Nuts and Bolts of MRI and FMRI

Vinai Roopchansingh

Functional MRI Facility, National Institute of Mental Health, National Institutes of Health, DHHS, USA

June 6, 2018

FMRIF
fmrif.nimh.nih.gov

NIH National Institute of Mental Health

Outline

- System overview
- Components of the acronym
    - What’s the Magnet for?
    - Where does Resonance come in?
    - How is Imaging accomplished?
- Some basic types of MR contrast
- Re-cap of System overview

Outline

- System overview
- Components of the acronym
    - What’s the Magnet for?
    - Where does Resonance come in?
    - How is Imaging accomplished?
- Some basic types of MR contrast
- Re-cap of System overview

System overview

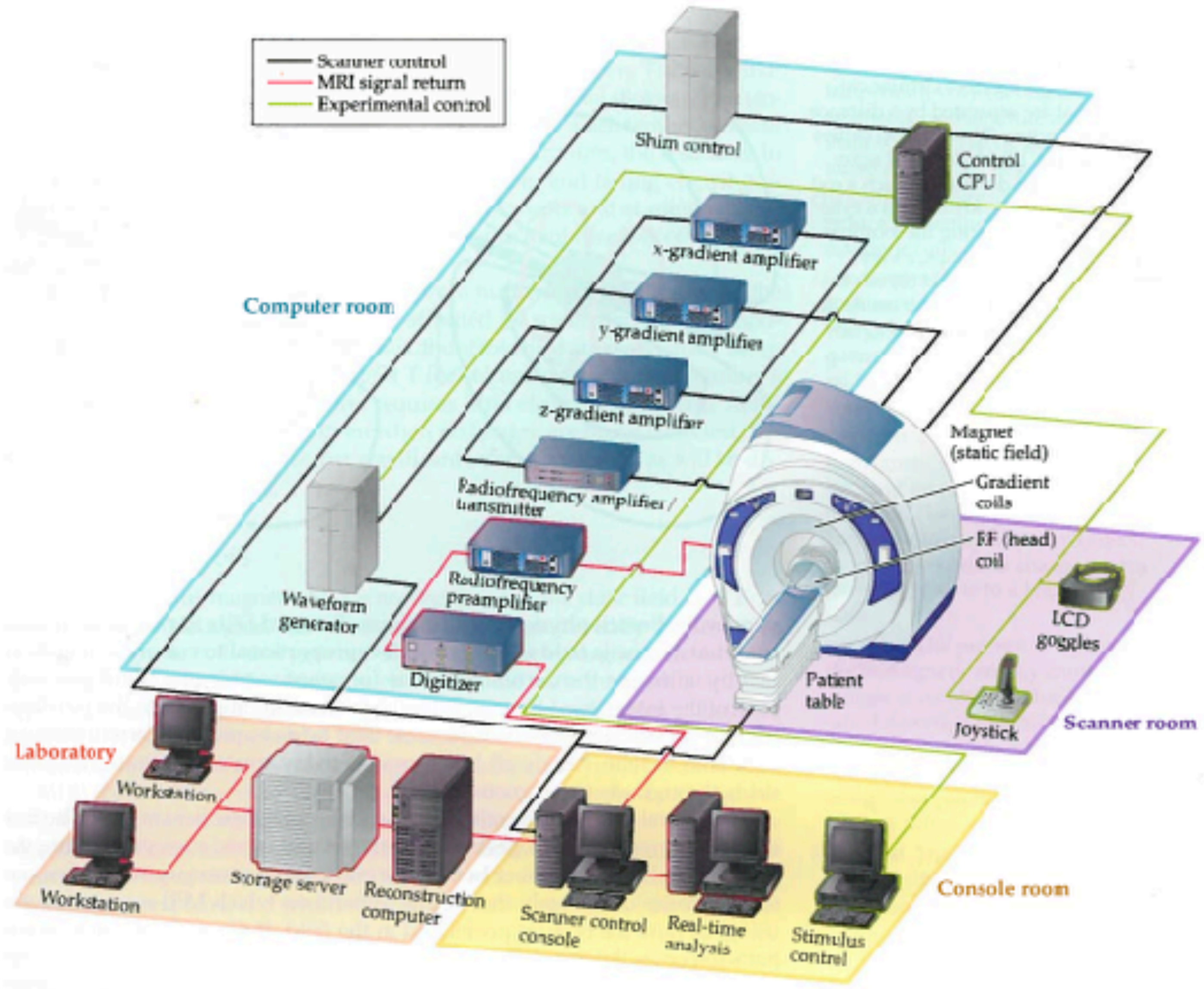


Figure 2.2 Schematic organization of the fMRI scanner and computer control systems. Two systems are important for fMRI studies. The first is the hardware used for image acquisition. In addition to the scanner itself, this hardware consists of a series of amplifiers and transmitters responsible for creating the gradients and pulse sequences (shown in black), and recorders of the MR signal from the head coil (shown in red). The second system is responsible for controlling the experiment in

Huettel - Functional Magnetic Resonance Imaging

Outline

- System overview
- Components of the acronym
  - What's the Magnet for?
  - Where does Resonance come in?
  - How is Imaging accomplished?
- Some basic types of MR contrast
- Re-cap of System overview

Magnets, magnets, everywhere

- 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 …

Magnets, magnets, everywhere

- 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).

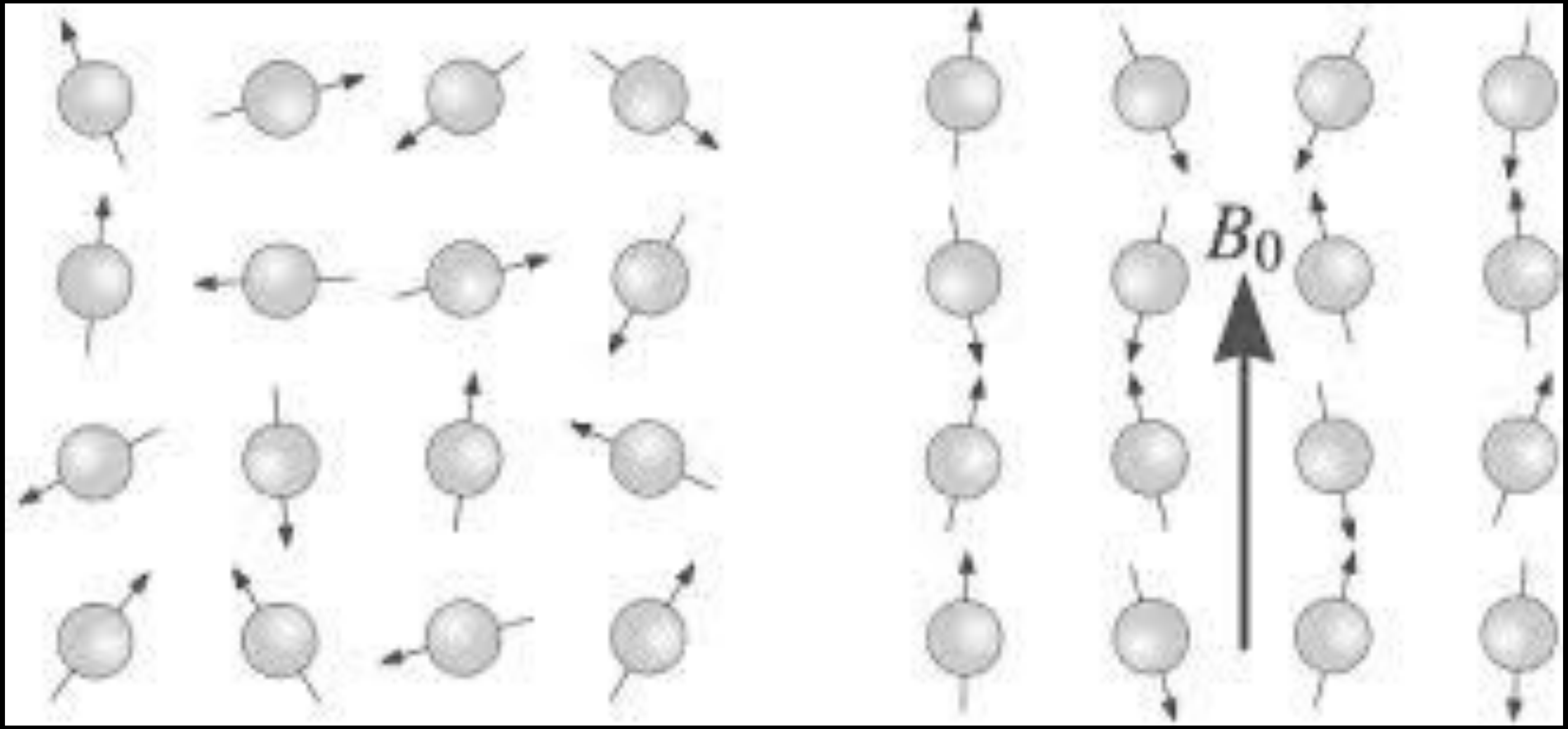
- Include ^{13}C, ^{23}Na, ^{31}P, ^{129}Xe, and …

- ^{1}H !

Magnets, magnets, everywhere

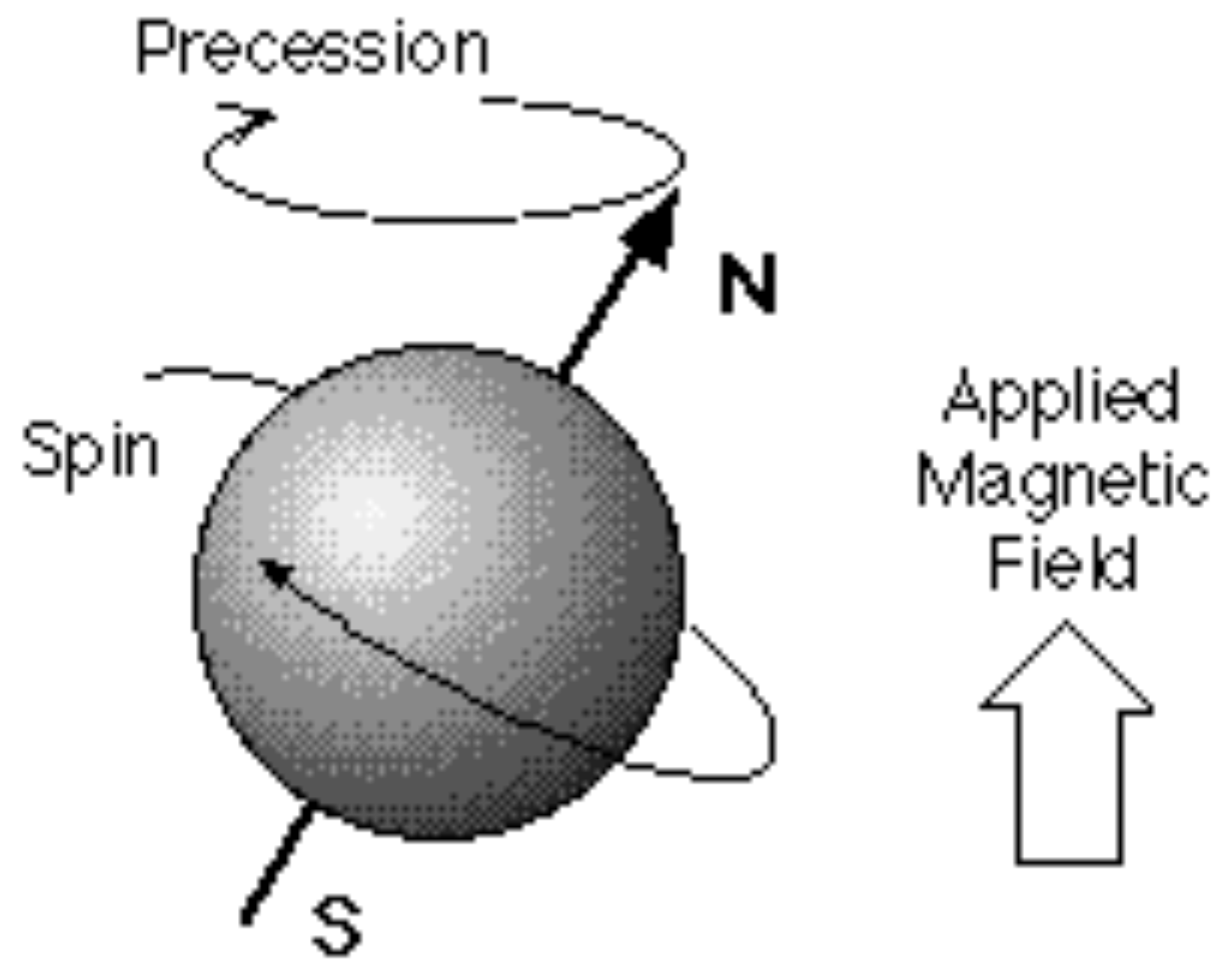
- Protons randomly aligned naturally
- Magnetic poles line up when exposed to strong magnets

