Basic MR image encoding

Lawrence L. Wald, Ph.D.

MGH-NMR Center

Wald@nmr.mgh.harvard.edu

Physical Foundations of MRI

What is NMR?
 The basic signal we excite and detect.

Tricks of NMR
 The gradient and spin echo

How do we encode an image?
 slice select, frequency and phase encoding.

What are some problems (artifacts) relevant to our application.

Physical Foundations of MRI

NMR: 60 year old phenomena that generates the signal from water that we detect.

MRI: using NMR to generate an image

Three magnetic fields (generated by 3 coils)

1) static magnetic field Bo
2) RF field that excites the spins B1
3) gradient fields that encode spatial info
   G_x, G_y, G_z

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What is NMR?

NUCLEAR

MAGNETIC

RESONANCE

A magnet, a glass of water,
and a radio wave source and detector….

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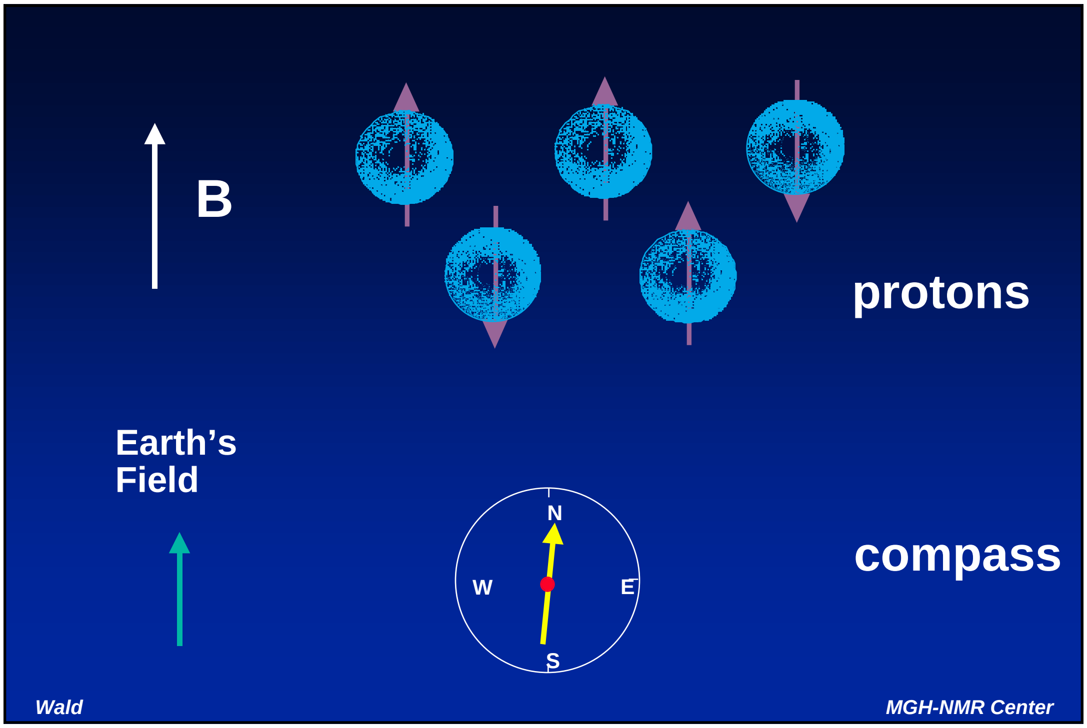


Nuclei and Magnetic Fields

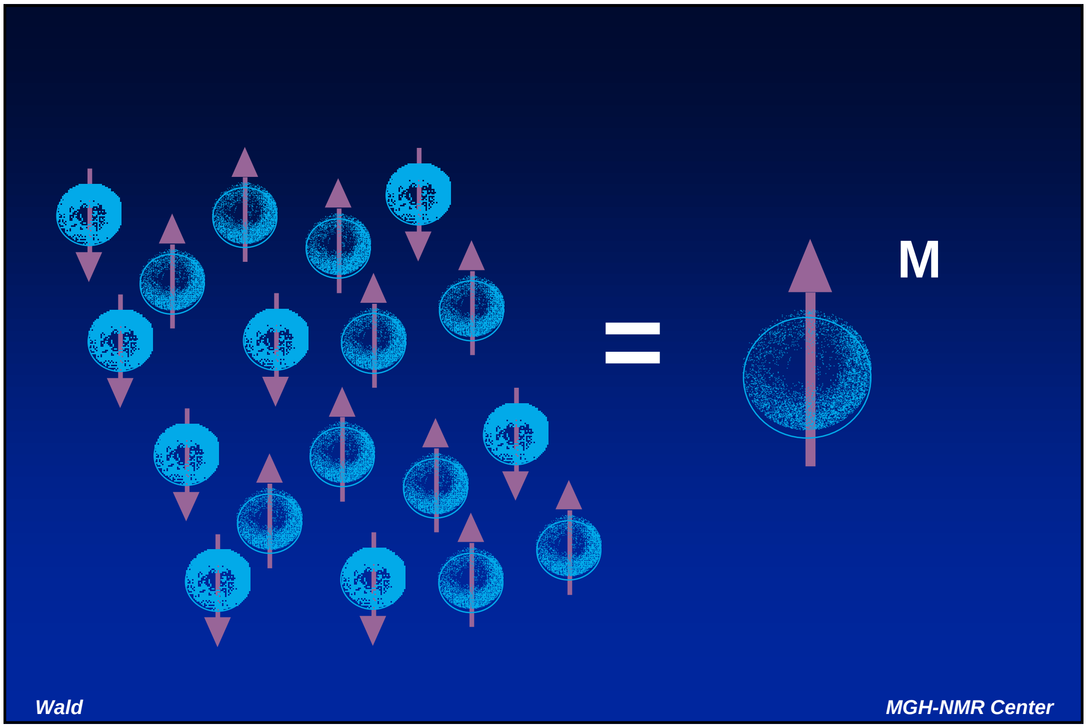
Not every nucleus lines up with applied magnetic field.

Why?

Direction of spins becomes randomized by thermal motion.

protons at 1.5 Tesla, at room temperature

net # aligned with field is 1 part in 100,000

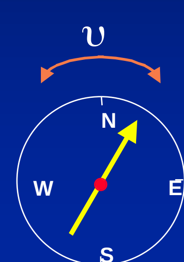


Compass needles

The vector sum of all the nuclei can be viewed as a compass needle.

Points North. (aligns along the magnetic field lines of the external field (earth or MR magnet)

If displaced from North, it will wobble about north with a characteristic frequency (called Larmor freq.)



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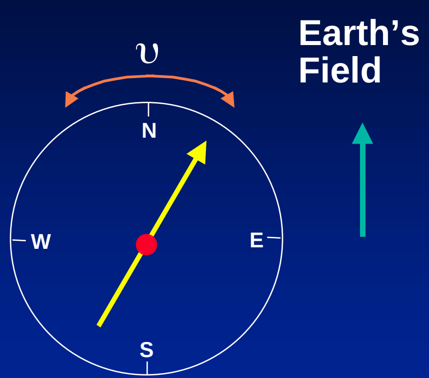
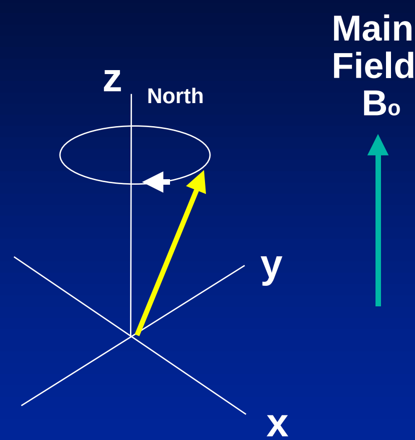
Compass needles





Freq = γ B

42.58 MHz/T

EXCITATION : Displacing the spins from Equilibrium (North)

Problem: It must be moving for us to detect it.

