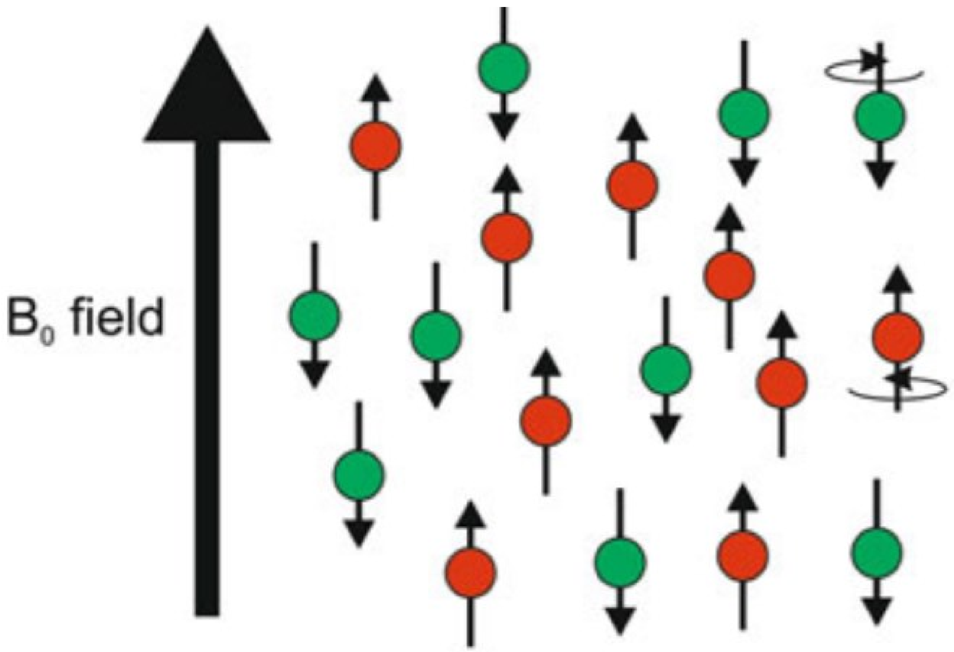
CS463/516 Medical Imaging

Lecture 4

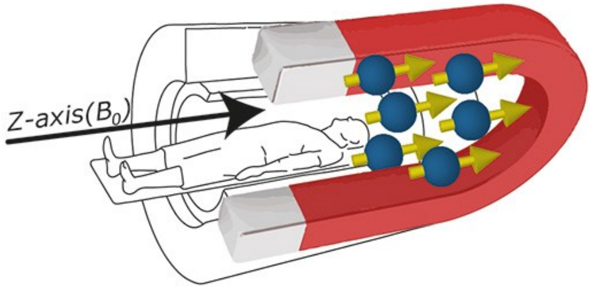
Warning – theoretical lecture, mostly physics.
We will get to more traditional image processing topics soon ☺

Magnetic Resonance Imaging (MRI)

- Protons and neutrons in nucleus of atom possess angular momentum called *spin*
- Can observe spin in atoms with odd number of nuclei (such as hydrogen)
  - In atoms with even number of nuclei, the spins cancel each other out
- MRI machine produces static magnetic field B_0, field strength measured in *Tesla*
- B_0 causes spins to align parallel or antiparallel to magnetic field direction
- Spin frequency ω depends on:
  - 1) strength of B_0
    - Measured in Tesla, typically 3 Tesla for clinical scanner
  - 2) atom-specific *gyromagnetic constant* γ
    - Measured in $MegaHz/Tesla$
  - $\omega = \gamma B_0$. Also known as the *Larmor frequency*
  - Example: hydrogen gyromagnetic ratio $= 42.58 \frac{MHz}{Tesla}$
  - $\Rightarrow 3\, Tesla\ * 42.58 \frac{MHz}{Tesla} = 127.74\ \text{MHz}$
    - We call this the *resonant frequency* of hydrogen at 3 Tesla

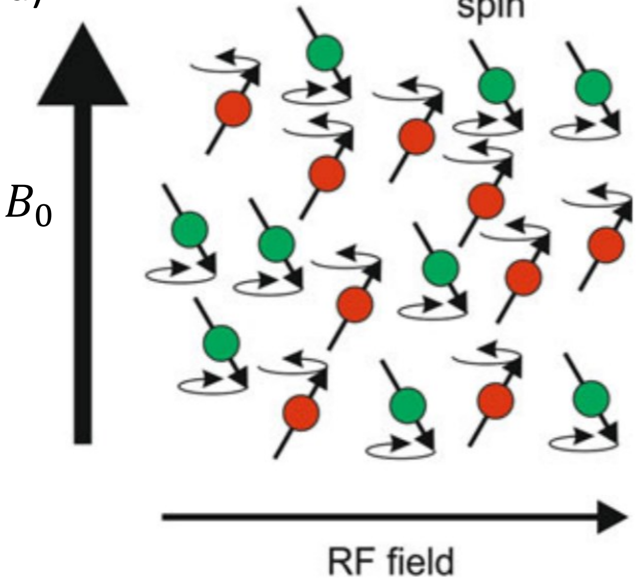


Free induction decay (FID)

