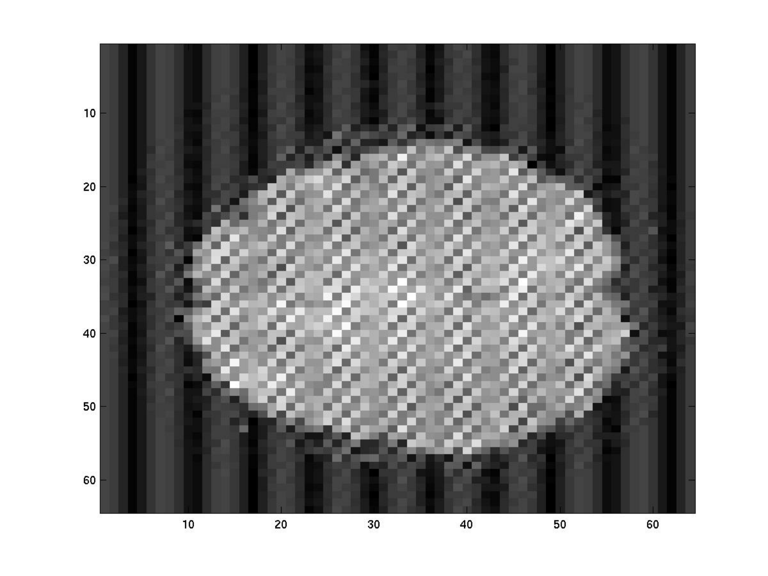
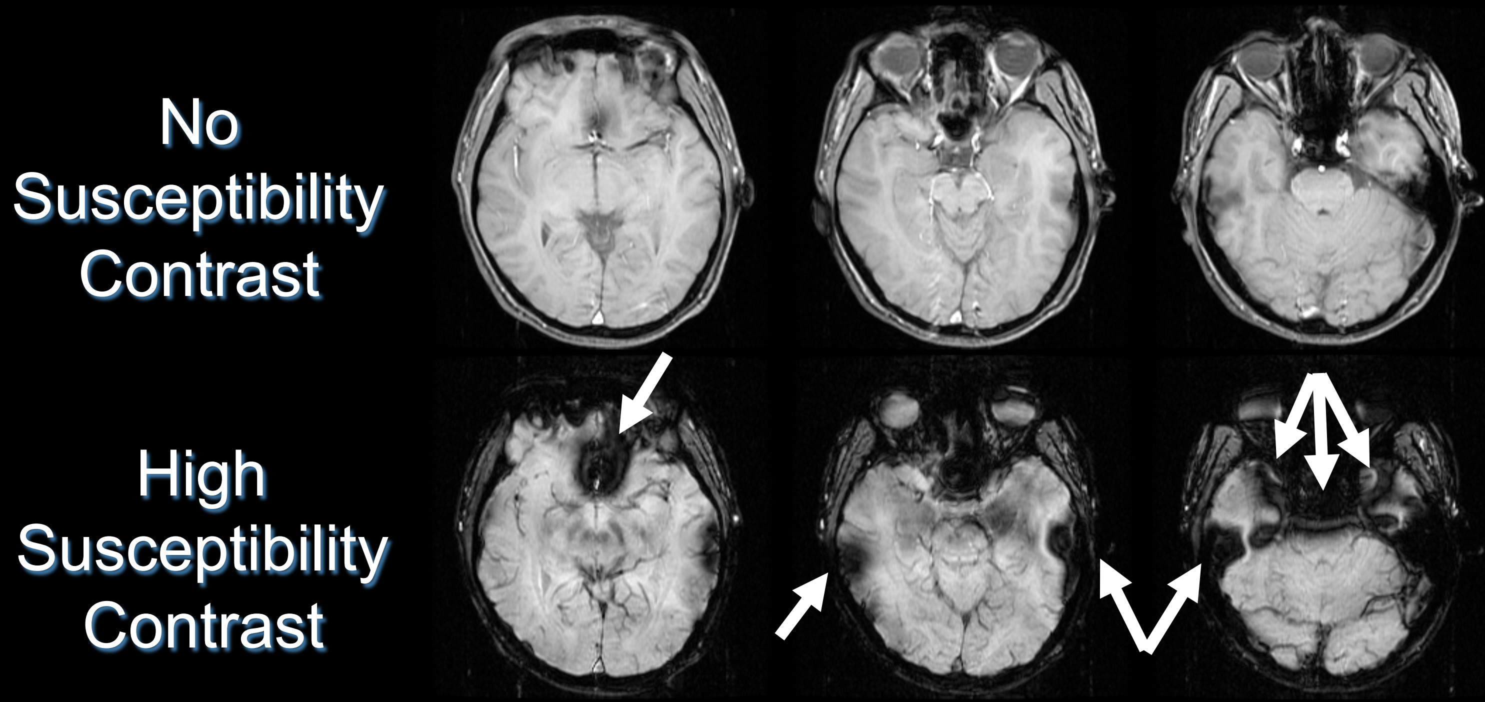
White Pixel Artifact

- Caused by a noise spike during acquisition
- Spike in K-space <--> sinusoid in image space