Solution: knock out of equilibrium so it oscillates

How? 1) Tilt the magnet or compass suddenly

2) Drive the magnetization (compass needle) with a periodic magnetic field

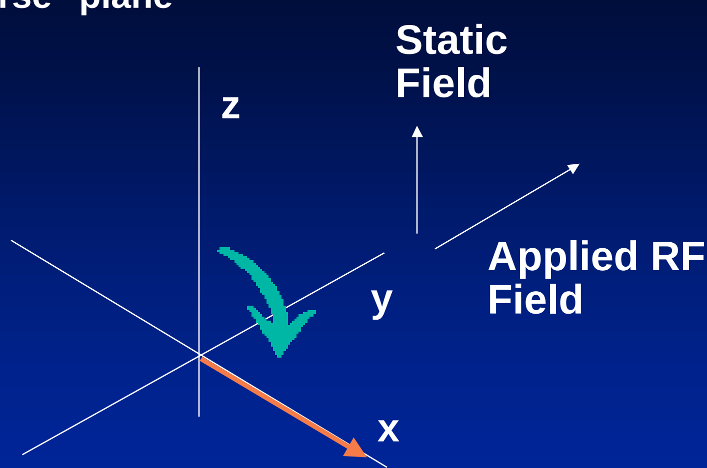
Excitation: Resonance

Why does only one frequency efficiently tip protons?

Resonant driving force.

It’s like pushing a child on a swing in time with the natural oscillating frequency.

z is "longitudinal" direction
x-y is "transverse" plane



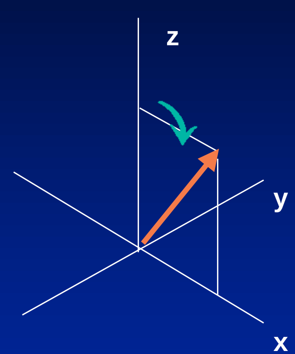
The RF pulse rotates Mo the about applied field

"Exciting" Magnetization

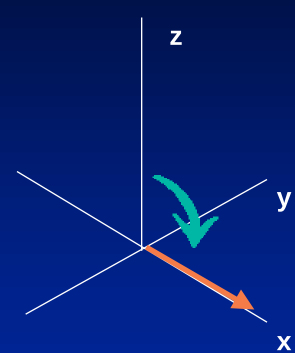
Magnetization processes about new axis (of oscillating RF B field) as long as resonant field is applied.

Total amount vector processes is called the "tip angle" of the excitation.

"Exciting" Magnetization tip angle

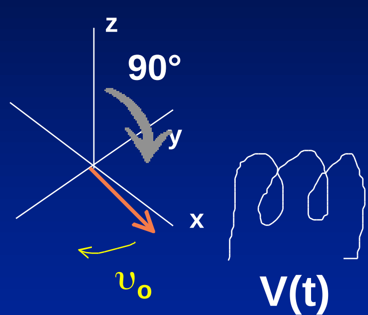


45°



90°

Detecting the NMR Signal



A moving bar magnet induces a Voltage in a coil of wire.
(a generator…)

The RF coil design is the #1 determinant of the system SNR

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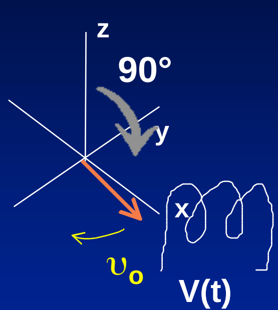
Detecting the NMR: the Signal



The coil should be close to the head.

Reciprocity Theorem:

The detection efficiency of a coil detecting a spin at location (x,y,z) is proportional to the B_1 field it would produce at that location if the coil was driven with 1 amp of current.

Detection efficiency map α B_1 (x,y,z)

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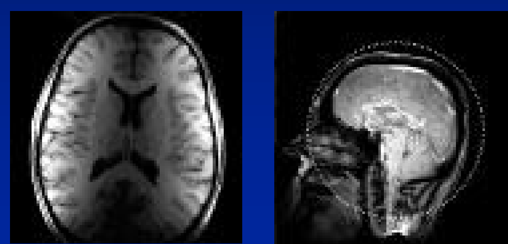
Detecting the NMR: the Signal

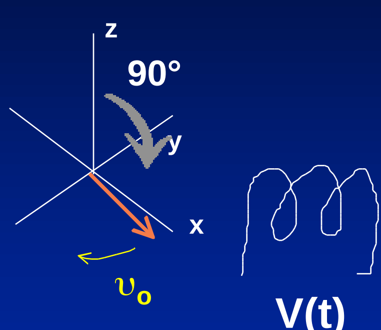
Detection efficiency map α B_1 (x,y,z)

Big is bad.

Small might mean that B_1 (x,y,z) is spatially varying.



Detecting the NMR: the noise



Noise comes from electrical losses in the resistance of the coil or electrical losses in the tissue.

For a resistor:
P_{noise} = 4kTRB

- Noise is white.
  >>Power α bandwidth
- Noise is spatially uniform.
- R is dominated by the tissue. >> big coil is bad.

Signal to Noise Ratio in MRI

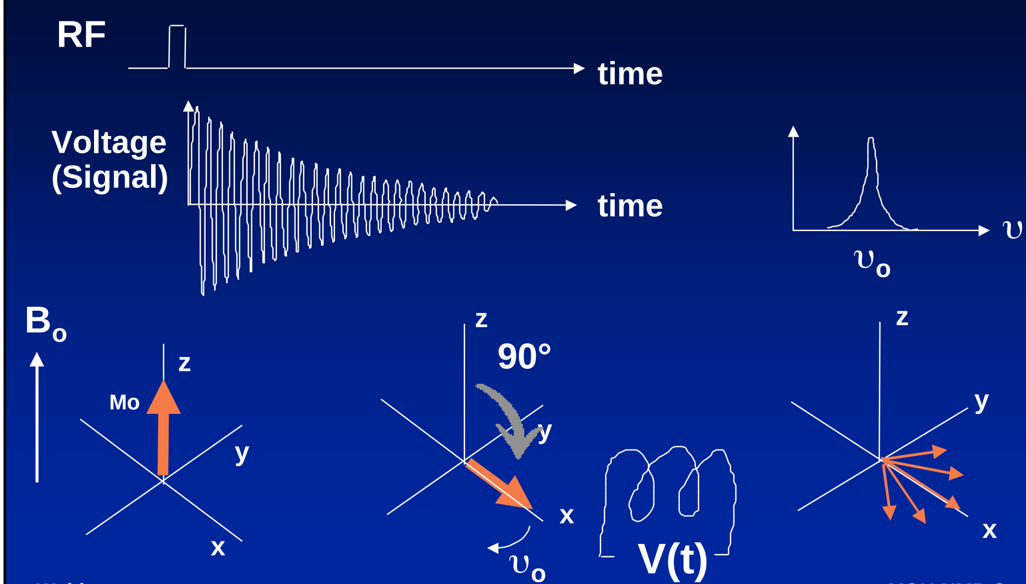
Most important piece of hardware is the RF coil.

SNR α voxel volume (# of spins)

SNR α SQRT(total time of data collection)

SNR is also dependent on the amount of signal you throw away to get contrast.

