Accelerating Advanced MR Image Reconstruction using GPUs

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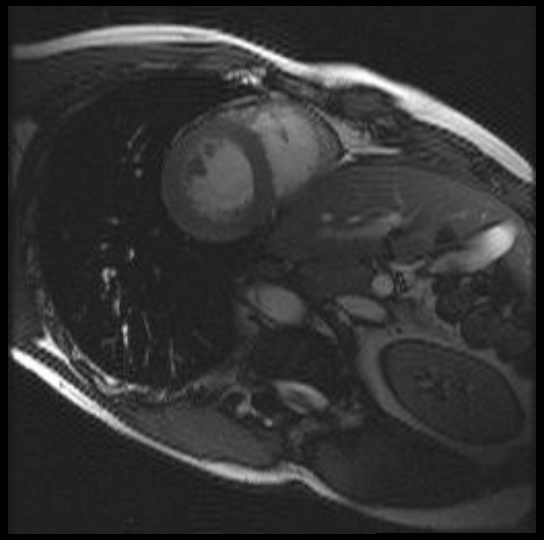
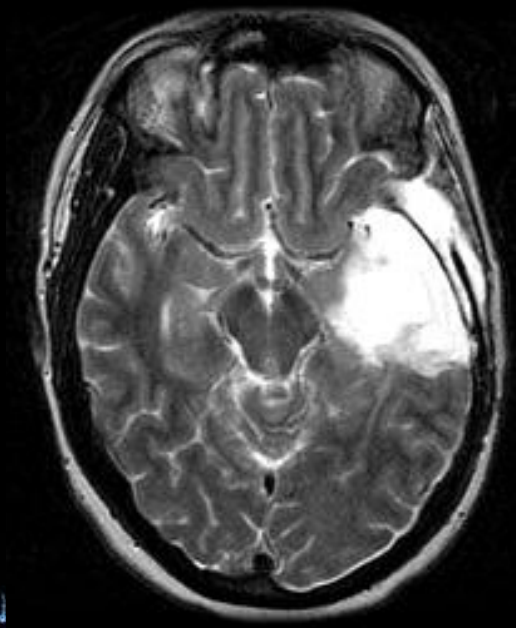
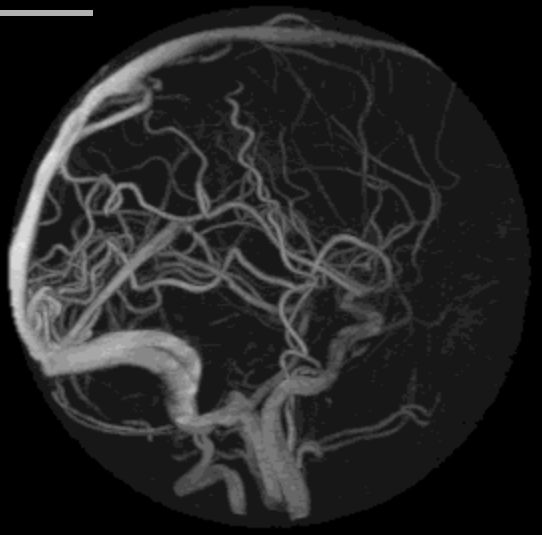
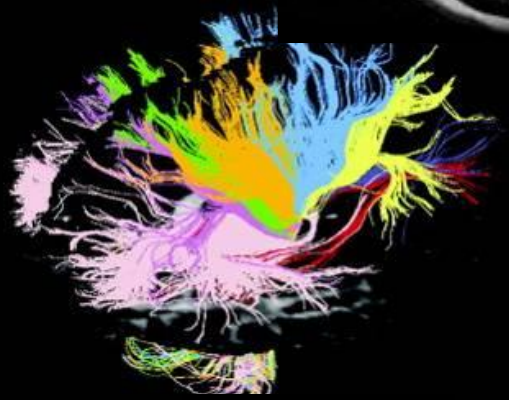
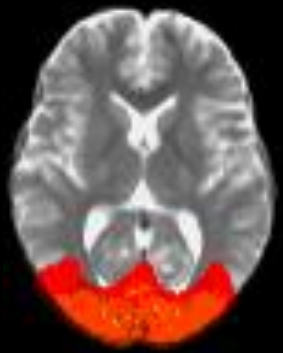
Introduction to MRI

