Discovering the Network of Sulcal Fundi in Human Brains

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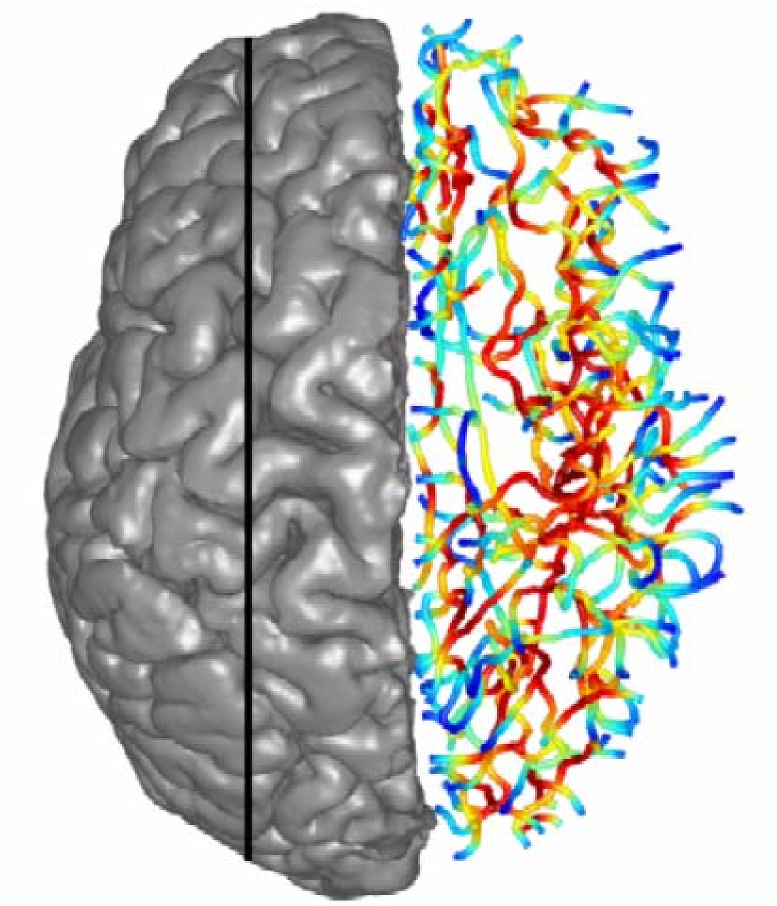
Outline

- Introduction to Sulcal fundi.
- Overview of Previous Methods
- Our Geometrical Method for Sulcal Fundi Extraction
- Open Questions and Future Plans
- Conclusion

What are sulcal fundi?