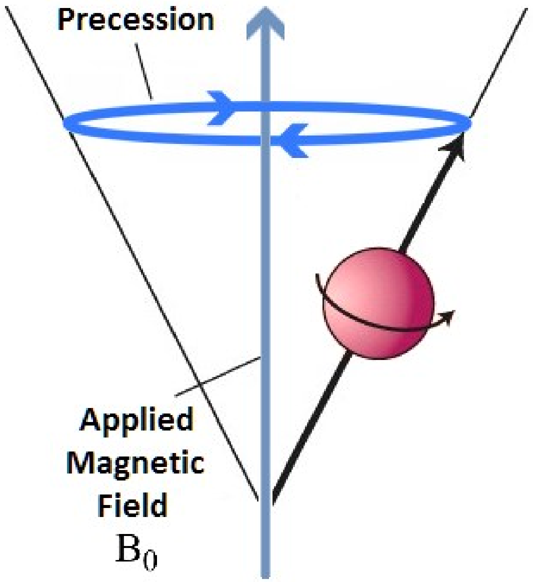


- How to measure a signal from all these spinning protons?
  - A spinning proton is a moving charge, which creates a magnetic field (electromagnetic induction)
  - However, spins are aligned with B_0 which is orders of magnitude stronger (signal from spins is obscured)
  - We therefore use a *radiofrequency (RF) pulse* perpendicular to B_0 to tilt spins away from B_0 (a)
  - RF pulse is an electromagnetic wave we construct to match hydrogen resonant frequency ω
  - Switch on RF pulse which deposits energy, tilting all spins by angle $0^{\circ} < \alpha < 180^{\circ}$
  - Switch off the RF pulse, spins will slowly return to original direction while still precessing (b)
    - c) Can now observe spins because they are out of alignment with B_0. Observed signal is called *free induction decay*

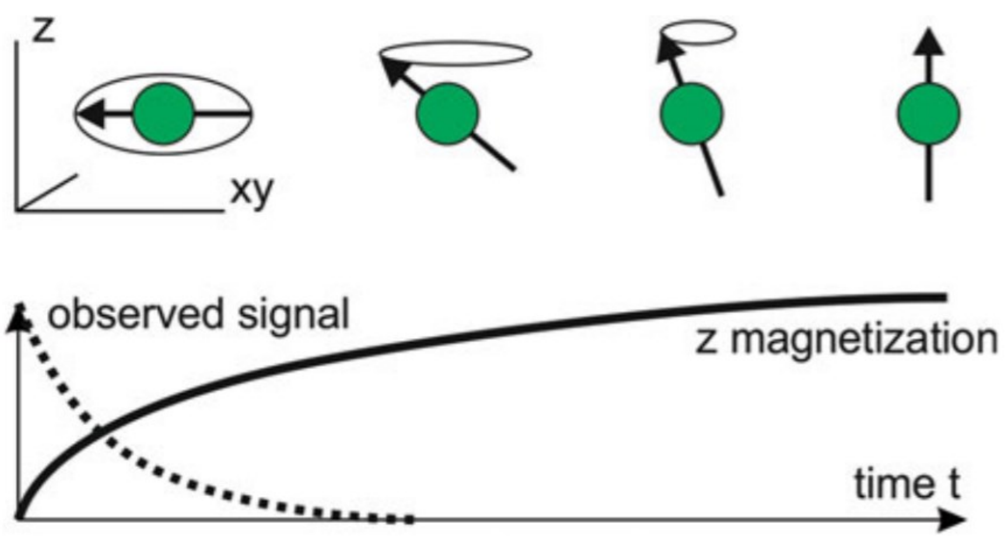
a)



b)



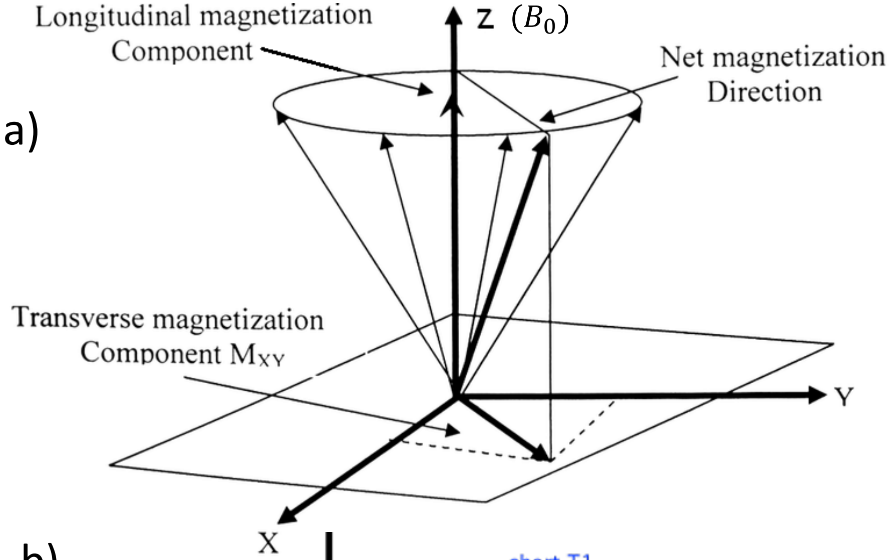
c)



