Direct Volume Rendering with Multi-Dimensional Transfer Functions -- and -- Diffusion Tensor Visualization with Glyphs and Tractography

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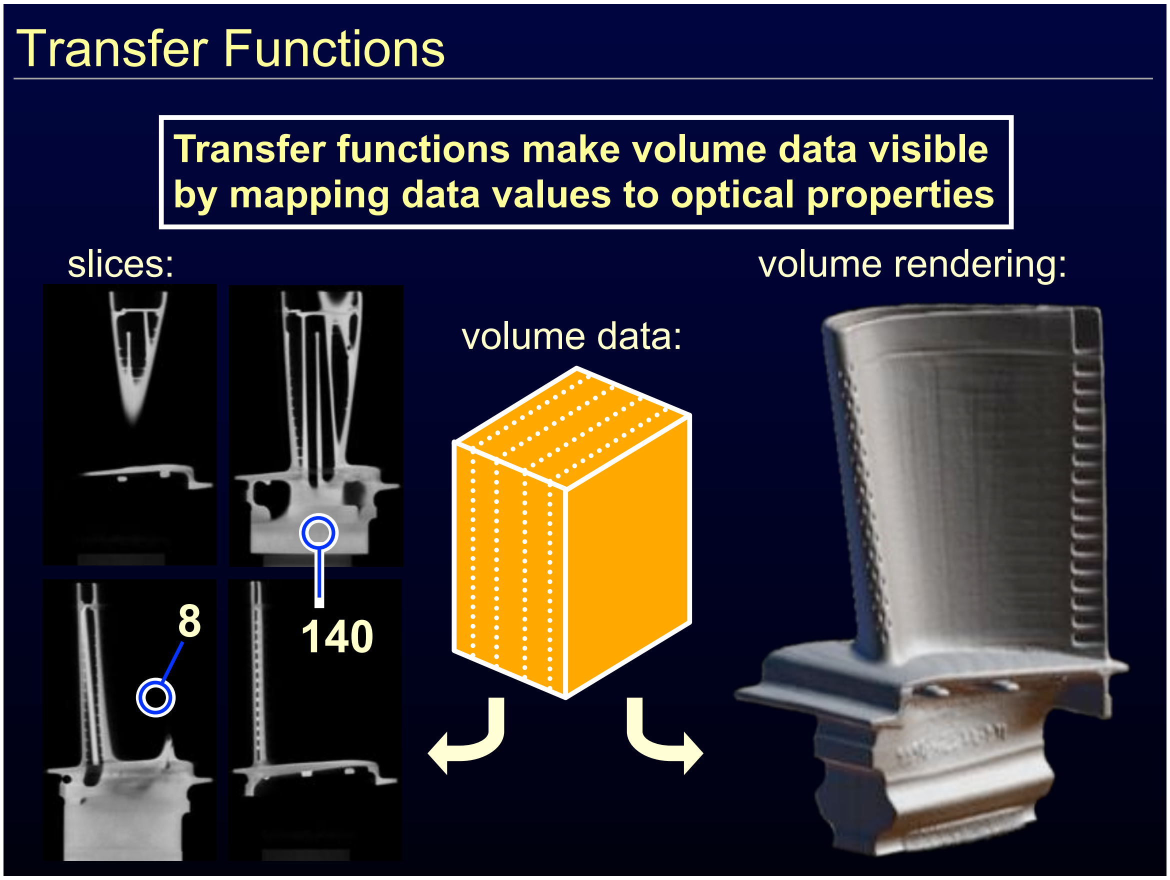
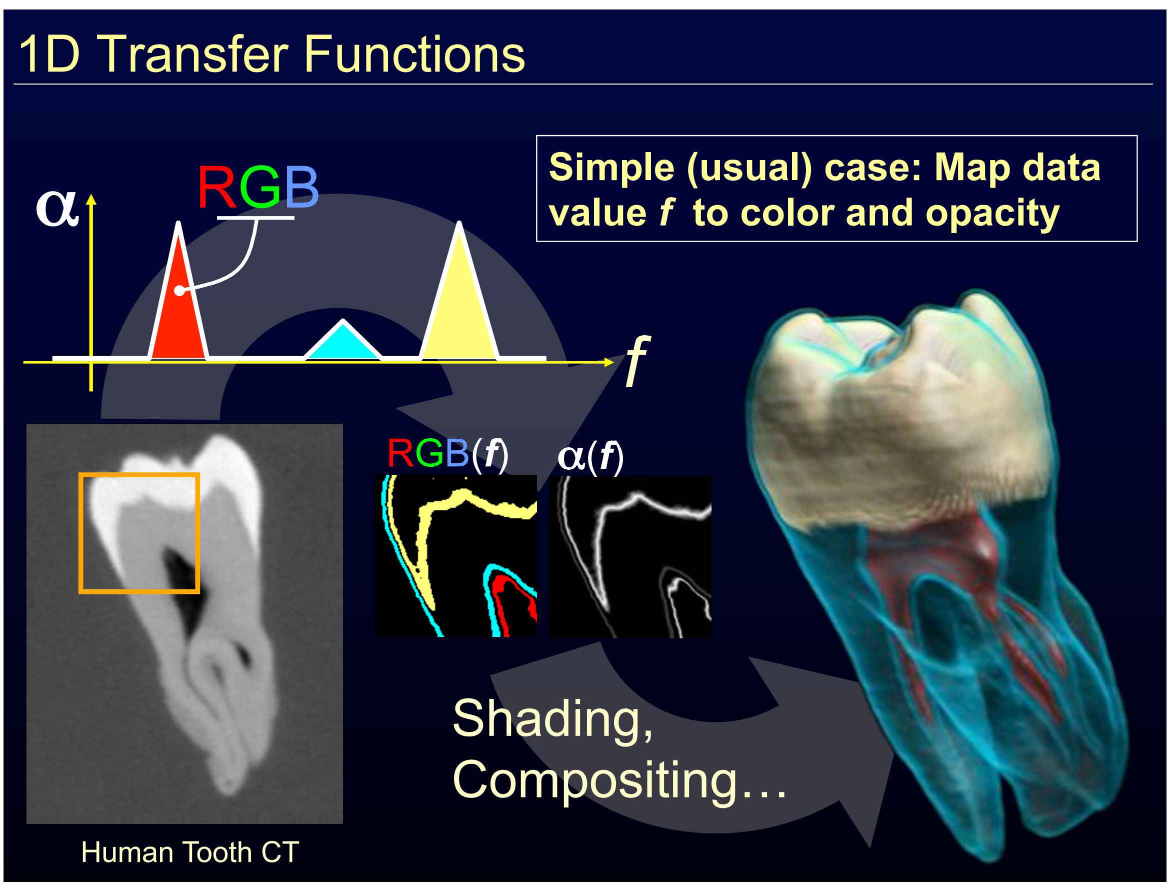
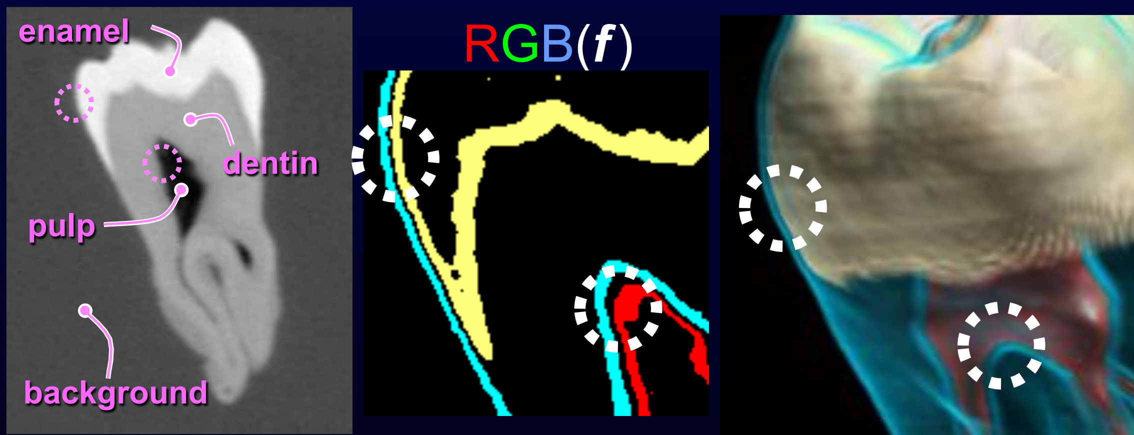
Outline

1. Volume Rendering and Transfer Functions
   - Multi-dimensional
   - Curvature-based transfer functions
   - Filtering for derivatives
   - Results and applications
2. Diffusion Tensor MRI
   - Neuroanatomy 101
   - Data acquisition
   - Tensor Shape and Orientation
   - Glyphs
   - Tractography
3. Reproducibility


Transfer Functions
Transfer functions make volume data visible by mapping data values to optical properties
slices:
volume rendering:
volume data:
8
140


1D Transfer Functions
Simple (usual) case: Map data value f to color and opacity
α
RGB
f
RGB(f)
α(f)
Shading,
Compositing…
Human Tooth CT

1D Transfer Functions: limitation



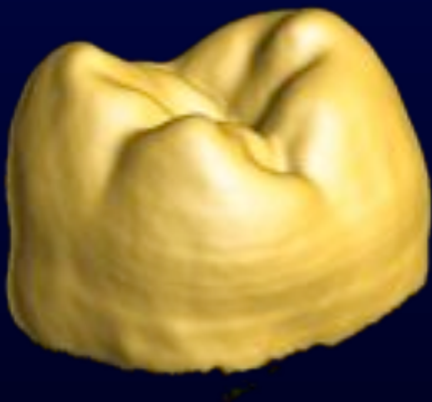
Slice | 1D TF output | Rendering

1D transfer functions can not accurately capture all material boundaries

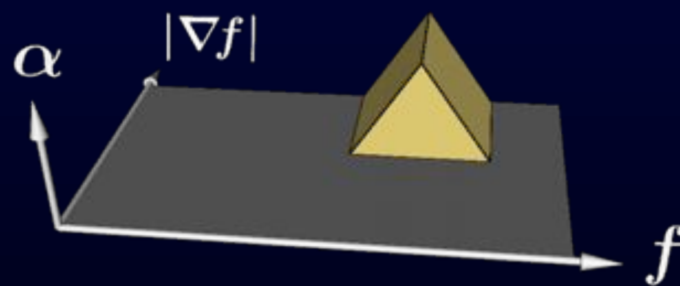
1D → 2D Transfer Function

$$\left.\begin{array}{r} RGB(f) \\ \alpha(f) \end{array}\right\} \text{Generalize…}$$