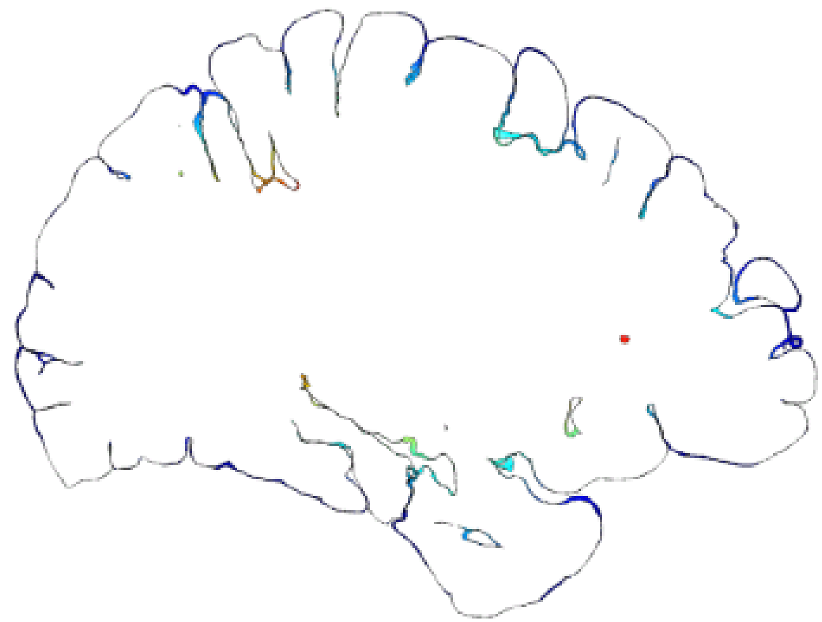


- **Sulci (plural of Sulcus) =**

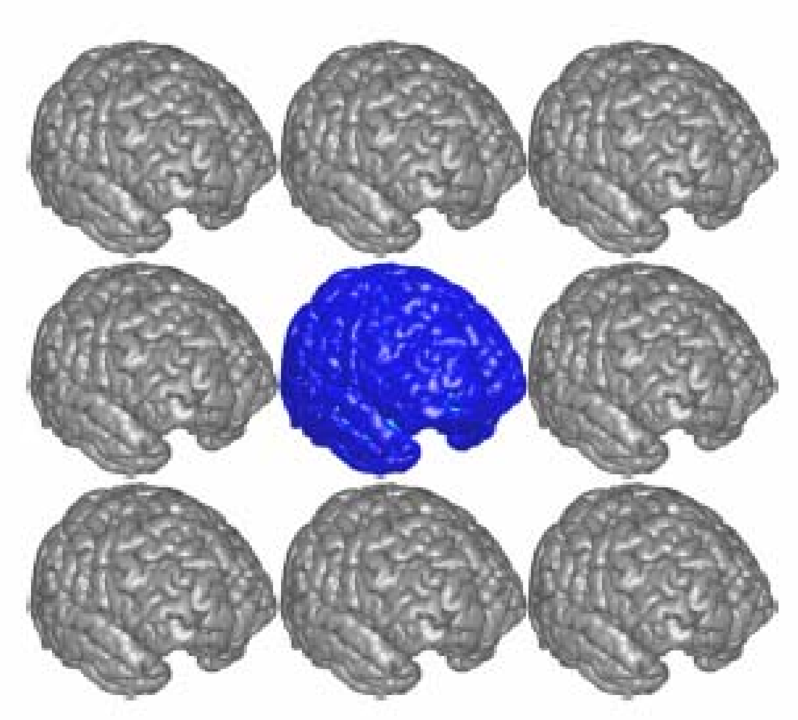
  crevices of convoluted human brain surface
- **Sulcal fundi (plural of fundus) =**

  3D curves lying in the depths of the

  cerebral cortex



Why are sulci and sulcal fundi important?



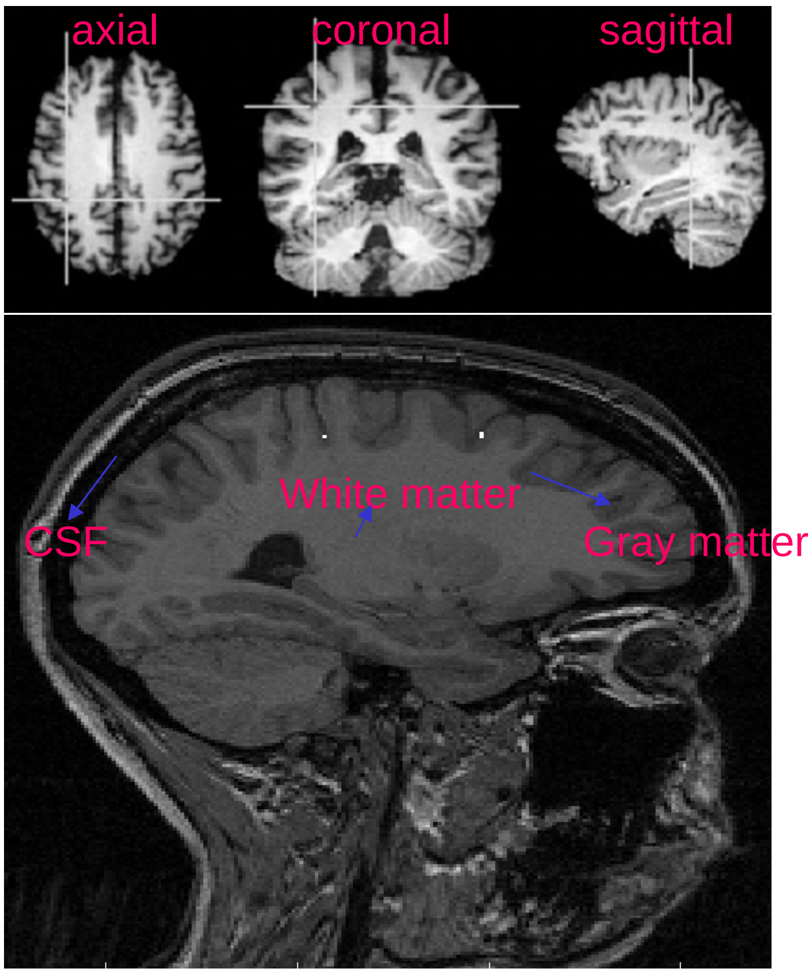
- Sulci and sulcal fundi are often used as anatomical landmarks for downstream computations in brain imaging
- Deformation fields for warping cortical surfaces of different brains onto each other
- Longitudinal and cross-sectional studies of brain structure

