Introduction to MRI Physics

Slides originally by Karla Miller, FMRIB Centre

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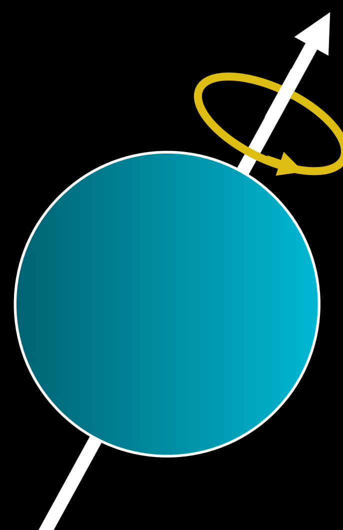


Slides available at:

http://users.fmrib.ox.ac.uk/~mchiew/teaching/

MRI Physics

Monday:

- ★ Basics of magnetic resonance
- ★ Image formation
- ★ Signal statistics (SNR)
- ★ Functional MRI

Wednesday:

- ★ Image contrast (T_2 and T_2^*)
- ★ Spin vs. gradient echo
- ★ Fast imaging
- ★ Diffusion MRI

What are we trying to achieve?

Informed decision making: You need to take responsibility for the design, implementation & execution of your study

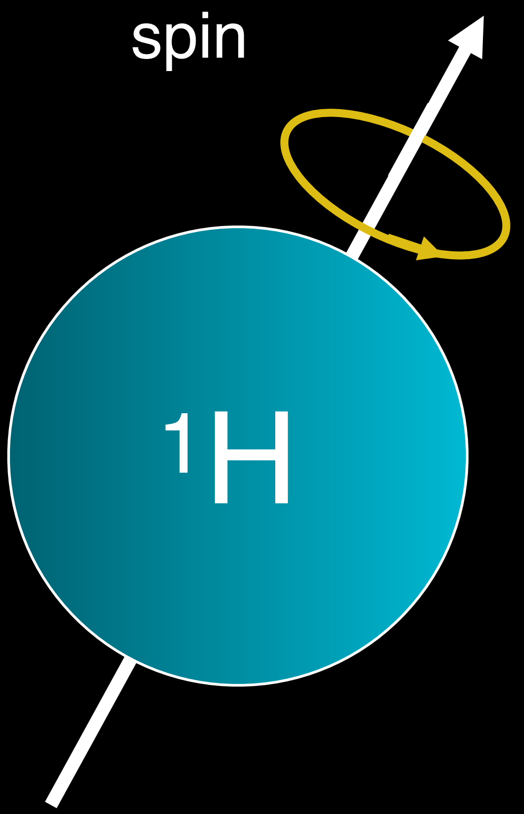
- Protocols need to be tailored to the problem
- Learning some physics will make this less daunting

A common language: You need to be able to talk to experts

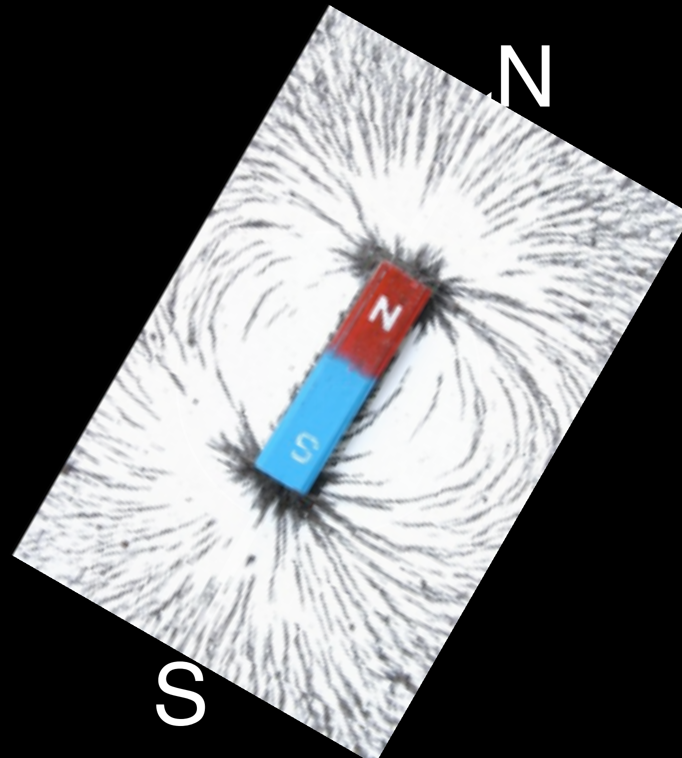
- Communicate your needs to physicists/radiographers/techs
- Build an MR vocabulary (terminology/jargon)
- Gain some intuition behind imaging concepts

MRI Physics

- ★ Basics of magnetic resonance
- ★ Image formation
- ★ Signal statistics (SNR)
- ★ Functional MRI



“Spin”

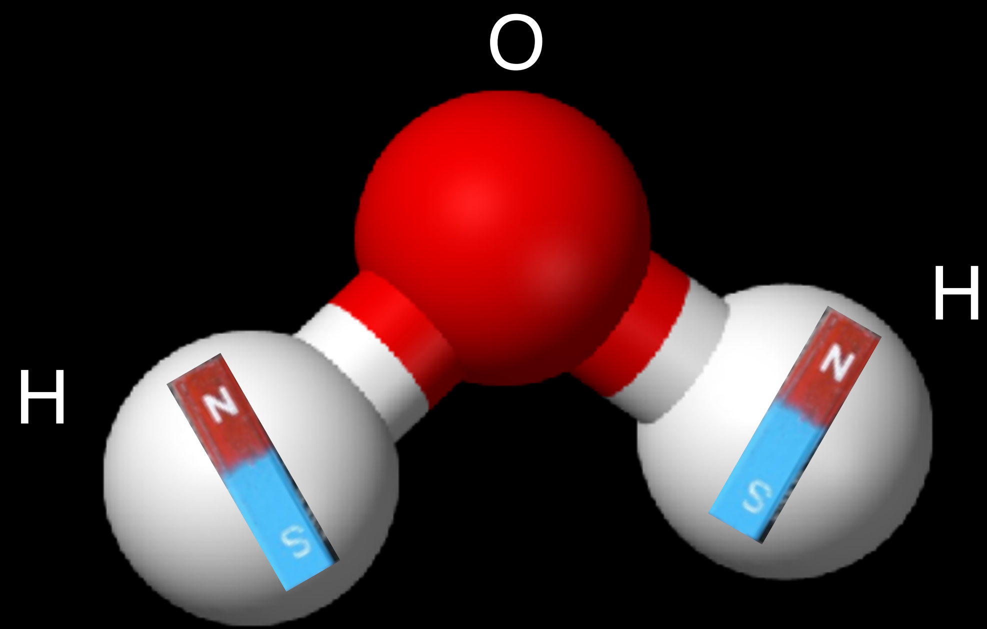


Almost all sub-atomic particles have “spin”

- All nuclei with odd numbers of protons/neutrons will have non-zero net spin

^{1}H, ^{13}C, ^{23}Na, ^{31}P

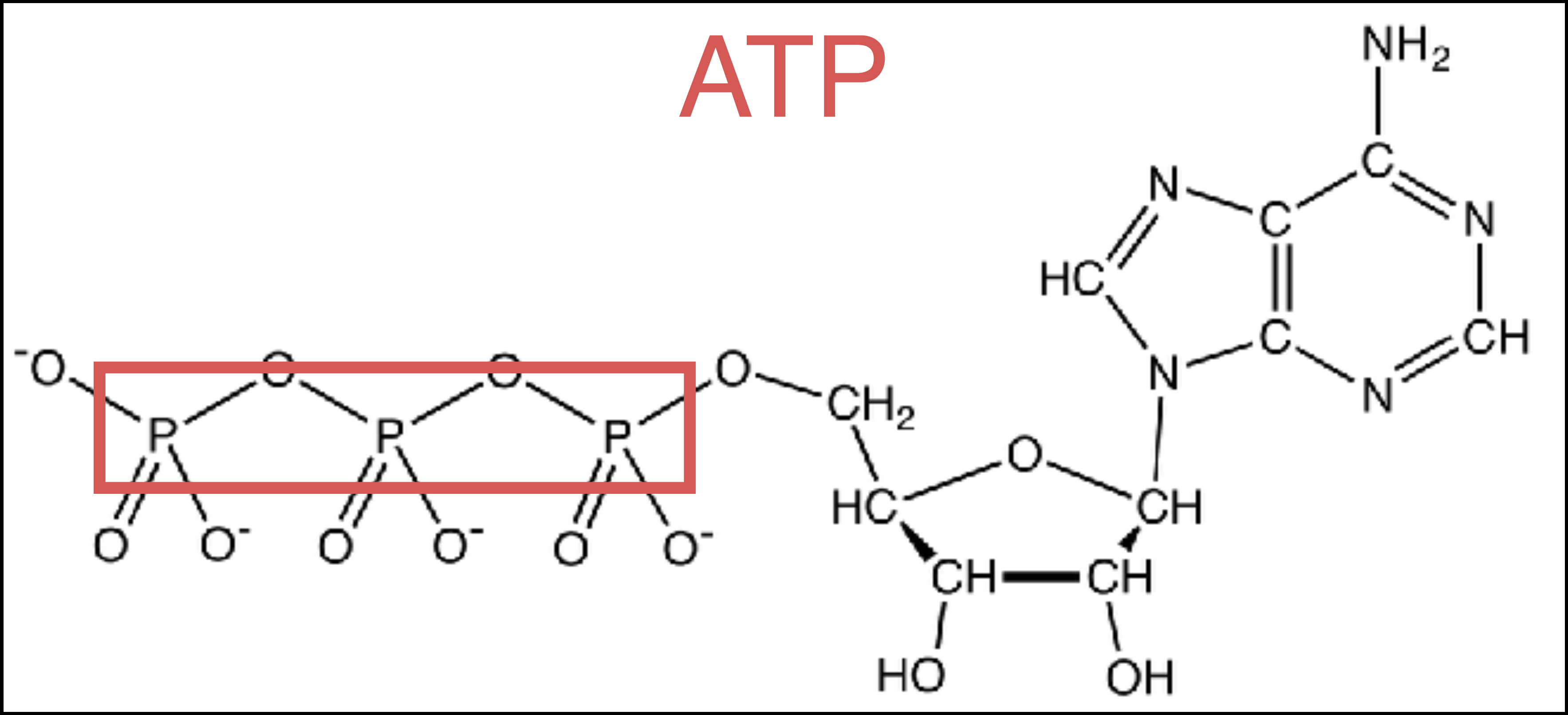
All hydrogen protons will act like little magnets



The abundance of water in the human body makes this very powerful!

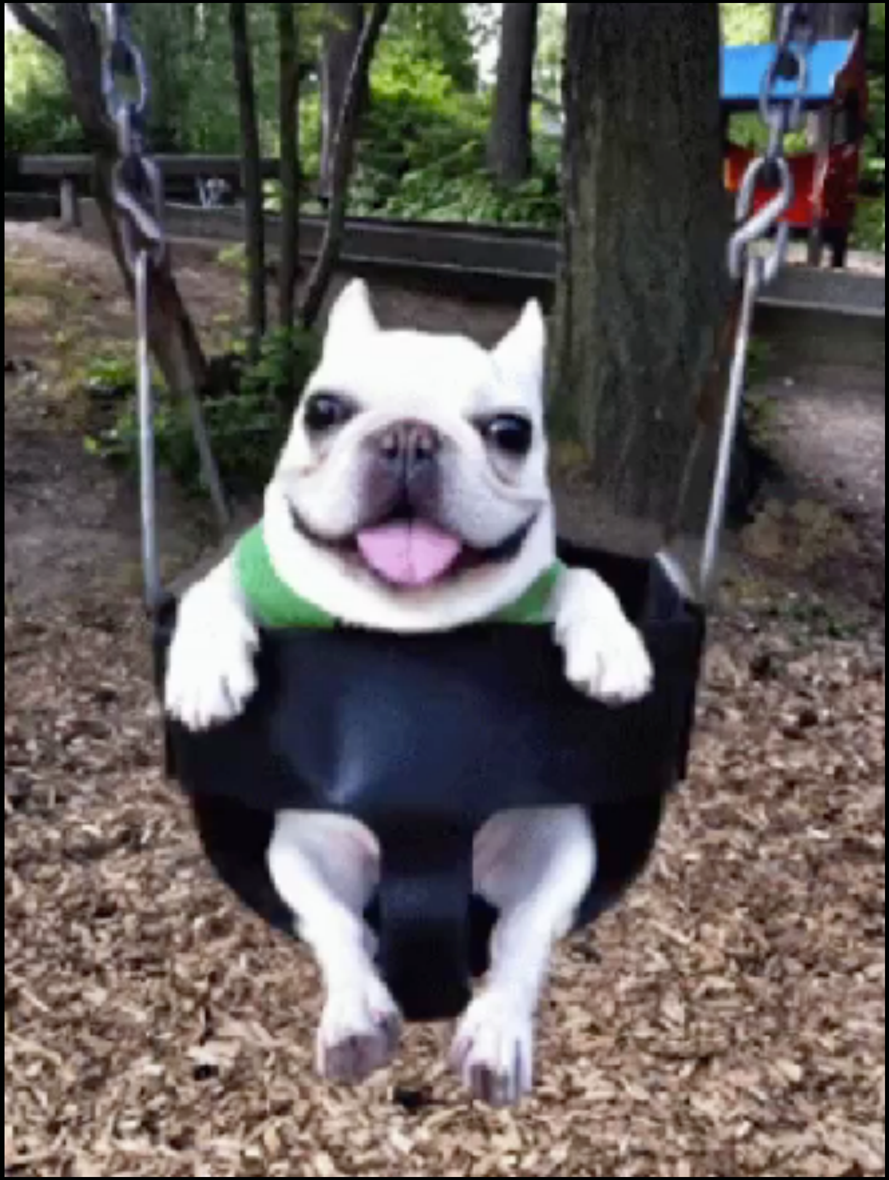
^{1}H, ^{13}C, ^{23}Na, ^{31}P

Can also do this with phosphorous nuclei



Spins, or magnetization (when referred to in bulk) behave similarly to classic physical systems

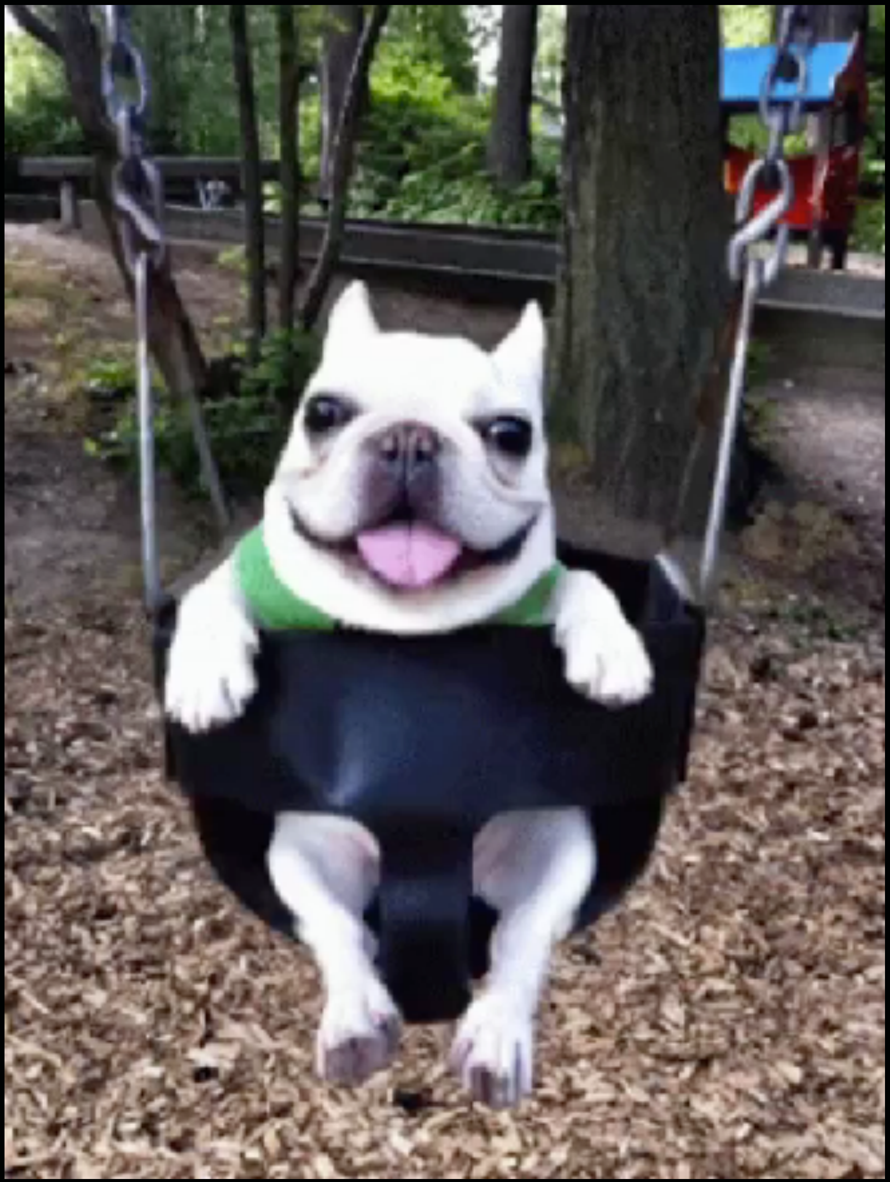
In many ways analogous to simple oscillators, like swings or pendulums



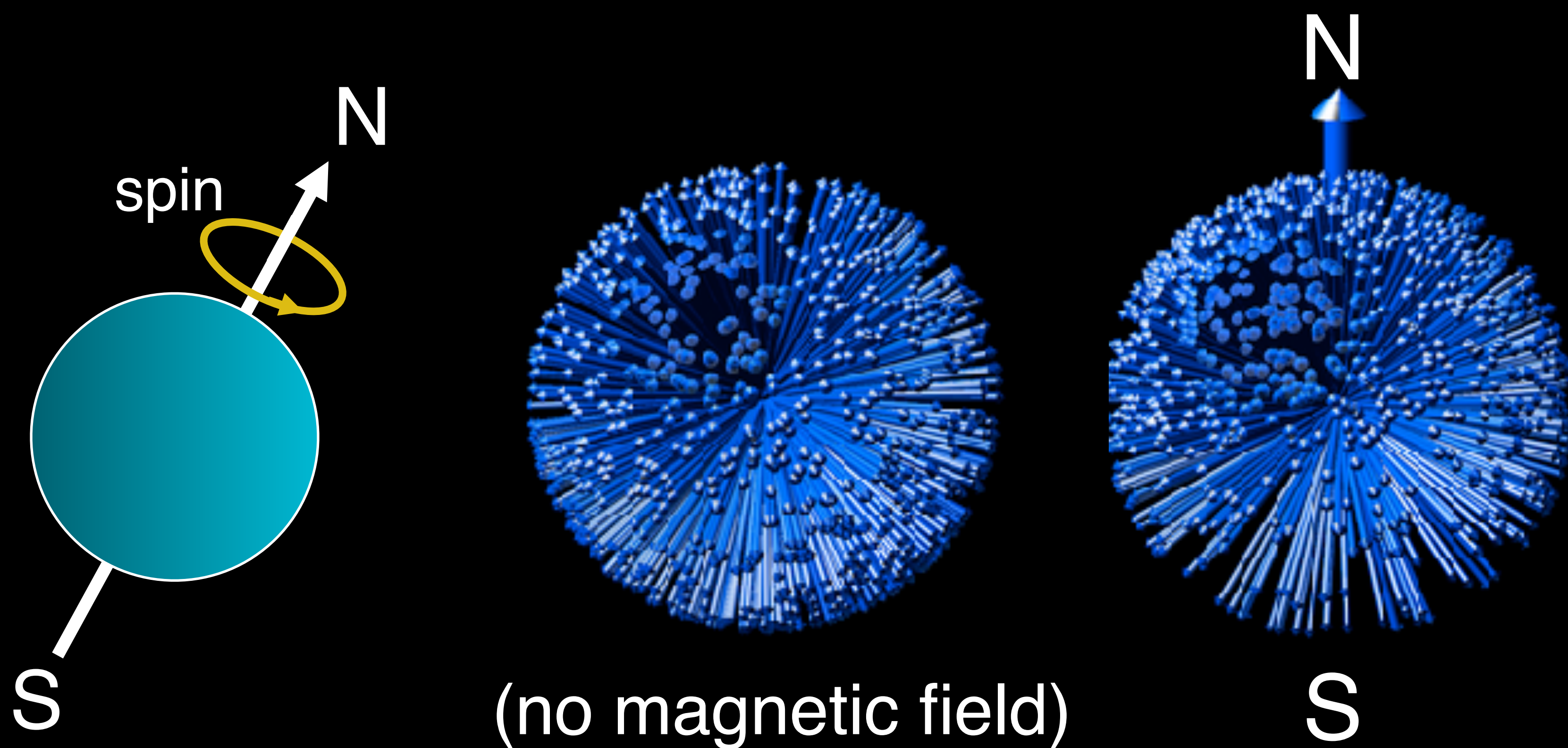
1. Excitation
   Magnetization can be moved or rotated by applying “excitation” magnetic fields (RF)

2. Resonance
   Magnetization will “resonate” at a frequency proportional to magnetic field strength

3. Relaxation
   The oscillations die out, i.e. magnetisation “relaxes” back to equilibrium – speed of relaxation is tissue-dependent!



The External Magnetic Field (B_0)



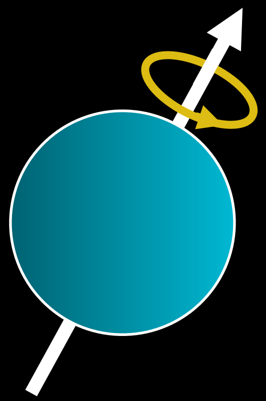
Normally: protons randomly oriented ⇒ no net magnetism

External field: protons align slightly ⇒ *net magnetization (M)*

Only a few parts-per-million!

Magnetic resonance

Magnetic: external field (B_0) magnetizes sample

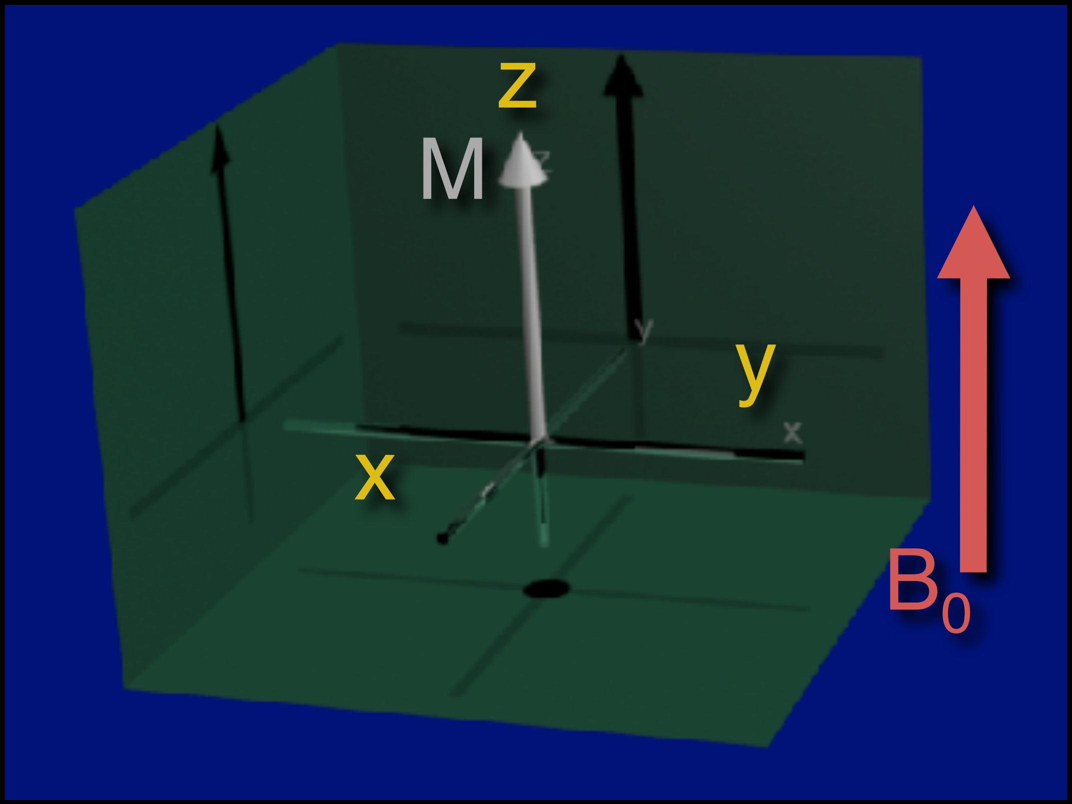


$$\omega_0 = \gamma B_0$$

This “Larmor Equation” defines the resonant frequency

Resonance: magnetization has characteristic (resonant) frequency proportional to external field B_0

Coordinate system

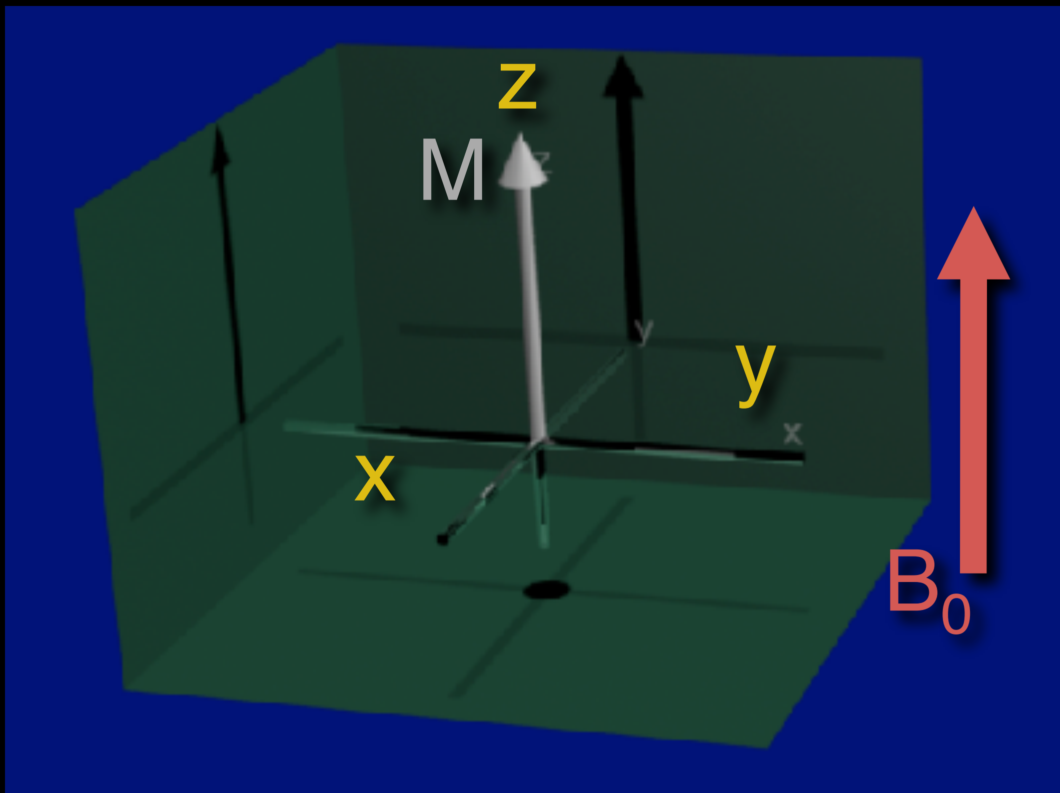


Direction of main field (B_0) defines coordinate system

Longitudinal axis: parallel to B_0 (typically z)

Longitudinal magnetisation: Portion of M aligned with B_0

Coordinate system

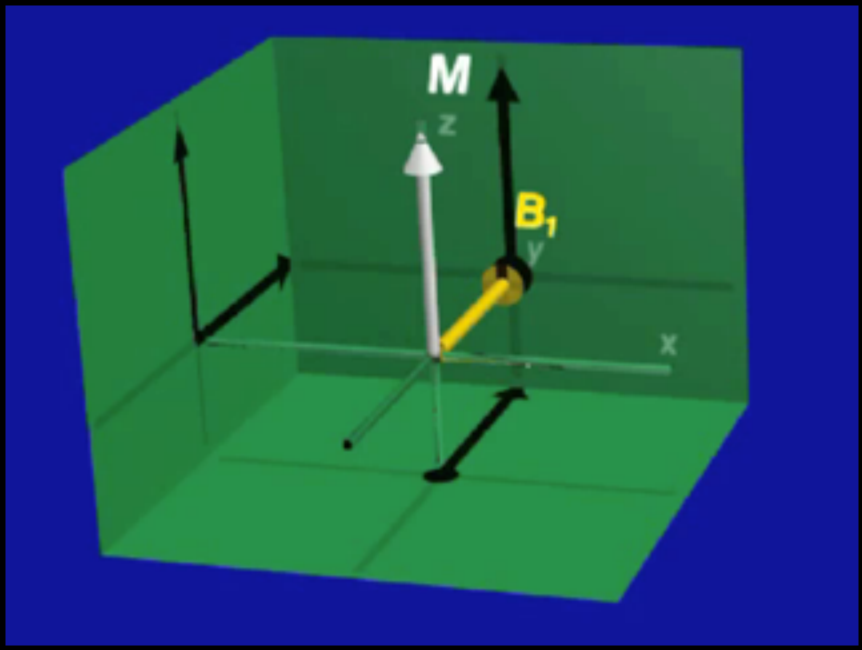


Direction of main field (B_0) defines coordinate system

Transverse plane: perpendicular to B_0 (typically x,y)

Transverse magnetisation: Portion of M perpendicular to B_0

The Basic MRI Experiment:
1. Excitation



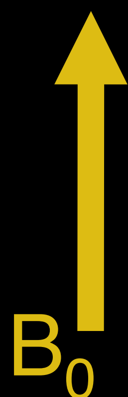
courtesy of William Overall

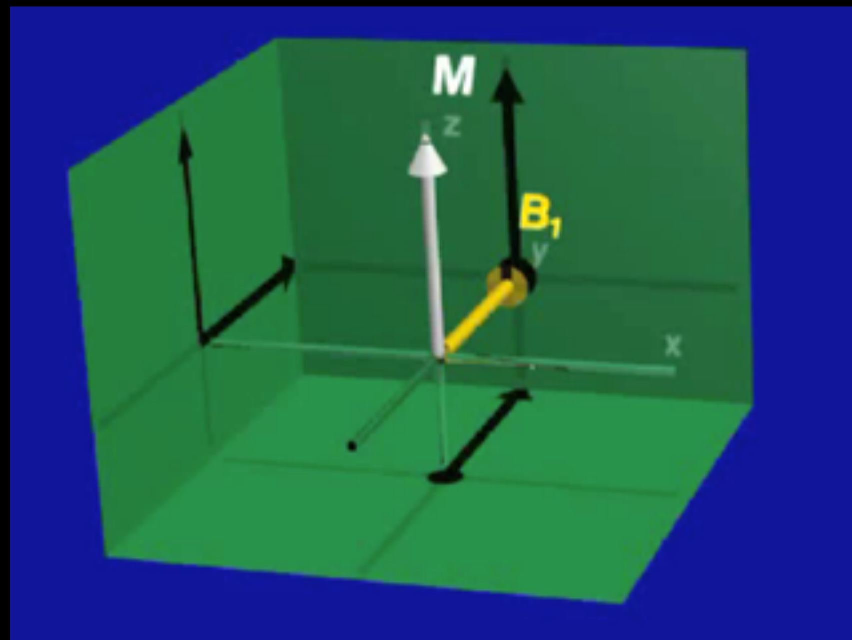
$$\omega_0 = \gamma B_0$$

Excitation pulse (yellow) tips magnetisation away from B_0

Excitation must occur at the resonant frequency ω_0

The Basic MRI Experiment:
1. Excitation



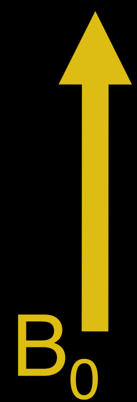


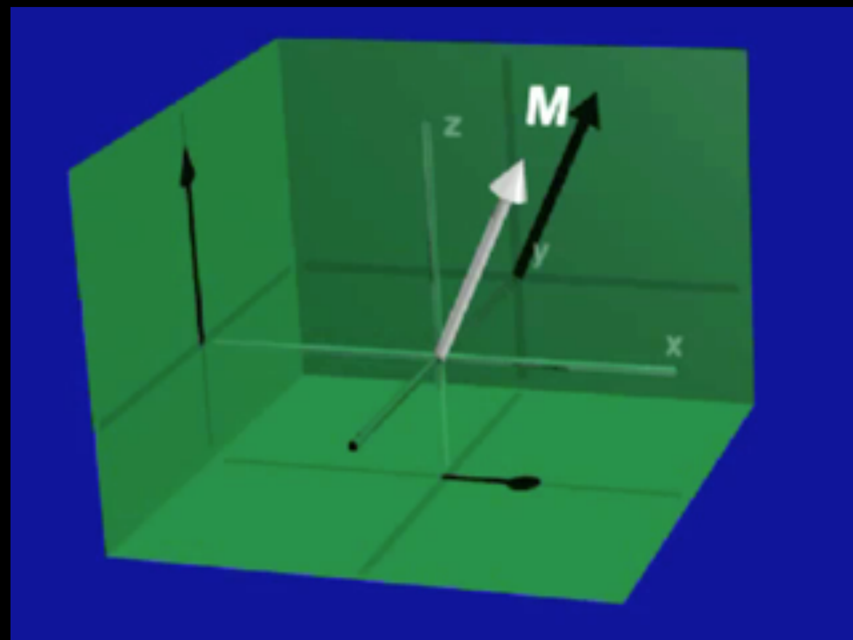
courtesy of William Overall

In a frame that rotates with B_1, magnetisation is simply "flipped" or "tipped" out of alignment with B_0

Hence the term "flip angle" or "tip angle"