Magnets, magnets, everywhere



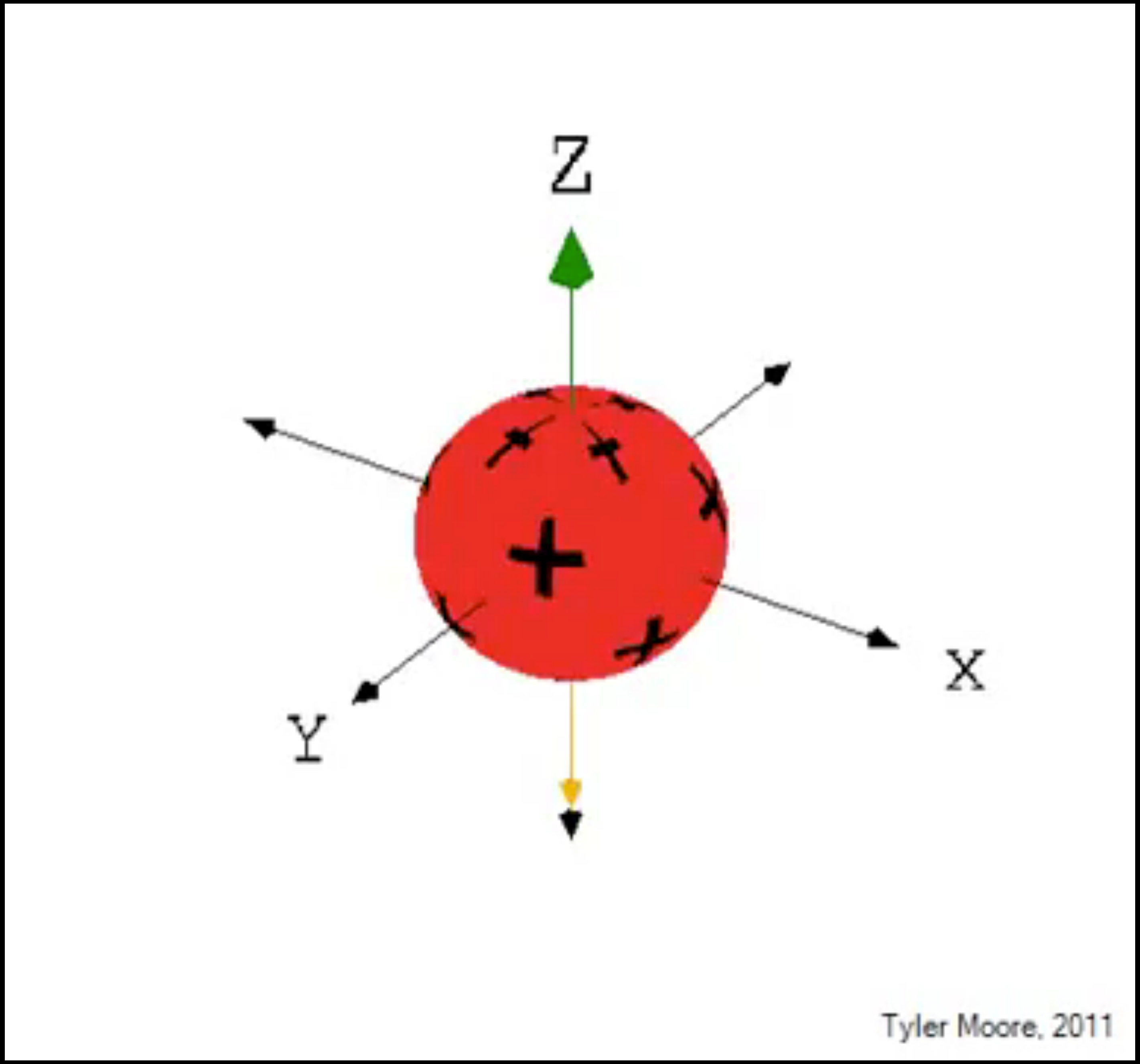
http://wikidoc.org/index.php/Basic_MRI_Physics

Magnets, magnets, everywhere



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

Magnets, magnets, everywhere



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

Magnets, magnets, everywhere

$$\omega_0 = \gamma \ B_0$$

B_0 Nuts and Bolts

- Stronger main field (larger B_0) - higher frequency (ω_0)
- More signal, i.e. larger net Magnetization (e.g. can be used to acquire higher resolution images)
- Different tissue contrast with stronger main field

B_0 Nuts and Bolts

- Stronger main field (larger B_0) - higher frequency (ω_0)
- More signal, i.e. larger net Magnetization (e.g. can be used to acquire higher resolution images)
- Different tissue contrast with stronger main field

However …

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

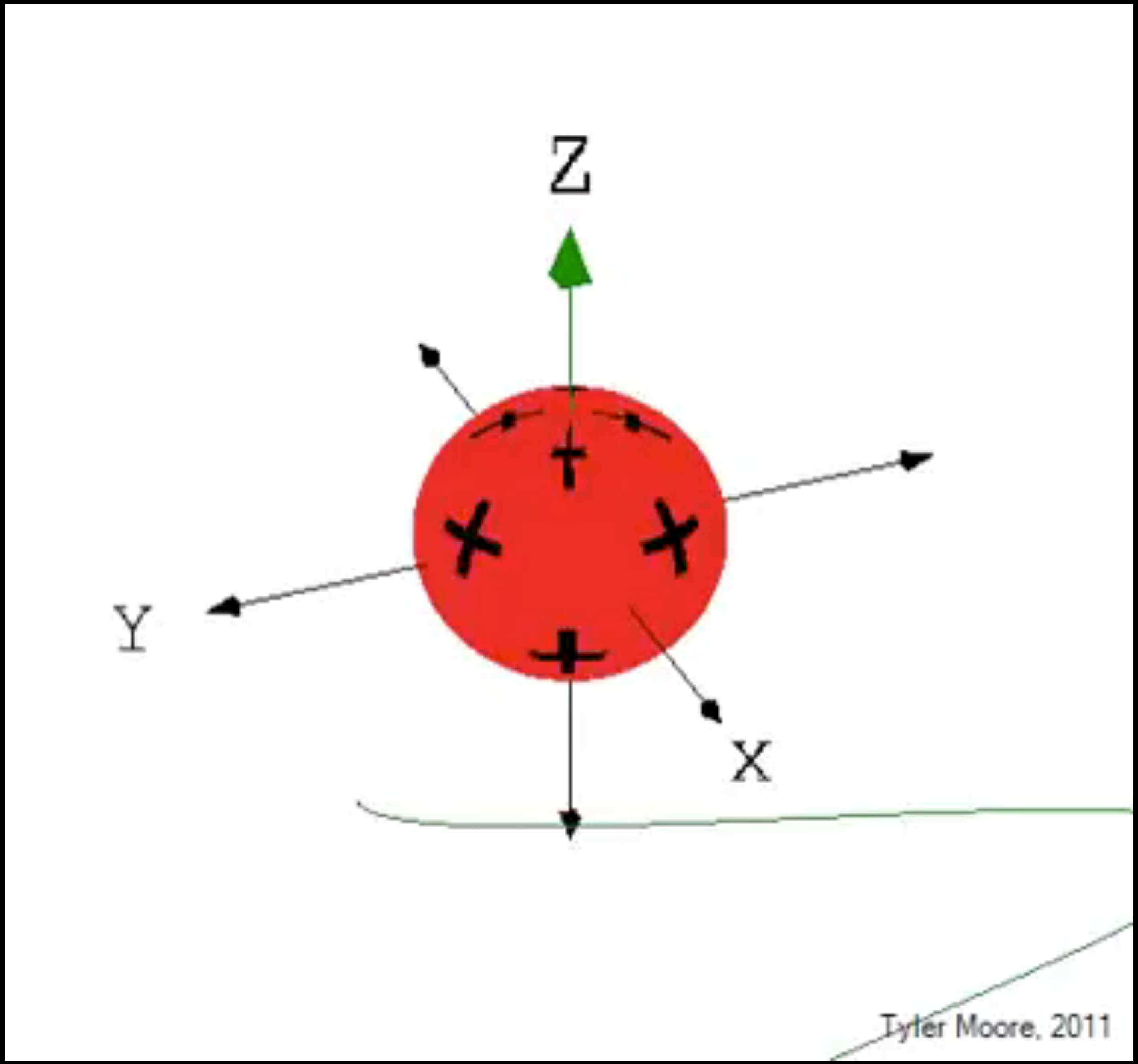
Outline

- System overview
- Components of the acronym
    - What’s the Magnet for?
    - Where does Resonance come in?
    - How is Imaging accomplished?
- Some basic types of MR contrast
- Re-cap of System overview

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://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.

RF Nuts and Bolts

- “Flip” angle ≈ degree of tip - a type of contrast
- High RF power for short time vs. low power for longer time. Same flip angle - but can give different contrast
- Types of RF pulse and timing give rise to lots of different MR tissue contrast (T_2, DTI, ASL)
- Sometimes, off-resonance excitation can be used to create contrast (MT) - high power and higher SAR experiment.
- Multi-band EPI is a higher SAR experiment than single-band

Outline

- System overview
- Components of the acronym
    - What’s the Magnet for?
    - Where does Resonance come in?
    - How is Imaging accomplished?
- Some basic types of MR contrast
- Re-cap of System overview

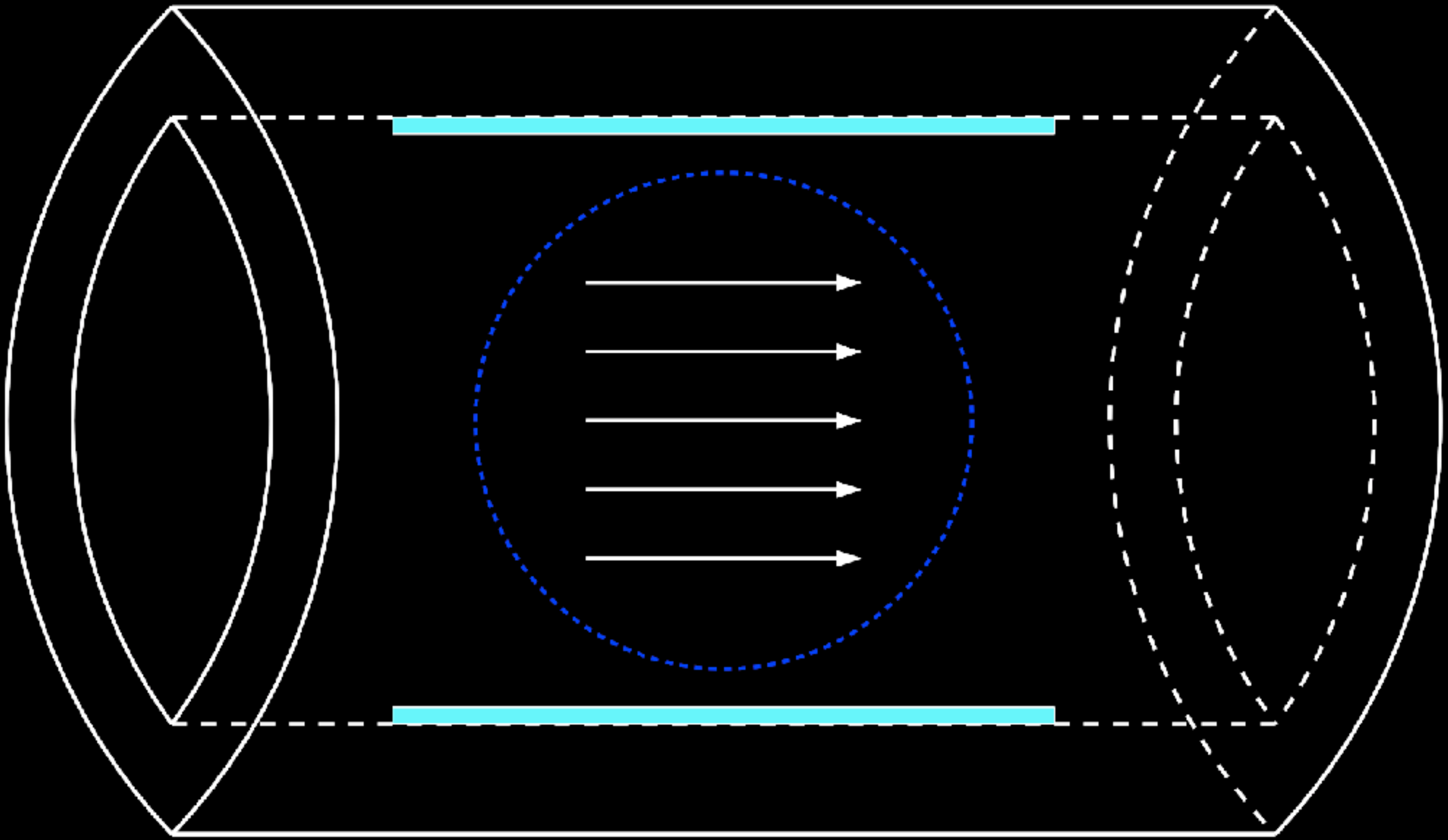
Imaging

- Uniform B_0 → uniform signal - cannot localize … so how to image?