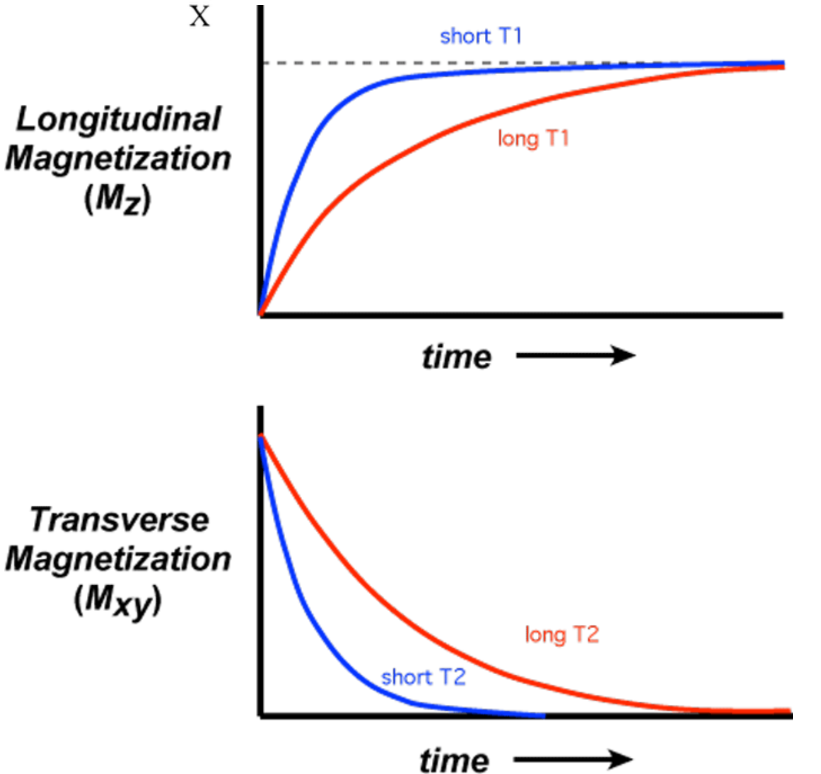
Longitudinal and transverse magnetization (T1 and T2)

- After RF pulse tilts spins, they precess in transverse (xy) plane, gradually re-aligning with B_0 (a)
  - This process is called *relaxation*
- Therefore, we speak of two magnetization components (b)
  - 1) **longitudinal** magnetization or M_z
  - 2) **transverse** magnetization or M_{xy}
- Biological tissue can be characterized by two different relaxation mechanisms:
  - **T1 relaxation** – the process by which net magnetization returns parallel to B_0
  - **T2 relaxation** – the process by which transverse component of magnetization decays

a)



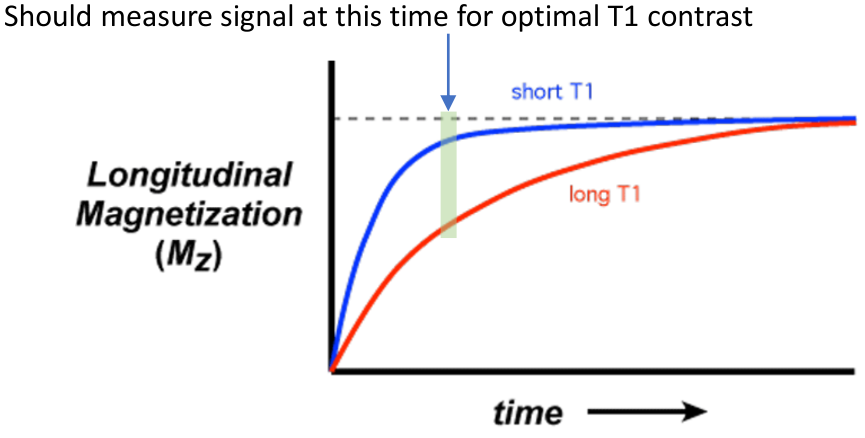
b)