Review: the NMR Signal



Three Steps in MR:

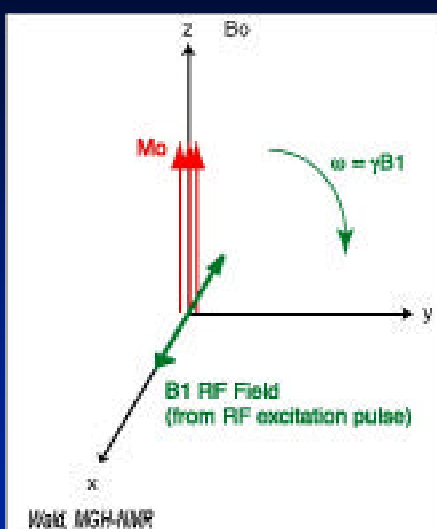
0) Equilibrium (magnetization points along Bo)

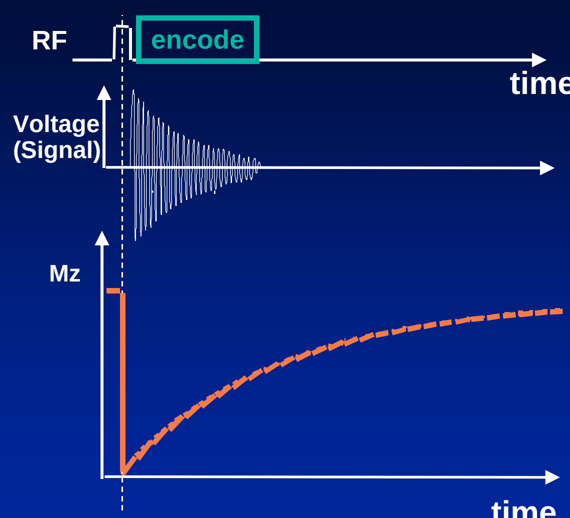
1) RF Excitation (tip magn. away from equil.)

2) Precession induces signal,
   dephasing (timescale = T2, T2*).

3) Return to equilibrium (timescale = T1).

Magnetization vector durning MR





Three places in process to make a measurement (image)

0) Equilibrium (magnetization points along Bo)

1) RF Excitation (tip magn. away from equil.)

proton density weighting

2) Precession induces signal, allow to dephase for time TE.

T2 or T2* weighting

3) Return to equilibrium (timescale =T1).

T1 Weighting

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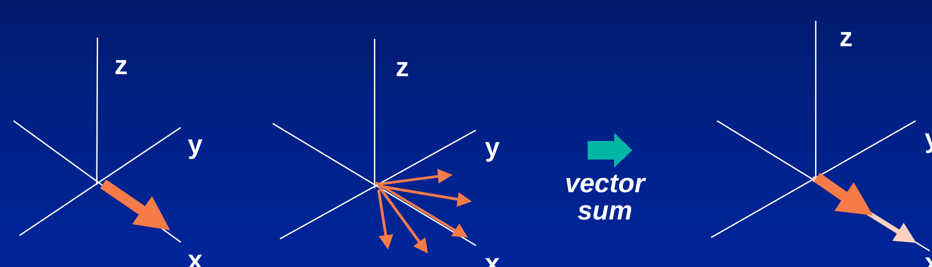
T2*-Weighting

Wait time <u>TE</u> after excitation before measuring M.
Shorter T2* spins have dephased



initially at t= TE

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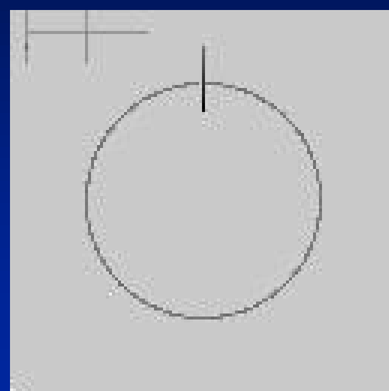
T2* Dephasing

Just the tips of the vectors…



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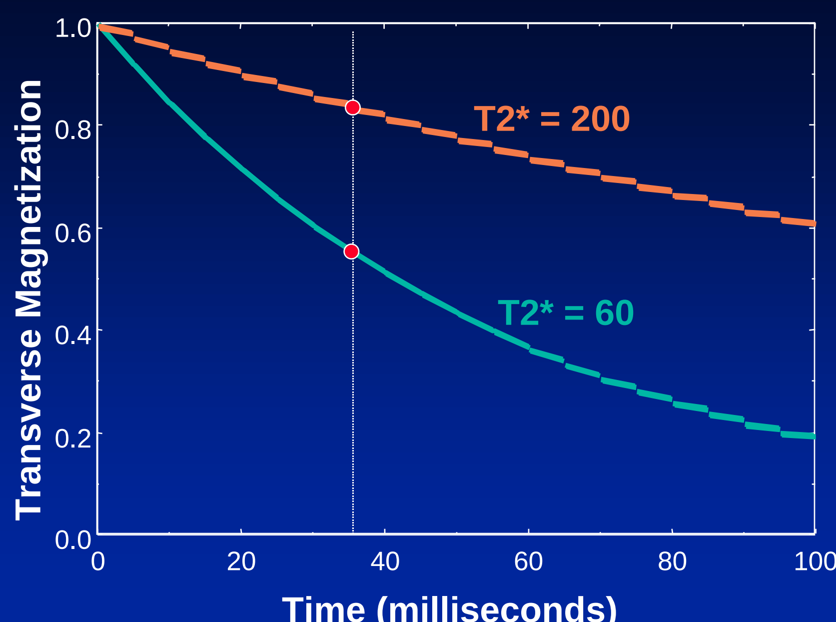

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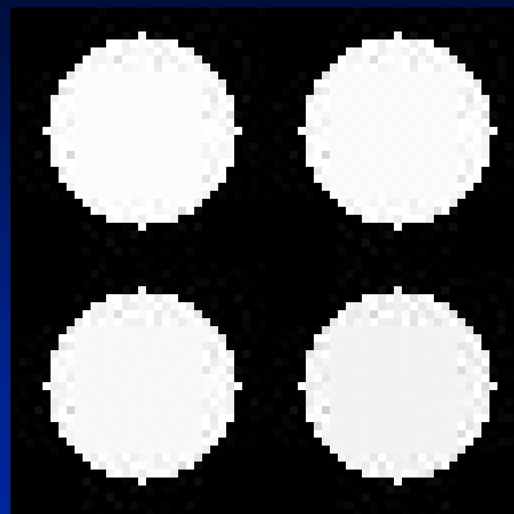
T2 Weighting

Phantoms with
four different T2 decay
rates...

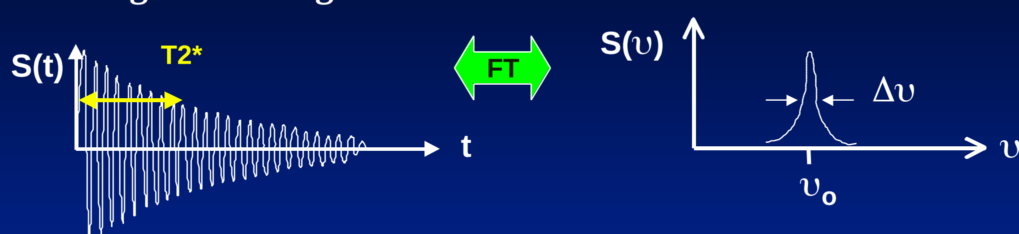
There is no contrast
difference immediately
after excitation, must
wait (but not too long!).

Choose TE for max.
inten. difference.

