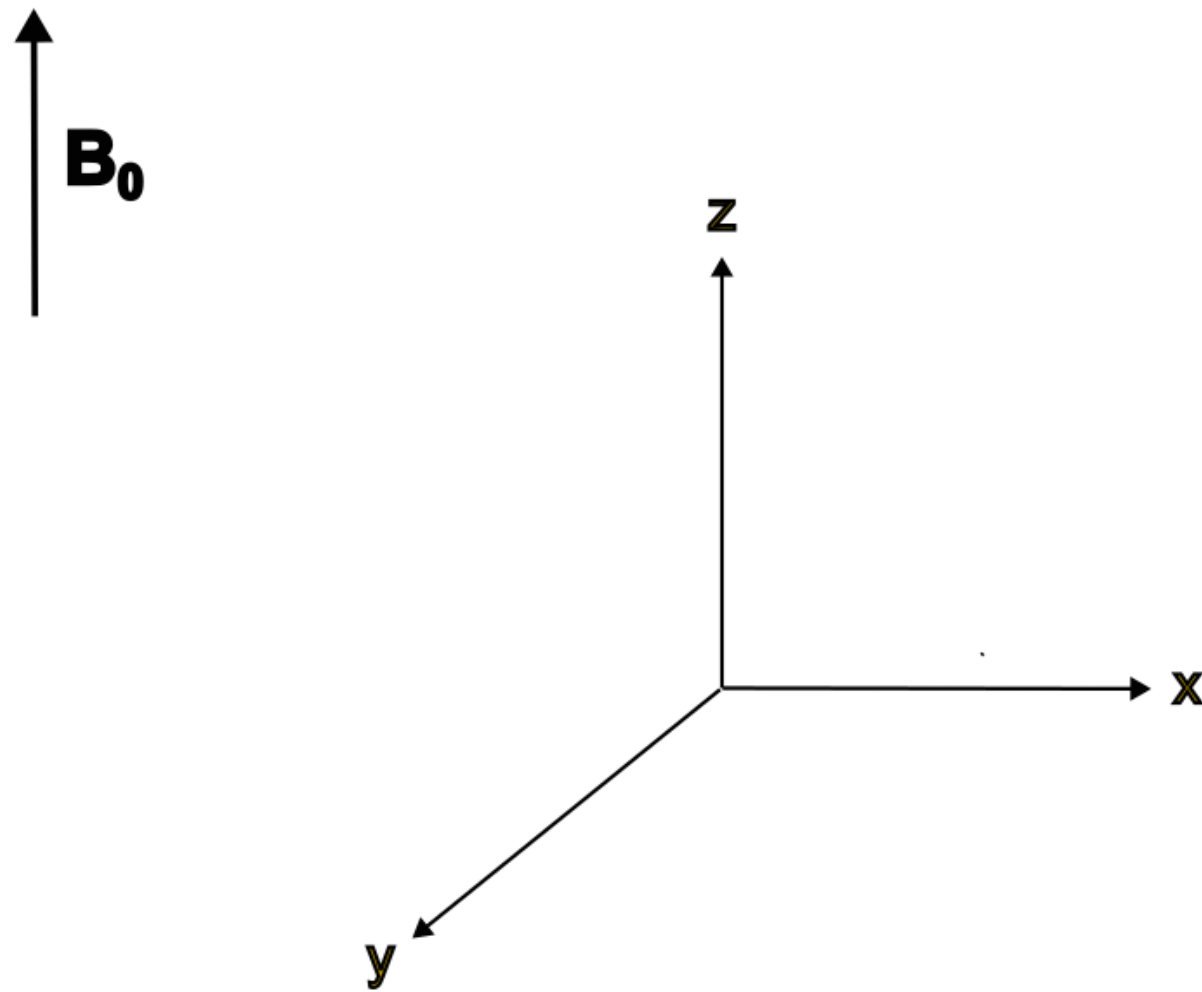
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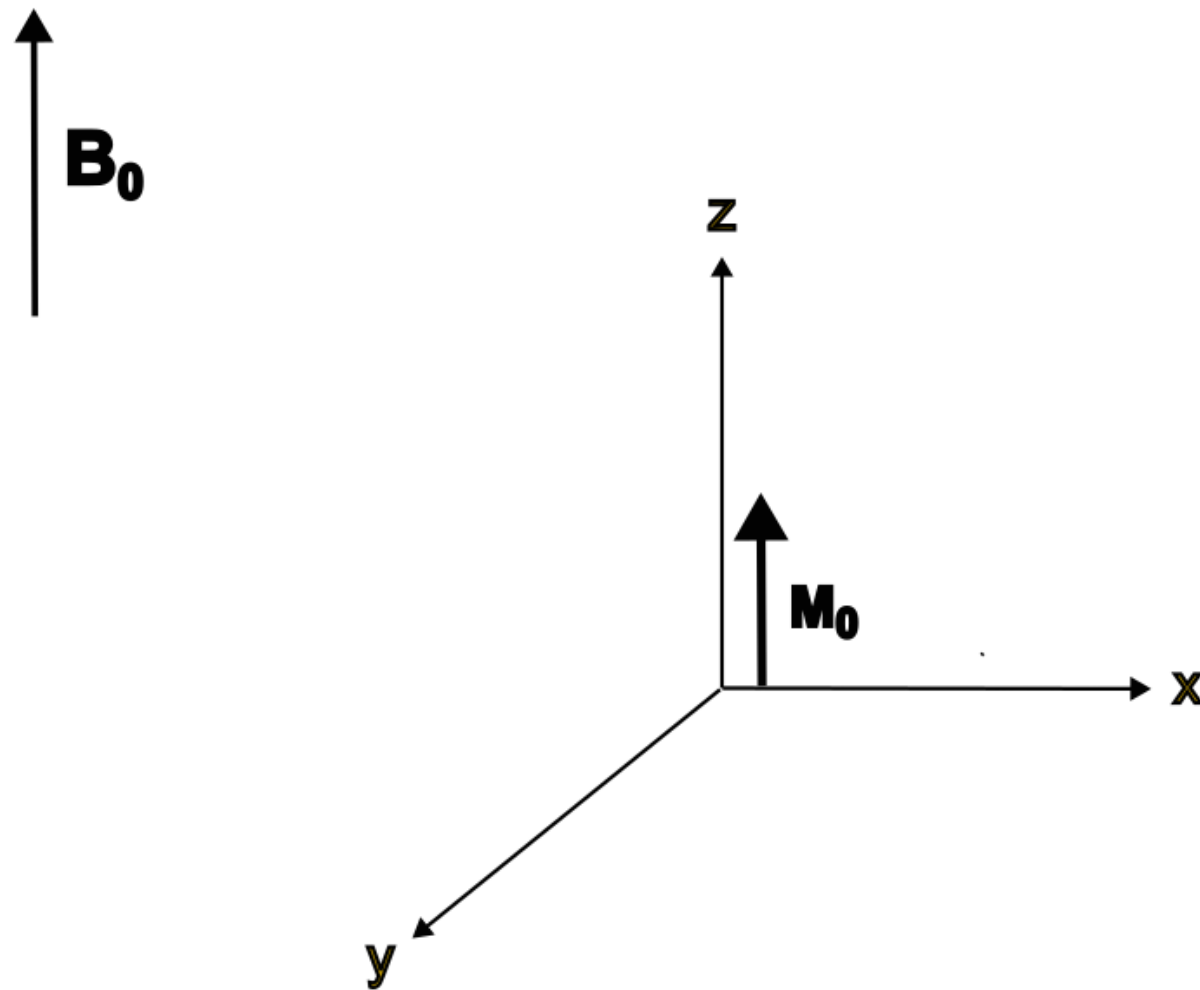