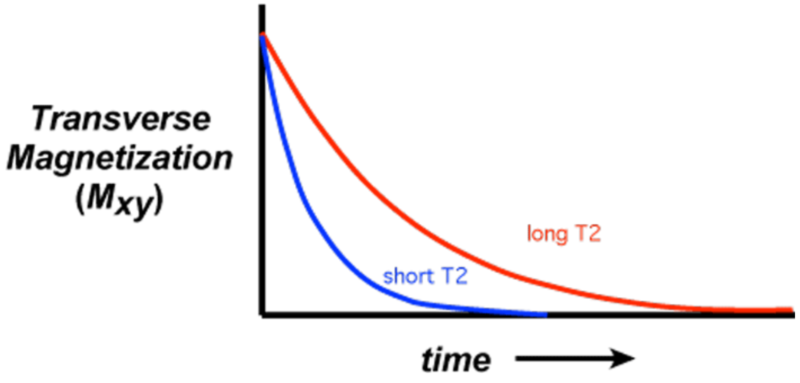


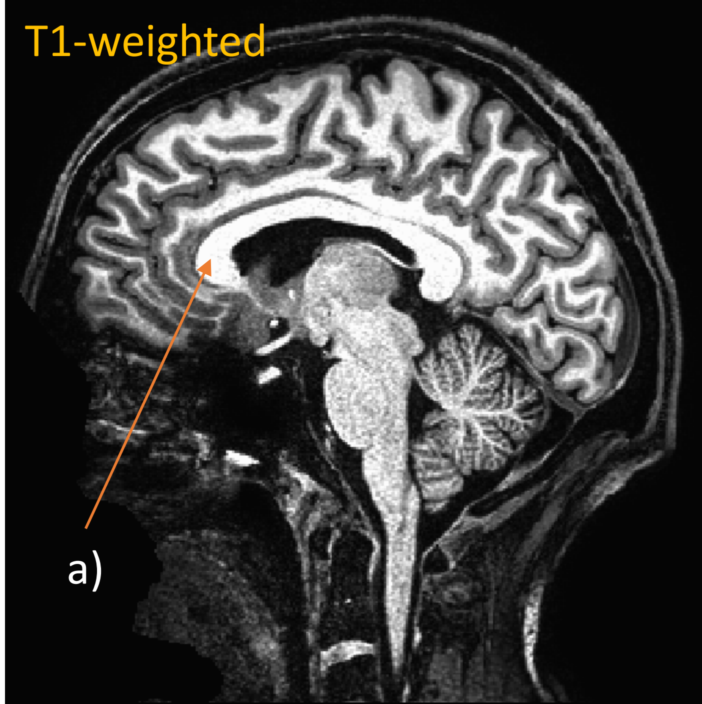
MRI image contrast

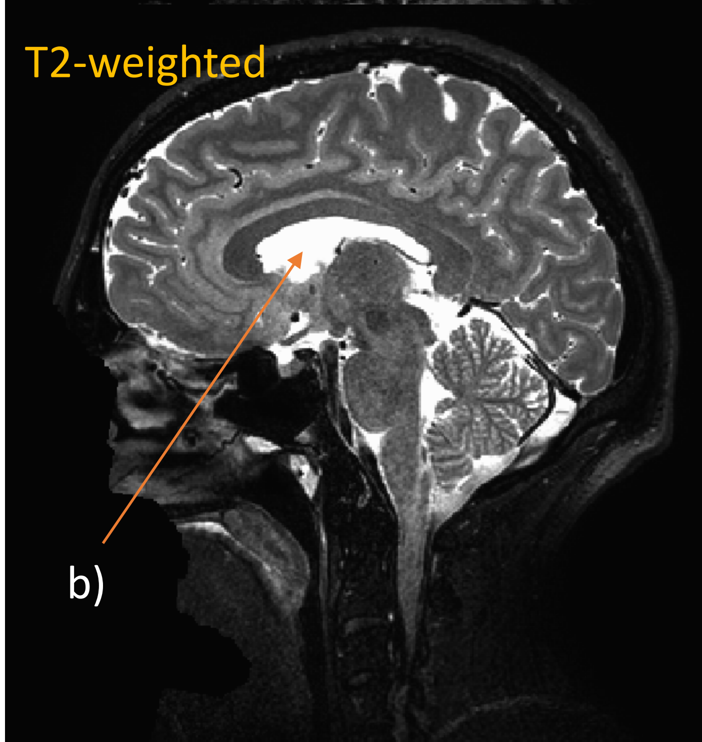
- What does it mean to say: ‘an image is T1-weighted’?
  - It means, roughly speaking, we are measuring in each voxel how long it takes for longitudinal magnetization (M_z) to recover
  - Tissue types where M_z recovers quickly will appear bright on a T1-weighted image – example: the *white matter* which is mostly fat (a)

- What does it mean to say: ‘an image is T2-weighted’?
  - It means, roughly speaking, we are measuring in each voxel how long it takes for transverse magnetization M_{xy} to decay
  - Tissue types where M_{xy} decays slowly (long T2) will appear bright on T2-weighted image – example: cerebrospinal fluid which is mostly water (b)