Overview of previous work

- Manual extraction
- Curvature based approaches
- Distance based approaches
- Combination of curvature and distance based approaches

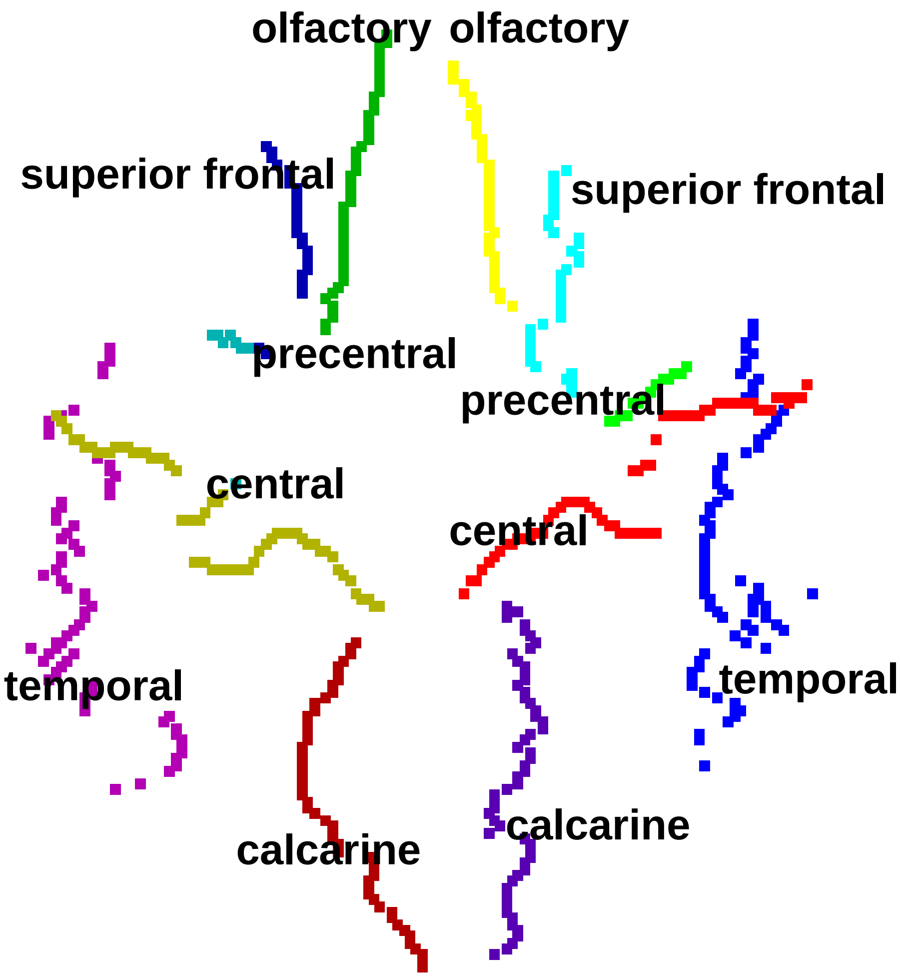
Drawbacks of manual extraction

Fig. From [Lohmann 1998]