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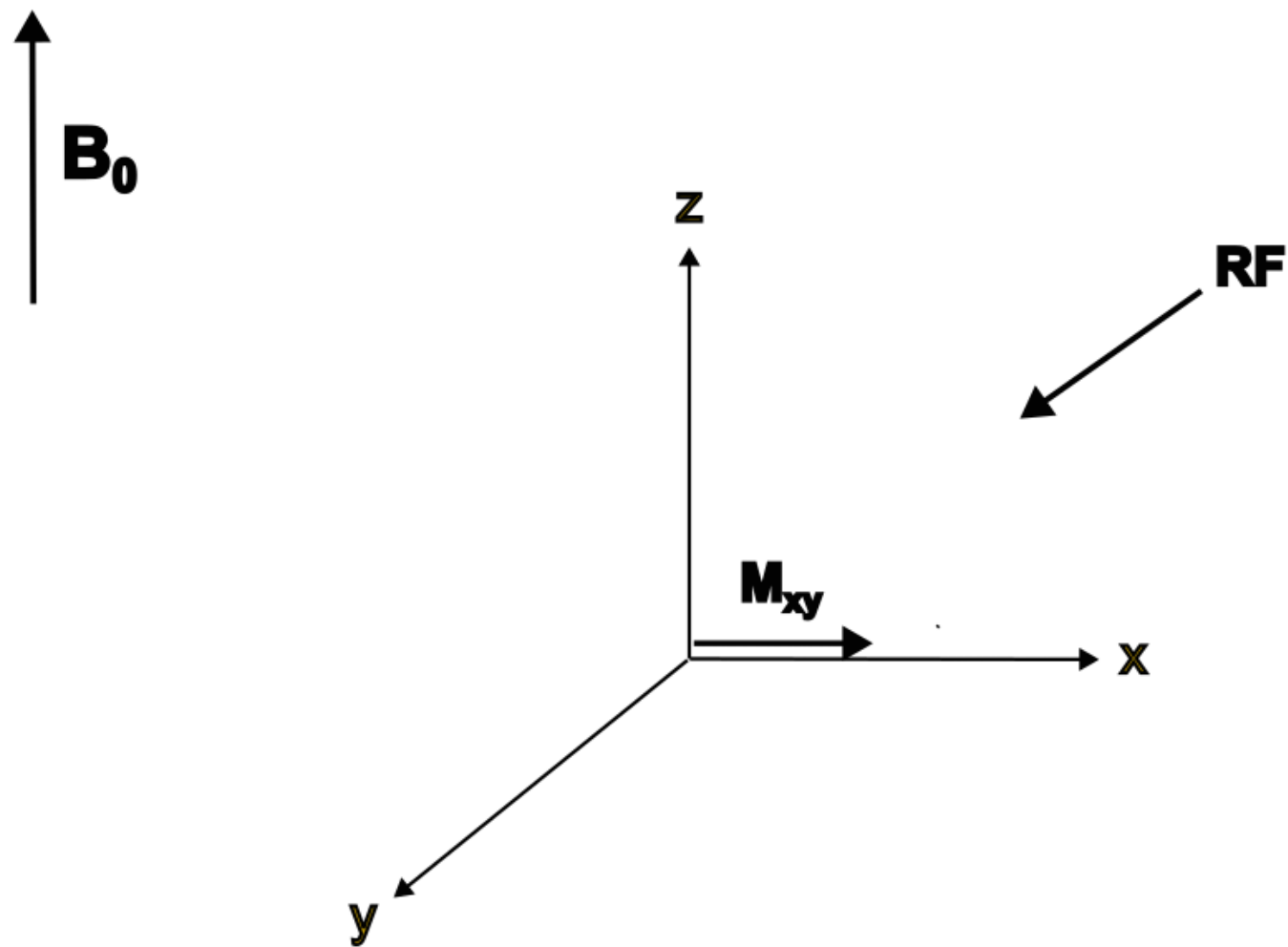
Contrast - basics