2D Transfer Function



$$RGB(f, |\nabla f|)$$
$$\alpha(f, |\nabla f|)$$

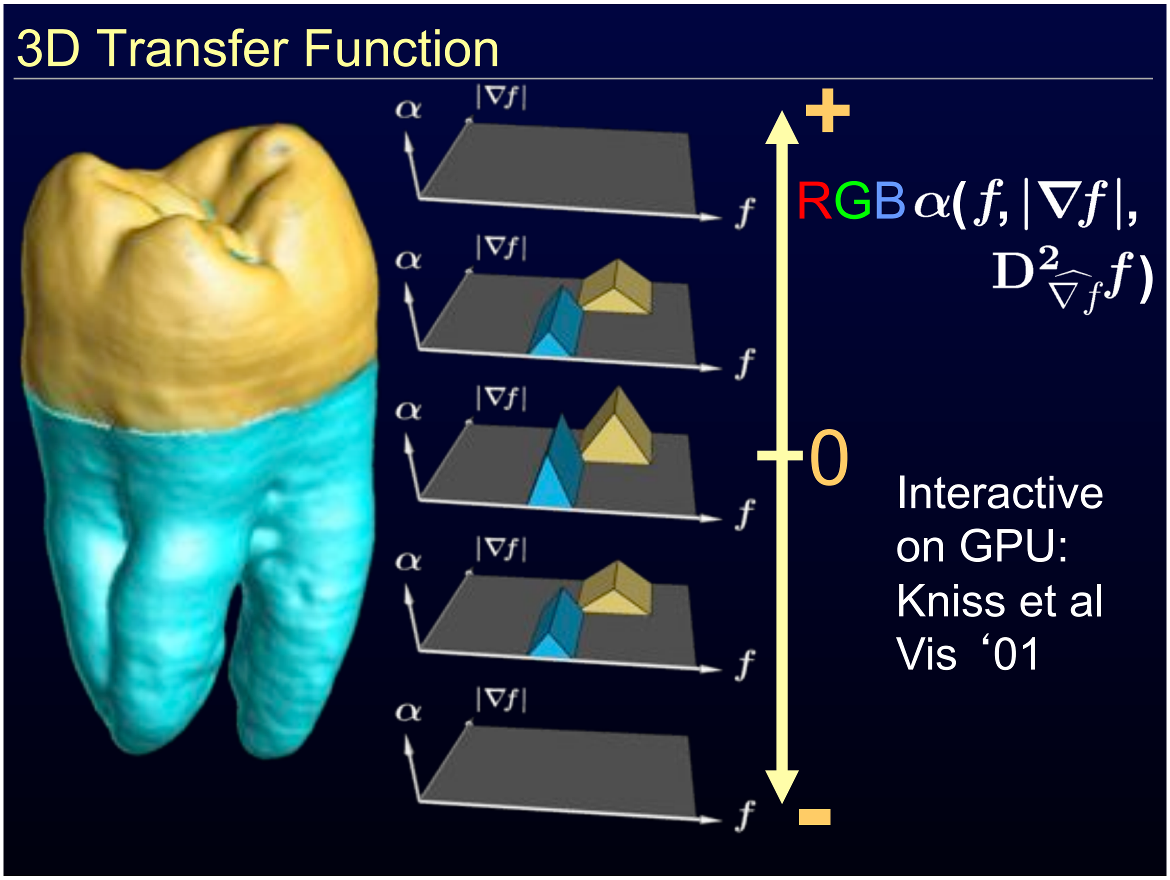


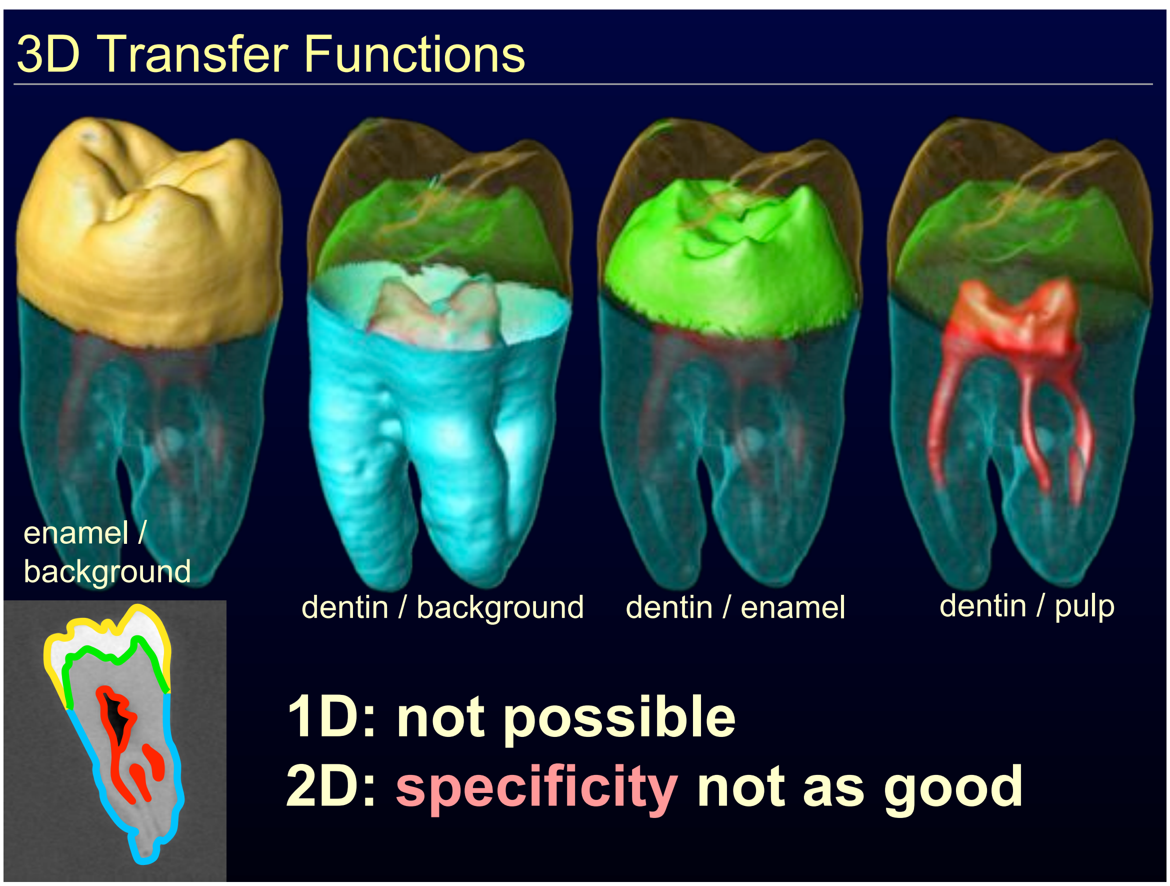
2D transfer functions give greater flexibility in boundary visualization

Display of Surfaces from Volume Data, Levoy 1988

2D Transfer Functions

Kindlmann et al 1998

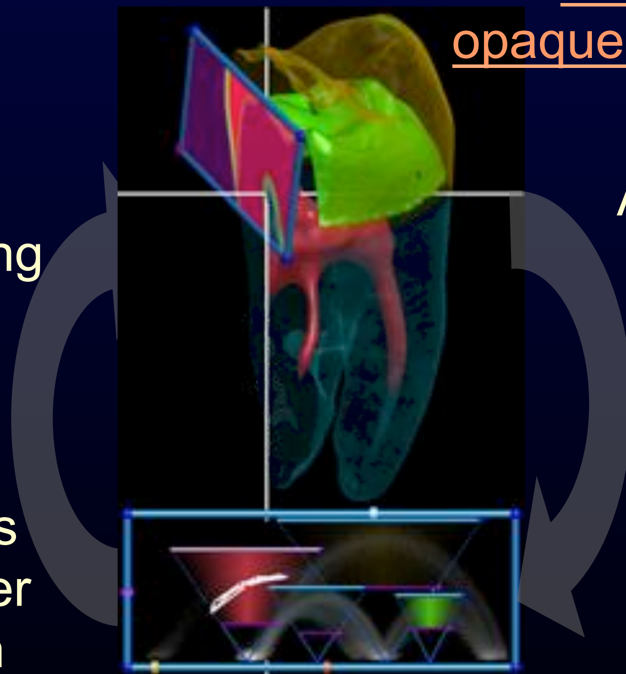

3D Transfer Function
α
|∇f|
f
+
RGB α(f, |∇f|, D²∇̂f f)
0
Interactive on GPU: Kniss et al Vis '01
-


3D Transfer Functions
enamel / background
dentin / background
dentin / enamel
dentin / pulp
1D: not possible
2D: specificity not as good

Interactivity

Dual-domain interaction

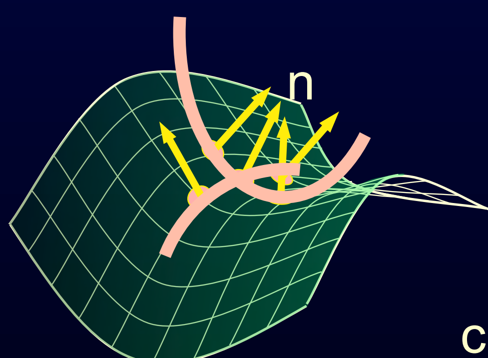
[Make features opaque by pointing at them]

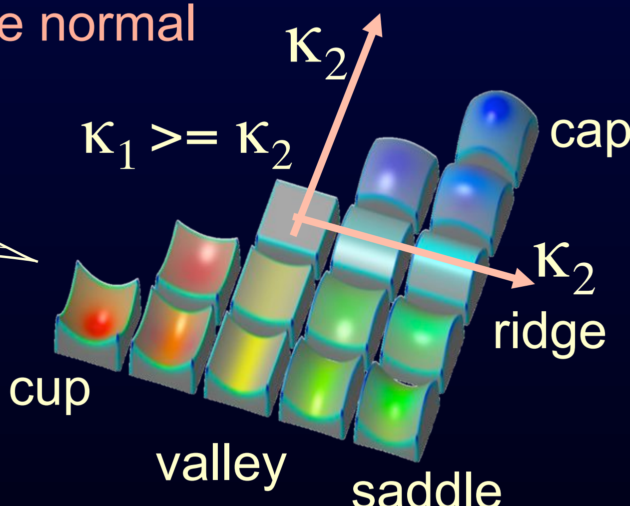


Curvature in Transfer Functions

Curvature: Small movements along the surface

$\Rightarrow$ change in surface normal



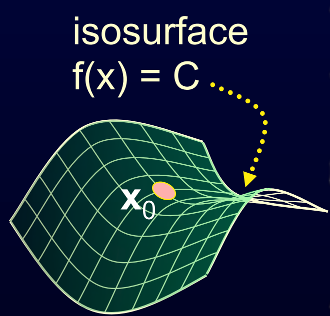


Principal curvature magnitudes

Principal curvature directions

Curvature measurement

Taylor expansion of scalar field f:



$$f(\mathbf{x}_0 + \mathbf{d}) \approx$$
$$f(\mathbf{x}_0) + \mathbf{d}\cdot\mathbf{g}(\mathbf{x}_0) + \mathbf{d}^T\mathbf{H}(\mathbf{x}_0)\mathbf{d}/2$$

$$\mathbf{g} = \nabla f = \begin{bmatrix} \partial f/\partial x \\ \partial f/\partial y \\ \partial f/\partial z \end{bmatrix}$$

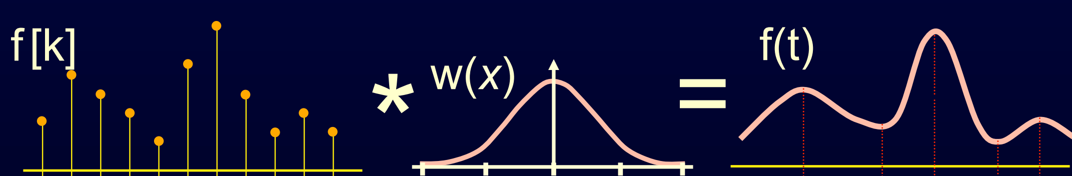
$$\mathbf{H} = \begin{bmatrix} \partial^2 f/\partial x^2 & \partial^2 f/\partial x\partial y & \partial^2 f/\partial x\partial z \\ \partial^2 f/\partial x\partial y & \partial^2 f/\partial y^2 & \partial^2 f/\partial y\partial z \\ \partial^2 f/\partial x\partial z & \partial^2 f/\partial y\partial z & \partial^2 f/\partial z^2 \end{bmatrix}$$

$$\mathbf{g}(\mathbf{x}_0 + \mathbf{d}) \approx \mathbf{g}(\mathbf{x}_0) + \mathbf{H}(\mathbf{x}_0)\mathbf{d}$$

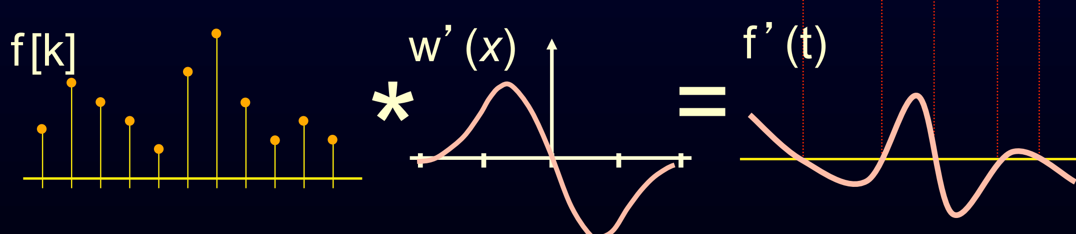
$\Rightarrow$ Hessian is basis of curvature

Convolution, derivatives

Continuous data values come from convolution with continuous reconstruction filters



How to differentiate: convolve with derivative of reconstruction filter



Multi-dimensional filter

3-D filter: separable product of 1-D filters:

$\mathbf{W}(x,y,z) = w(x)\, w(y)\, w(z)$

$d\,\mathbf{W}/dx = w'(x)\, w(y)\, w(z)$ ← for measuring gradient

$d^2\,\mathbf{W}/dxdy = w'(x)\, w'(y)\, w(z)$
$d^2\,\mathbf{W}/dx^2 = w''(x)\, w(y)\, w(z)$ } ← for measuring Hessian

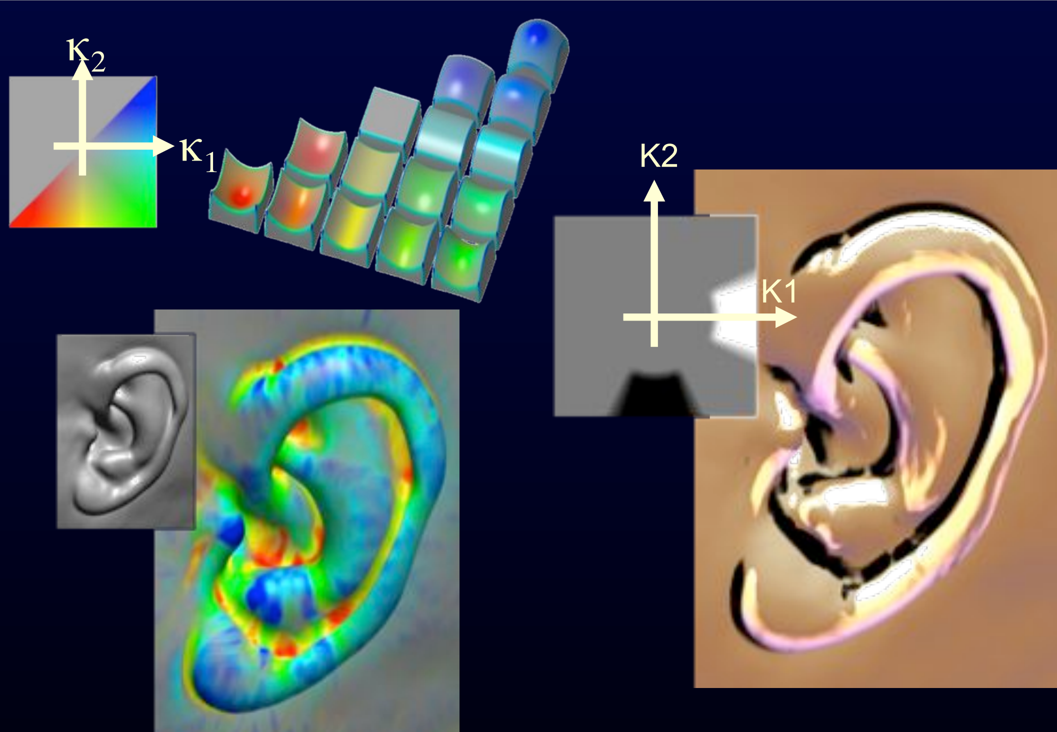
Combination of 1-D filters for 3-D partial derivative

No pre-computation or storage overhead

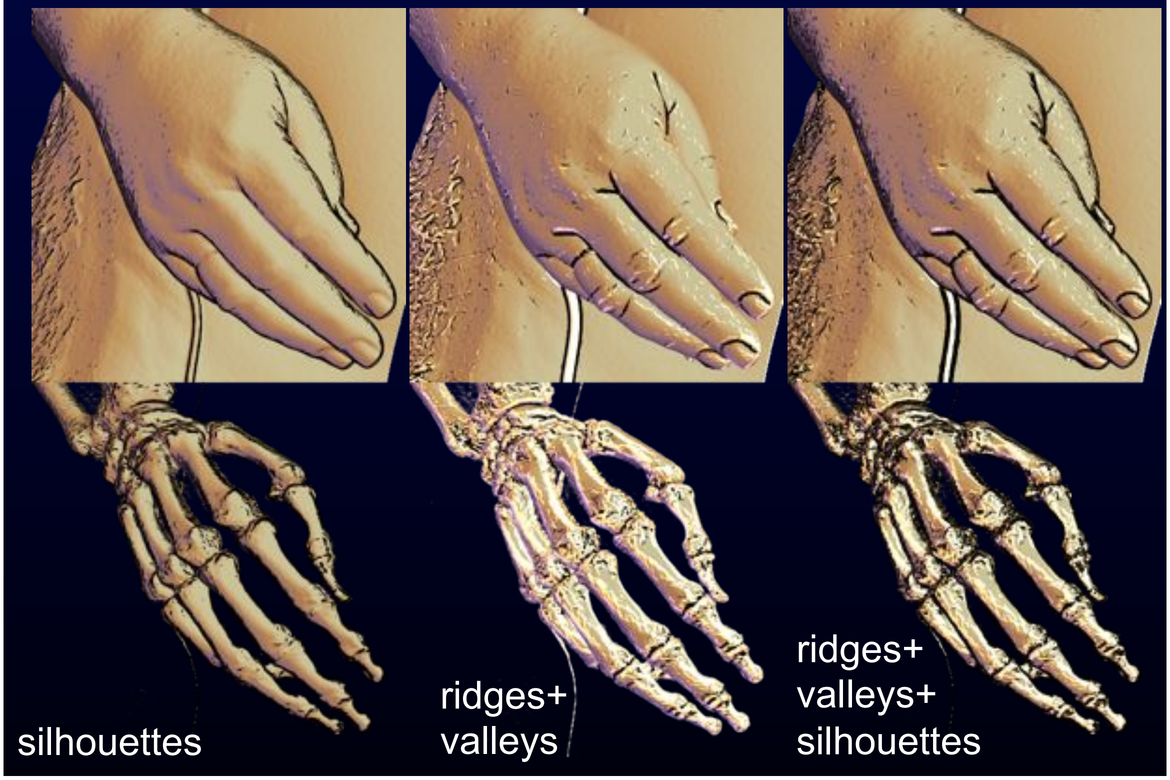
See Kindlmann et al IEEE Vis 2003 for details

Local measurements can now be done on GPU

Ridge and Valley Emphasis



Visible Human, Female Frozen CT



Visible Human, Male Frozen CT

Visible Human, Male Frozen CT

(Movie)

Software: “gage”, “mite”, “nrrd” libraries in Teem (http://teem.sf.net)

SIGGRAPH 2005 Course 31: Computer-Generated Medical, Technical, and Scientific Illustration

Now interactive on GPUs:
Real-Time Ray-Casting and Advanced Shading of Discrete Isosurfaces
Hadwiger et al, Eurographics 2005

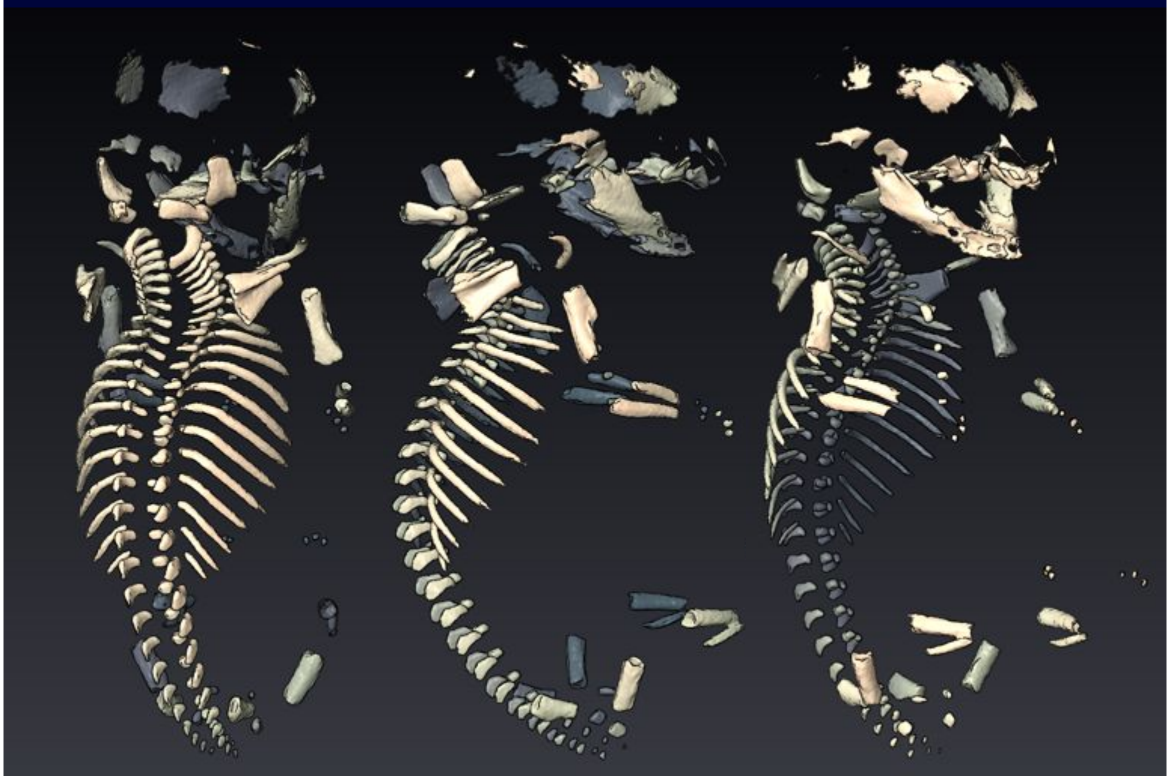
Application: Mouse embryo bone growth

- Studying mutations with phenotypical bone deformations
- Standard technique requires intensive manual staining
- Don’t need 3D model: want shapes and relationships
  “Science without segmentation”

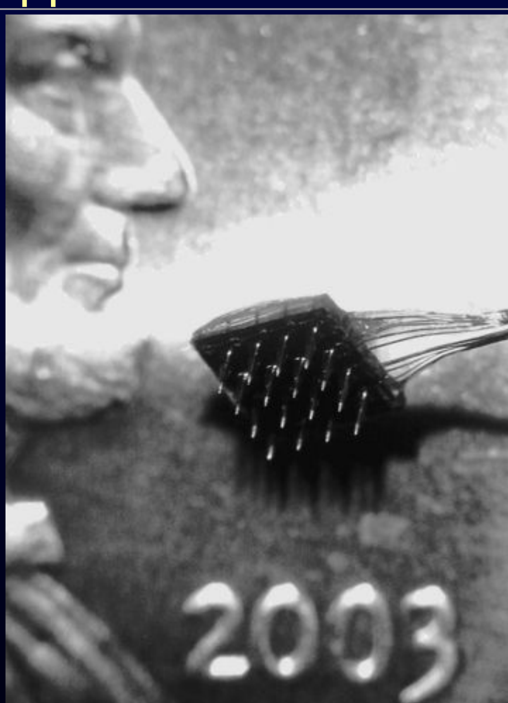
Basic isosurface | Curvature-based silhouettes | With depth cueing