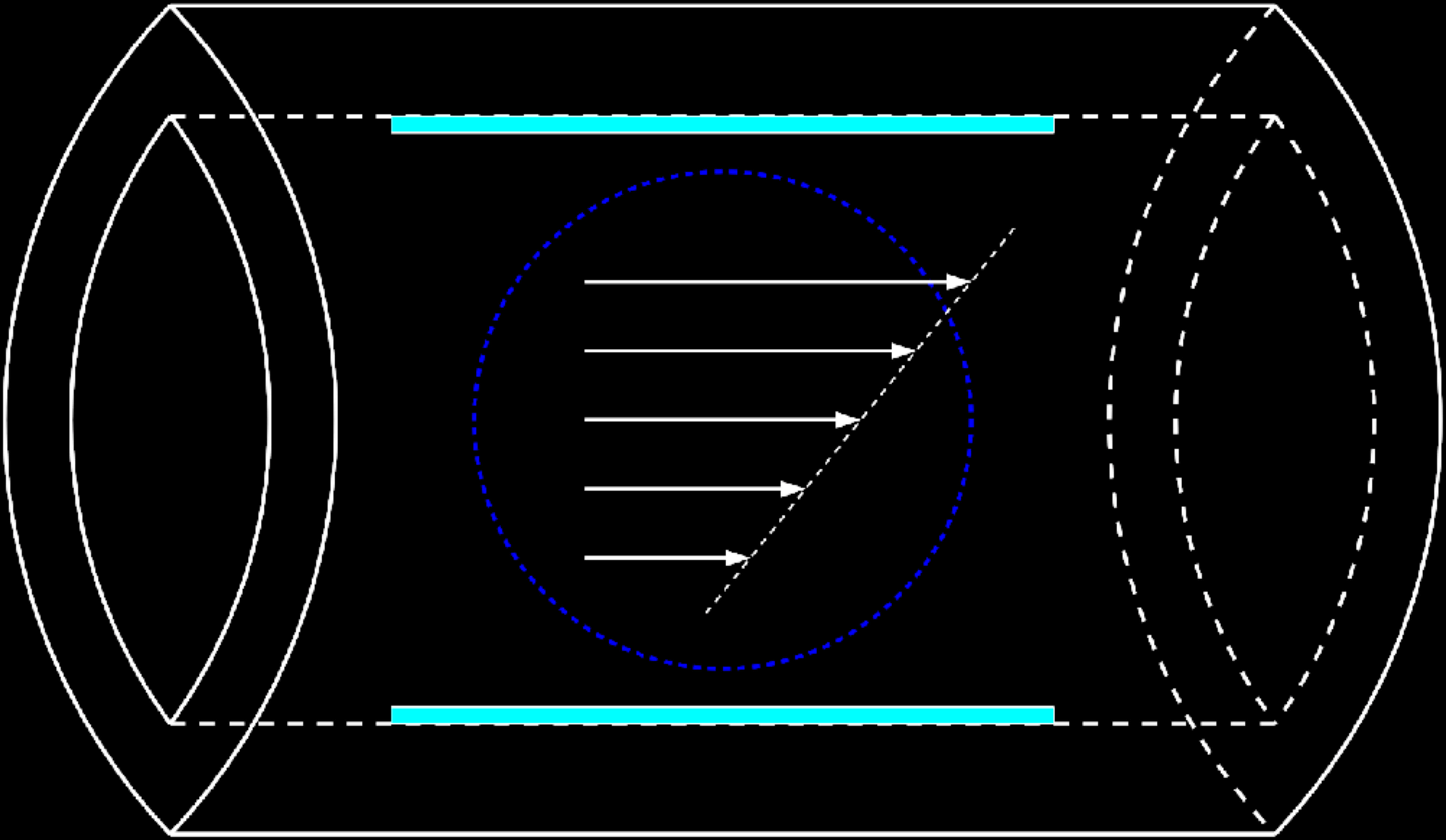
Imaging

- Uniform B_0 → uniform signal - cannot localize … so how to image?
- Apply controlled distortion to B_0

Imaging



Imaging



Imaging

- Uniform B_0 → uniform signal - cannot localize … so how to image?
- Apply controlled distortion to B_0
- → → → Spatially varying frequency

Imaging

$$\omega_0 = \gamma \ B_0$$

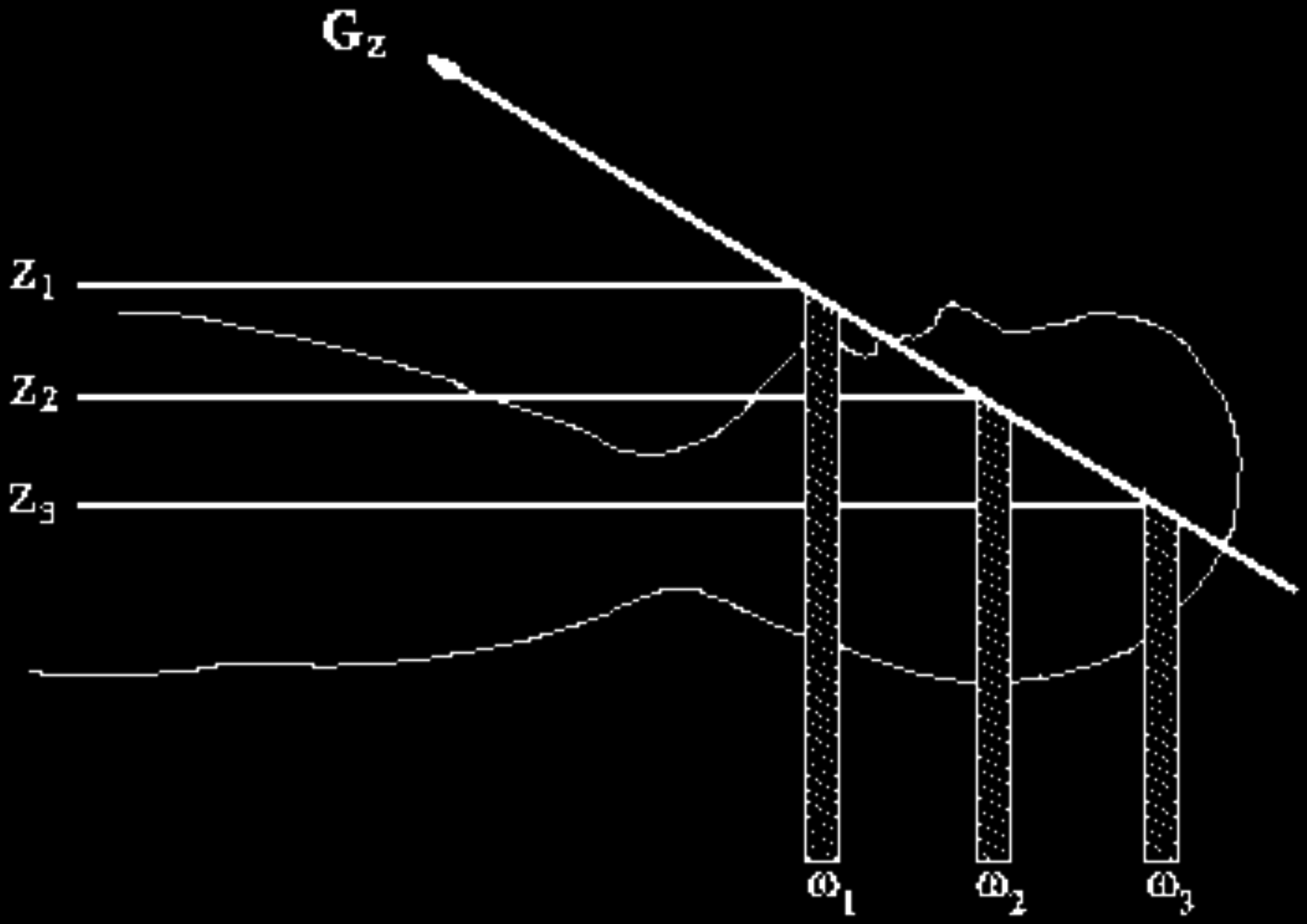
Imaging

$$\omega_x = \gamma \ B_x$$

Imaging

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

Imaging

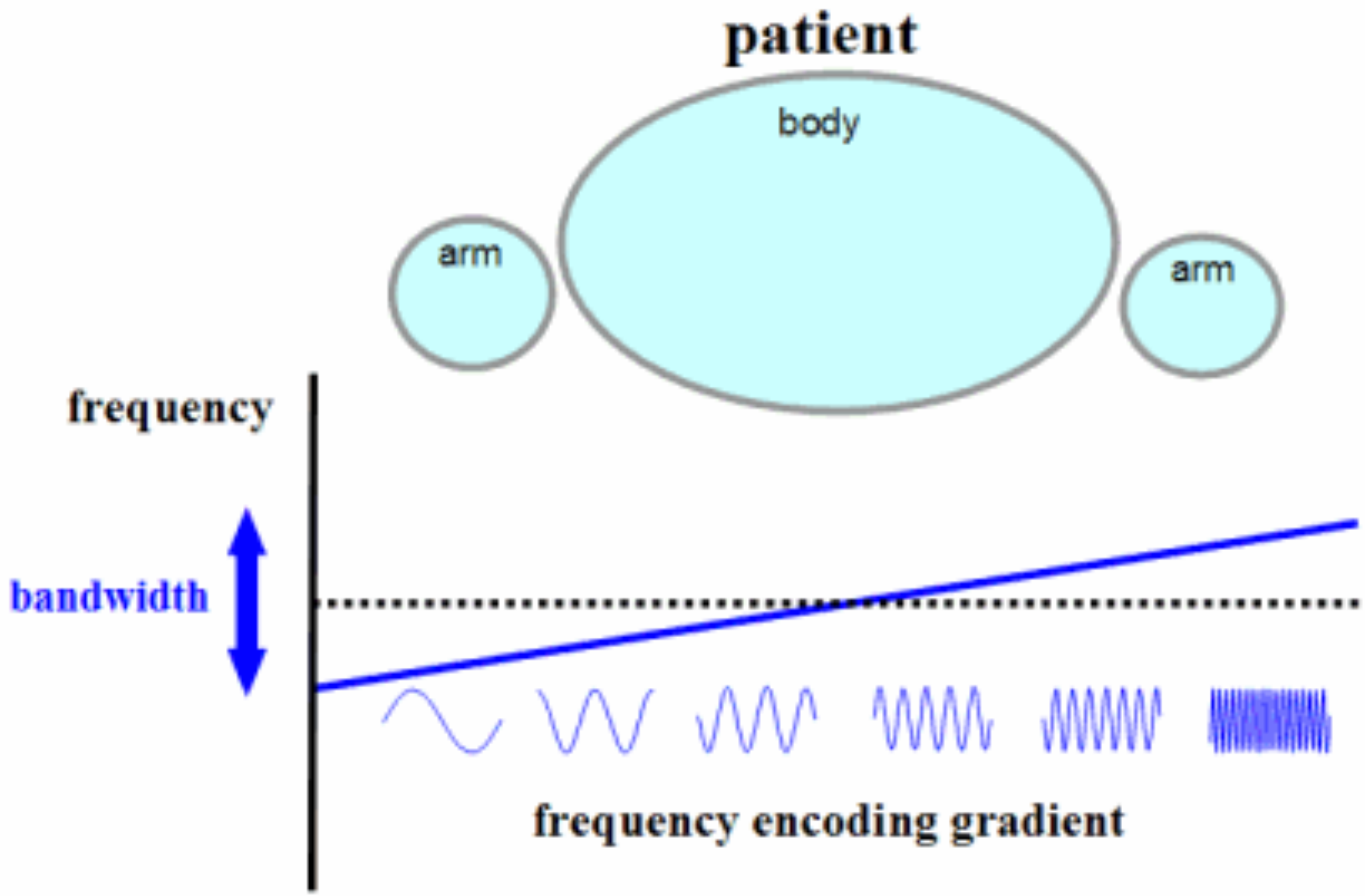


http://sfb649.wiwi.hu-berlin.de/fedc_homepage/xplore/ebooks/html/csa/node255.html