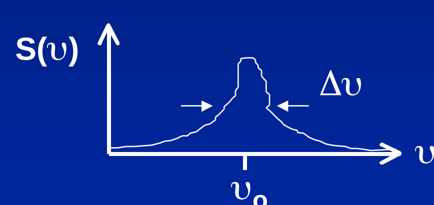


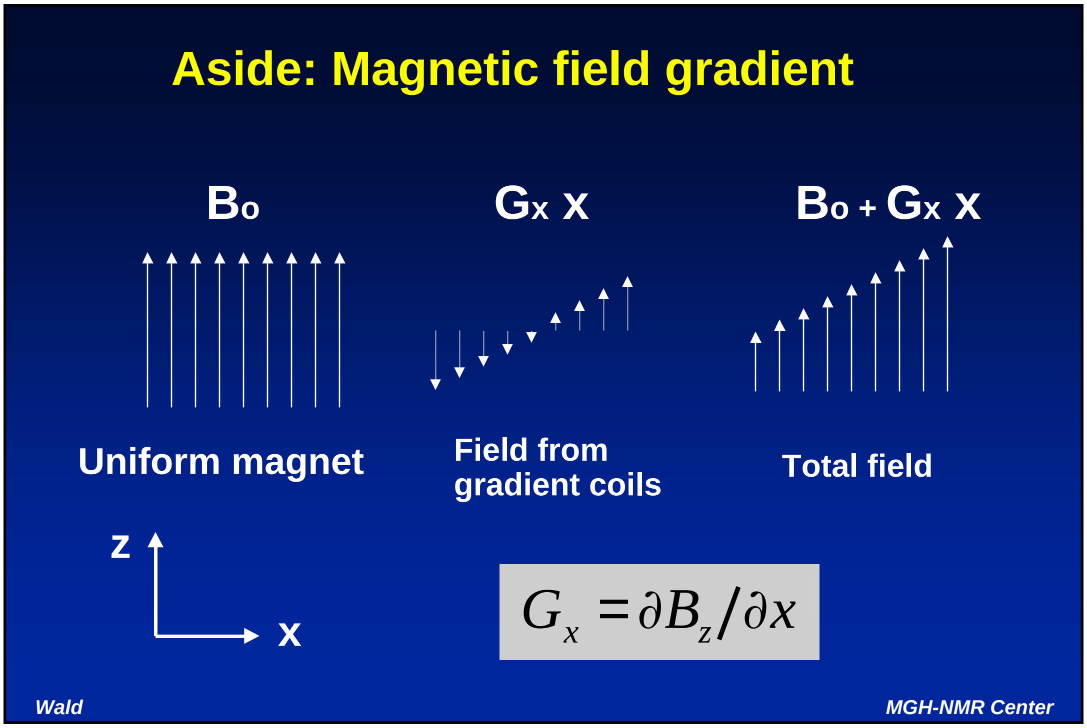
Dephasing: local field variations

homogeneous magnet.



inhomogeneous magnet.




Aside: Magnetic field gradient
Bo
Gx x
Bo + Gx x
Uniform magnet
Field from
gradient coils
Total field
z
x
$G_x = \partial B_z / \partial x$
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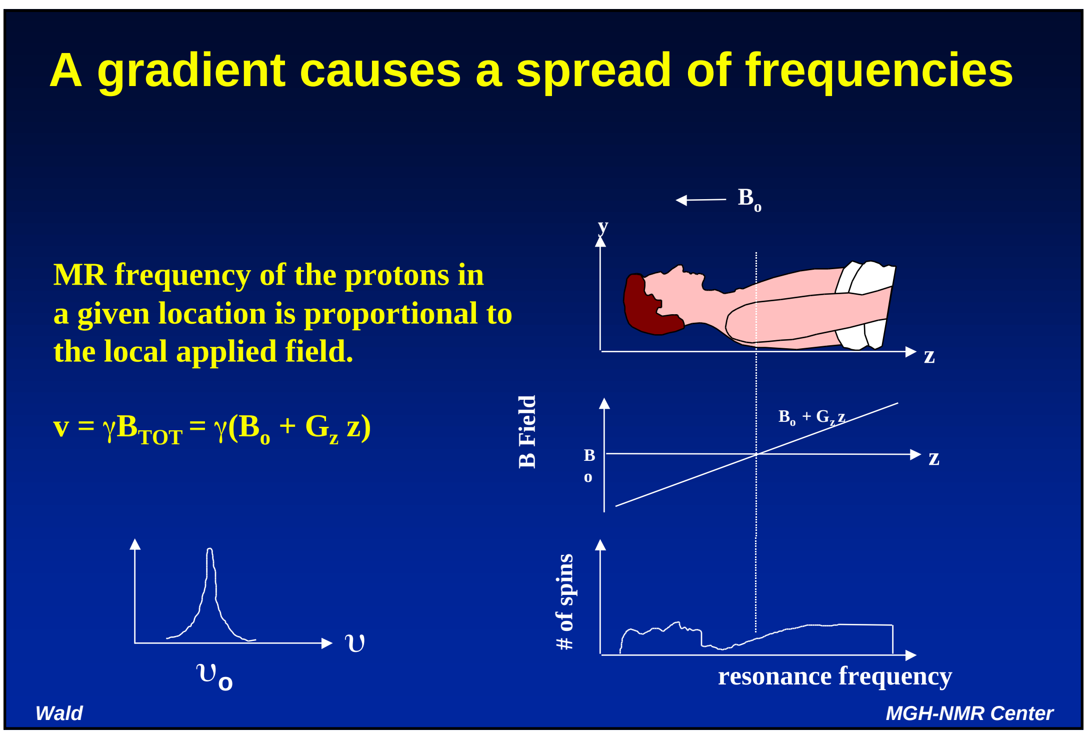
A gradient causes a spread of frequencies
MR frequency of the protons in
a given location is proportional to
the local applied field.
$v = \gamma B_{TOT} = \gamma(B_o + G_z z)$
υ
υ_o
B_o
y
z
B Field
$B_o + G_z z$
B
o
z
# of spins
resonance frequency
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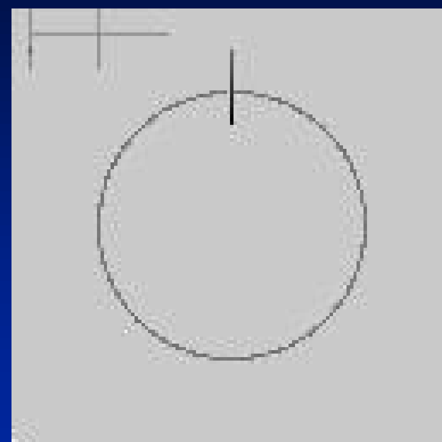
If I control it, I can reverse it…
Gradient echo

G_z vs time



$\upsilon = \gamma \mathbf{B_{TOT}} = \gamma B_0 + \mathbf{G_z\, z}$

$\Delta\upsilon = \gamma\Delta \mathbf{B_{TOT}} = \gamma\, \mathbf{G_z\, z}$

Gratuitous manipulation…
(?)

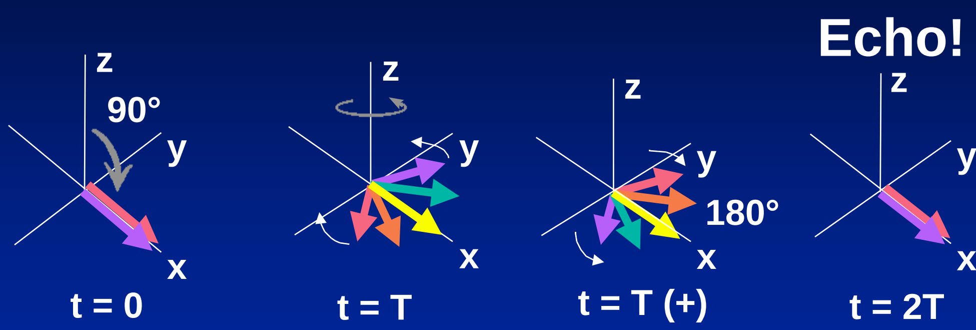
What happens if the spin moves?

Less trivial manipulation…
the Spin Echo

Refocus the dephased signal without resorting to direct control of the B_0 field.

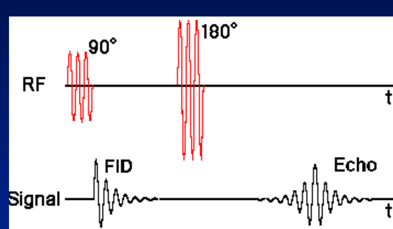
Spin Echo

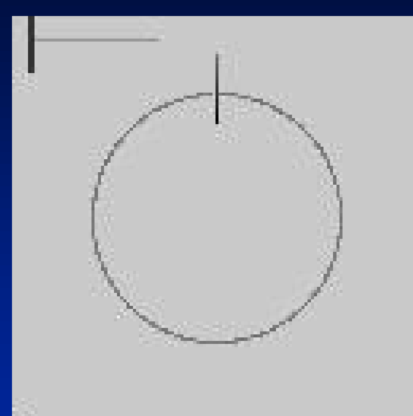
Some dephasing can be refocused because its due to static fields.