Kindlmann et al 2004

Application: Mouse embryo bone growth



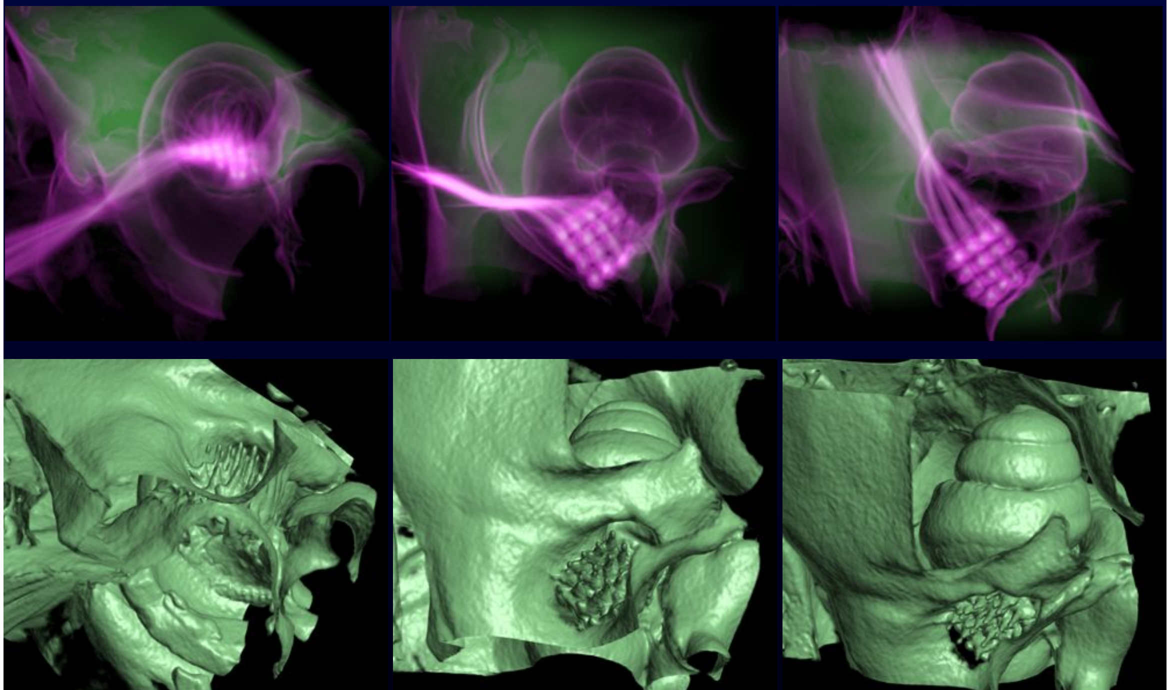
Application: electrode array surgery analysis



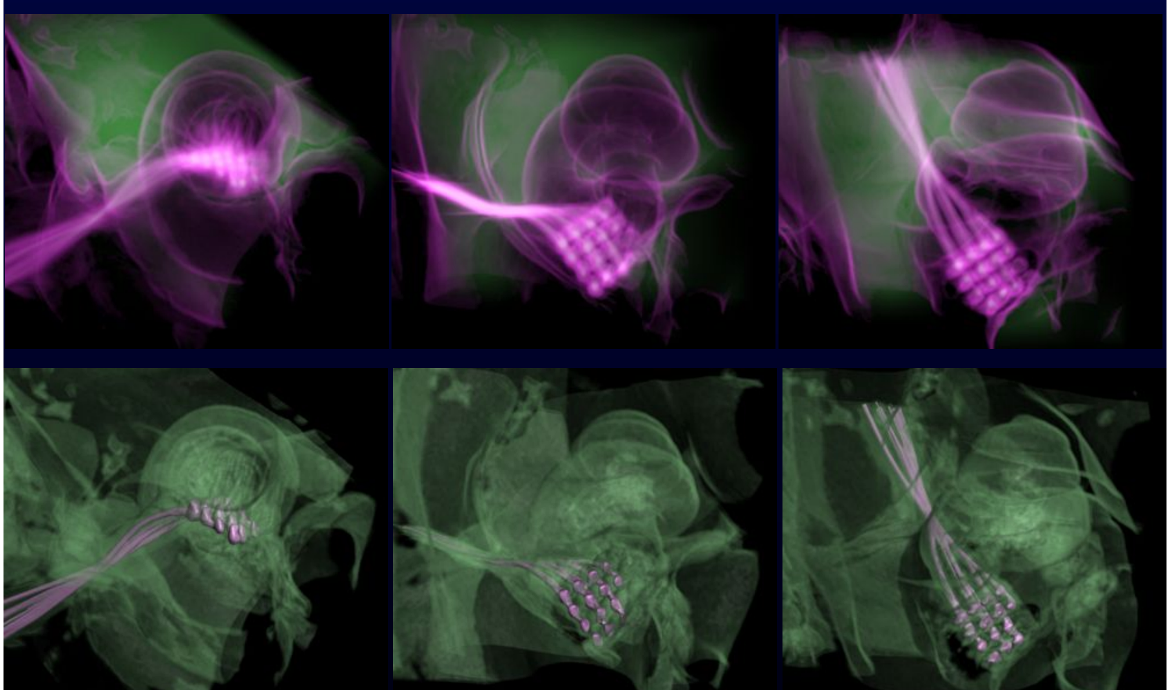
- More efficient than standard cochlear implants
- Requires more difficult surgery

Kindlmann et al 2004

Auditory Electrode Implants

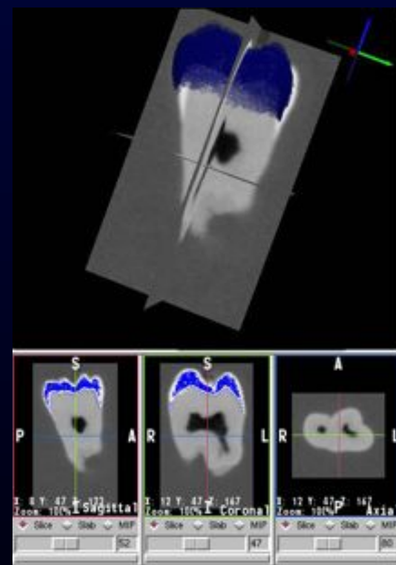


Auditory Electrode Implants



Available Software

- BioPSE / BioImage
- http://www.sci.utah.edu/ncrr/software/biopse.html

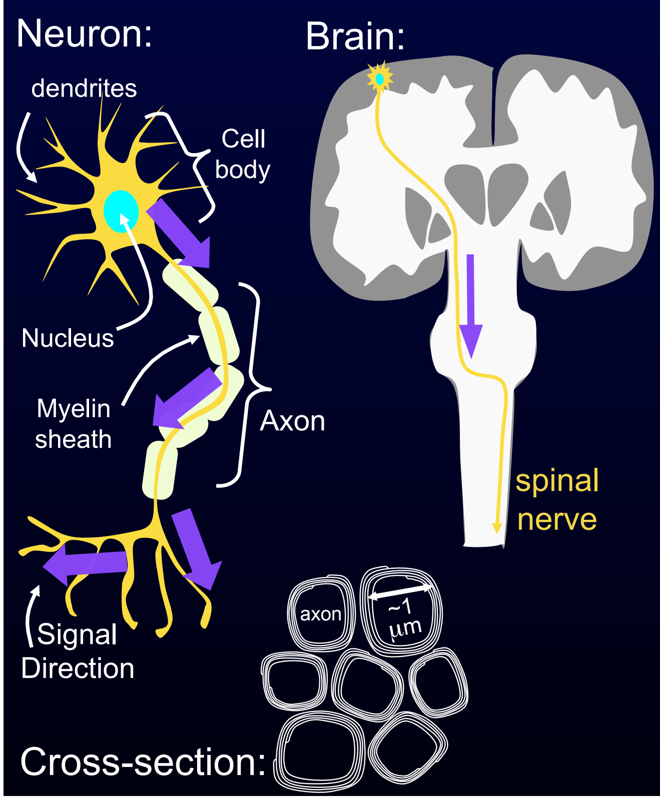


Application: dynamic CT of lungs

Dr. George Chen, Mass General Hosptial
Studying tumors with time-resolved CT

(Movie)

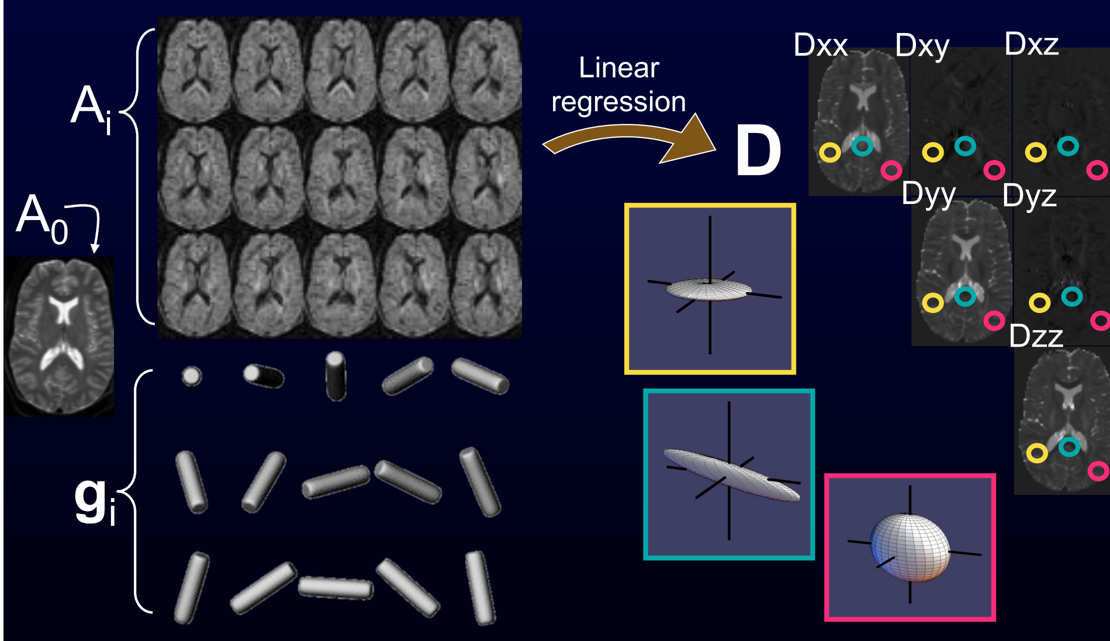
Diffusion MRI: neuroanatomy 101



- Gray matter (cortex + nuclei): cell bodies
- White matter: axons
- Myelin sheath aids signal conduction
- Axon + sheath = nerve fibers
- Major white matter pathways aggregate many fibers into bundles
- Directionally constrains water diffusion along fiber direction (LeBihan 1985)

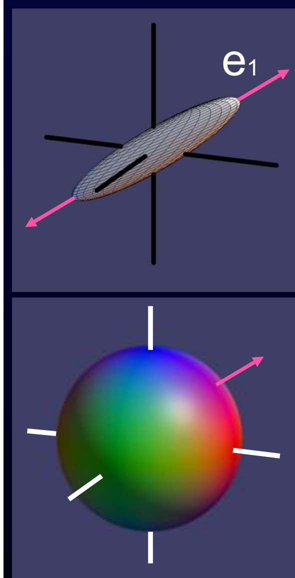
Diffusion Tensor MRI

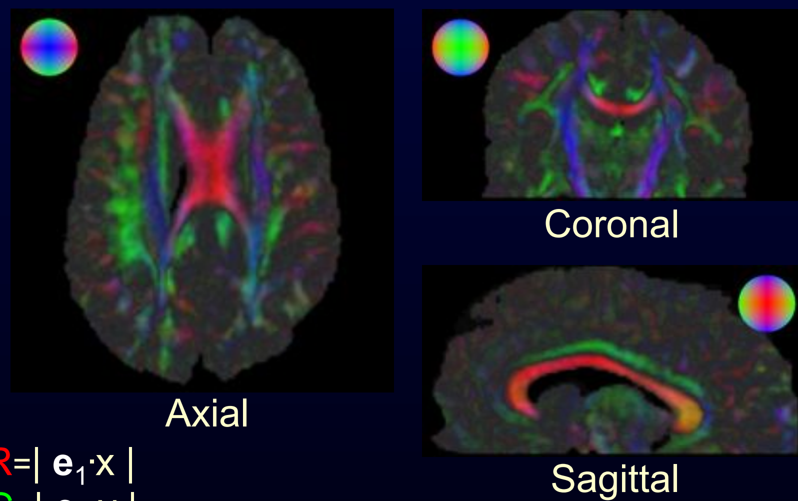
Single Tensor Model (Basser 1994) $A(b, \mathbf{g}) = A_0 e^{b\mathbf{g}^T \mathbf{D}\mathbf{g}}$



Significance of Tensor Orientation

Principal eigenvector gives axon bundle direction





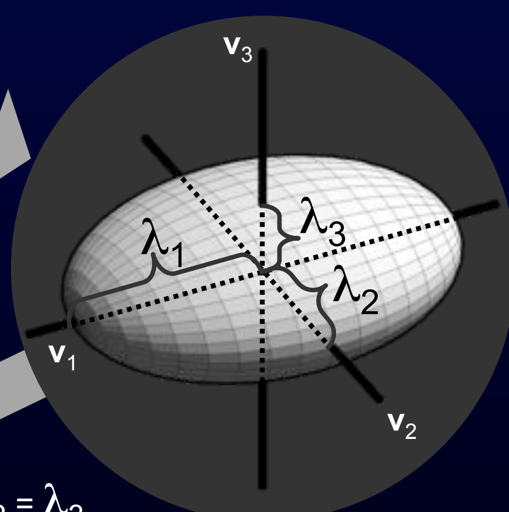
$R = | \mathbf{e}_1 \cdot x |$
$G = | \mathbf{e}_1 \cdot y |$
$B = | \mathbf{e}_1 \cdot z |$