Imaging

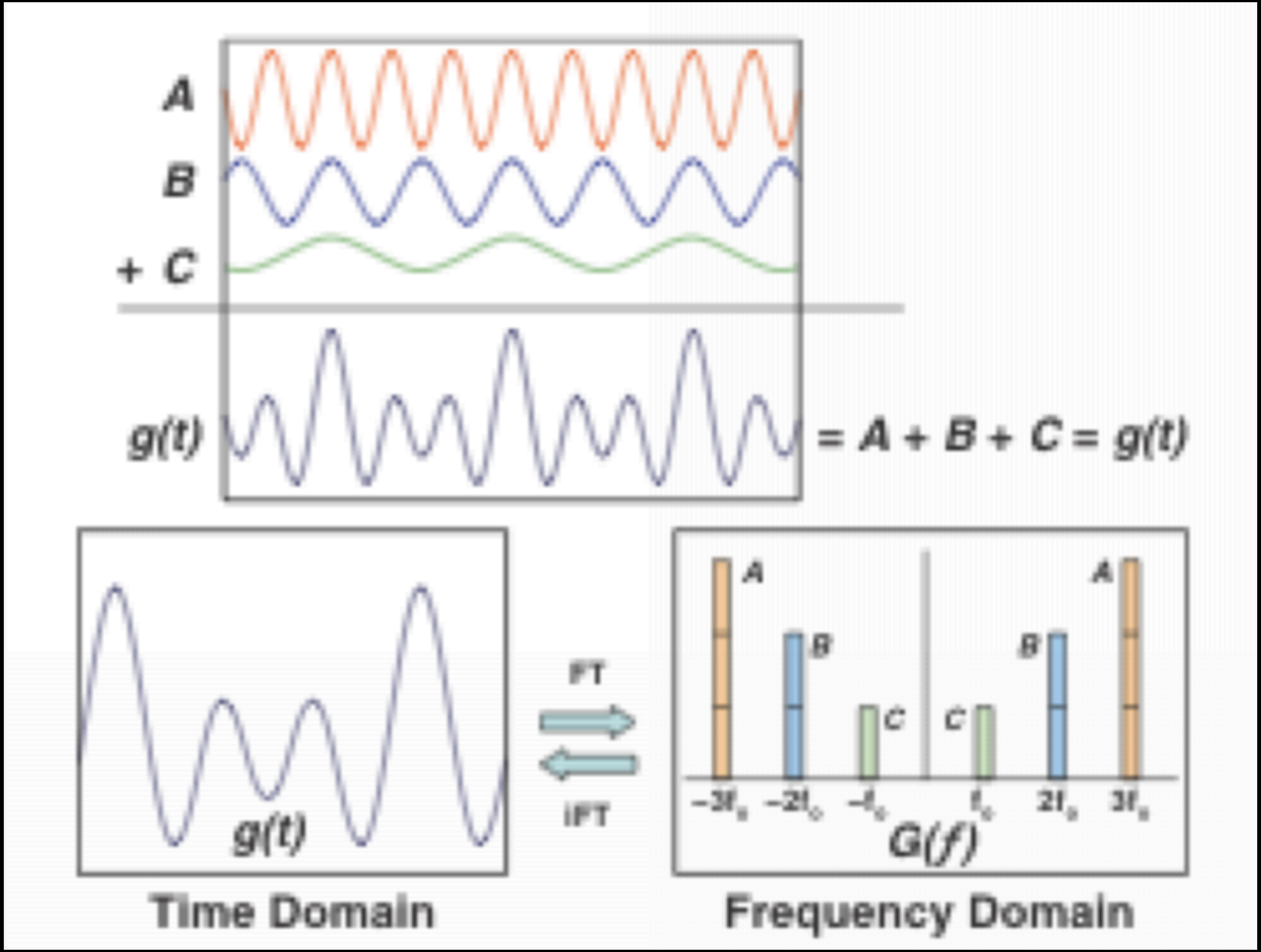
- Extend frequency change to other dimensions (x, y) for image encoding.
- 1st dimension → frequency encoding
- 2nd dimension → phase encoding

Imaging



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

Imaging

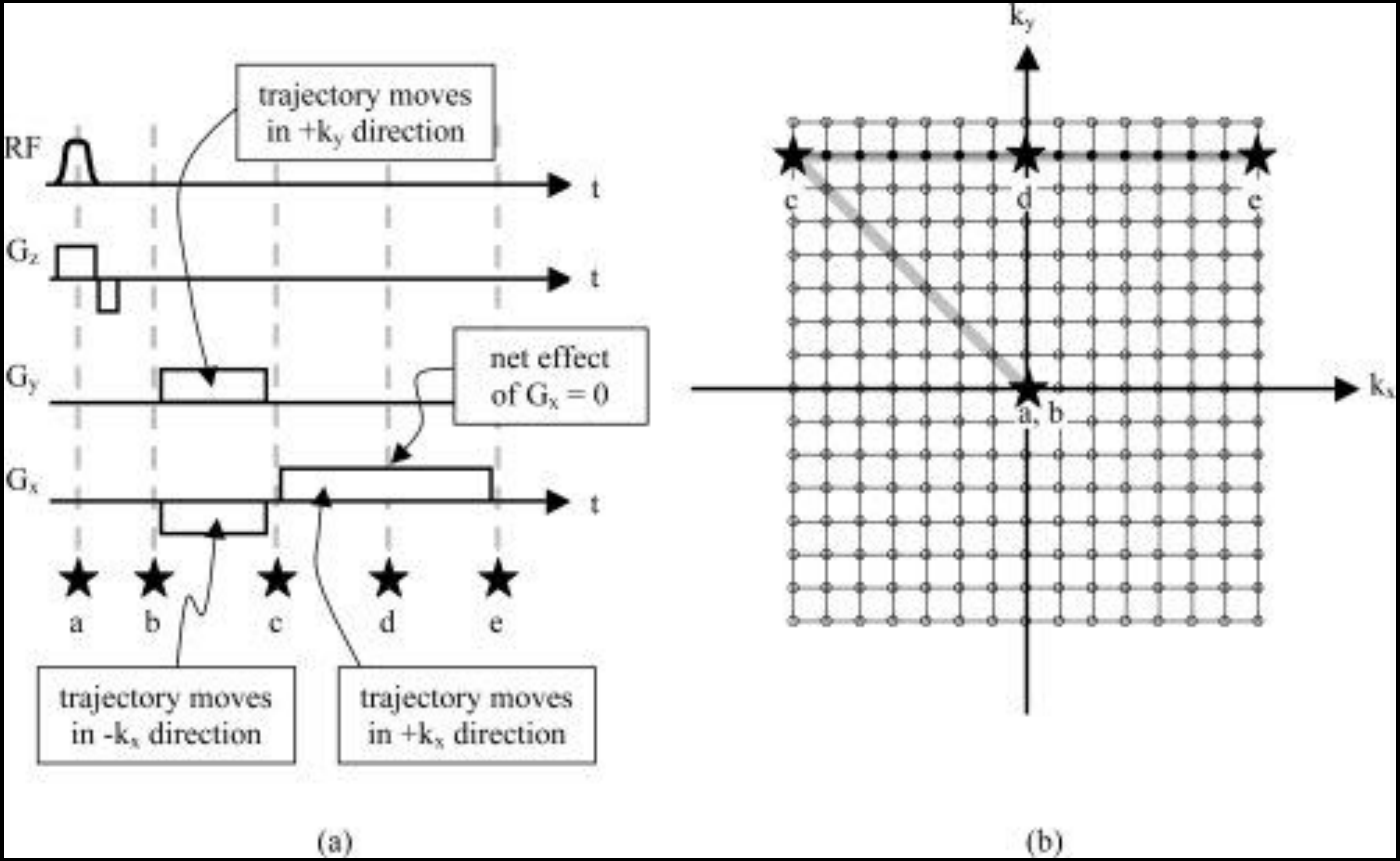


AJNR, Gallagher, DOI:10.2214/AJR.07.2874

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



JMRI, Paschal and Morris, DOI: 10.1002/jmri.10451

Imaging

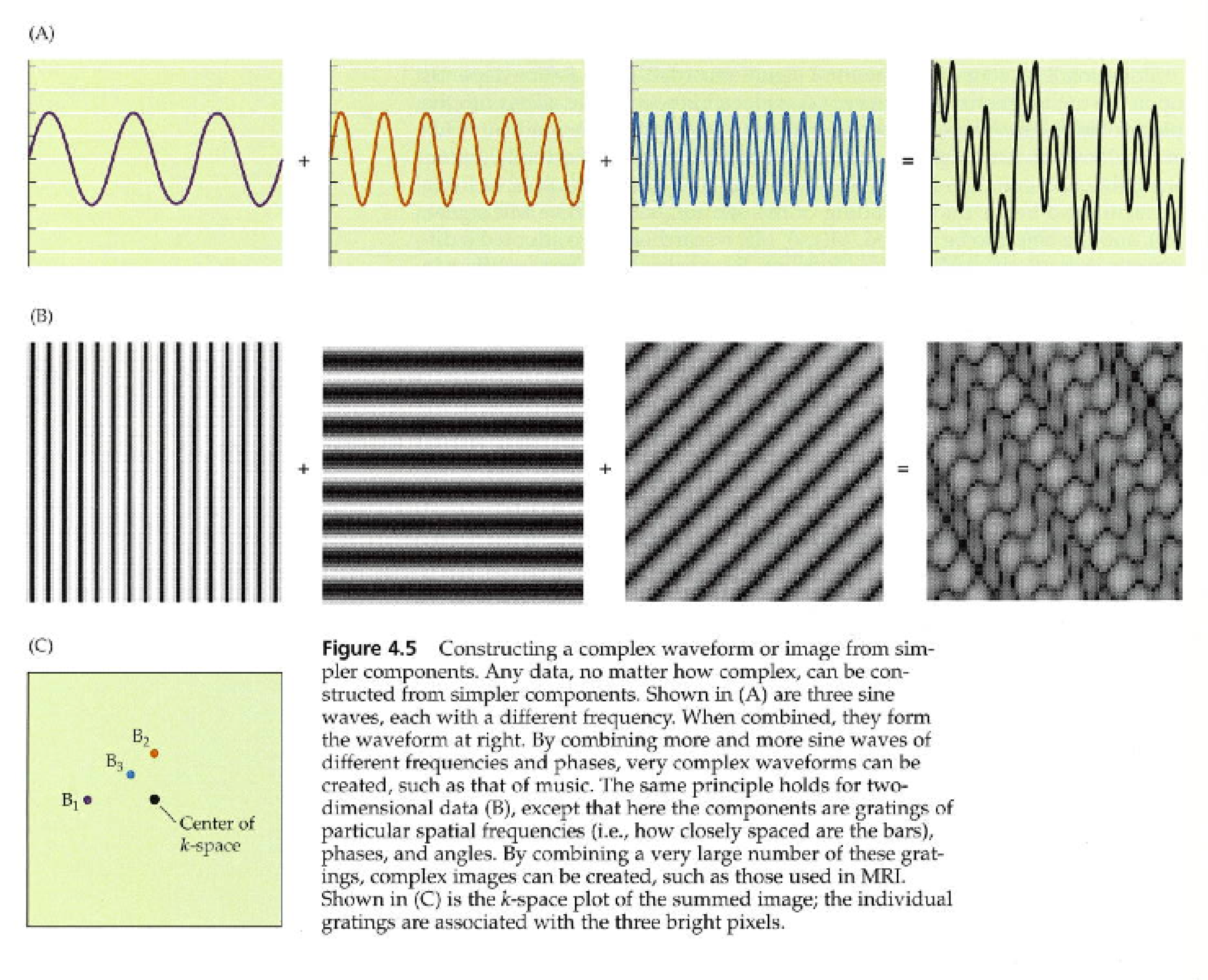


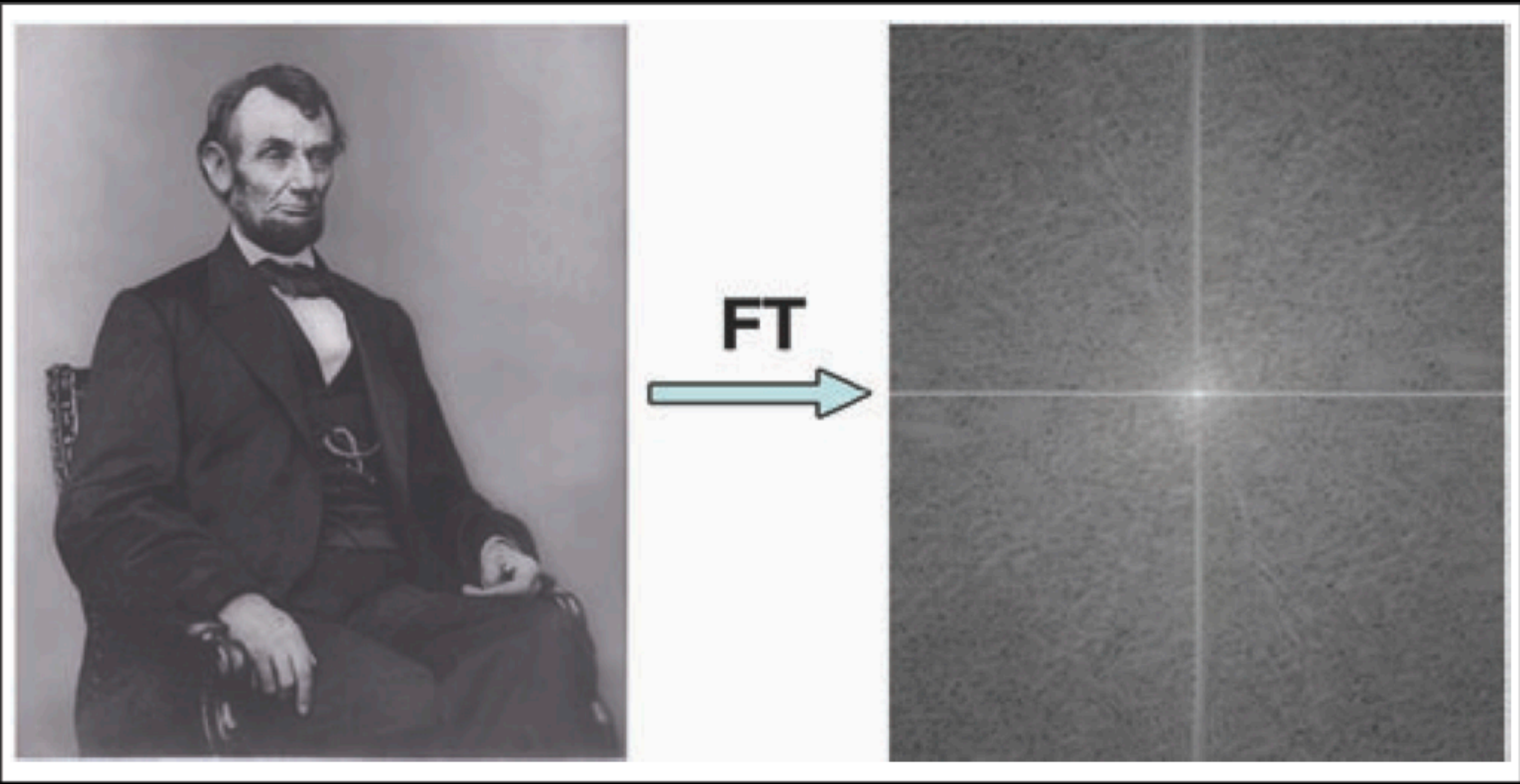
Figure 4.5 Constructing a complex waveform or image from simpler components. Any data, no matter how complex, can be constructed from simpler components. Shown in (A) are three sine waves, each with a different frequency. When combined, they form the waveform at right. By combining more and more sine waves of different frequencies and phases, very complex waveforms can be created, such as that of music. The same principle holds for two-dimensional data (B), except that here the components are gratings of particular spatial frequencies (i.e., how closely spaced are the bars), phases, and angles. By combining a very large number of these gratings, complex images can be created, such as those used in MRI. Shown in (C) is the *k*-space plot of the summed image; the individual gratings are associated with the three bright pixels.