Blue/Green arrows precesses faster due to local field inhomogeneity than red/orange arrow

Spin Echo



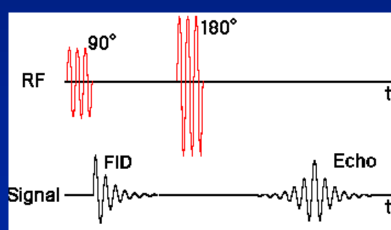


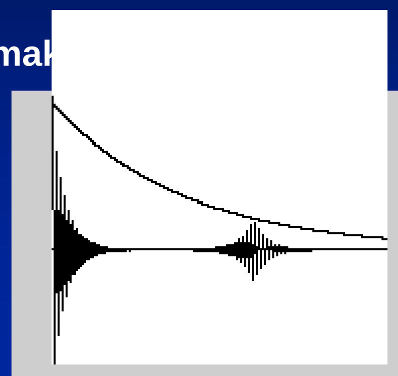
Spin Echo

180° pulse only helps cancel static inhomogeneity

The “runners” can have static speed distribution.

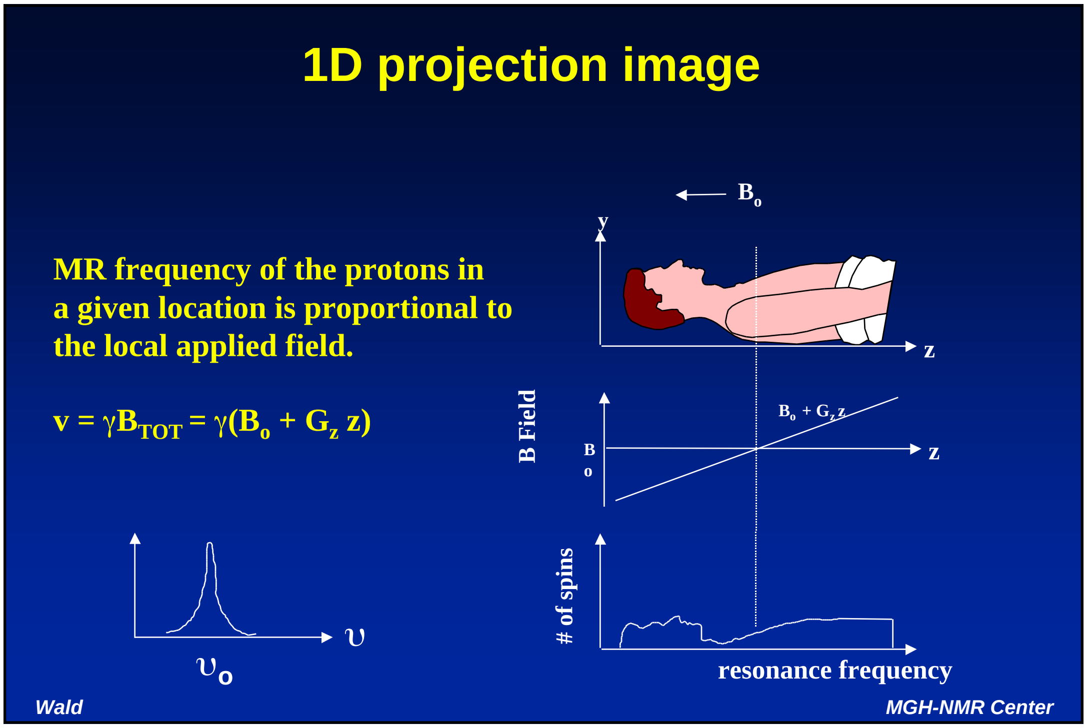
If a runner trips, he will not mak
with the others.





Part II

Image encoding


1D projection image
B$_o$
y
z
MR frequency of the protons in a given location is proportional to the local applied field.
v = γB$_{TOT}$ = γ(B$_o$ + G$_z$ z)
B Field
B$_o$ + G$_z$ z
B
o
z
# of spins
υ
υ$_o$
resonance frequency
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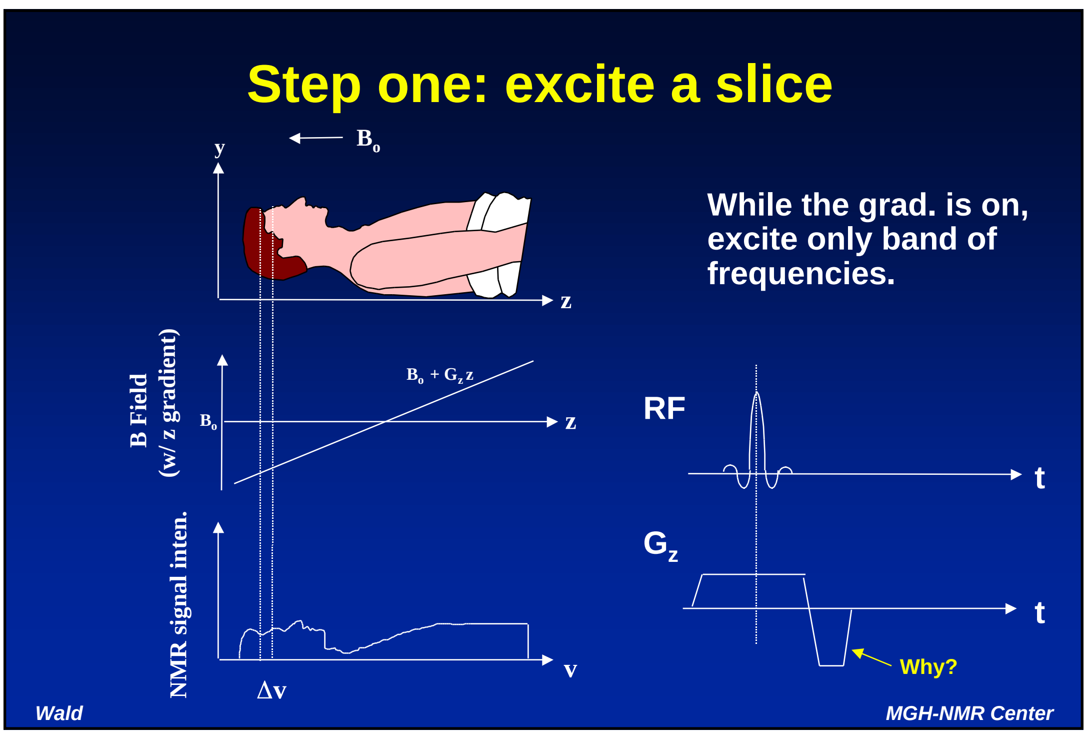
Step one: excite a slice
B$_o$
y
z
While the grad. is on, excite only band of frequencies.
B Field (w/ z gradient)
B$_o$ + G$_z$ z
B$_o$
z
RF
t
G$_z$
t
Why?
NMR signal inten.
v
Δv
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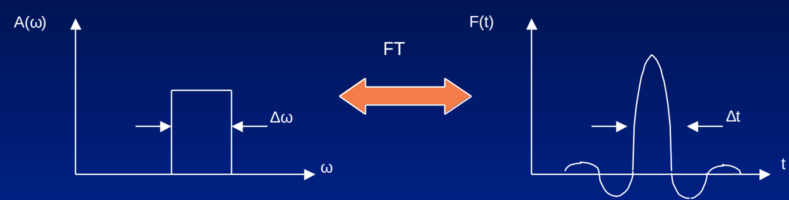
Slice profile considerations



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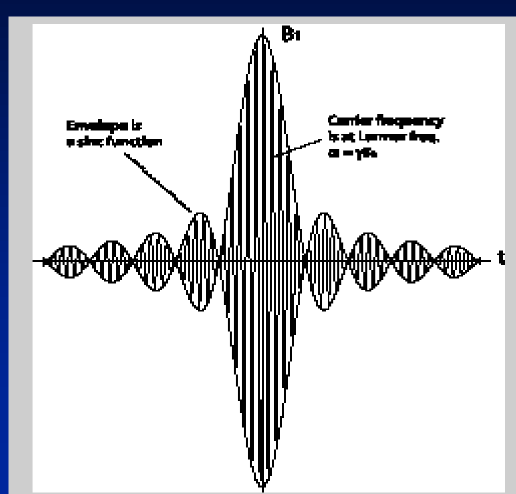
Slice selective RF pulse