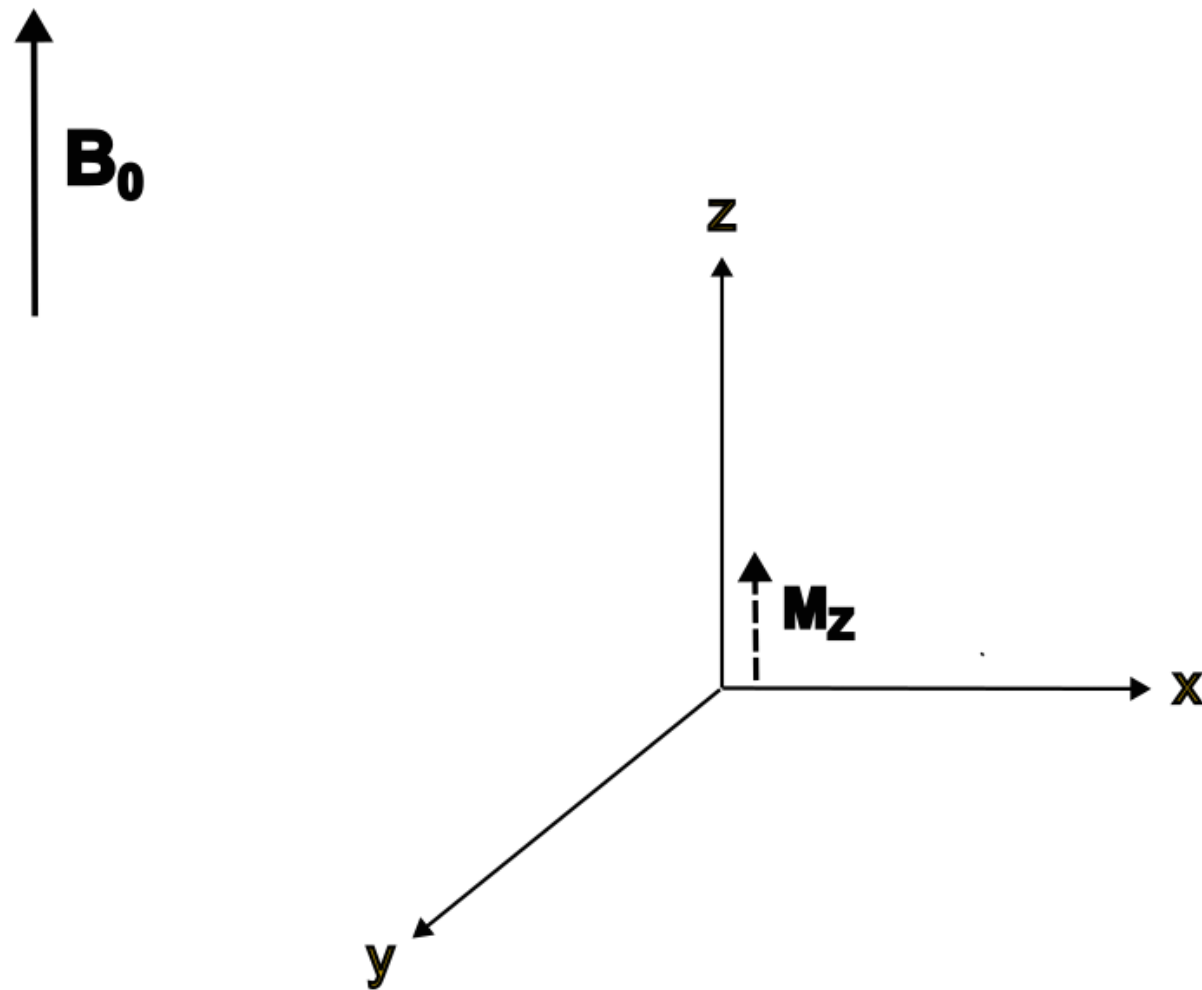
Contrast - basics



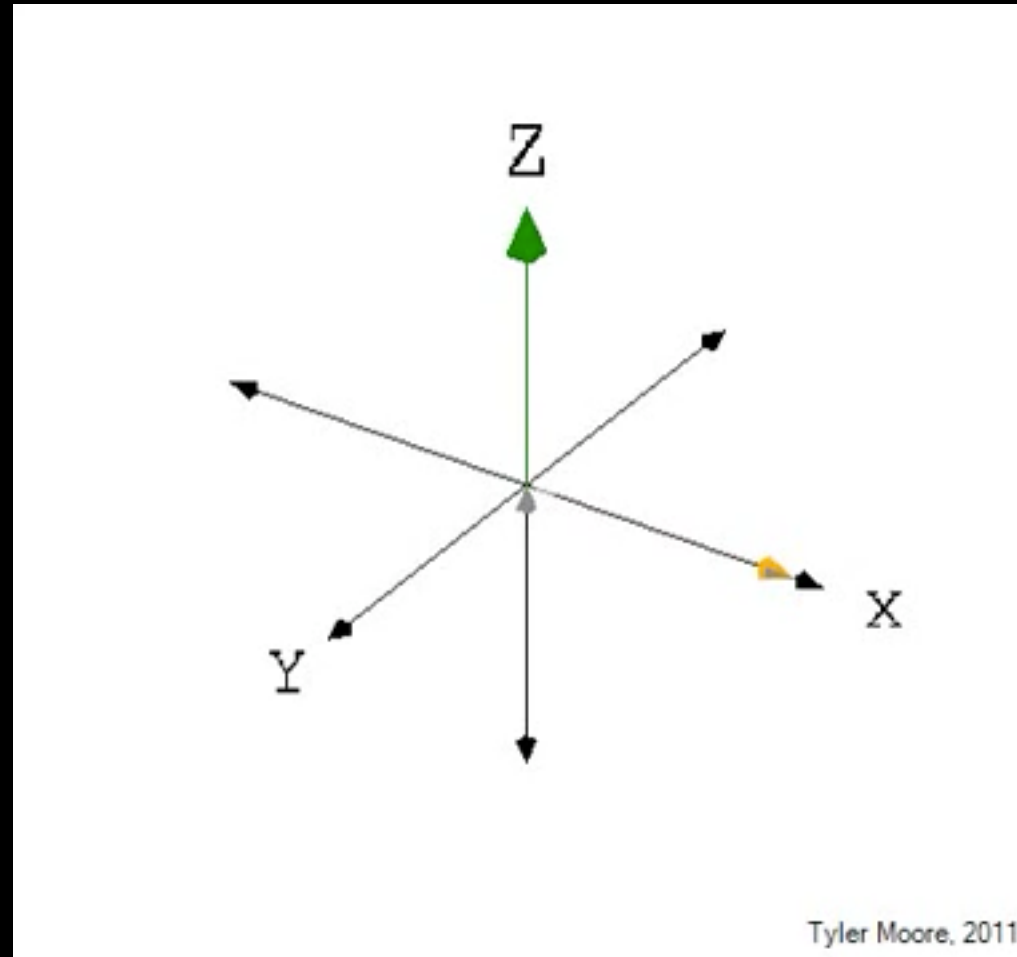
Contrast - basics