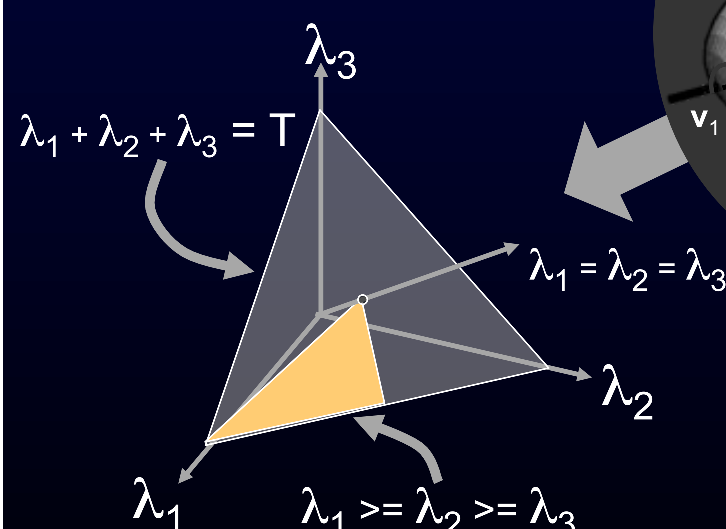
(Pierpaoli, 1997)

Glyphs for showing tensor shape

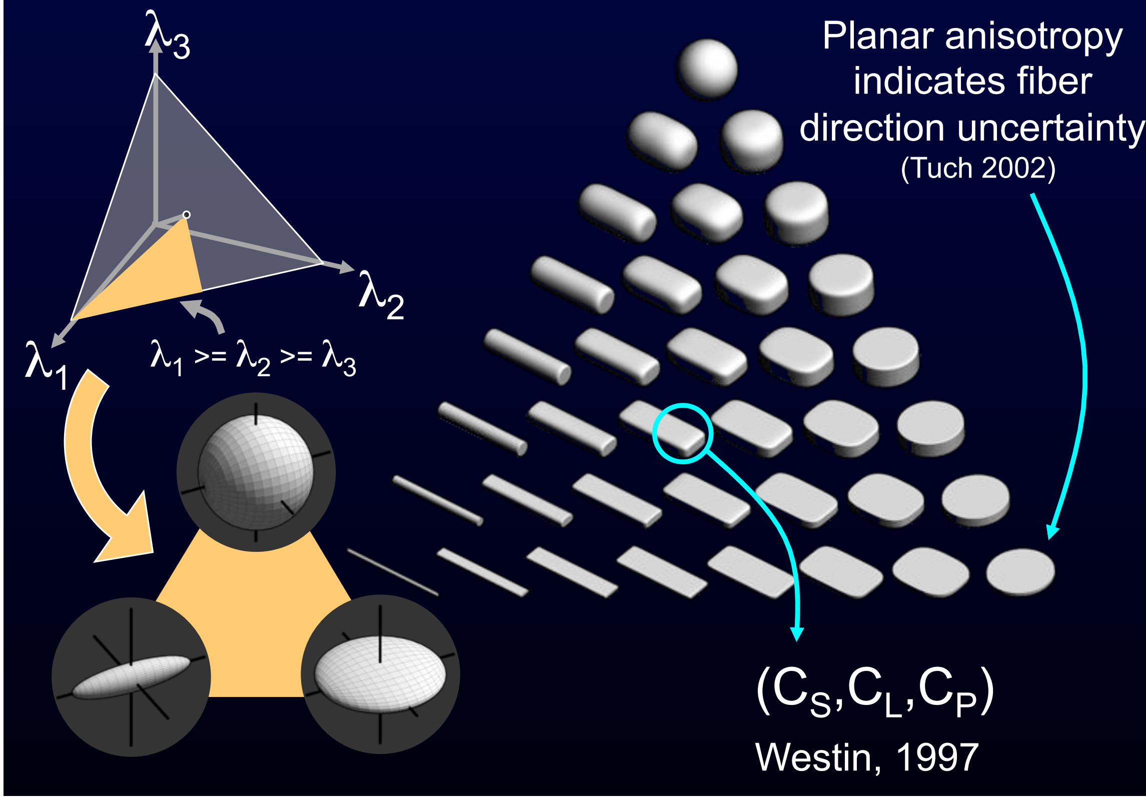
$$\mathbf{D} = \mathbf{R}\Lambda\mathbf{R}^{-1}$$

$$= \begin{bmatrix} \mathbf{v}_1 & \mathbf{v}_2 & \mathbf{v}_3 \end{bmatrix} \begin{bmatrix} \lambda_1 & 0 & 0 \\ 0 & \lambda_2 & 0 \\ 0 & 0 & \lambda_3 \end{bmatrix} \begin{bmatrix} \mathbf{v}_1 \\ \mathbf{v}_2 \\ \mathbf{v}_3 \end{bmatrix}$$



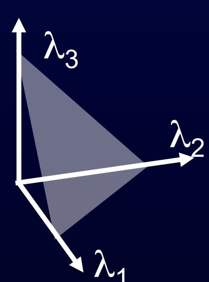


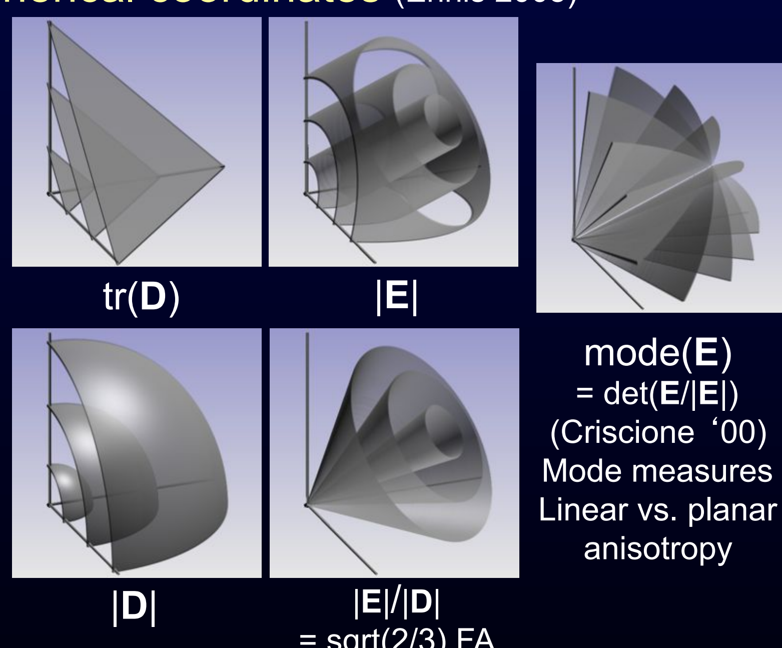
Space of Tensor Shape



Invariants as shape parameterizations

Cylindrical or spherical coordinates (Ennis 2005)





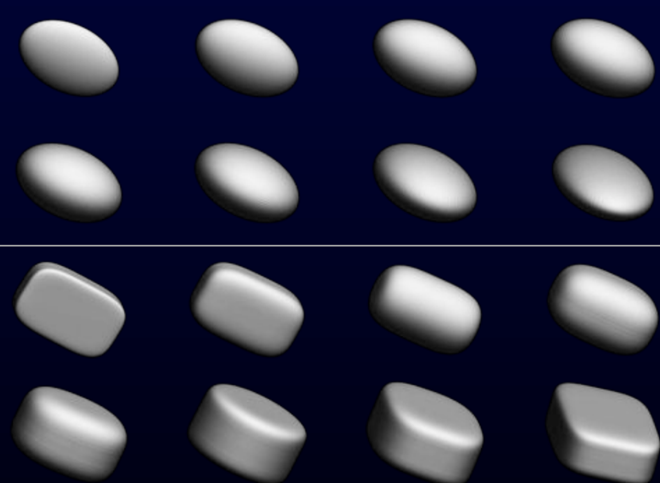
tr(**D**) = Dxx+Dyy+Dzz
|**D**| = sqrt(tr($\mathbf{D}^T\mathbf{D}$))

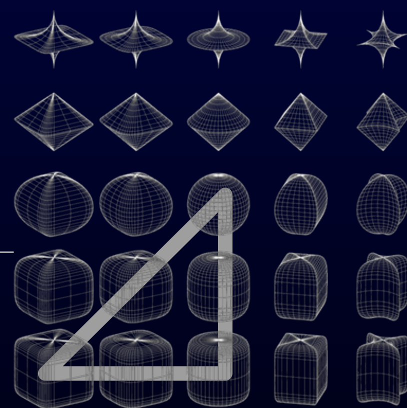
E = deviatoric(**D**)
= **D** - trace(**D**)*$\mathbf{I}$/3

Data Inspection

Superquadric tensor glyphs (Kindlmann 2004)

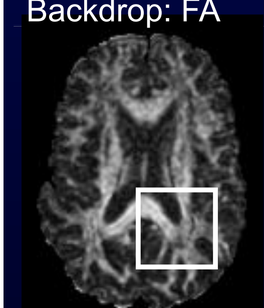
- Avoids visual ("bas-relief") ambiguity



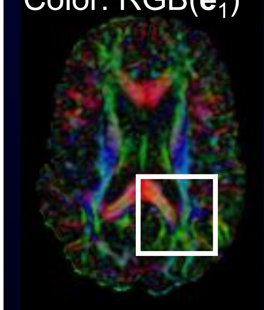


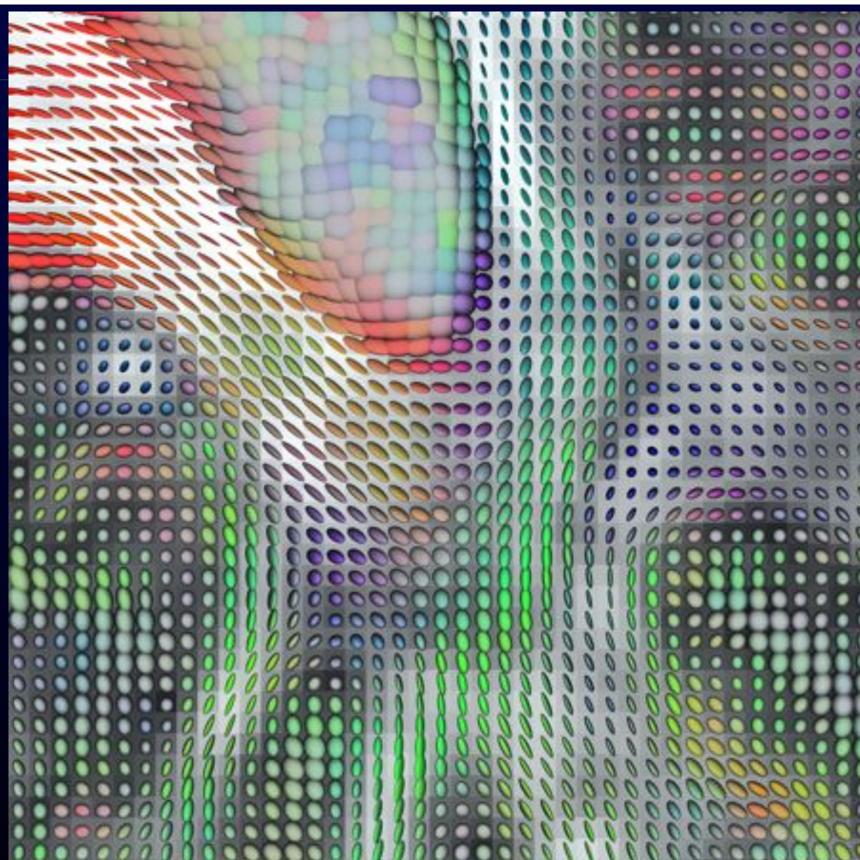
(Barr 1981)