The Basic MRI Experiment:
2. Resonant Precession



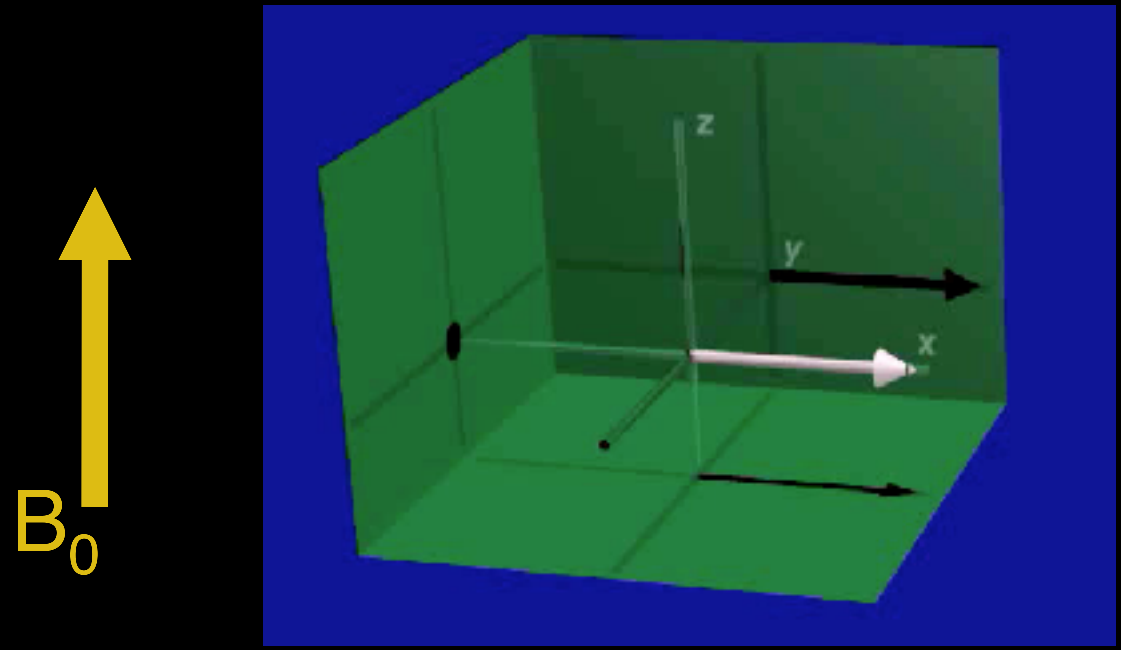


courtesy of William Overall

$$\omega_0 = \gamma B_0$$

Once excited, magnetisation precesses/oscillates/rotates at resonance frequency

The Basic MRI Experiment:
3. Relaxation

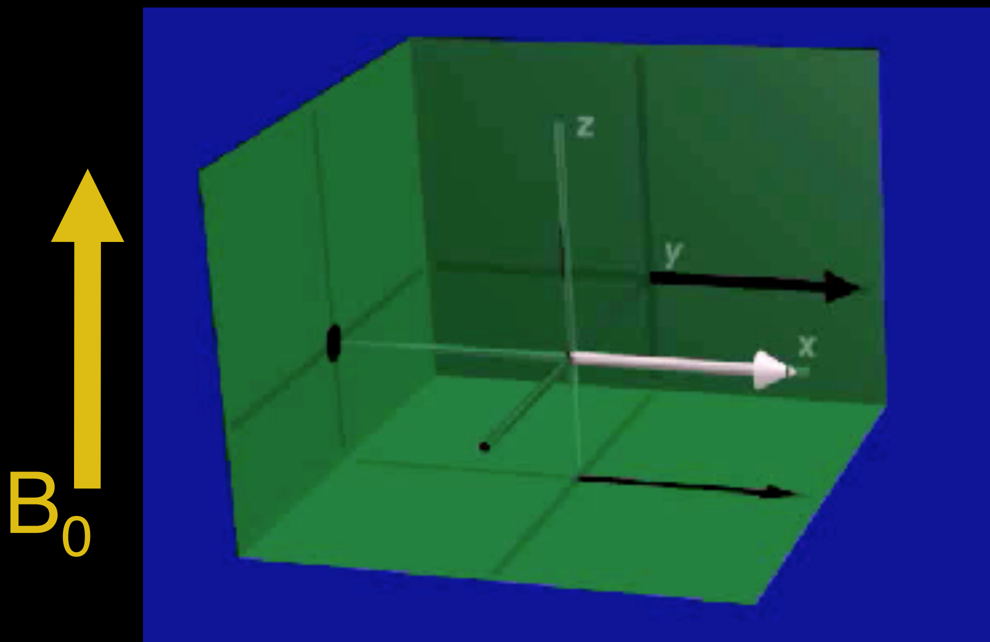


courtesy of William Overall

As it precesses, it also "relaxes" back into alignment with B_0

Speed of relaxation has time constants: T_1, T_2, T_2^*, which relate to the image contrast

The Basic MRI Experiment:
3. Relaxation



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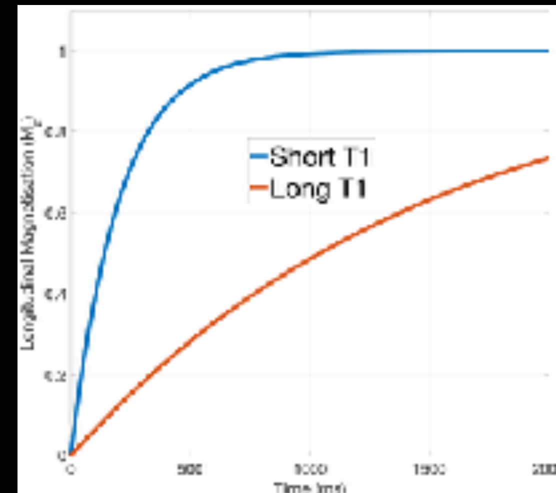
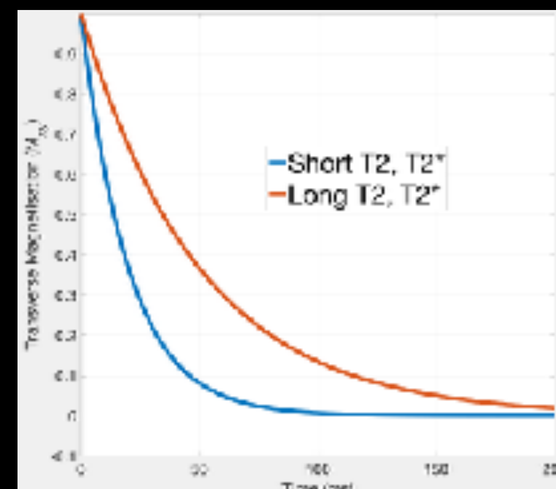
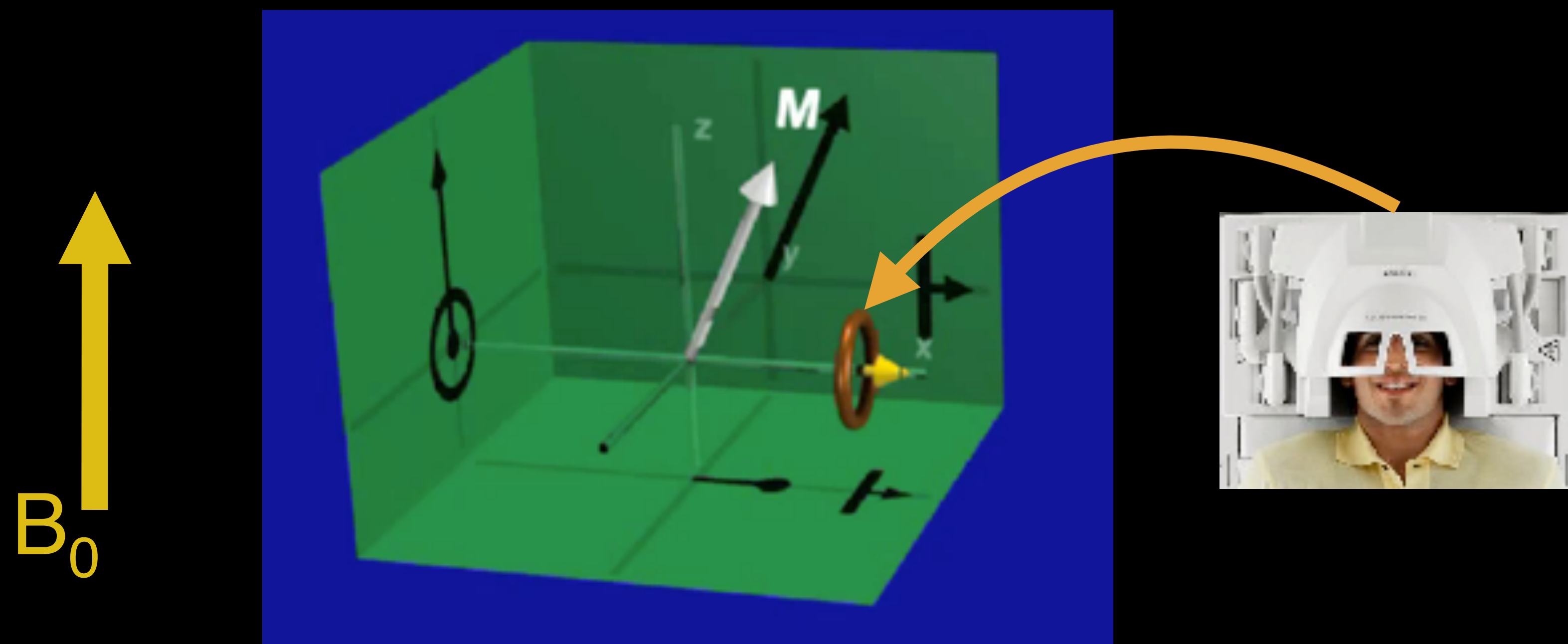




T_1 : describes speed of recovery along longitudinal (z) axis

T_2, T_2^* : describe speed of signal decay in transverse (x-y) plane

The Basic MRI Experiment:
4. Signal Detection



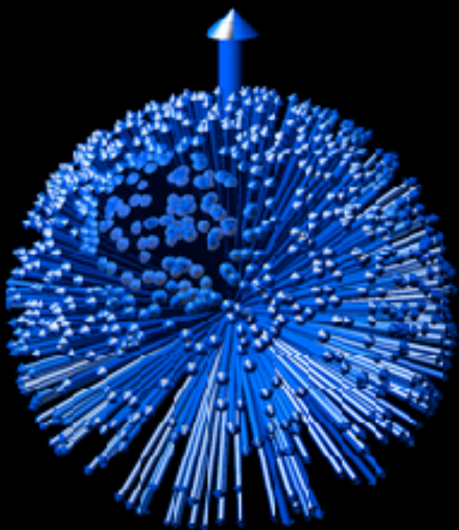
courtesy of William Overall

As the magnetization precesses and relaxes

The precession induces a voltage in the receive coils

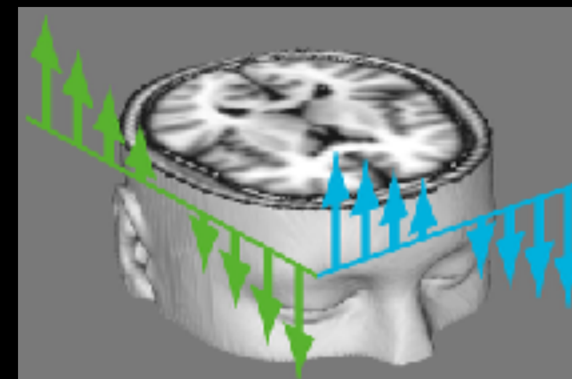
Coils only detect rotating, transverse magnetisation

Magnetic fields everywhere…



B_0

B_1



G_x, G_y

Main magnetic field (B_0): always on, static

Excitation RF field (B_1): pulsed on & off, 60-300 MHz

Magnetic field gradients (G): pulsed on & off, “static”

MRI scans: carefully timed RF and gradient “pulse sequences”

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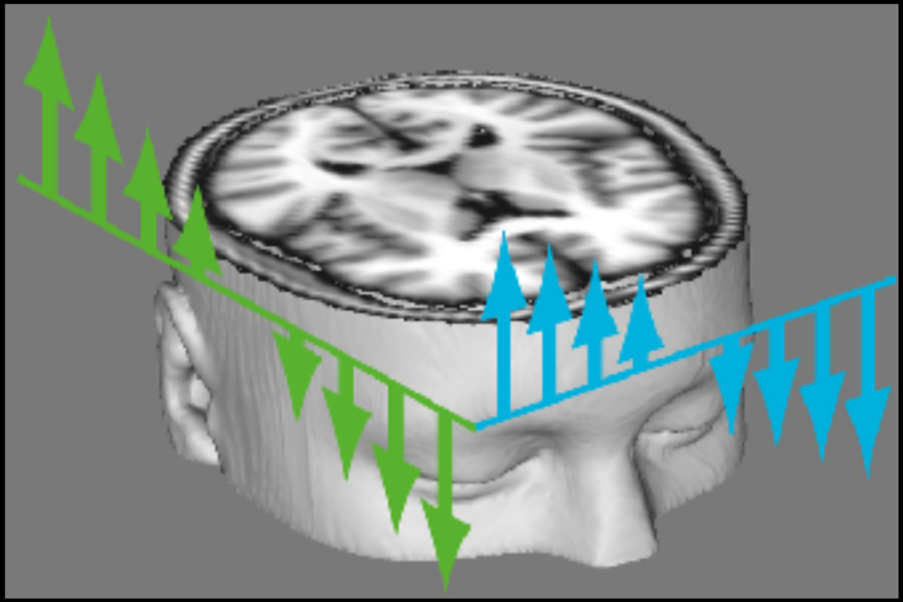
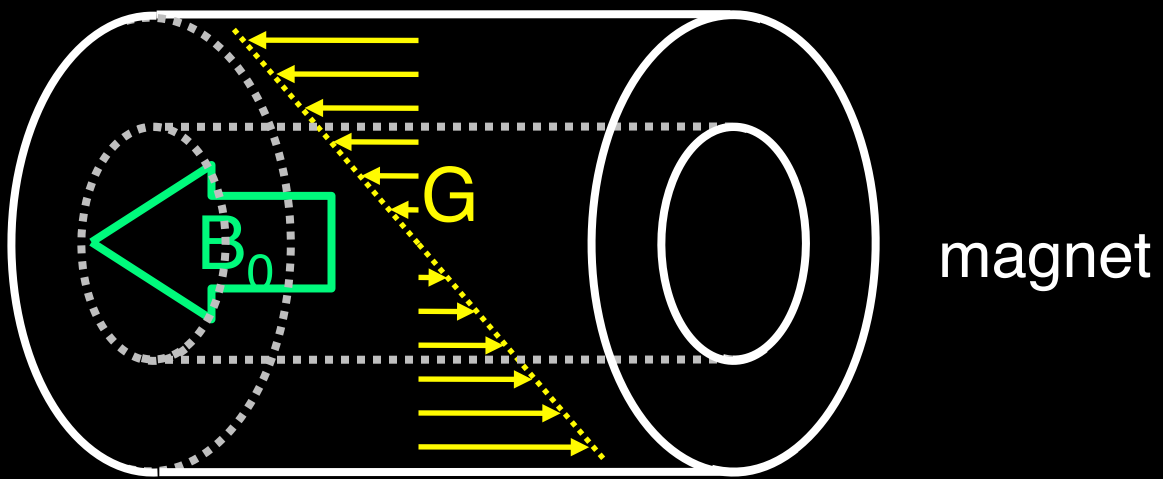


Magnetic Field Gradients

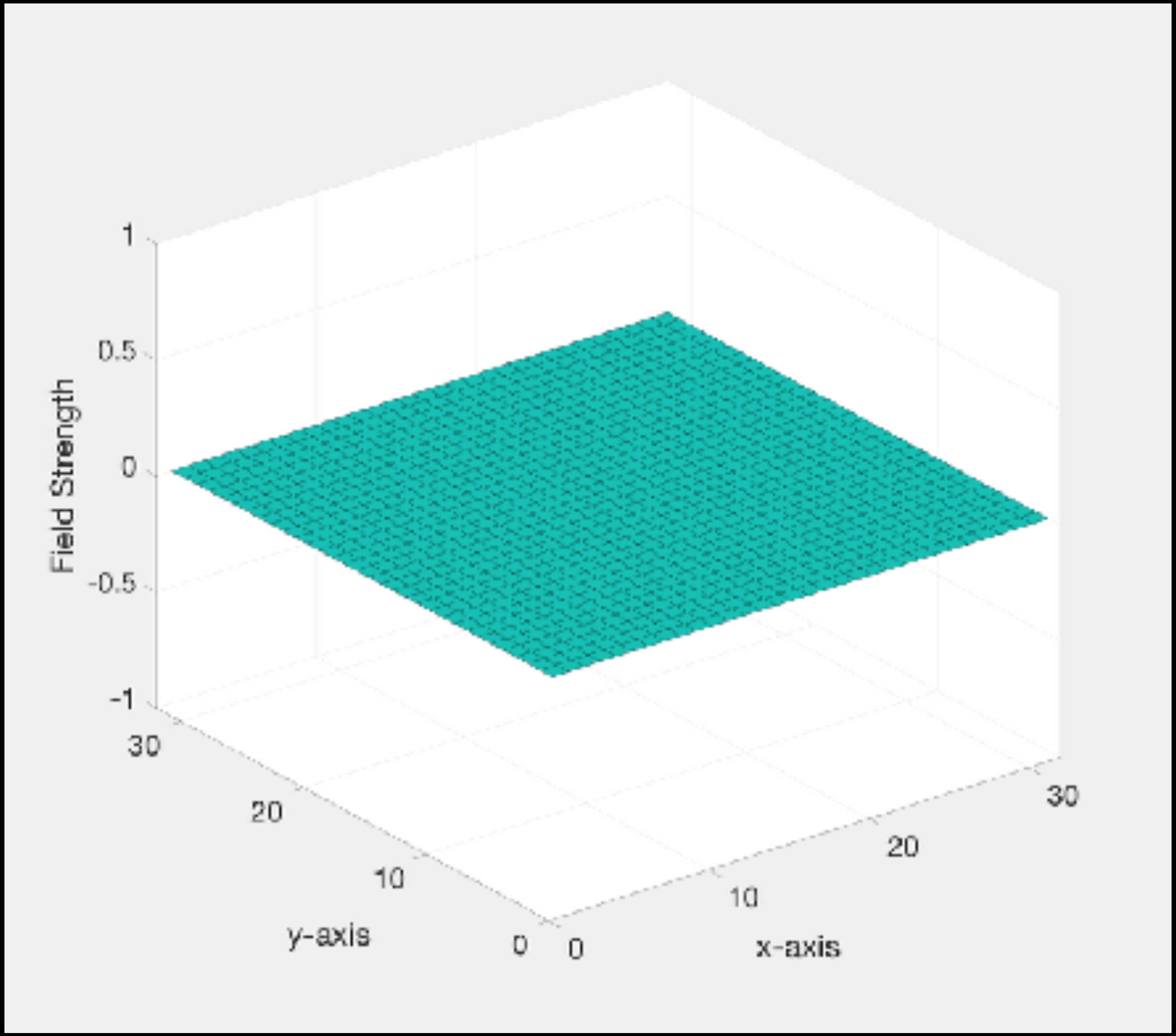


Differentiate between signal from different locations

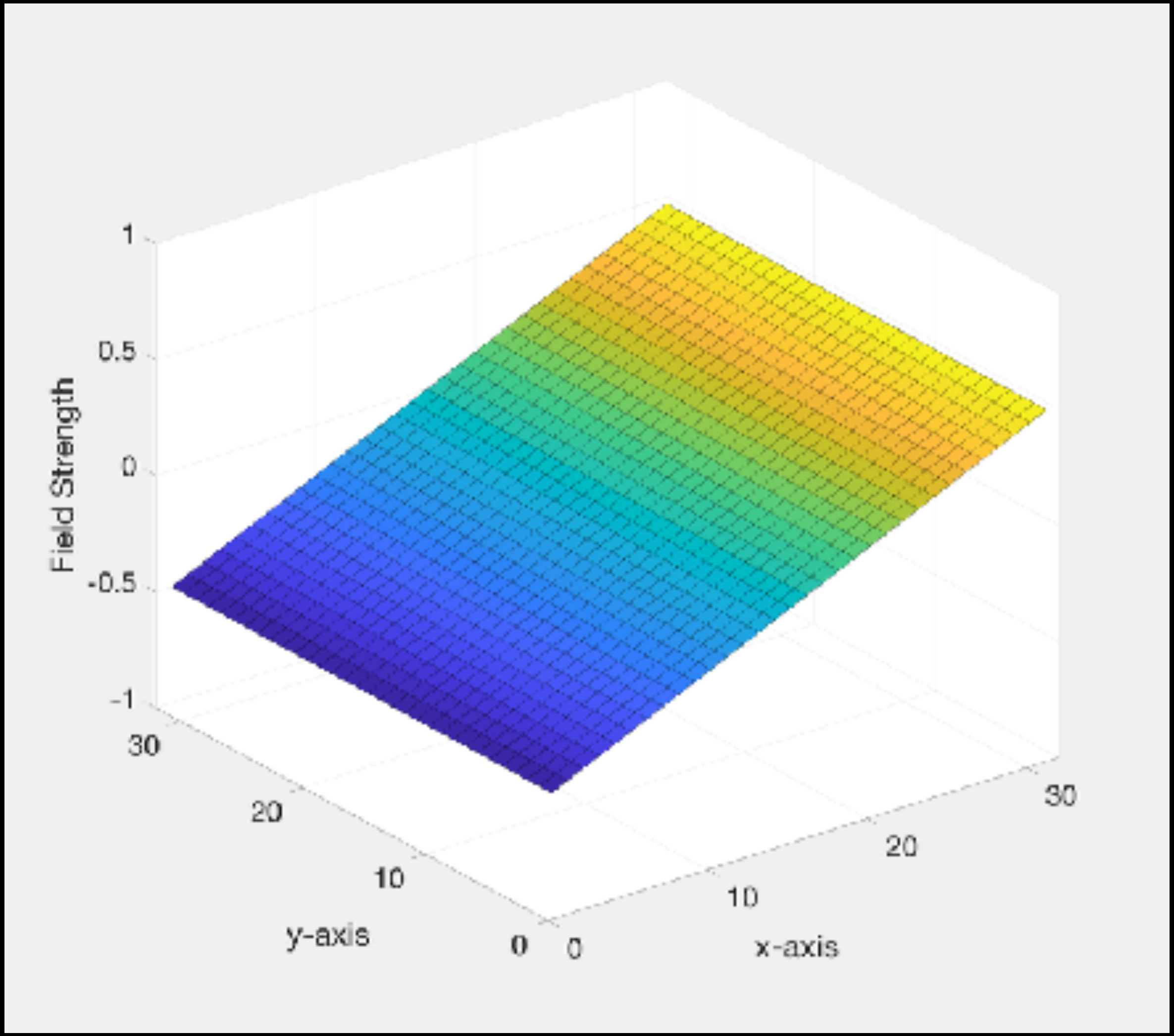
Add a spatially varying magnetic field gradient (G)

- Field varies linearly along one direction
- Gradient field adds to or subtracts from B_0

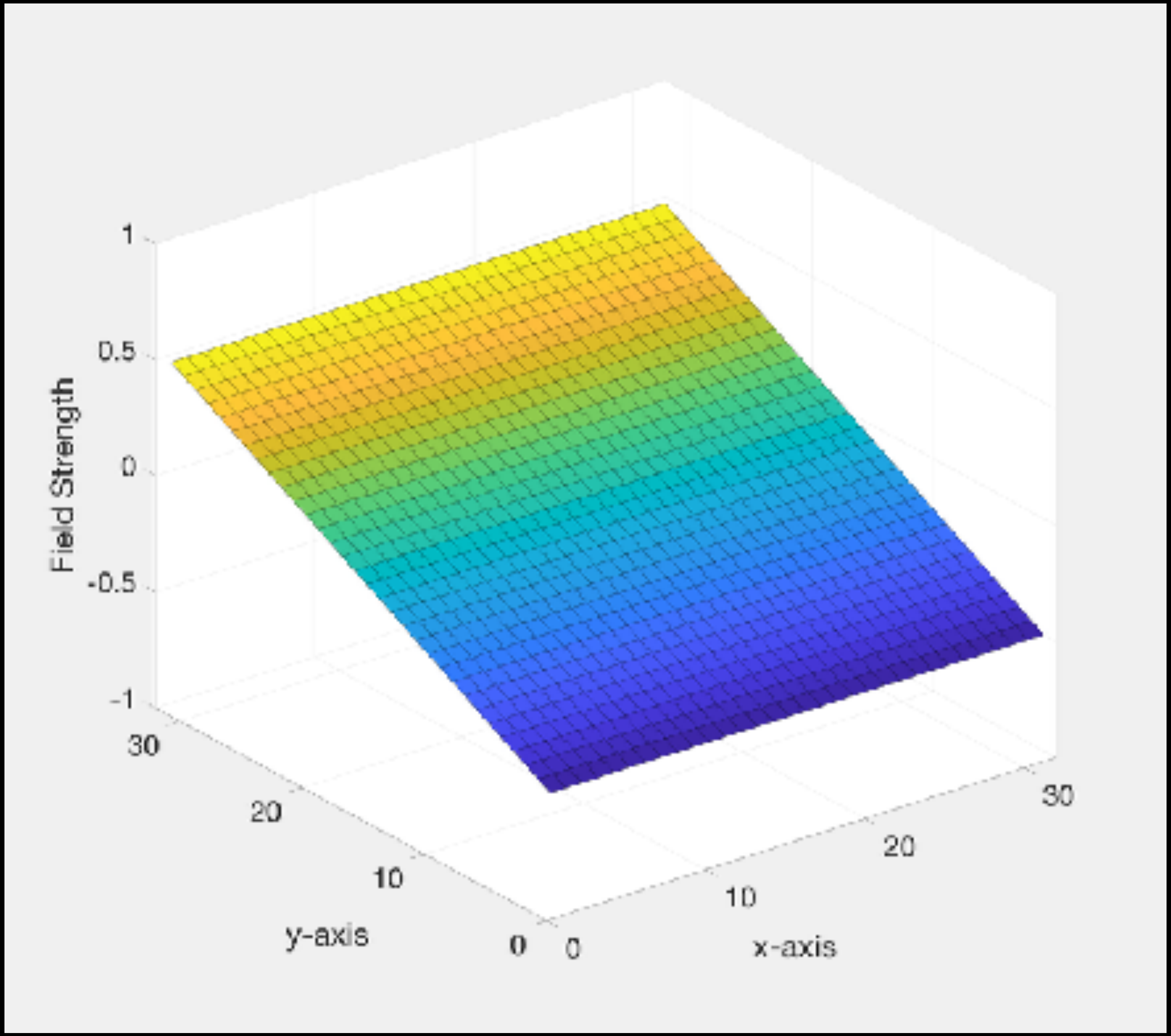
No Gradient



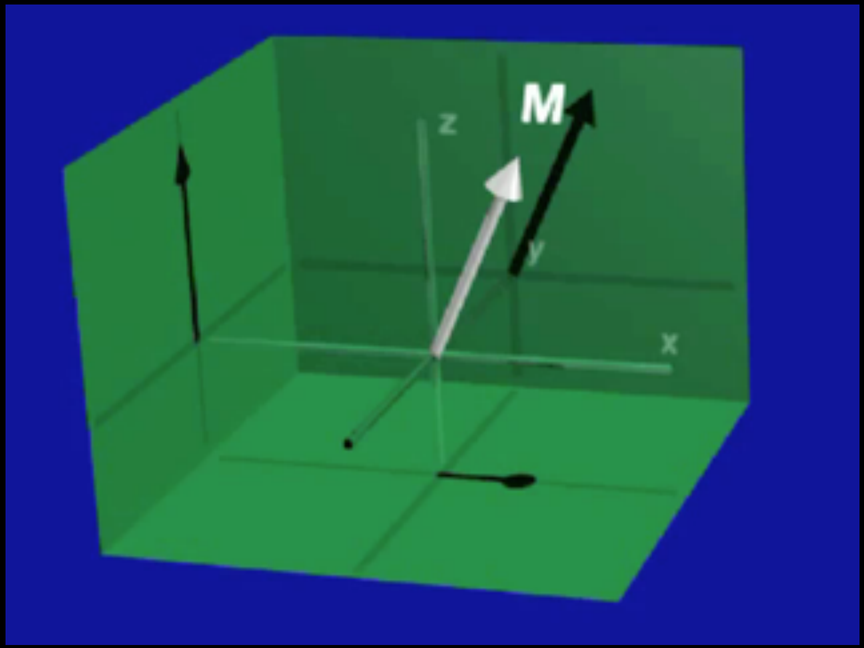
x-Gradient



y-Gradient



Precession



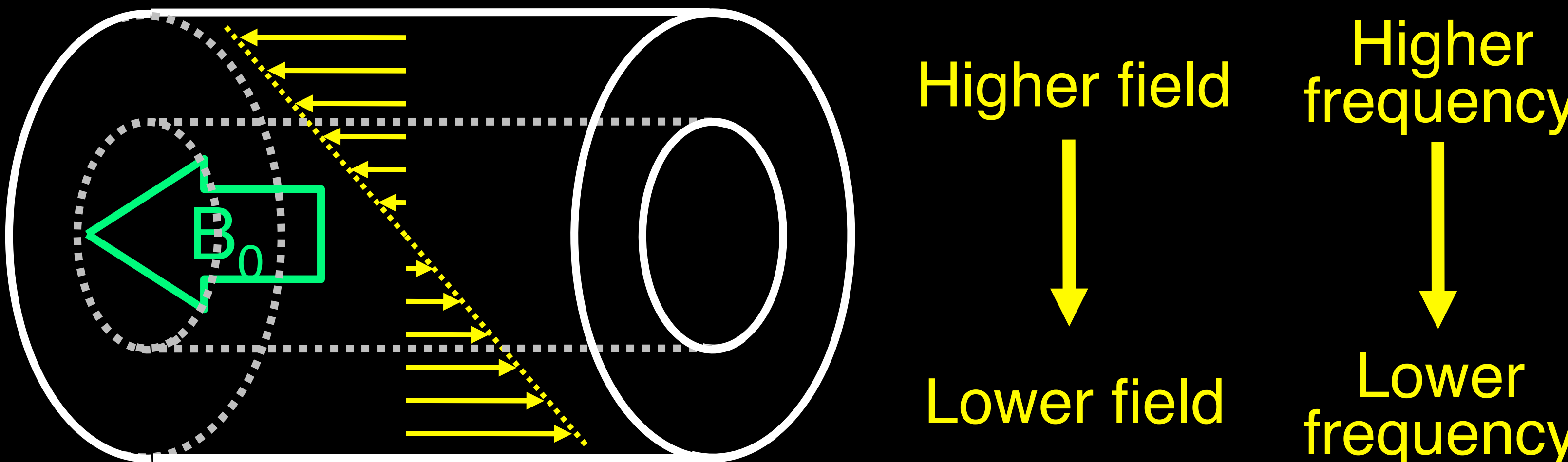
courtesy of William Overall

$$\omega_0 = \gamma(B_0 + G(x,y,z))$$

Resonance frequency is proportional to total field:
Static B_0 + applied gradients

Gradients and Resonance

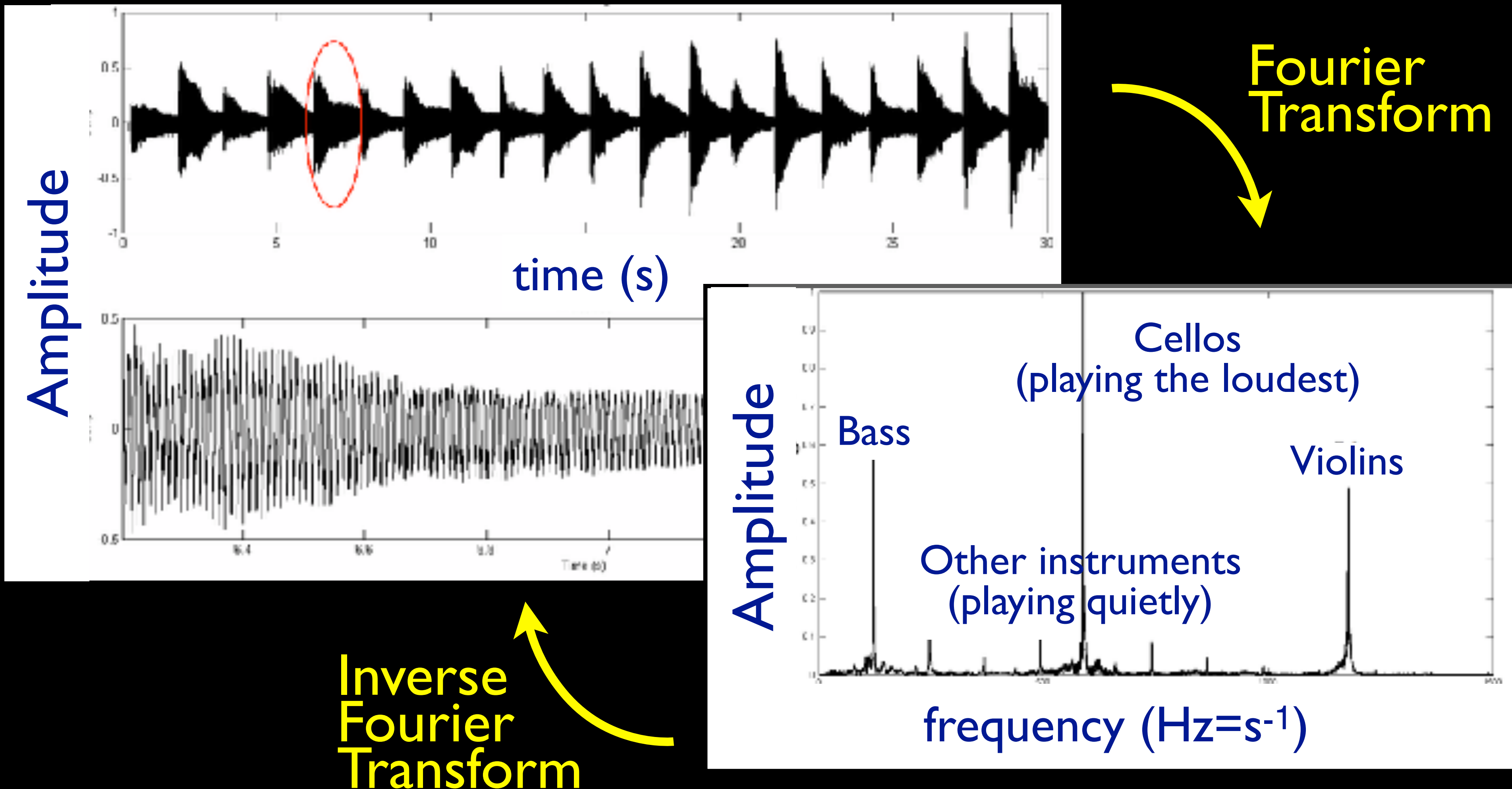
$$\omega_0 = \gamma(B_0 + G(x,y,z))$$



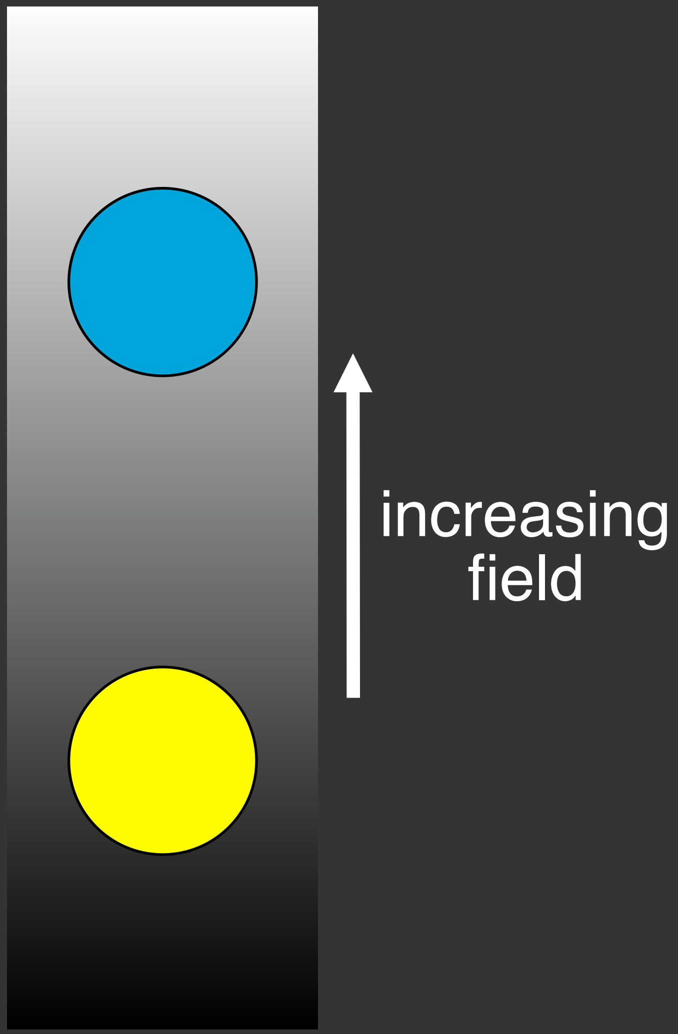
Distinguish different spatial locations by assigning different resonant frequencies to different positions

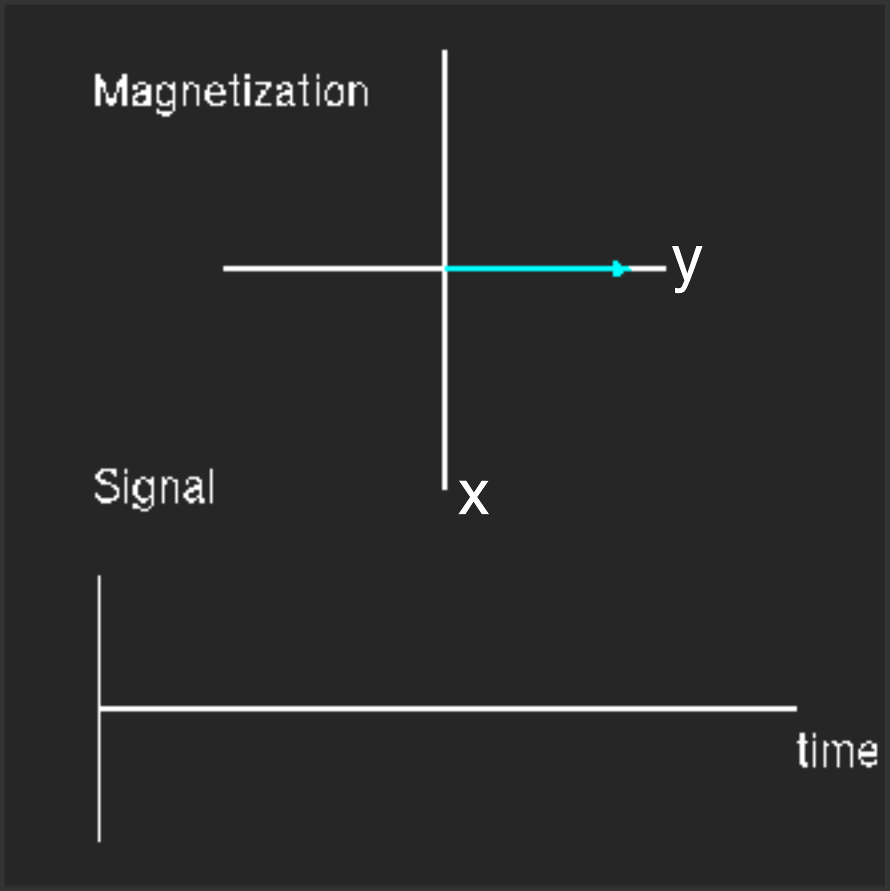
Imagine differentiating between instruments based on their frequency content!