Contrast - T_1



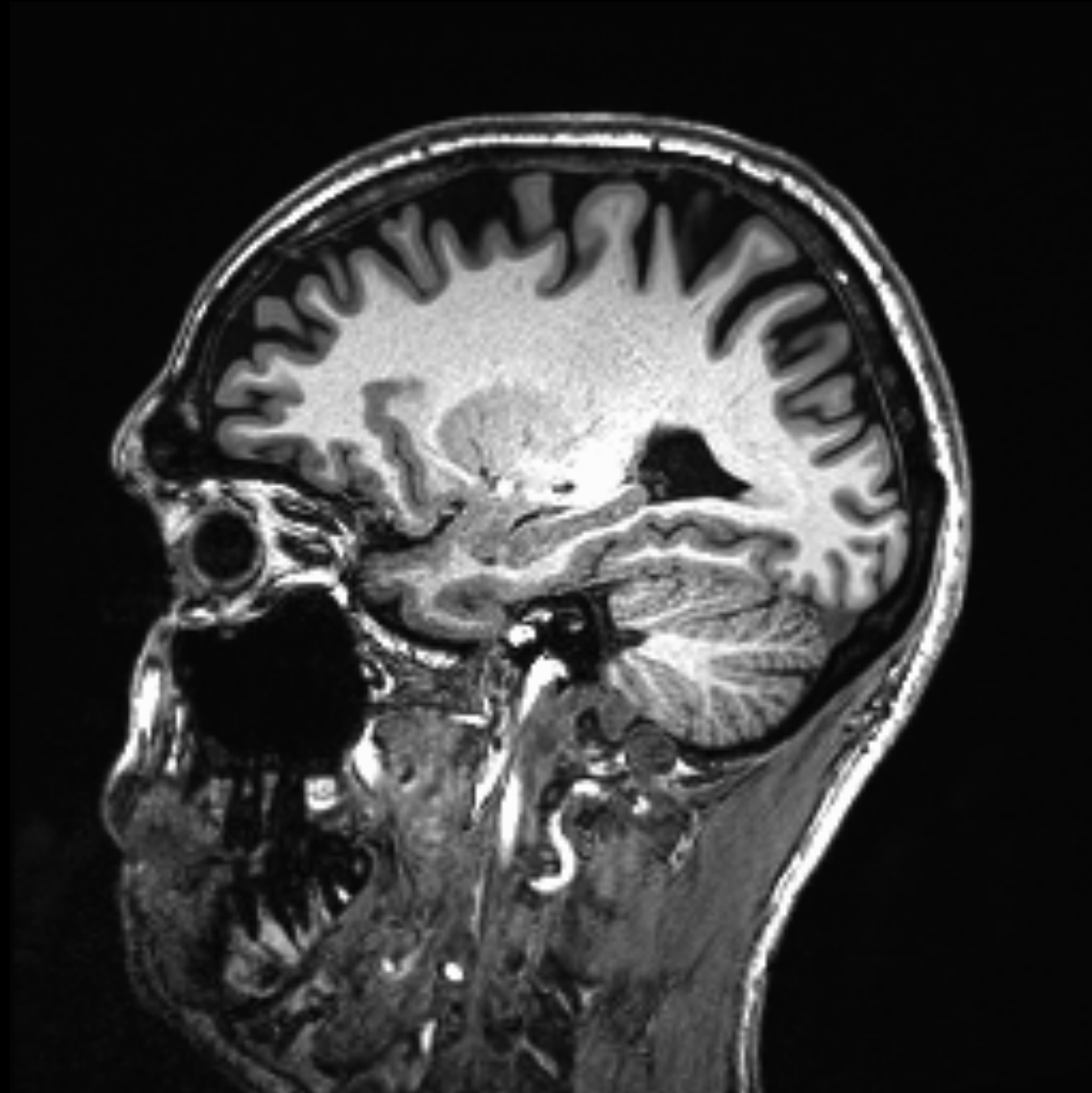
Contrast - T_1



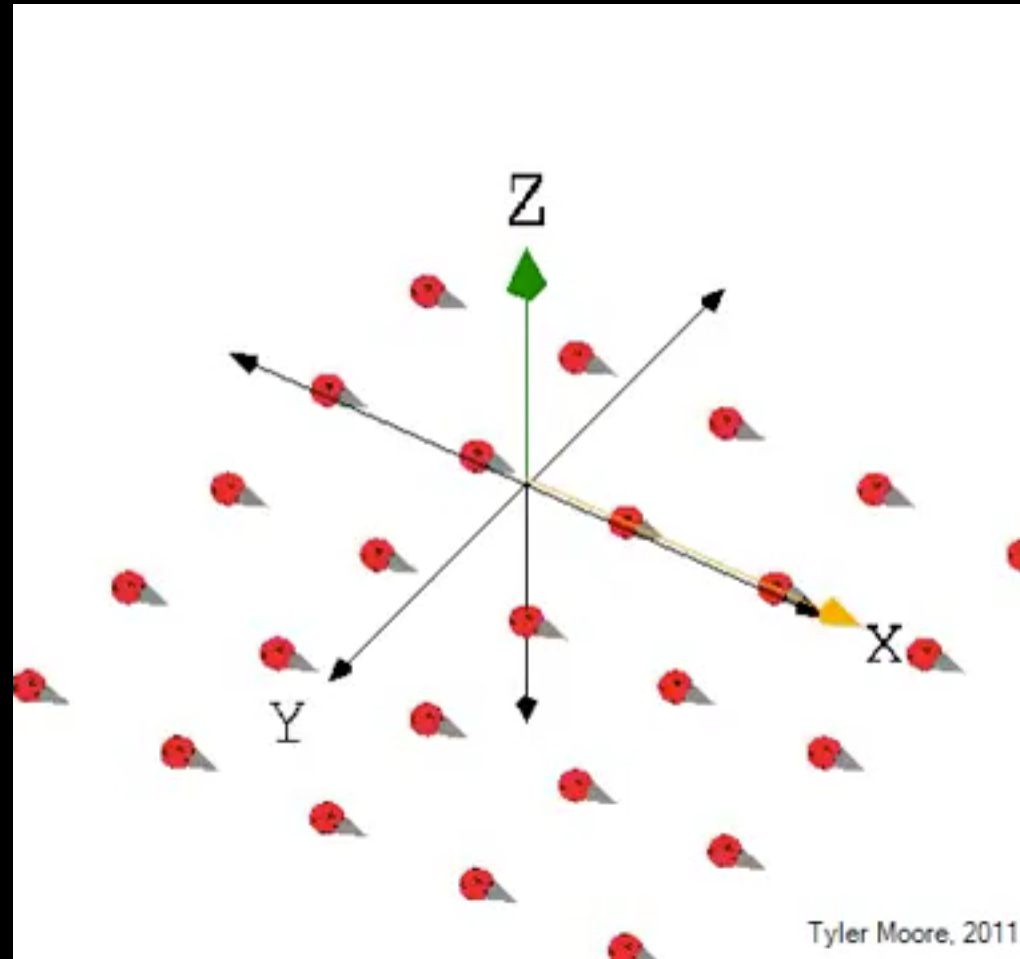
Contrast - T_1

- Regrowth of equilibrium (i.e. M_0) magnetization, along B_0 / z-axis.
- Longer T_1 $\rightarrow$ lower signal ...