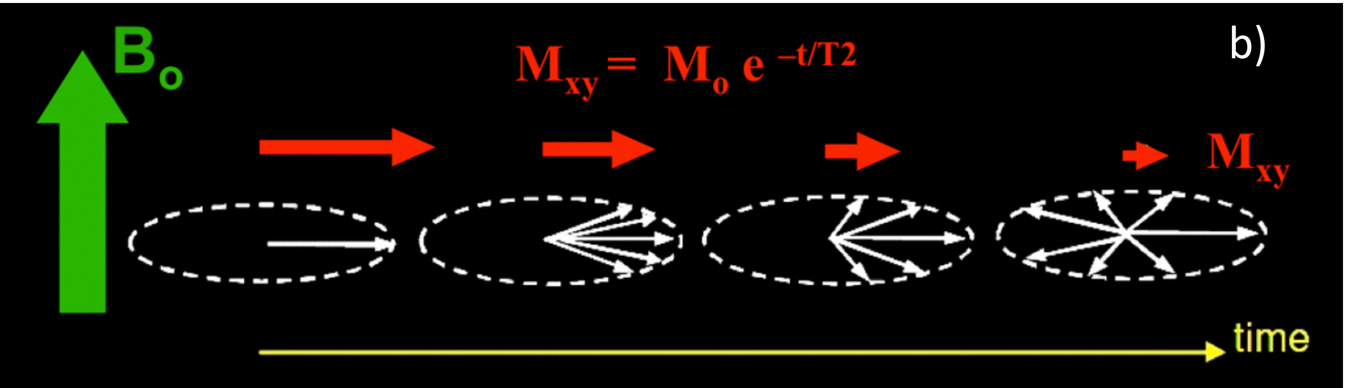






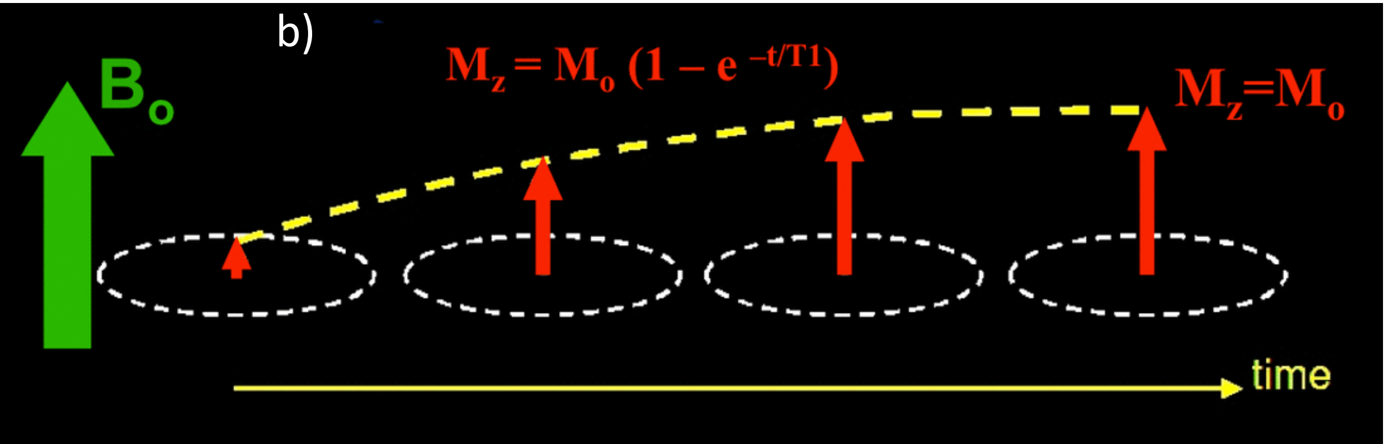
Closer look at T2 relaxation

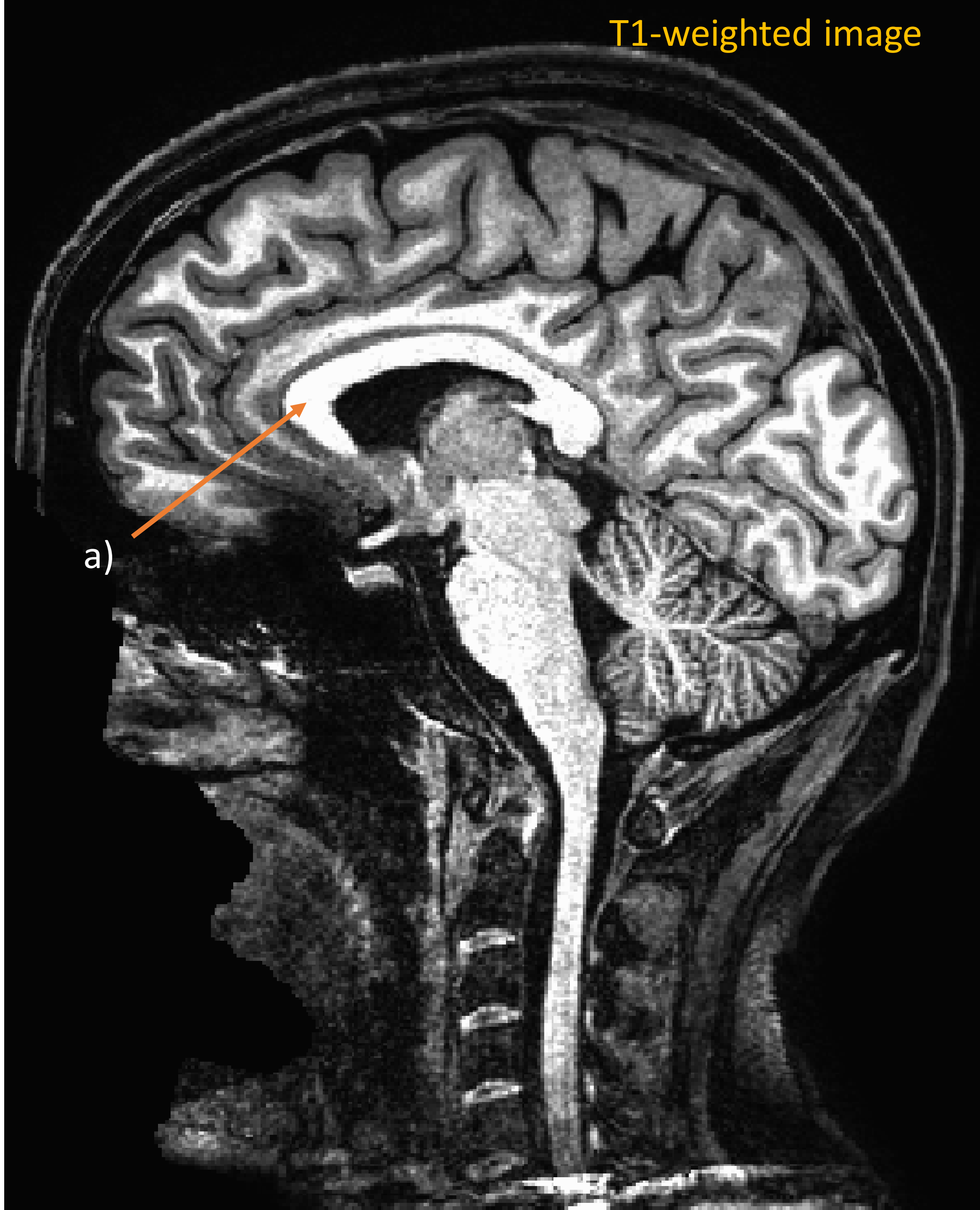
- a) the fluids appear bright on a T2-weighted image because transverse magnetization (M_{xy}) decays more slowly in fluids than in solid tissue
  - M_{xy} decay also called 'spin-spin relaxation'
- Can take 3-4 seconds for M_{xy} to decay in water
- Why does M_{xy} decay more slowly in fluid?
- Reasons for M_{xy} decay are complex, but basically, in water, M_{xy} decay occurs more slowly because spin-spin interactions aren't as strong as in other tissues
- b) M_{xy} decays exponentially with time due to *dephasing* (more on this later)



Closer look at T1 relaxation

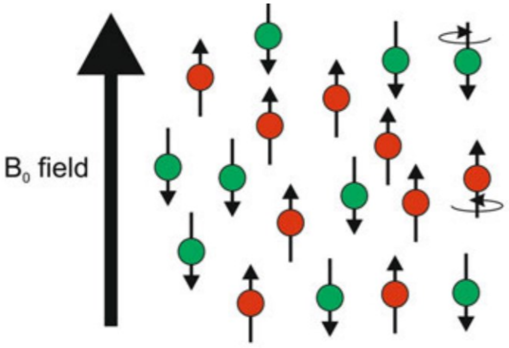
- a) solid tissue (fat in this example) appear bright in a T1-weighted image because longitudinal magnetization (M_z) recovers more quickly in solid tissues
  - T1 relaxation also called 'spin-lattice relaxation'
- Why does M_z recover more quickly in solids than in fluids?
- M_z recovery is fastest when molecular tumbling rate is equal to Larmor frequency
- Water has wide range of tumbling rates, so M_z recovery is slower in water
- b) T1 relaxation is the process by which net magnetization returns to its initial maximum value M_0