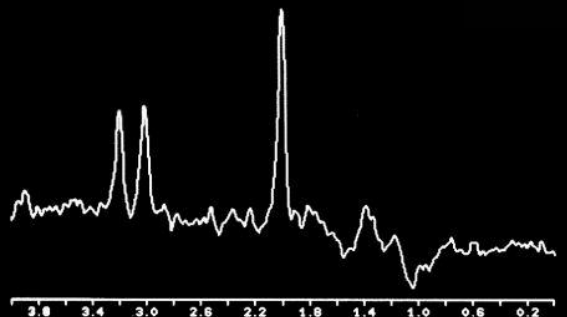


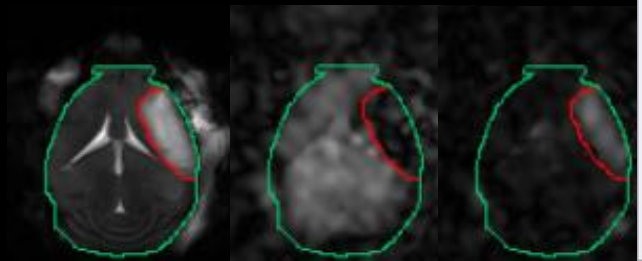


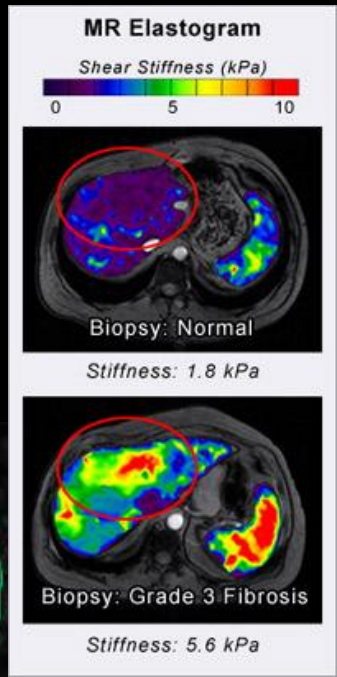












MRI Pipeline

Data Acquisition

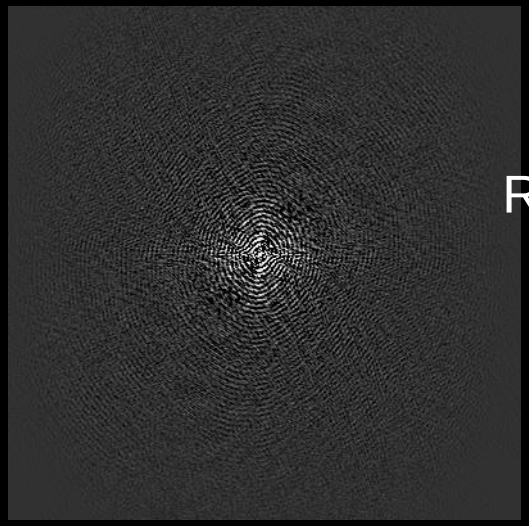
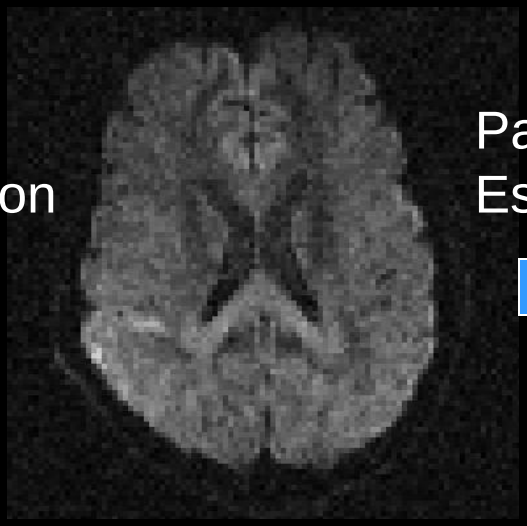
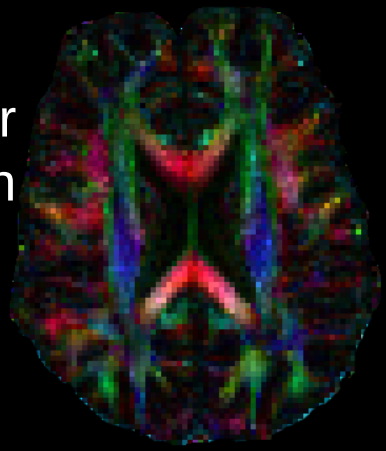


