MRI Hardware:
An Overview for Clinicians

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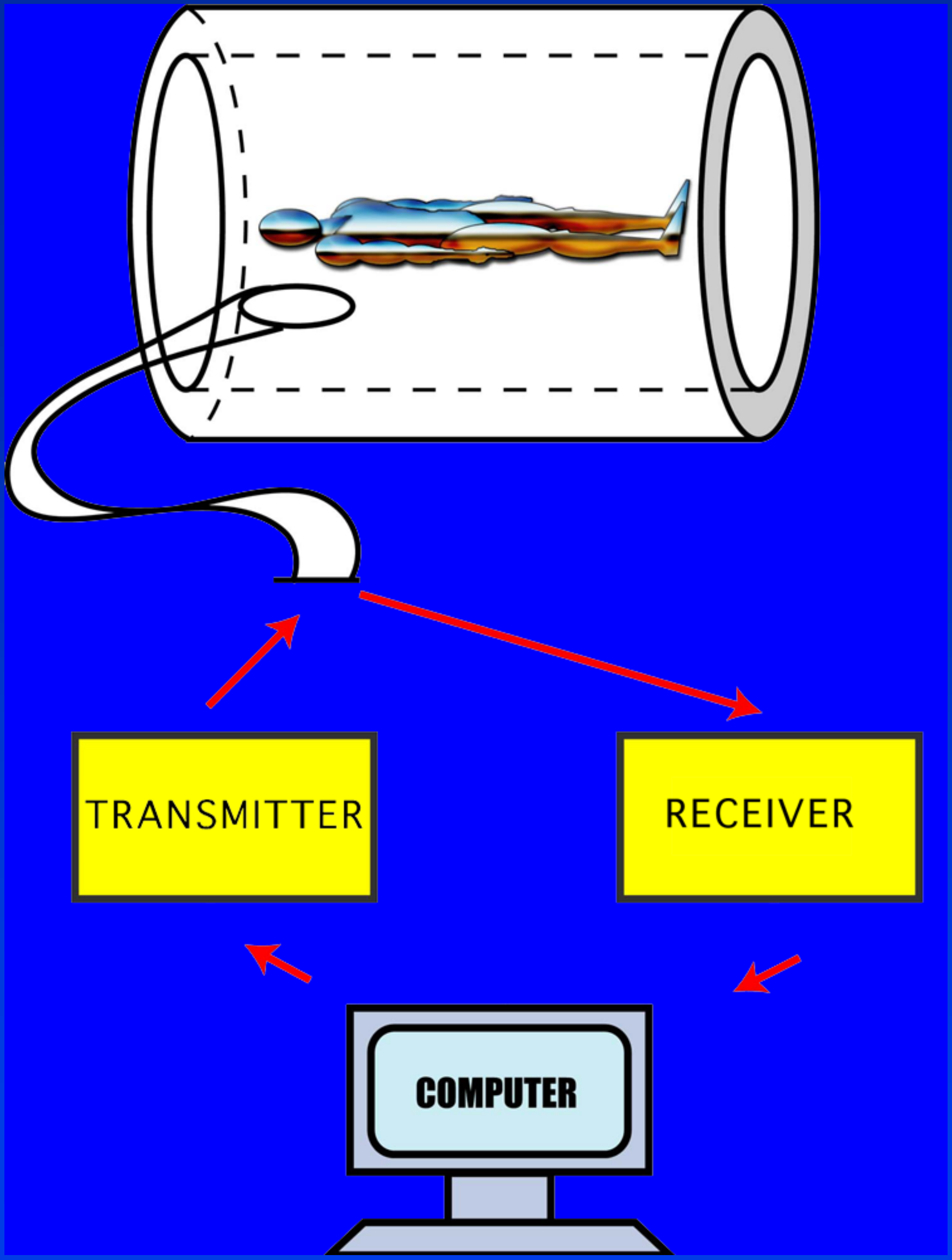
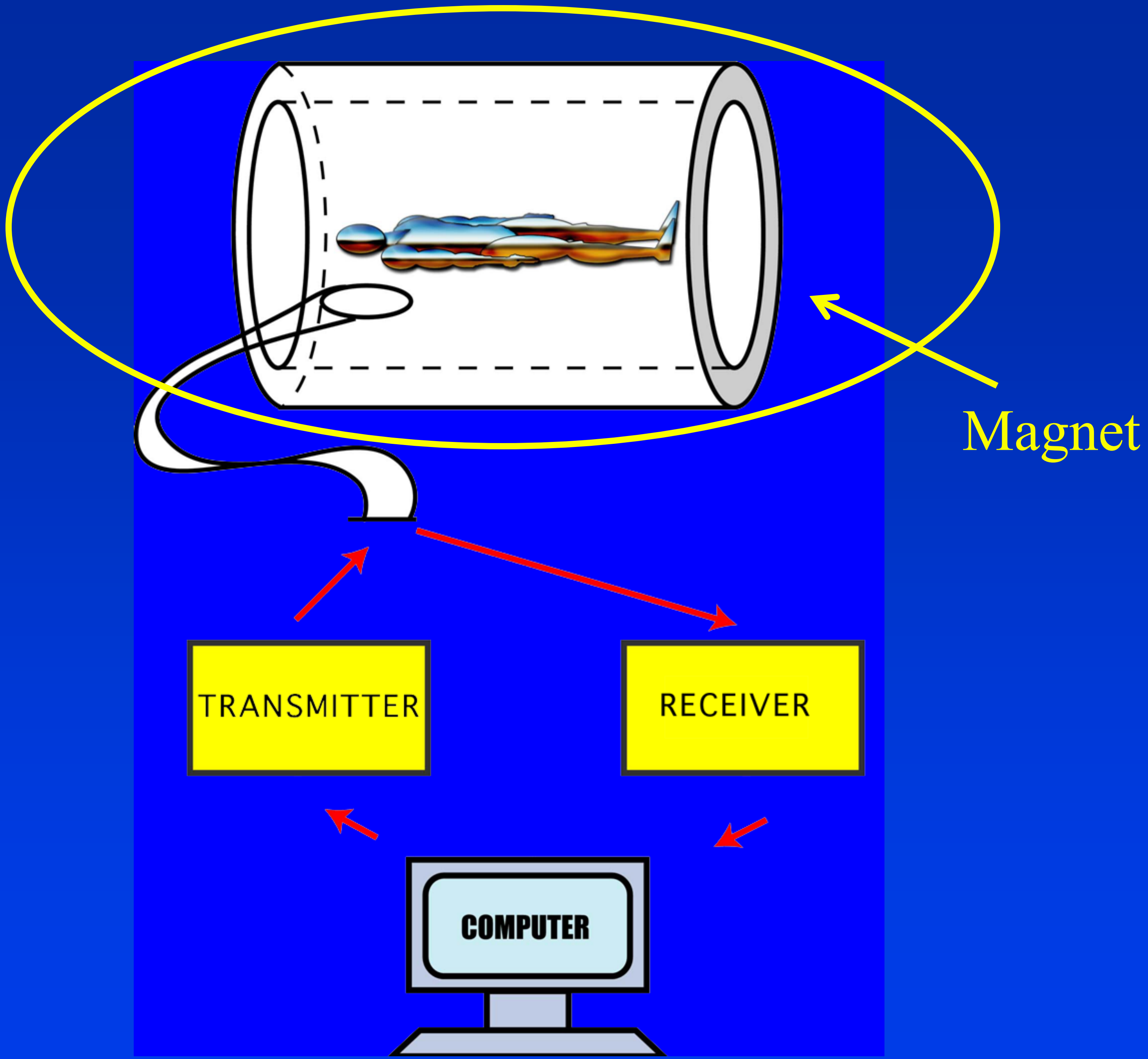
Why go to a talk?

i) to ask good questions

ii) to give good answers



1. Magnet
2. Gradients
3. Transmitter
4. Receiver
5. Probe
    - Considerations
    - Reasonable questions
    - A few details
    - A few specifications



NIH/NIA/GRC

Magnet Considerations

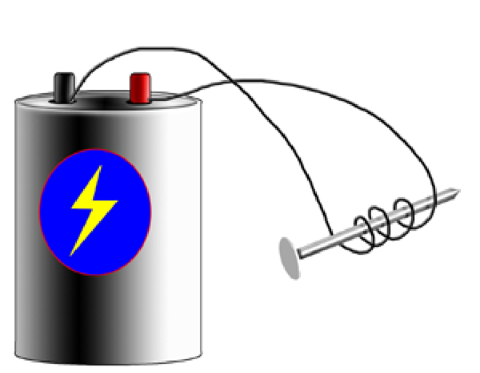
- High field for high signal-to-noise ratio
- Weight
- Diameter and length (patient experience; field homogeneity)
- Homogeneity (spatial); Field stability (temporal)
- Configuration (access; patient experience)
- Cryogenic efficiency (operating costs)


What type of magnet is it? Is it shielded?
Field strength? Bore size?
What's the field homogeneity?
How stable is the field?

Resistive Magnet Type

$$B = \frac{\mu_0 I}{2\pi r}$$

Wire



$$B = \mu_0 I n$$

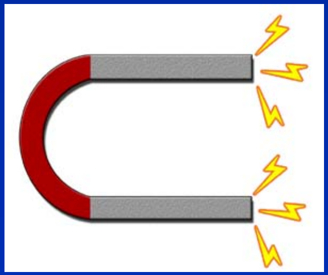
Solenoid

- Field stability ⇒

  need a very stable 10’s of kW power supply
- Power requirements $\propto B^2$ ⇒

  cooling requirements ⇒ 0.2 T or less

Permanent Magnet Type



- Excellent field stability
- Configuration: *open systems are available*
- No power consumption

however...

- Weight--can be enormous: iron 0.2 T whole body weighs about 25 tons
- 0.2 T neodymium alloy ~ 5 tons
- Homogeneity--can be a problem

Open Permanent Magnet System

Siemens Viva--0.2 T

Superconducting Magnet Type

- Required for high field systems
- Homogeneous field
- Stable field

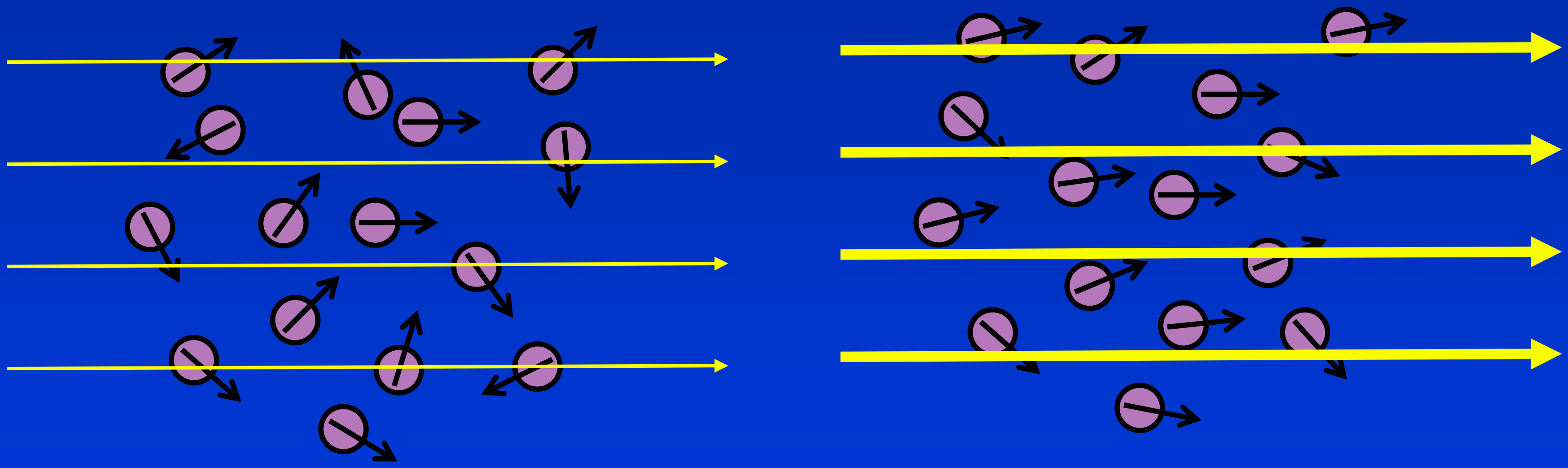
however...

- Expensive
- Quench phenomenon

Siemens/Bruker Magnetom Allegra-3T, head only

Field Strength

- Polarization of atomic nuclei

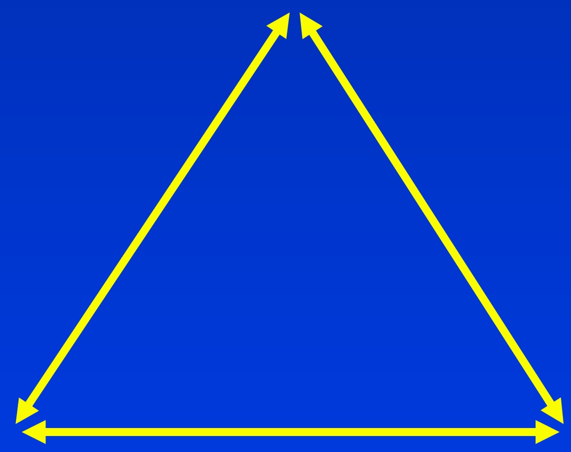


Larger field ⇒

More spin alignment ⇒

More signal from each pixel or voxel

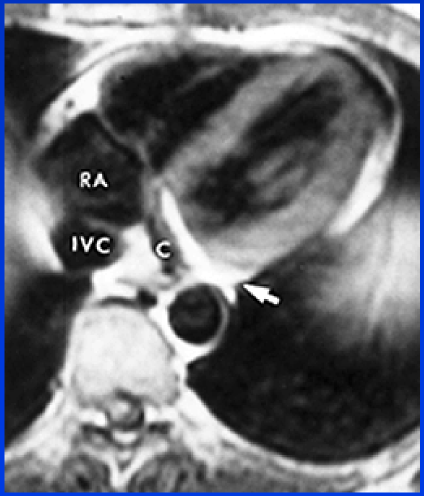
Trading Rules



More signal from each pixel means:
Each pixel can be smaller

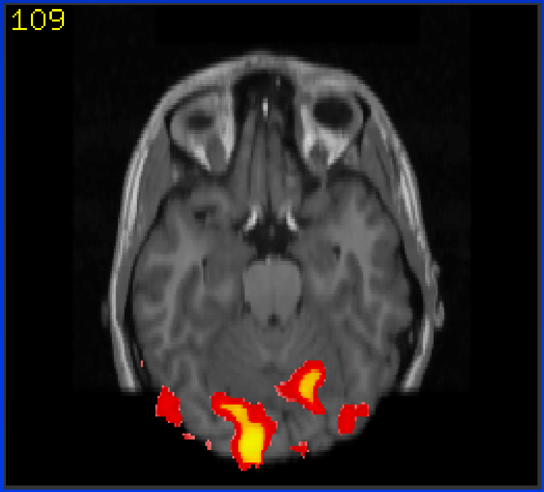
More signal per unit time means:
Images can be acquired faster