Huettel - Functional Magnetic Resonance Imaging

Signal (Fourier Transform) Equation in MRI

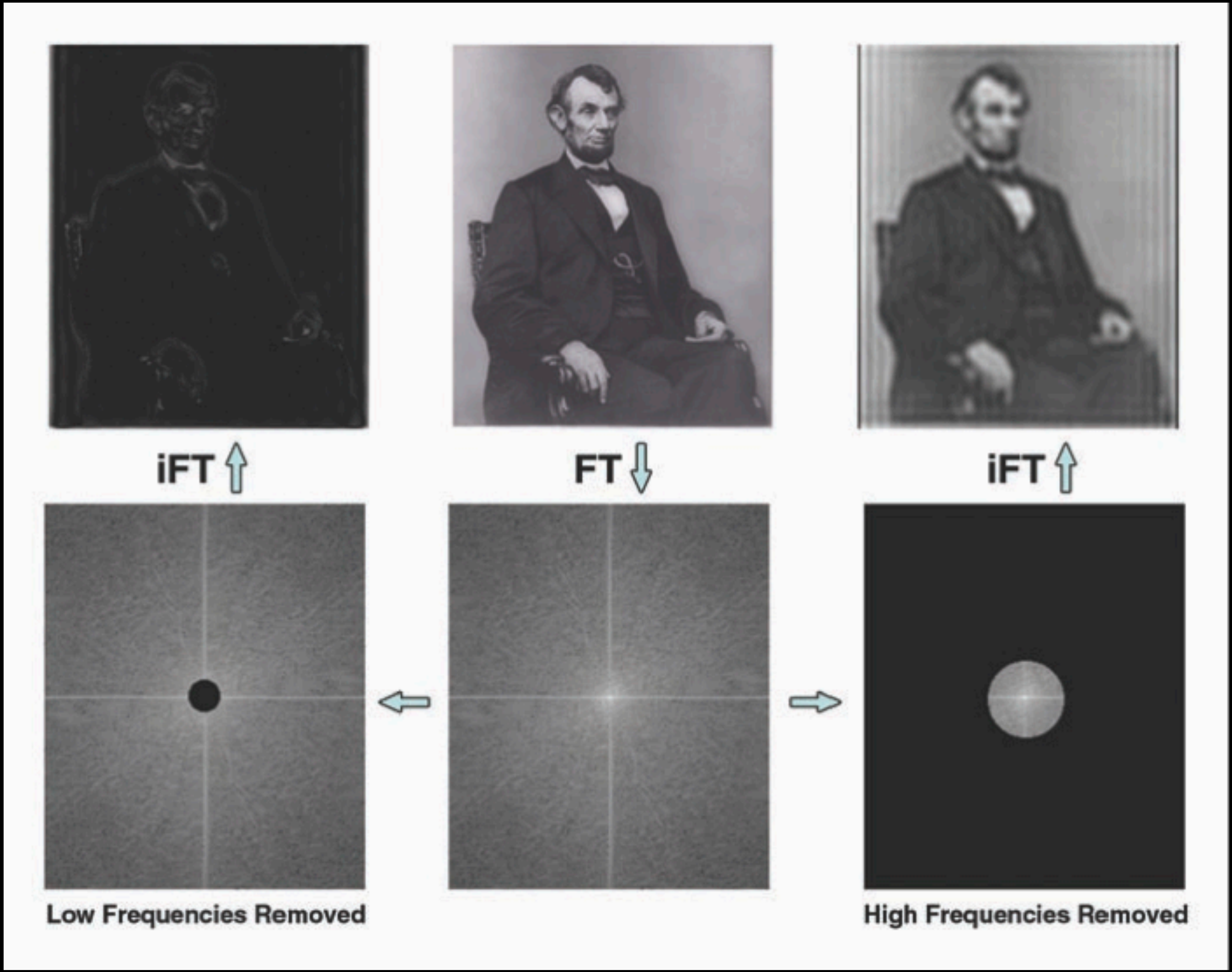
$$s(t) = \int_{\vec{r}} M_{xy}(\vec{r},0)e^{-i2\pi\vec{k}(t)\cdot\vec{r}}d\vec{r}$$

Imaging



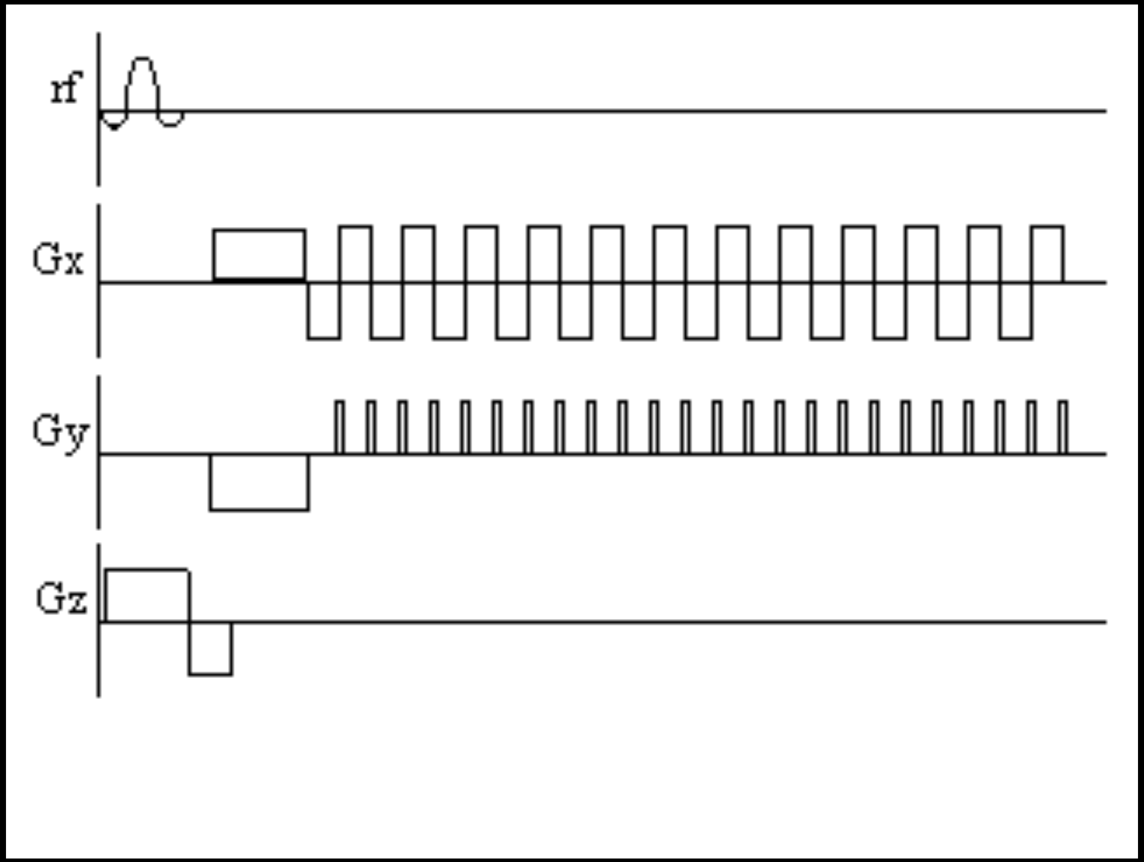
AJNR, Gallagher, DOI:10.2214/AJR.07.2874