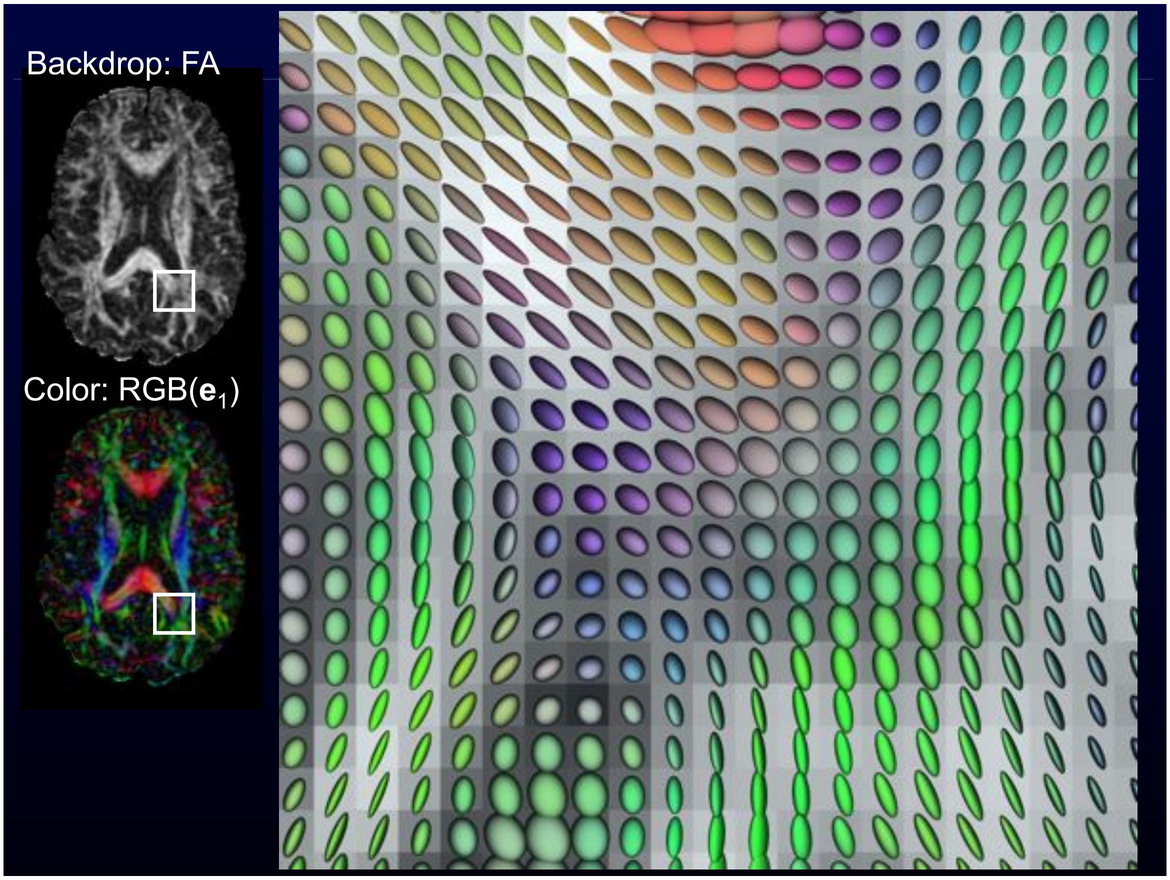
Backdrop: FA



Color: RGB($\mathbf{e}_1$)