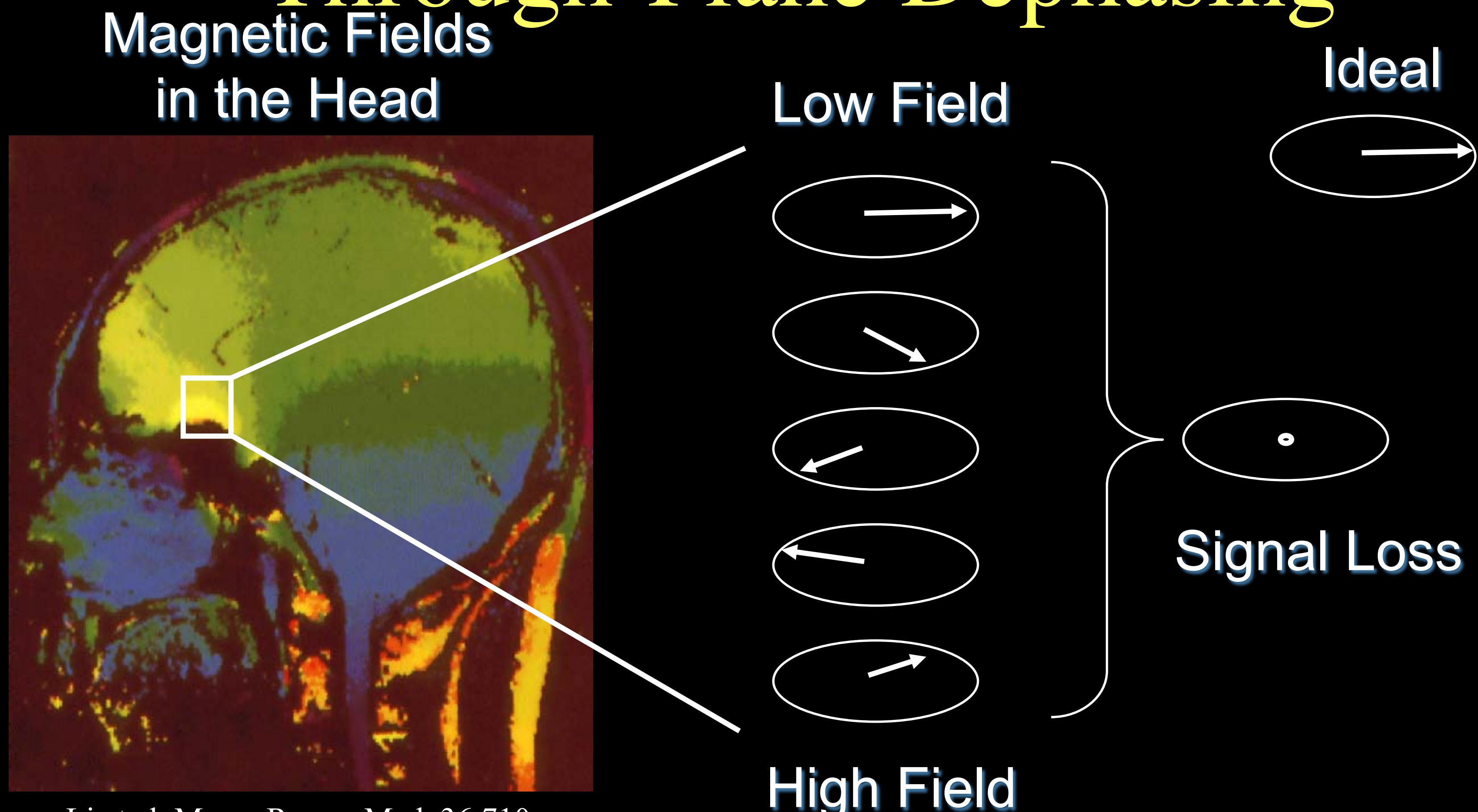
Susceptibility Artifacts

- Off-resonance artifacts caused by adjacent regions with different Susceptibility
- **BOLD** signal requires susceptibility weighting… but this also leads to image artifacts



courtesy of Douglas Noll

Through-Plane Dephasing



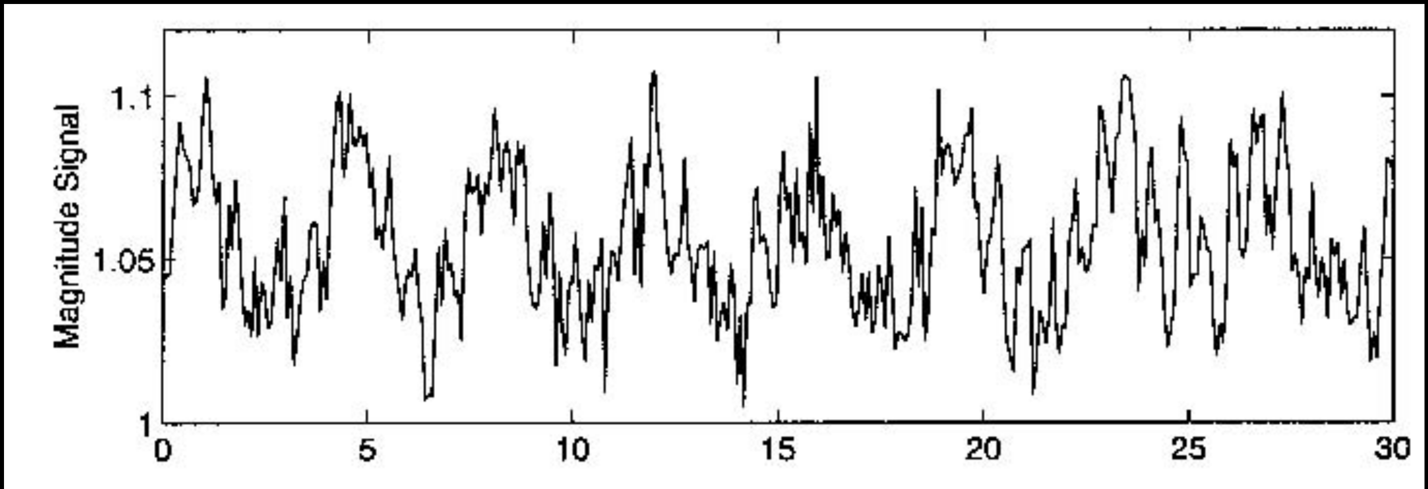
Li et al. Magn. Reson. Med. 36:710 (1996)