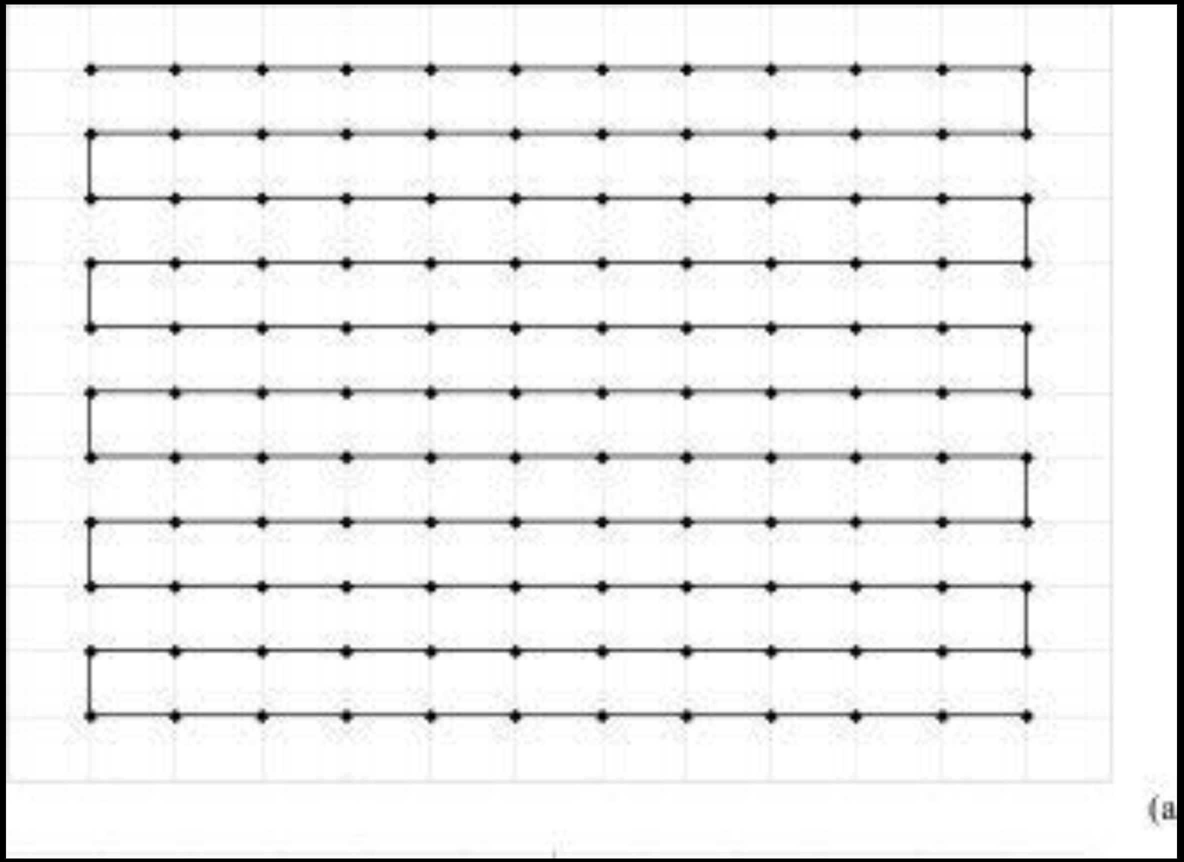
Imaging



AJNR, Gallagher, DOI:10.2214/AJR.07.2874

Imaging

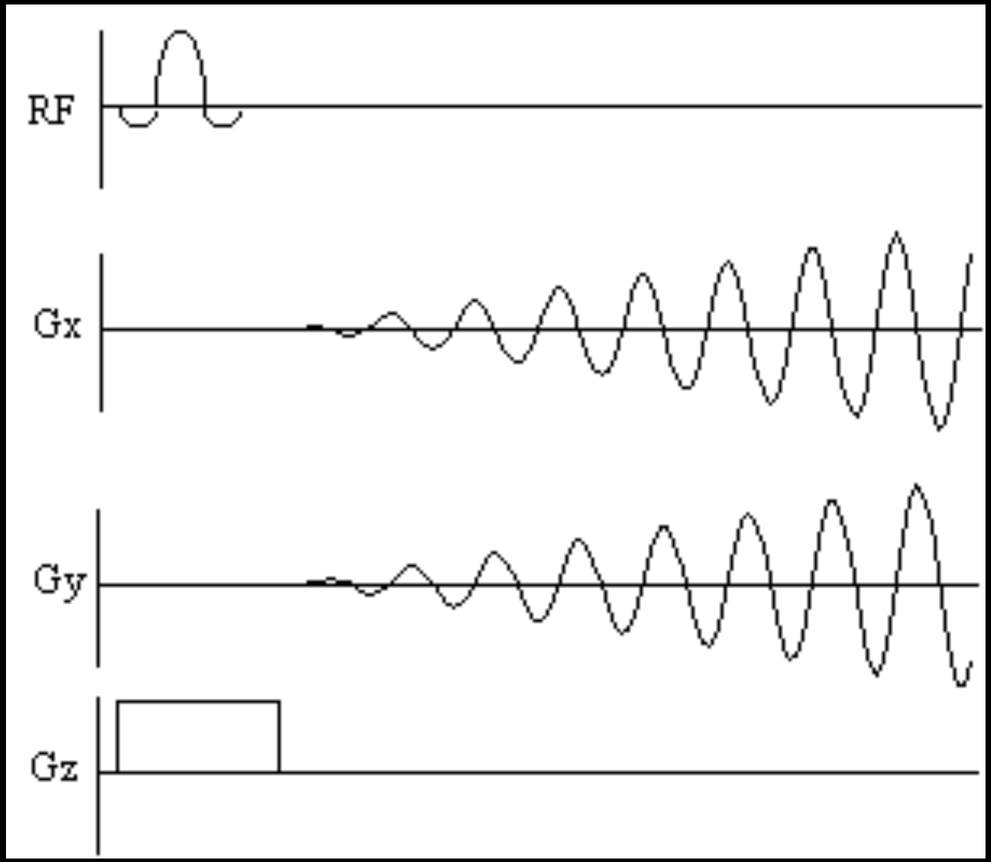


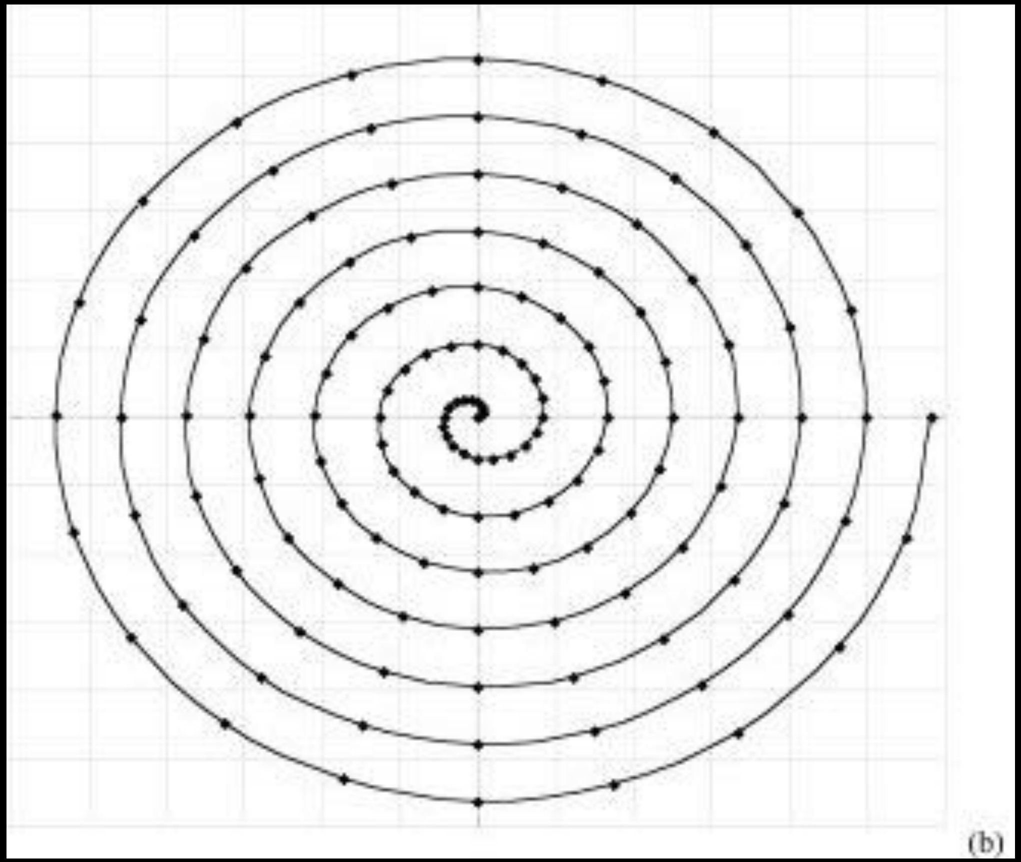


https://users.fmrib.ox.ac.uk/~stuart/thesis/chapter_2/section2_3.html

JMRI, Paschal and Morris, DOI: 10.1002/jmri.10451

Imaging





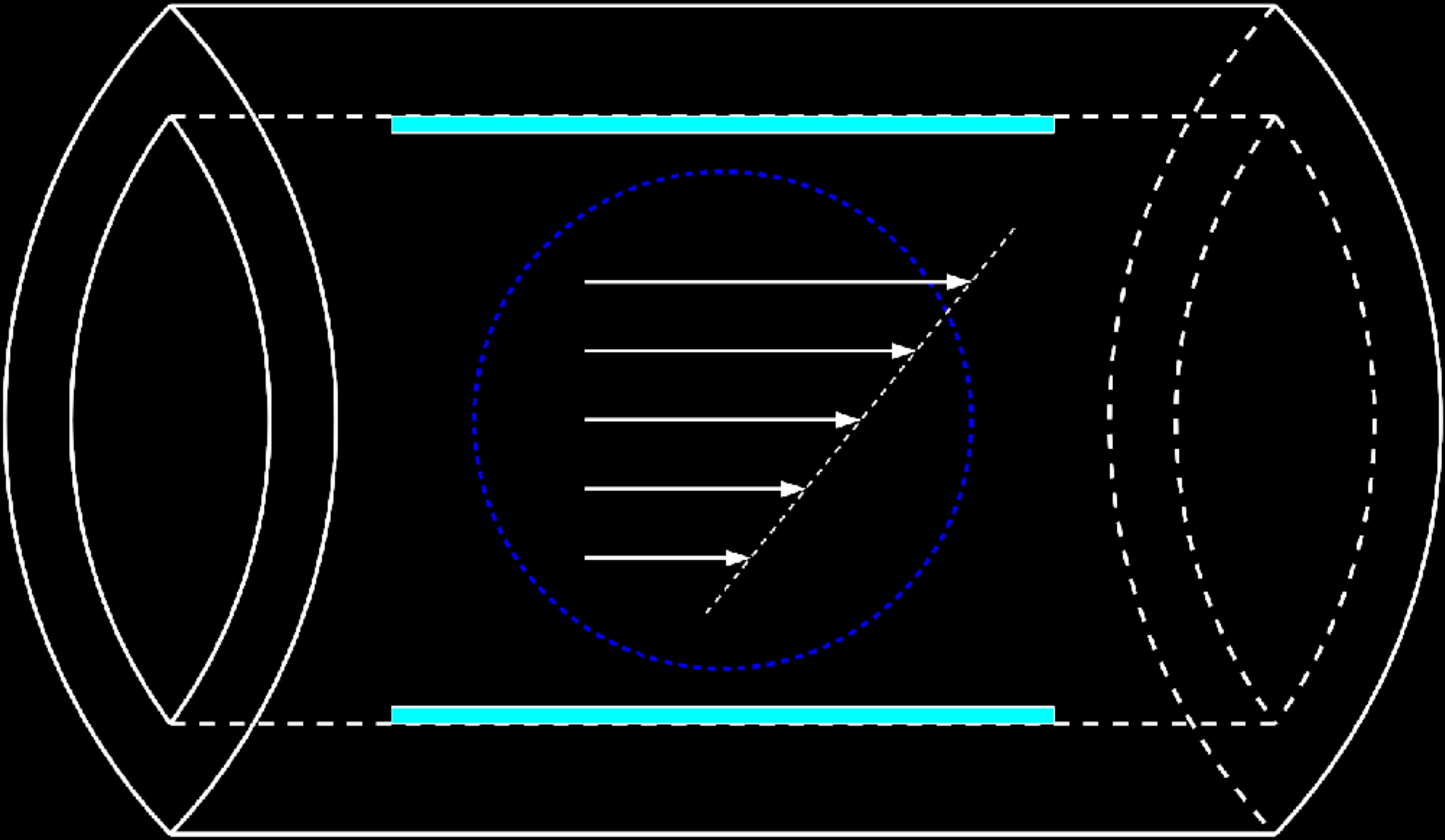
https://users.fmrib.ox.ac.uk/~stuart/thesis/chapter_2/section2_3.html

JMRI, Paschal and Morris, DOI: 10.1002/jmri.10451

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.