Image Reconstruction



Parameter Estimation



Interpretation

MRI Pipeline

Data Acquisition

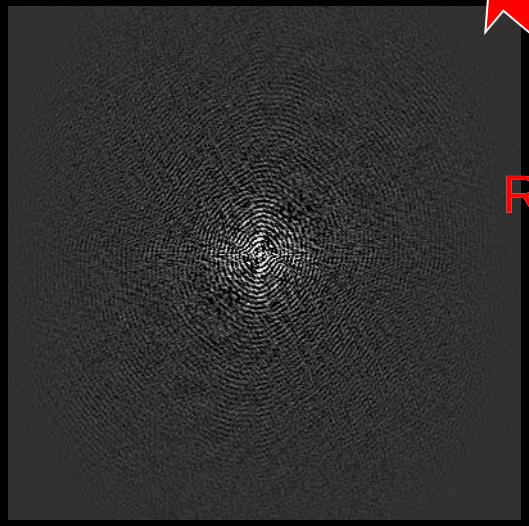
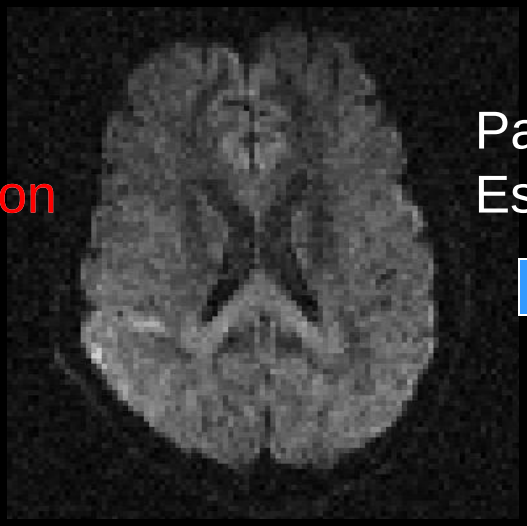