Contrast - T₁



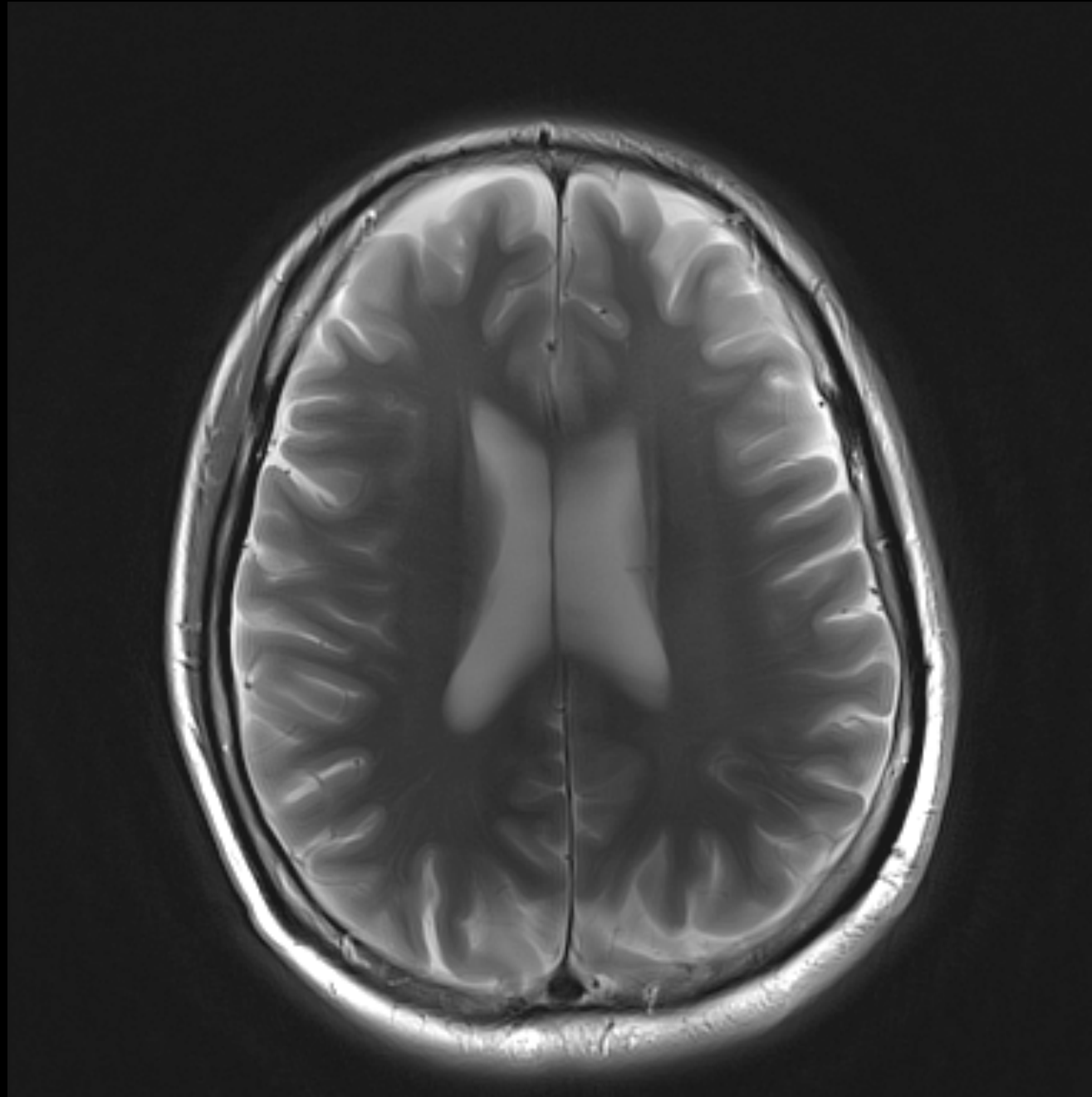
Contrast - T_2



Contrast - T_2

- Dephasing (loss of coherence) of magnetization signal (i.e. M_{xy}).
- Longer $T_2 \rightarrow$ higher signal ...