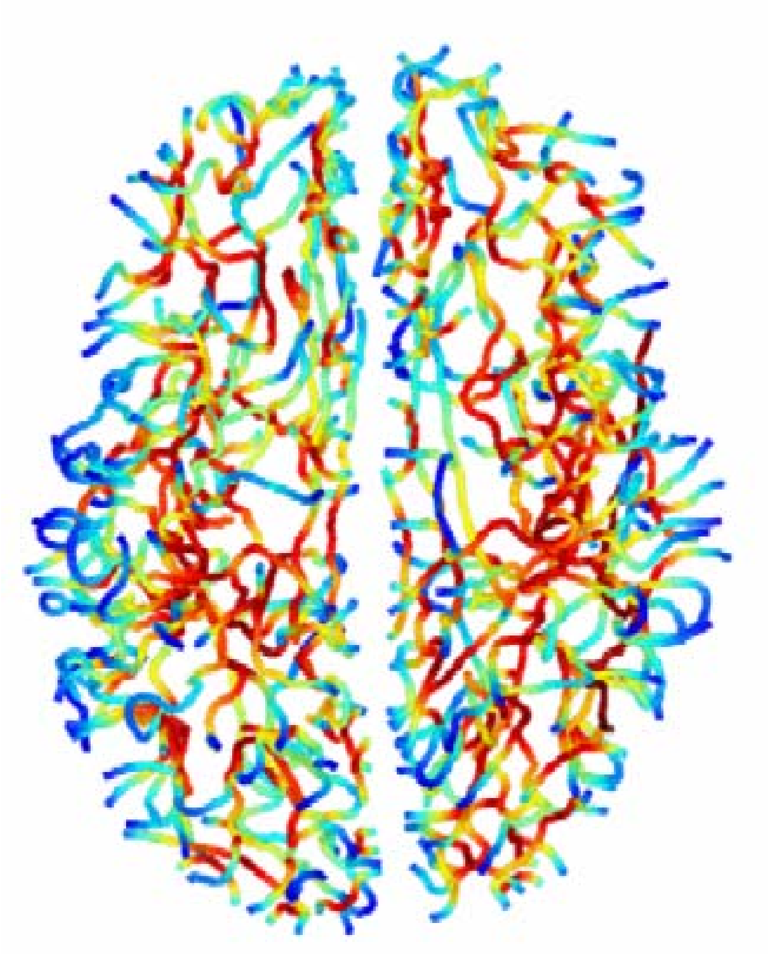
- Manual labeling of voxels in MRI brain volume using GUI which displays three orthogonal 2D brain slices
- Process is extremely tedious, time consuming and prone to human error
- Expert anatomist needs 1 day for manually marking 6 fundi per hemisphere

Result of manual extraction



- Expert anatomist needs 1 day for manually marking 6 fundi per hemisphere
- Manual extraction is considered as “gold standard”

Advantages of automatic extraction



- Improved quality and Reproducibility of process
- Considerable time savings
- Automatically process large number of high-resolution MRI data sets

Previous work: curvature based approaches

Fig. From [Bartesaghi et al 2001]

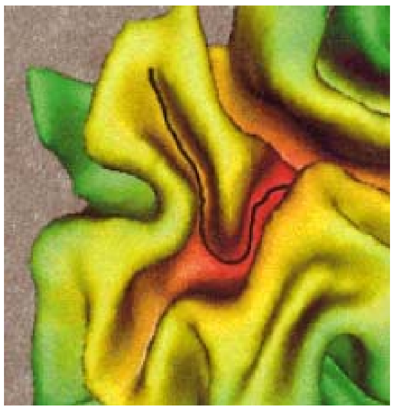
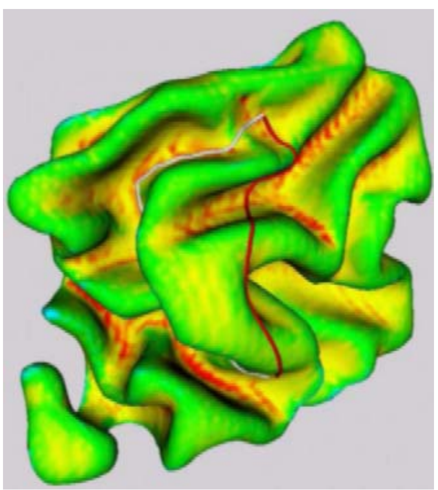


Fig. From [Mémoli et al 2004]