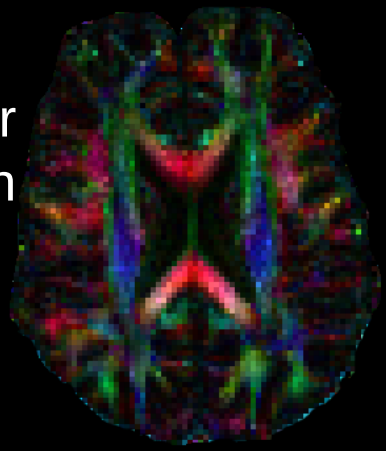
Image Reconstruction

GPU



Parameter Estimation

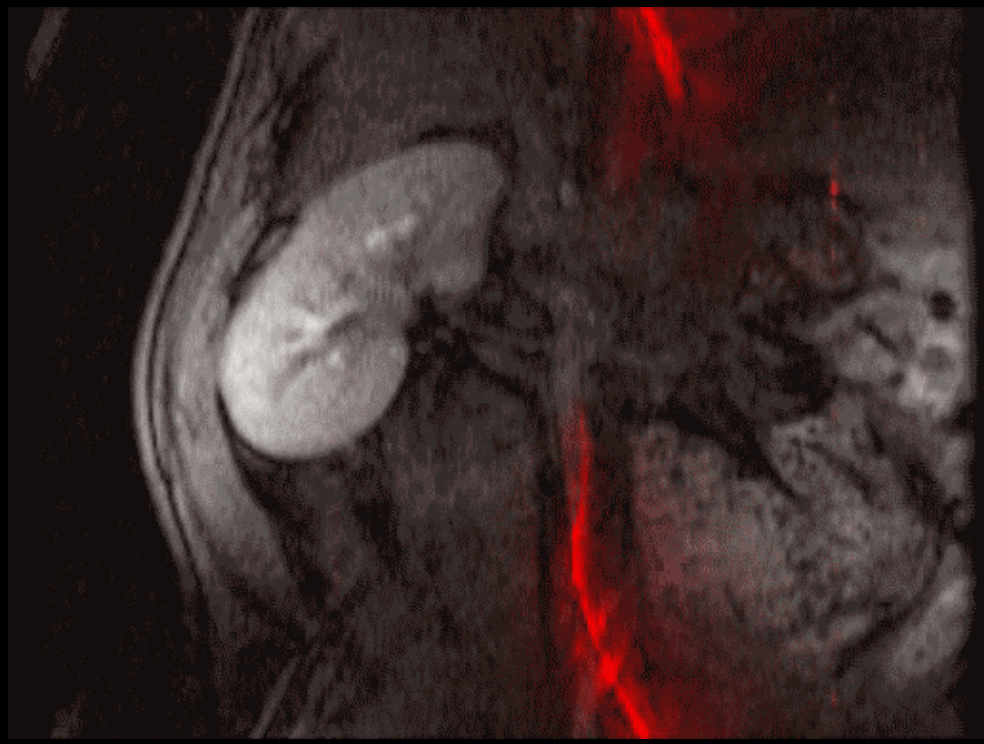
GPU



Interpretation

Faster is better!

Example: Interventional MRI



Real-time reconstruction is necessary to provide feedback to surgeon

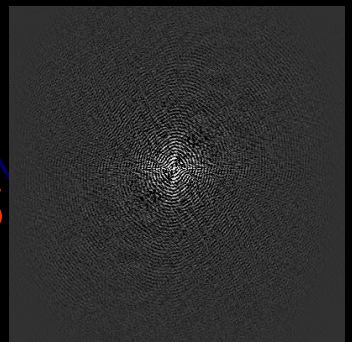
MRI data in Fourier Space

- Ignoring several effects, MRI image and signal are a Fourier transform pair

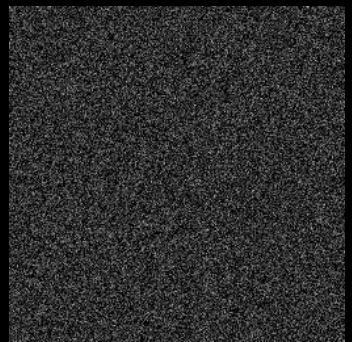
true image

Fourier kernel

data samples



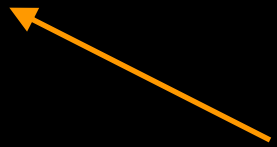
noise



Discretization

- Infinite dimensional variables are inconvenient for computation

Finite dimensional image representation



voxel basis function

Integral equation

Matrix equation

Very Large Matrix Equations

- Typical 2D images: N of ρ =256x256
- Typical 3D images: N of ρ =256x256x256

If thinking in megapixels – this is a low res camera

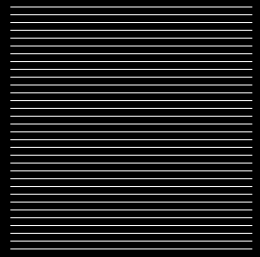
- **F** Matrix entries are complex floats, so storage of matrix (single precision):
  - 2D: dimension of F is $(256X256)^2$ ~ 34 GB
  - 3D: $(256X256X256)^2$ ~ 2 PB