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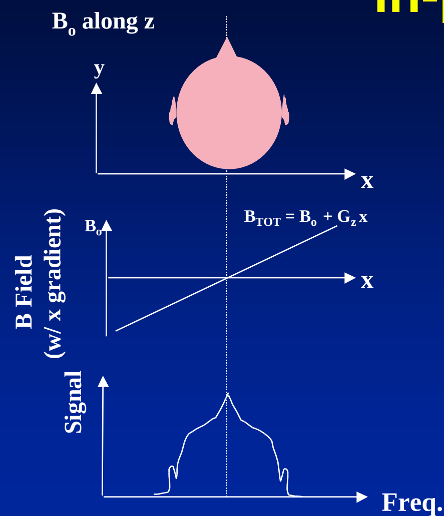
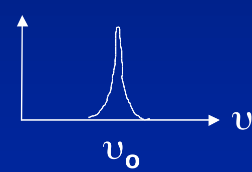
Step two: encode spatial info. in-plane



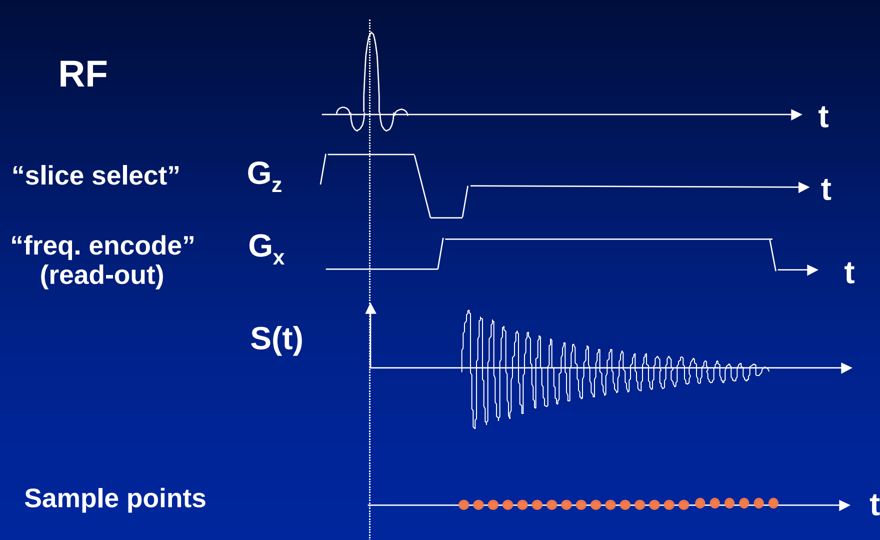
“Frequency encoding”



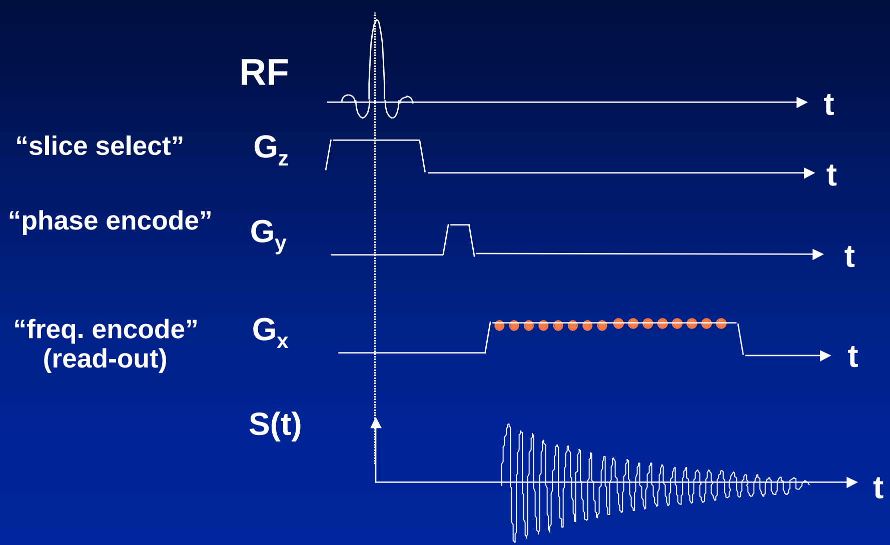
with gradient

without gradient

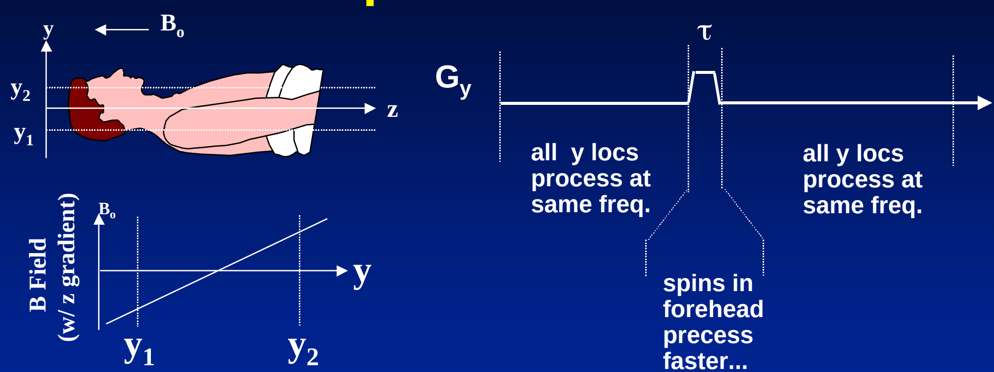
‘Pulse sequence’ so far



"Phase encoding"



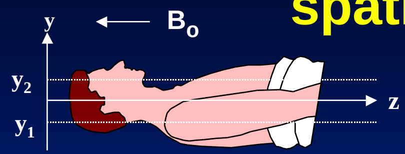
How does blipping on a grad. encode spatial info?



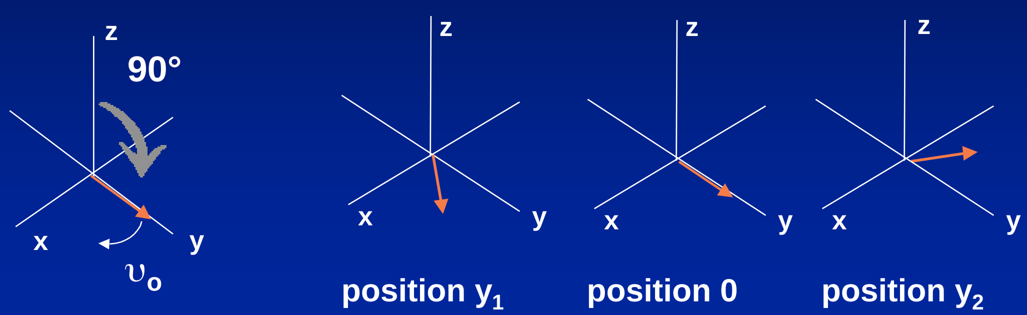
$$\upsilon(\mathbf{y}) = \gamma \mathbf{B}_{TOT} \quad = \gamma\, \mathbf{B_o}\ \Delta \mathbf{y}\ \mathbf{G_y}$$

$$\theta\,(\mathbf{y}) = \upsilon(\mathbf{y})\,\tau \quad = \gamma\, \mathbf{B_o}\, \Delta \mathbf{y}\ (\mathbf{G_y}\,\tau)$$

How does blipping on a grad. encode spatial info?