Cardiac MRI



RN Berk, UCSD

Functional MRI

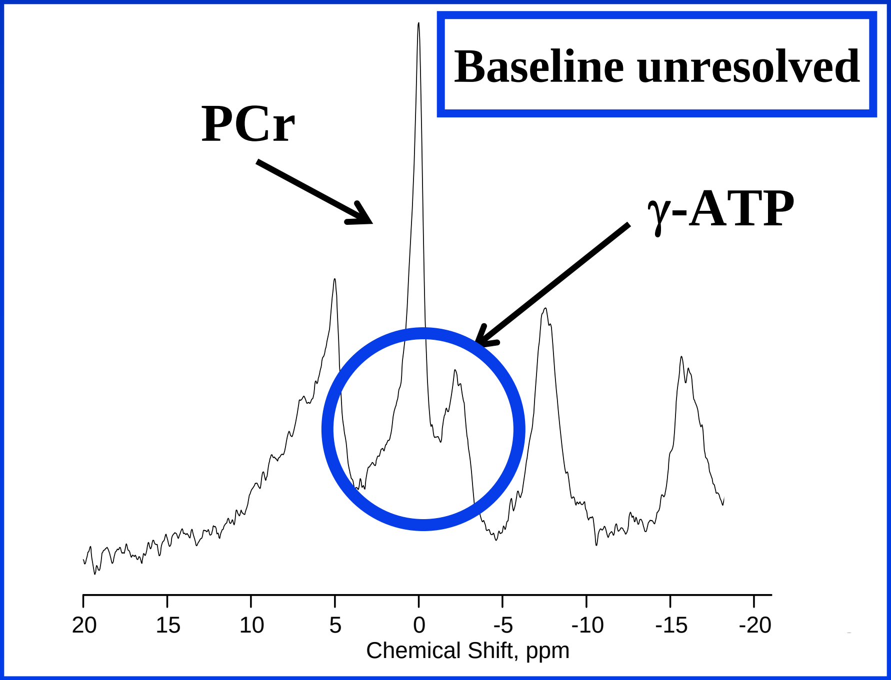


S Smith, Oxford

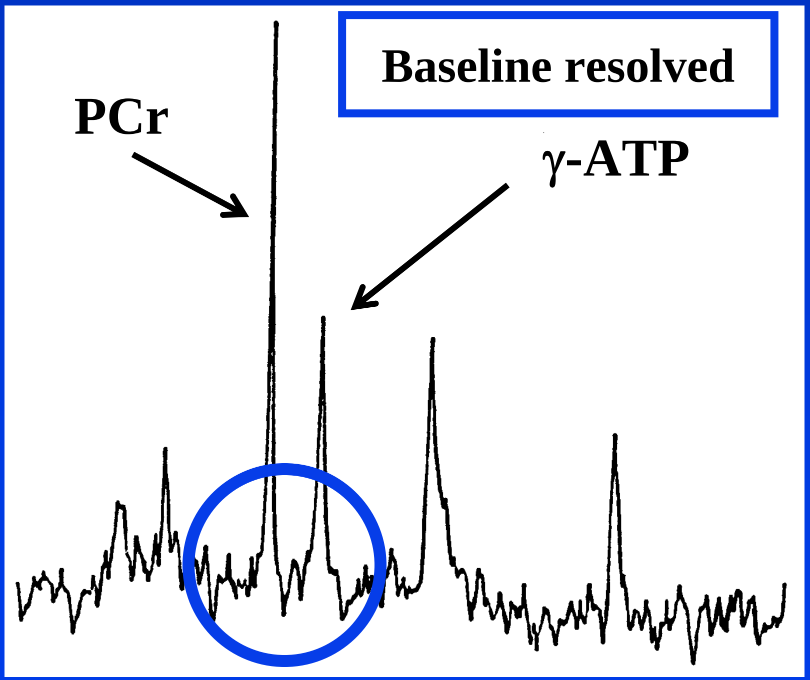
Field Strength in Spectroscopy

- Greater spectral resolution

^{31}P NMR Spectrum of Skeletal Muscle at 1.9 T



^{31}P NMR Spectrum of Rat Heart at 9.4 T



Field Strength Considerations

However, at higher field:

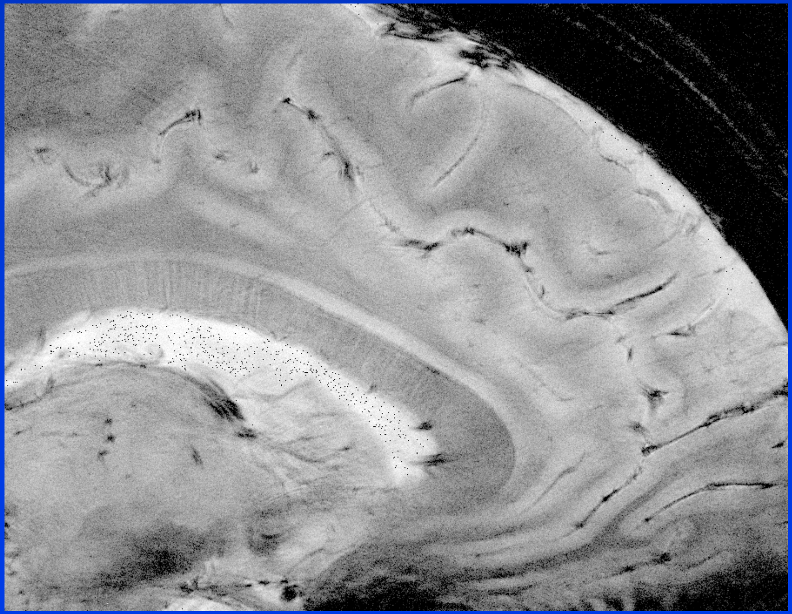
- increased chemical shift artifacts, e.g. fat/water
- increased susceptibility artifacts
- increased siting cost
- increased initial cost

Field Strength

Typical clinical systems: 0.2 T to 1.5 T to 3 T

Whole-body: 3 T, 4 T, … , 8 T, 9.4 T available

Ohio State, Bruker 8T Whole-body System Gradient-echo Images



Field Strength

High field especially useful for fMRI and spectroscopy--less obviously so for standard imaging

- Typical animal systems:

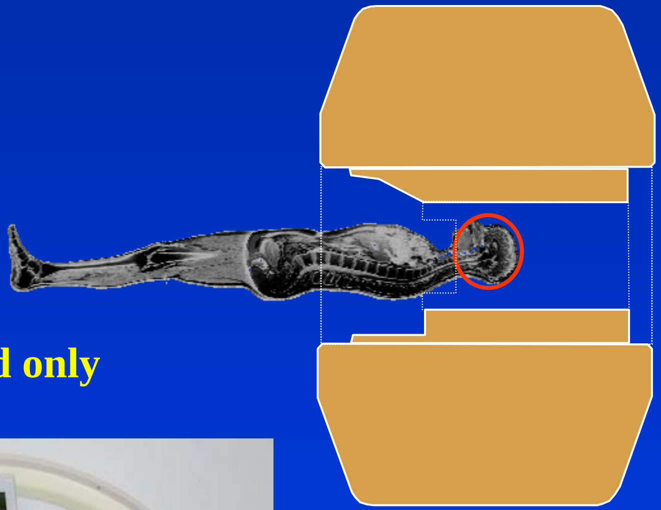
    4.7 T, 7 T,…, 9.4 T, 11 T horizontal

    9.4 T, 11 T vertical

Bore Size

- Bigger is better--e.g. “head only” fits only heads!

600 mm magnet warm bore
570 mm magnet at shoulder incl. shim
360 mm gradient coil inner diameter
265 mm RF-headcoil inner diameter



Siemens/Bruker Magnetom Allegra-3T, head only

Bore Size

- *Human*
  - *i) Whole Body (typical: 100 cm)*
  - *ii) Head only (typical: 80 cm)*
- Animal
  - 15 cm, 20 cm, 30 cm, 40 cm, ...

However:

- Larger bore ⇒larger fringe field
- Larger gradient sets can be slower
- Cost

Magnetic Shielding: Containment of the Fringe Field

- Fringe field: portion of the magnetic field that extends beyond the magnet bore

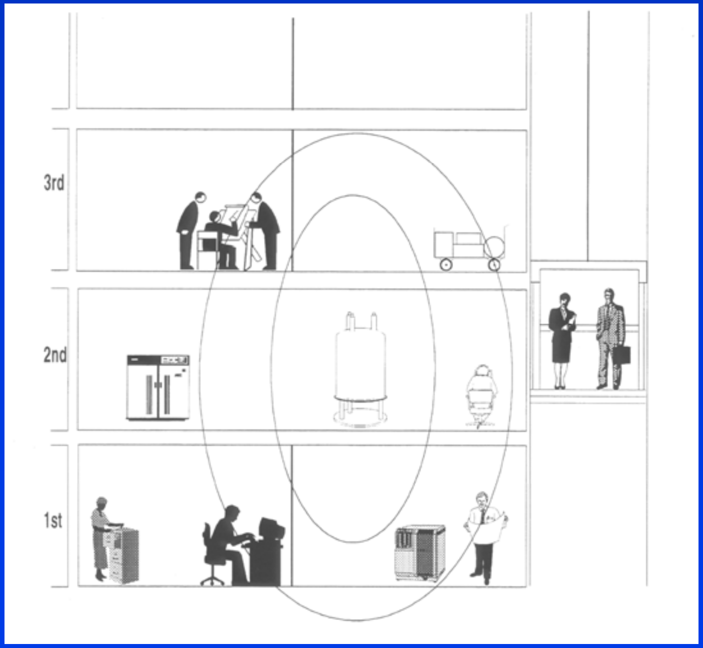
- 5 G taken as maximum safe public exposure

- Effect ***on*** e.g. pacemakers, steel tools, and magnetic cards

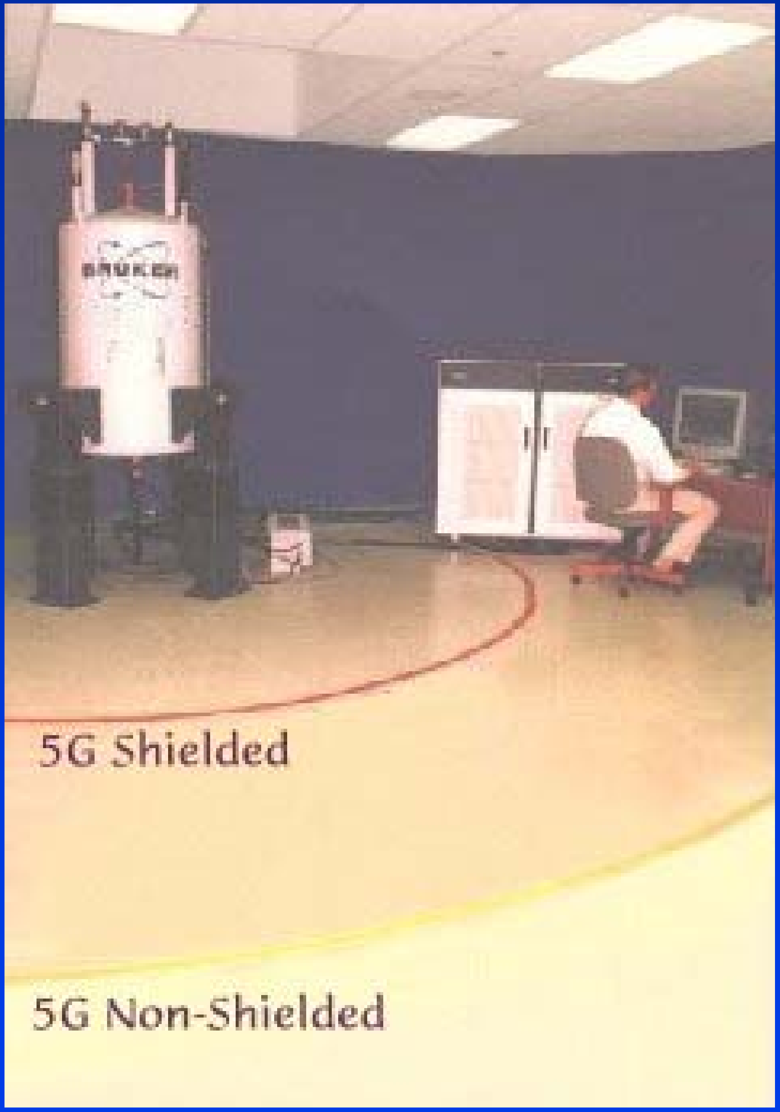
- Effect ***from*** e.g. moving cars and elevators

Magnetic Shielding Considerations

- Weight
- Footprint
- Expense *including space*



Note: fringe field is 3D



Magnetic Shielding Options

- **Unshielded:**
  - Lightest, cheapest

    However: largest field footprint, most expensive space
- **Passive shielding: *ferromagnetic material placed outside magnet***
  - Small field footprint: decrease by factor of 2 in all directions

    However: heaviest--10's of tons of iron
- **Active shielding: *electromagnetic counter-windings outside the main magnet coil***
  - Similar field footprint as for passive shielding
  - Mild increase in weight vs unshielded