Frequency decomposition

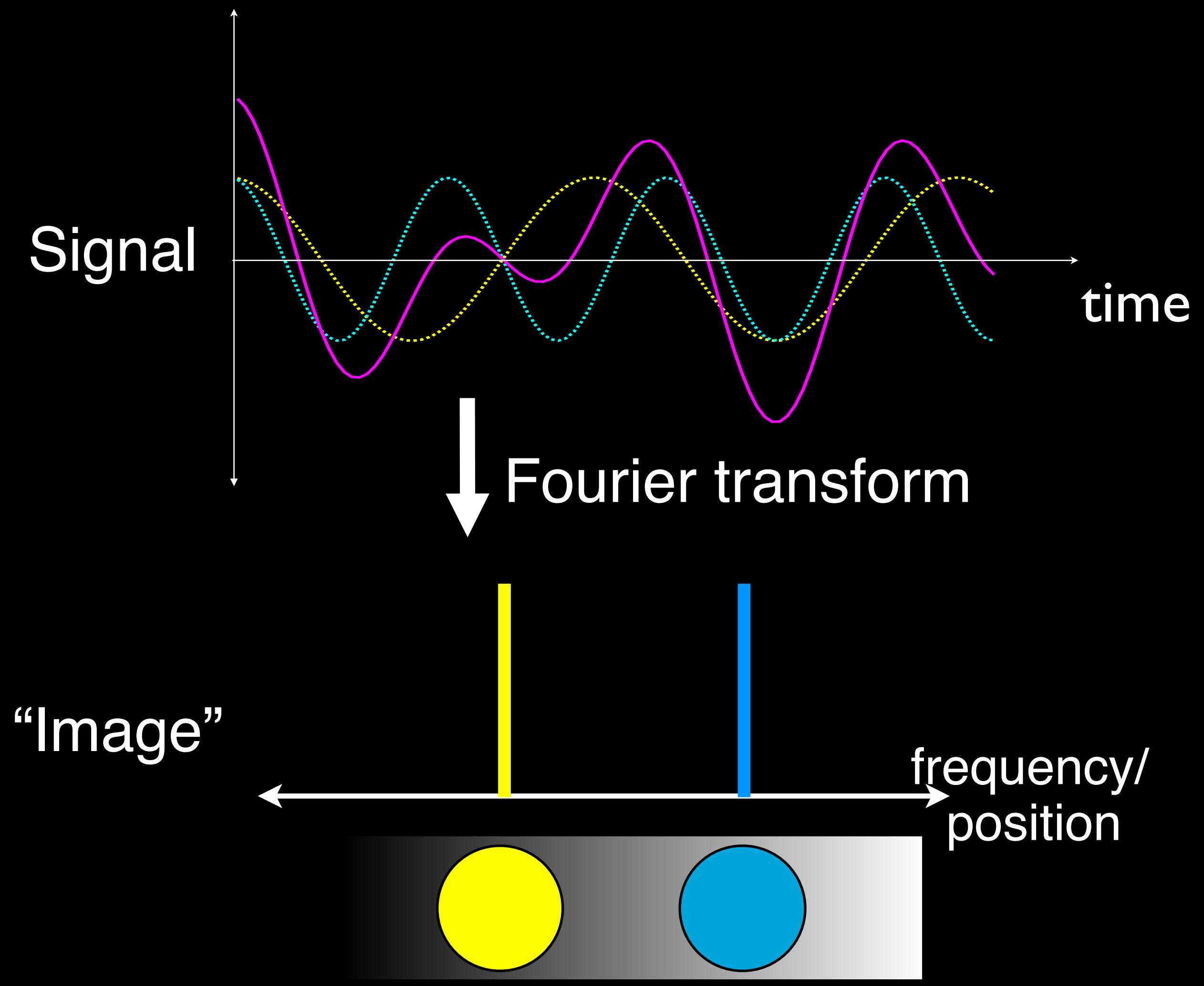


Simple “imaging” experiment (1D)



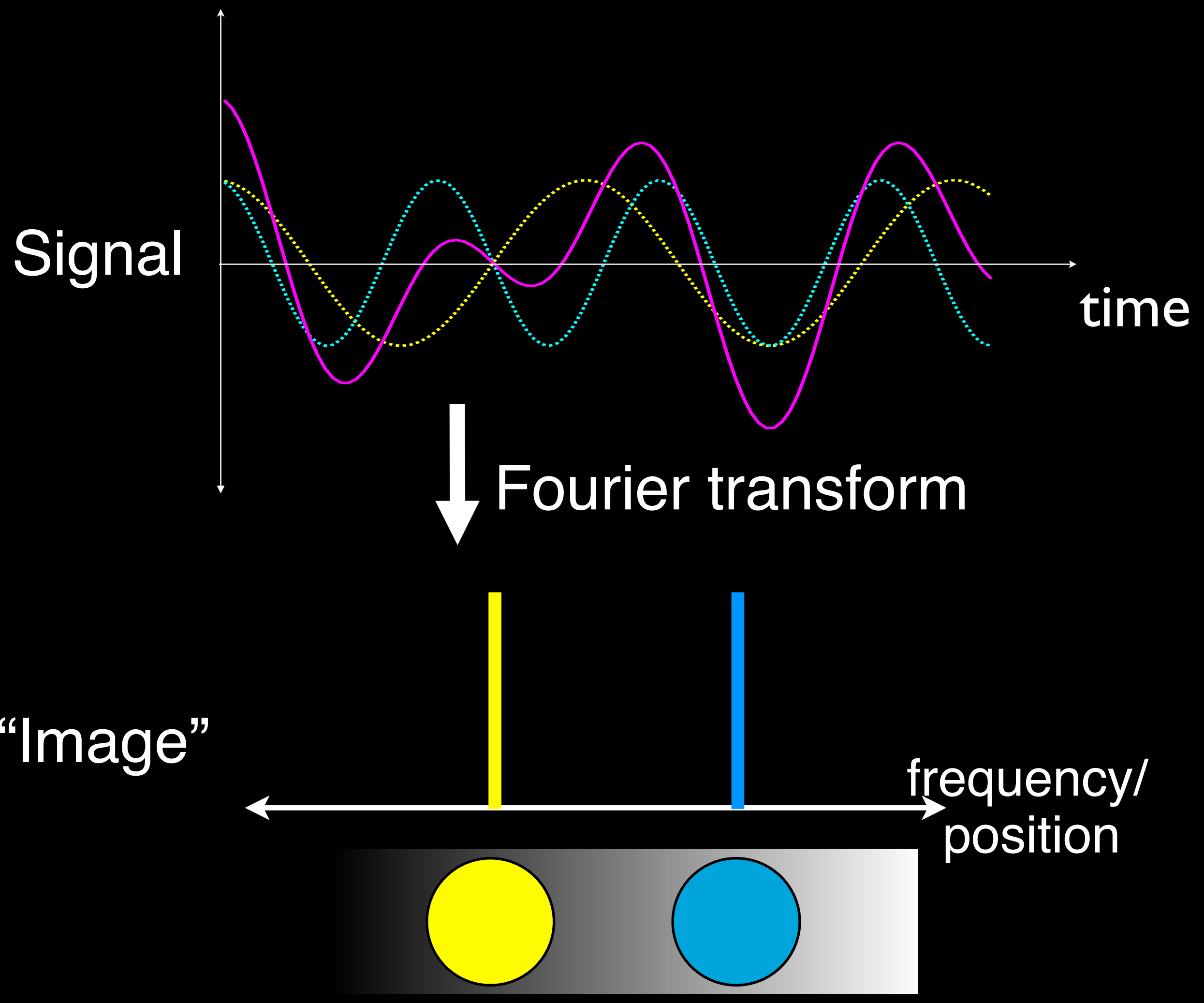


Simple "imaging" experiment (1D)



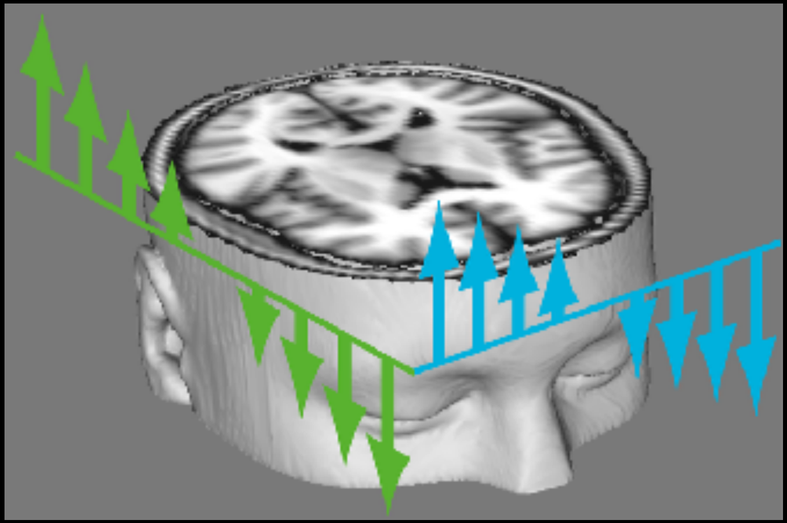
Fourier Transform: Gives us the "frequency content" of our signals

Simple “imaging” experiment (1D)



This is “frequency encoding”

Magnetic gradients



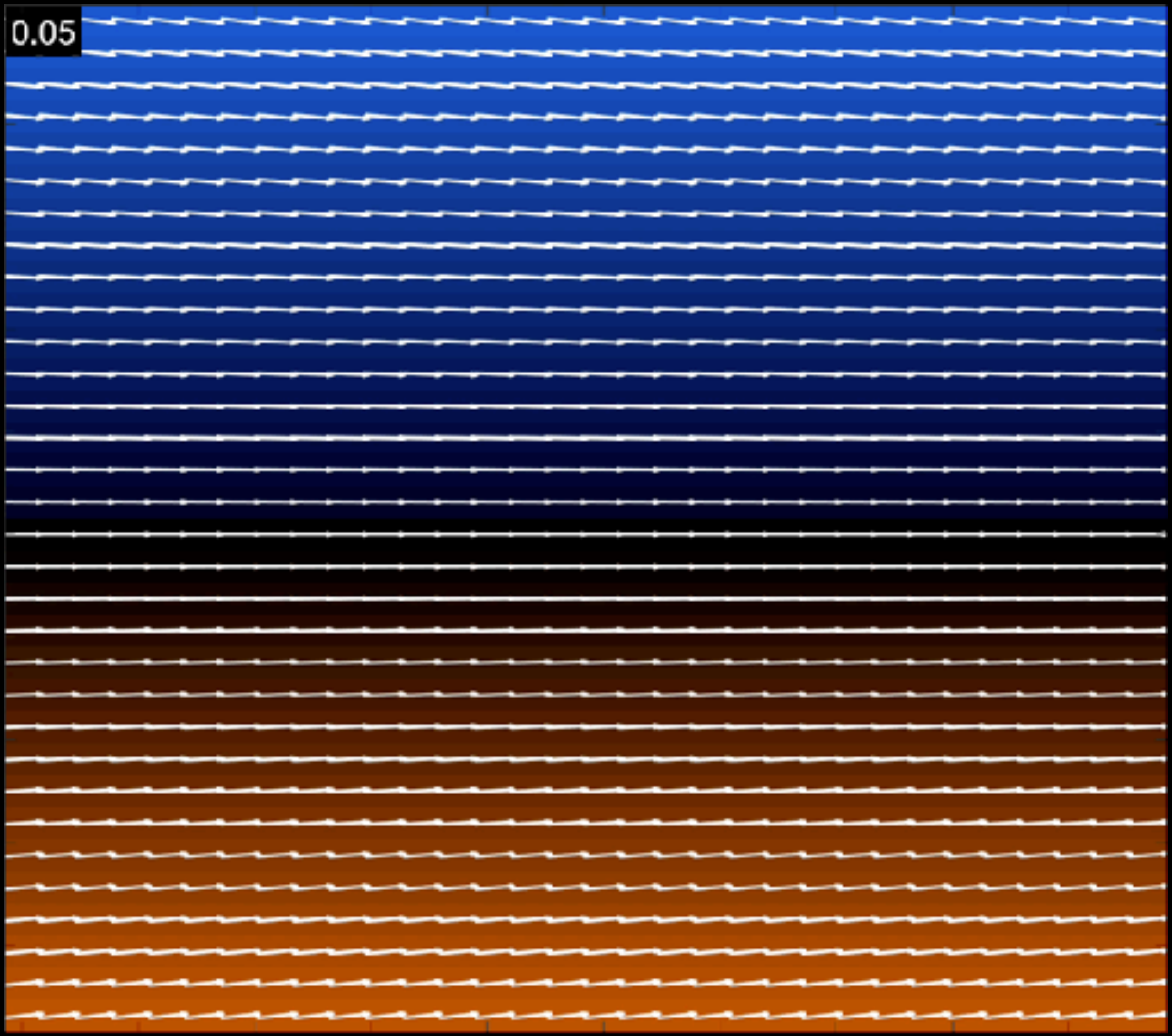
G_x, G_y

It’s a bit more complex in more than 1 dimension

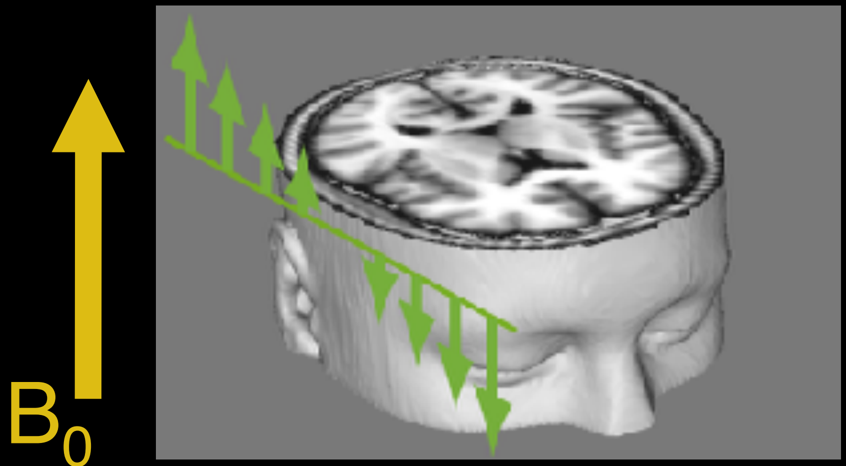
Have 3 gradient fields (along x, y, z)

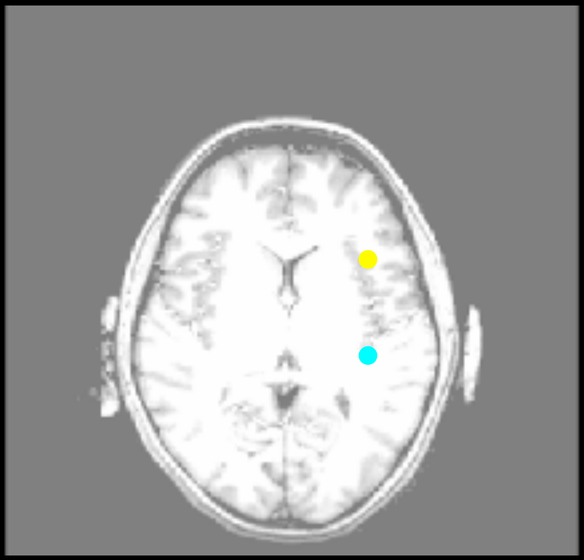
Manipulate the strength & timing independently

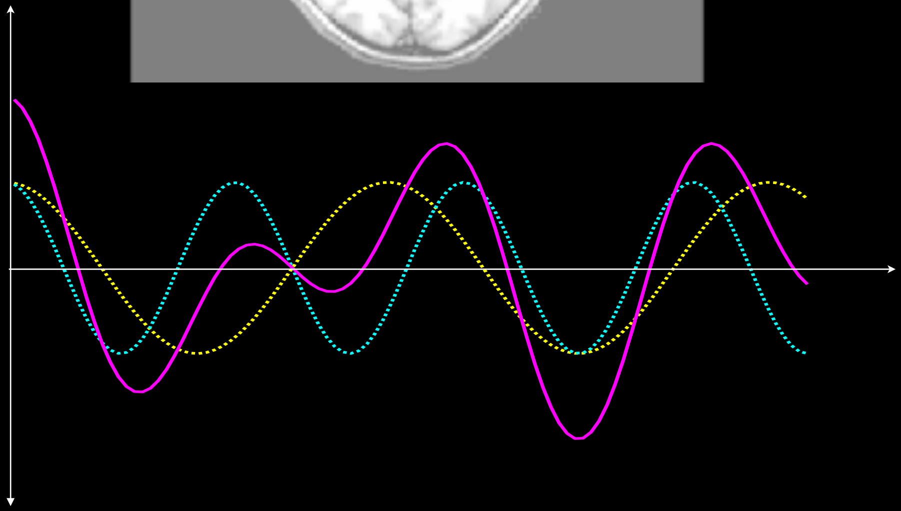
Gradients in multiple dimensions



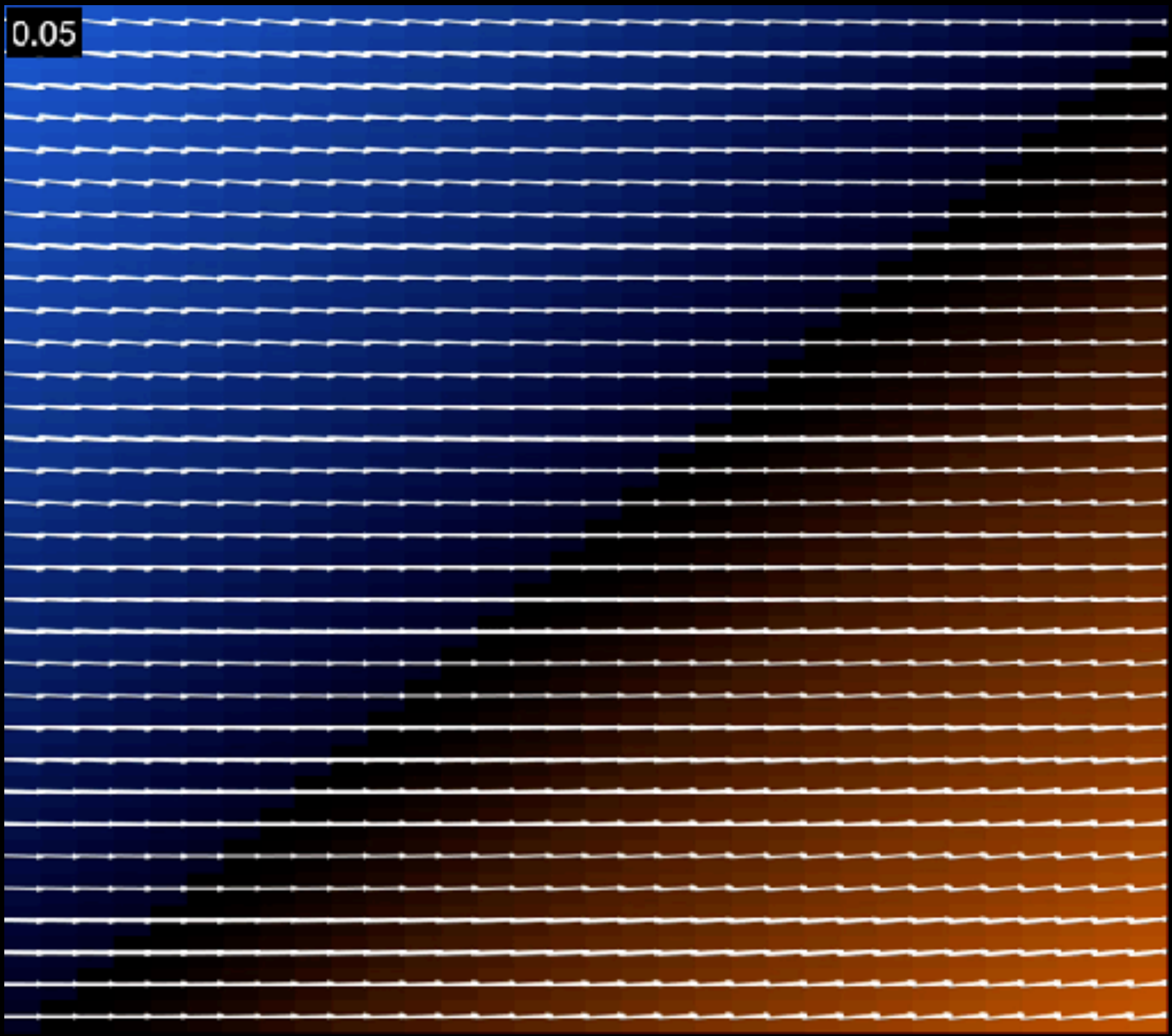
Magnetic field gradients



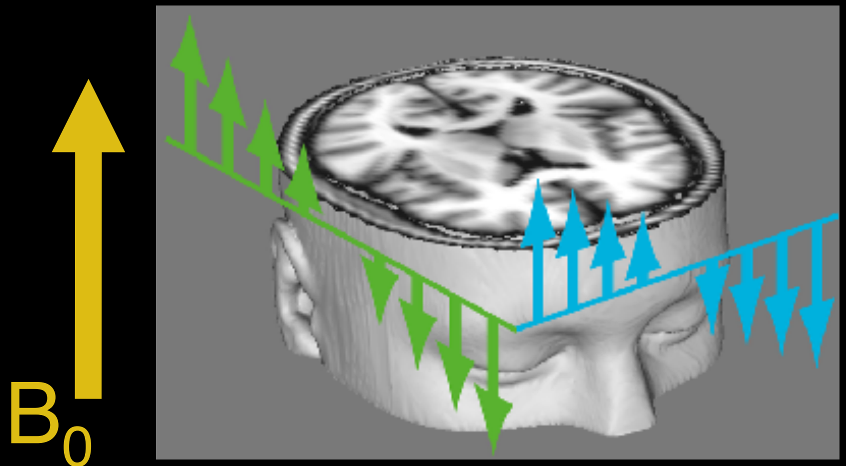


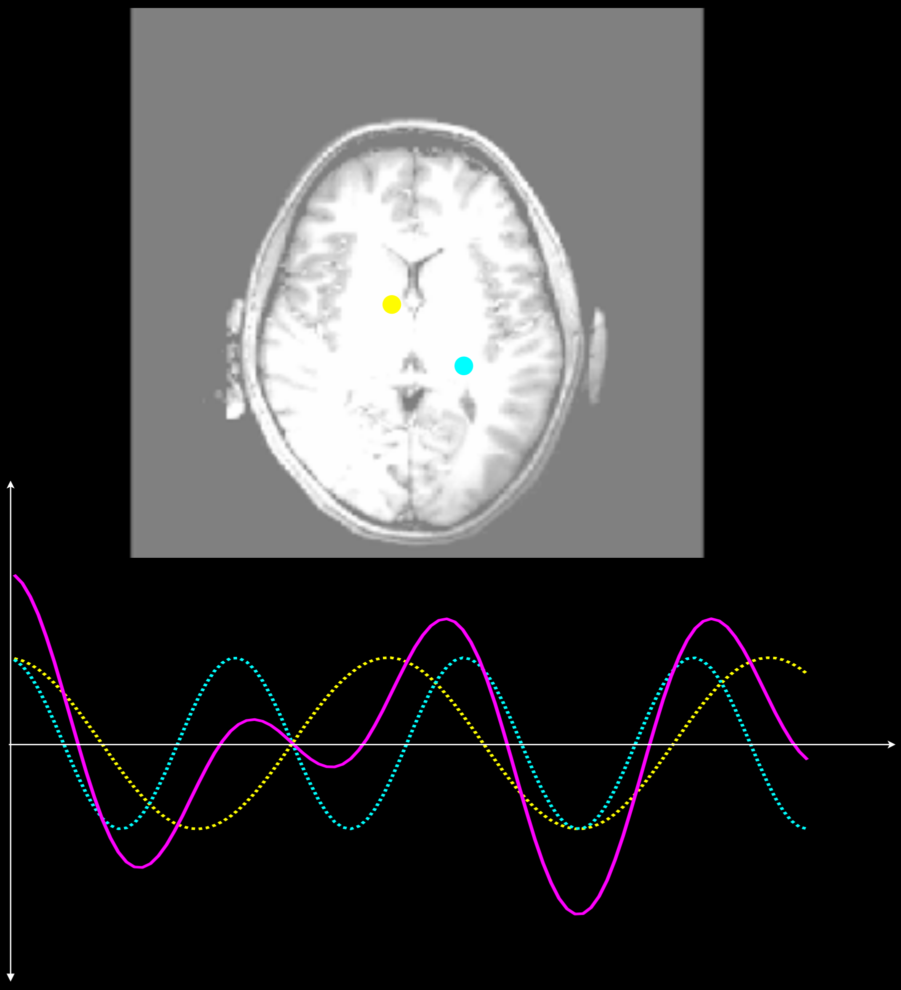


Gradients in multiple dimensions

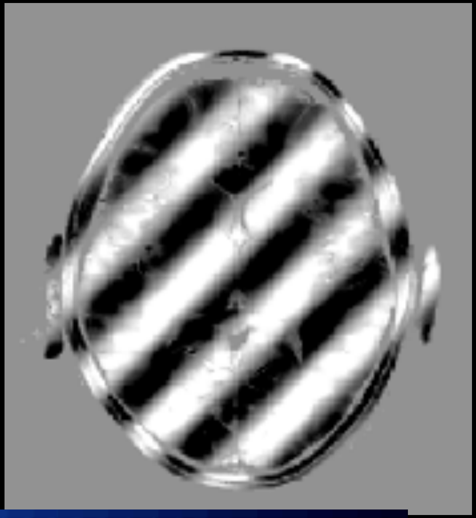


Combined field gradients



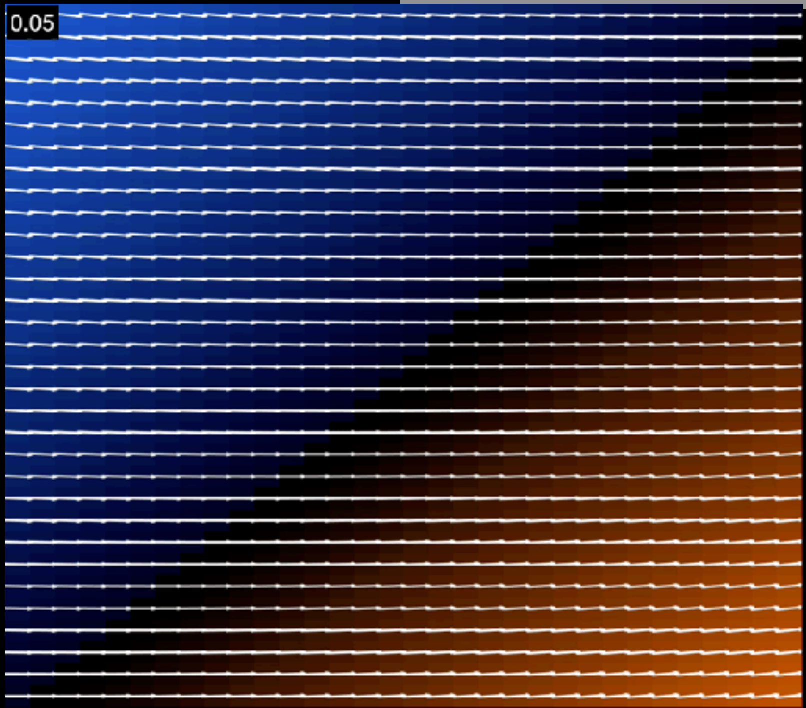


Spatial frequencies or patterns



At any instant in time, signal is across space is defined by a specific “pattern” of the magnetisation phase (orientation),

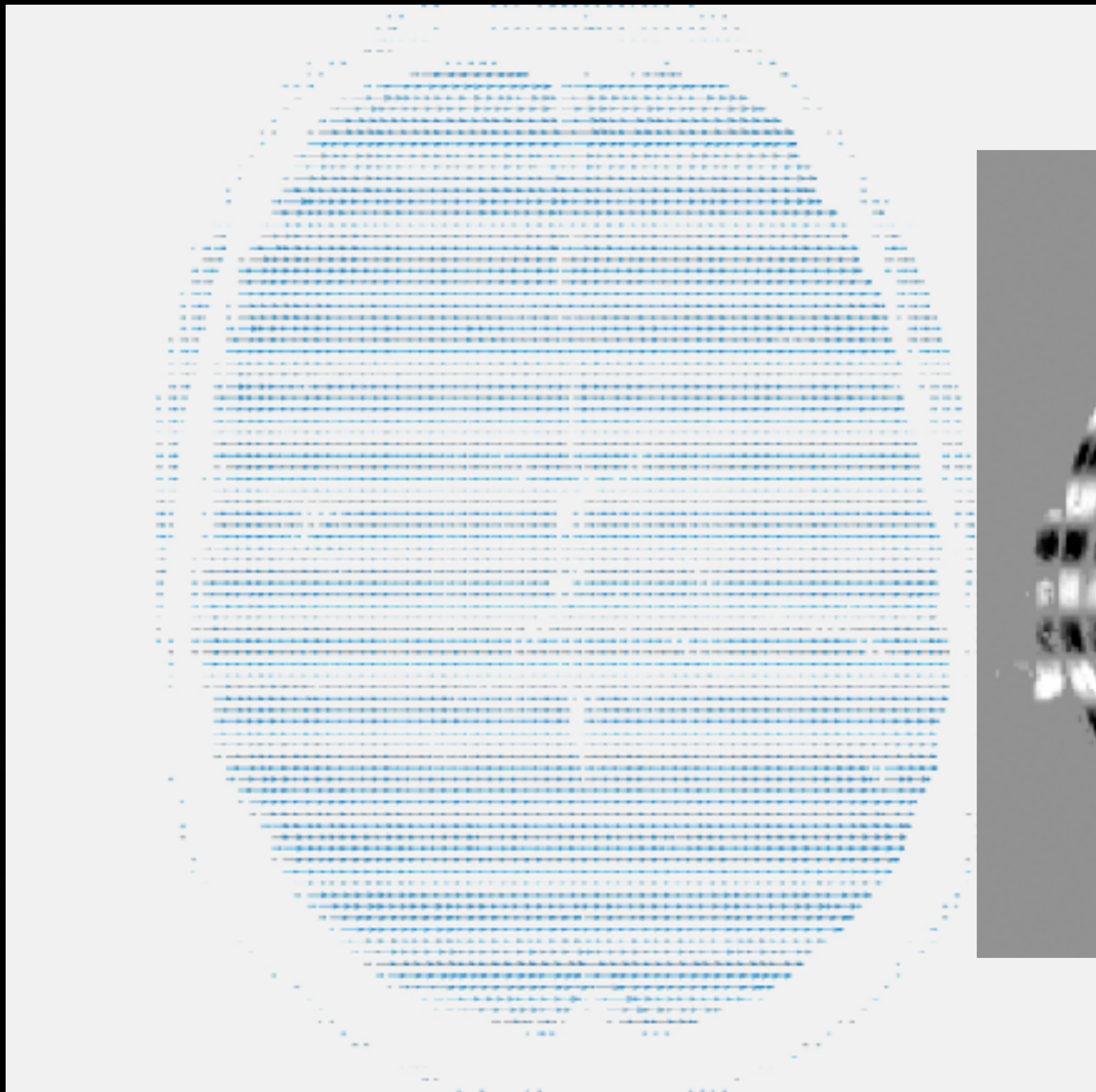
i.e., its *spatial frequency* that depends on the applied gradients