Reconstructing Fourier Data

- Discretized Inverse Fourier Integral
  - Data sampled on a rectilinear grid

7X-10X speedup

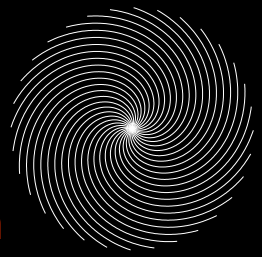
FFT Reconstruction



  - Noncartesian data

28X speedup

Conjugate Phase Reconstruction



6X speedup

Gridding Reconstruction

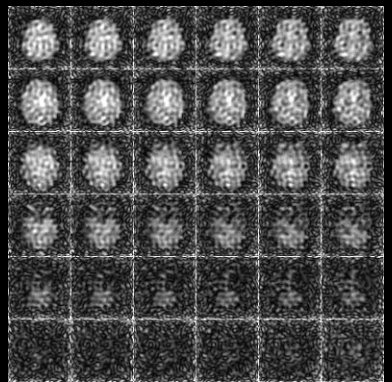
- Regularized Inverse Problem

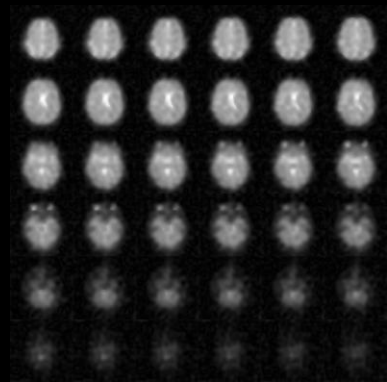
Solutions often derived by solving one or more matrix inversions, e.g.,