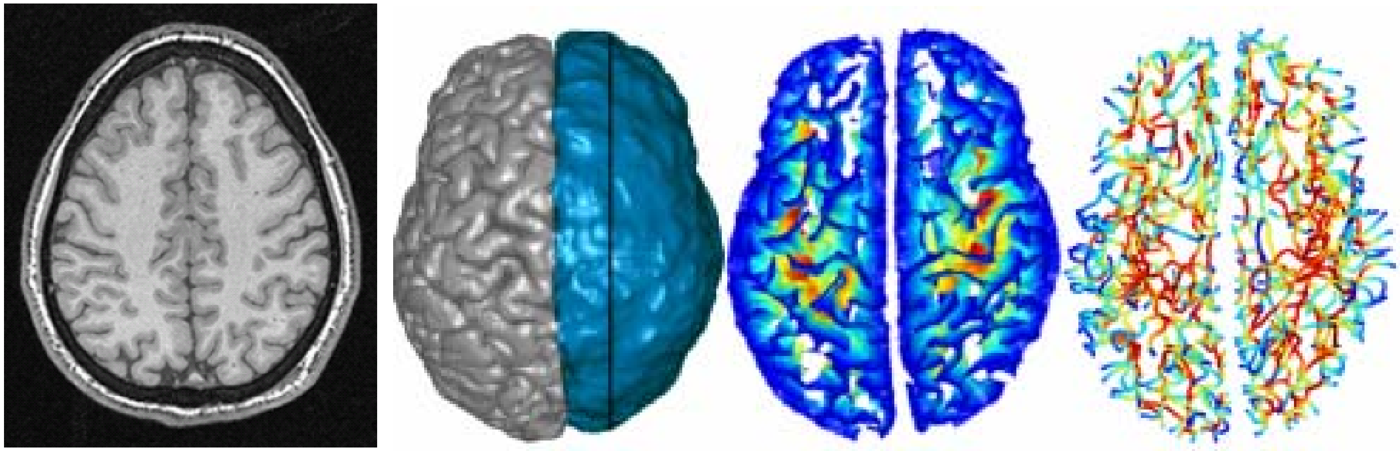
- Extract WM-GM boundary surface and compute mean surface curvature
- Fundi are curves lying within areas of extremal mean surface curvature
- Manually mark two endpoints of a fundi
- Using fast marching algorithm on triangulated meshes [Bartesaghi et al. 2001] or implicit surfaces [Mémoli et al. 2004] to connect two points with a Weighted geodesic

Previous work: distance based approaches

Figs. from [Le Goualher et al. 1999]

- Distance based approaches compute medial sulcal surfaces (“sulcal ribbons”) from volumetric data
  Curvature and dynamic programming (Miller et al).
- Fundi are inferior margins of these surfaces [Lohmann 1988, Le Goualher et al. 1999, Cachia et al. 2003]
- Combination of curvature and distance based computations [Tao et al. 2004]

Overview of our algorithm

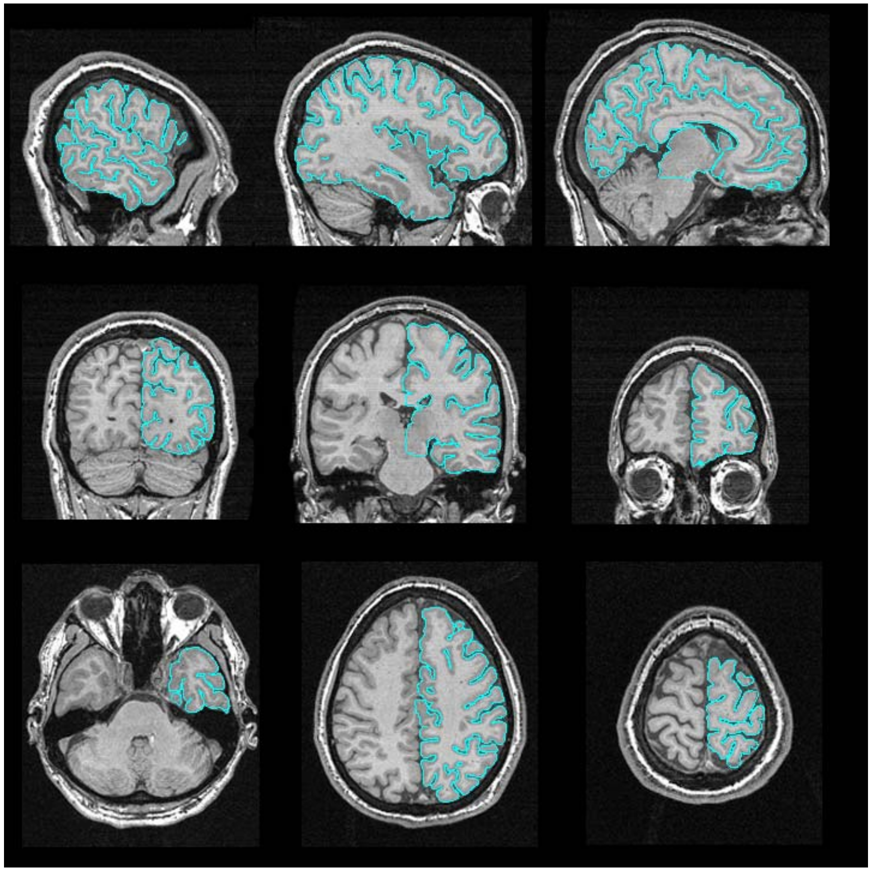


Input: MRI brain image volume

1. Segmentation and Surface Extraction (preprocess)
2. Outer hull surface computation
3. Geodesic depth computation
4. Sulcal fundi extraction