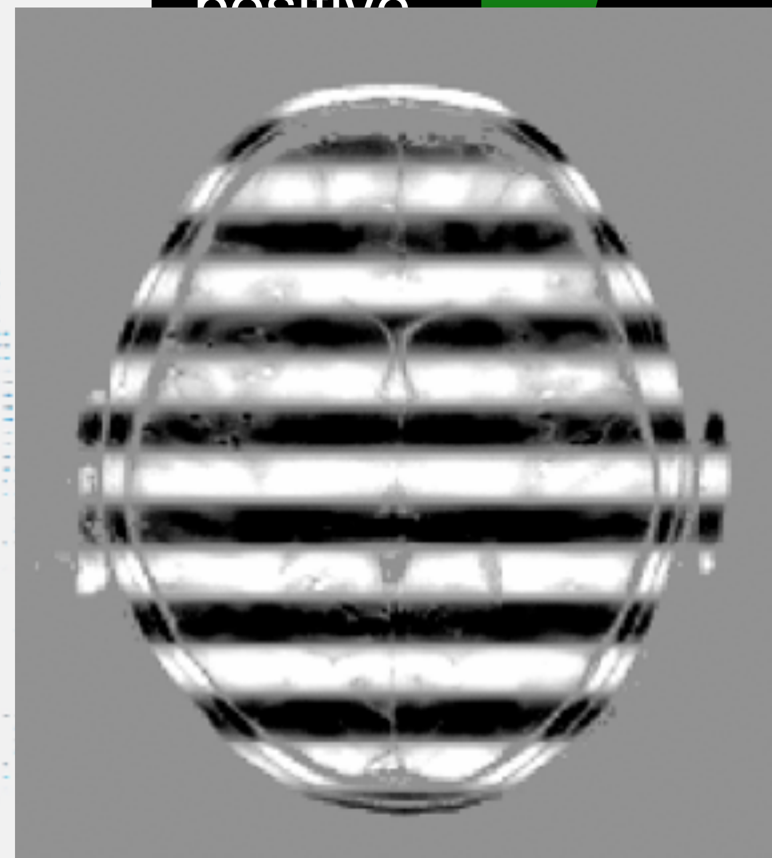
Spatial frequencies:

- sinusoidal pattern over space instead of time
- extend to multiple dimensions

Gradients and Spatial Frequency

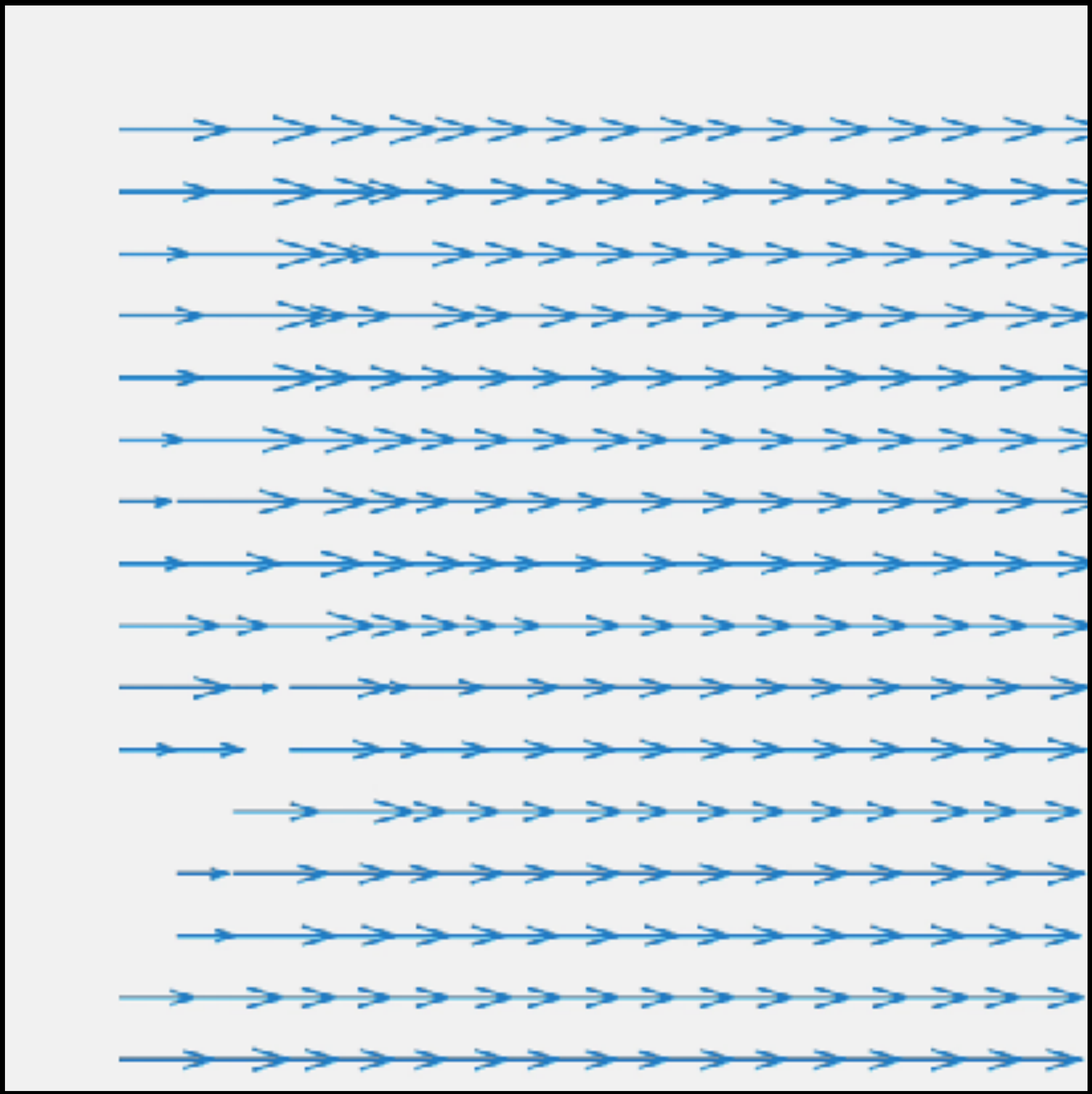


Strong,



gradient

Gradients and Spatial Frequency



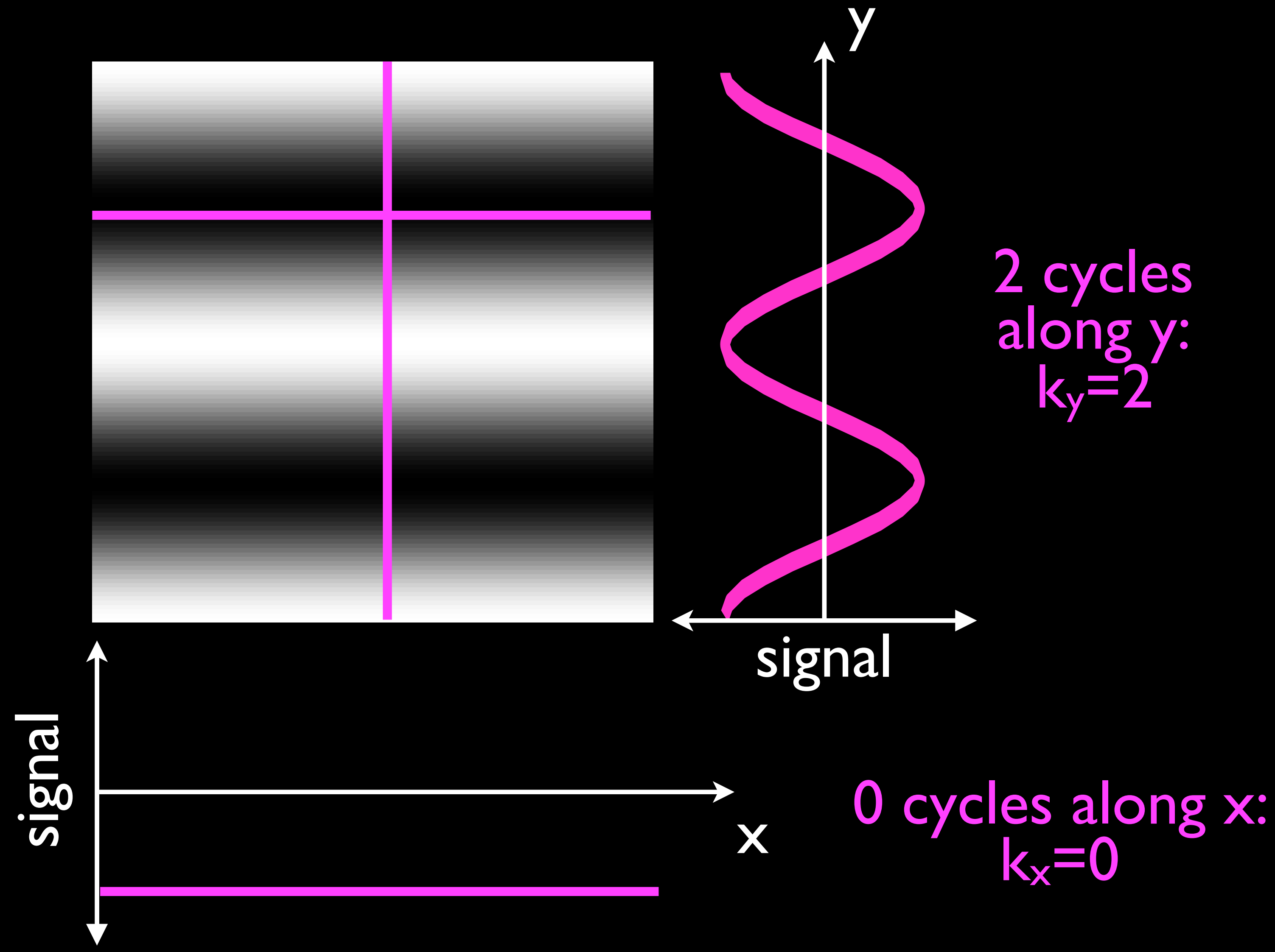
higher resonance frequency

faster precession

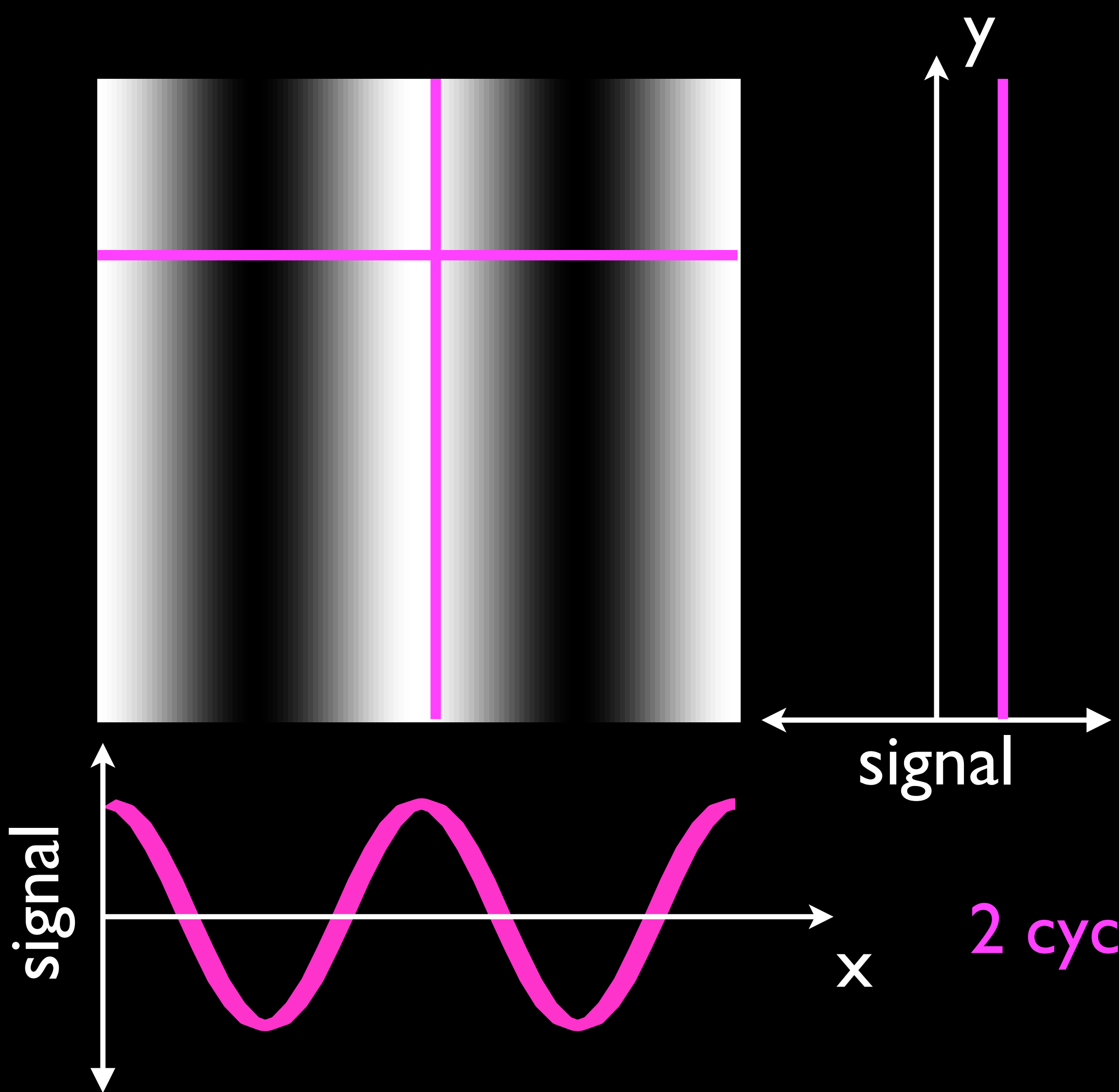
lower resonance frequency

slower precession

This is one spatial frequency...



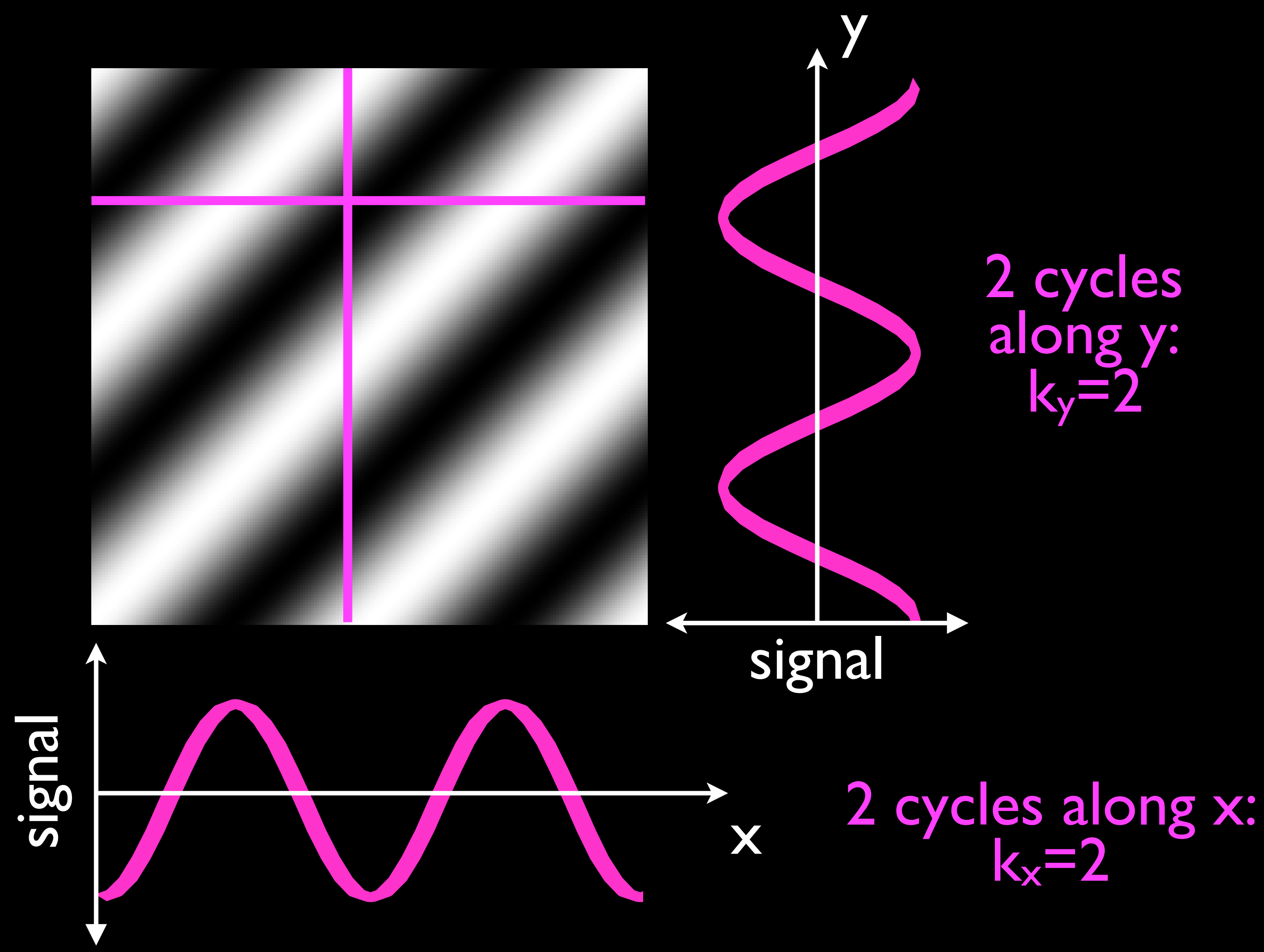
This is another one...



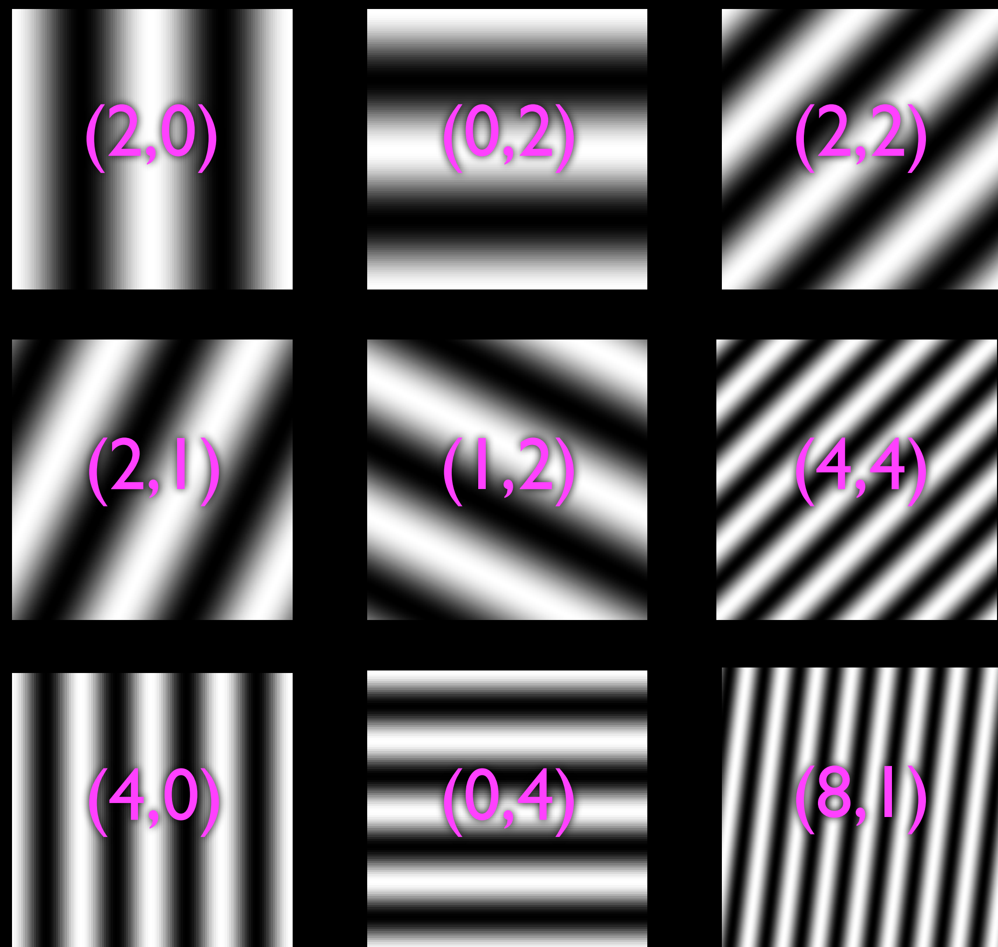
0 cycles along y: $k_y=0$

2 cycles along x: $k_x=2$

This is another one...



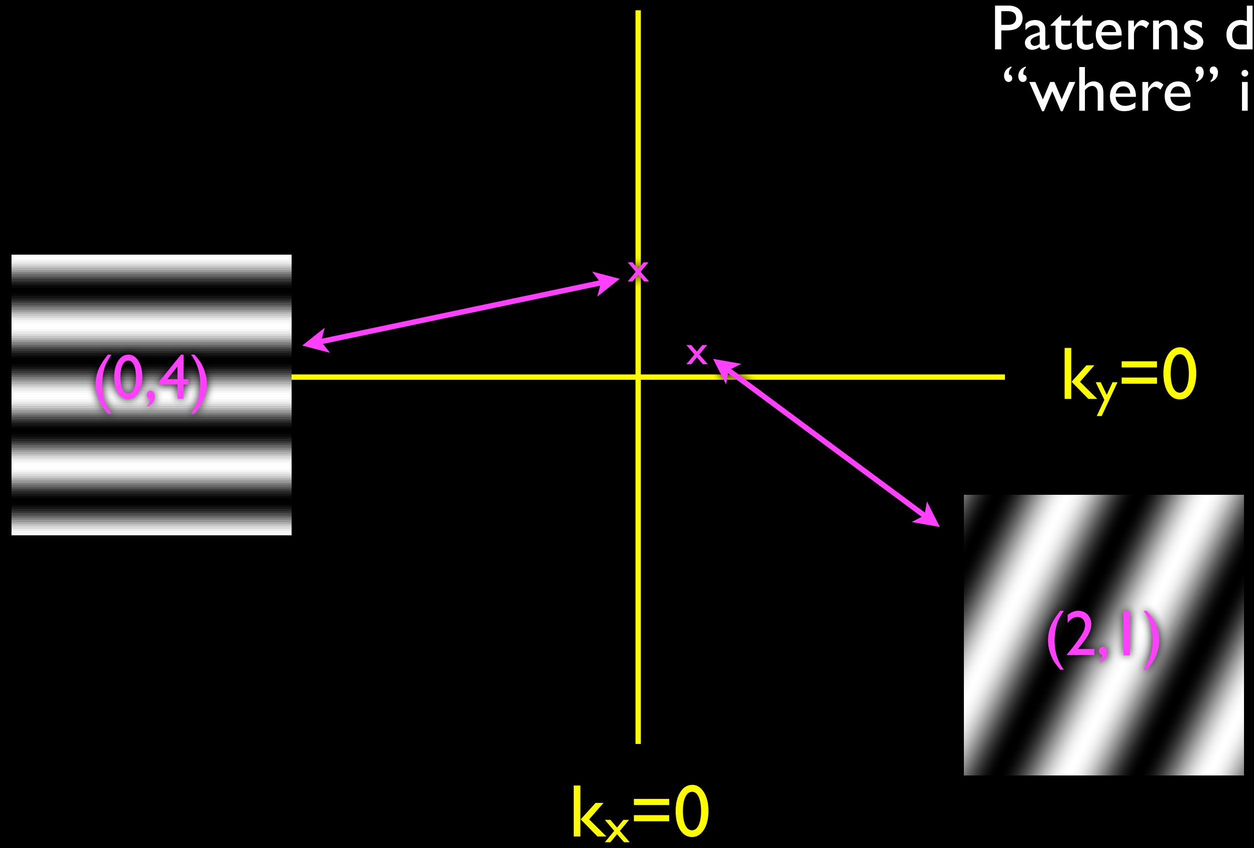
Each of these represents one 2D pattern or frequency: denote (k_x, k_y)



“k” values are the number of cycles in each direction

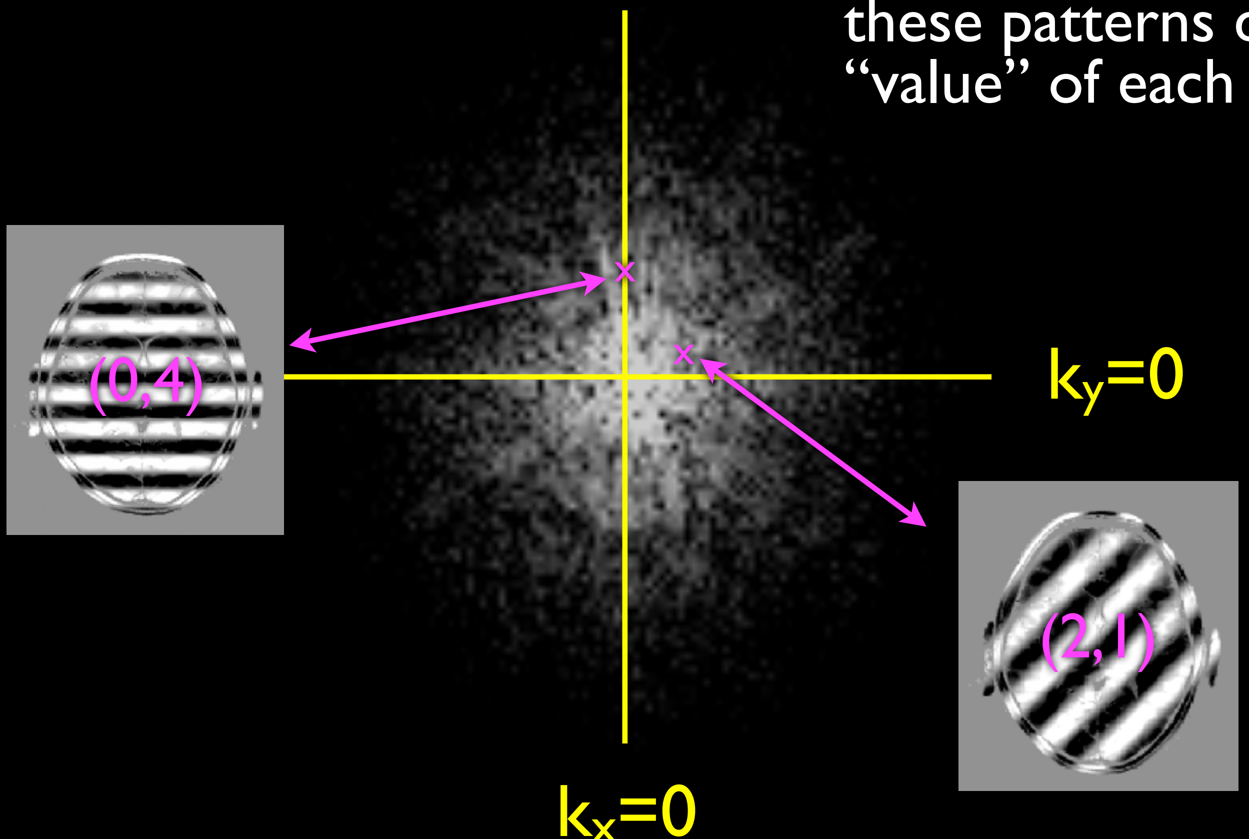
2D “k-space” describes contribution of each spatial frequency

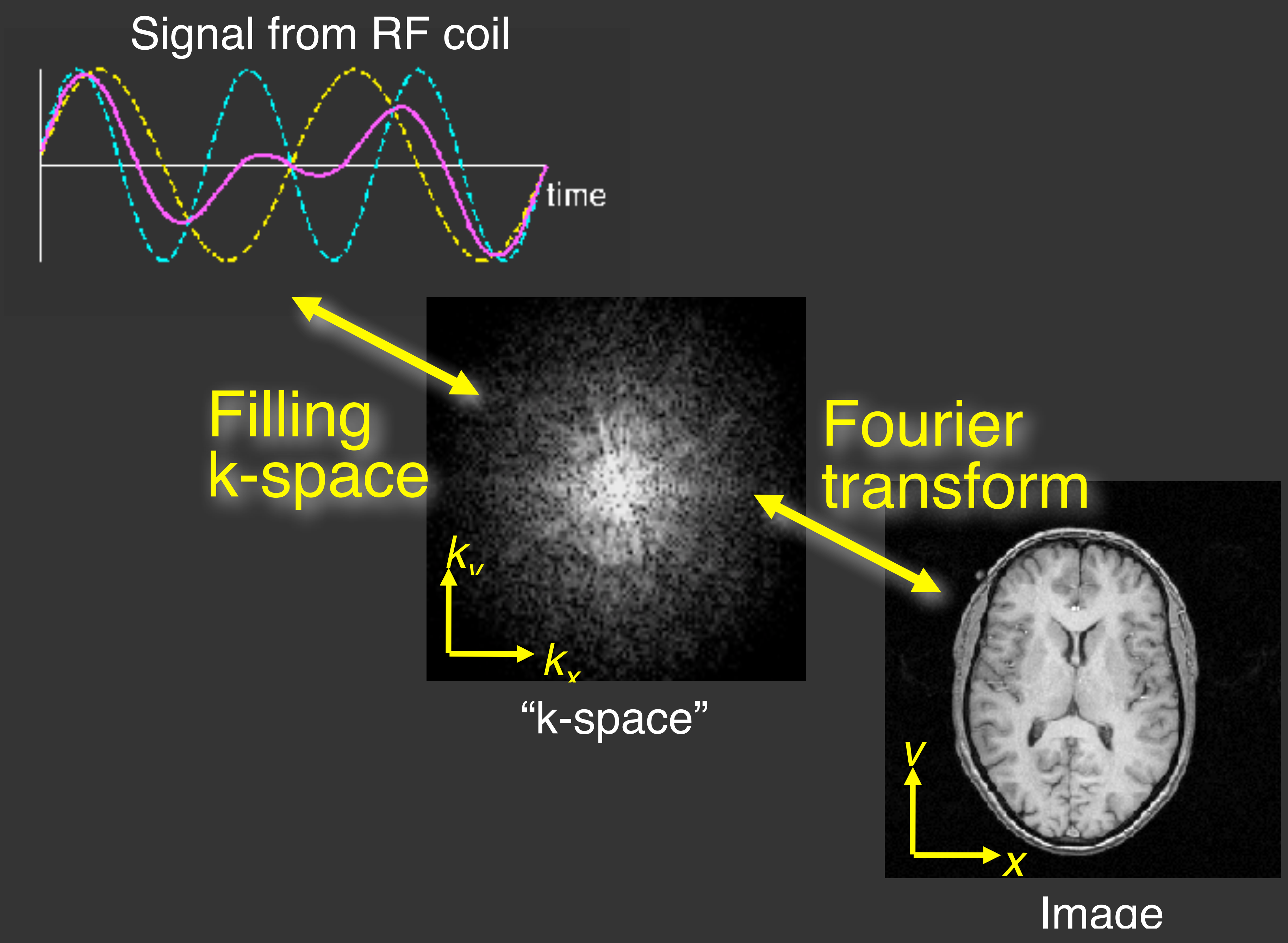
Patterns determine the “where” in k-space



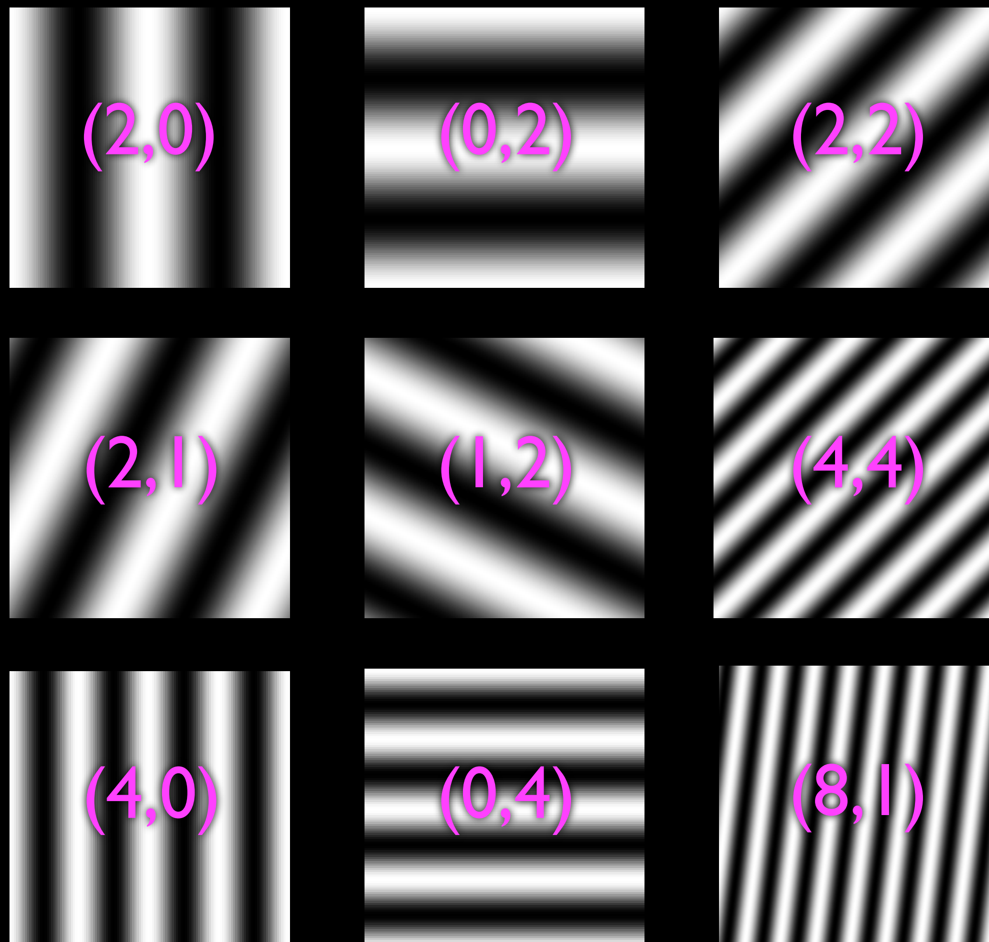
2D "k-space" describes contribution of each spatial frequency

Sum total signal after application of these patterns determines the "value" of each k-space location