courtesy of Douglas Noll

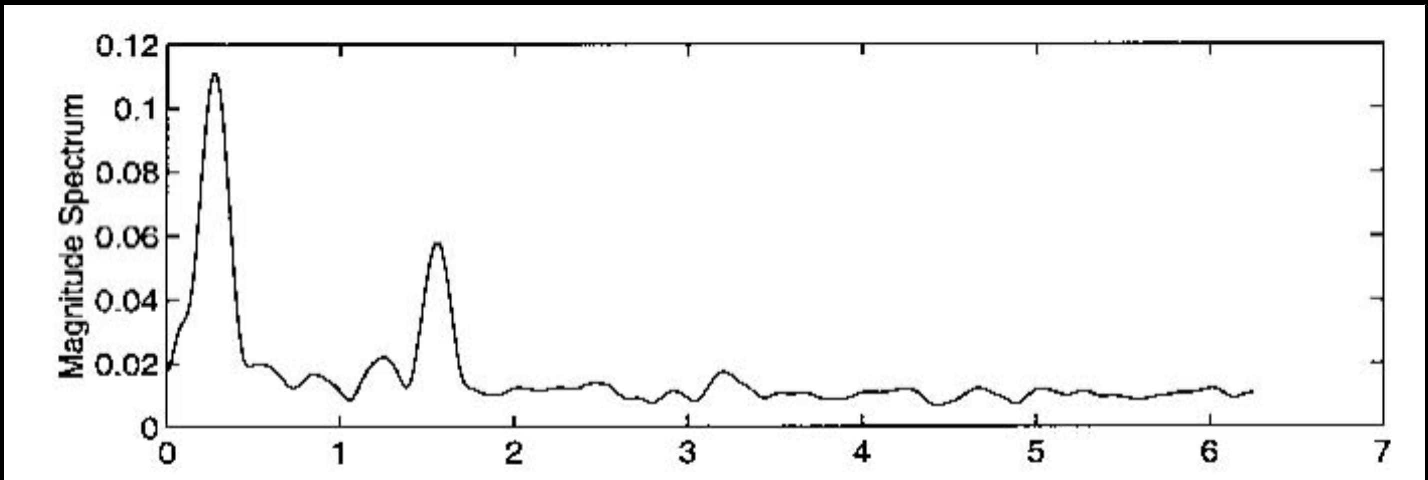
Susceptibility Artifacts

- Local gradients cause:
  - extra dephasing when the gradient occurs through the imaging plane (destructive interference). Result is signal loss.
  - distortion (skewing of the k-space trajectory in different voxels) when the gradient happens in the plane. Signal loss and distortions of the image.
- Solution: this is an active research field, lots of tricks you can do, but they all have an associated cost in time, SNR, computation, hardware..
  - Simplest: design acquisition parameters such that the artifacts are minimized.
  - Z-shimming: apply set of additional gradients
  - Active shims: create additional gradient using materials, coils
  - iterative reconstructions: crunch the numbers

Physiological oscillations



Time domain



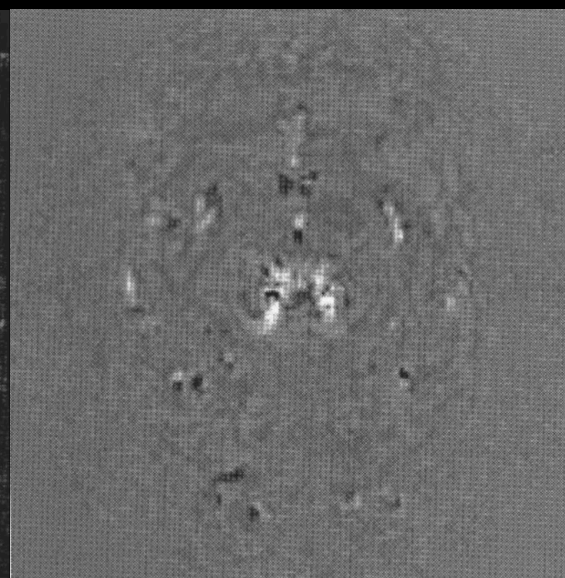
Frequency domain

courtesy of Douglas Noll

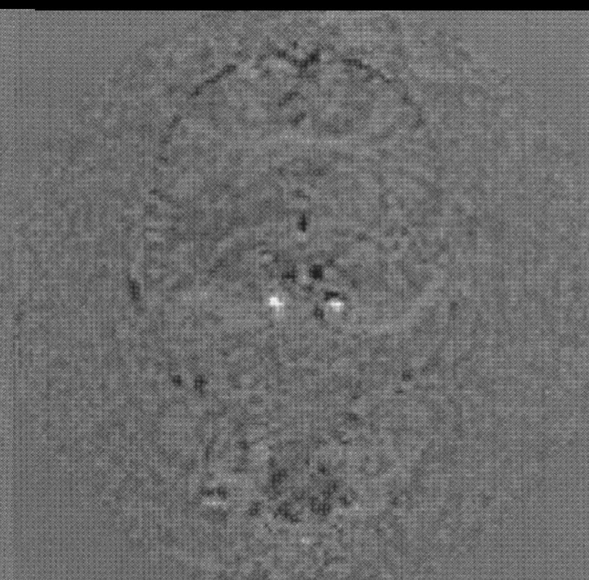
Cardiac and Respiratory Variance

anatomy

Residual Variance w/o Physio correction



Residual Variance w/ Physio correction



courtesy of Douglas Noll

Cardiac Noise

- Blood flow is pulsatile -> changes blood volume, and velocity.
- Other blood flow effects on MR signal:
  - Flow enhancement (incoming spins have not received any RF , fully relaxed -> more signal)
  - Flow void (sometimes spins flow so fast through the plane that they don't see the RF pulse, or they flow out before they can be encoded -> less signal)
  - Flow induced displacement (additional phase acquired because of in-plane movement -> distorted/displaced signal, ghosting)