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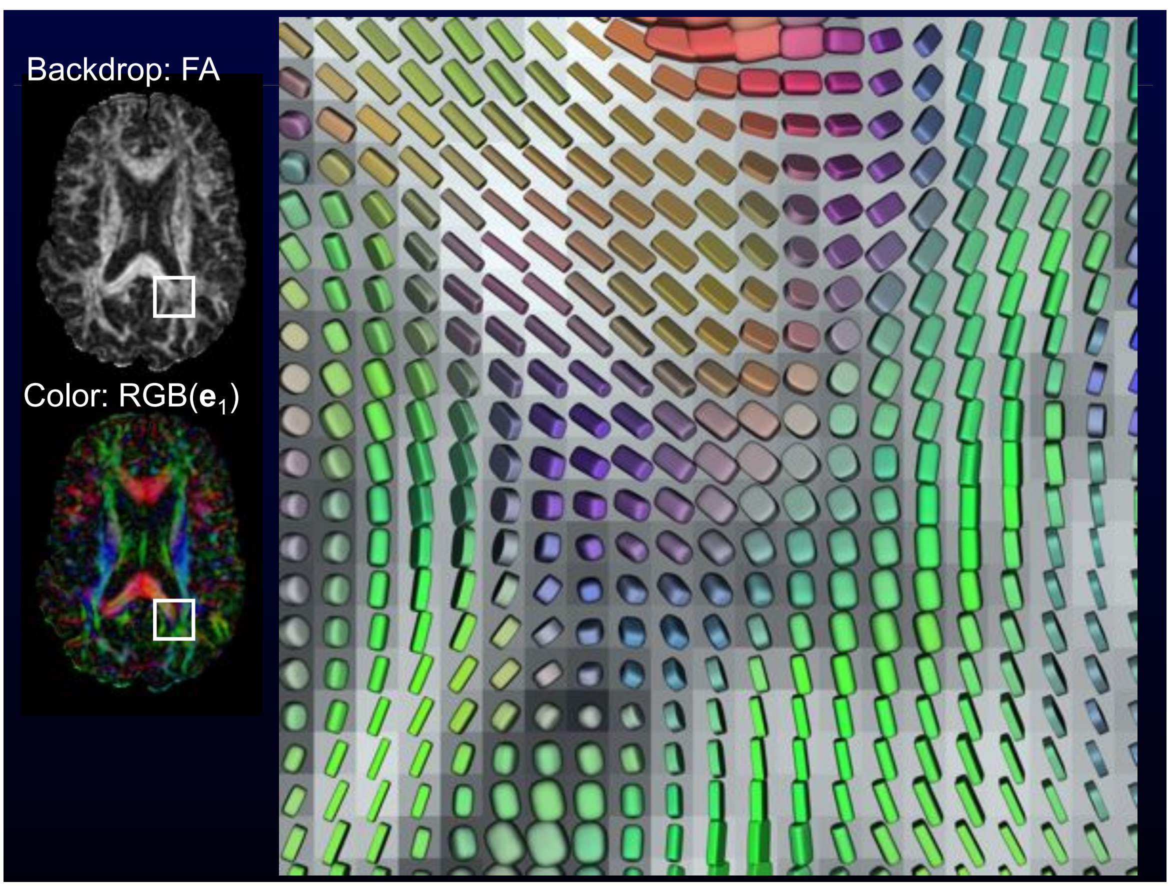
Color: RGB($\mathbf{e}_1$)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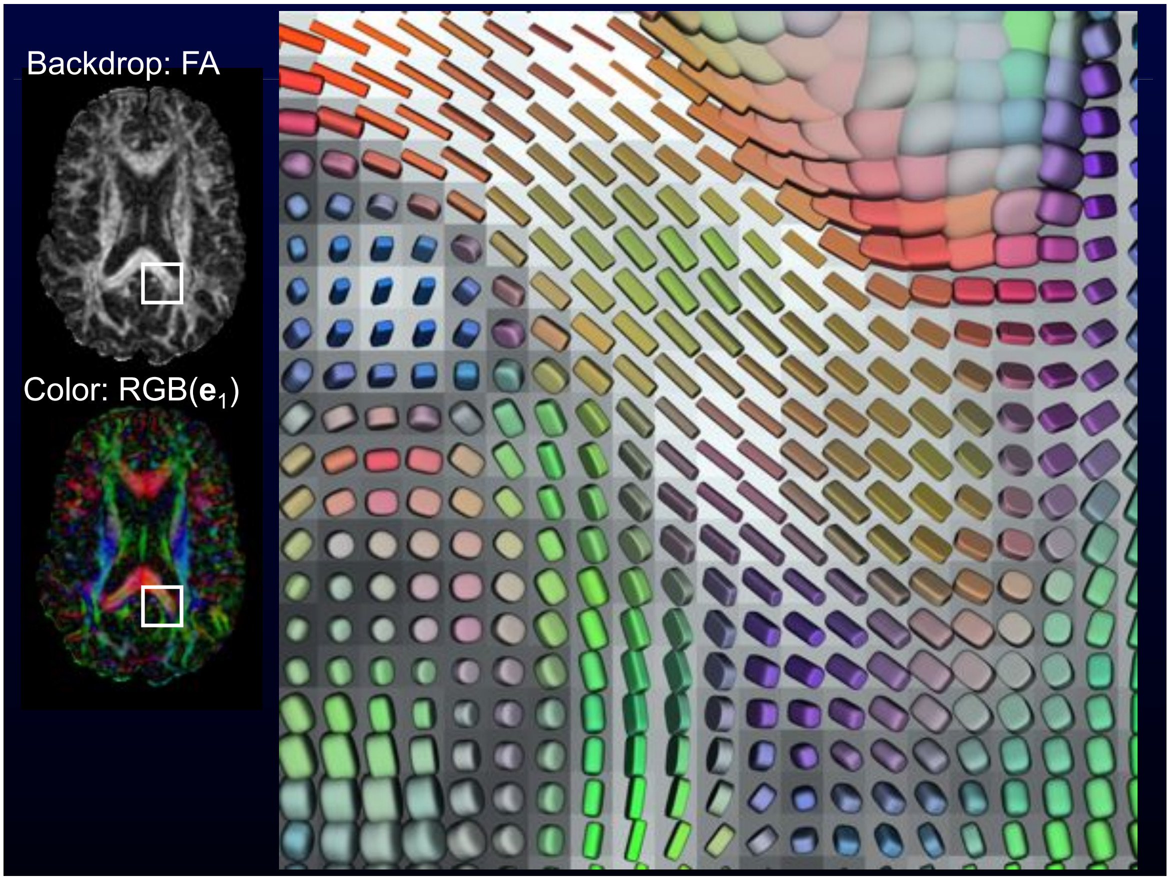
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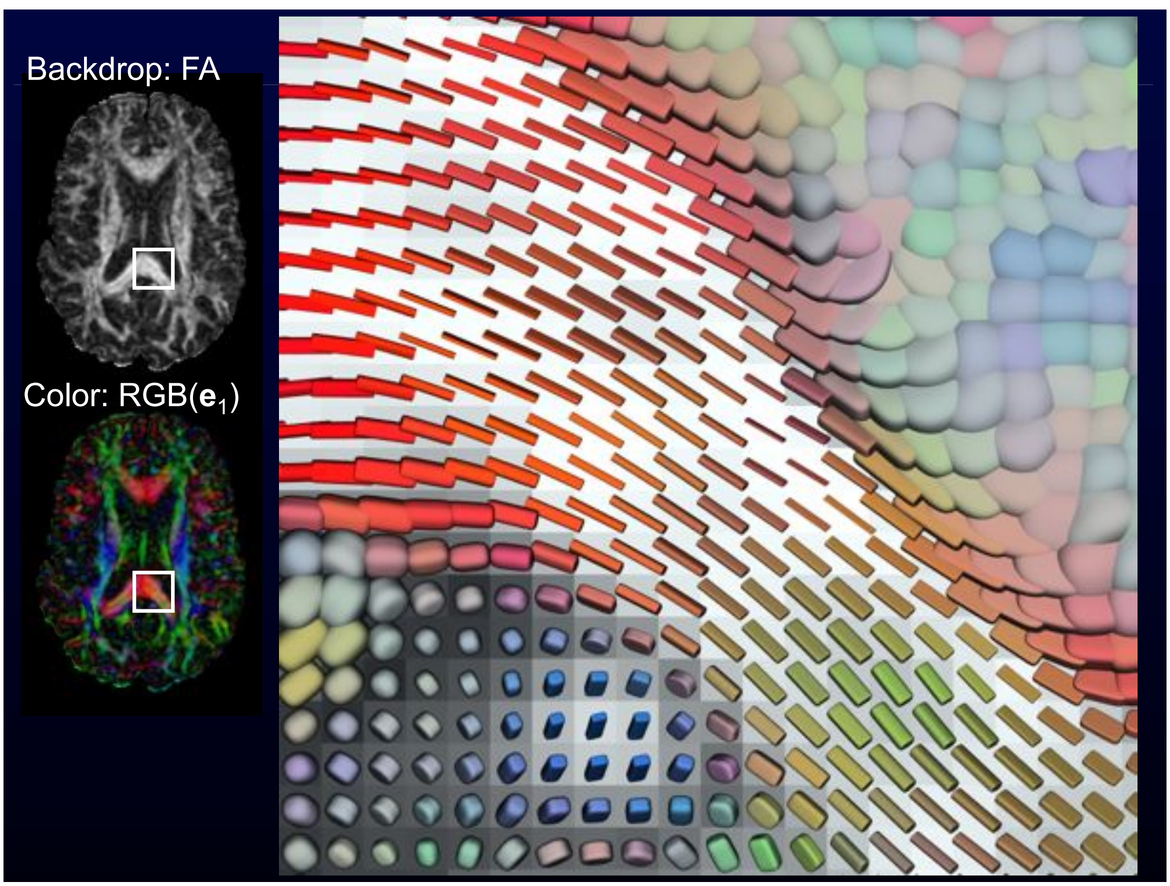
Color: RGB(e1)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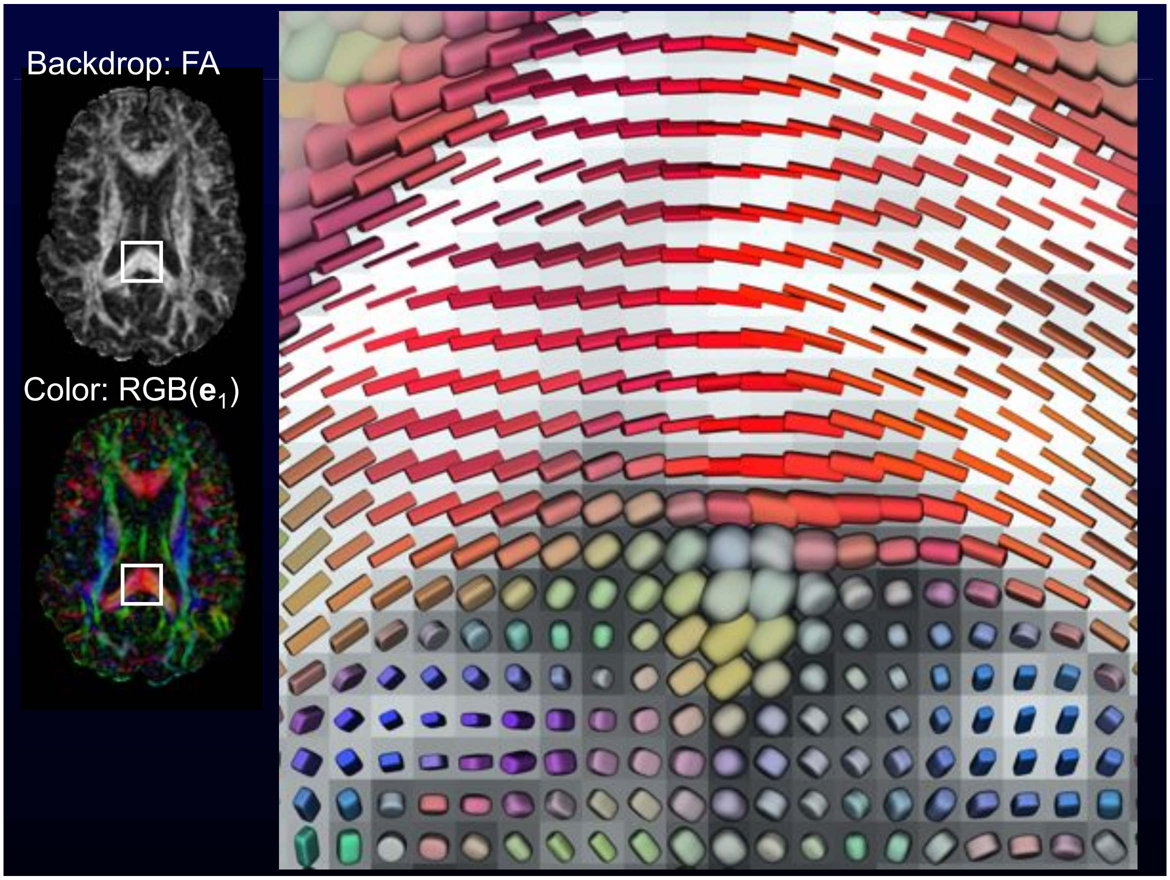
Color: RGB(e1)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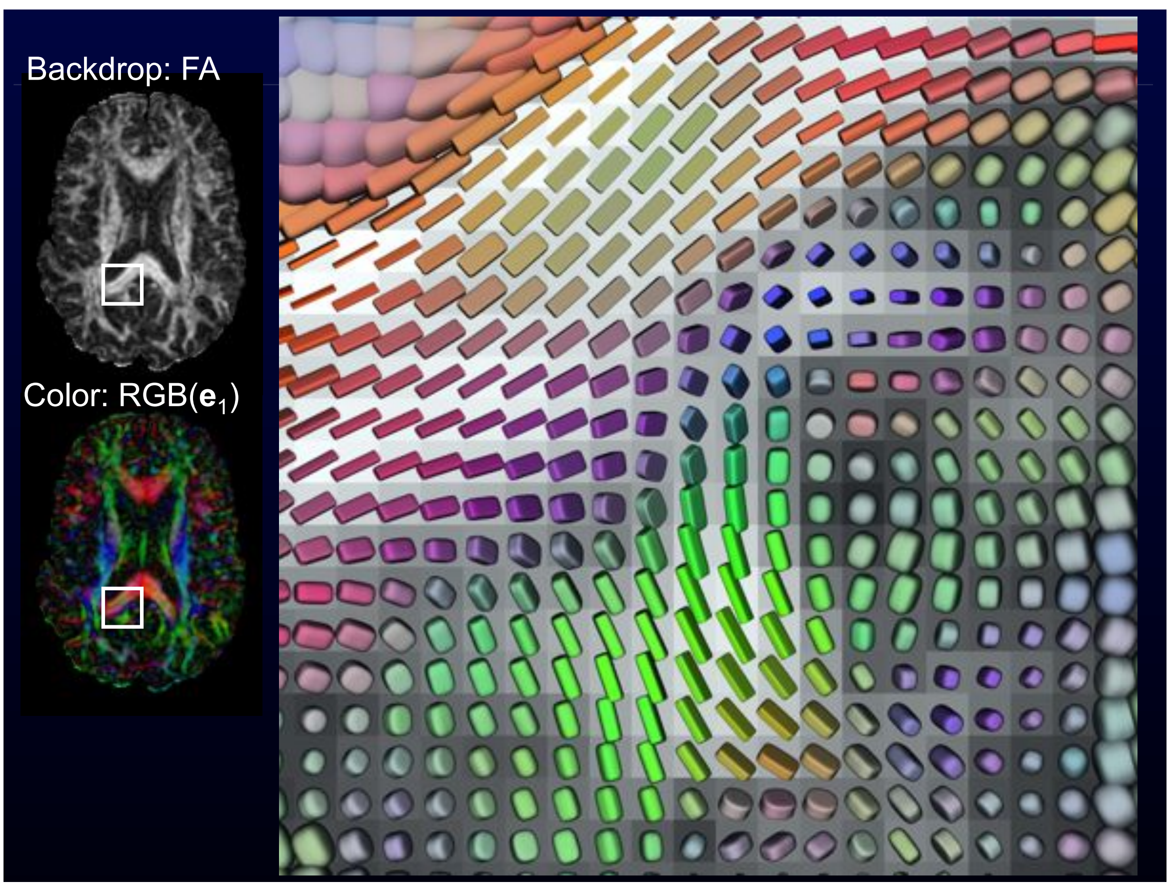
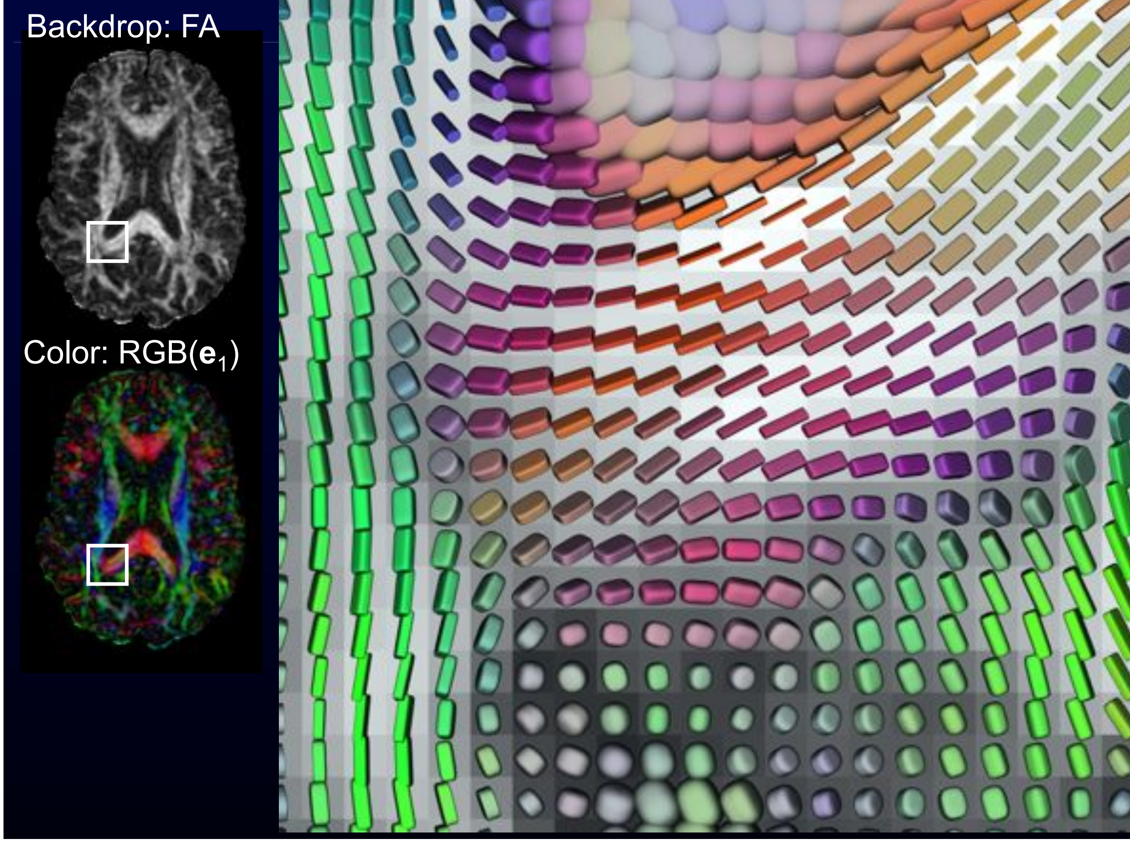
Color: RGB($\mathbf{e}_1$)


Backdrop: FA
Color: RGB($\mathbf{e}_1$)



Fiber Tracking

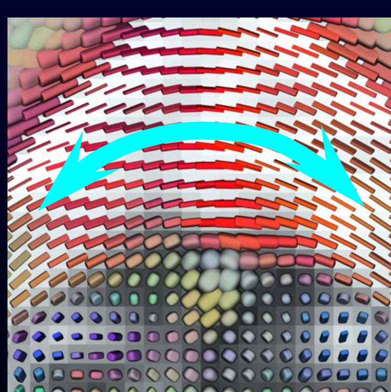
Path integration along principal eigenvector

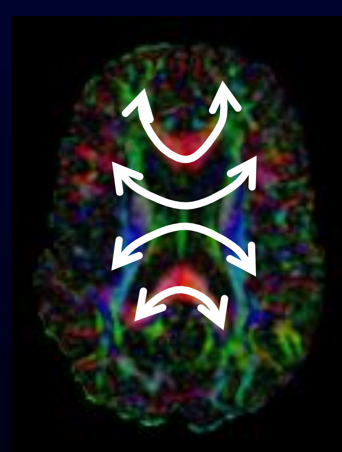
- Delmarcelle 1993, Basser 1999

Idea: follow paths of individual axons!