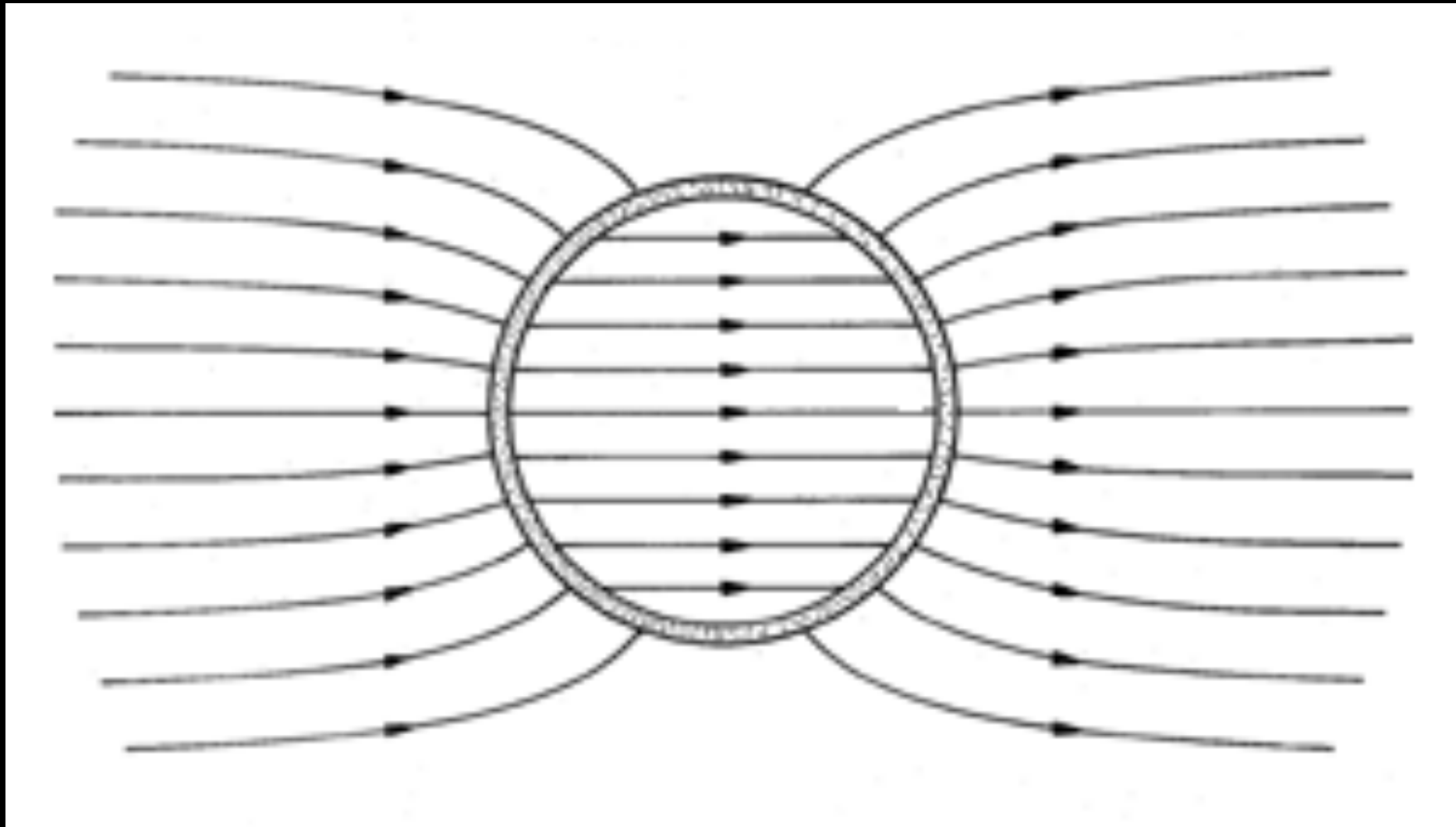
Contrast - T₂



Contrast - BOLD

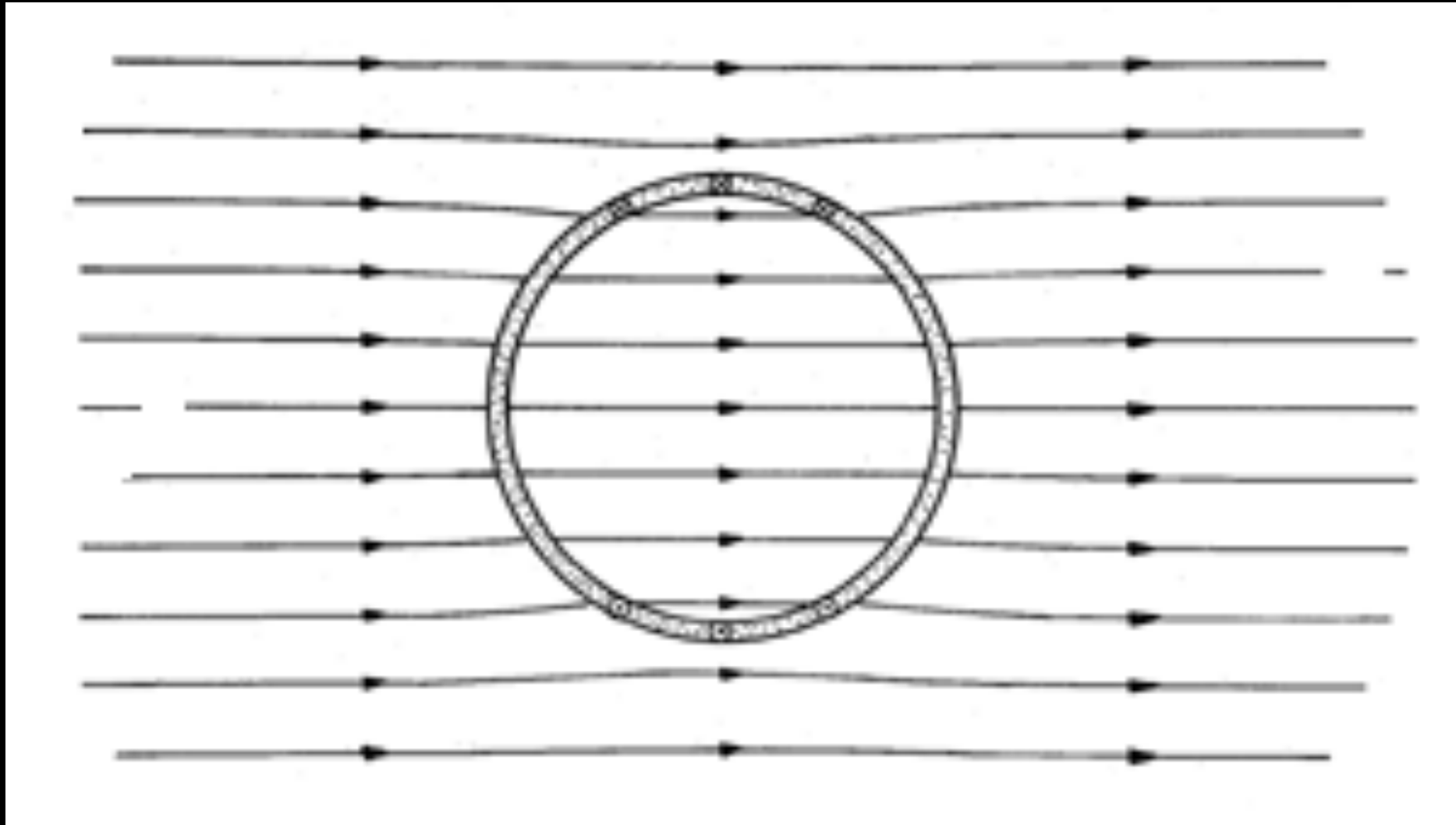
- Similar in principle to T2 relaxation, 'enhanced' by background magnetic field gradient $\rightarrow T_2^*$