Reduction of cardiac effects during Acquisition

- Use a smaller flip angle - reduces flow enhancements and voids.
- Use flow "spoilers" to remove vascular signals. (pair of symmetric gradient pulses, a.k.a. "crushers", refocus the signal from stationary spins but not from moving spins.)
- Use fast acquisition (single shot) to reduce ghosting.
- "Cardiac Gating"

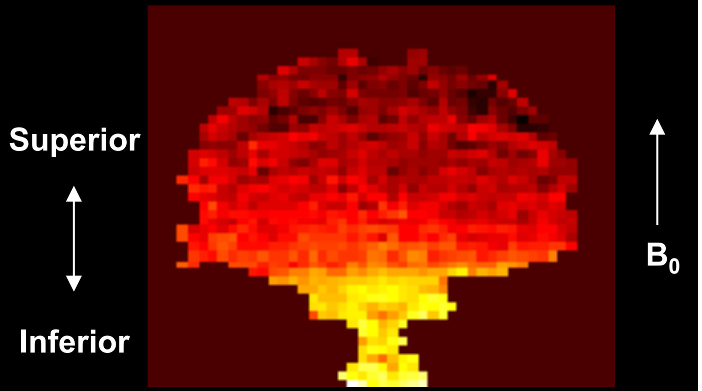
Reduction of cardiac artifacts after acquisition

- Digital Filters …
- Measure cardiac waveform and include in analysis as a confound.
- Note: watch out for aliasing!!
  - heartbeat ~from 0.5-2 Hz, typically ~1 Hz
  - typical Nyquist frequency < 0.5 Hz

Respiration

- Air and Tissue difference in χ :

  Distortion of B_0 field

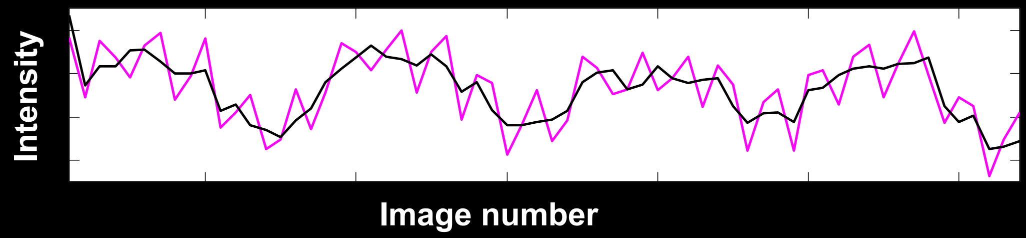


Phase difference between inspiration and expiration for a coronal slice.

- Chest movement changes the shape of the B_0 field. Changes gradients too.
- Resonant frequency changes slightly (Recall that $\omega_0 = \gamma B_0$)
- Blood Pressure changes slightly with respiration (pulsation of arteries and hence blood volume)

Corrections for Respiration

- Fast image acquisition (single shot)
- "Notch" or "band-stop" Filters
- Record Respiratory waveform and use as a confound. (Note- sometimes it's correlated with task of interest)



Timecourse before (purple) and after (black) regression correction.

- Aliasing is not as much of a problem as in cardiac fluctuations, but might still interfere with design
  - Respiration ~ from 0.1 to 0.5 Hz, typically 0.3 Hz
  - BOLD ~ from 0.01 to 0.05 (broad)
  - typical fMRI Nyquist frequency < 0.5 Hz