Output: 3D polylines representing sulcal fundi

Segmentation & surface extraction



- MRI brain volume
  (1mm isotropic voxels) acquired
  at Montreal Neurologic institute,
  provided by Dr. Alan C. Evans
- Skull stripping using Brain Extraction
  Tool (*BET*)
  http://www.fmrib.ox.ac.uk/fsl/bet/)
- Topologically correct triangular mesh
  representing the pial (GM-CFS) surface
  of cerebral cortex extracted by publicly
  available software *FreeSurfer*
  http://surfer.nmr.mgh.harvard.edu

Explicit and implicit representation for curves and surfaces

- **Continuous:**

  Explicit Representation (Parameterized boundaries)

  $2D:\ x = \cos(t),\ \ y = \sin(t),\ 0 \le t \le 2\pi$

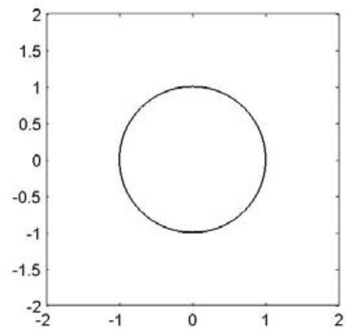
  $3D:\ x = \sin(\theta_2)\cos(\theta_1),\ y = \sin(\theta_2)\sin(\theta_1),\ z = \cos(\theta_2)$

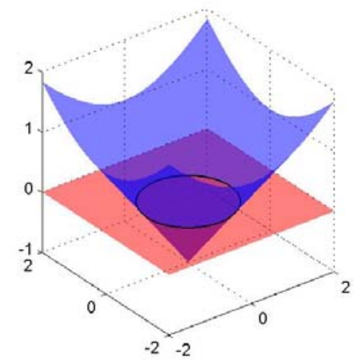
  $0 \le \theta_1 \le 2\pi,\ 0 \le \theta_2 \le \pi$

  Implicit Representation
  (boundaries given by zero level set)

  $2D:\ \phi = \sqrt{x^2 + y^2} - 1$

  $3D:\ \phi = \sqrt{x^2 + y^2 + z^2} - 1$





- **Discrete:**

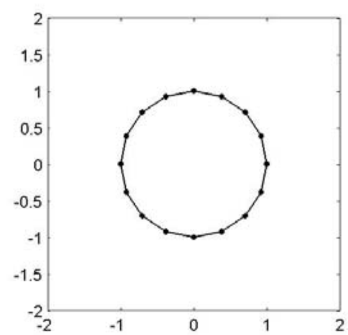
  Explicit Representation
  (determine node points and element connectivity)

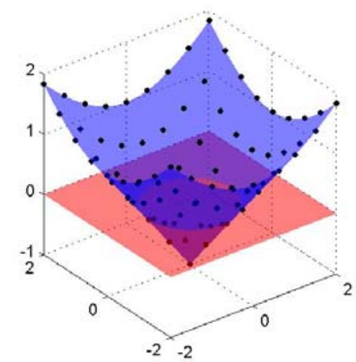
  2D: line segments
  3D: triangulated mesh

  Implicit Representation (values on rectangular mesh)