    However: highest magnet expense

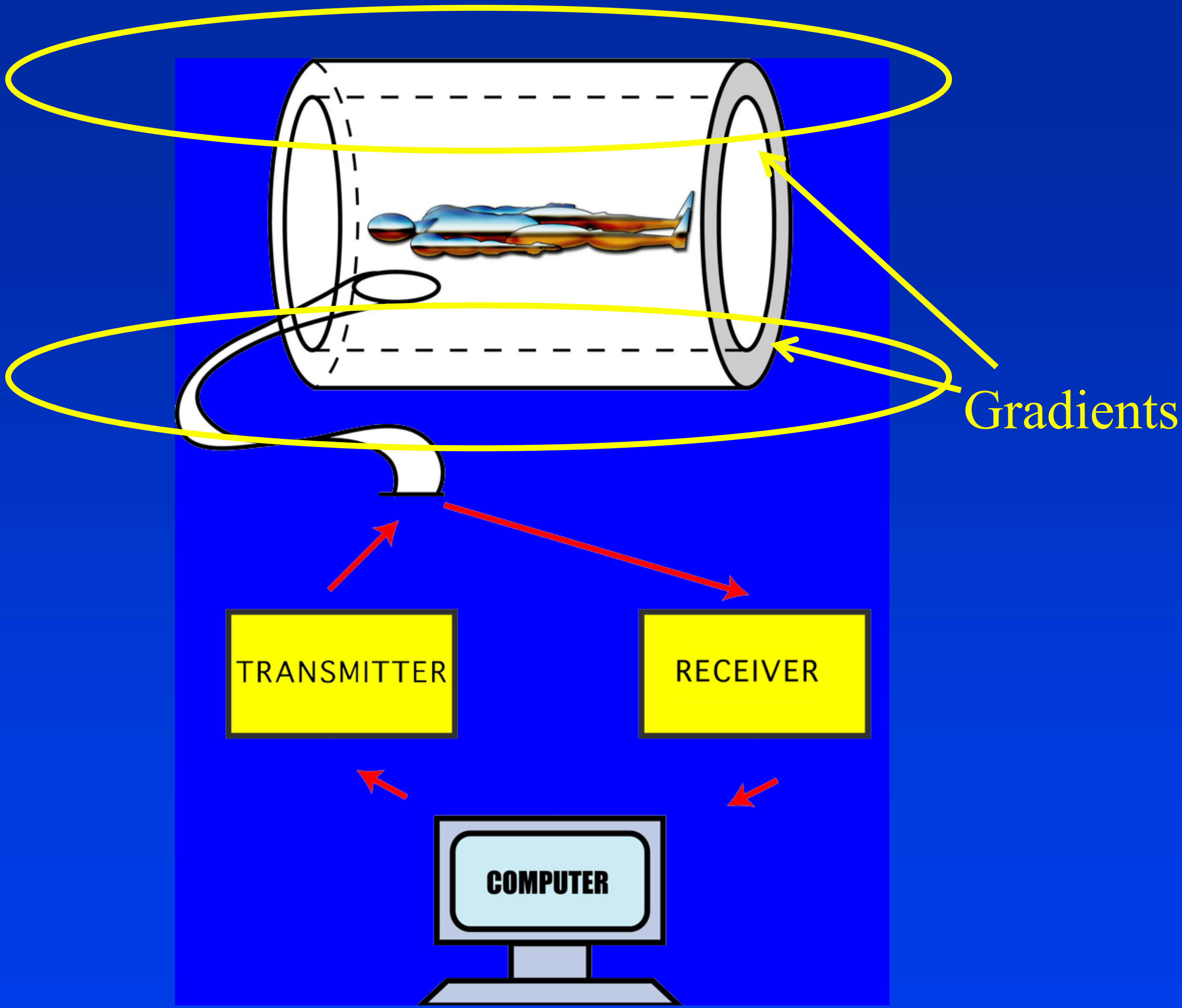
Sample Magnet Specifications

• Field stability: better than 0.1 ppm/hour drift
Note: fat-water separation = 3.5 ppm

• Field homogeneity*: better than
0.3 ppm over 22 cm and ***5 ppm over 50 cm***
diameter spherical volume (DSV)

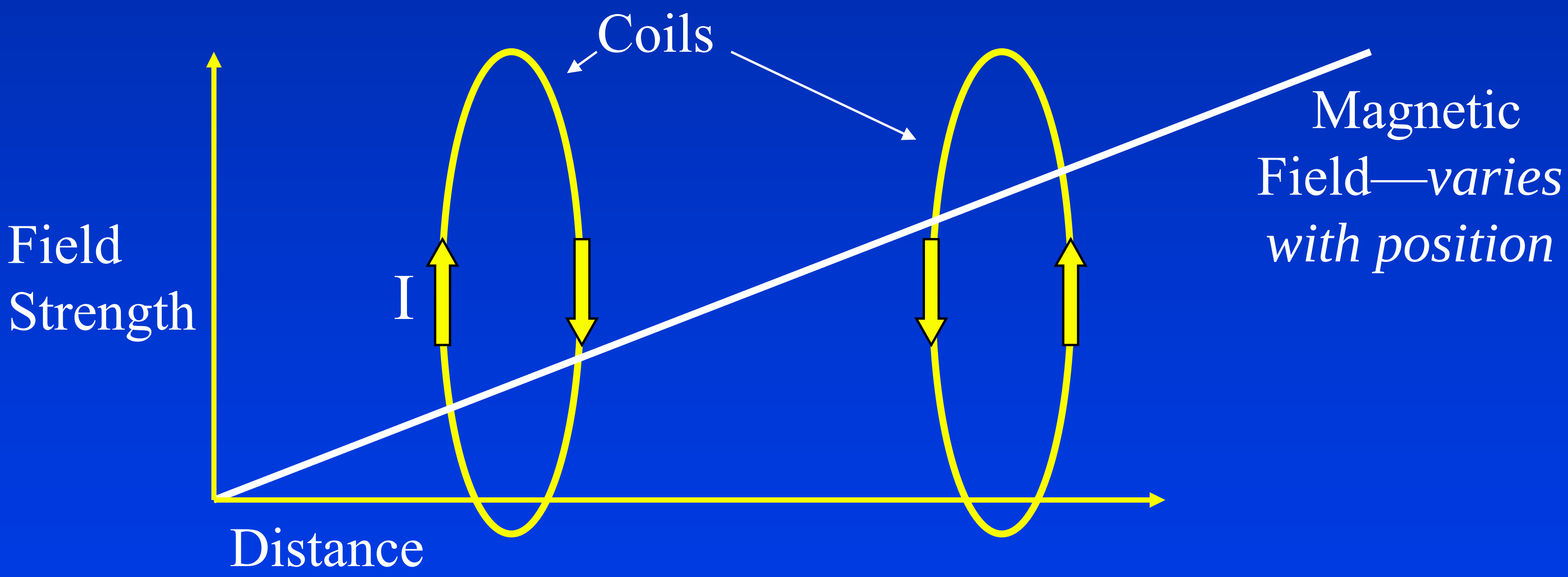
*without room-temperature shims

1 ppm = 0.00001%



NIH/NIA/GRC

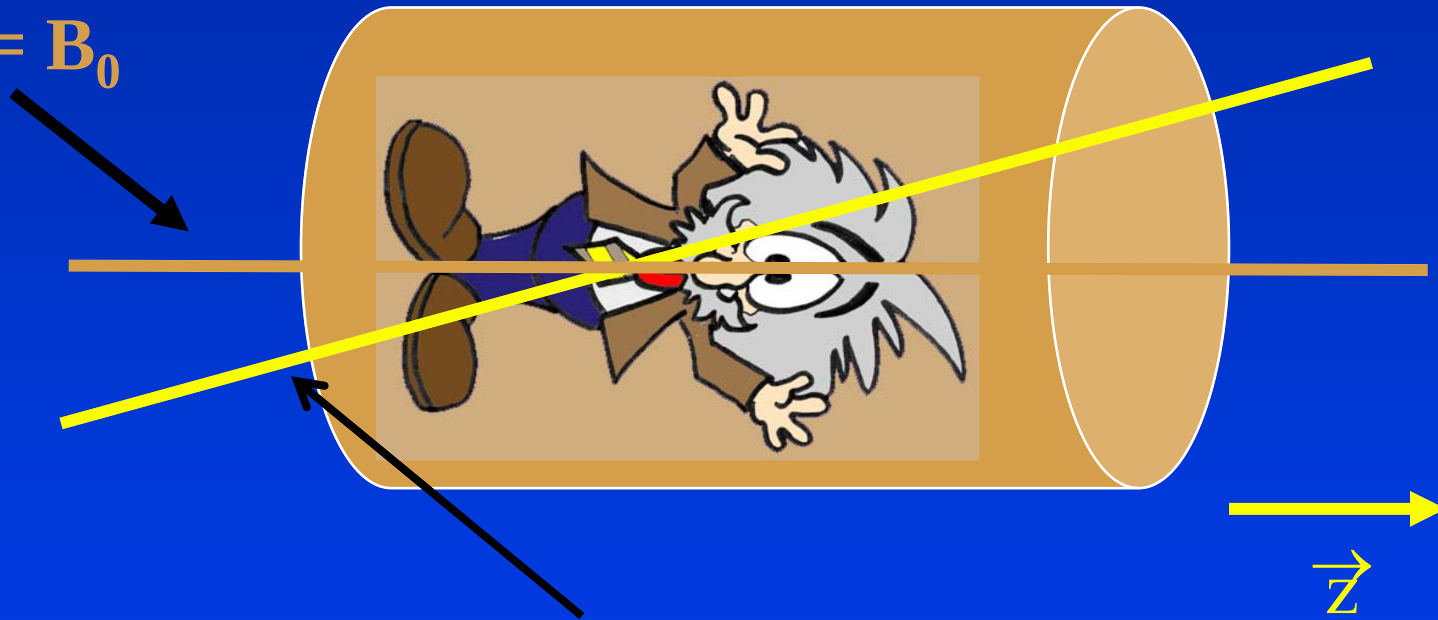
Magnetic Field Gradients:
required along all three axes



I (current)
direction indicated by ↑

Operation of Gradients

No gradient:
$B_{z,Local} = B_0$

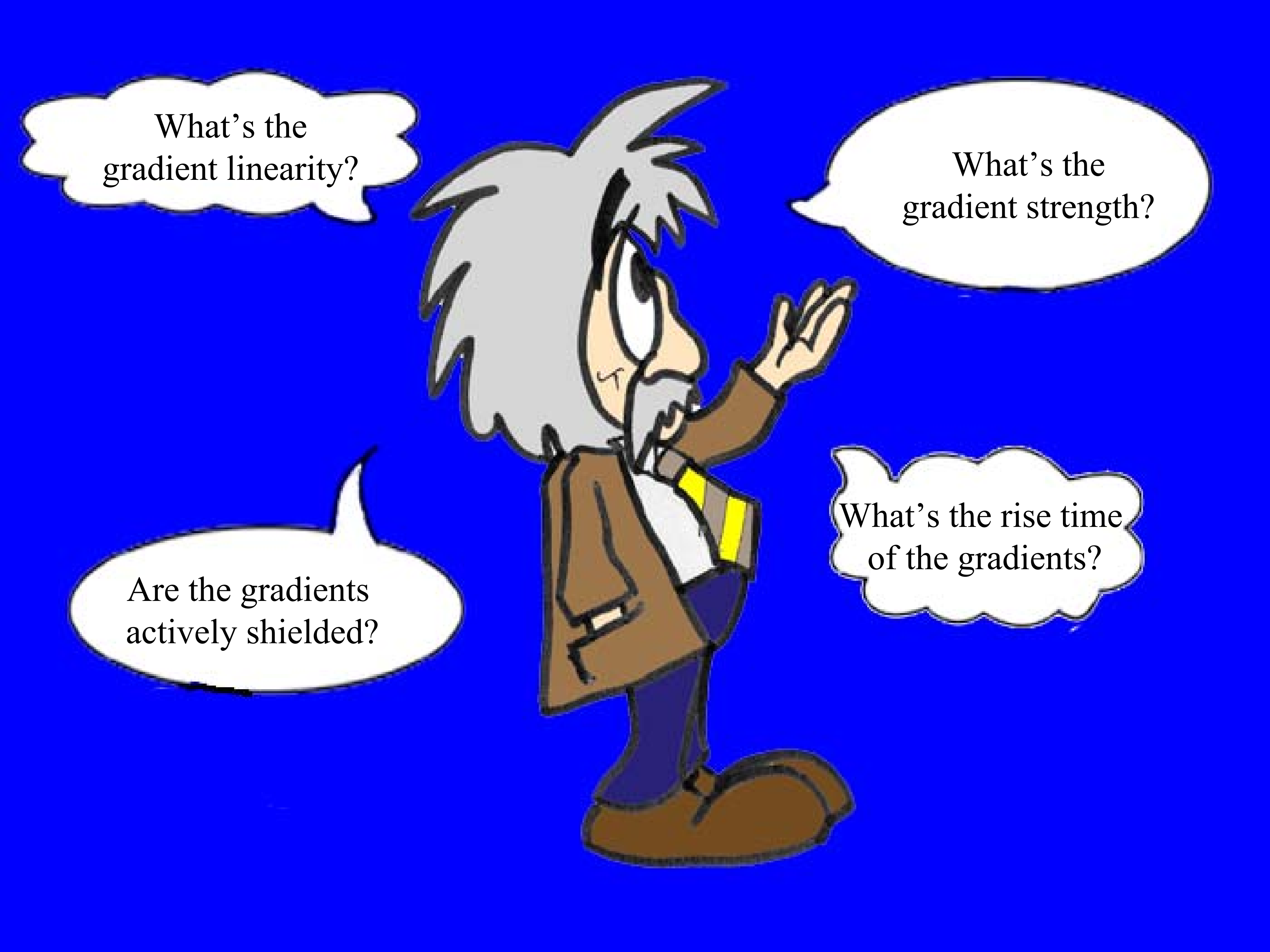


With gradient: $B_{z,Local} = B_0 + z\,G_z$

Spatial variation of the B field permits spatial mapping of spins:
frequency $\propto$ spatial position

Gradient Considerations

- Want high in-plane resolution
- Want narrow slice capability in 2D imaging
- Want images which aren't distorted
- Want to be able to image quickly


What's the gradient linearity?
What's the gradient strength?
What's the rise time of the gradients?
Are the gradients actively shielded?