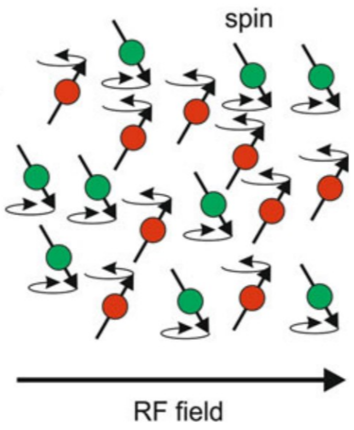


Magnetic resonance <u>imaging</u>

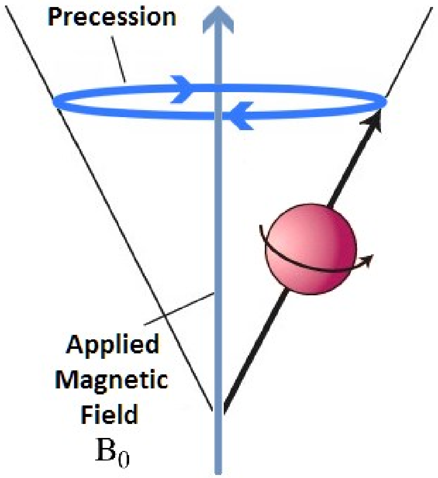
1)



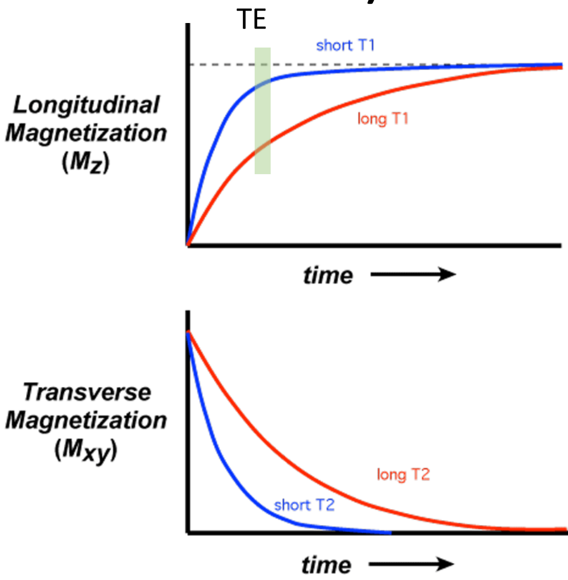
2)



3)



4)

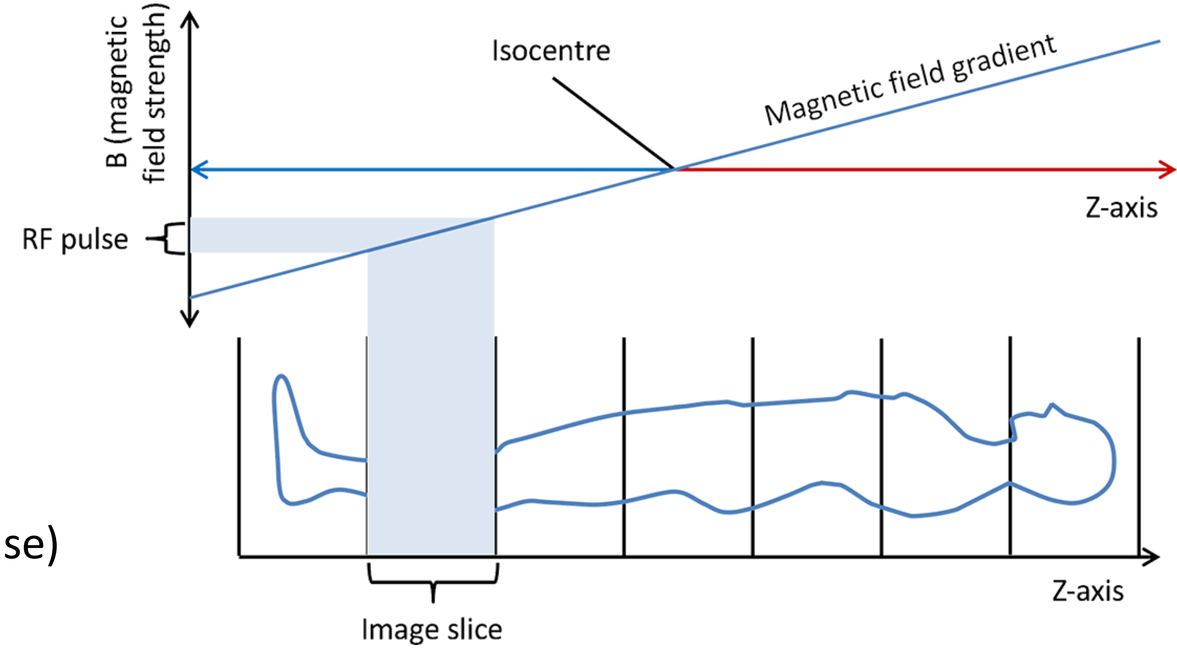


- We saw basic MRI experiment is as follows:
  - **1)** place sample in strong magnetic field B_0, causing hydrogen atoms (spins) to align with B_0
  - **2)** apply RF pulse to deposit energy into sample, tilting spins away from B_0 direction
    - If you want to understand *why* this works, take PHY361 Quantum Mechanics
  - **3)** spins precess back into alignment with B_0, creating measurable signal (electromagnetic induction)
  - **4)** decide some optimal time to measure signal from this changing magnetic field
    - Time at which we measures is called ‘echo time’ or TE, we set TE to achieve maximum contrast
- Problem? This doesn’t give us an **image**.
  - RF pulse tilts spins in entire sample (all spins have same resonant frequency due to B_0)
    - This basic experiment captures signal from *entire sample.* We want to know signal from each voxel!
  - We need a way to *spatially encode* which spins our RF pulse will tilt away from B_0
  - Solution? Magnetic field *gradients* (next slide)