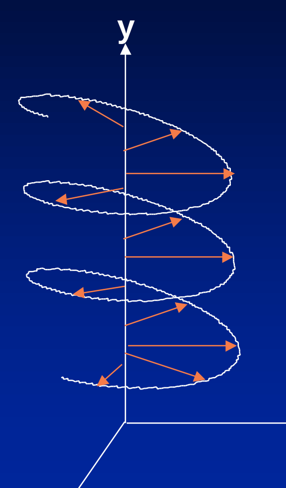
$$\theta(y) = \upsilon(y)\,\tau \;\; = \gamma\, B_o\, \Delta y\, (G_y\, \tau)$$



How does blipping on a grad. encode spatial info?

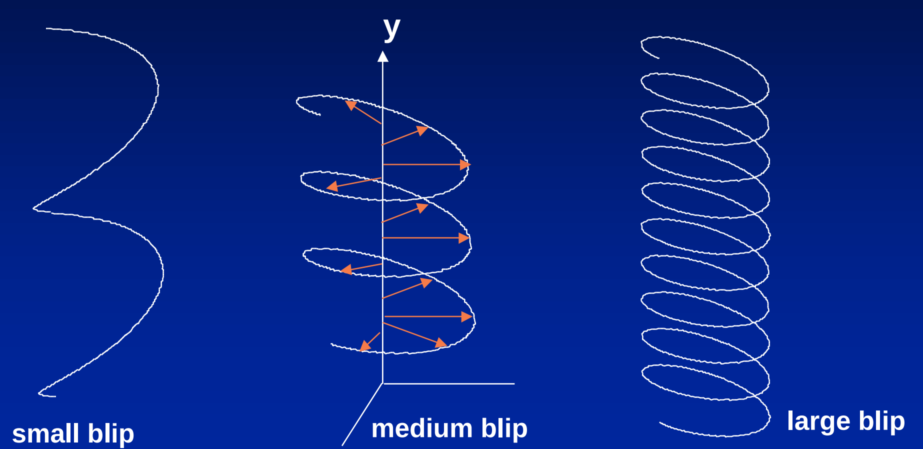
The magnetization vector in the xy plane is wound into a helix directed along y axis.

Phases are 'locked in' once the blip is over.



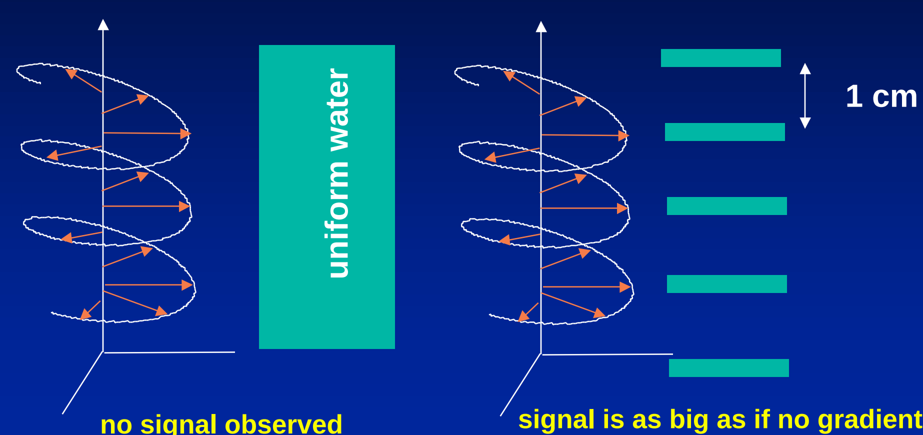
The bigger the gradient blip area, the tighter the helix

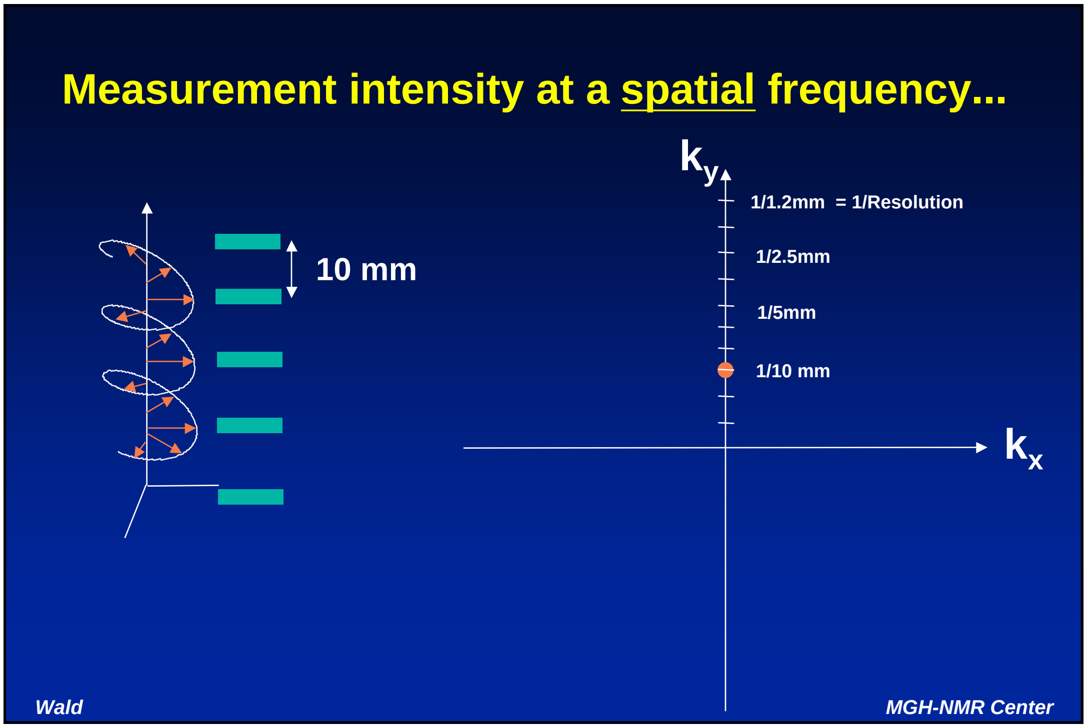
$$\theta(y) = \upsilon(y)\,\tau = \gamma B_o \Delta y\,(G_y\,\tau)$$



What have you measured?

Consider 2 samples:





Measurement intensity at a spatial frequency...
10 mm
k_y
1/1.2mm = 1/Resolution
1/2.5mm
1/5mm
1/10 mm
k_x
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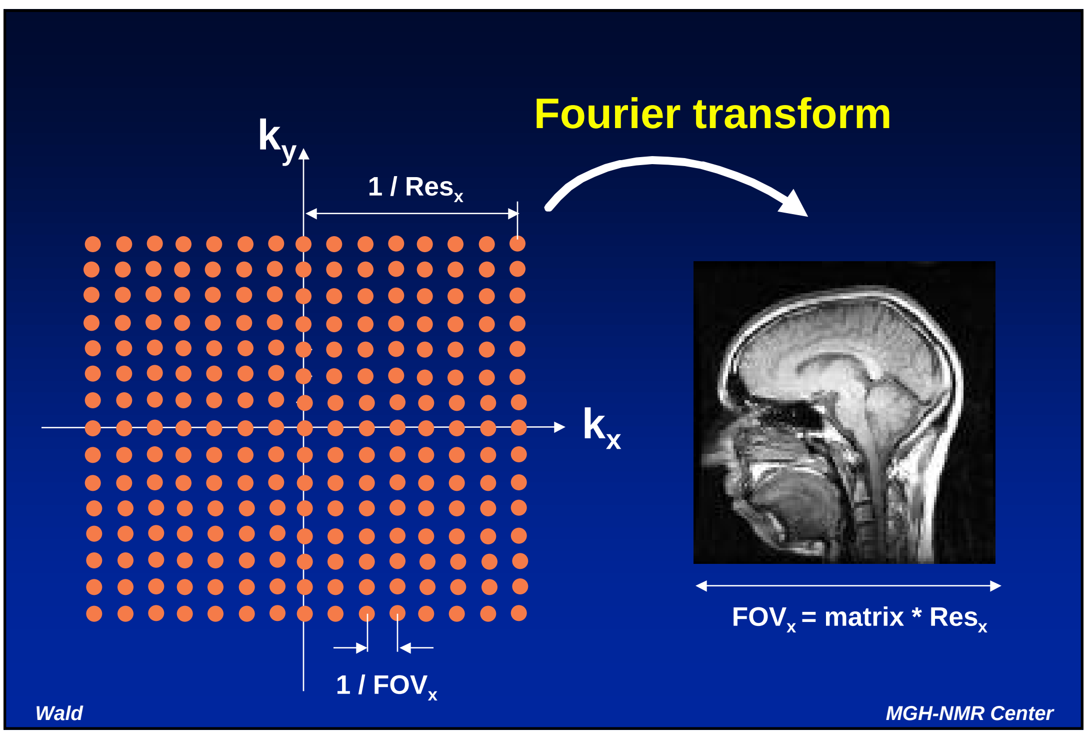