Two Different "Bandwidths" in MRI

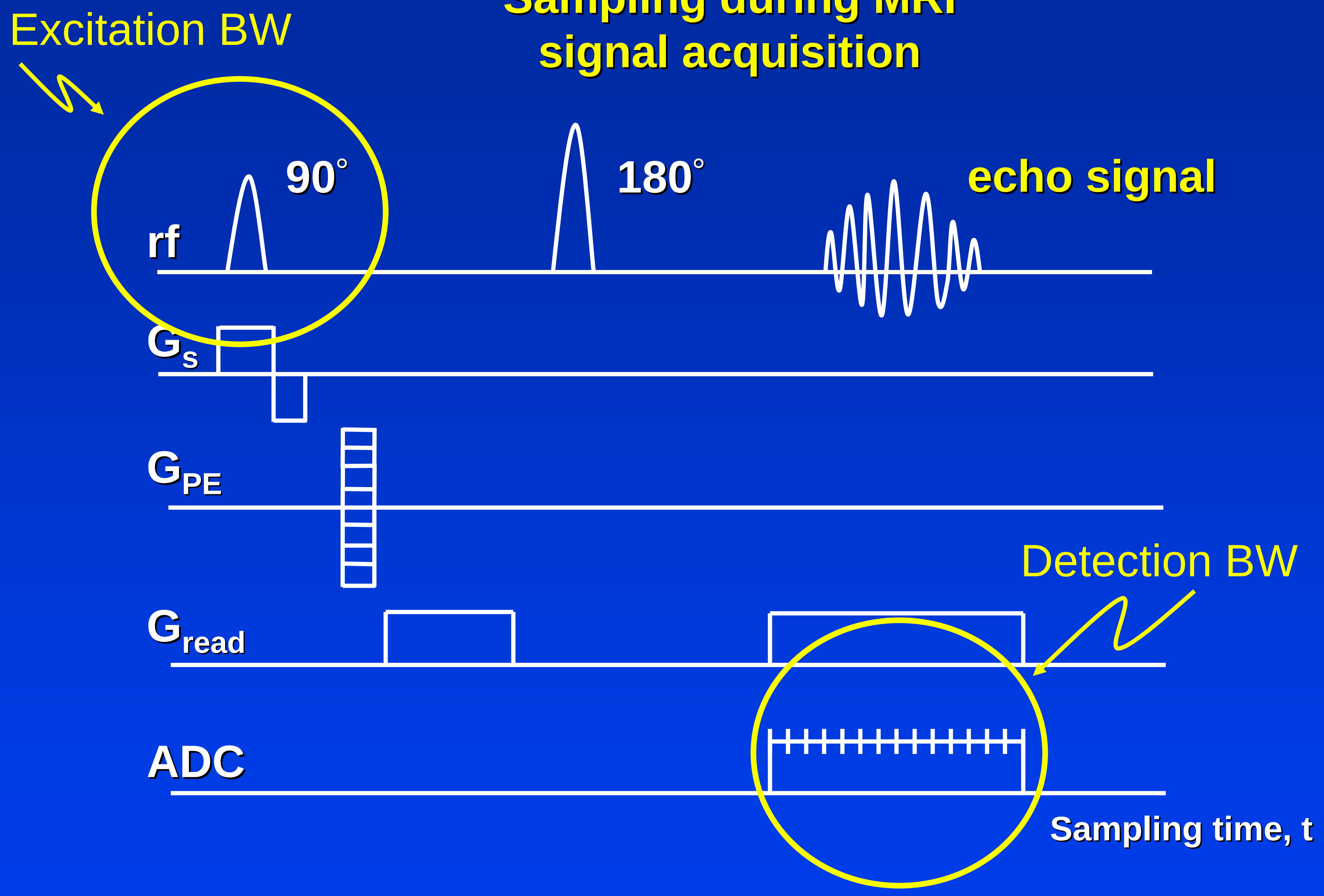
- ***Excitation Bandwidth* of a radiofrequency pulse**

  *The pulse **excites spins** in this range of frequencies*

- ***Receiver Bandwidth***

  *The receiver can **detect signals** in this range of frequencies*

Sampling during MRI signal acquisition

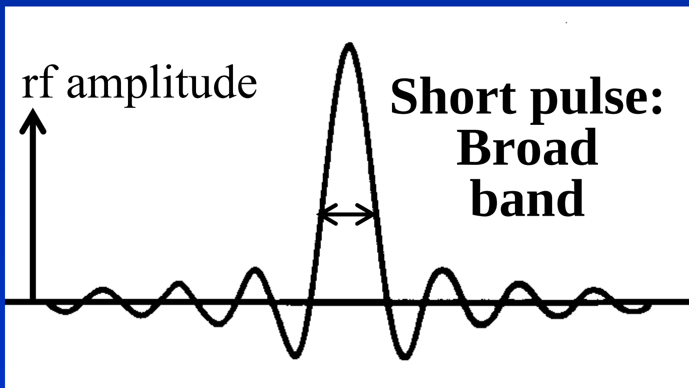


Excitation Bandwidth and Gradient Strength

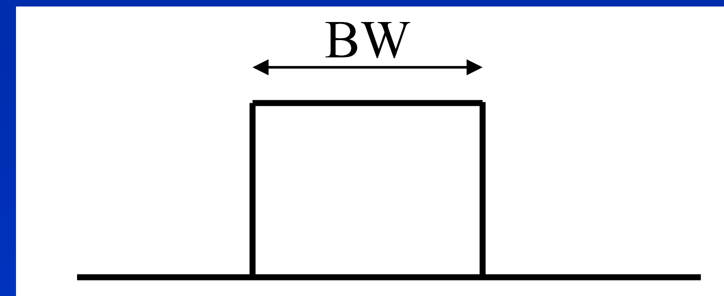
Excitation Bandwidth

Excitation pulse

Frequency band excited

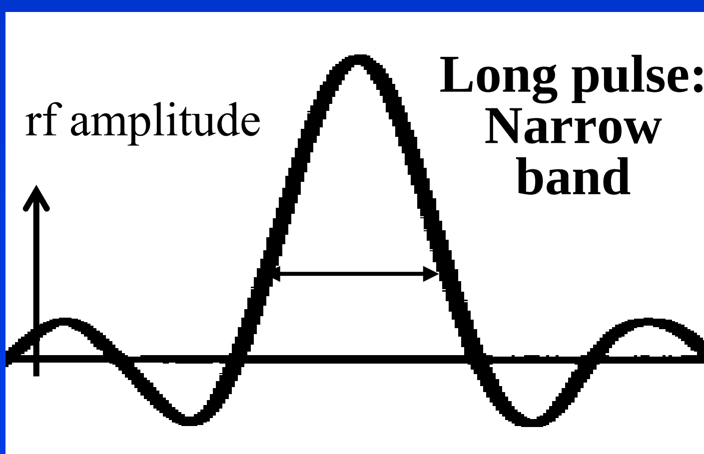


Fourier

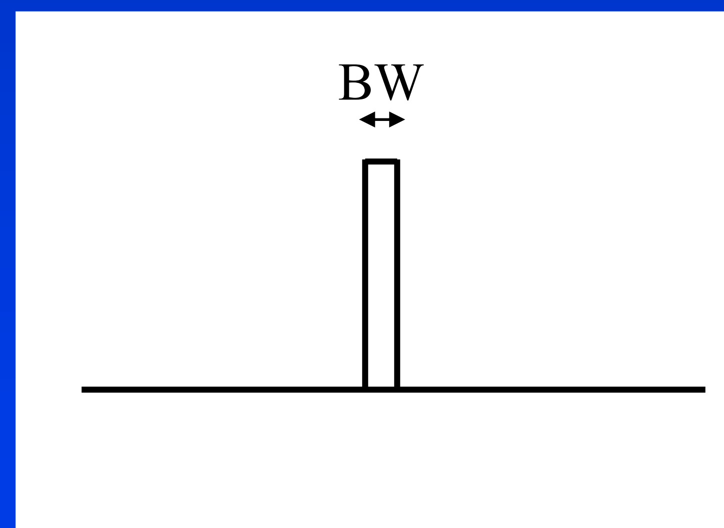


t (milliseconds)

ν (kilohertz)



Fourier



t (milliseconds)

ν (kilohertz)

NIH/NIA/GRC

Pulse Bandwidth
a.k.a. Excitation Bandwidth

Longer duration pulses ⇒

• narrower excitation bandwidth

however…

• longer echo time—loss of signal from short T_2 species

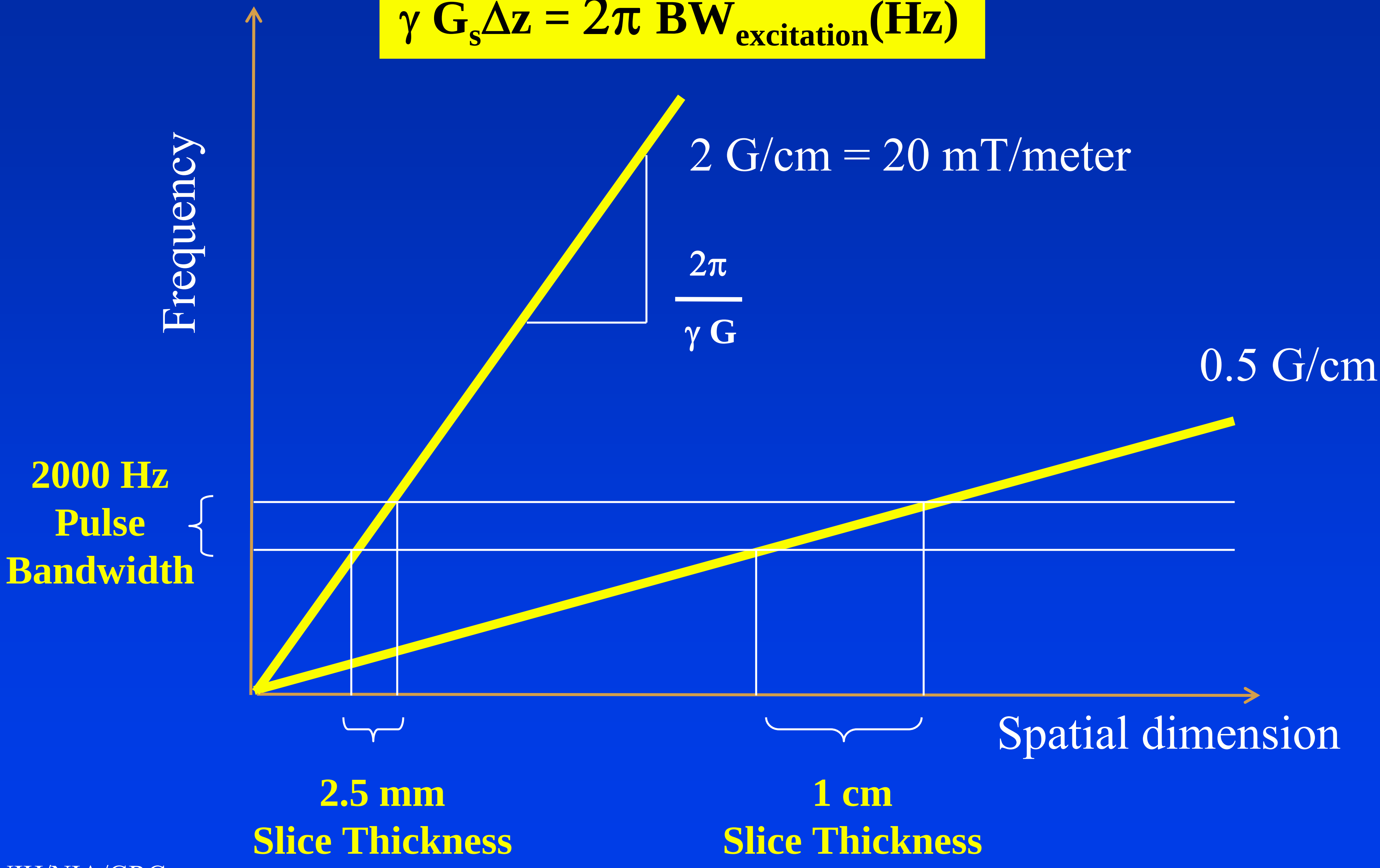
• greater sample heating

• relaxation effects during pulses

Would like to be able to use short pulses and still have narrow slice

Slice gradient strength + Pulse bandwidth ⇒ Slice thickness

$$\gamma\, G_s \Delta z = 2\pi\, BW_{excitation}(Hz)$$



Effect of Slice Gradient Strength on Slice Thickness

$$\text{Slice Thickness} \propto \frac{1}{G_{slice}}$$

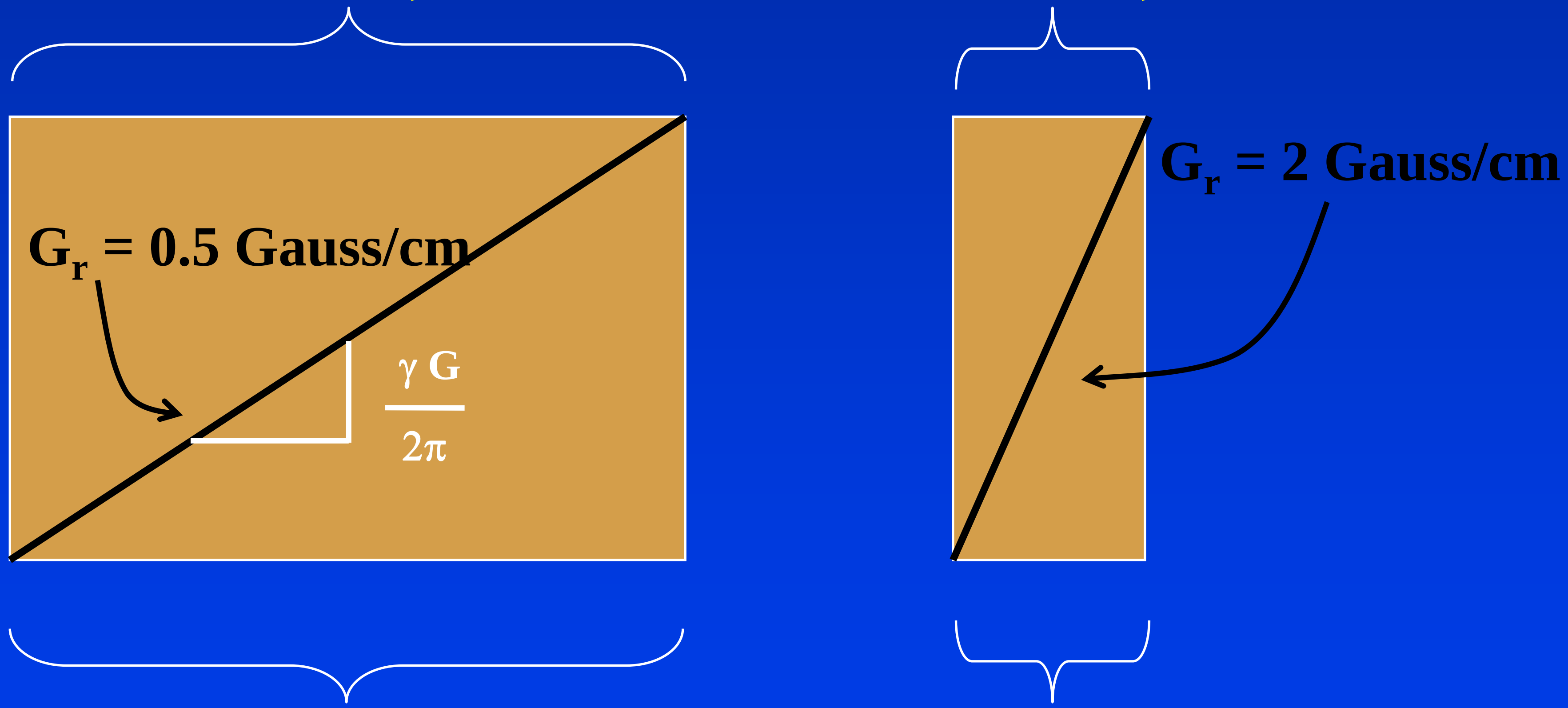
$$\uparrow G_{slice} \Rightarrow \downarrow$$ **Slice Thickness**