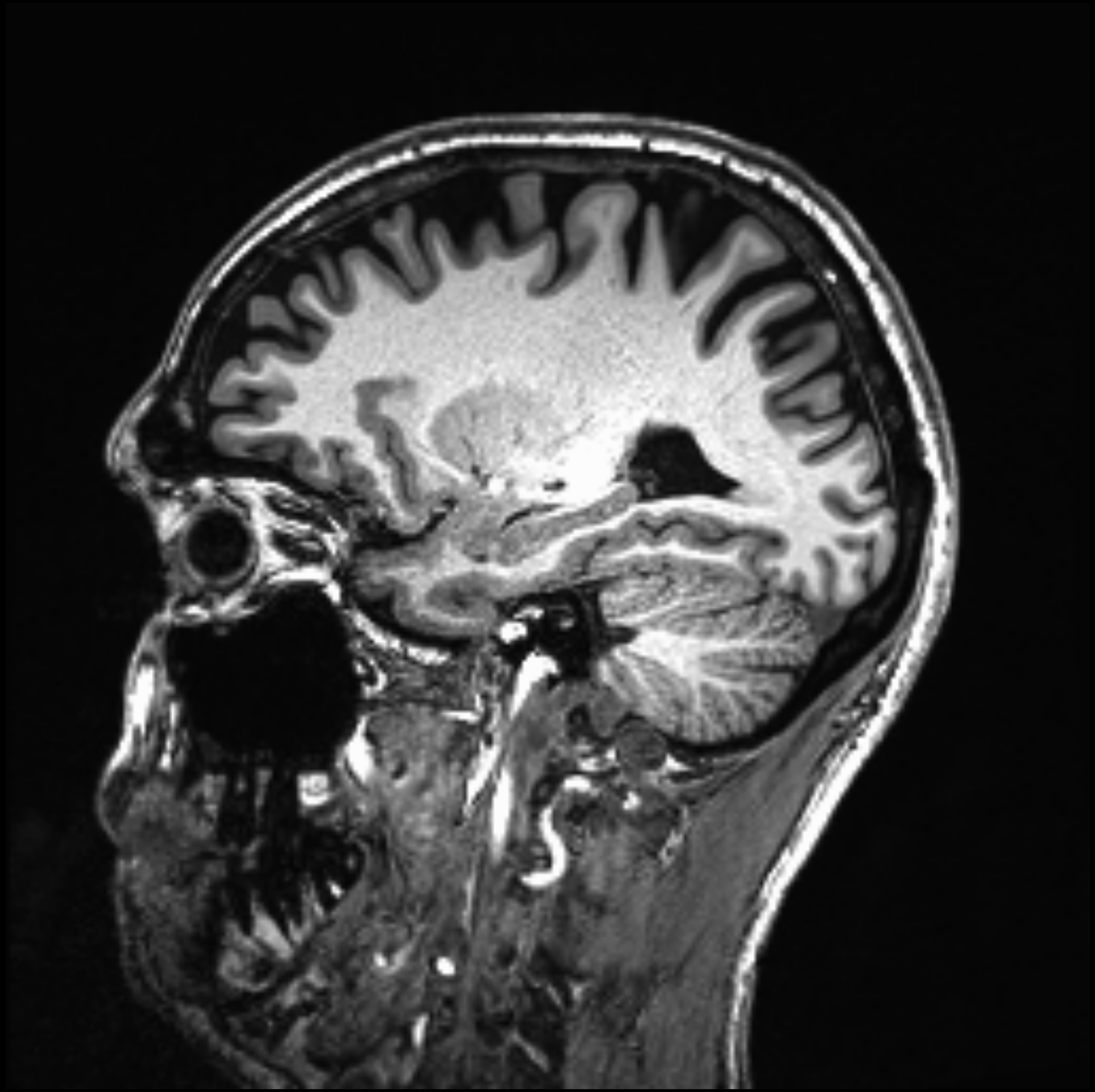
Gradients Nuts and Bolts



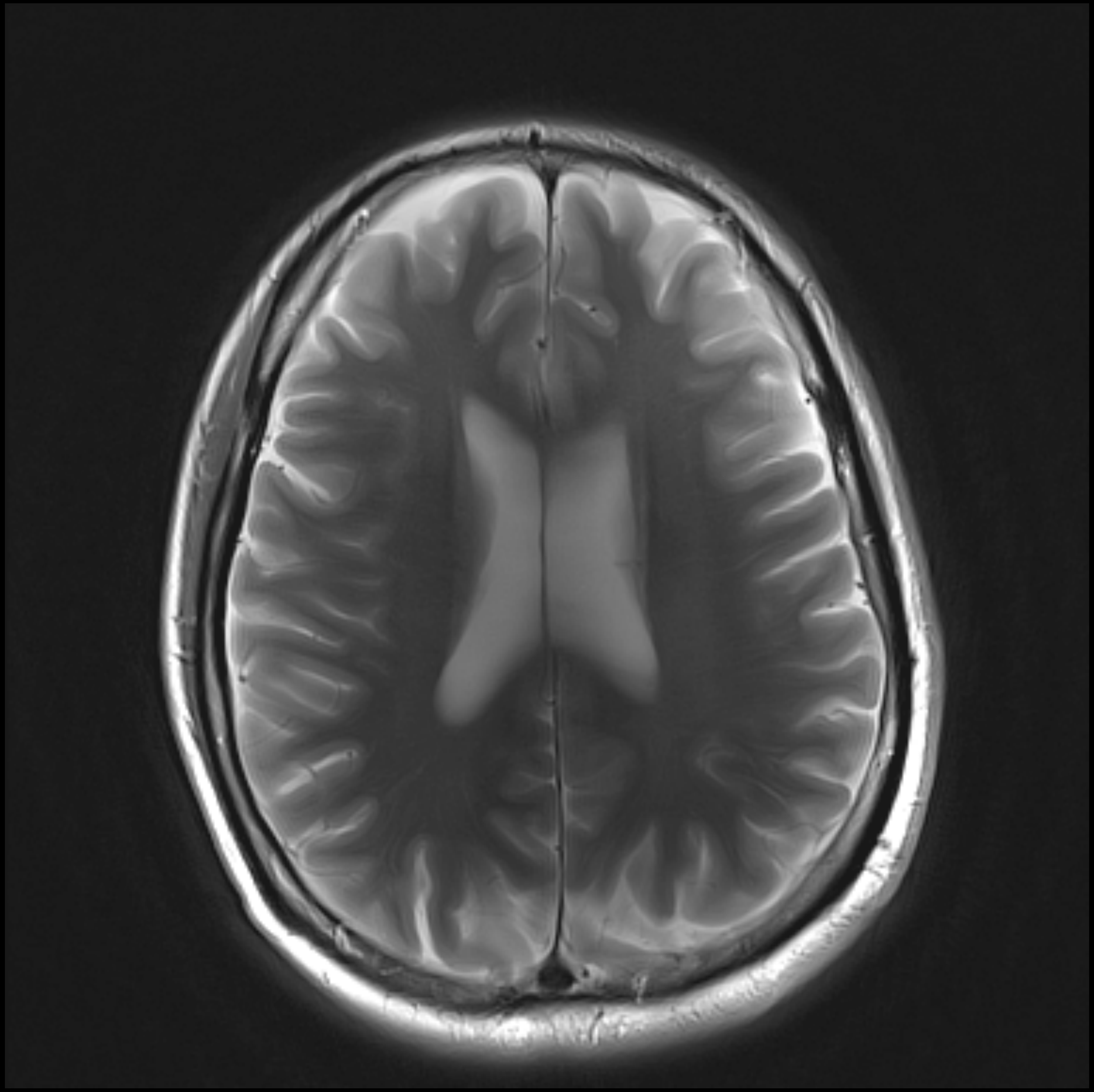
Outline

- System overview
- Components of the acronym
    - What’s the Magnet for?
    - Where does Resonance come in?
    - How is Imaging accomplished?
- Some basic types of MR contrast
- Re-cap of System overview