Fourier transform
k_y
1 / Res_x
k_x
1 / FOV_x
FOV_x = matrix * Res_x
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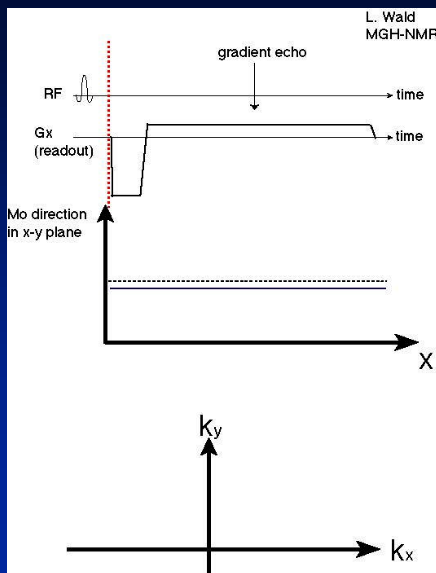
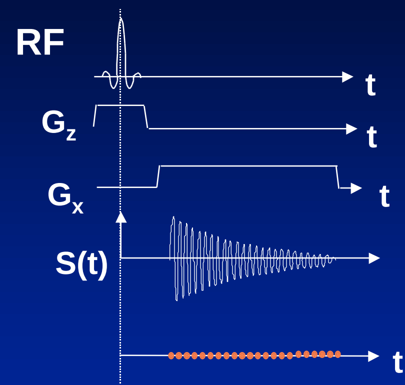
Frequency encoding revisited





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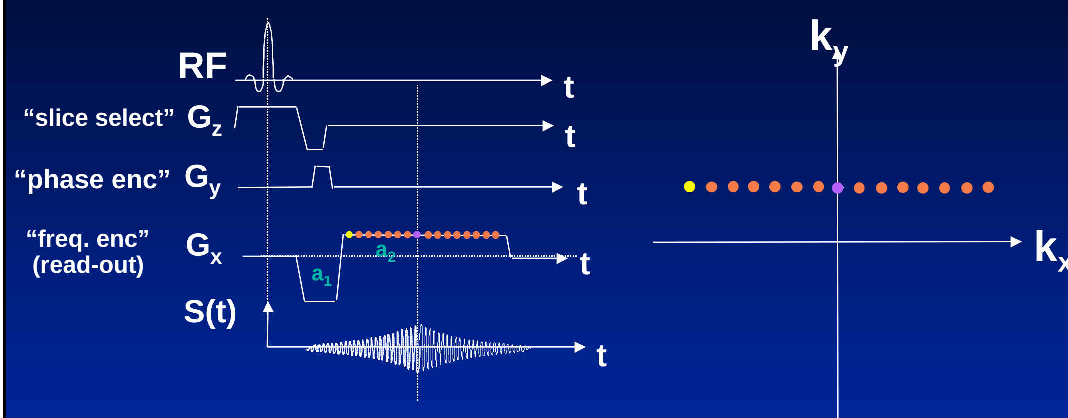
"Spin-warp" encoding



one excitation, one line of kspace...

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"Spin-warp" encoding mathematics

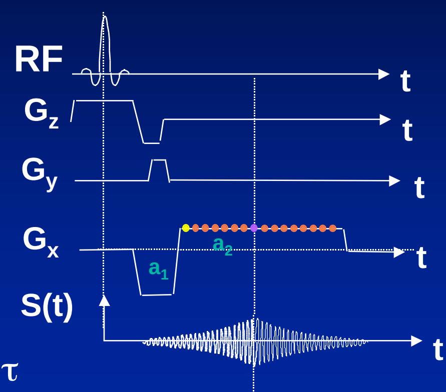
The "image" is the spin density function: ρ(x)

Phase due to readout:

$$\theta(t) = \omega_o t + \gamma G_x x t$$

Phase due to P.E.

$$\theta(t) = \omega_o t + \gamma G_y y \tau$$



$$\Delta\theta(t) = \omega_o t + \gamma G_x x t + \gamma G_y y \tau$$

"Spin-warp" encoding mathematics

Signal at time t from location (x,y)

$$S(t) = \rho(x,y) e^{i\gamma G_x x t + i\gamma G_y y \tau}$$

The coil integrates over object:

$$S(t) = \iint_{object} \rho(x,y) e^{i\gamma G_x x t + i\gamma G_y y \tau} dxdy$$

Substituting $k_x = -\gamma G_x t$ and $k_x = -\gamma G_x t$:

$$S(k_x, k_y) = \iint_{object} \rho(x,y) e^{-ik_x x - ik_y y} dxdy$$

"Spin-warp" encoding mathematics

View signal as a matrix in kx, ky…

$$S(k_x, k_y) = \iint_{object} \rho(x, y) e^{-ik_x x - ik_y y} dxdy$$

:

Solve for ρ(x,y,)

$$\rho(x,y) = FT^{-1}\left[S(k_x, k_y)\right]$$

$$\rho(x,y) = \iint_{kspace} S(k_x, k_y) e^{ik_x x + ik_y y} dk_x dk_y$$

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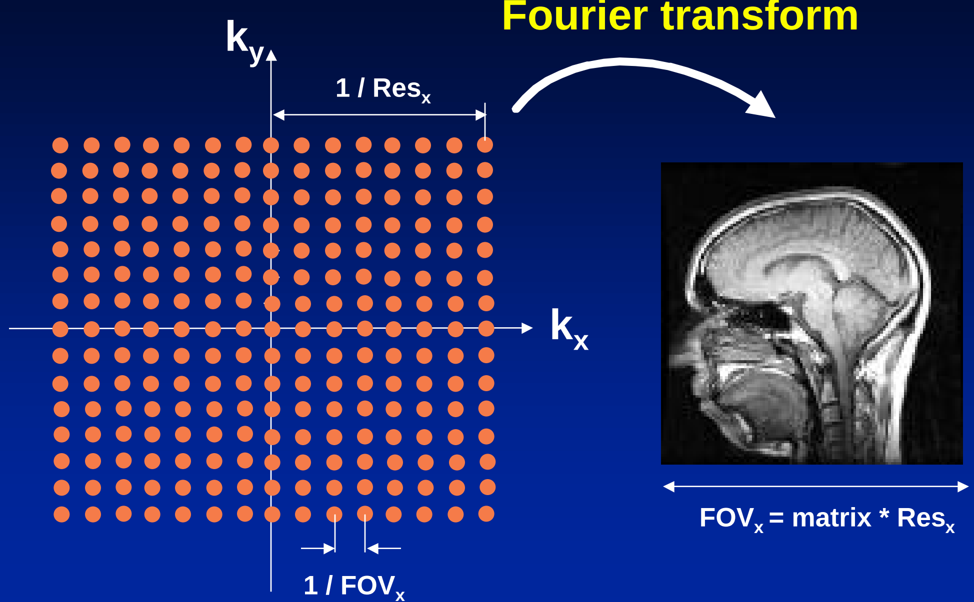
Fourier transform



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