Receiver Bandwidth and Gradient Strength

MRI maps a frequency range to a spatial range

$$\gamma\, G_r\, FOV = 2\pi\, BW_{receiver} (Hz)$$

Receiver BW=4,300 Hz **Receiver BW=4,300 Hz**



FOV = 2 cm **FOV = 5 mm**

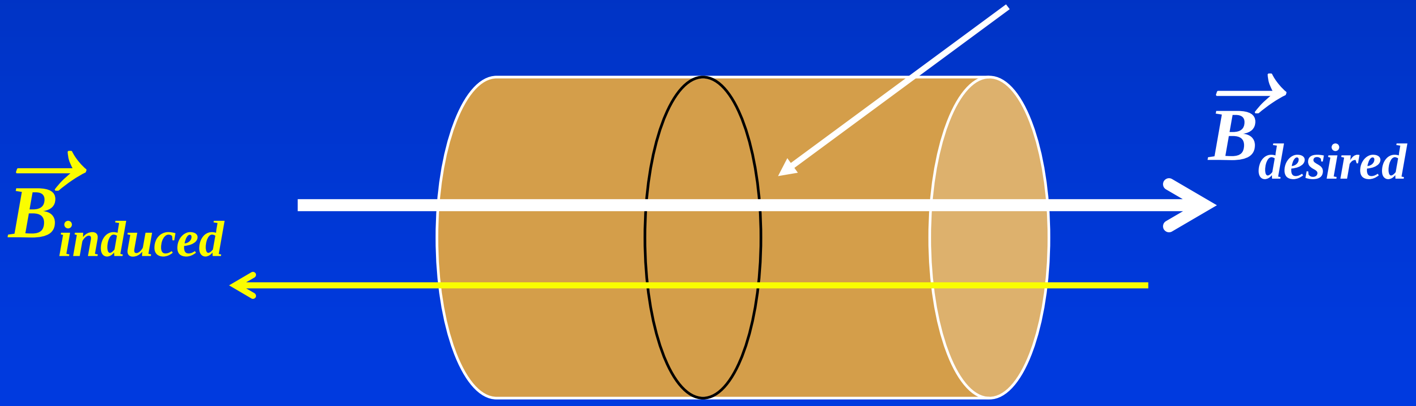
Effect of Read Gradient Strength on In-plane Resolution

$$\text{Resolution} \propto \frac{1}{\textit{Pixel Size}} \propto \frac{1}{FOV} \propto G_r$$

Gradient Eddy Currents

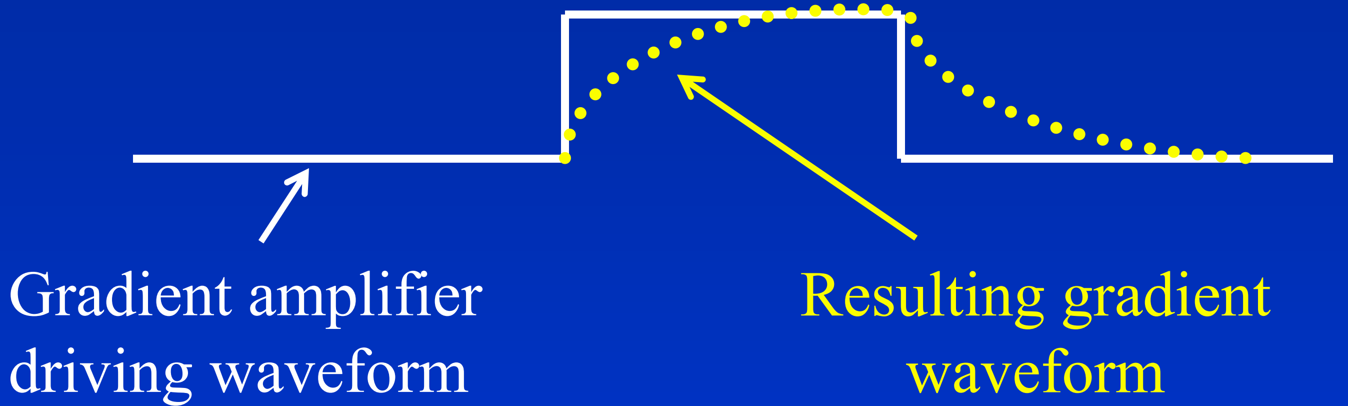
Faraday's Law

$$Voltage = -\frac{d}{dt}\int \vec{B}\cdot d\vec{S}$$

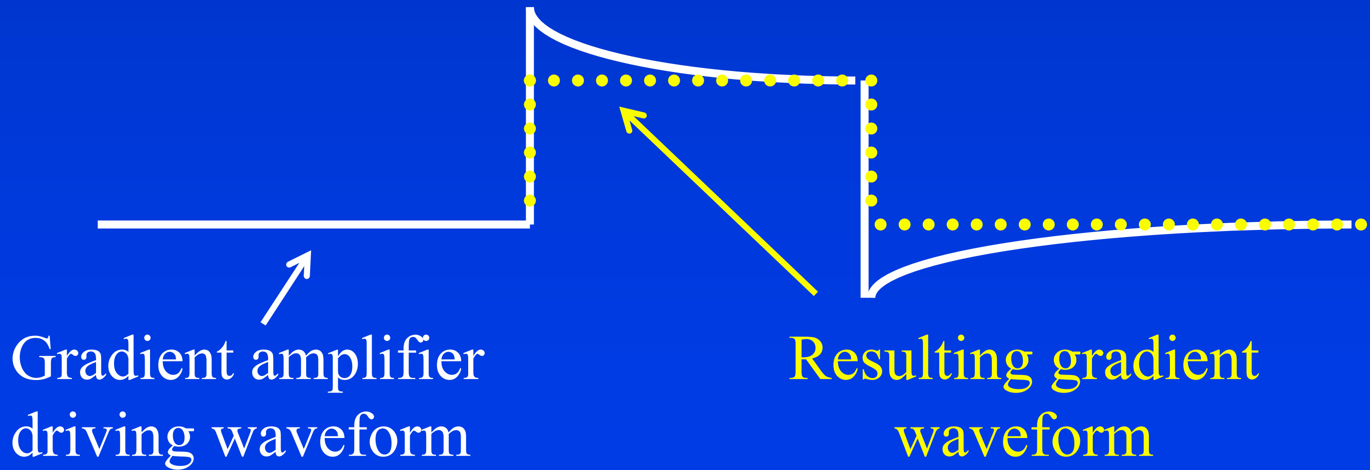


Increased currents with more rapid switching

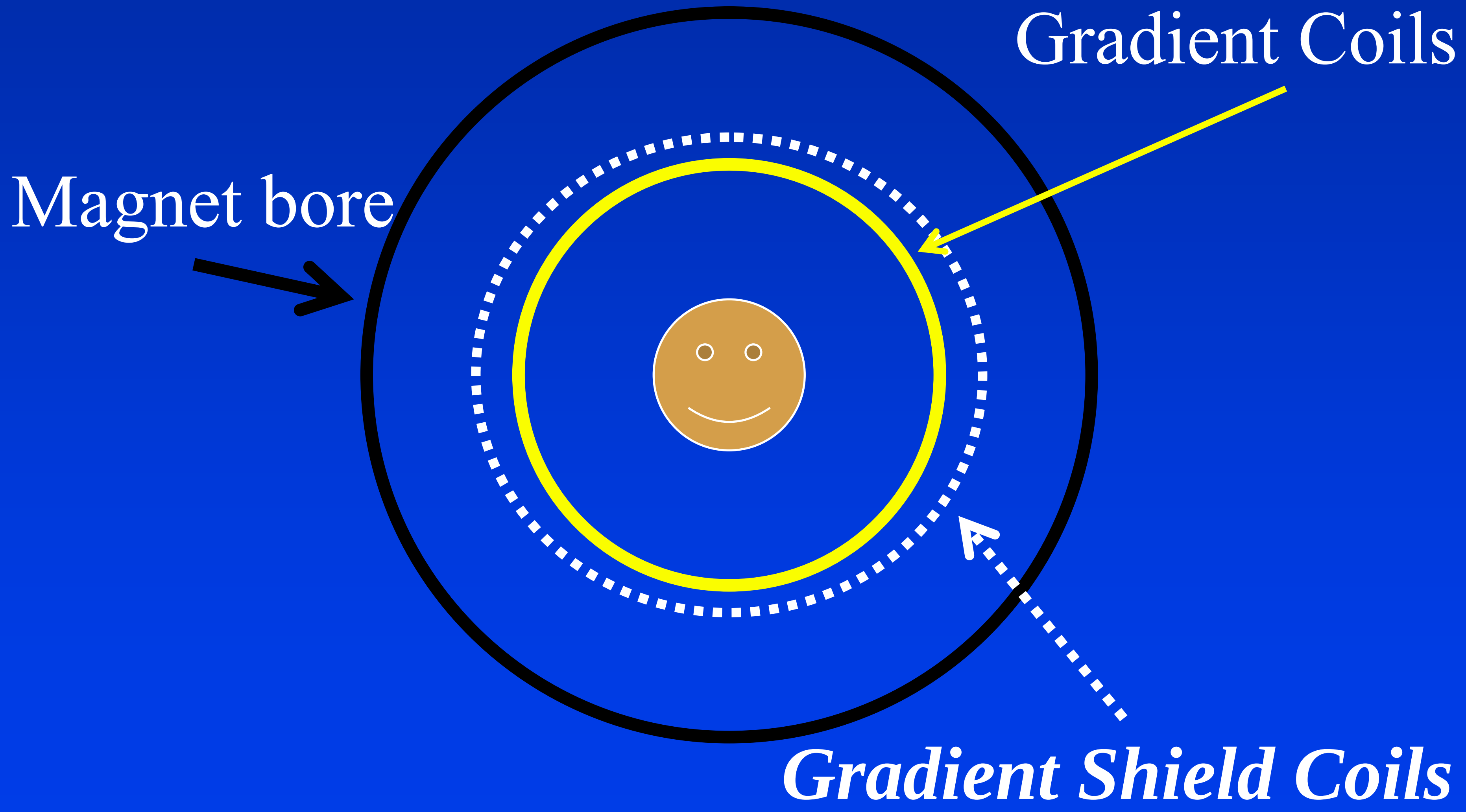
$B_{induced}$ causes B-field distortions



Cure #1: Pre-emphasis



Cure #2: Shielded Gradients



Gradient Linearity

Effect on Image Accuracy

$B_{z,\,Local} = B_0 + G_z(z)$

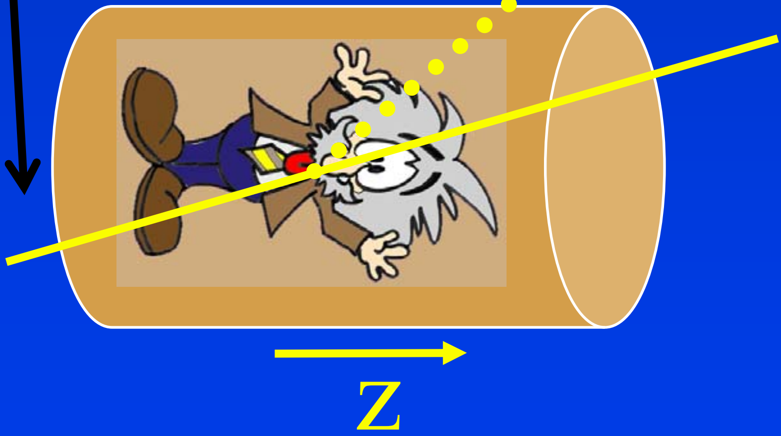
nonlinear

Nonlinear gradient: geometric distortion

$B_{z,\,Local} = B_0 + z\,G_z$

linear

Linear gradient: nondistorted image



Sample Gradient Specifications

- Gradient strength:

  2.5 G/cm (clinical)→ 4 G/cm, 8 G/cm

  10-100 G/cm (animal)

Increased gradient strength → higher resolution, narrower slices
however: also increased heating, increased rise time (slower)

- Gradient switching time (rise and fall time) depends upon inductance and driving voltage:

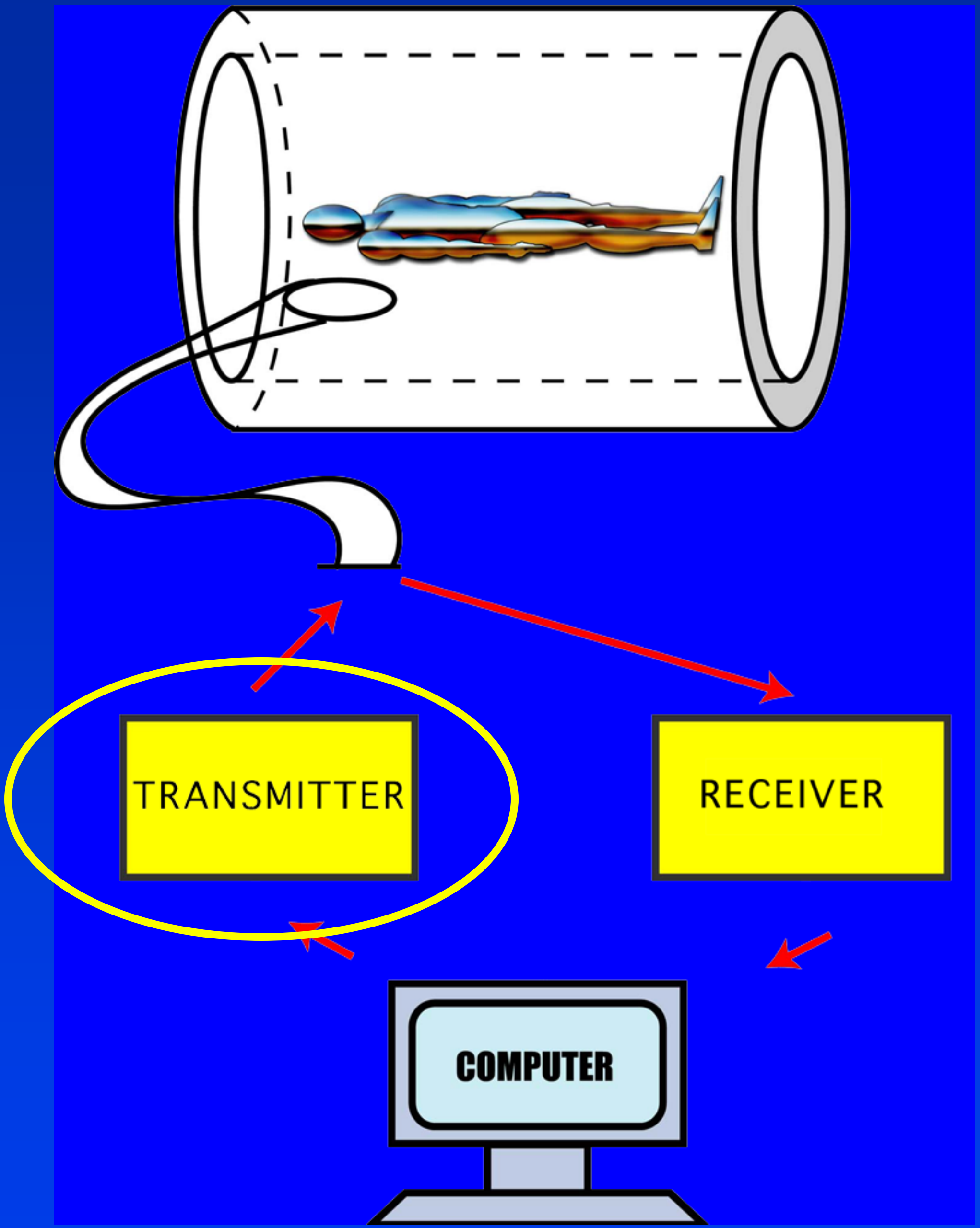
  0.2 ms to rise to 2 G/cm

Faster switching → better performance in rapid imaging sequences

- Gradient linearity:

  5% over 22 cm diameter spherical volume

Better linearity → less image distortion

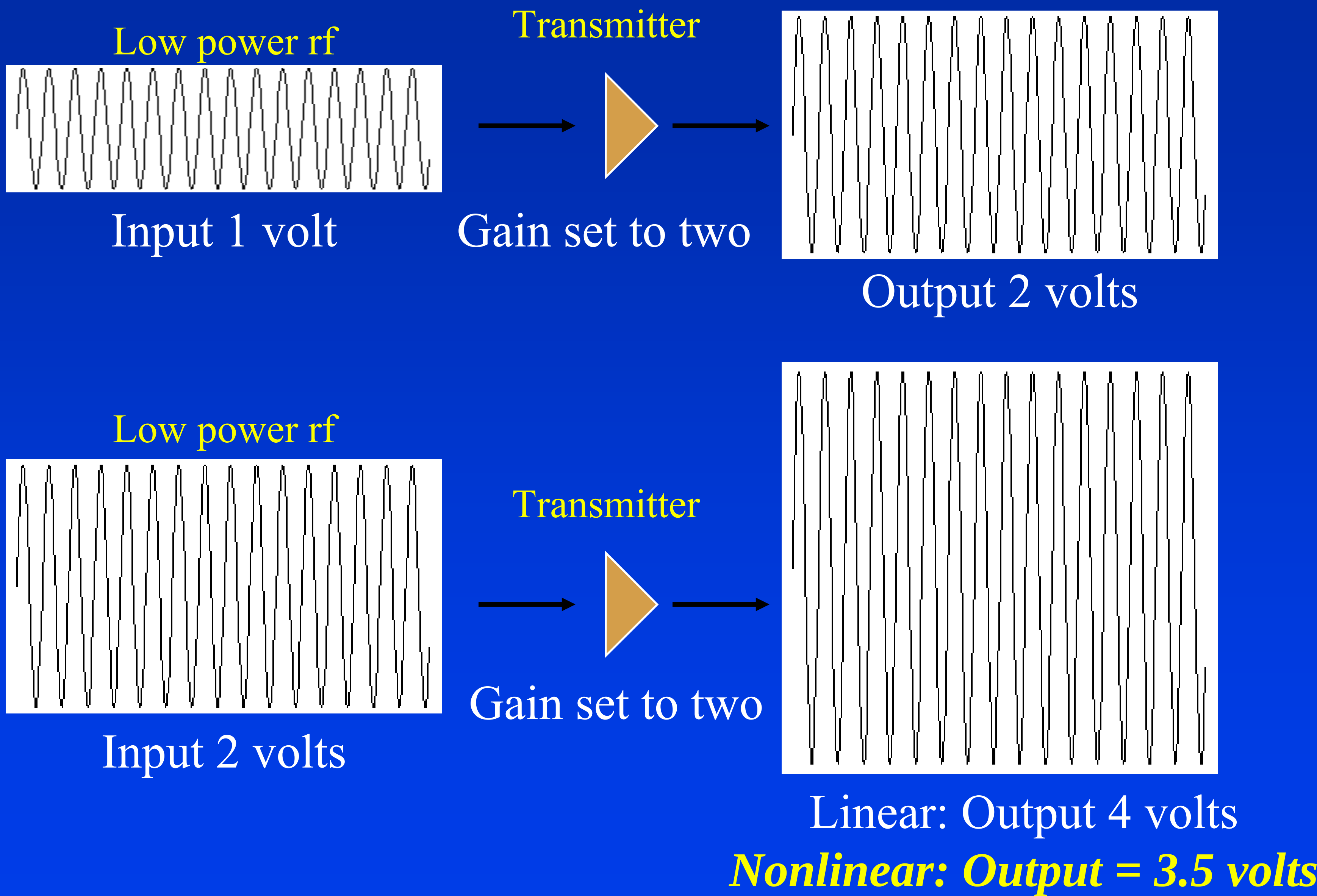

TRANSMITTER
RECEIVER
COMPUTER

Transmitter Considerations

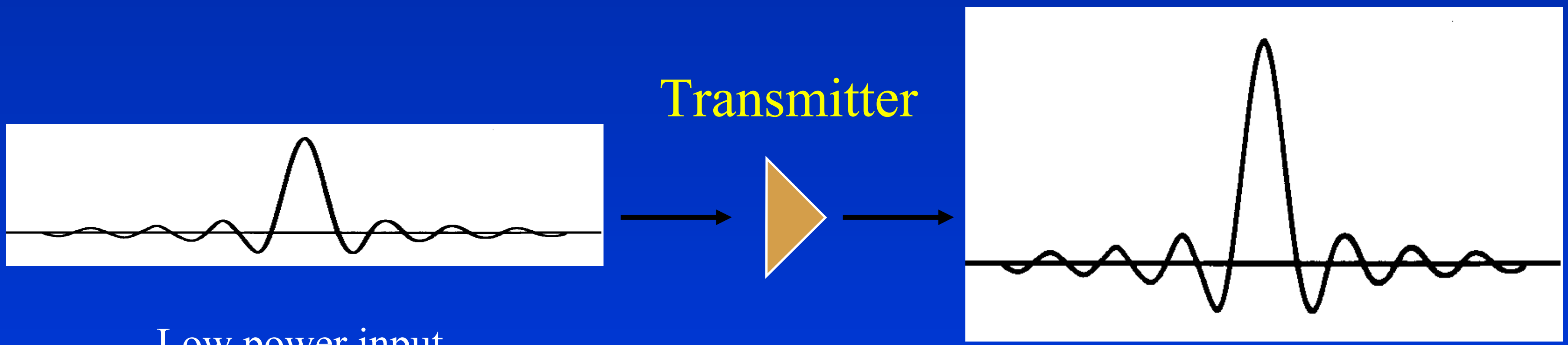
- Need to uniformly excite large bandwidth
- Require accurate shaped pulses (time, amplitude)
- Desire easy-to-control power output
- Frequency stability


What's the transmitter power?
What's the linearity of the amplifier?

Transmitter Linearity



Transmitter linearity is important for accurate shaped pulses



Low power input
to transmitter amplifier

High power output from
transmitter amplifier

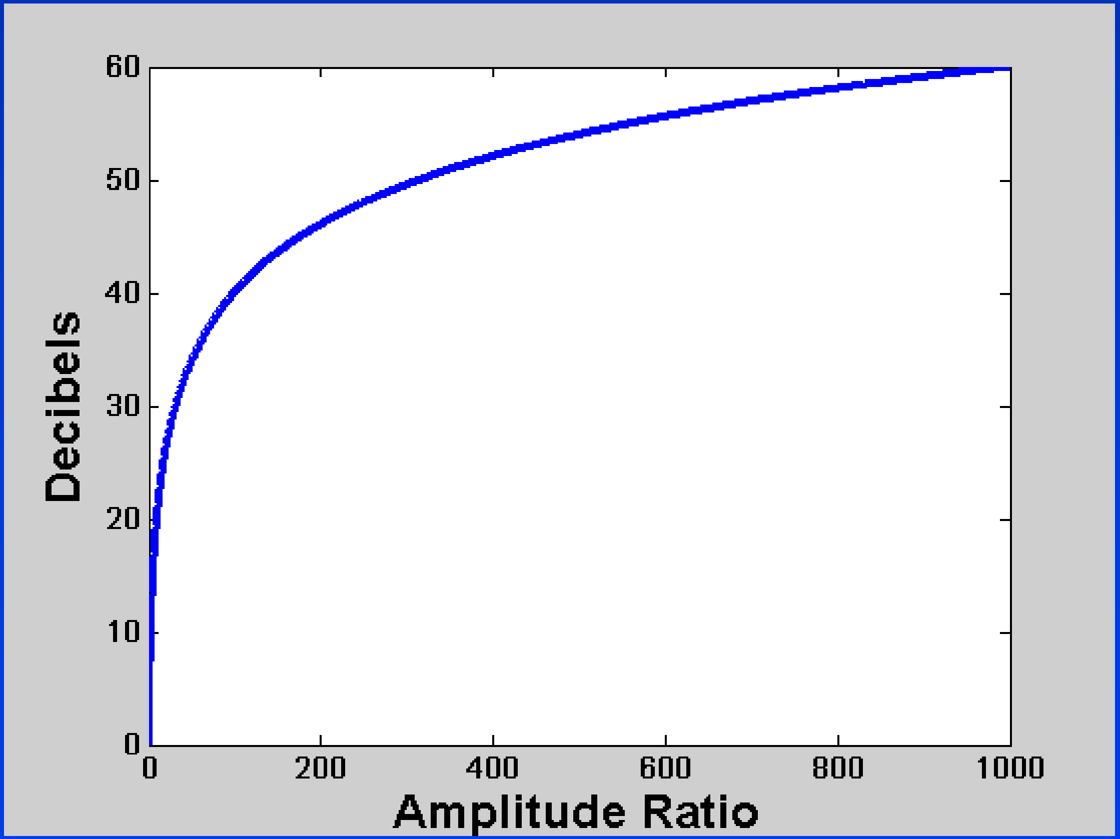
...and for calibrating pulses

What is a decibel?

The dB scale expresses amplification or attenuation as the logarithm of a ratio:

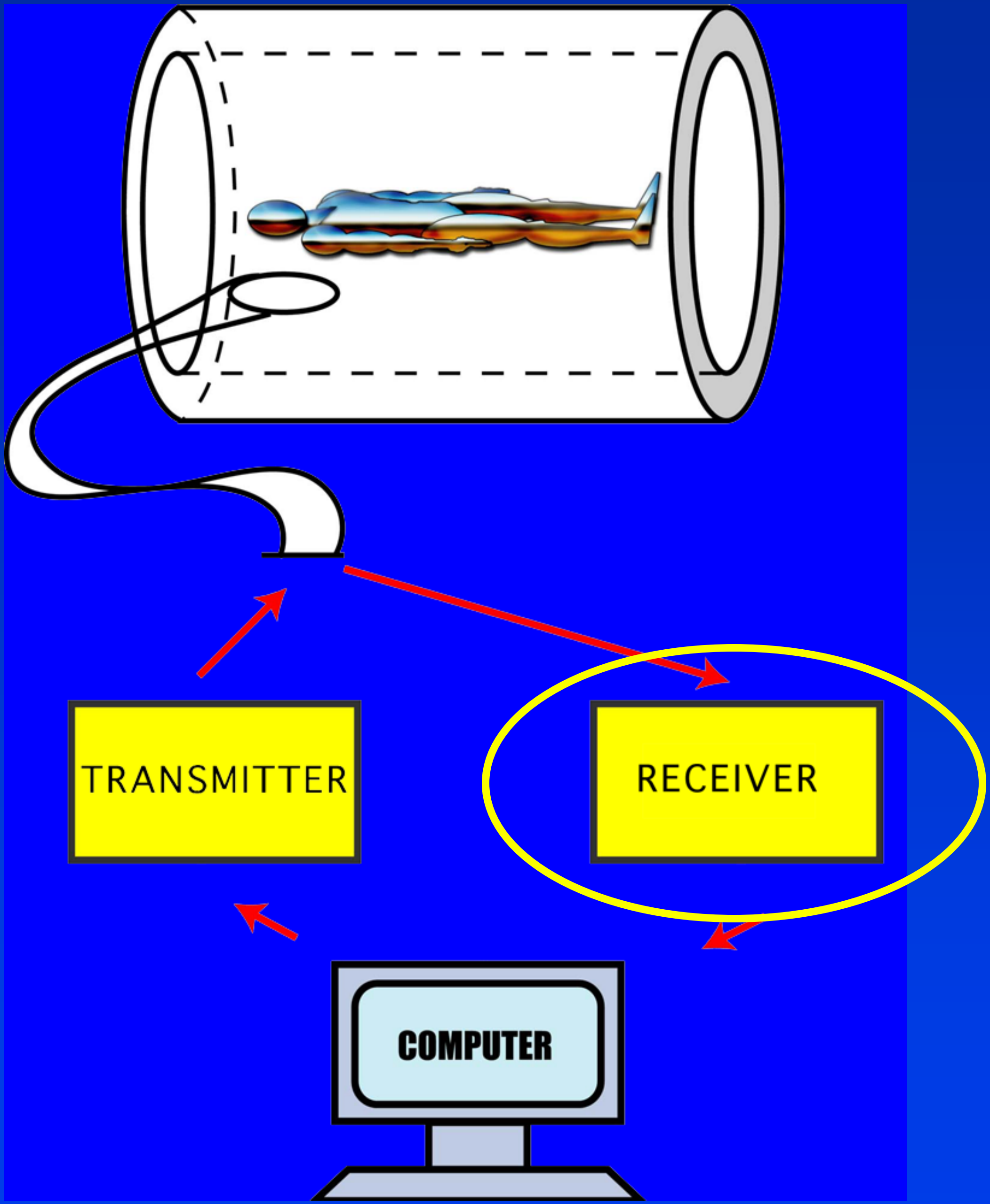
$$dB = 20\ \log_{10}(A_2/A_1)$$

A_2/A_1	dB
2	6
10	20
100	40



Sample Transmitter Specifications

- Maximum output: 15 kW
- Linear to within 1 dB over a range of 40 dB
- Output stability of 0.1 dB over 10 ms pulse
- Output stability of 0.1 dB pulse-to-pulse



NIH/NIA/GRC

Receiver Considerations

Goal: Receive the microvolt NMR signal and convert it to a detectable echo/FID

- Without corruption by noise
- With faithful amplitude reproduction
- With faithful frequency reproduction


What's the digitizer resolution?
What's the receiver bandwidth?