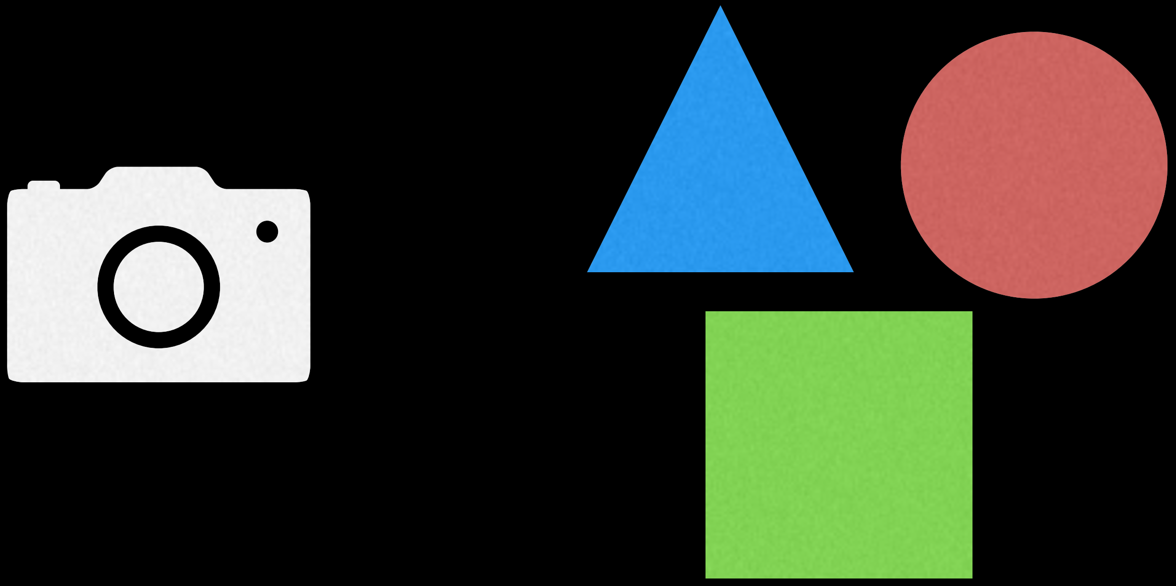



Signal from RF coil
time
Filling
k-space
k_y
k_x
"k-space"
Fourier
transform
y
x
Image

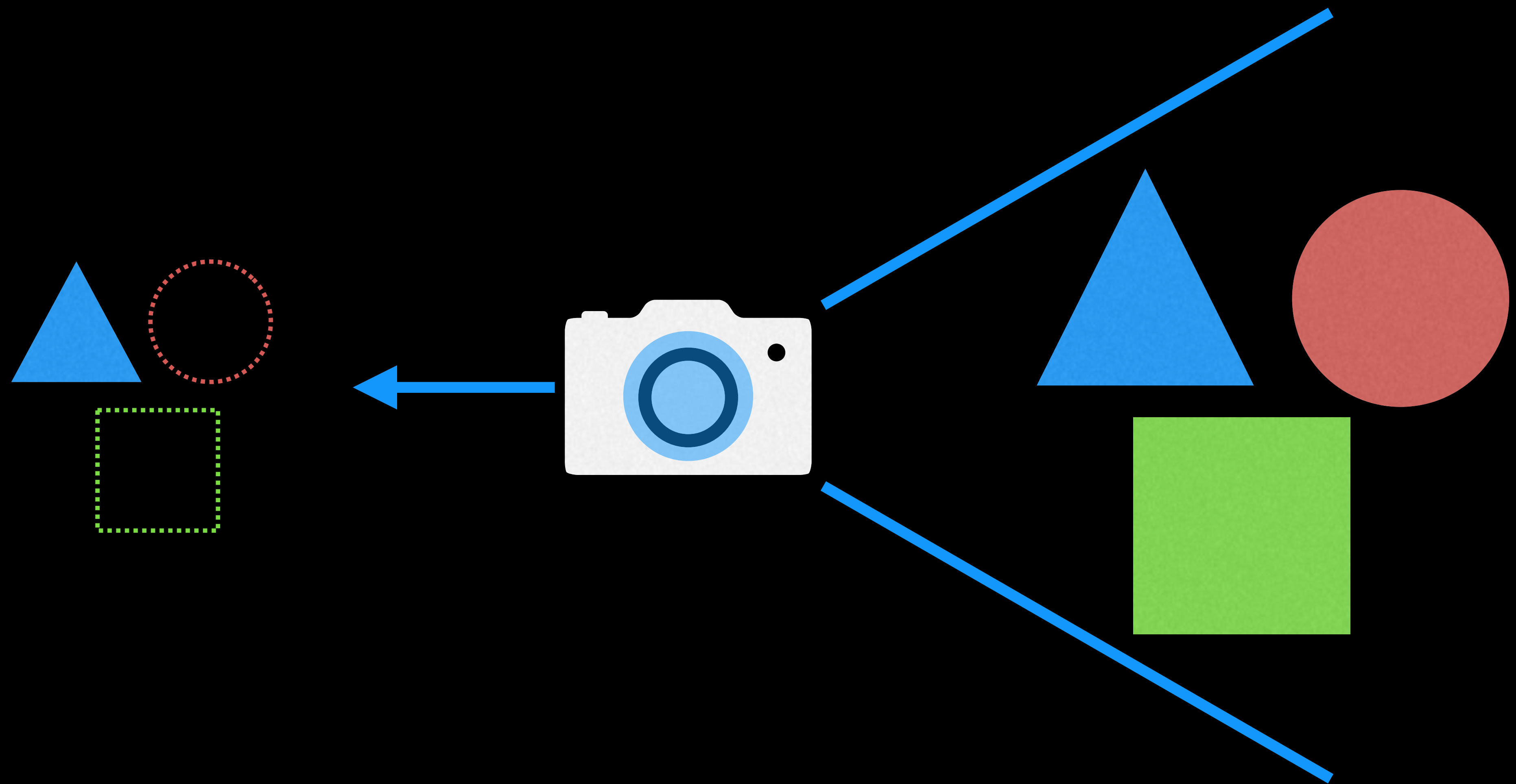
Think of each pattern (k-space location) as a filter on a camera



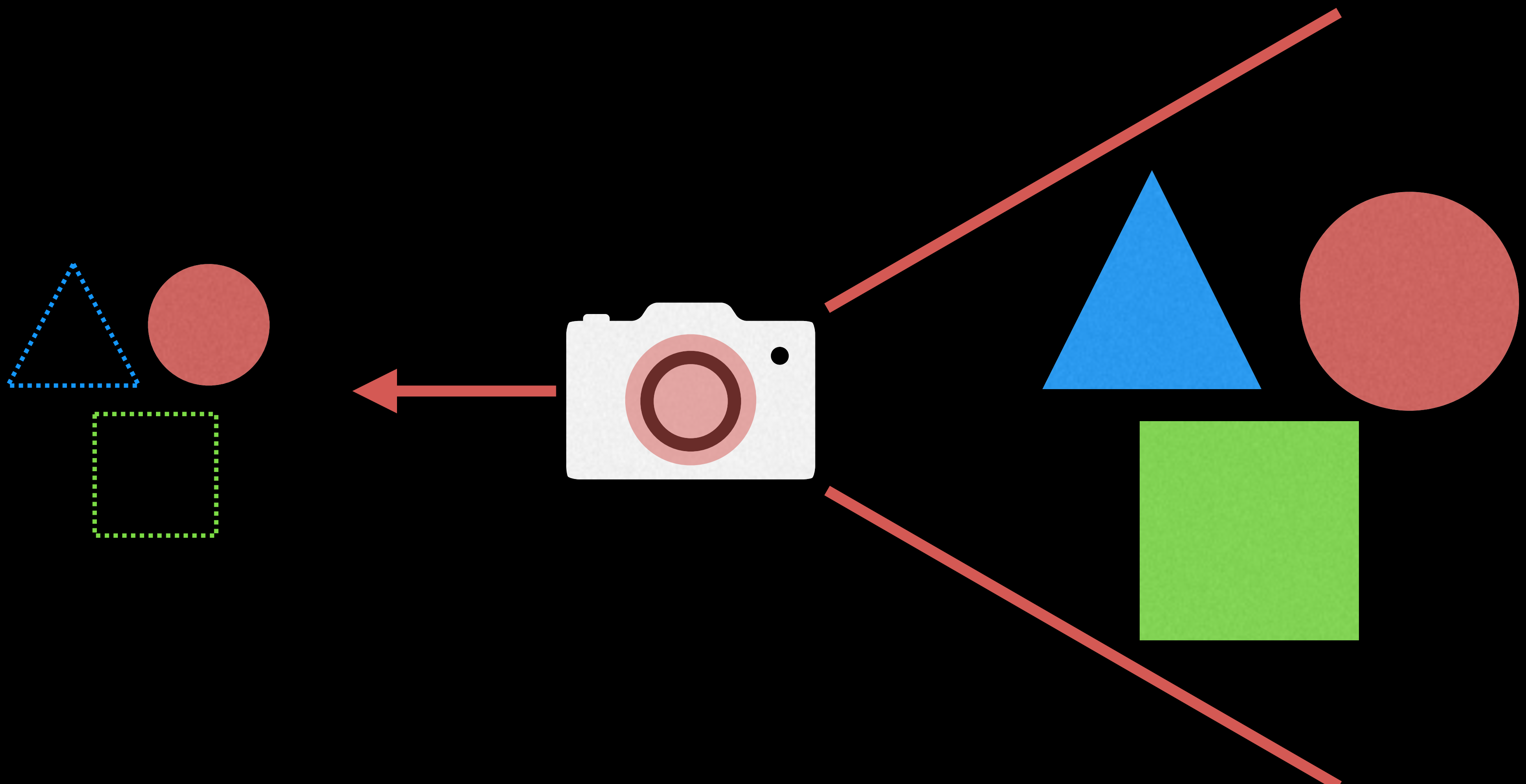
Imagine our "camera" can only see one colour at a time



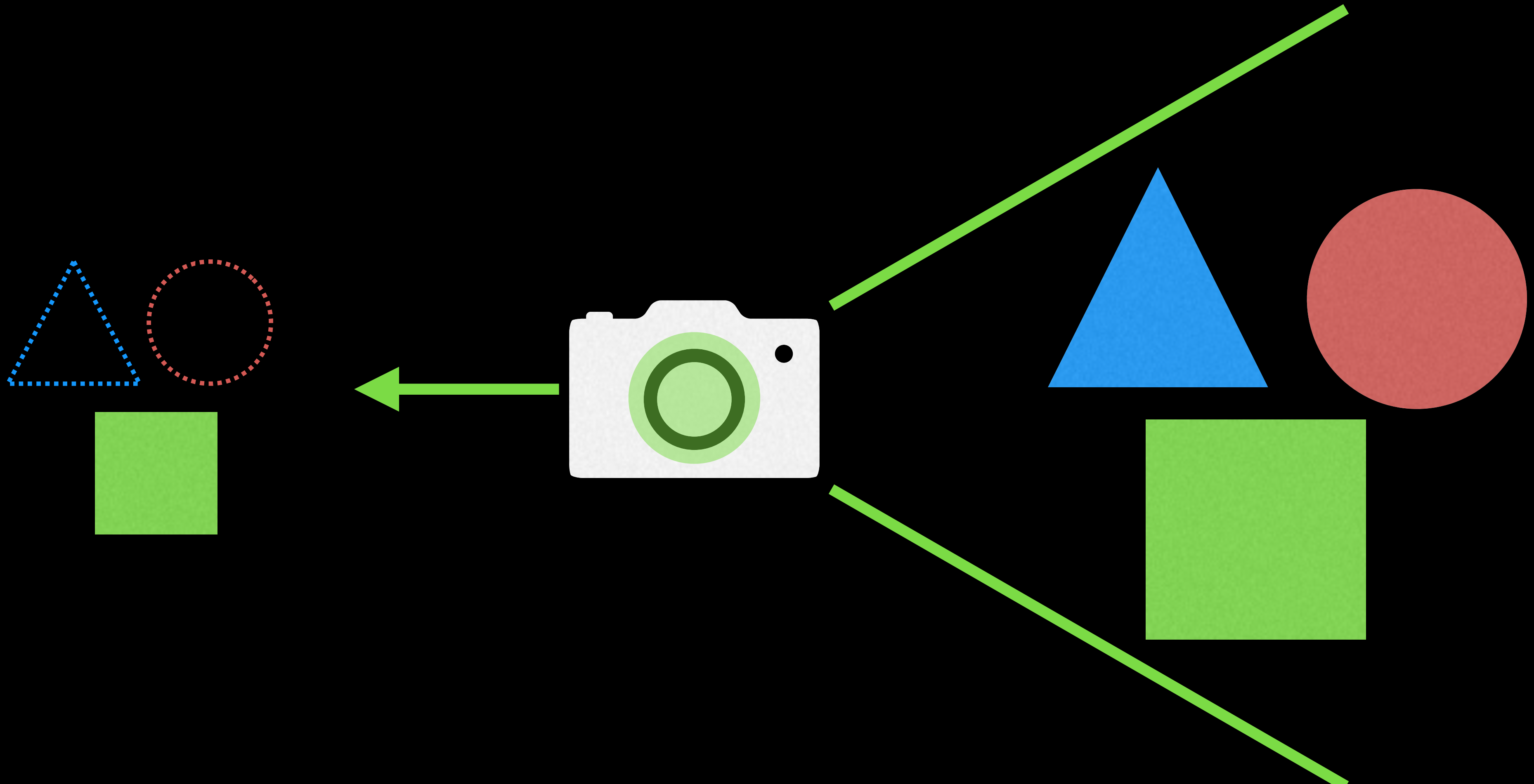
Imagine our "camera" can only see one colour at a time (blue filter)



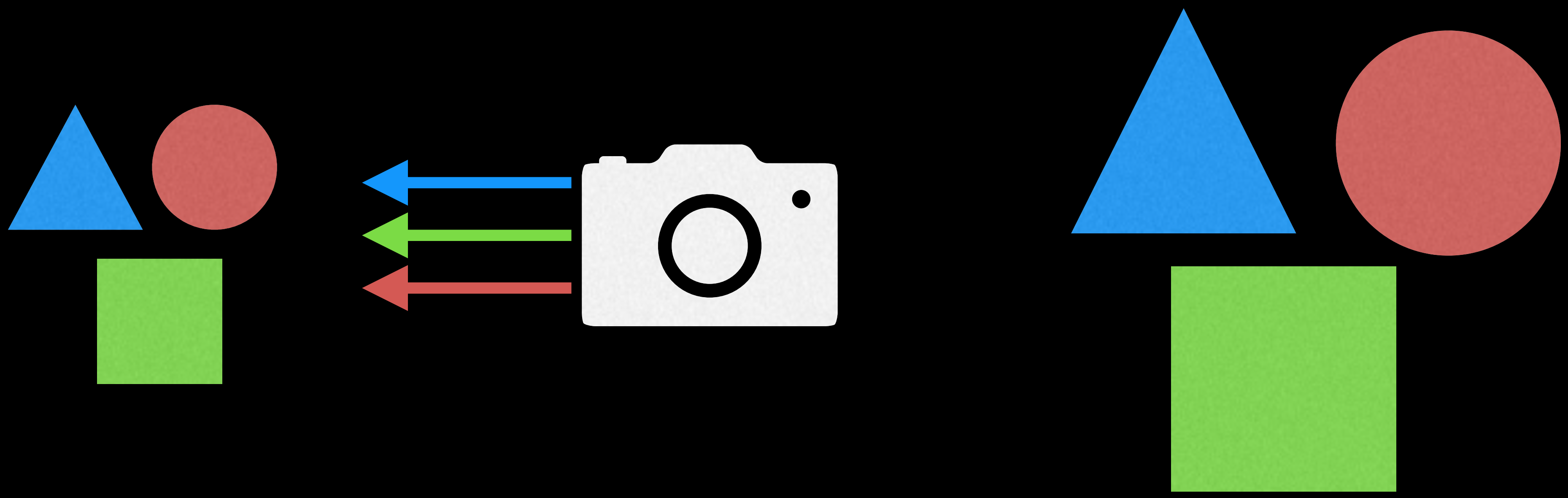
Imagine our "camera" can only see one colour at a time (red filter)



Imagine our “camera” can only see one colour at a time (green filter)

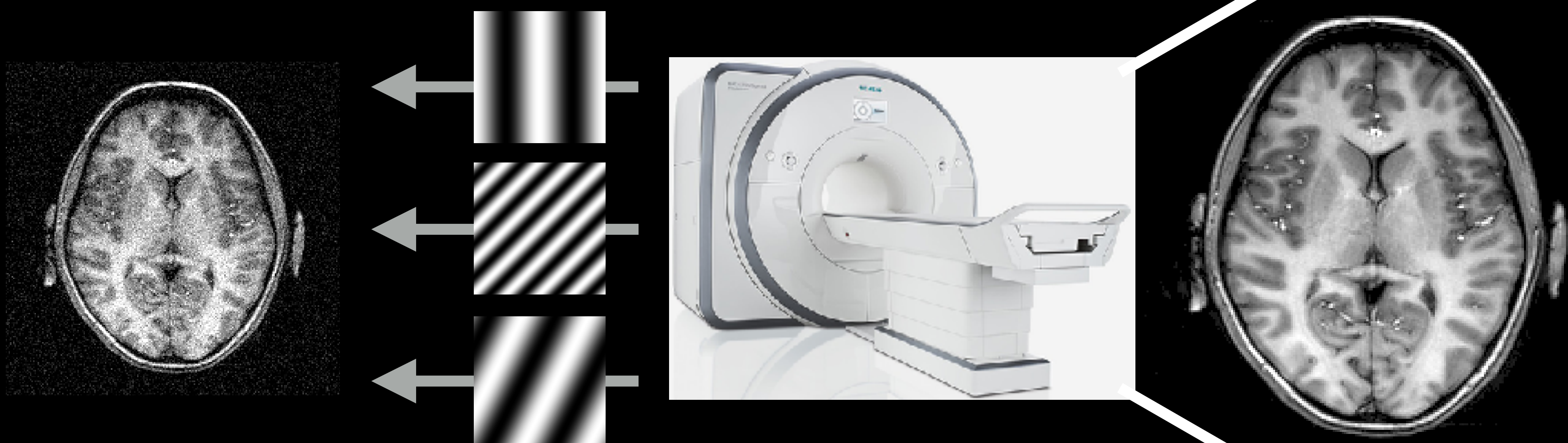


Combine the filtered images to form the final image



Scanner takes a series of measurements with each k-space “spatial filter” (as many filters as voxels)

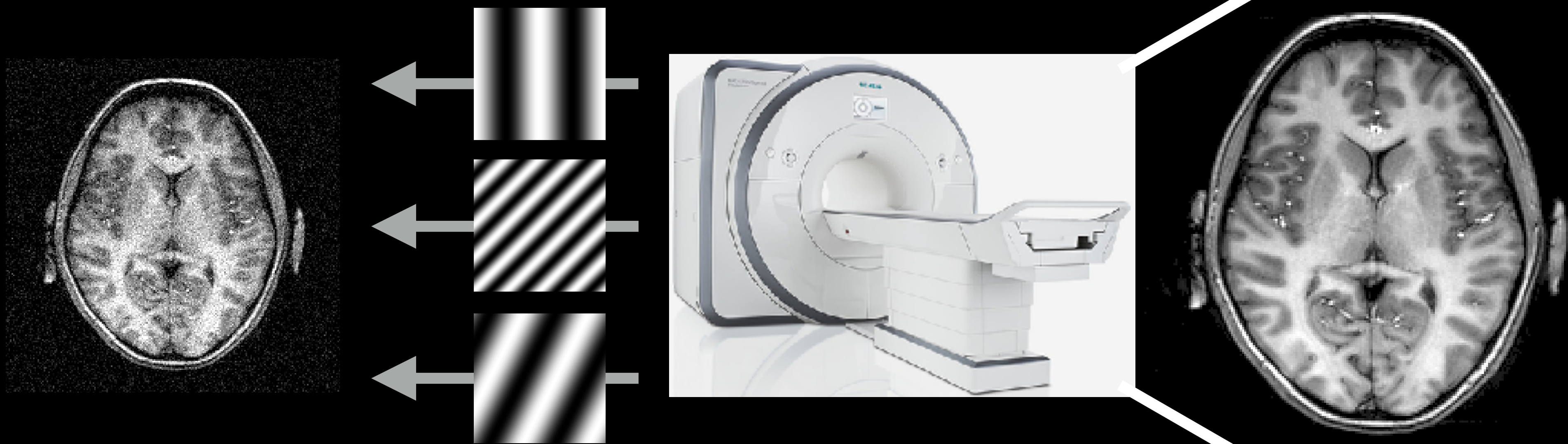
The “spatial filters” are applied using gradients



Measurements are then combined using the Fourier Transform to form image

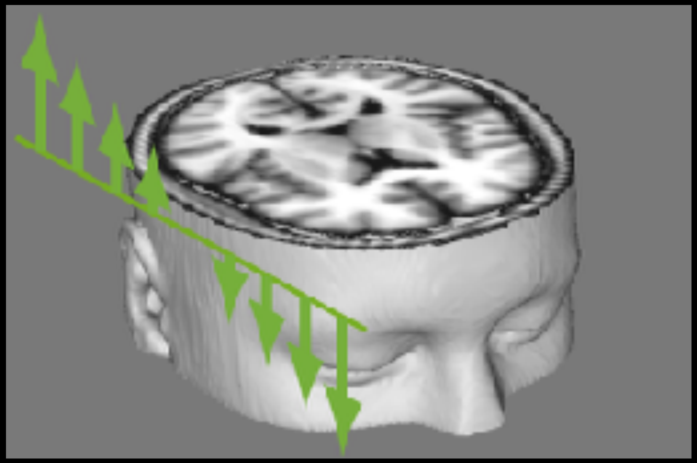
Scanner takes a series of measurements with each k-space “spatial filter” (as many filters as voxels)

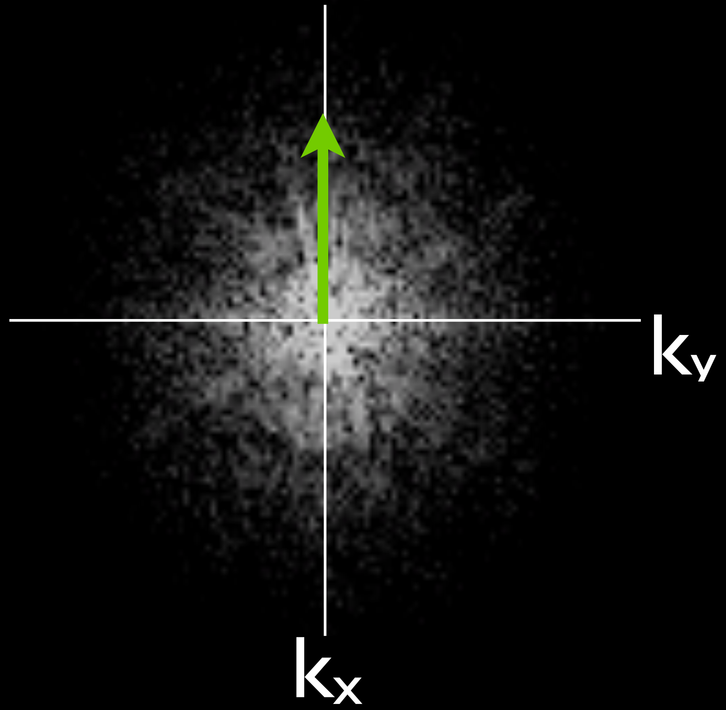
Higher resolution means “finer” features, which require “finer” filters

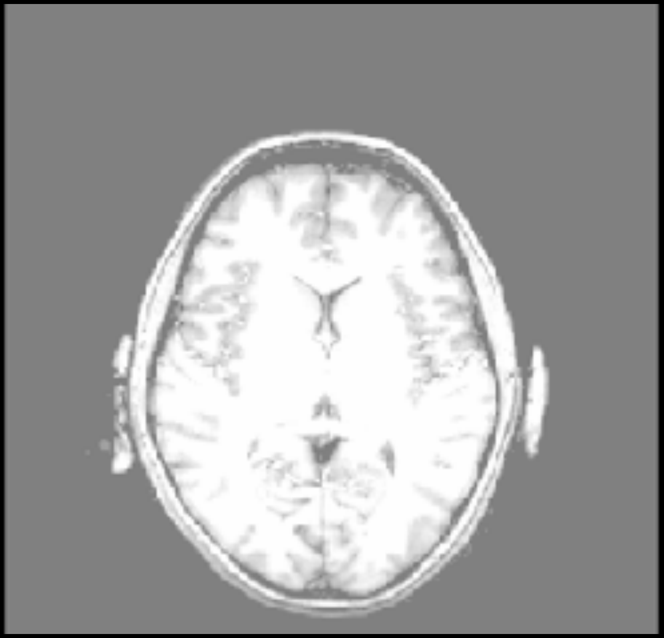


More spatial resolution → more voxels and filters needed → longer acquisition time

If gradient is on, spatial frequencies change over time

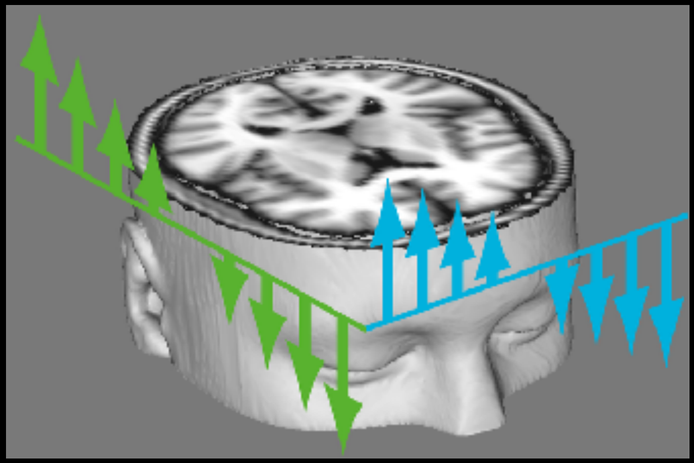


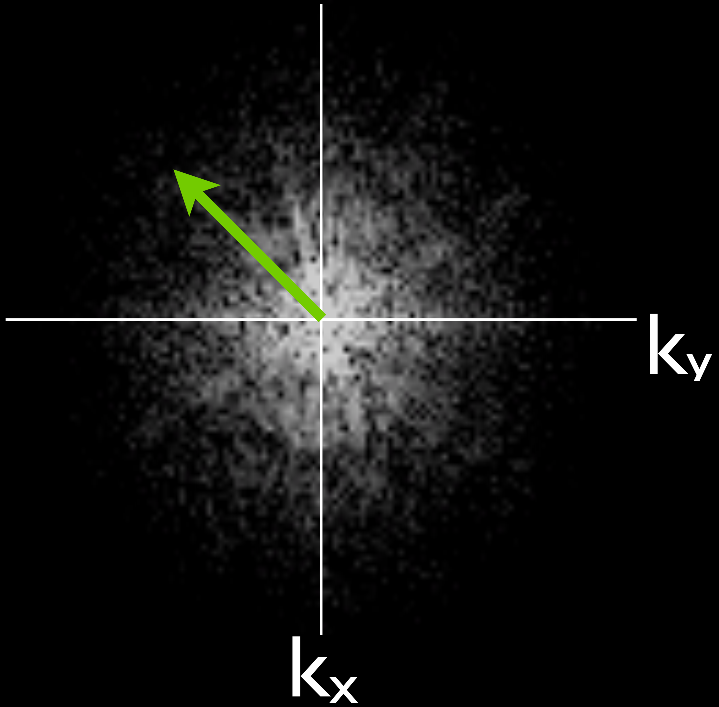


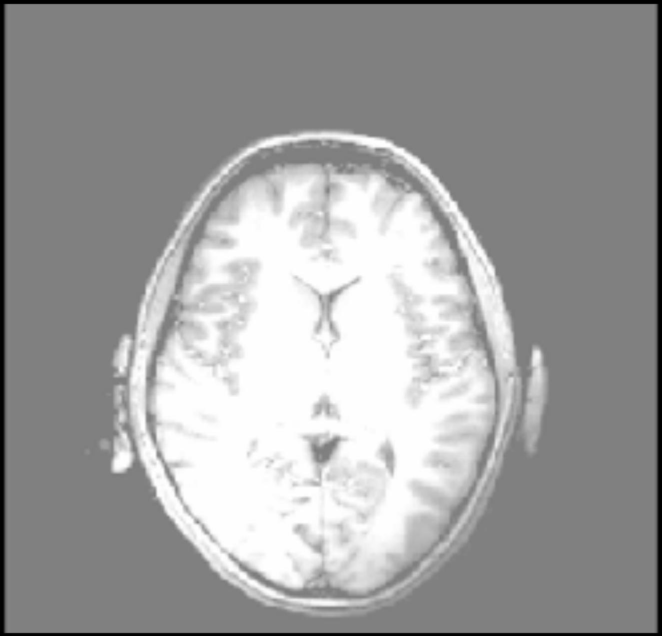


Visualize as gradients "move us" through k-space!

If gradient is on, spatial frequencies change over time

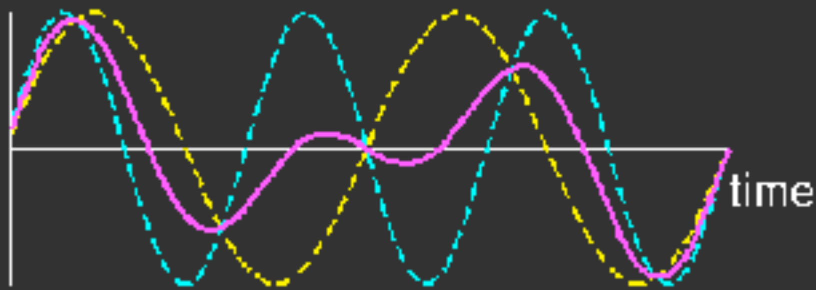






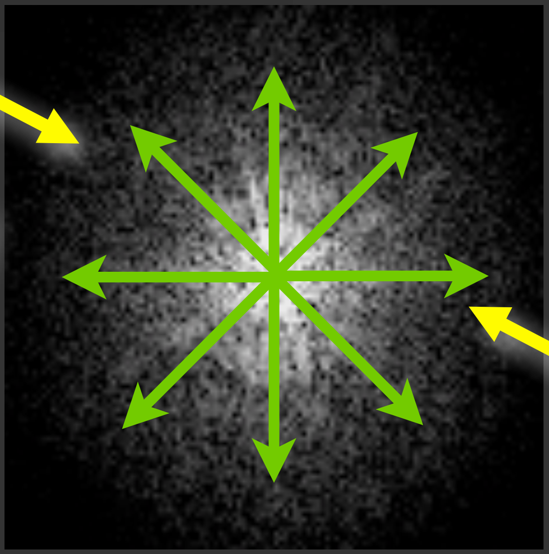
Visualize as gradients “move us” through k-space!

Signal from RF coil



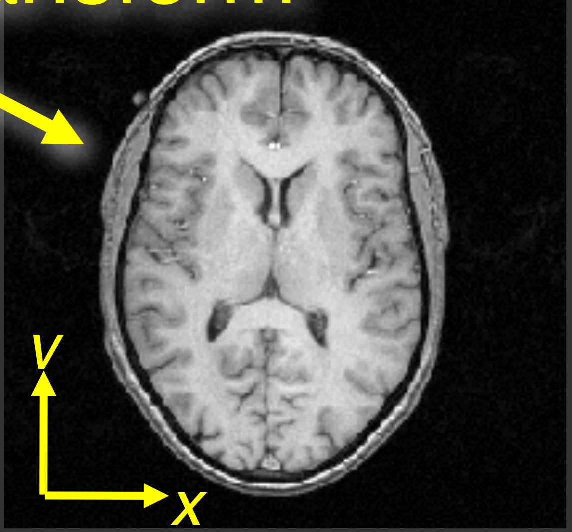
The trajectory is the ordering of k-space data acquisition

k-space trajectory



"k-space"

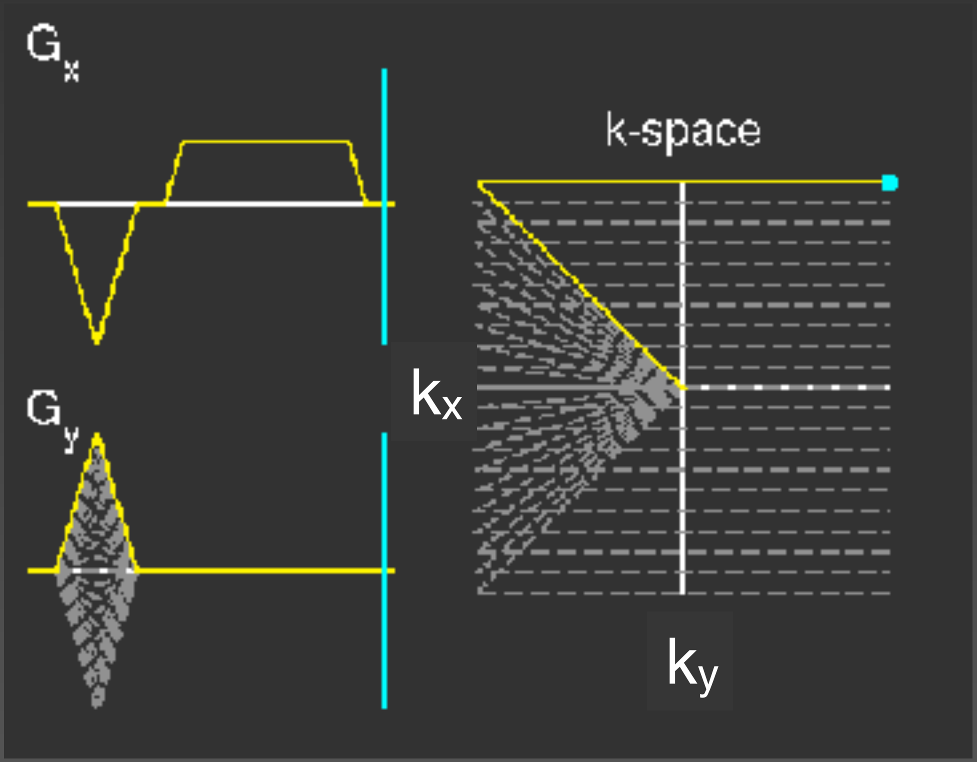
Fourier transform



Image

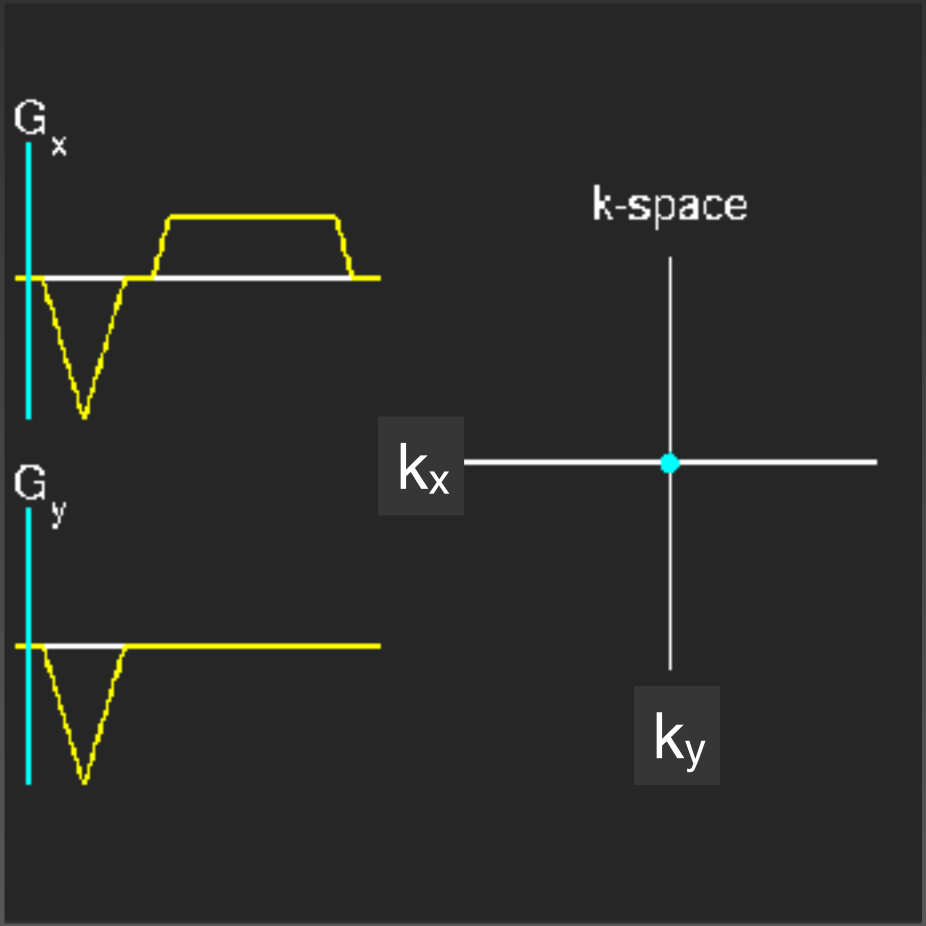
Trajectory = Path through k-space or the sequence of spatial filters