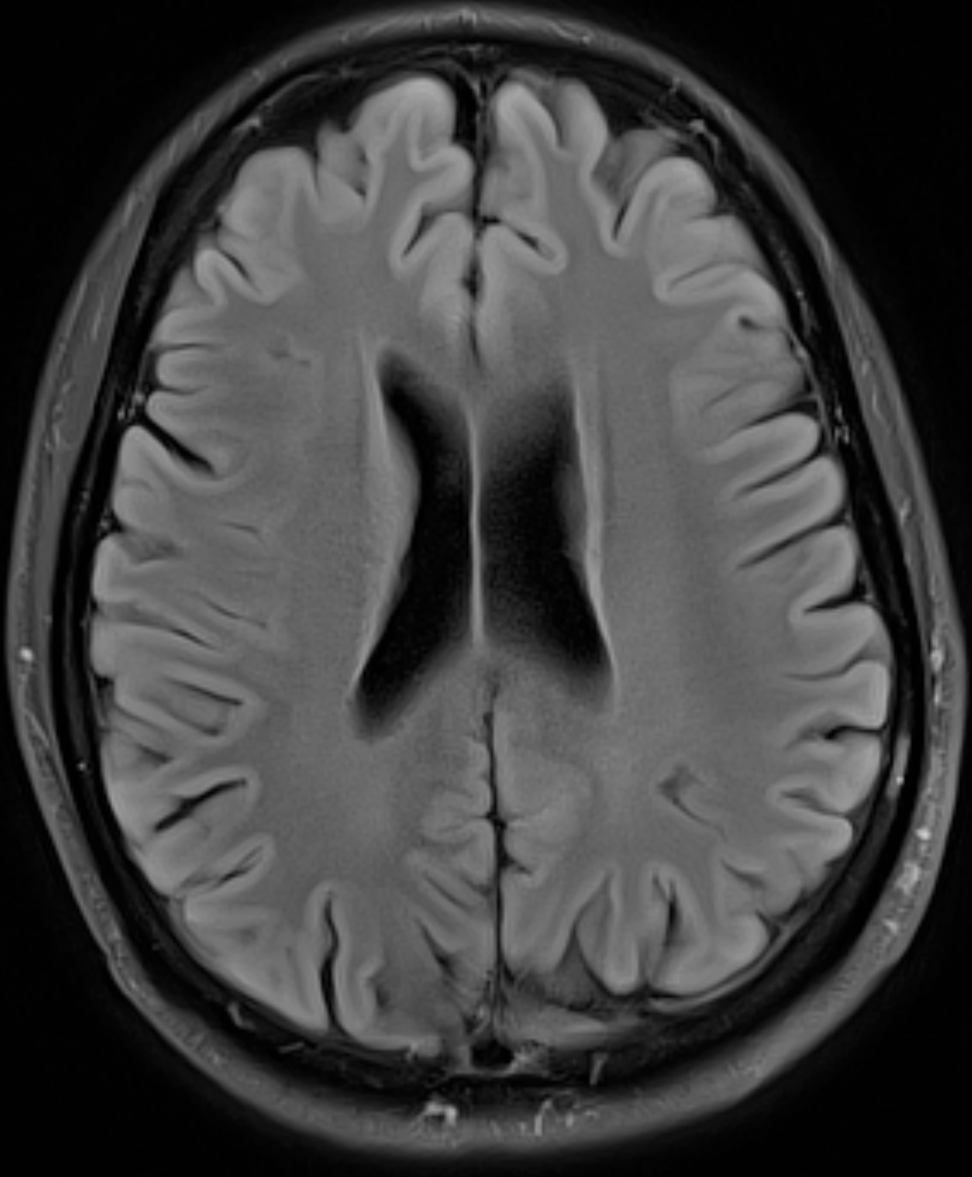
Contrast - T_1



Contrast - T_2

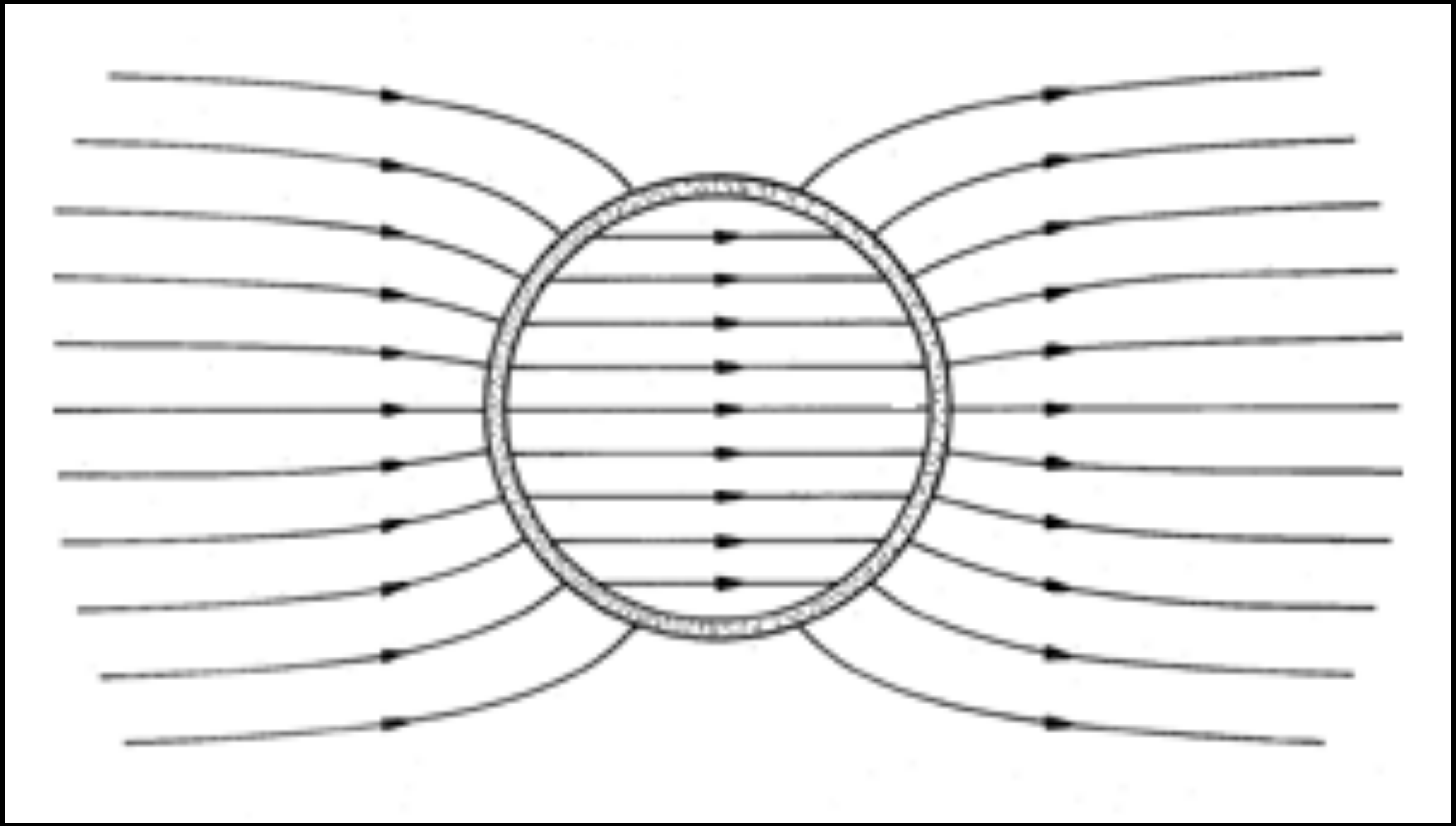


Contrast - T_2 FLAIR



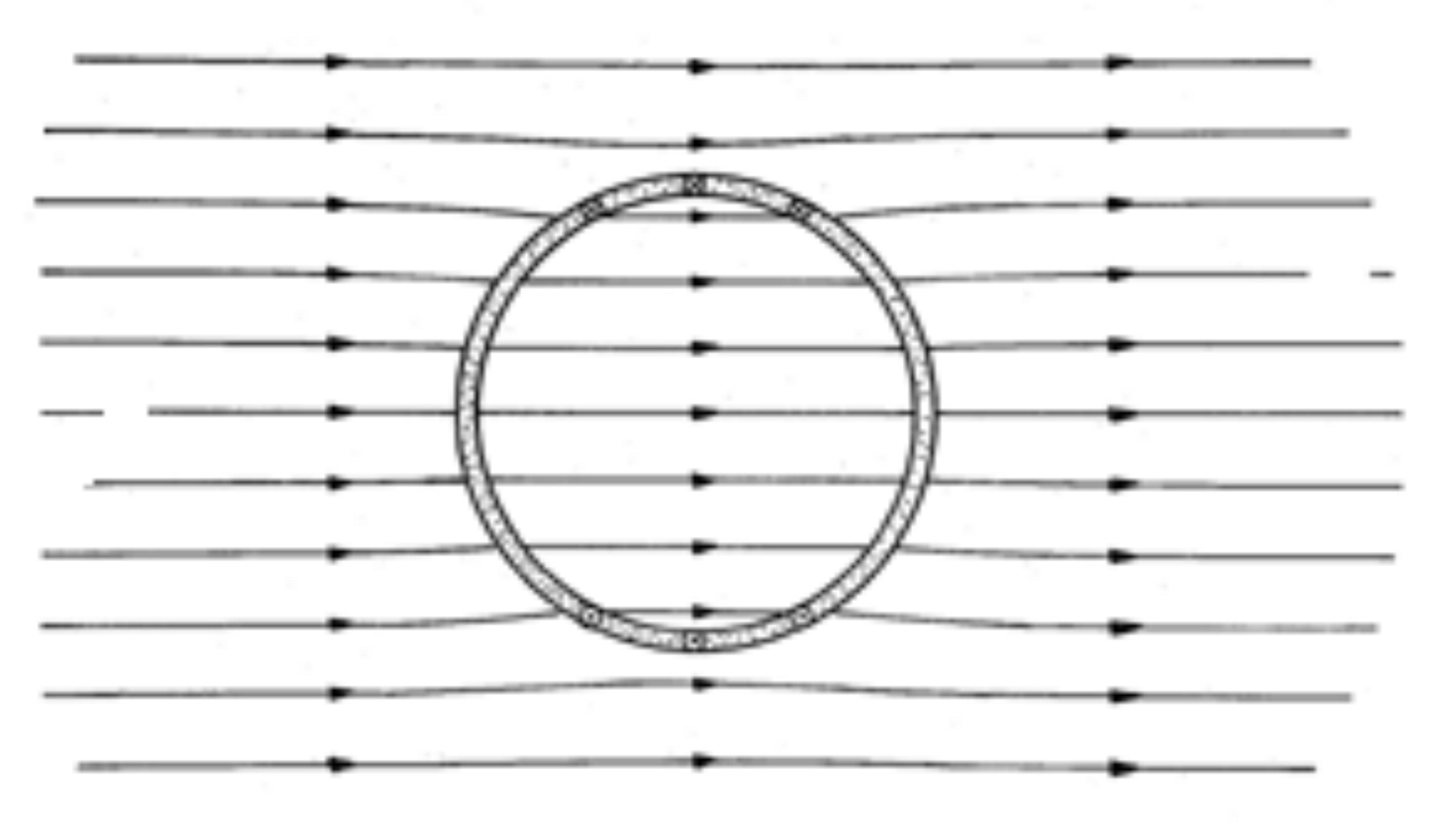
Contrast - BOLD

Contrast - BOLD



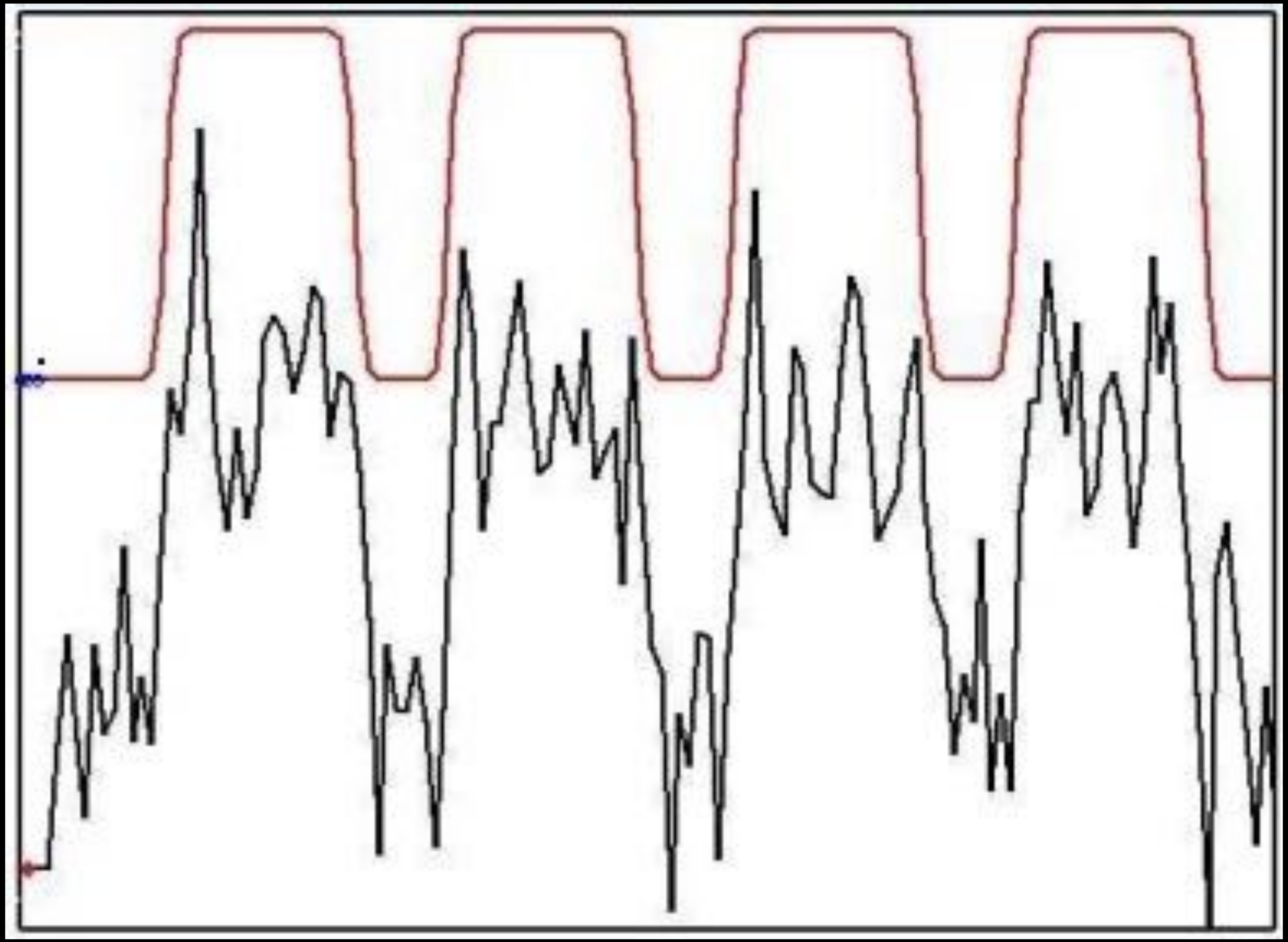
http://web.mit.edu/6.013_book/www/chapter10/10.4.html

Contrast - BOLD

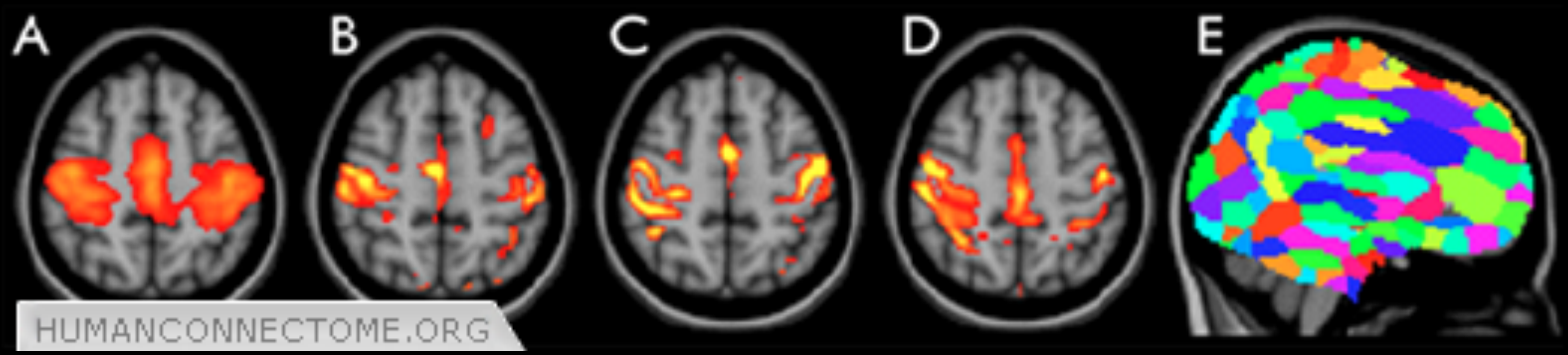


http://web.mit.edu/6.013_book/www/chapter10/10.4.html

Contrast - BOLD



Contrast - BOLD



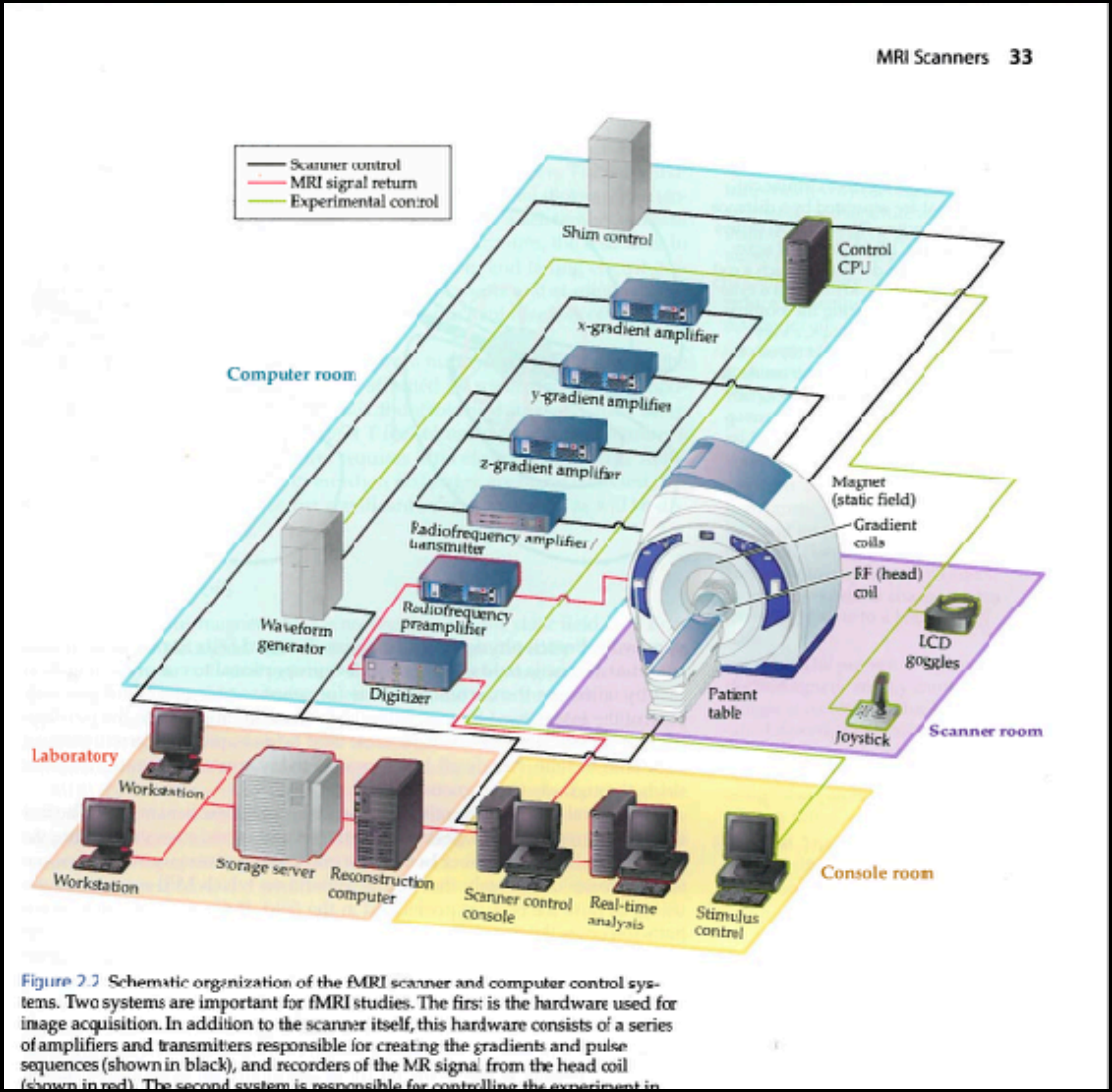
Contrast

- BOLD == T_2^*
- FLAIR (Fluid Attenuated Inversion recovery)
- Magnetization Transfer (MT) - MRM, 1989 Vol 10:135-144 - Wolff and Balaban
- Perfusion imaging - MRM, 1992 Vol 23:37-45 - Detre et.al.
- Diffusion imaging - Nature Reviews Neuroscience 4, 469-480 (June 2003) - DOI:10.1038/nrn1119 (review paper)
- Phase imaging - PNAS, 2007 Vol 104(28):11796-11801 - Duyn et.al.
- …

Outline

- System overview
- Components of the acronym
    - What’s the Magnet for?
    - Where does Resonance come in?
    - How is Imaging accomplished?
- Some basic types of MR contrast
- Re-cap of System overview

System overview



MRI Scanners 33

Figure 2.2 Schematic organization of the fMRI scanner and computer control systems. Two systems are important for fMRI studies. The first is the hardware used for image acquisition. In addition to the scanner itself, this hardware consists of a series of amplifiers and transmitters responsible for creating the gradients and pulse sequences (shown in black), and recorders of the MR signal from the head coil (shown in red). The second system is responsible for controlling the experiment in

Huettel - Functional Magnetic Resonance Imaging