11X speedup

Toeplitz Structure

Often sparse

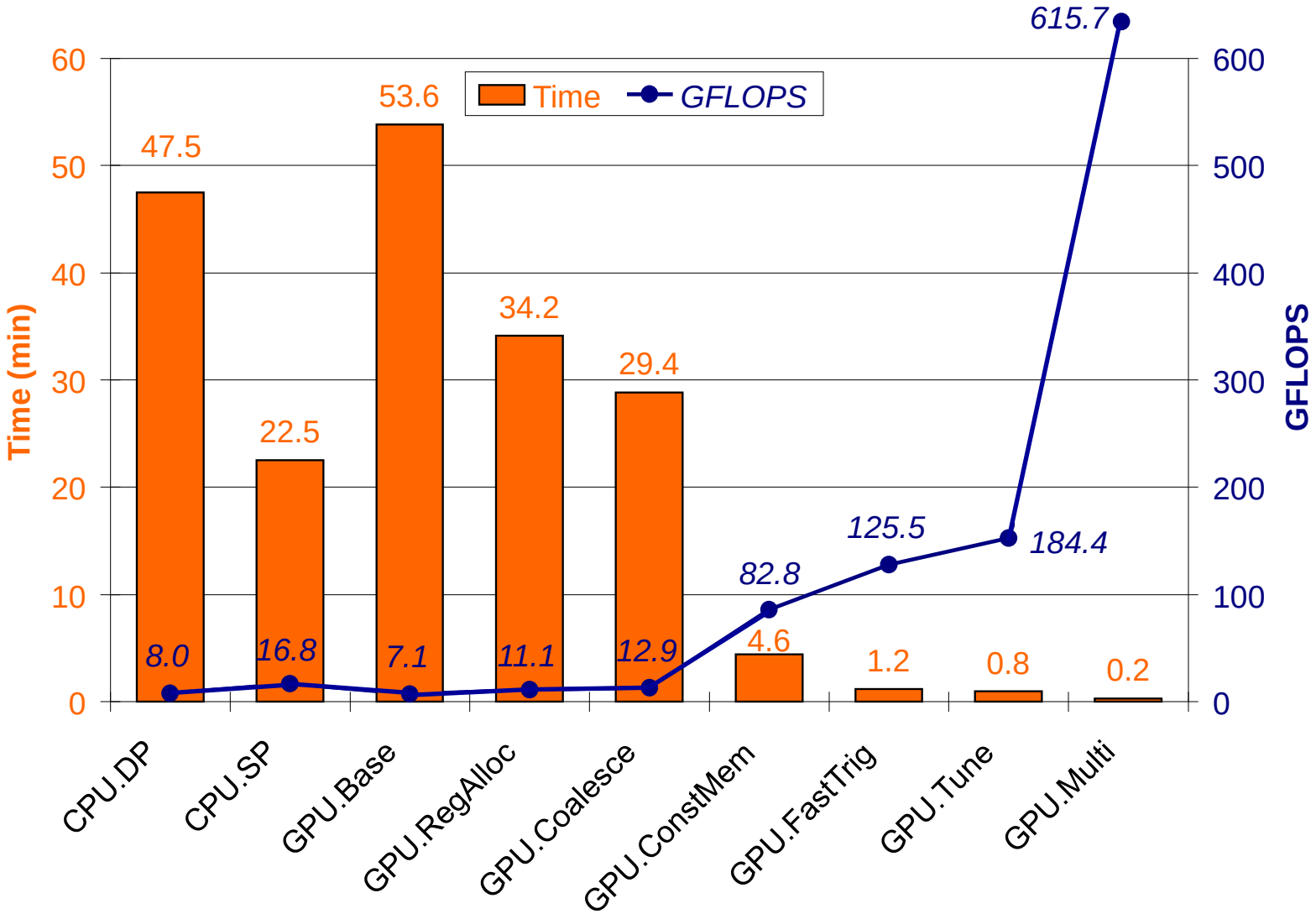




$F^H d$

- F – *M* x *N* matrix
  - Typical *M* and *N* range from 2^{14}-2^{24} (higher in certain applications)
- Ordinary matrix-vector multiplication
  - Complexity *O*(*MN*)
  - Easily parallelized
  - Matrix entries can be calculated on the fly
    - Lots of trigonometric function evaluations
- 28x speedup over CPU, 180 GFLOPs

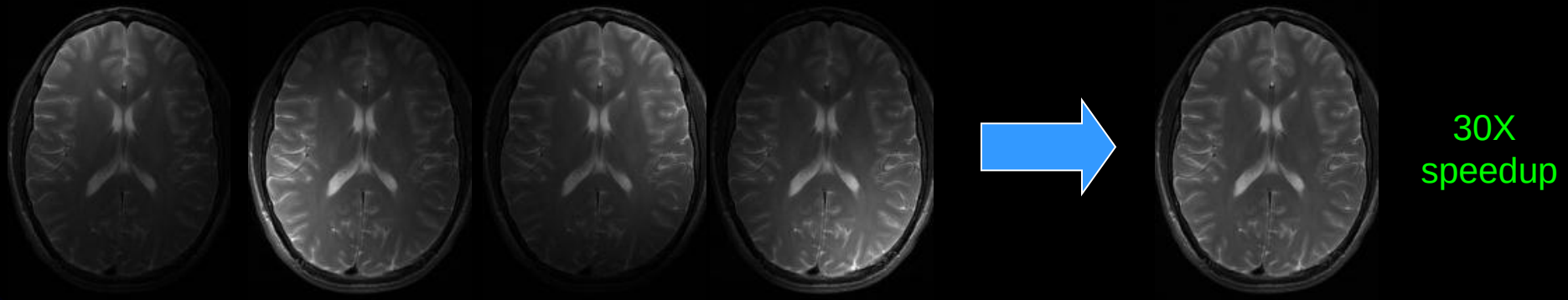
Summary of F^Hd Results



S. Stone *et al., J Parallel Distrib Comput* 68:1307-1318, 2008.

Non-Fourier MR Reconstruction

- Parallel Imaging
  - Data acquired with multiple spatially diverse sensors



- Field inhomogeneity correction

Summary

- Common MRI computations have been accelerated by orders-of-magnitude using GPUs
  - Enables more practical use of advanced reconstruction algorithms to reduce scan time/image artifacts
  - Key primitives: 3D convolution, 3-D histogram, sparse/Toeplitz matrix-vector multiplication, sparse CG solver, (I) FFT
- Current challenge: To develop a common, modular framework for GPU reconstruction of MR data (and other imaging modalities)
  - Single framework for multi-core CPUs and many-core GPUs
  - Automatic tuning and selection for each primitive
- Future work:
  - Continued optimization, scaling of reconstruction algorithms
  - GPU implementation of MR parameter estimation
  - Support for integration into production MRI pipelines

Further Reading

Journal

- S. S. Stone, *et al*. "Accelerating Advanced MRI Reconstructions on GPUs." *Journal of Parallel and Distributed Computing* 68:1307-1318, 2008.

Conferences

- W.-m. W. Hwu, *et al.* "Accelerating MR Image Reconstruction on GPUs." *Proc IEEE ISBI*, Boston, 2009, pp. 1283-1286.
- S. S. Stone, *et al*. "Accelerating Advanced MRI Reconstructions on GPUs." *Proc ACM Computing Frontiers*, Ischia, 2008, pp. 261-272.
- J. P. Haldar, *et al*. "Fast MR Image Reconstruction using Graphics Processing Units." *Proc ISMRM*, Toronto, 2008, p. 1493.
- S. S. Stone, *et al*. "How GPUs Can Improve the Quality of Magnetic Resonance Imaging." *Proc GPGPU*, Boston, 2007.