Linescan (2DFT) Acquisition



Acquire one line after each excitation

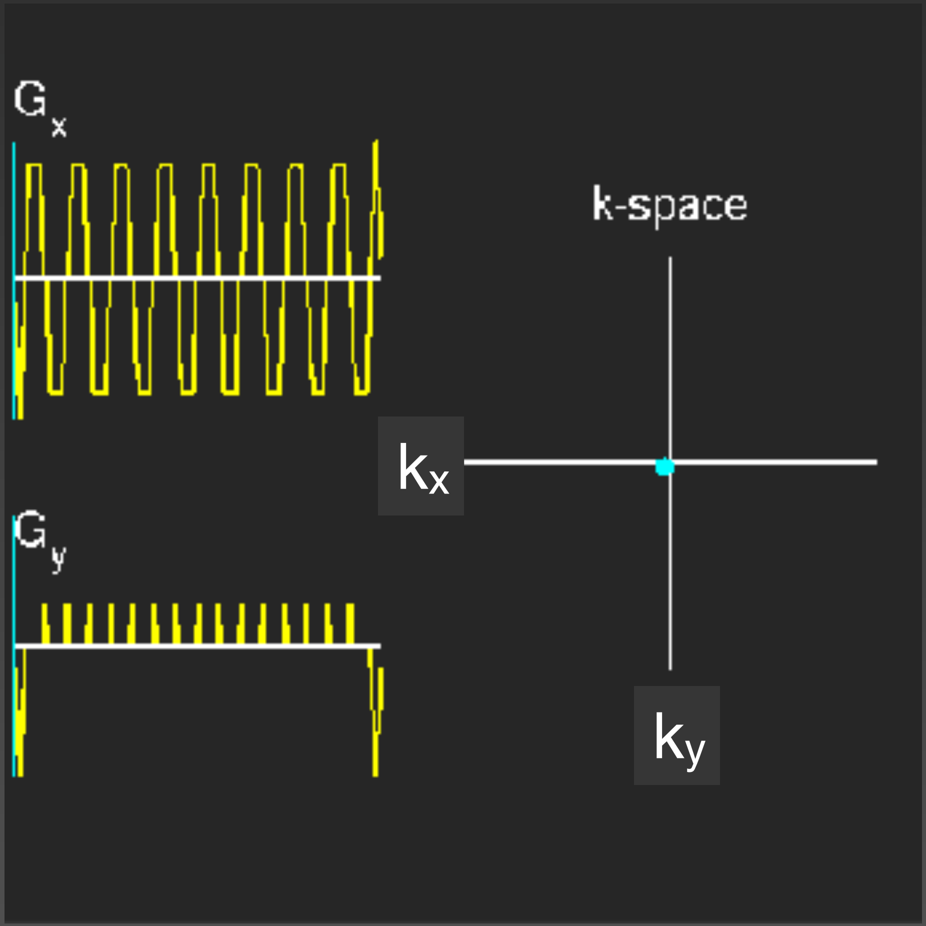
Linescan (2DFT) Acquisition



Acquire one line after each excitation

Useful for structural images (minimal artifacts)

Echo-planar Imaging (EPI) Acquisition

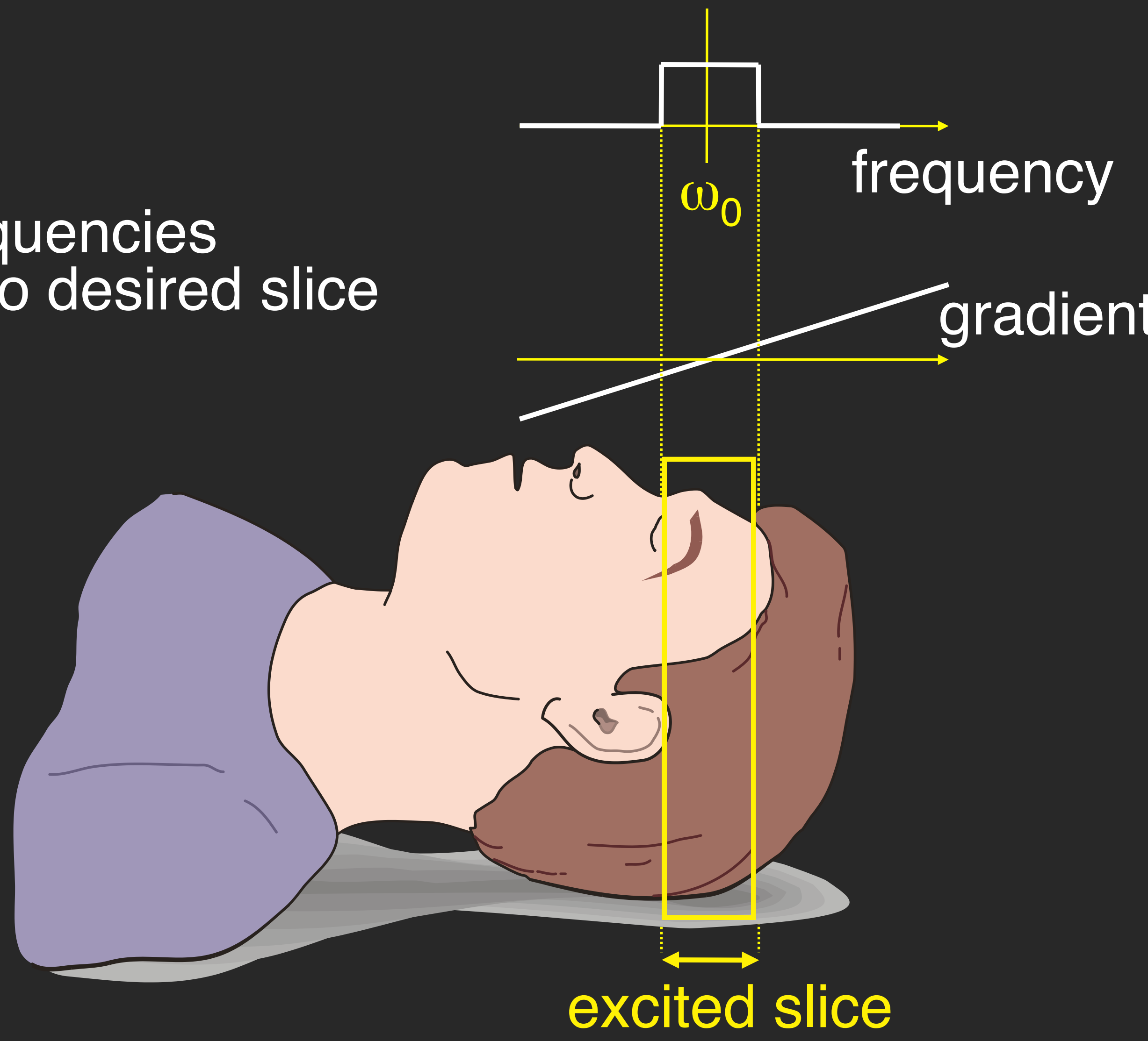


Acquire all of k-space in a “single shot”

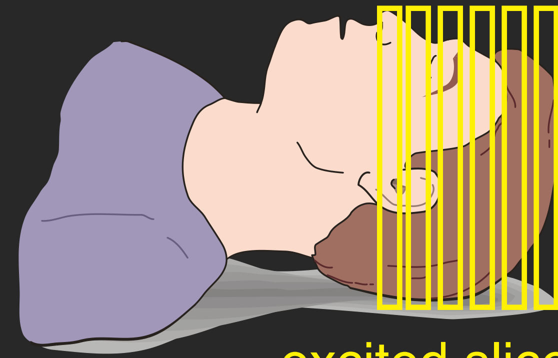
Used for FMRI, diffusion imaging

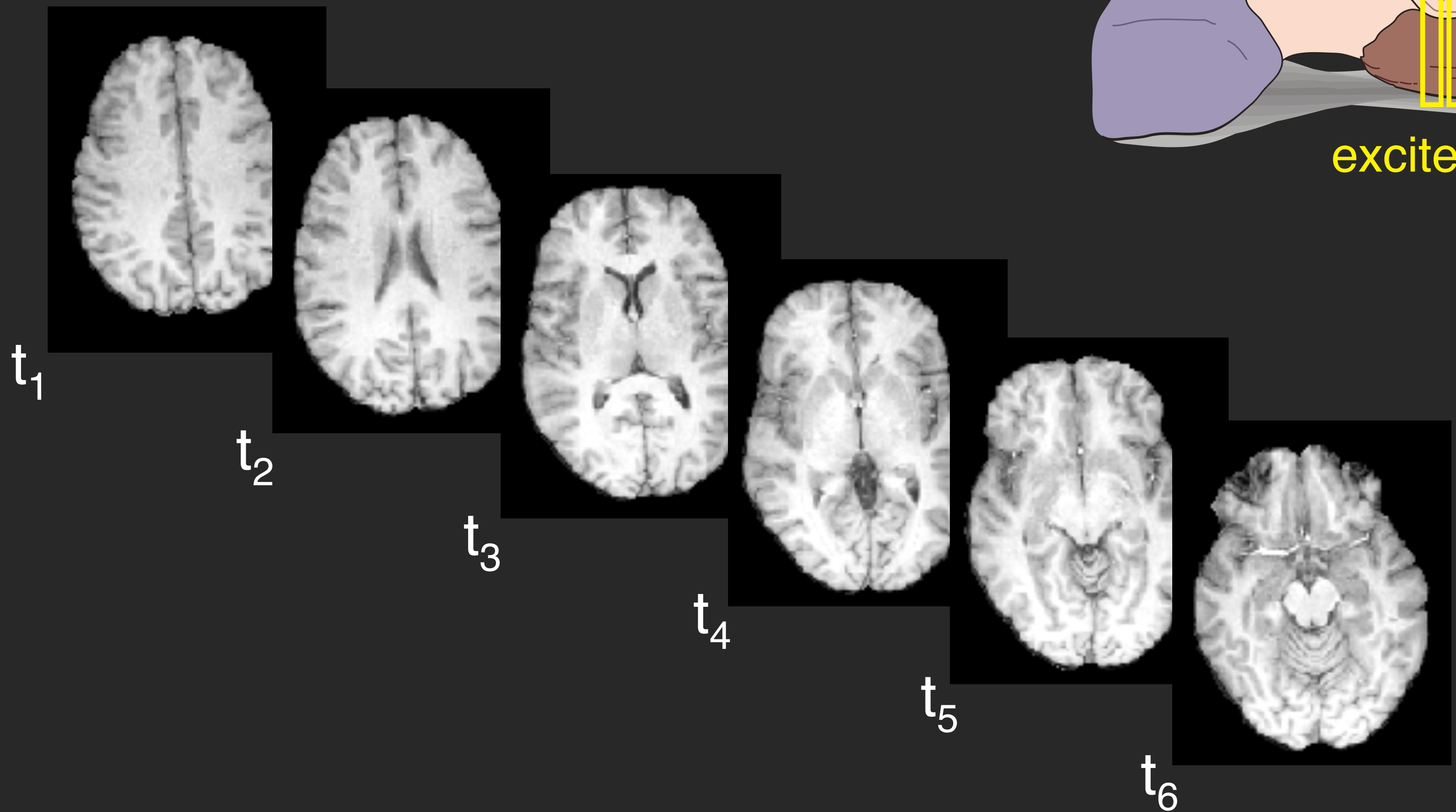
Slice Selection

Transmit all frequencies corresponding to desired slice



2D Multi-slice Imaging

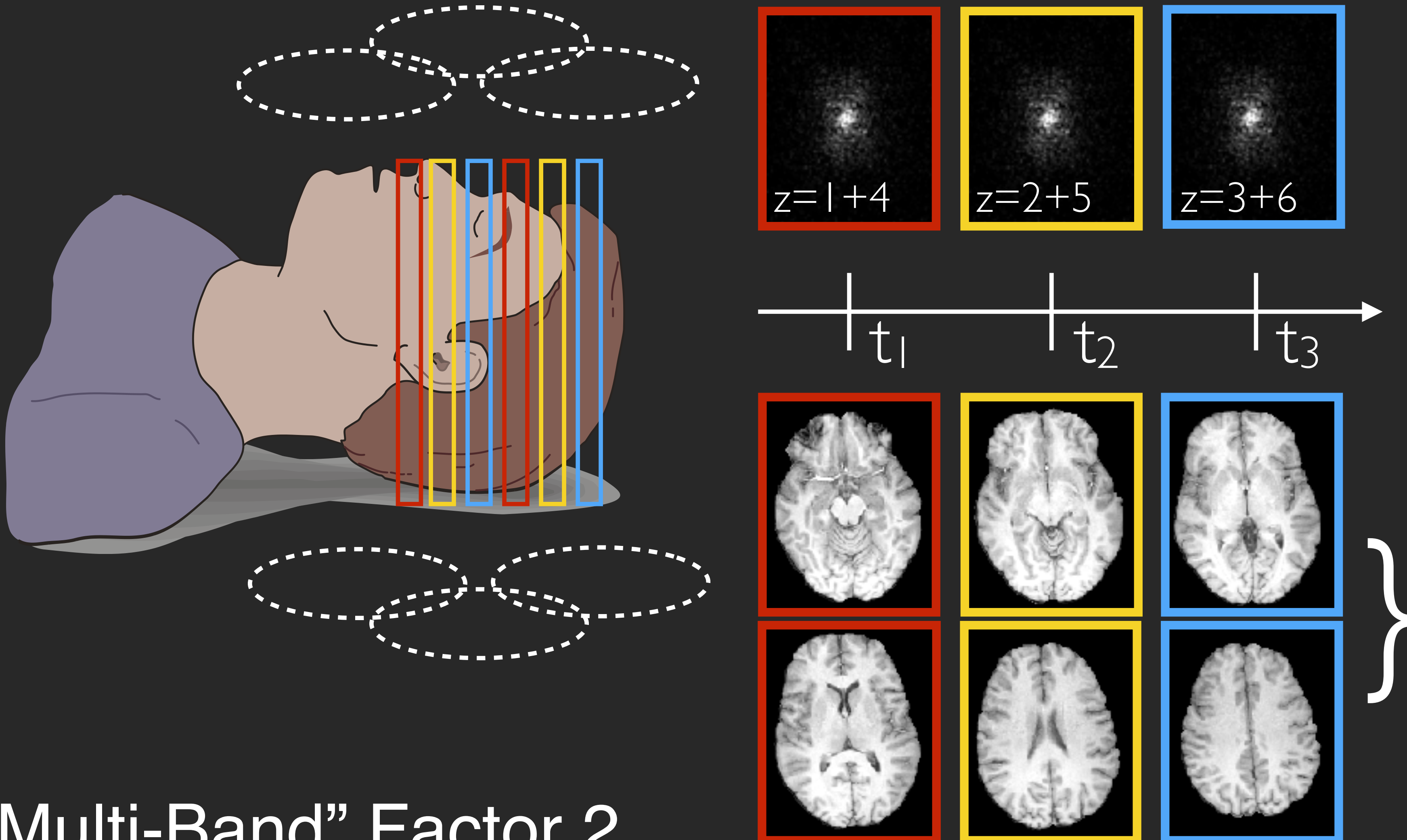




Slices excited and acquired sequentially (separately)

Most scans acquired this way (including FMRI, DTI)

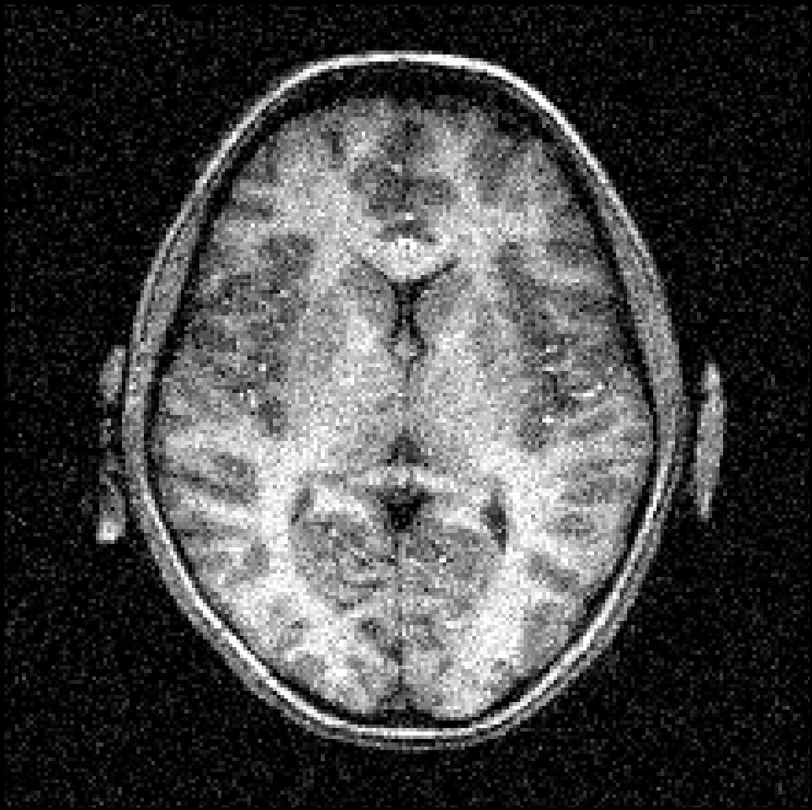
Simultaneous Multi-slice Imaging



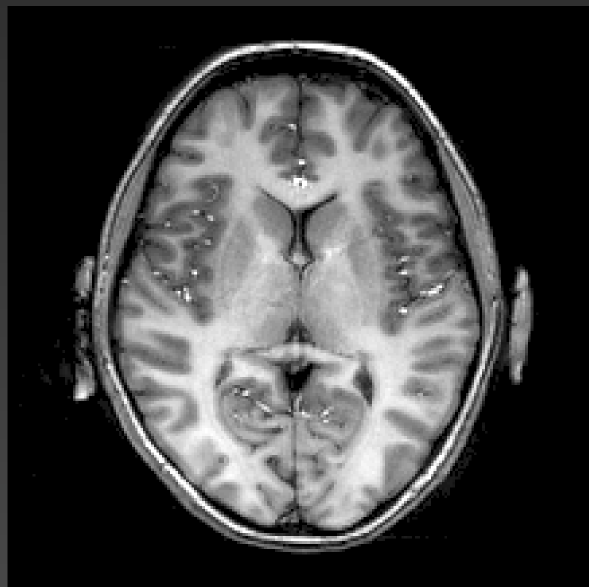
"Multi-Band" Factor 2

MRI Physics

- ★ Basics of magnetic resonance
- ★ Image formation
- ★ Signal statistics (SNR)
- ★ Functional MRI



Signal-to-noise ratio (SNR)



high SNR

low SNR

$$\mathrm{SNR} = \frac{\mathrm{Signal}}{\sigma_{noise}}$$

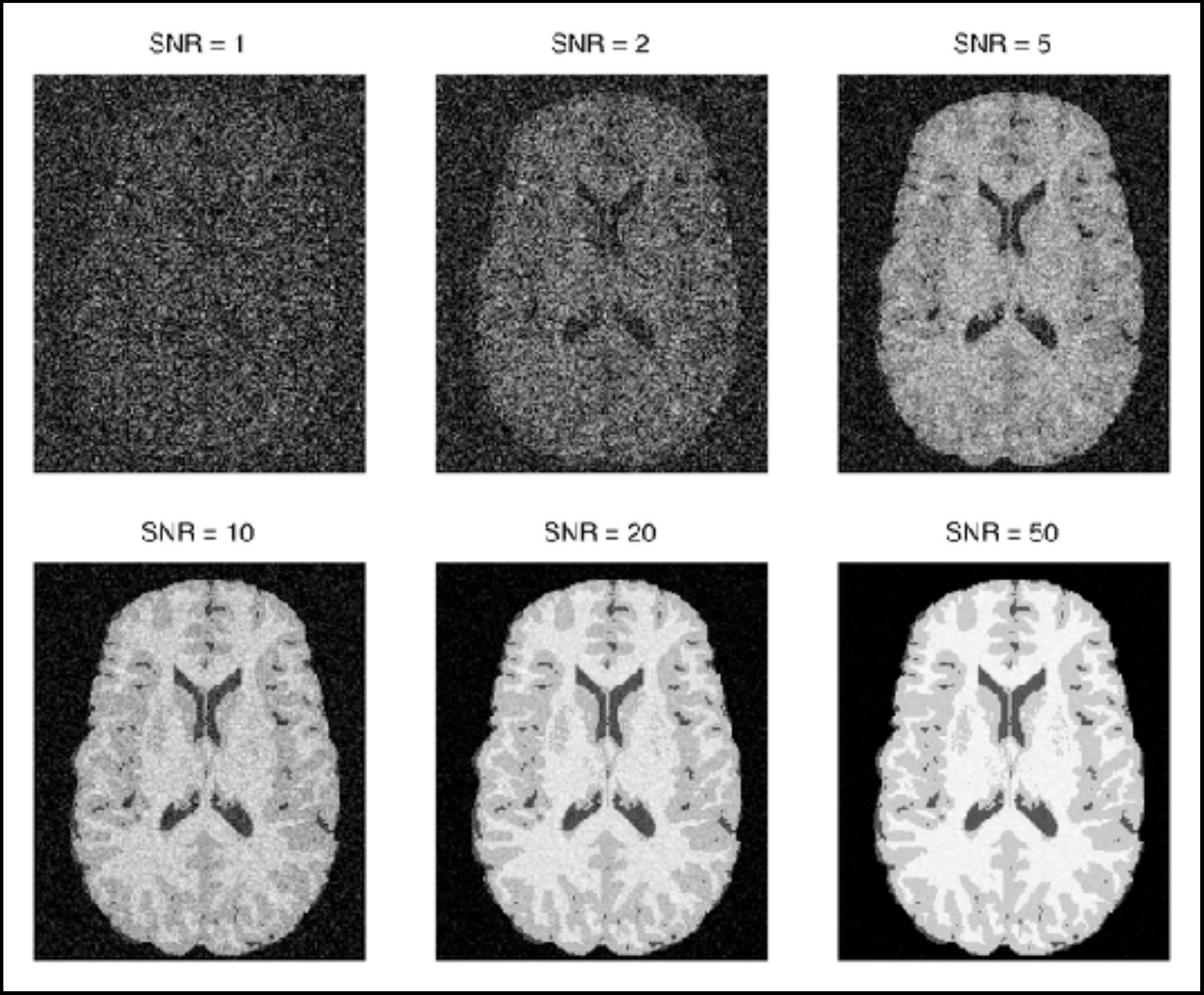
Signal: (magnitude)

σ_{noise}: (standard deviation)

Signal-to-noise ratio: describes signal “robustness”

All else being equal, we want to maximize SNR!!

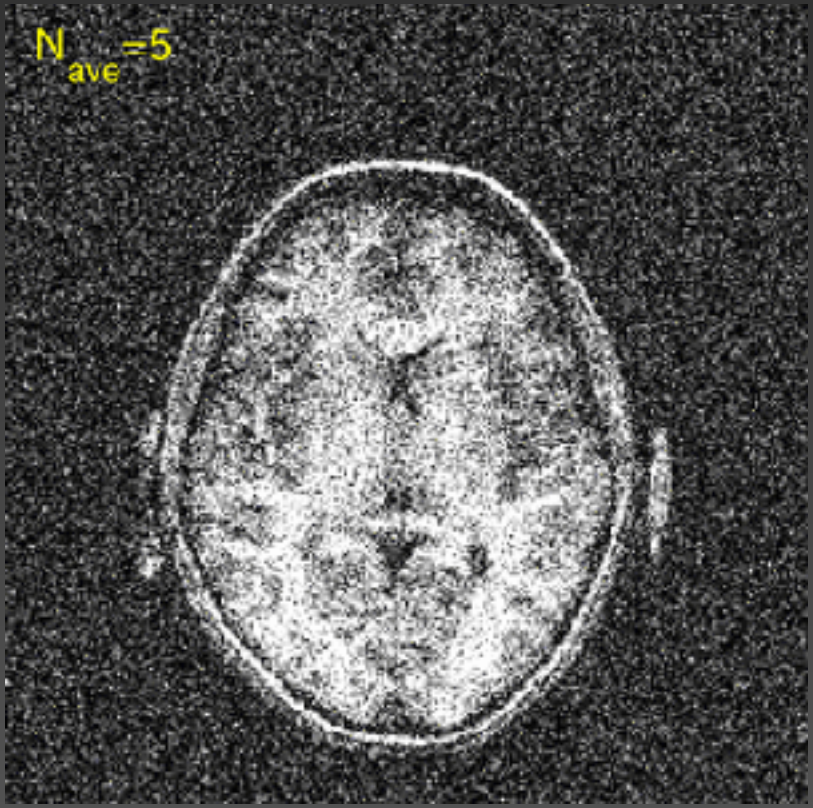
Signal-to-noise ratio (SNR)

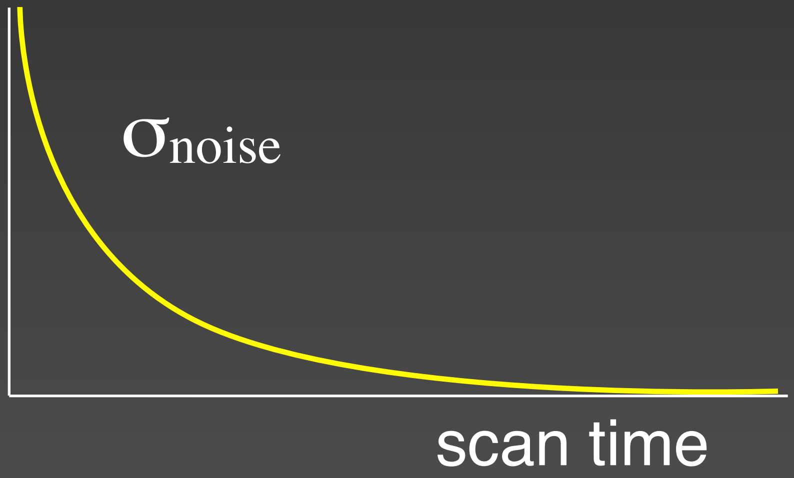


Protocol choices affecting SNR...

- RF receive coil & field strength
- Timing: bandwidth, TE & TR
- Voxel volume
- Scan duration (imaging time)
- Anything affecting signal!!!

SNR and acquisition time or averages

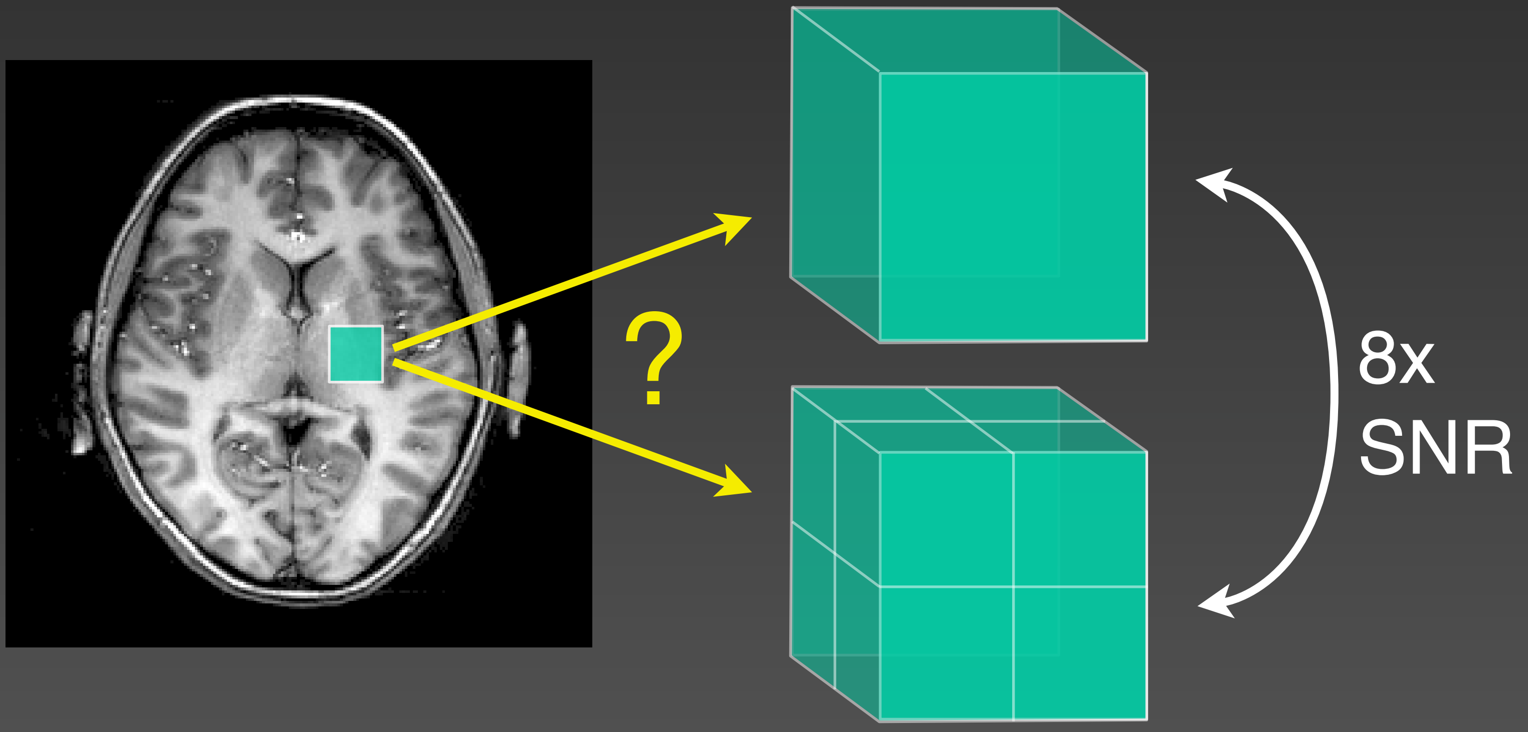




Longer acquisition ⇒ less noise ⇒ higher SNR

SNR improves with the *square root* of scan time
i.e., to *double* SNR you need to scan *4x* longer

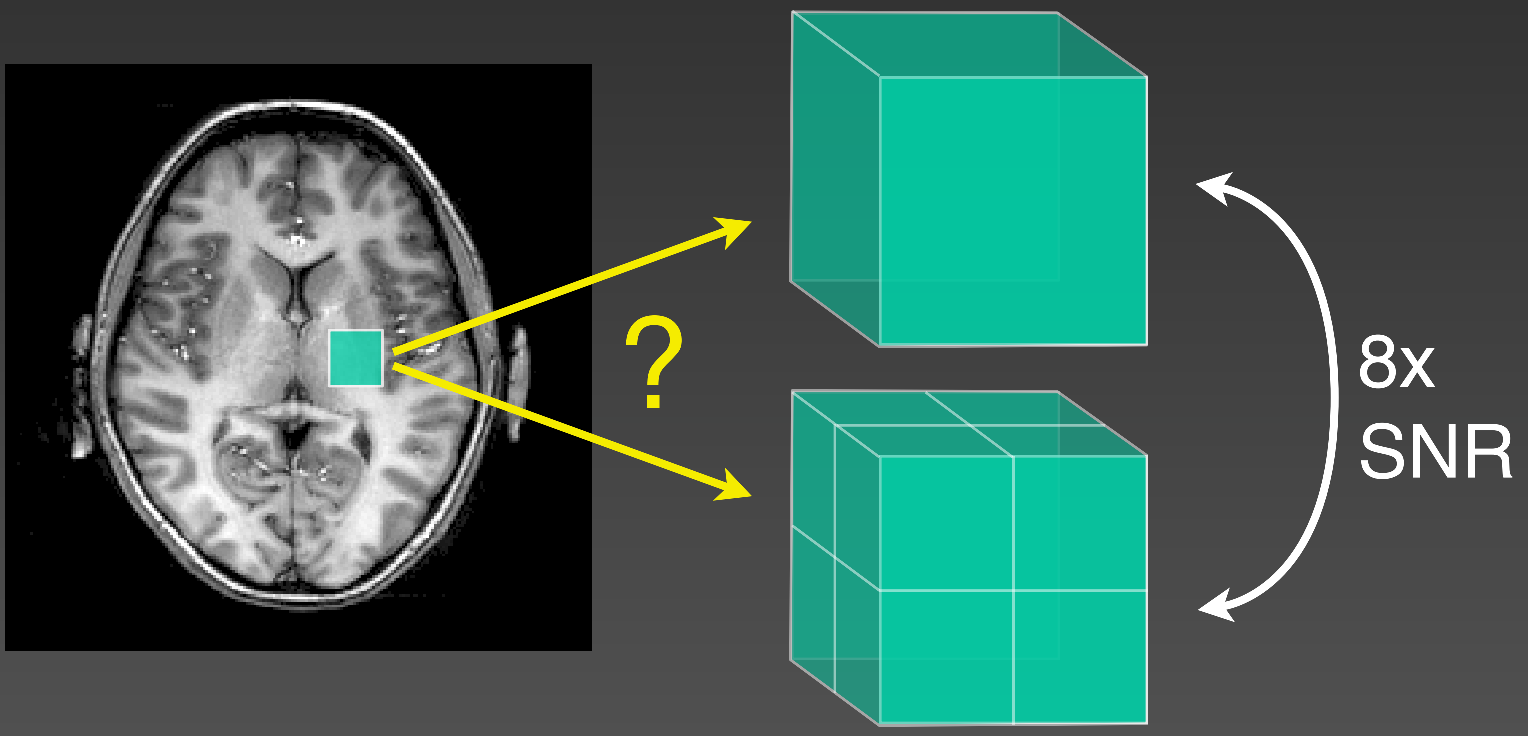
SNR and voxel volume



Larger voxels have signal from more tissue!

- Signal proportional to voxel volume
- 2x2x2mm has 8x higher SNR than 1x1x1mm!