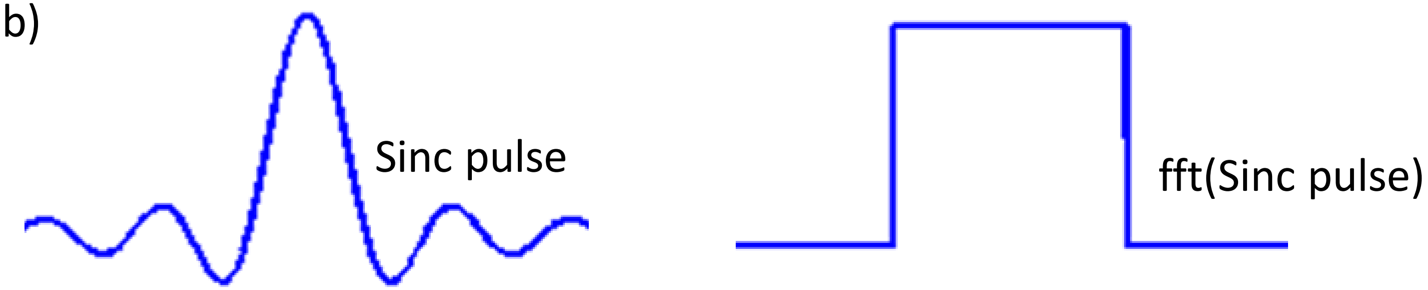
Slice selection with magnetic field gradients

- Recall the Larmor frequency: $\omega = \gamma B_0 = 127.74\ \text{MHz}$ for hydrogen at 3 Tesla
  - Basically, all hydrogen atoms are spinning at 127.74 MHz, if placed in a 3 T magnetic field
- To *select a slice* for imaging, apply *magnetic field gradient* (a)
  - Changes slightly the Larmor frequency of spins (gradient adds to B_0)
    - Example (a) – spins slightly slower near feet, spins slightly faster near head
    - Protons now spin with frequency that depends on their location in Z
- Craft RF pulse to match Larmor frequency of slice we want to image
  - Typically, *sinc pulse* (b) is used because it's FFT is a rectangle (allows to select rectangular slice)
  - Applying sinc pulse while gradient is on allows to selectively measure signal from spins in a single slice of the body we are attempting to image

a)



b)

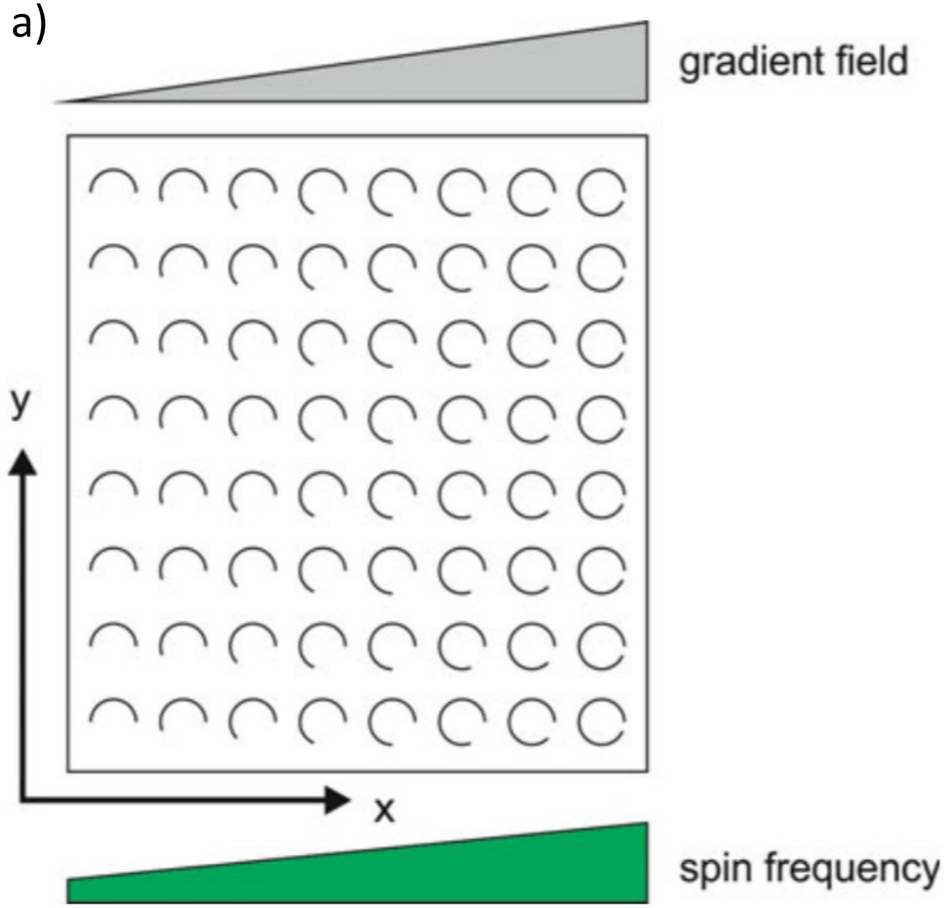


Frequency encoding

- Gradient applied and sinc pulse delivered. Now measuring spins from single slice.
- How to localize spins within a slice? Use *frequency encoding*