Receiver Bandwidth

The largest detectable frequency

Suppose G_r = 1 G/cm
FOV = 10 cm

⇒ Signal frequency range = 40 kHz

Nyquist: have to sample at 80 kHz to accurately record frequencies

Receiver Digitization

12 bits: maximum amplitude ratio observable
$= 2^{12} / 1 = 4096$

16 bits: maximum amplitude ratio observable
$= 2^{16} / 1 = 65{,}536$

High digitization in imaging:

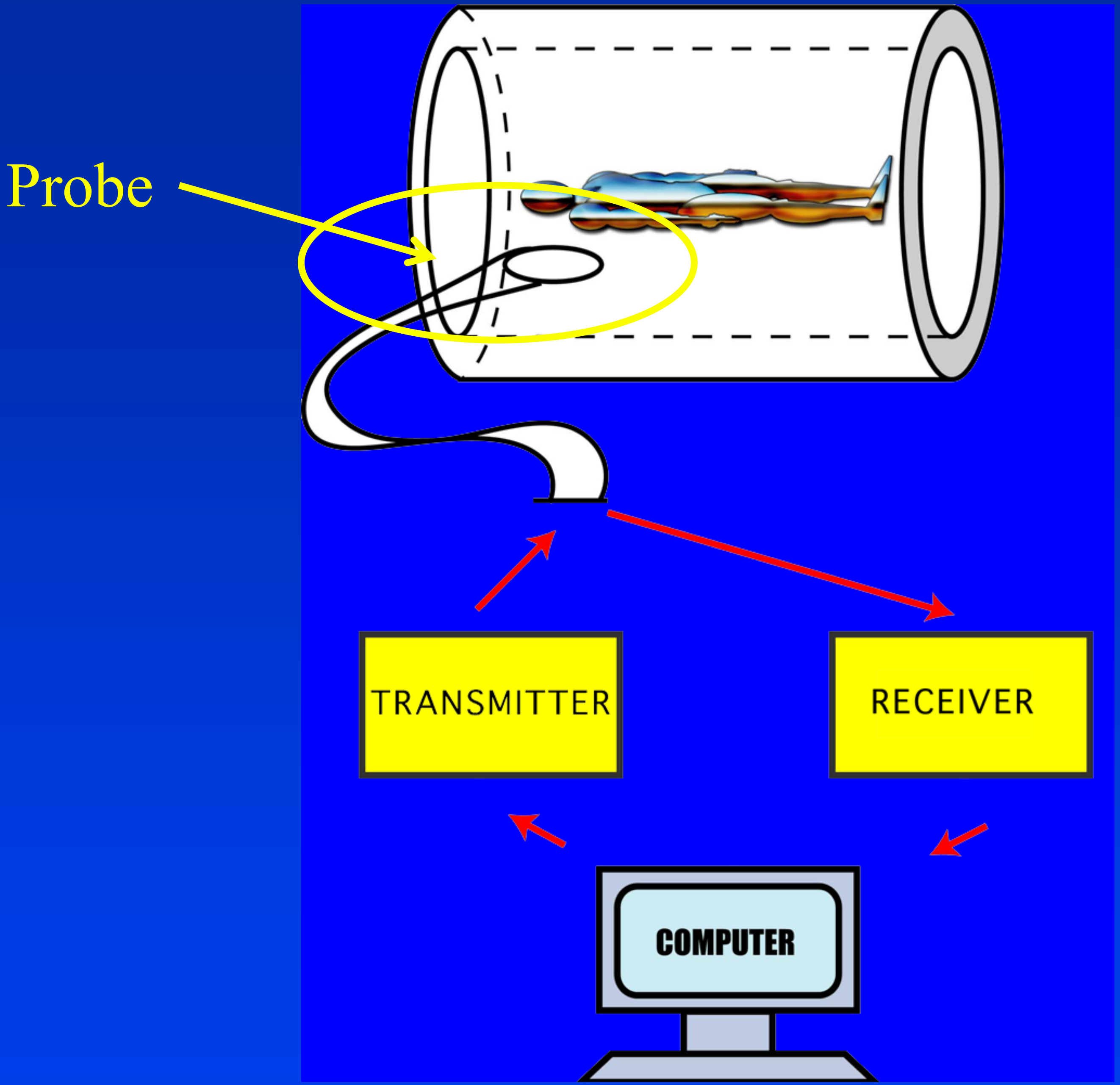
- ***improved use of data from the periphery of k-space (low signal, but high-resolution information)***

High digitization in spectroscopy:

- ***water suppression***
- ***low-concentration metabolites***

Sample Receiver Specifications

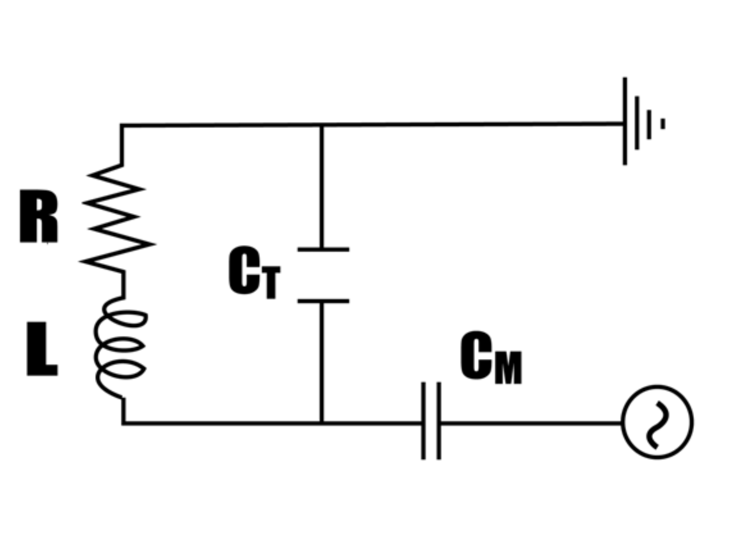
- Digitizer: 14 bit or greater
- Receiver Bandwidth: 500 kHz (± 250 kHz) or greater
- Preamp gain: 30 dB or greater
- Preamp noise: 0.7 dB or less
- System noise: 1.4 dB or less



NIH/NIA/GRC

Probe* Considerations

i) Transmit coils ii) Receive coils



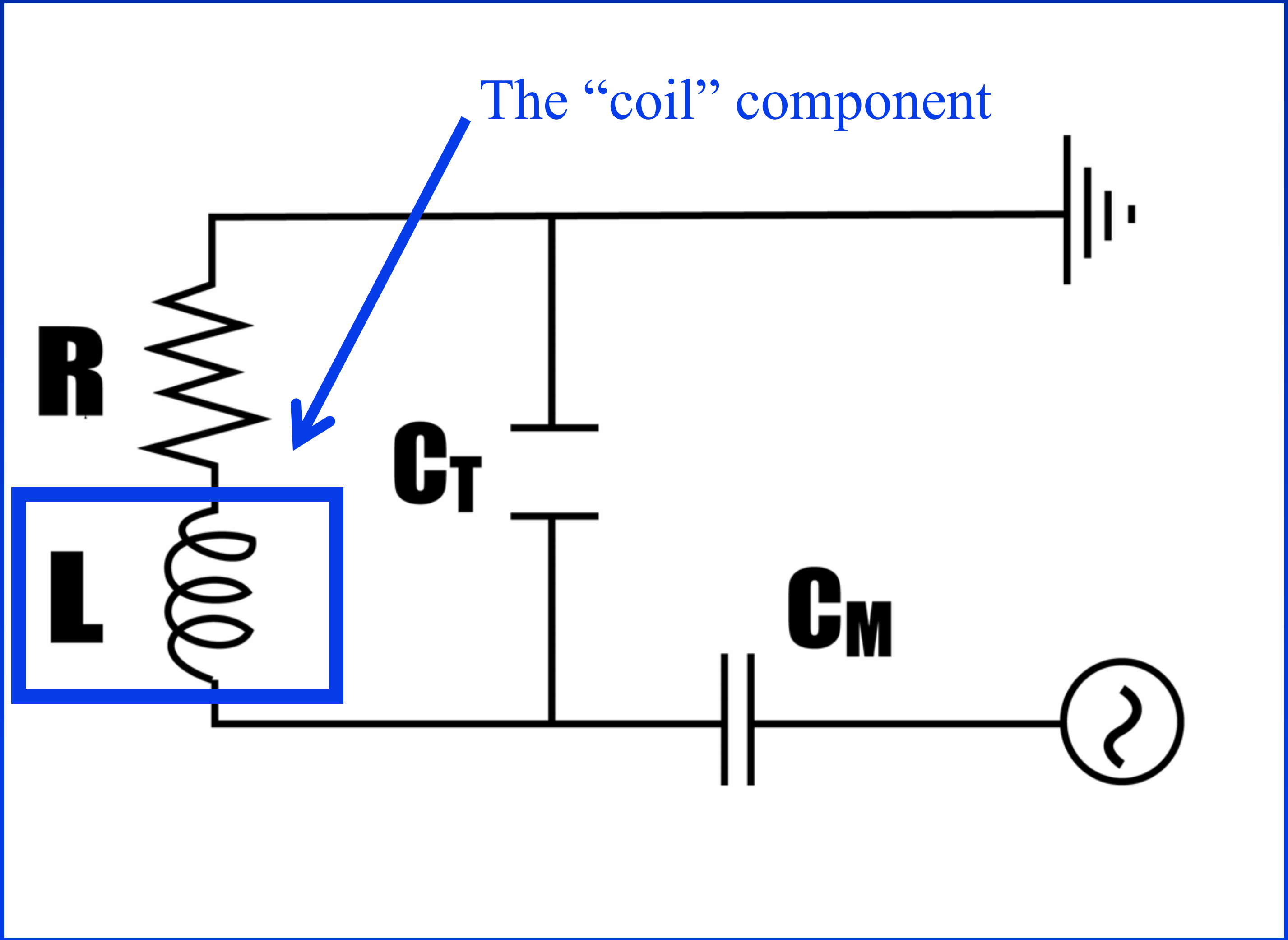
Basic probe circuit

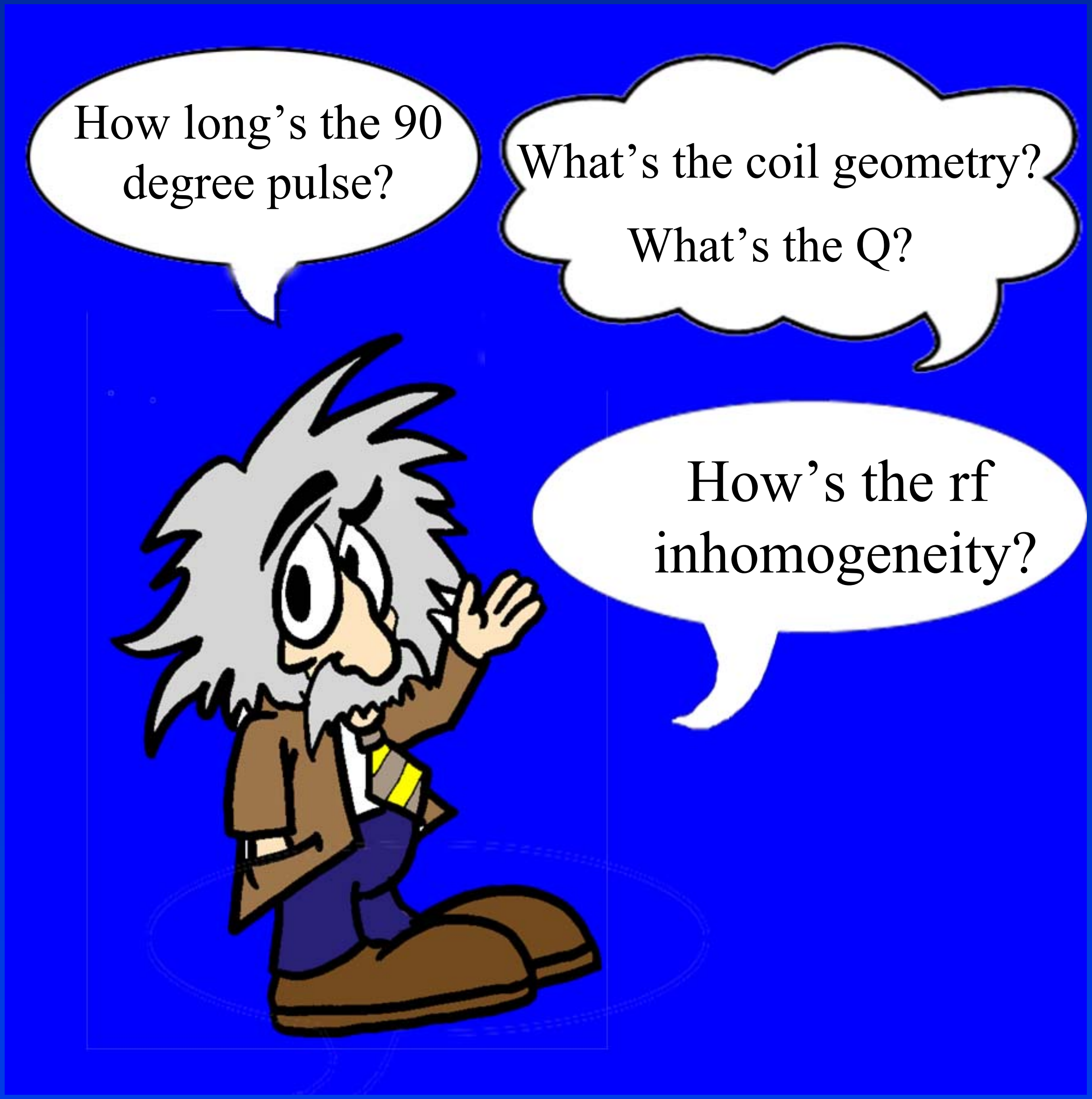
C_M: matching capacitor
C_T: tuning capacitor
R: intrinsic resistance
L: the coil