Averaging to achieve high resolution

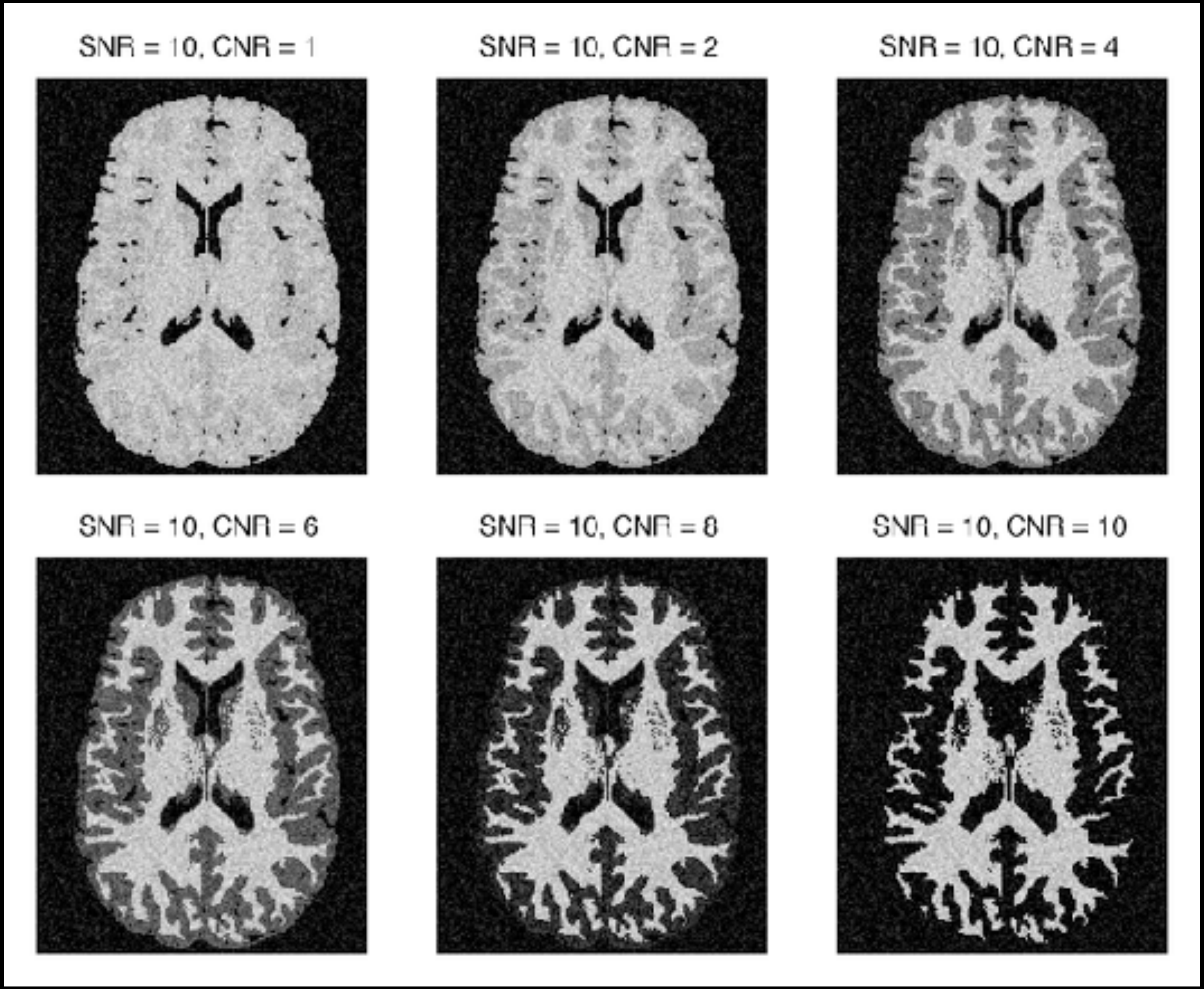


Can we recover lost SNR by averaging?

Yes! But requires a 64-fold increase in scan time

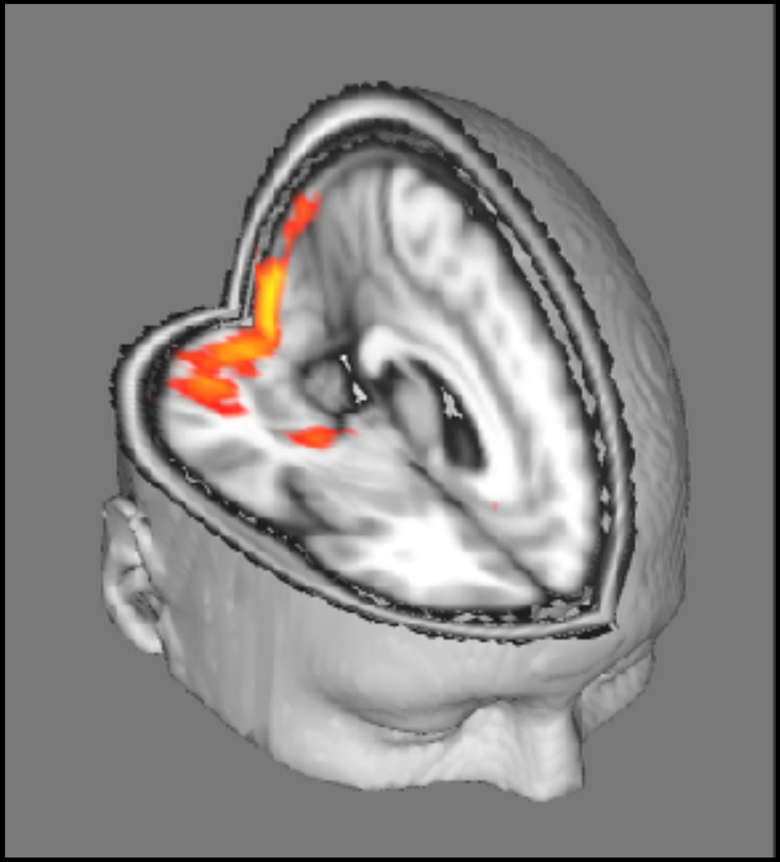
(because you only get square root benefit)

Contrast-to-noise ratio (CNR)

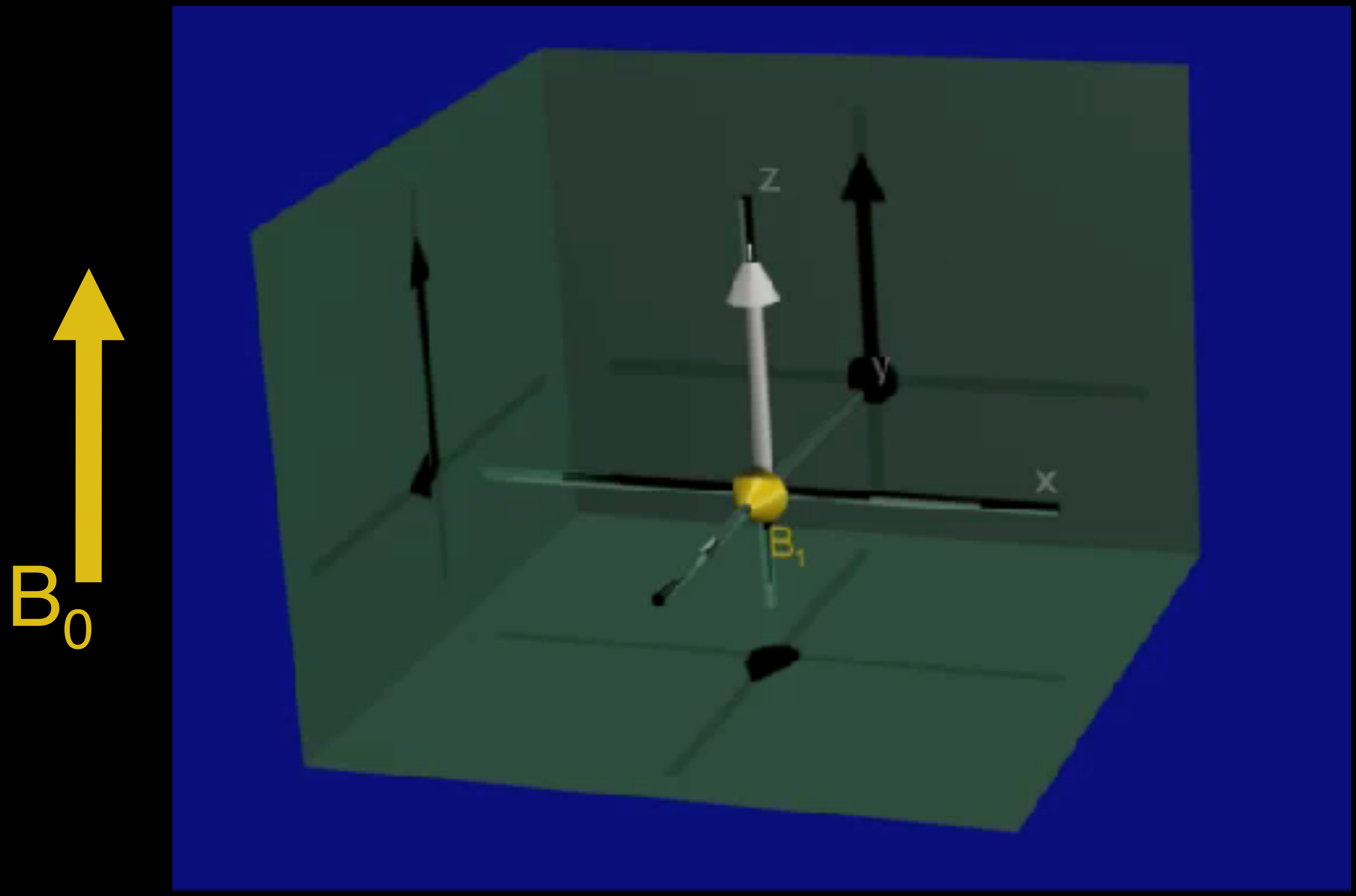


MRI Physics

- Basics of magnetic resonance
- Image formation
- Signal statistics (SNR)
- Functional MRI



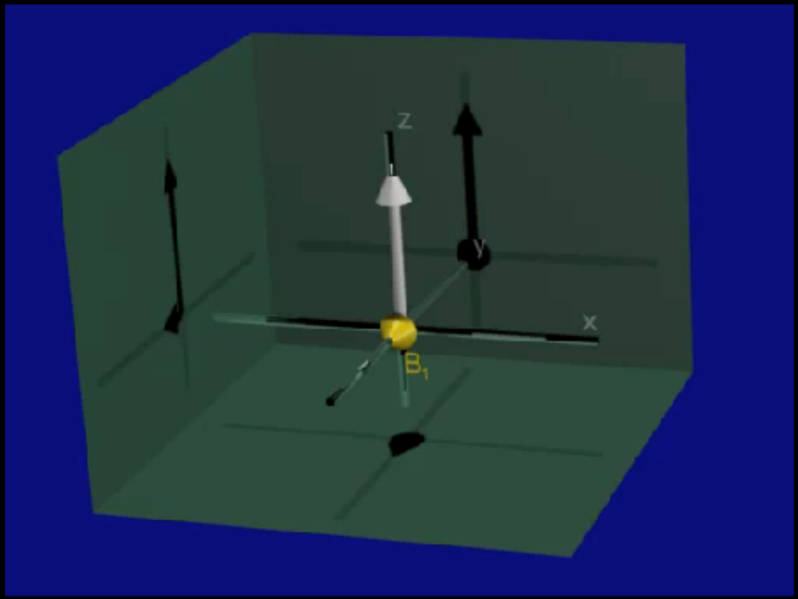
A source of signal loss: dephasing

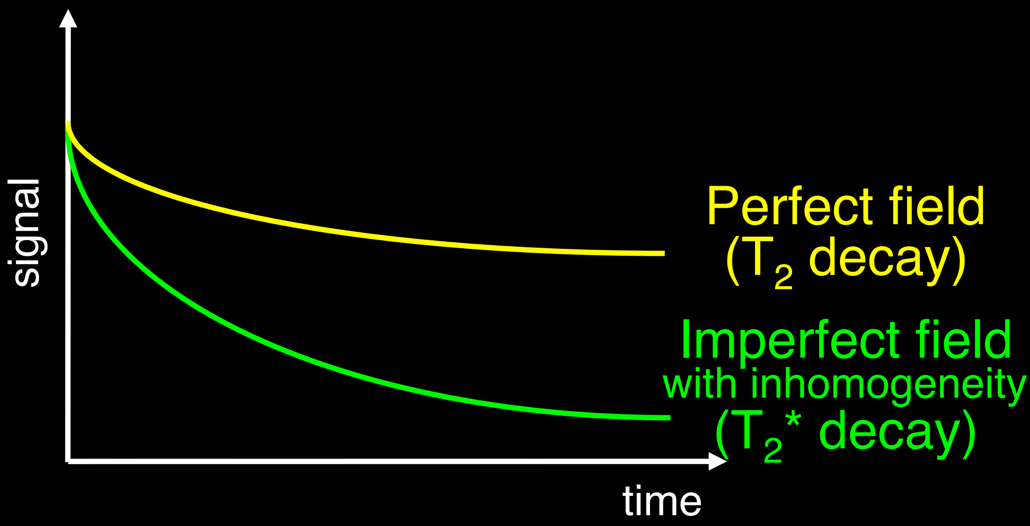


When spins are “in-phase”, they are all oriented the same way

Over time, the spins within a voxel lose alignment (“dephase”)

Apparent increase in $T_2 = T_2^*$



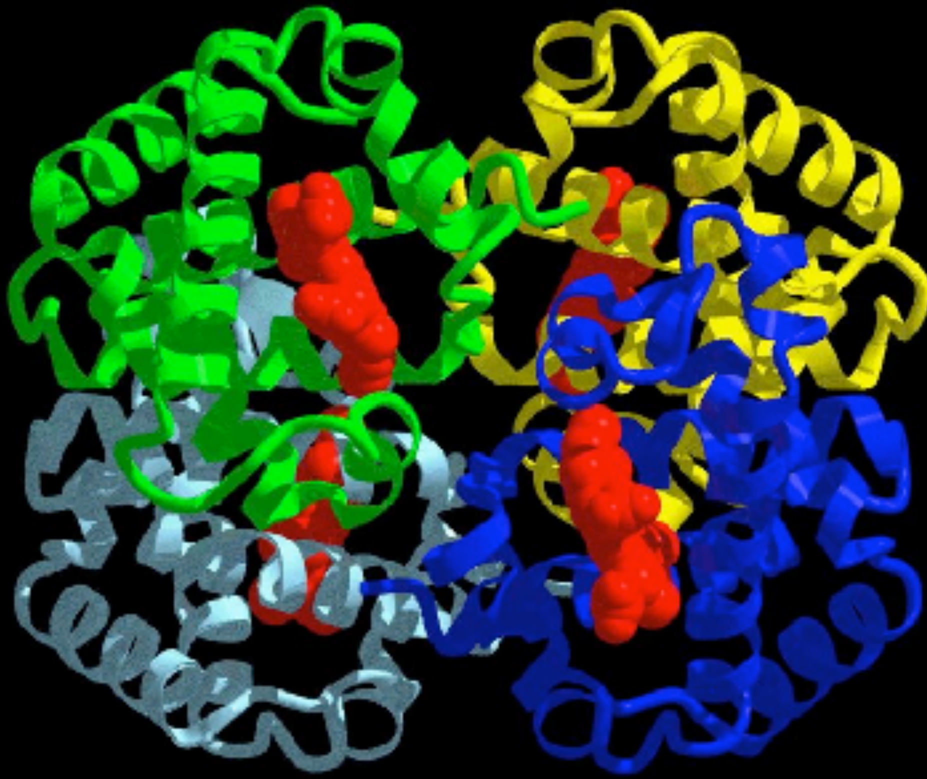


Dephasing causes magnetization vectors to partially "cancel" each other out

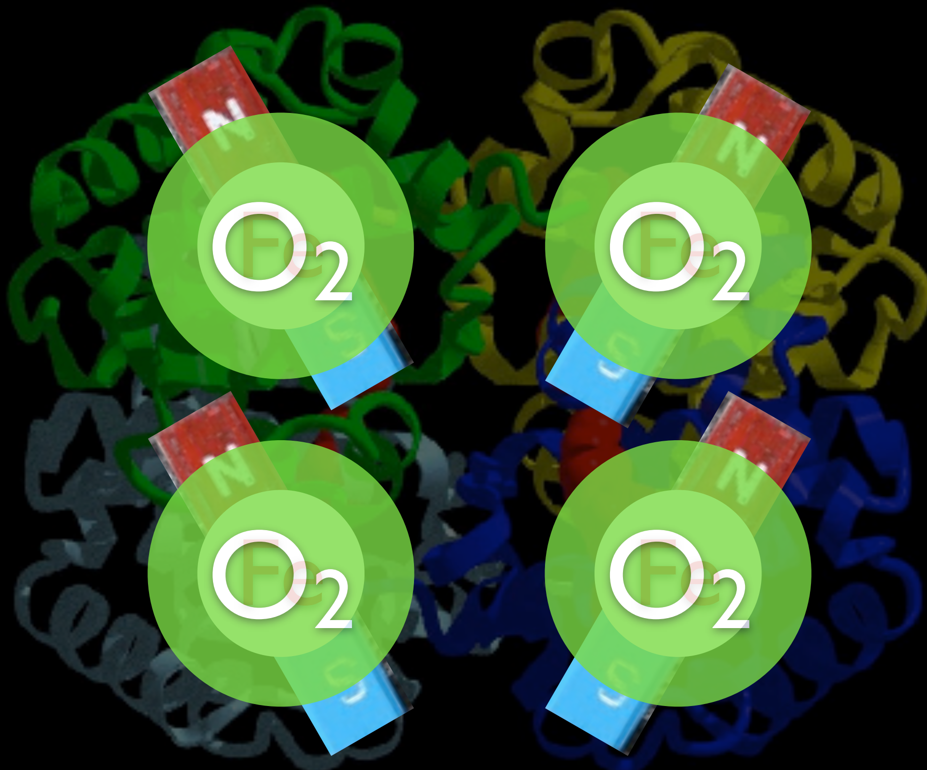
Dephasing results in a lower *net* signal magnitude

Apparent decrease in T_2: called T_2^* (more on Wednesday)

Deoxyhaemoglobin is the source of FMRI signal

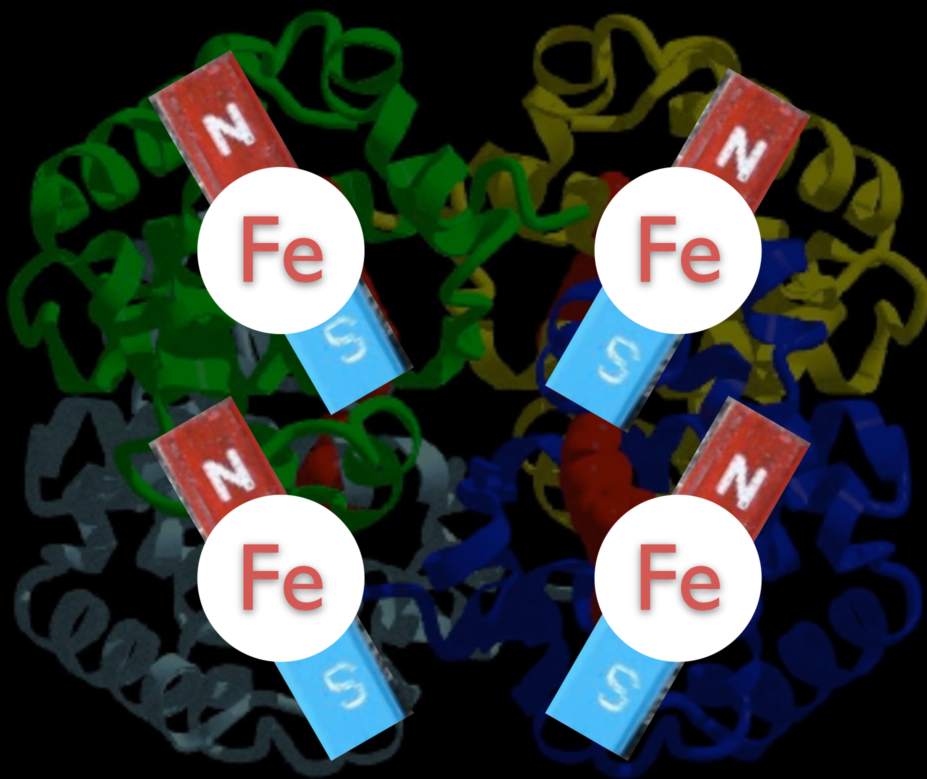


Deoxyhaemoglobin is the source of FMRI signal



When oxygen is bound to the haemoglobin, it shields the magnetic effects of iron atoms in the heme groups

Deoxyhaemoglobin is the source of FMRI signal

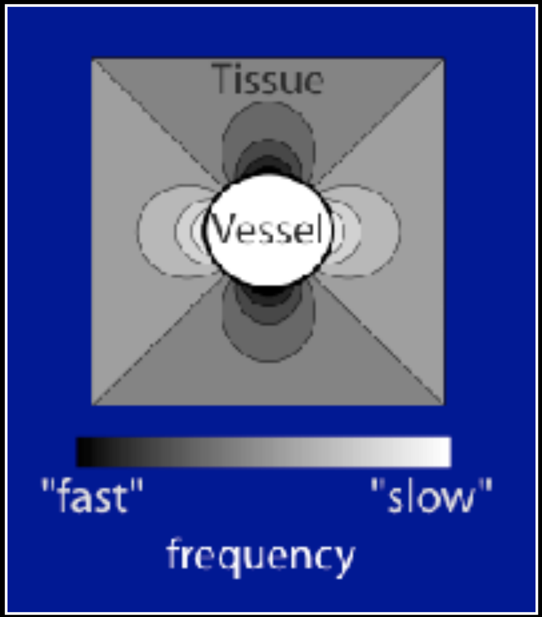


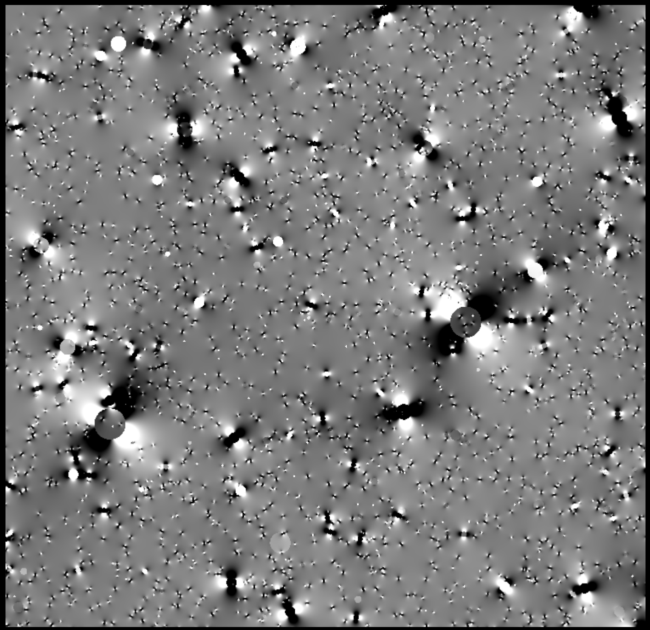
Without oxygen, the iron (Fe) is exposed, causing magnetic field inhomogeneities due to its strong magnetic properties

Field inhomogeneity leads to T2* change (FMRI signals)

The BOLD Effect

[Ogawa et al, 1990]



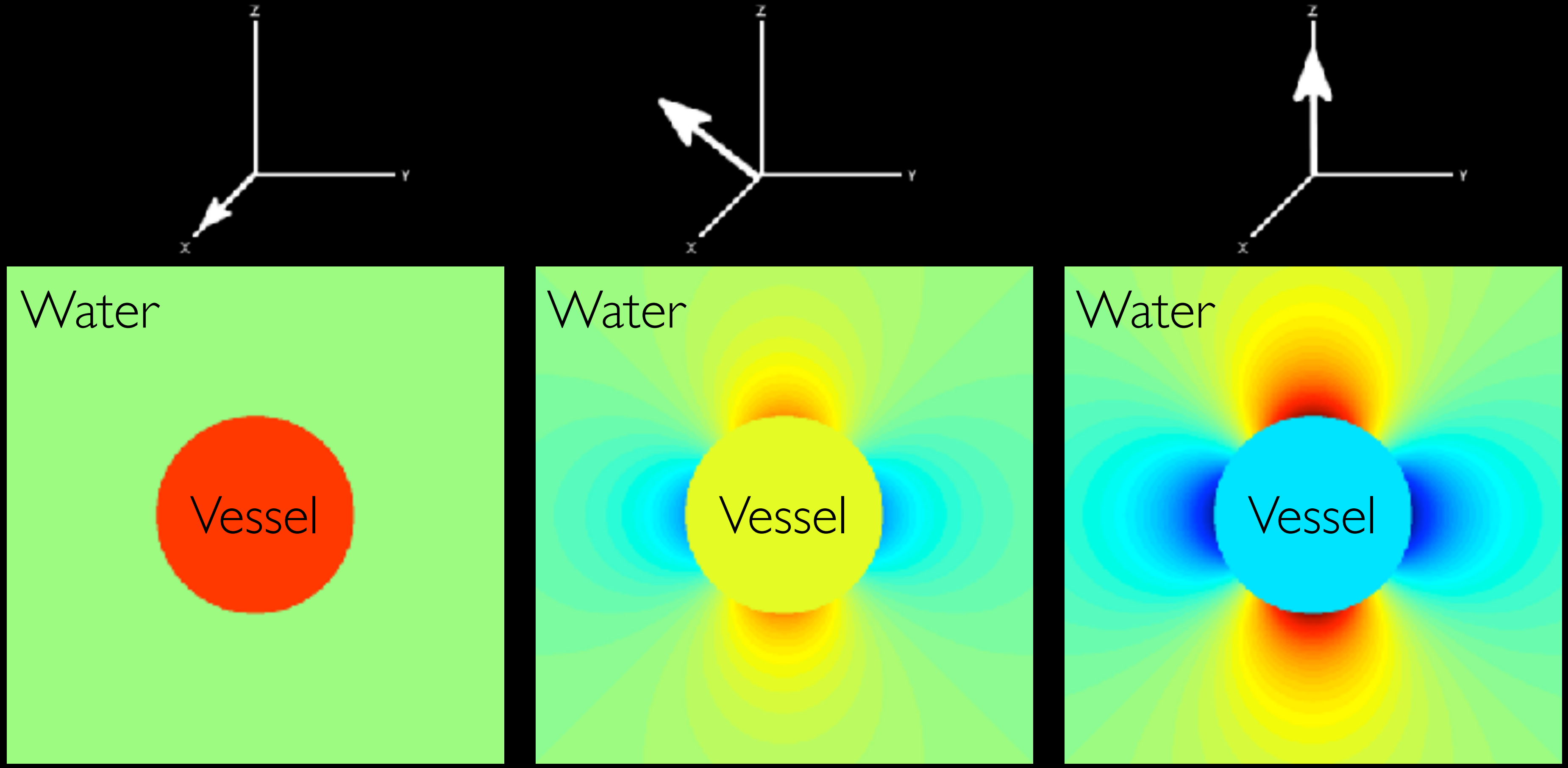


imaging voxel

Blood Oxygenation Level Dependent (BOLD) effect

Vessels, depending on orientation and blood oxygen content will alter their local magnetic fields