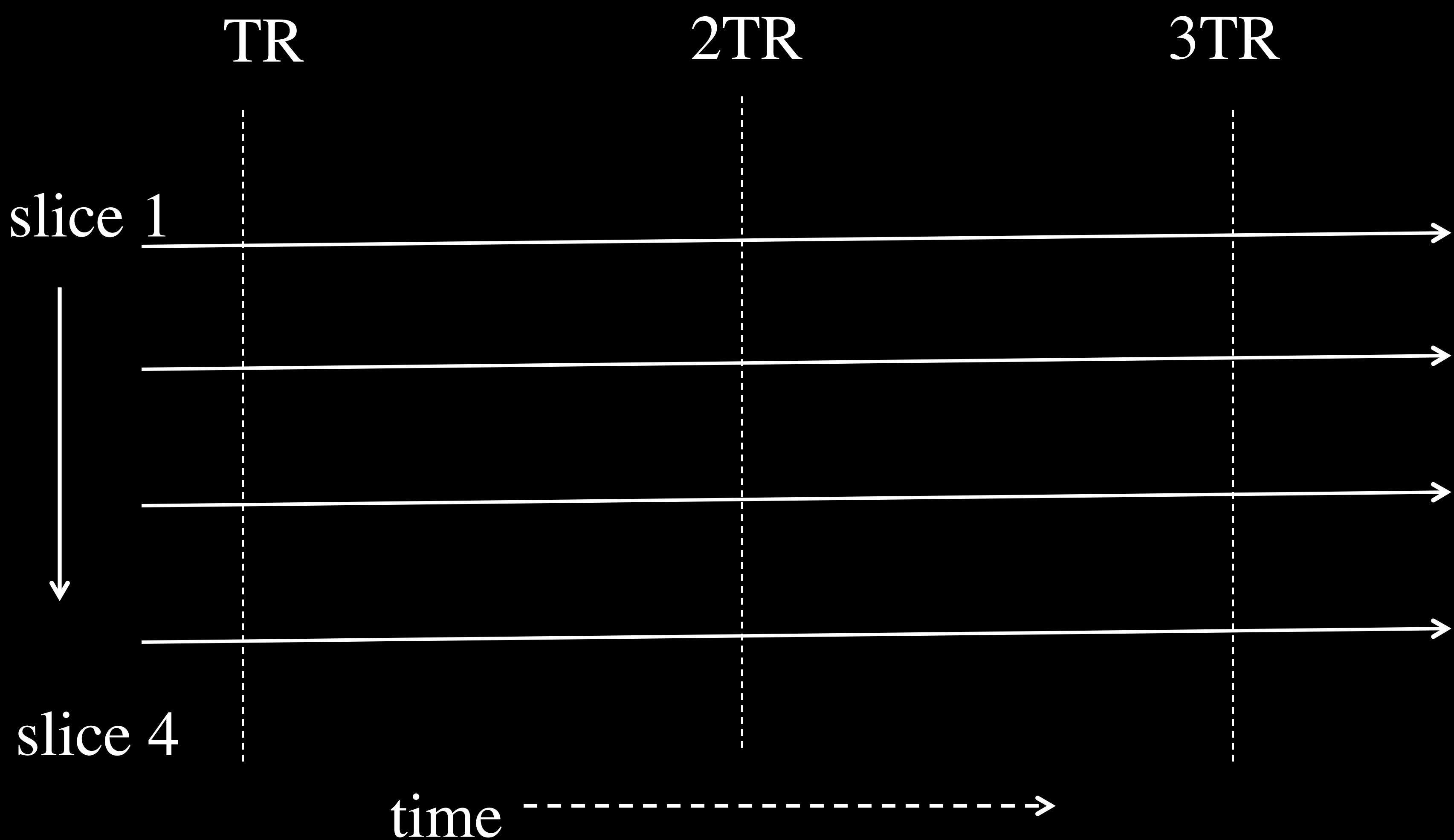
Timing Errors

- MR images are typically collected one slice at a time (exception: 3D imaging)
- The slices can be collected sequentially or interleaved.
- Delay between slice excitations is typically