Contrast - BOLD



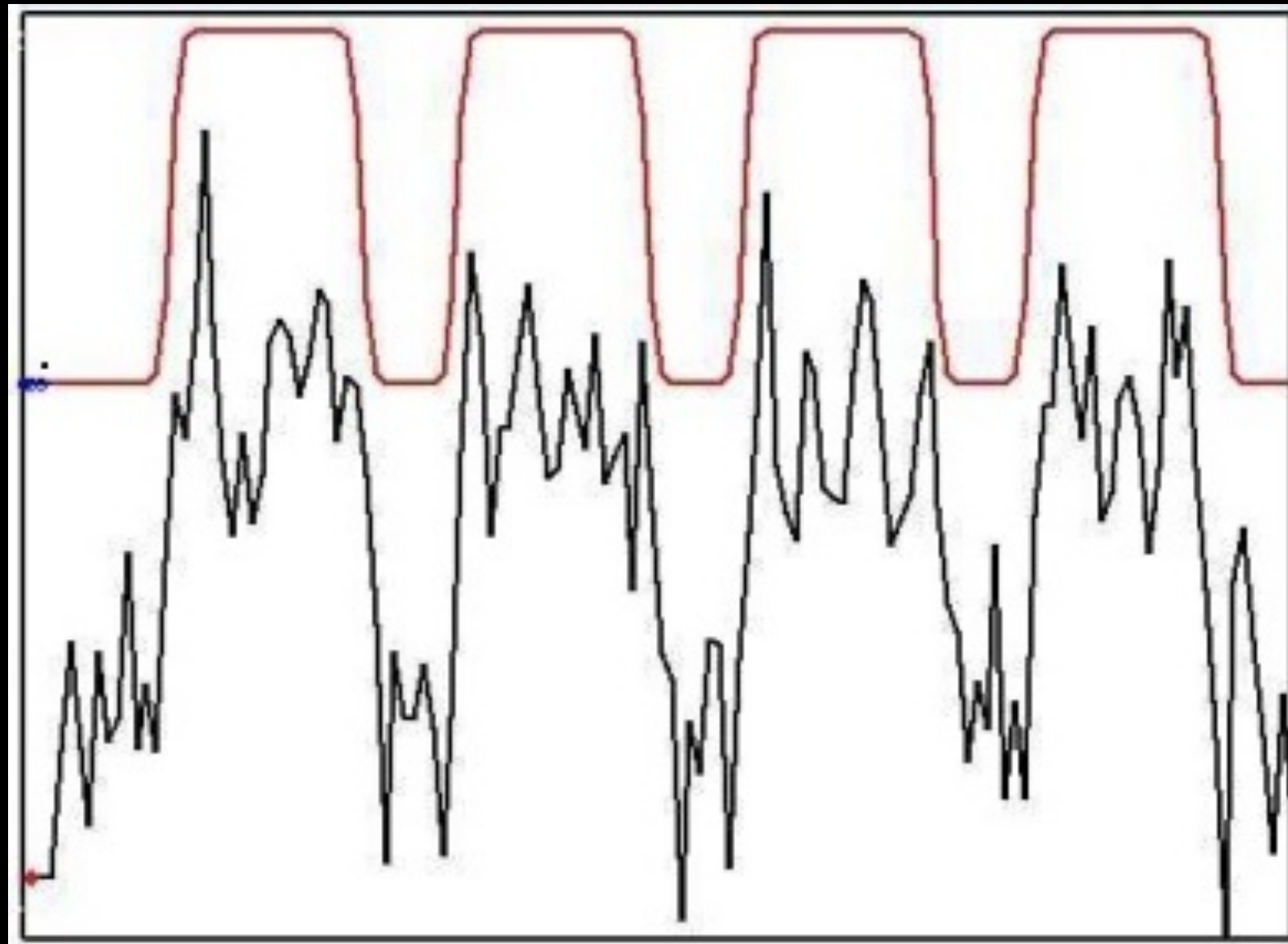
http://web.mit.edu/6.013_book/www/chapter10/10.4.html

Contrast - BOLD

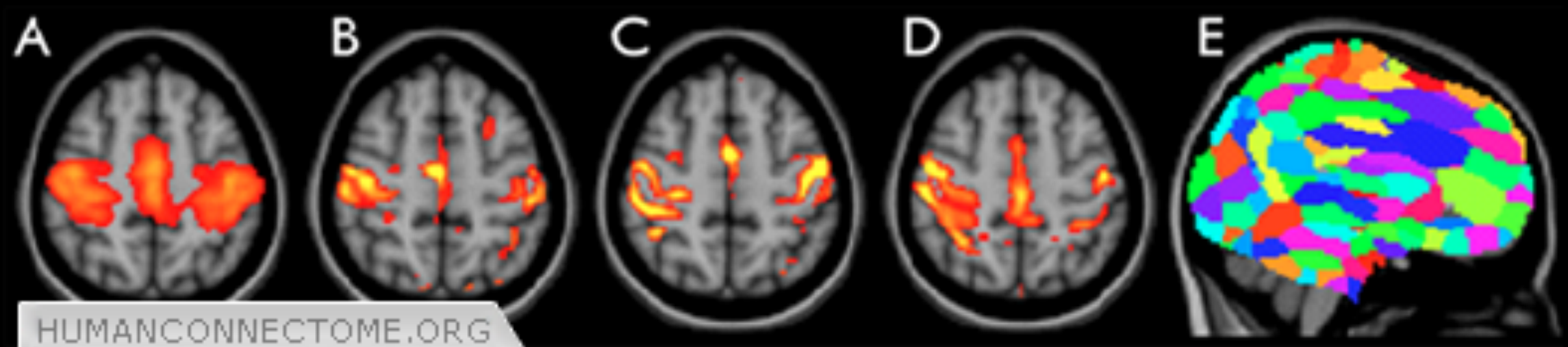


http://web.mit.edu/6.013_book/www/chapter10/10.4.html

Contrast - BOLD



Contrast - BOLD



Contrast

- FLAIR (Fluid Attenuated Inversion recovery)
- Magnetization transfer contrast (MTC) - Wolff and Balaban - MRM, 1989 (DOI: 10.1002/mrm.1910100113)
- Perfusion imaging - Detre et.al. - MRM, 1992 (DOI: 10.1002/mrm.1910230106)
- Diffusion imaging - Nature Reviews Neuroscience 4, 469-480 (June 2003) - DOI: 10.1038/nrn1119 (review paper)
- Phase imaging - Duyn et.al. - PNAS, 2007 (DOI: 10.1073/pnas.0610821104)
- ...

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“Main field” considerations

- Stronger main field (larger B_0) - higher frequency (ω_0)
- Sample magnetization proportional to B_0 $\rightarrow$ more signal, which can be used to acquire higher resolution images, acquire image data faster, or some combination of these.
- Tissue contrast (T_1/T_2) varies with field

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However ...

- Higher frequency RF (larger ω_0) gives rise to more SAR issues
- More issues with keeping B_0 and B_1 (RF) fields uniform
- Might not be appropriate for some applications

Other considerations

- Relaxation times - appropriate for the tissue of interest
- Resolution vs. time trade-off
- How much can I accelerate - what does the hardware allow
- What other kinds of data can be / should be measured — eye-tracking, physiology, EEG, field camera, other types of MR data (e.g. to help with distortion correction) to help with post-processing and analyses to determine your signal of interest