BOLD Effect – vessel orientation

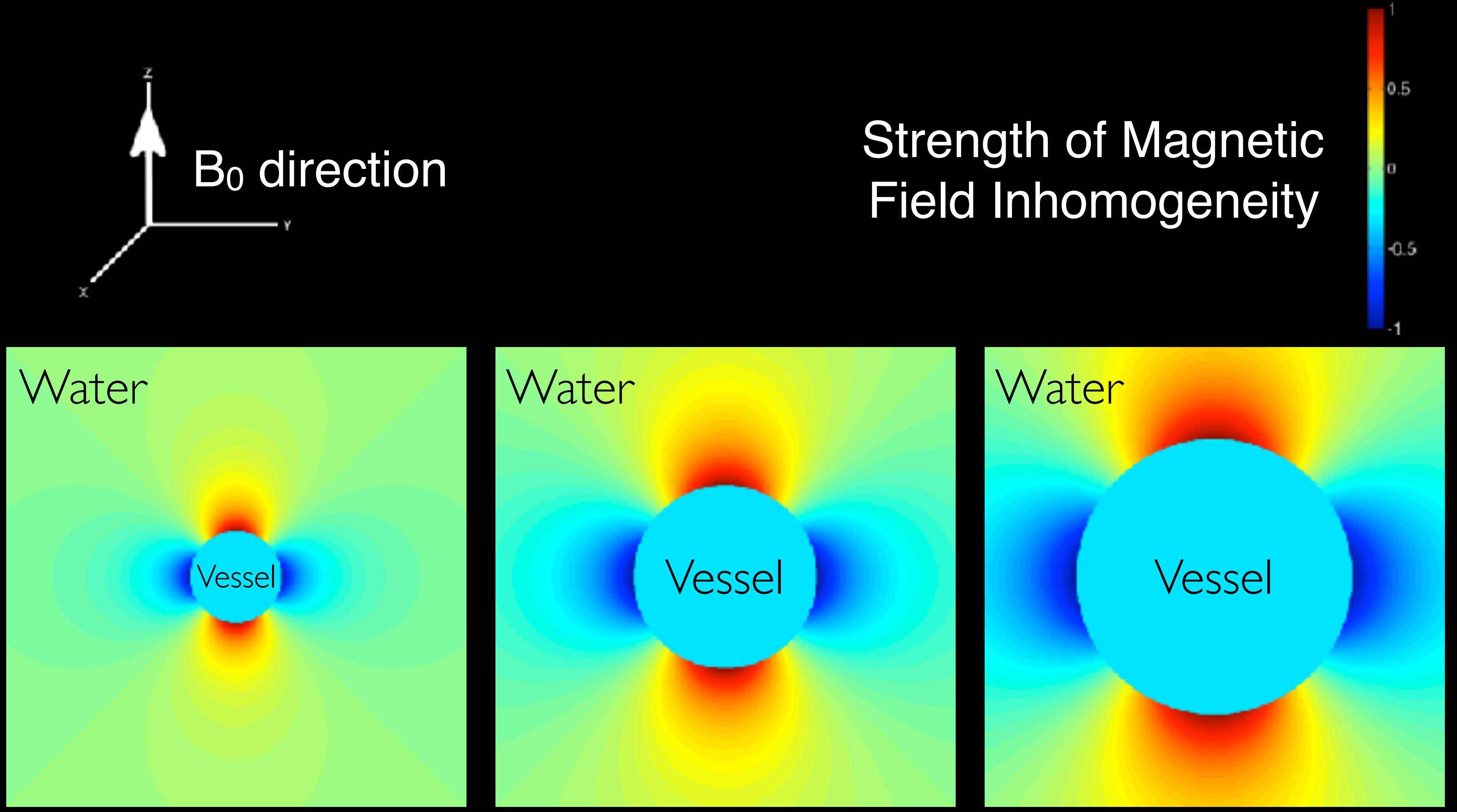


0°
Vessel parallel

45°

90°
Vessel perpendicular

BOLD Effect – vessel size

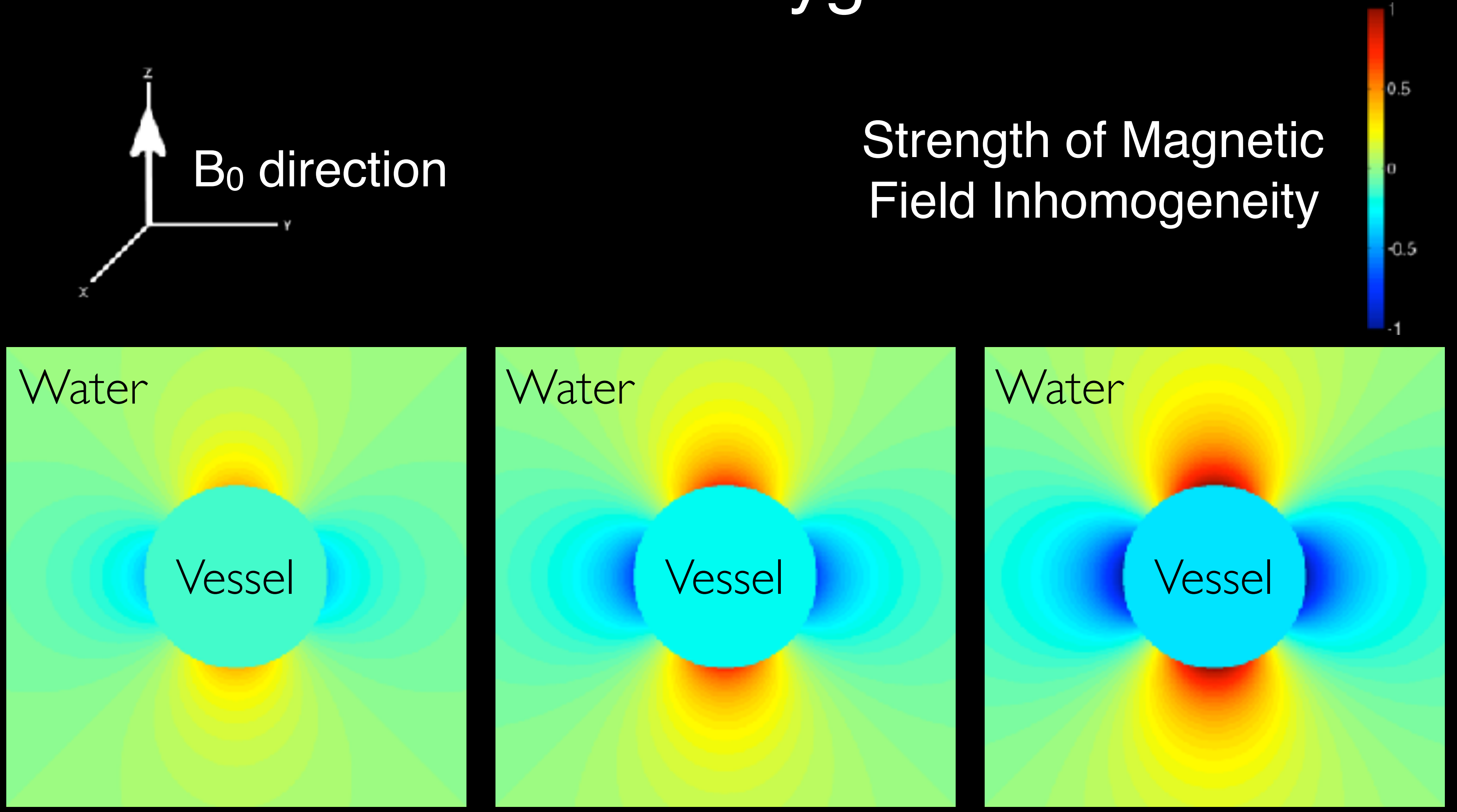


radius = 50 µm

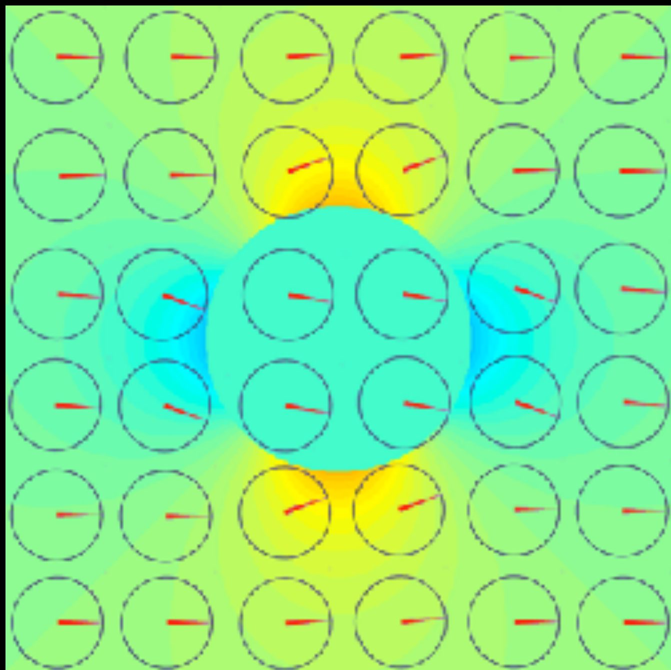
radius = 100 µm

radius = 150 µm

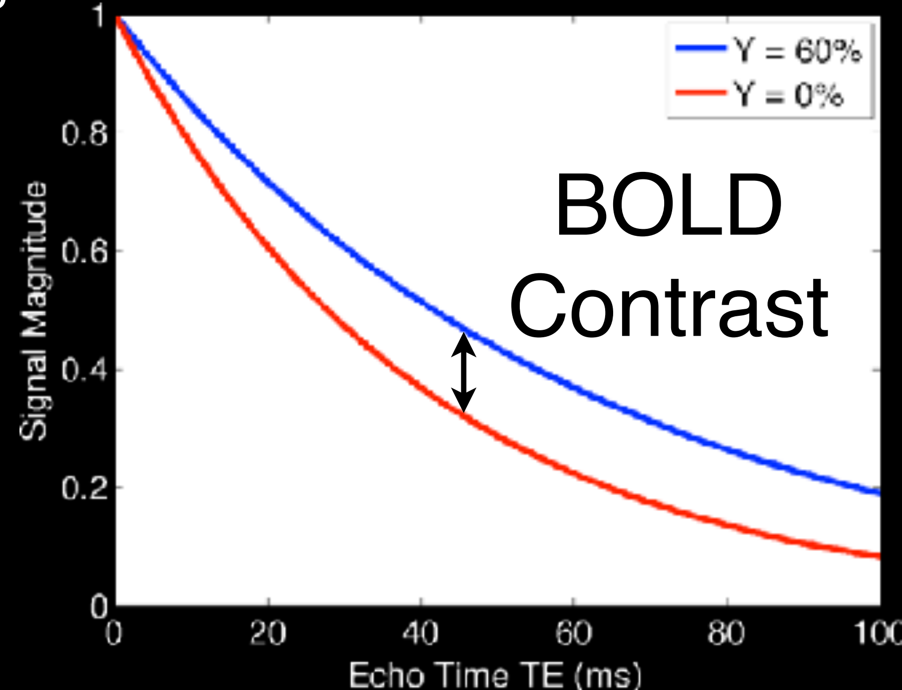
BOLD Effect – blood oxygenation level

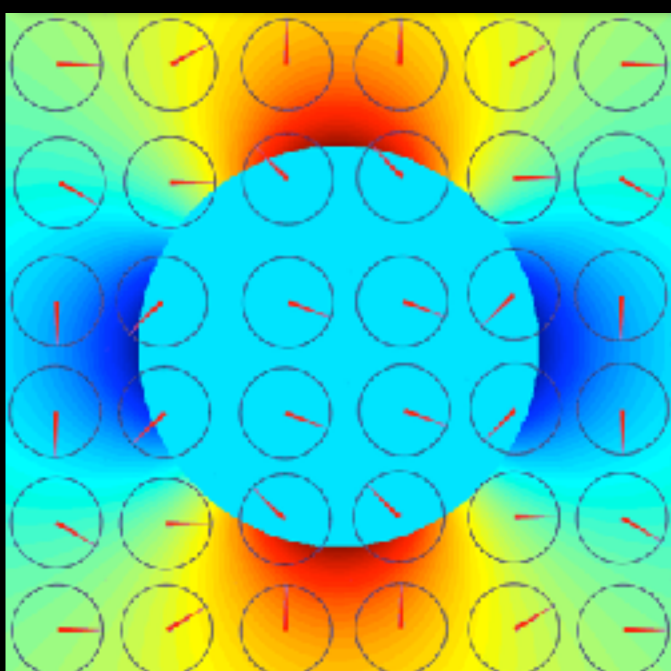


Oxygenation = 60%   Oxygenation = 30%   Oxygenation = 0%



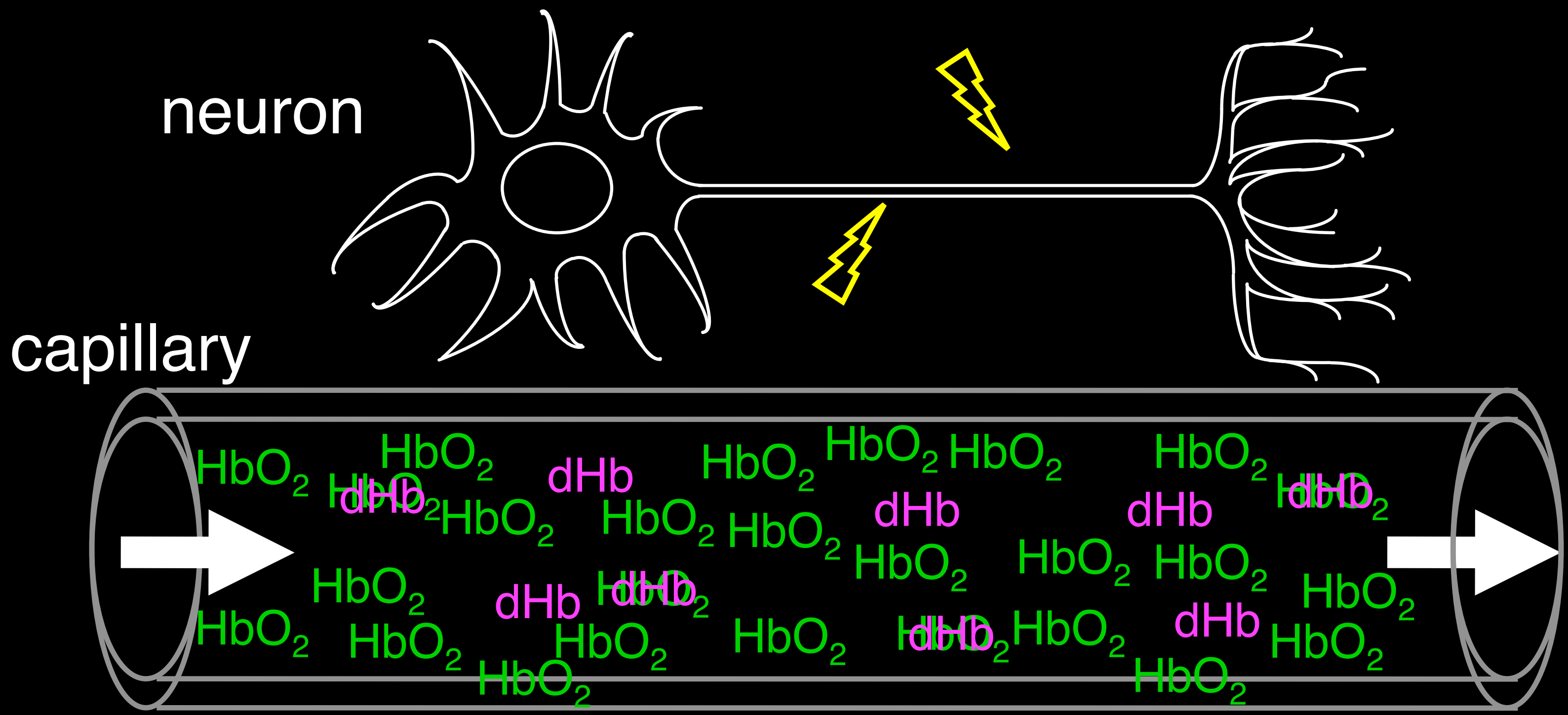
Oxygenation: Y=60%
More Oxygenated Hb
Low inhomogeneity
Longer T2*
Higher signal





Oxygenation: Y=0%
More de-oxygenated Hb
High inhomogeneity
Shorter T2*
Lower signal

Vascular Response to Activation



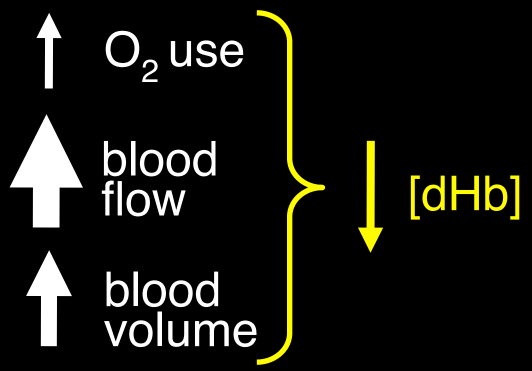
HbO$_2$ = oxyhemoglobin

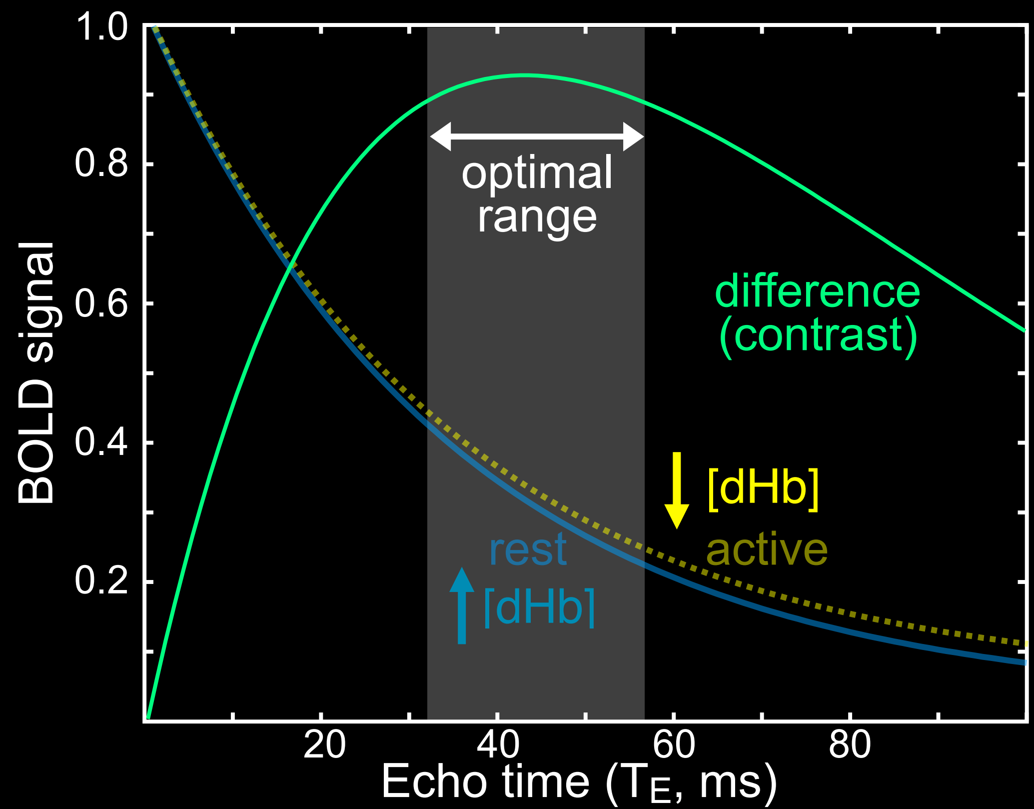
dHb = deoxyhemoglobin

↑ O_2 metabolism	↑ dHb
↑ blood flow	↑ HbO$_2$
↑ blood volume	↑ HbO$_2$

↓ [dHb]

BOLD Contrast



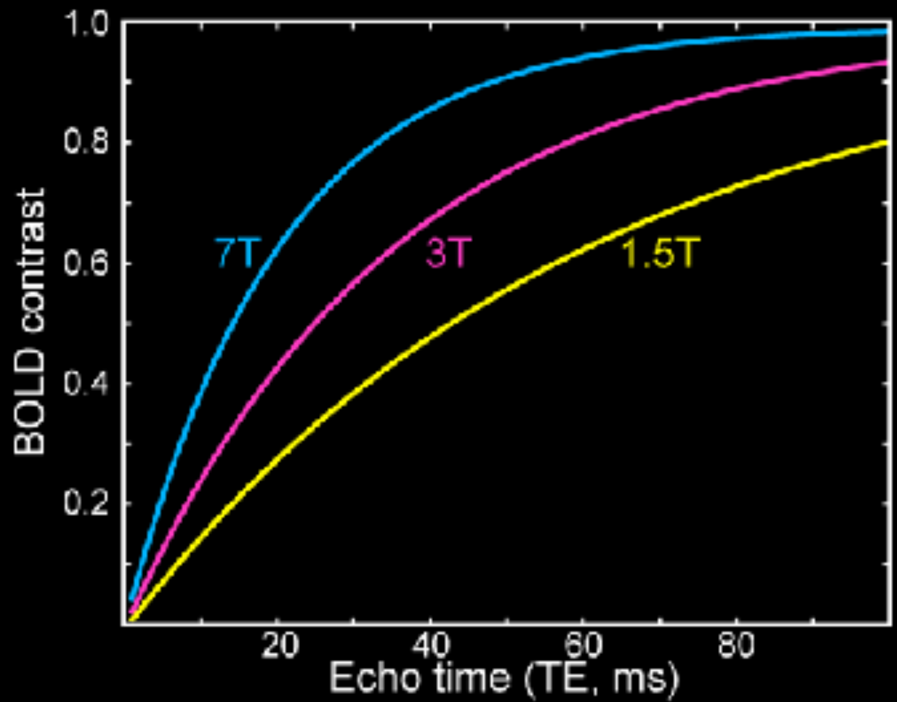


Signal increases during activation (less decay)

Signal change for longer delay (T_E)

Typically, 1–5% signal change

BOLD signal and field strength (B_0)

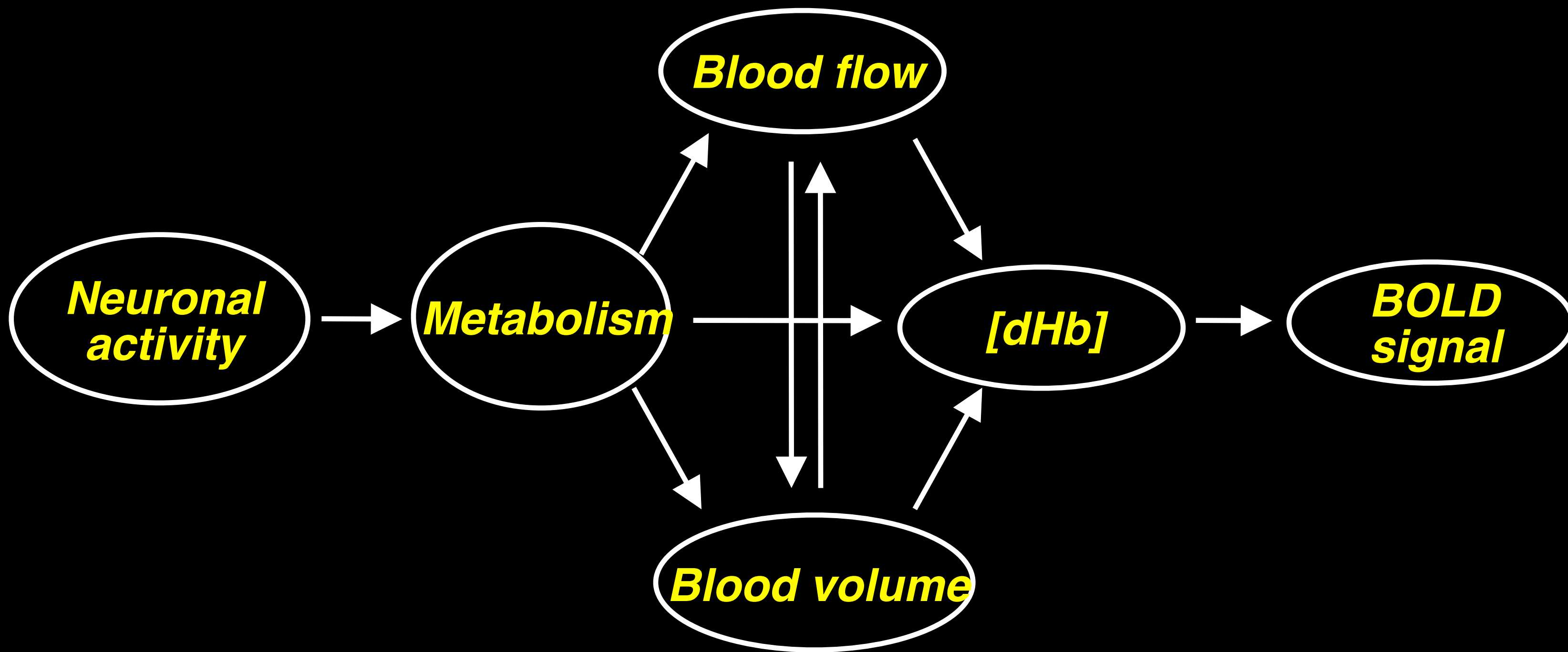


SNR and BOLD effects can increase with field strength

But image artefacts get worse at higher field strength

3T is currently a good tradeoff of signal vs artefacts

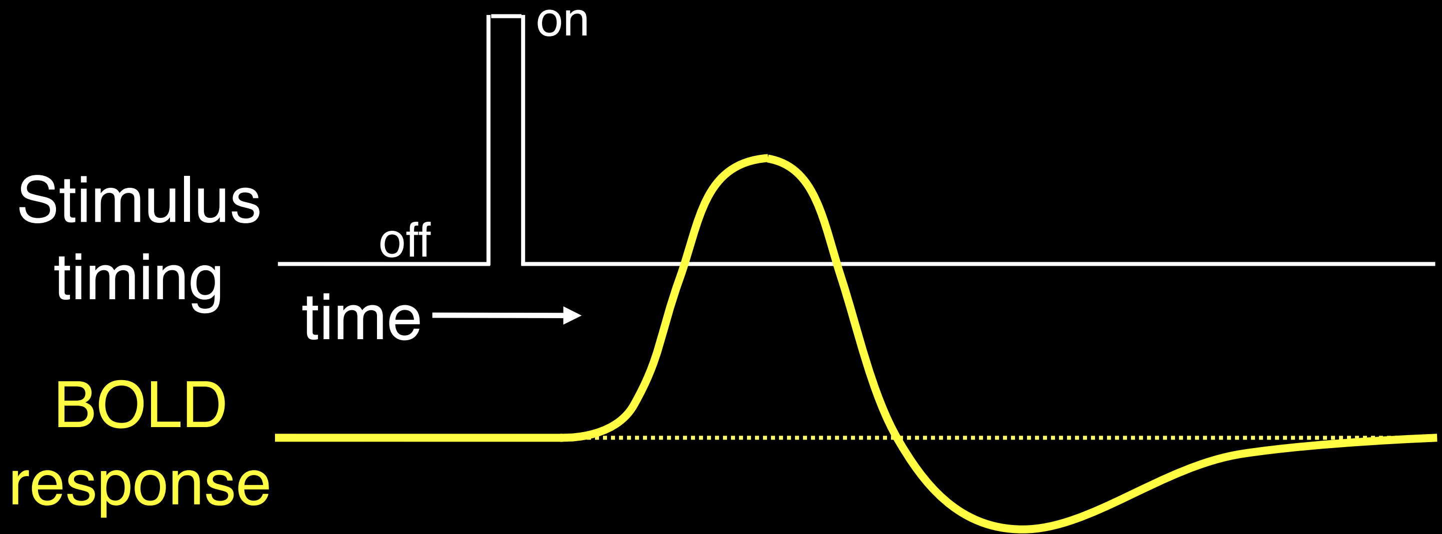
Sources of BOLD Signal



Indirect measure of activity (via metabolism!)

Subject's physiological state & pathology can change neurovascular coupling, muddying interpretation

Hemodynamic response function (HRF)



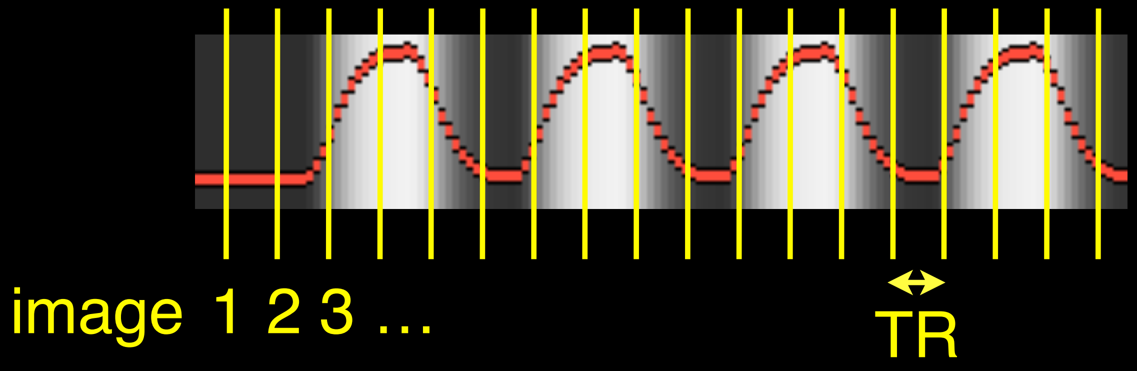
Vascular response to activity is delayed & blurred

Described by “hemodynamic response function”

Limits achievable temporal resolution

Must be included in signal model

What is required of the scanner?



Typical stimulus lasts 1–30 s

Rapid imaging: an image every few seconds

Anatomical images take minutes to acquire!

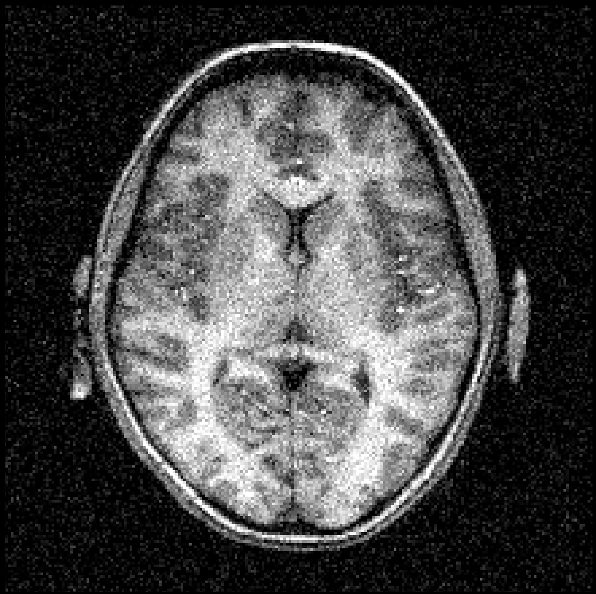
Acquire “single-shot” images (e.g., EPI)

Typical* FMRI Parameters

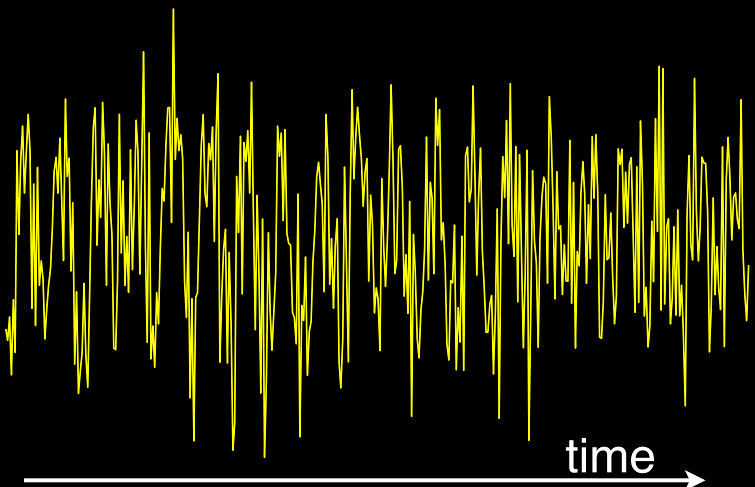
* Typical, *not* fixed!!

Parameter	Value	Relevant points
T_E (echo time)	1.5T: 60 ms 3.0T: 30-40 ms 7.0T: 15-25 ms	Determines functional contrast, set ≈T2*
T_R (repeat time)	1–4 s	HRF blurring < 1s; Poor resolution > 4s
Matrix size / Resolution	64x64 – 96x96 2–3 mm	Limited by distortion, SNR, FOV
Scan duration	2-15 mins	Lower limit: sensitivity Upper limit: compliance

Confounds: Noise



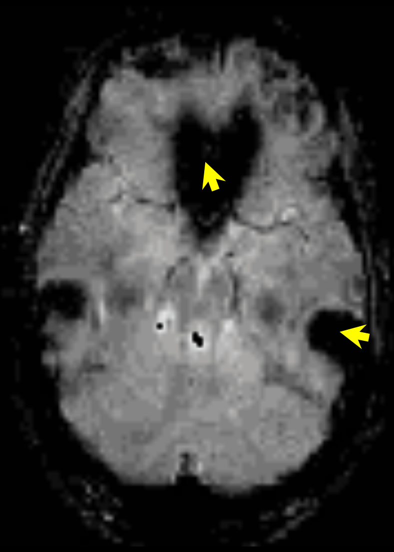
Purely random noise
(example: “thermal”)



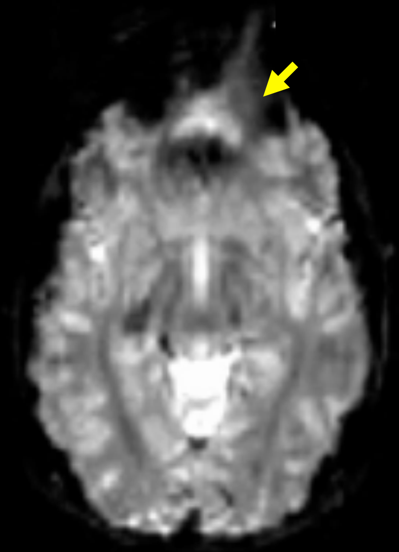
Structured noise
(example: “physiological”)

Noise: signal fluctuations leading to less robust detection with respect to statistical measures

Confounds: Artefacts



Dropout

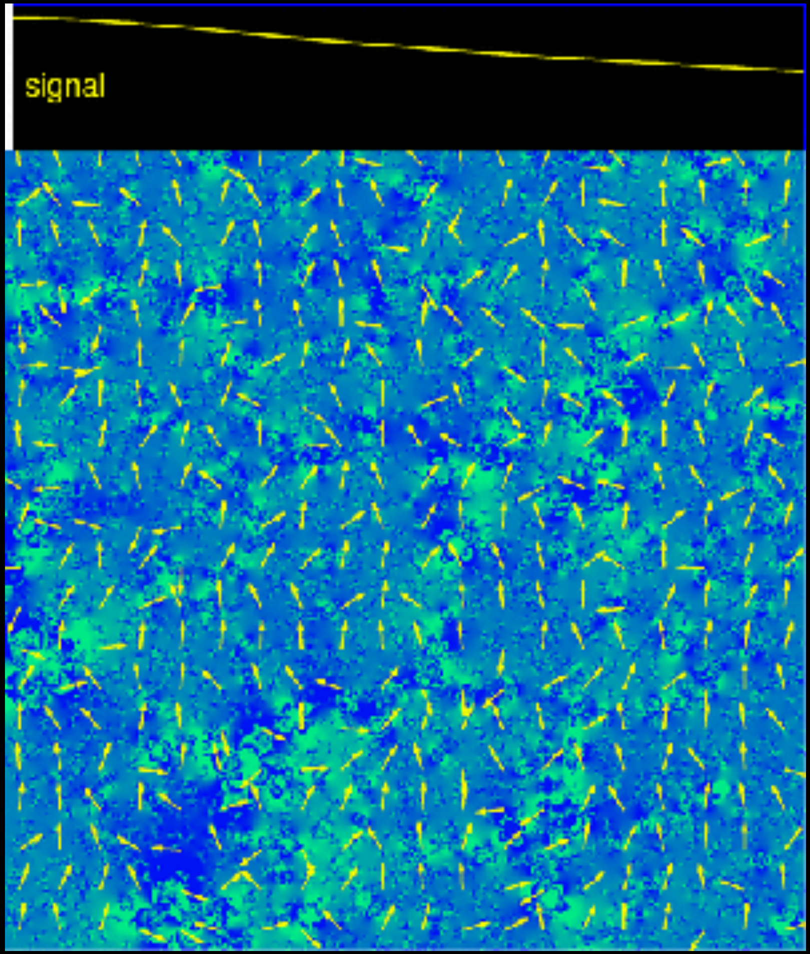


Distortion

“Ghosting”

Artefacts: systematic errors that interfere with interpretability of data/images

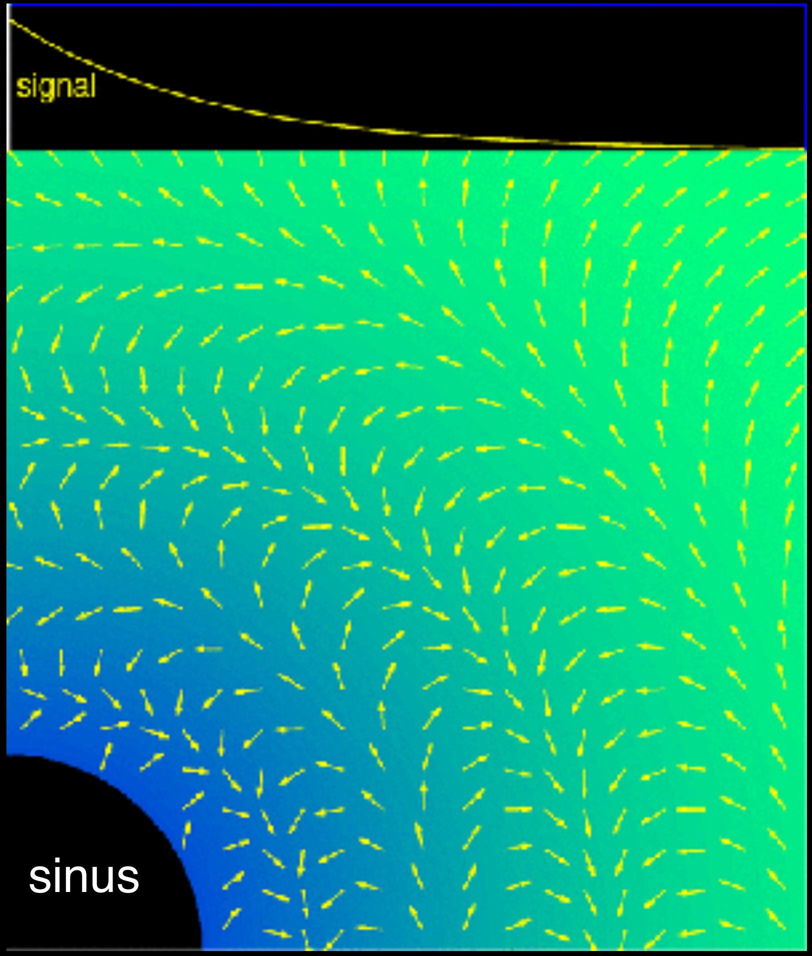
Source of signal dropout



BOLD contrast is based on signal dephasing

BOLD imaging requires longish delay (T_E) for contrast

Dropout is just extreme dephasing

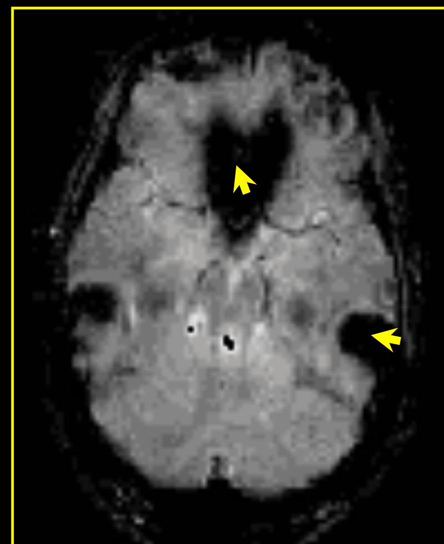


Dephasing also occurs near air-tissue boundaries

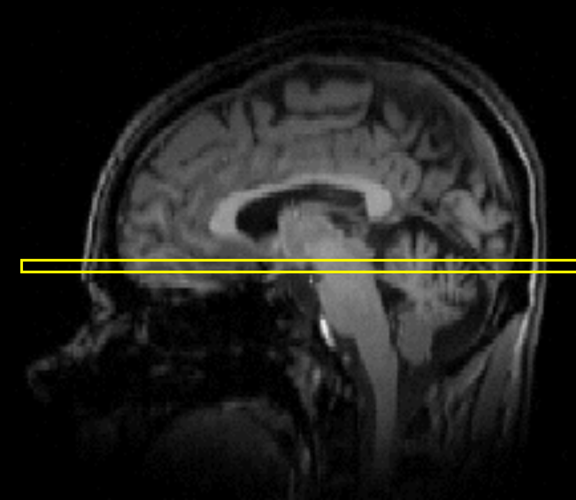
Sensitivity to BOLD means signal loss near air-tissue boundaries

BOLD Signal Dropout

Short TE



Long TE



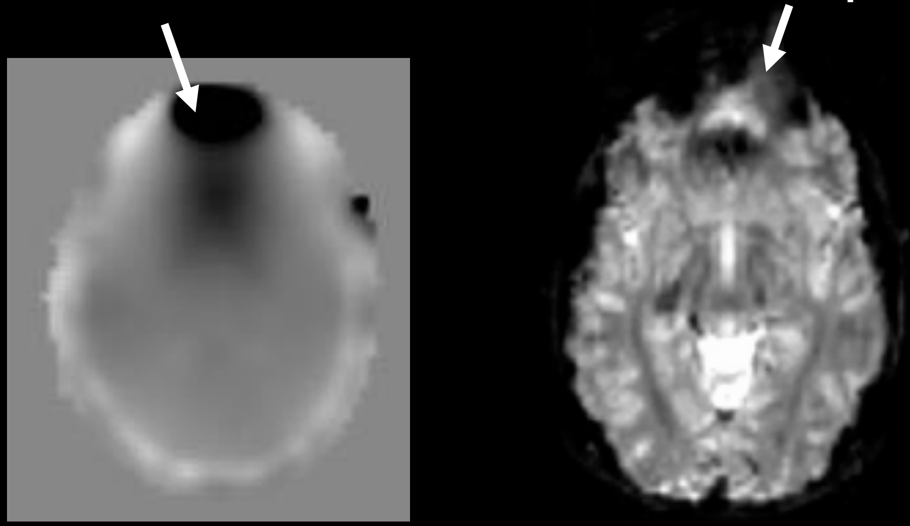
Dephasing near air-tissue boundaries (e.g., sinuses)

BOLD contrast coupled to signal loss ("black holes")

Air-tissue effect is often larger than BOLD effect

Dropout is not correctable post-acquisition!

Image distortion



Field map EPI

We think frequency maps to spatial location...

So errors in frequency cause spatial mis-localization!

More on Wednesday...

Final thoughts

Understand how different experimental parameters affect SNR and image artefacts

Tradeoffs: you can’t get something for nothing, but you do have options

Get to know an engineer/physicist/radiographer: get help setting up study protocols, show them your artefacts

Quality assurance: always look at your data, even if you are running a well-tested protocol

Questions:

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