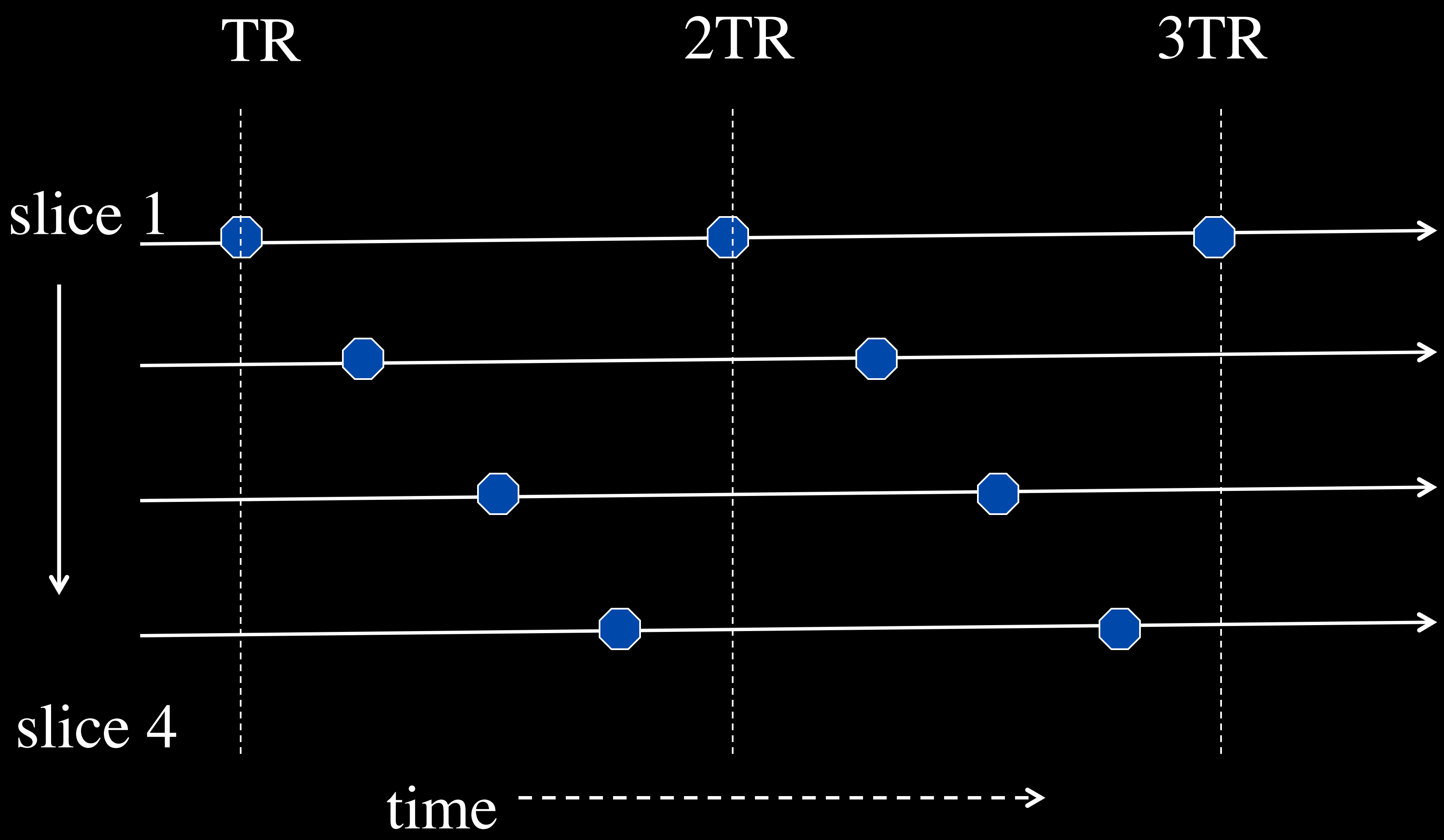
$$TR\ /\ (num.\ slices)$$

- Therefore, the time series are time-shifted differently in each slice

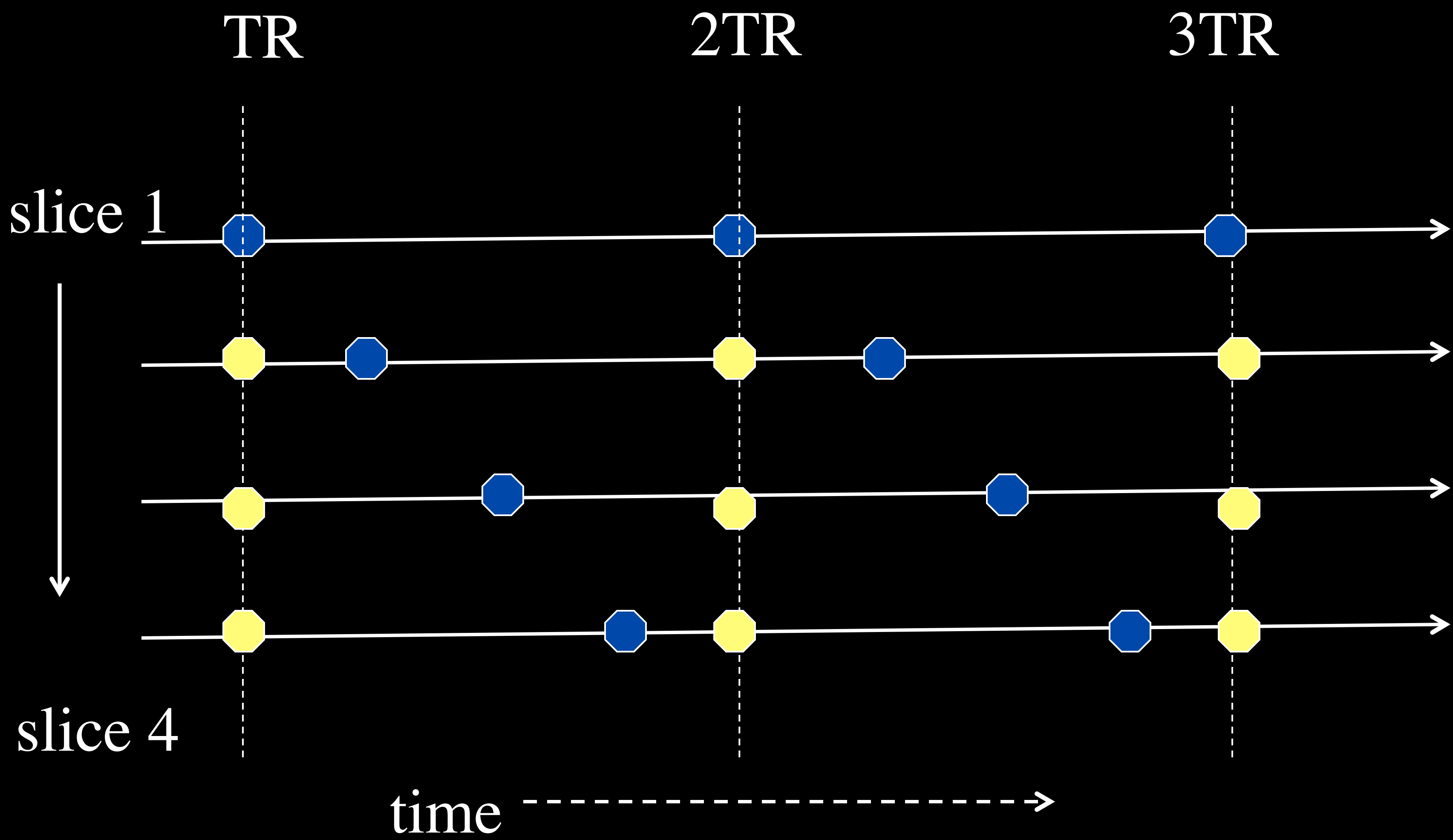
FMRI data "layout"