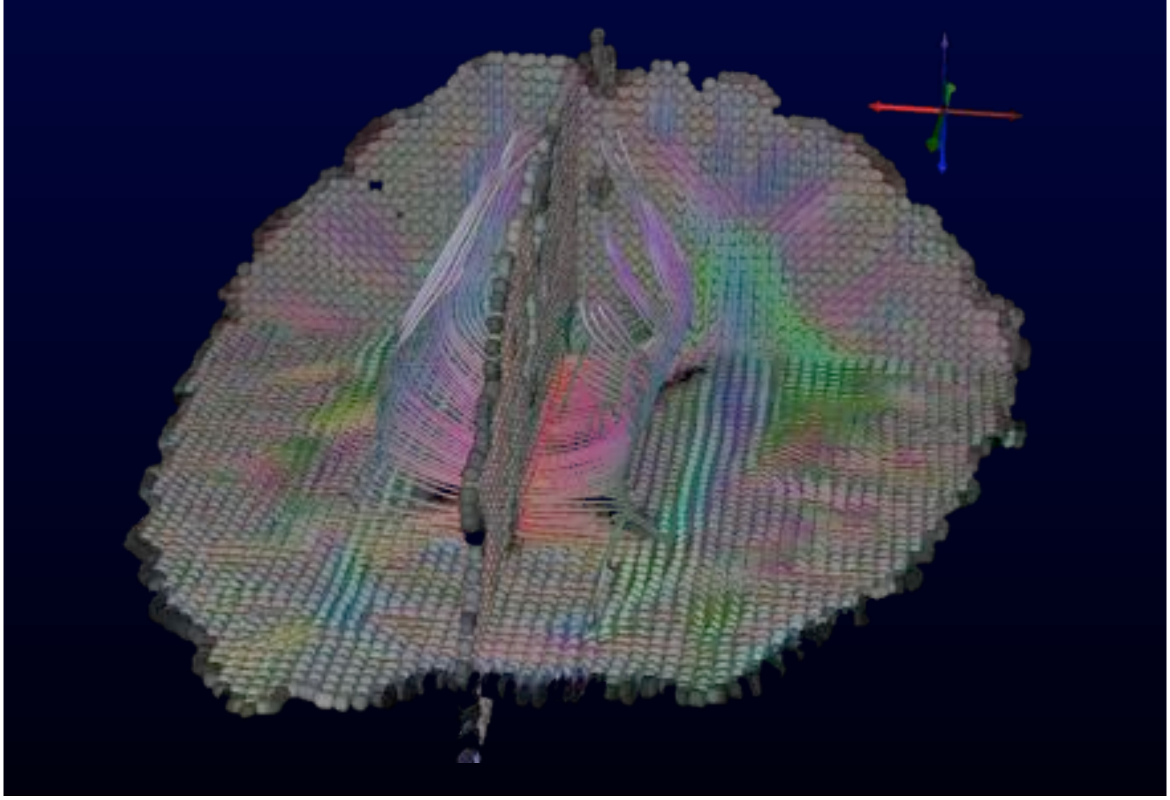
Reality: 2-3 orders of magnitude too coarse

Validation ongoing

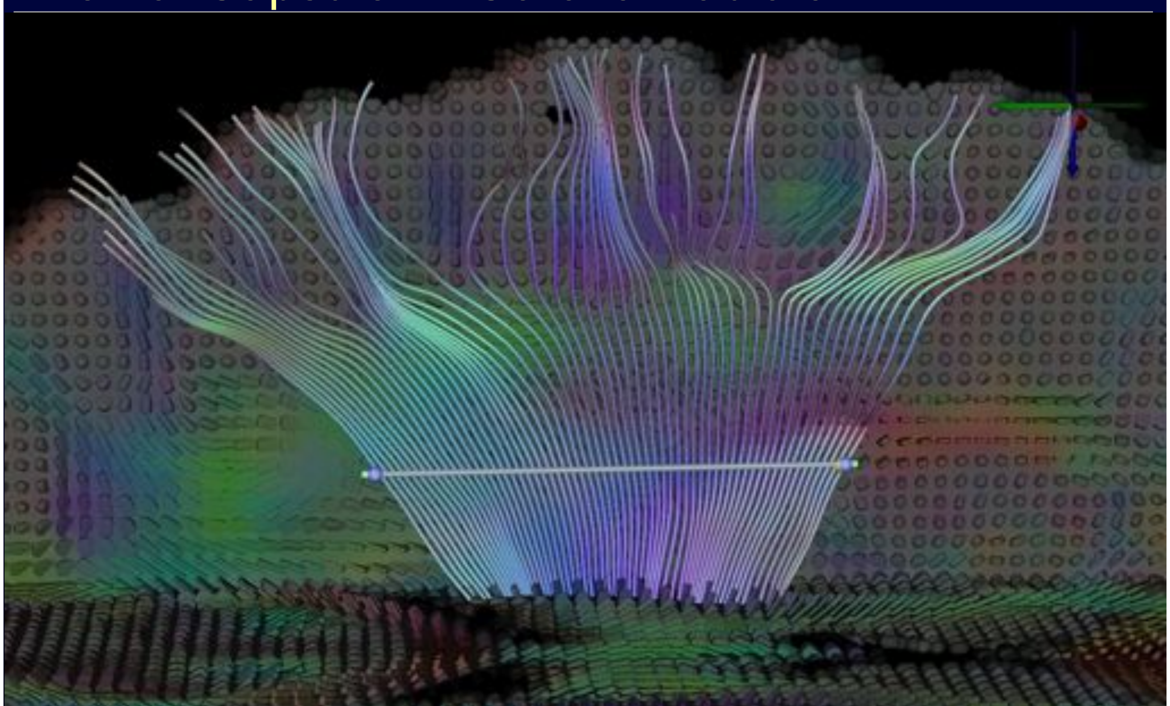




Corpus Callosum

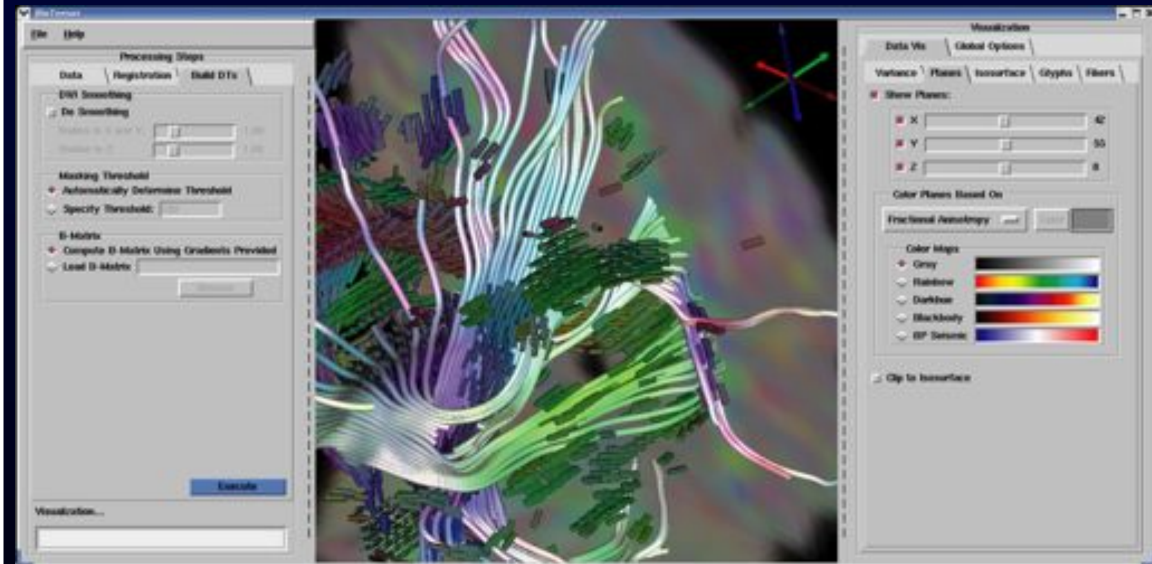


Internal Capsule → Corona Radiata



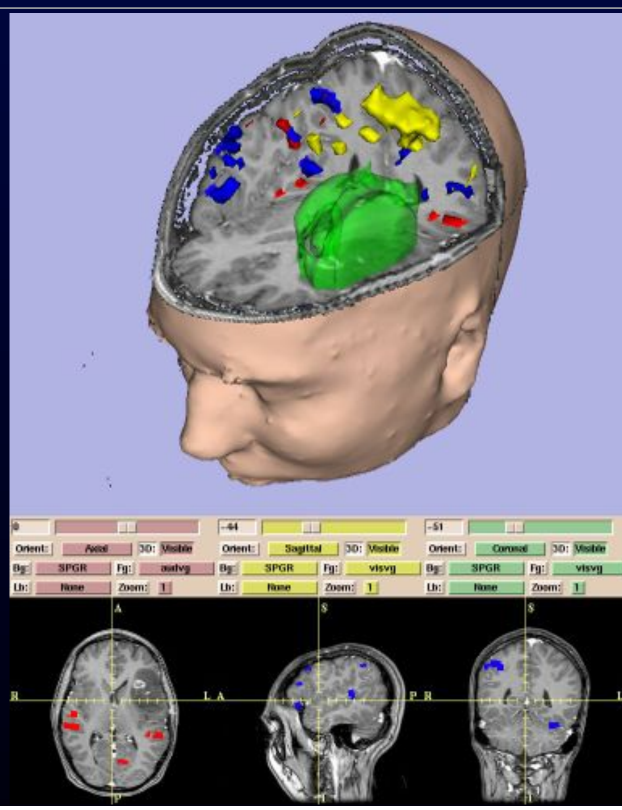
Open Source Software

- BioPSE / BioTensor
- http://www.sci.utah.edu/ncrr/software/biopse.html



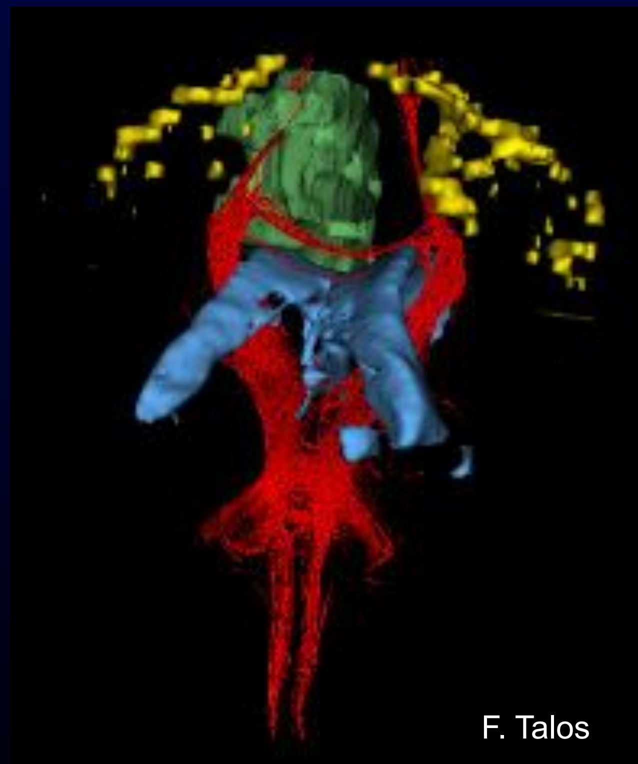
3D Slicer

- Visualization
- Registration
- Segmentation
- Measurements
- Realtime Integration
- http://www.slicer.org



Tumor study

- Brain connectivity important question
- Relationship between tumor and surrounding white matter



Reproducibility and Open Source

- Vis research is not reproducible in scientific sense
- Two-fold problem: software + parameters
- Open Source software fosters reproducibility
  - Community creates, debugs, refines, reuses code
- Does releasing code imply supporting it?
- Some frameworks have support infrastructure
  - Insight Toolkit, http://www.itk.org
- “Every figure can be reproduced …”
  - http://www.sci.utah.edu/~gk/vis03
  - http://www.sci.utah.edu/~gk/vissym04/
- Insight Software Consortium: Insight Journal
  - http://insightsoftwareconsortium.org/InsightJournal/
  - Creative Commons Licensing: Attribution