- High SNR: high sensitivity, low noise
- Good homogeneity for transmission and reception
- Efficient power transmission to the sample

***probe = rf coil**

Probe Construction

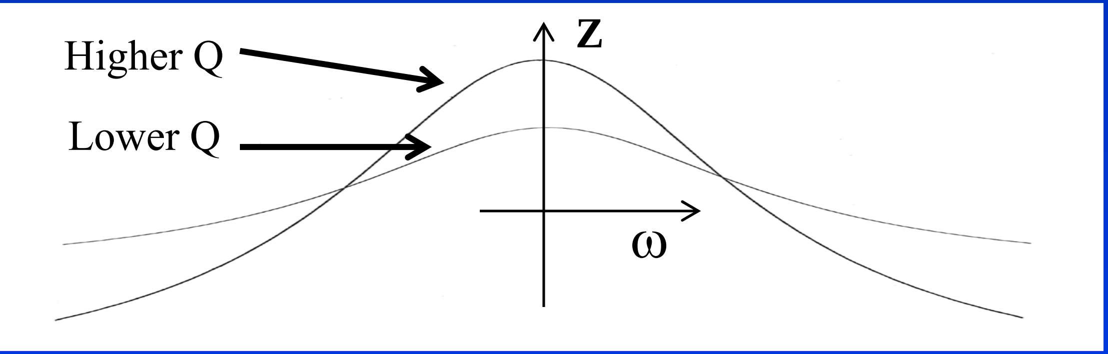



How long's the 90 degree pulse?
What's the coil geometry?
What's the Q?
How's the rf inhomogeneity?

Q

Q is for *Quality* (“efficiency”) of a coil

Q defines how much of the transmitted energy is delivered to the sample at the proper frequency



Q also defines the sensitivity of the coil during reception

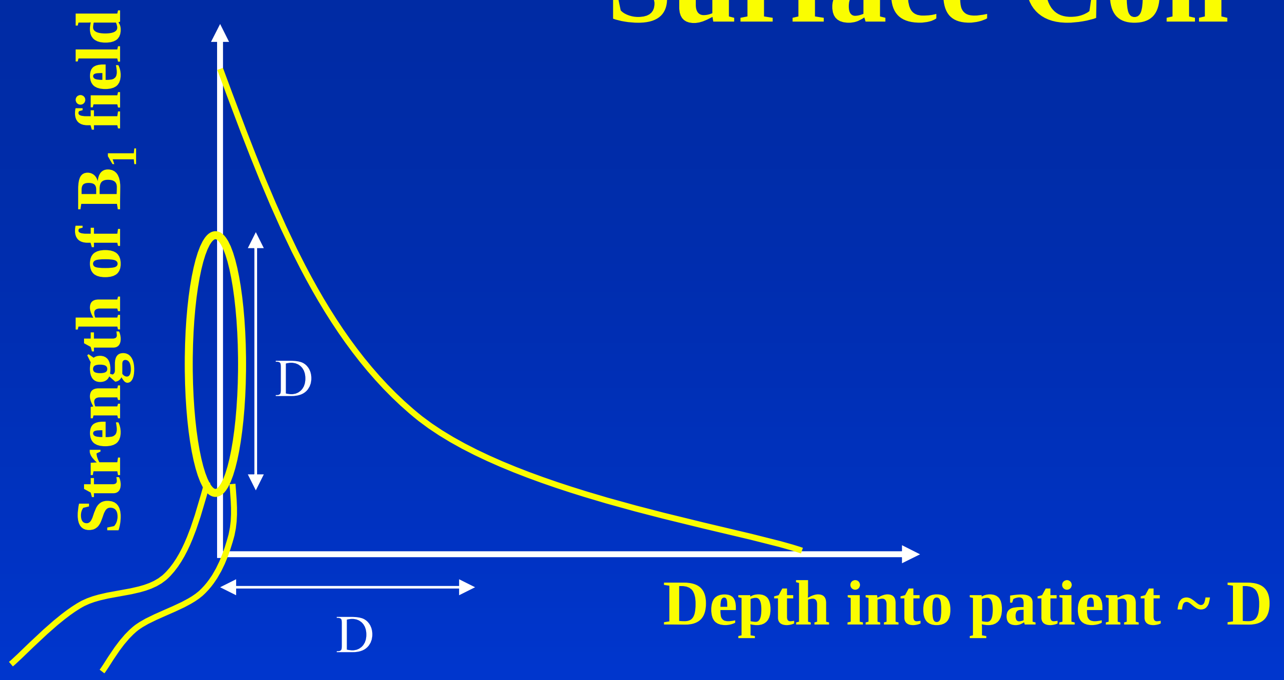
Typical Surface Coil

One or more loops of wire
form a surface coil

Bruker Biospec surface coil

Siemens loop flex surface coil

Surface Coil



Advantages:

- High B_1 field: the coil is close to the sample
- Low noise: sees only desired imaging region
- Can be arranged into a phased array for greater spatial coverage

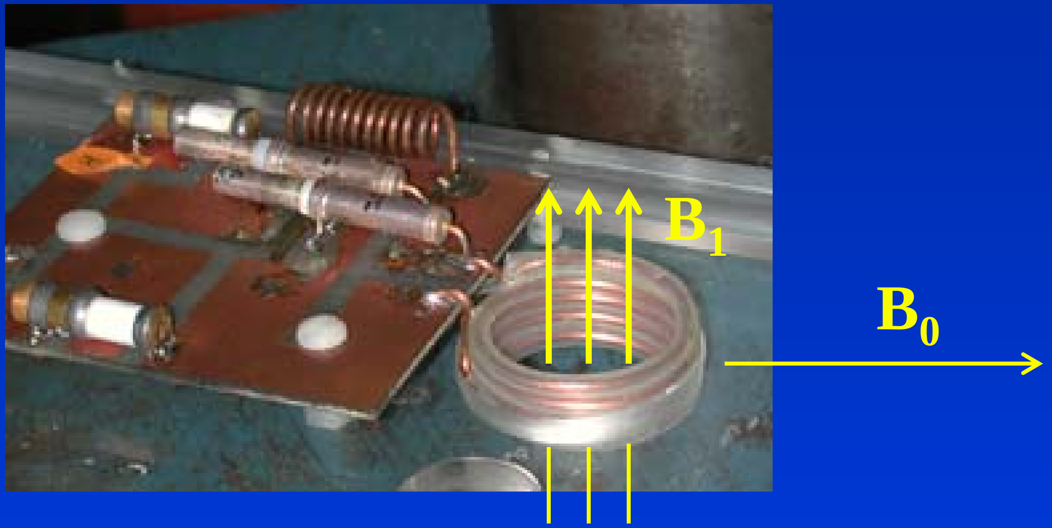
Disadvantages:

- Inhomogeneous transmission
- Inhomogeneous reception

} *Shaded images*

Solenoidal Coil

Multiple loops form a solenoidal coil



Advantages:

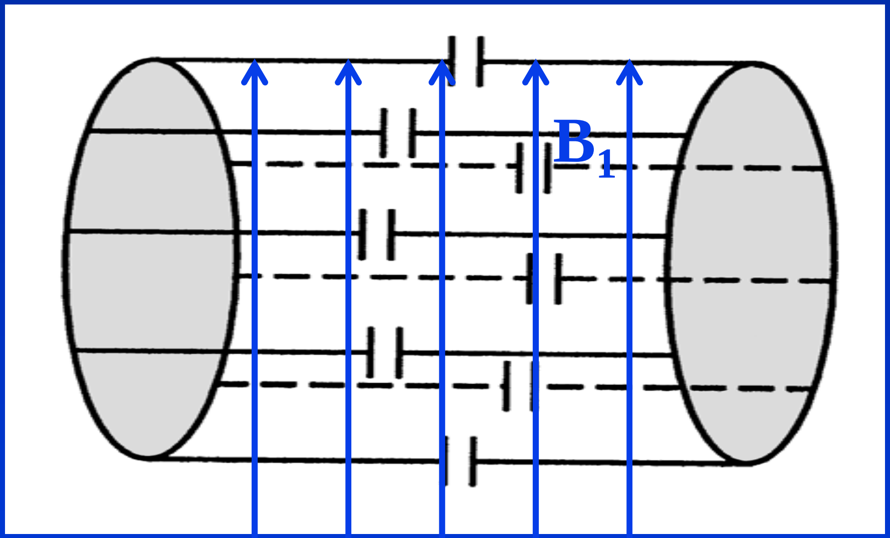
- **Homogeneous field**
- **High SNR**

Disadvantages

- **Can't orient with axis along the B_0 field--the spins won't flip**

Birdcage Coil

Multiple parallel wires form a birdcage resonator



Head coil; body coil

Siemens Pathway MRI™ 1.5T Head Coil

Advantages:

- Much more homogeneous field
- Intrinsically high SNR
- Can run in quadrature mode for $\sqrt{2} \uparrow$ SNR
- Can use as transmit-only coil w/surface coil

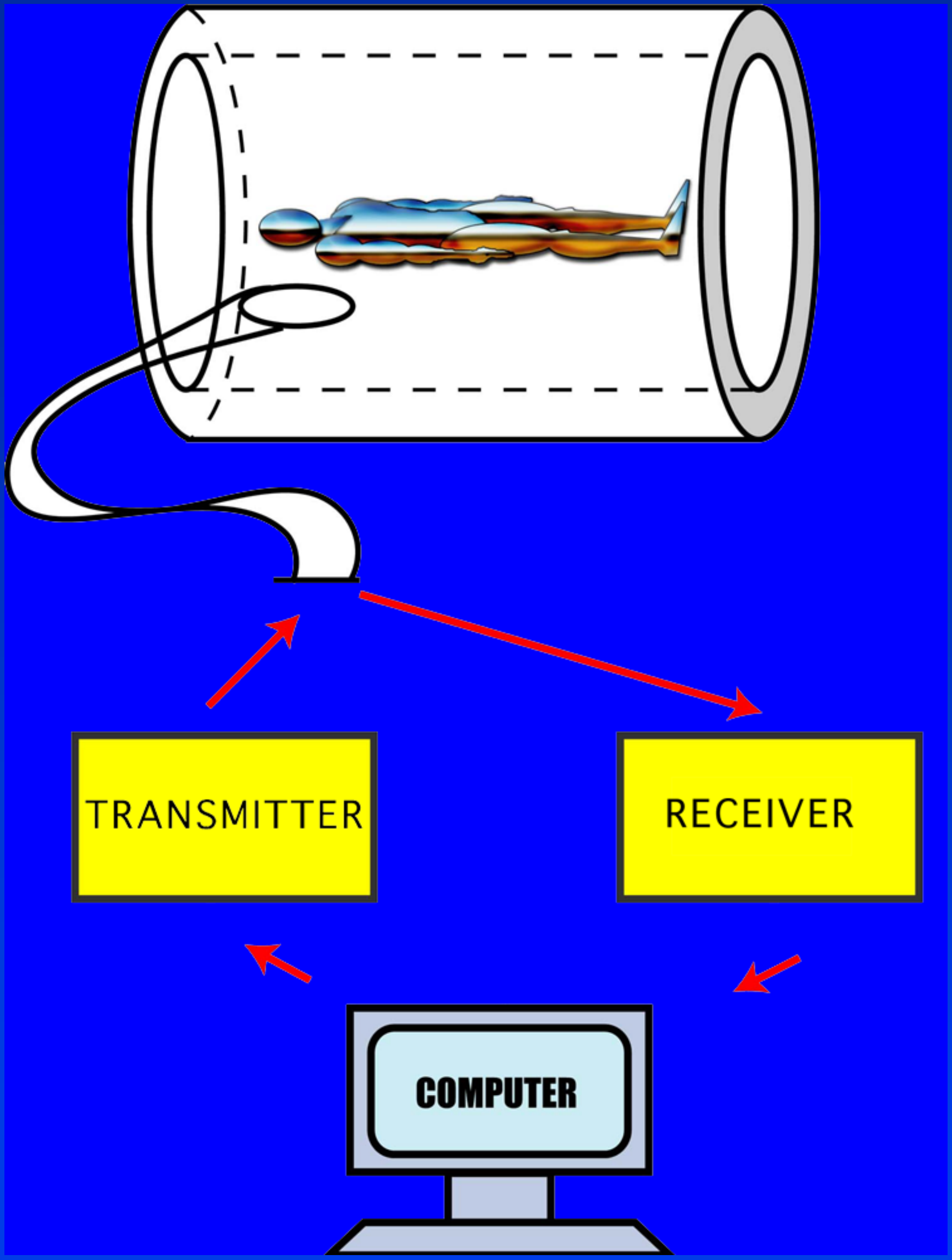
Disadvantages:

- Complicated design and construction

Phased array coils

Siemens Body Array

•Maintain SNR advantages of surface coils
•Large sensitive region



1. Magnet
2. Gradients
3. Transmitter
4. Receiver
5. Probe

Basic understanding needed to specify, purchase, and operate an MRI system

Magnetic Resonance Imaging
Haacke, Brown, Thompson, Venkatesan
Wiley, 1999

In vivo NMR Spectroscopy
de Graaf
Wiley 1998

Electromagnetic Analysis
and Design in MRI
Jin
CRC 1999

Biomedical MR Technology
Chen and Hoult
Adam Hilger, 1989