Acquisition

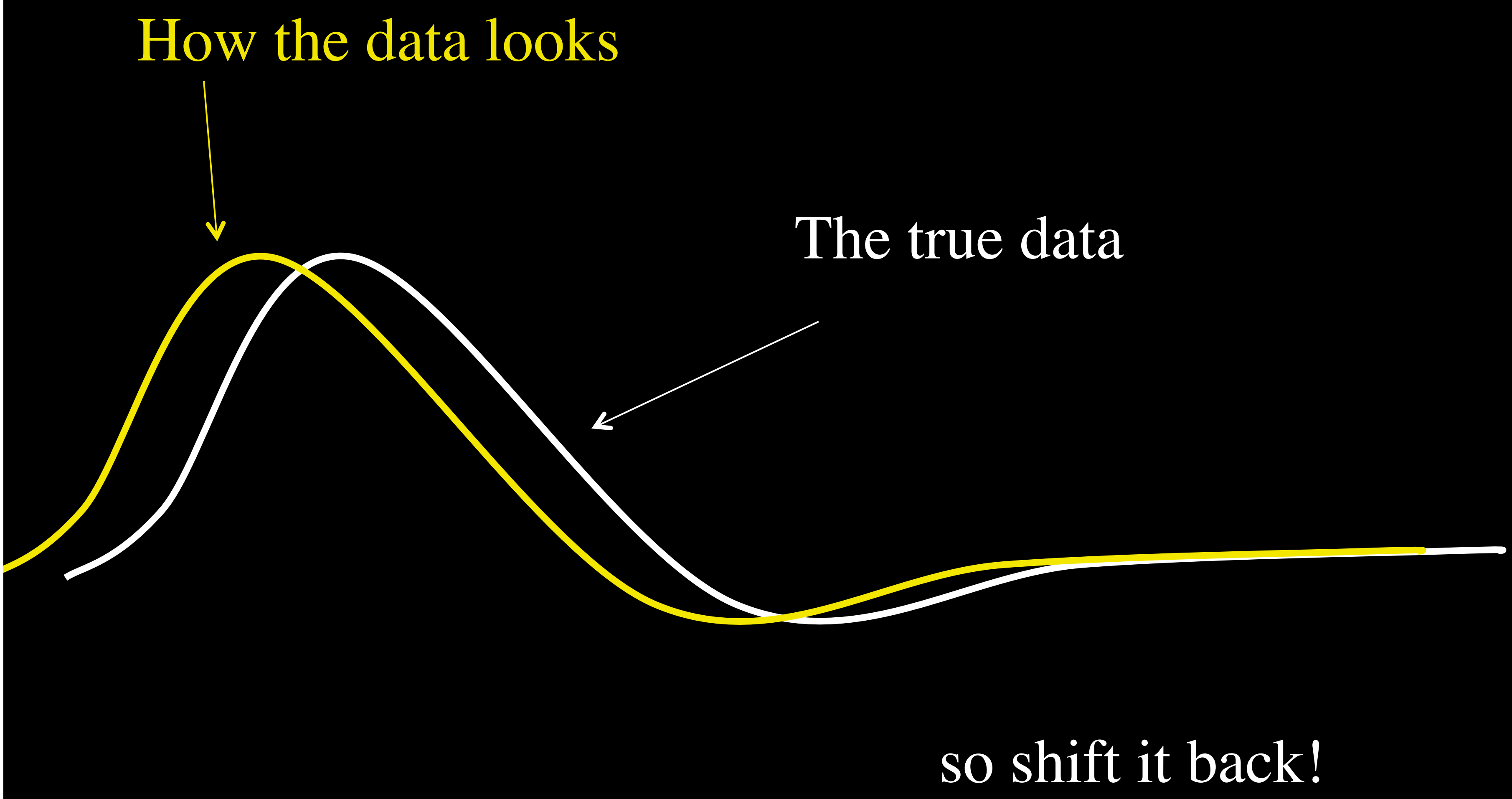


Acquisition

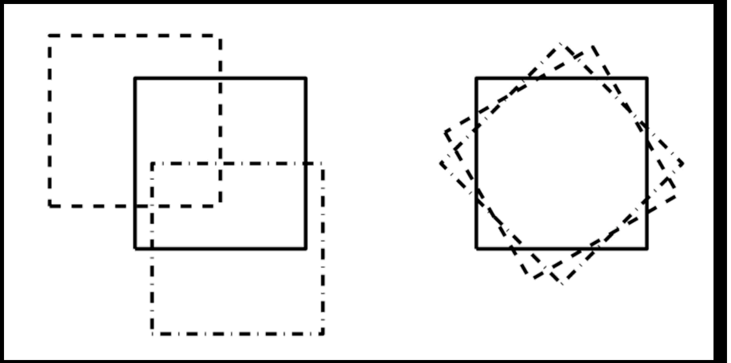


Sampling Error in Time

Sampling Error in Time



Movement



In 2 Dimensions:

- shift from (x_1,y_1) to (x_2,y_2):

$$x_2 = x_1 + \Delta x$$

$$y_2 = y_1 + \Delta y$$

- Rotation from (x_1, y_1) to (x_2,y_2):

$$x_2 = x_1 cos(\theta) + y_1 sin(\theta)$$

$$y_2 = -x_1 sin(\theta) + y_1 cos(\theta)$$

2-D Transformation matrix

- Both Together (note that the order matters)

$$x_2 = x_1 \cos(\theta) + y_1 \sin(\theta) + \Delta x$$

$$y_2 = -x_1 \sin(\theta) + y_1 \cos(\theta) + \Delta y$$

or In Matrix Form …

$$\begin{bmatrix} x_2 \\ y_2 \\ 1 \end{bmatrix} = \begin{pmatrix} \cos(\theta) & \sin(\theta) & \Delta x \\ -\sin(\theta) & \cos(\theta) & \Delta y \\ 0 & 0 & 1 \end{pmatrix} \begin{bmatrix} x_1 \\ y_1 \\ 1 \end{bmatrix}$$

2-D Transformation matrix

$$(x_2, y_2) = \boldsymbol{A}(x_1, y_1)$$

this extends to N-dimensions too

3-D Rotation matrices

$$\begin{pmatrix} \cos(\theta) & \sin(\theta) & 0 & 0 \\ -\sin(\theta) & \cos(\theta) & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

xy plane rotation

$$\begin{pmatrix} \cos(\theta) & 0 & \sin(\theta) & 0 \\ 0 & 1 & 0 & 0 \\ -\sin(\theta) & 0 & \cos(\theta) & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

xz plane rotation

$$\begin{pmatrix} 1 & 0 & 0 & 0 \\ \cos(\theta) & 1 & \sin(\theta) & 0 \\ -\sin(\theta) & 0 & \cos(\theta) & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

yz plane rotation

Estimation of Movement

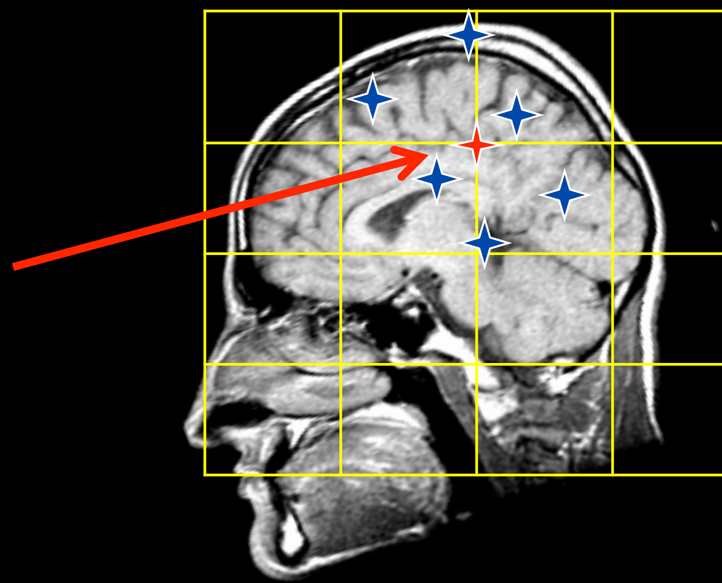
1. Choose a set of translations, rotations
2. Combine the six transformations matrices (linear operators) into one “rigid body” transformation

$$r_2 = A\ r_1$$

3. Resample the images at the new locations
4. Are the two images more alike?
5. Repeat and search for the best matrix **A**