- Frequency encoding:
    - Turn off original (Z) gradient used for slice selection
    - Apply gradient in x-direction, recorded signal now contains a *range* of frequencies (a)
    - Frequencies w_0 to w_{max} correspond to x-values x_0 to x_{max}.
    - Do FFT of measured signal, magnitude of frequency $w_0 + (w_{max} - w_0) \cdot (x_k - x_0)/(x_{max} - x_0)$ now corresponds to response of all protons on line $x = x_k$
    - This produces projection of spin density along y onto the x axis
    - Complete set of projections can be obtained by adding projections at measurements with gradient fields along different directions.
    - Using this data, can reconstruct image using filtered backprojection
    - This was the original method. Now we use k-space imaging (next slide)

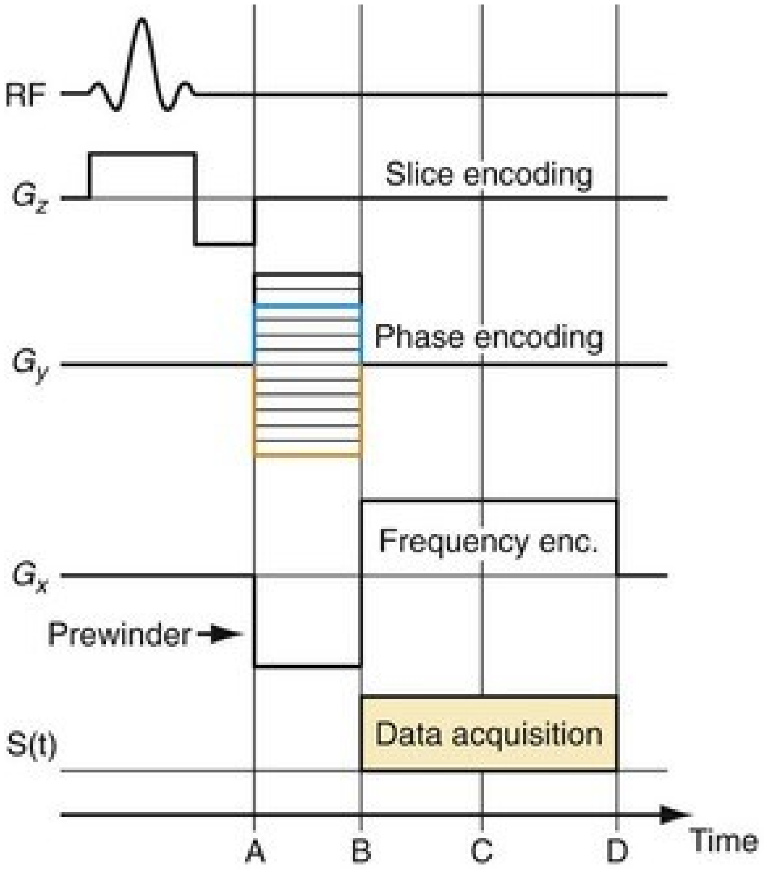
a)



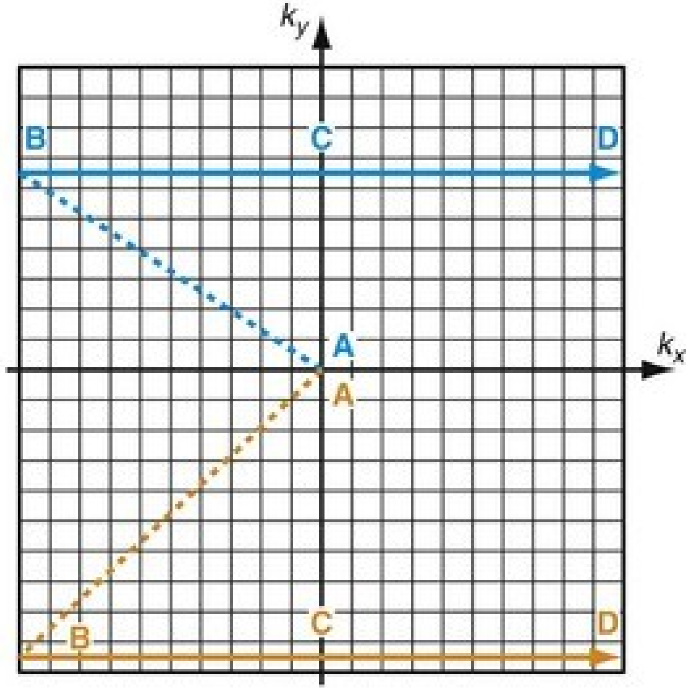
K-space imaging (frequency space imaging)

- K-space imaging: generate image in frequency space, then apply ifft to get image

- 1) apply gradient G_z in z-direction to isolate a slice
- 2) apply another linear gradient in y-direction, increasing spin frequency along y, spins dephase (this is called the *phase encoding* gradient)
- 3) apply frequency encoding gradient and acquire data, signal is transformed into frequency space
- Result is integrated spin densities along x weighted with cosine wave of frequency 1 for each line of constant y.
- In other words, we have produced real-valued part of next line in k-space of the Fourier transform in the k_x direction. Imaginary part is computed by weighting signal with corresponding sine wave.
- Repeat the measurement with phase encoding for remaining lines in k-space. Once k-space is filled, image is generated by transforming it back into spatial domain (ifft)



K-space (frequency space)
Each cell in the grid represents a 2d wave with specific spatial frequency and orientation



- Excellent talk by David Higgins. Watch this talk, come back and re-read slides. Repeat until you understand.
- https://youtu.be/29iffcZPQeM