Movement

Interpolate this point from its neighbors



Resampling the image

- Think of realignment as transforming the sampling grid, rather than the image.
- Interpolation:
  - Choose weighting function (kernel):
    - Nearest neighbor
    - bi-linear, tri-linear interpolation
    - sinc interpolation

Comparing images: cost function

- How do you know two images match?

1. Least squares difference

$$\Sigma (I_1 - I_2)^2$$

2. Normalized correlation, correlation ratio

$$\frac{\Sigma(I_1 \; I_2)}{(Var(I_1)\,(Var(I_2)\,)^{1/2}} \qquad \frac{Var(E[I_1 I_2])}{Var(I_2)}$$

3. Mutual information

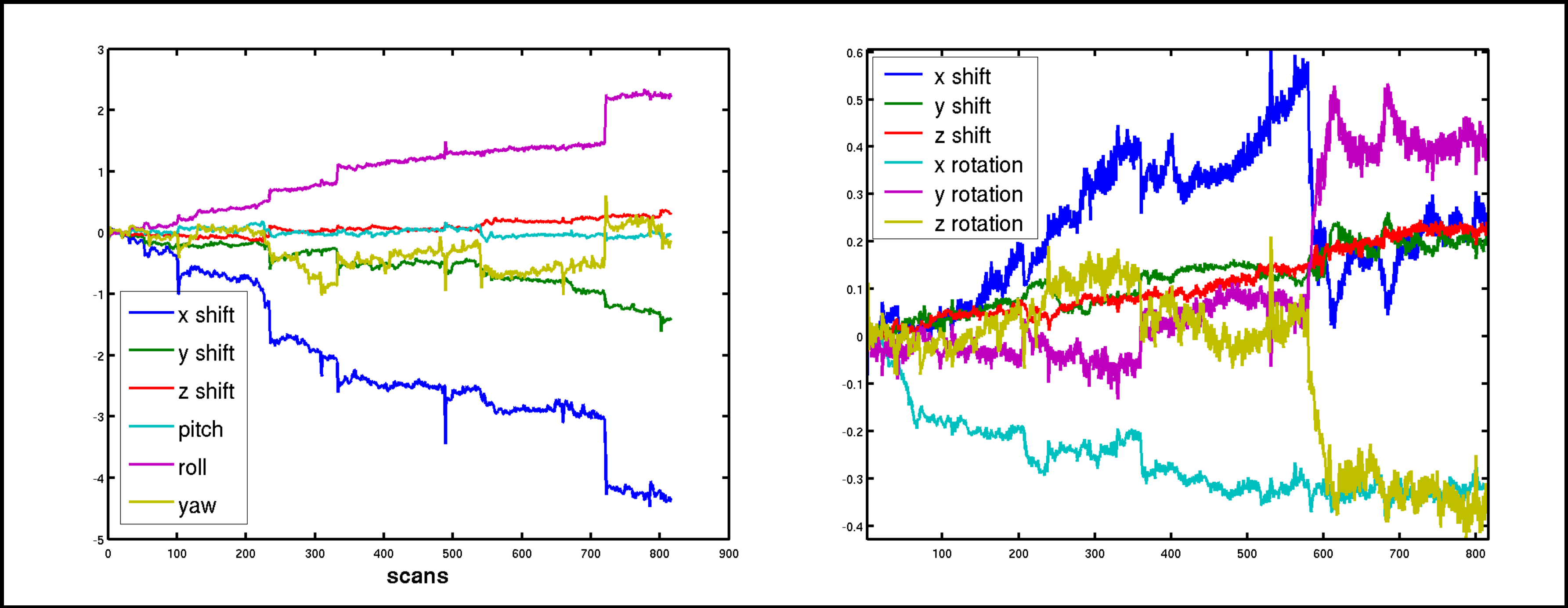
$$M(I_1,I_2) = \sum_{i,j} p(I_1,I_2)\log_2\left(\frac{p(I_1,I_2)}{p(I_1)\,p(I_2)}\right)$$

4. others ….M. Jenkinson and S.M. Smith. Medical Image Analysis, 5(2):143-156, June 2001

Search Strategies

- least squares ($Y=\beta X$) …
- Steepest descent: vary parameters and compute the gradient in the cost function (error). Keep going as long as it gets better.
- There are variations on this theme:
  - simplex
  - Newton's method / gradient descent
  - Adaptive methods
  - others…

Sample Movement Parameters



Movement Noise

- In addition to mixing voxels, you introduce a fluctuation in signal intensity during realignment
- This is a complicated function of the movement:
  - affects the k-space data acquisition
  - mixes partial volumes,
  - interpolation methods also have an effect on intensity.

Movement Noise corrections

- Minimize movement while acquiring data whenever possible !!
- Include movement parameters as confounding regressors.
  - Complicated function, but the signal fluctuation is well correlated with the movement parameters.
  - Including movement regressors will strongly reduce variance.
  - If movement is correlated with task = BIG TROUBLE!

Putting it all together : pre-processing stream