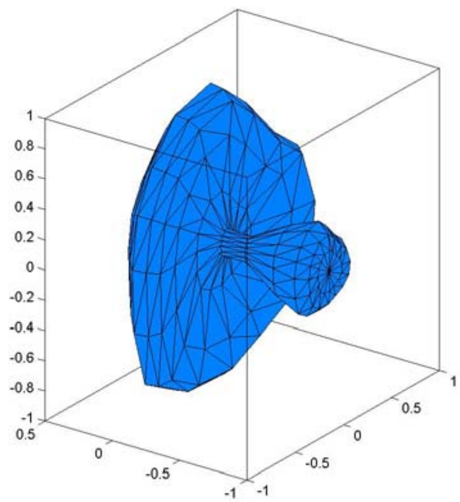
  $2D:\ \phi_{i,j} = \phi(x_i, y_j)$

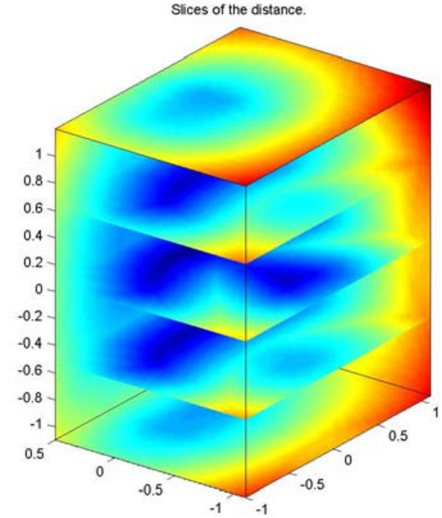
  $3D:\ \phi_{i,j,k} = \phi(x_i, y_j, z_k)$

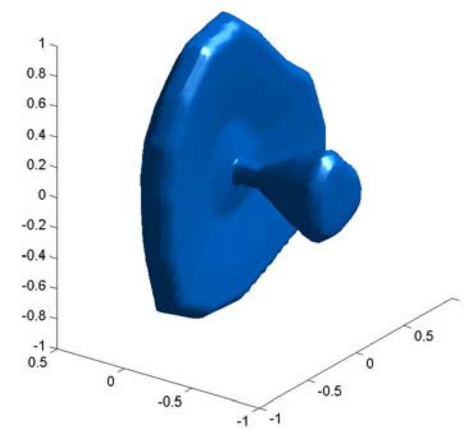


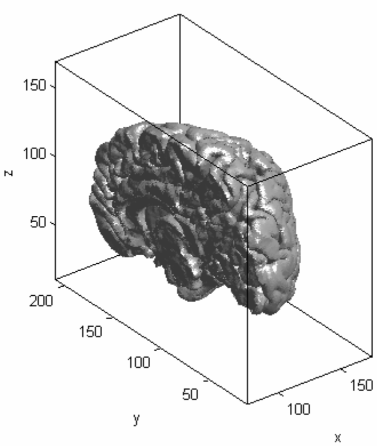


Explicit and implicit representation for surfaces

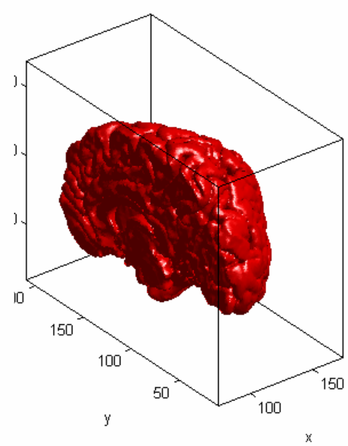




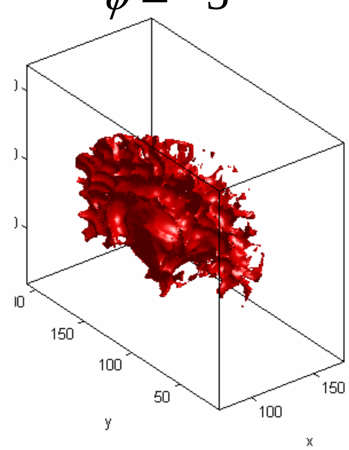




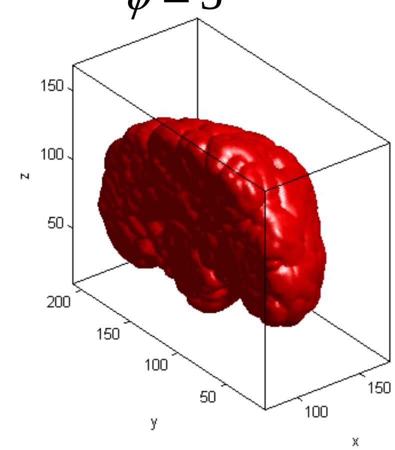
$\phi = 0$



$\phi = -5$



$\phi = 5$



Motion of the implicit-represented curves or surfaces

- Lagrangian formulation:

$$\frac{d\vec{x}}{dt} = \vec{V}(x(t))$$

- Level Set formulation:

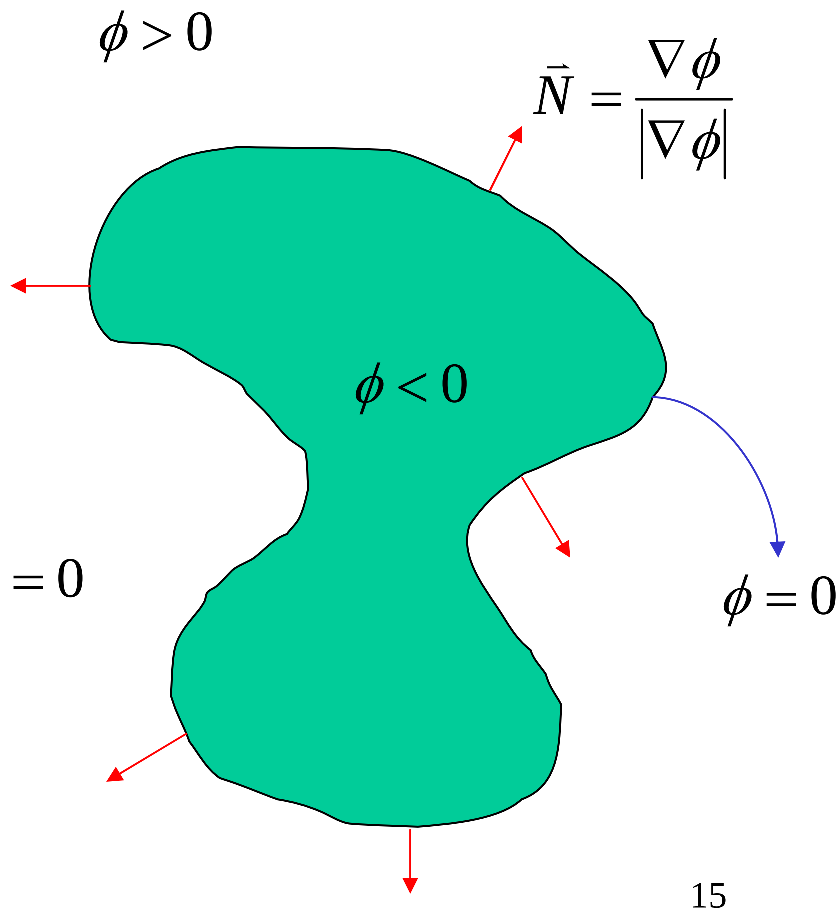
$$\phi(\vec{x}(t),t) = 0 \Rightarrow \phi_t + \nabla\phi \cdot \frac{d\vec{x}}{dt} = 0$$

$$\Rightarrow \phi_t + \nabla\phi \cdot \vec{V} = 0$$

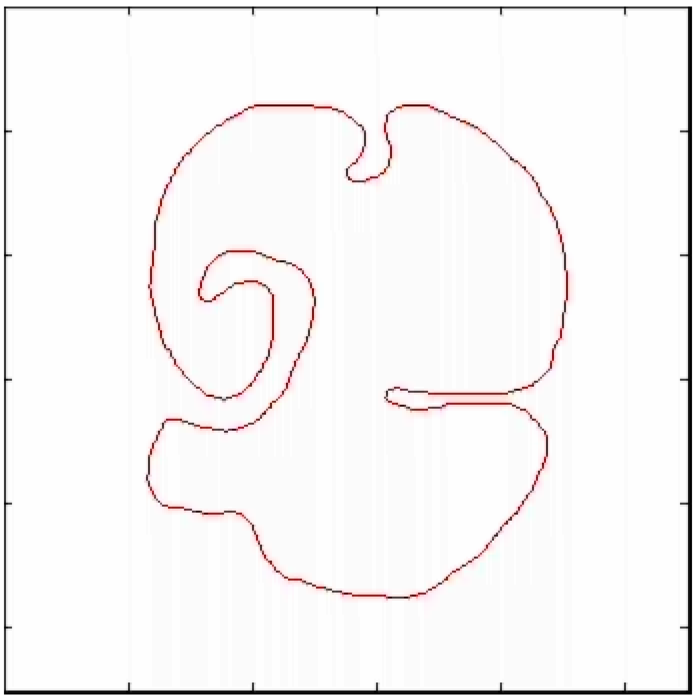
$$\Rightarrow \phi_t + \nabla\phi \cdot (\vec{V}_N + \vec{V}_T) = 0$$

$$(where\ \vec{N} = \frac{\nabla\phi}{|\nabla\phi|})$$

Osher & Sethian (88) $\Rightarrow \phi_t + V_N |\nabla\phi| = 0$



Outer hull surface computation: a demo



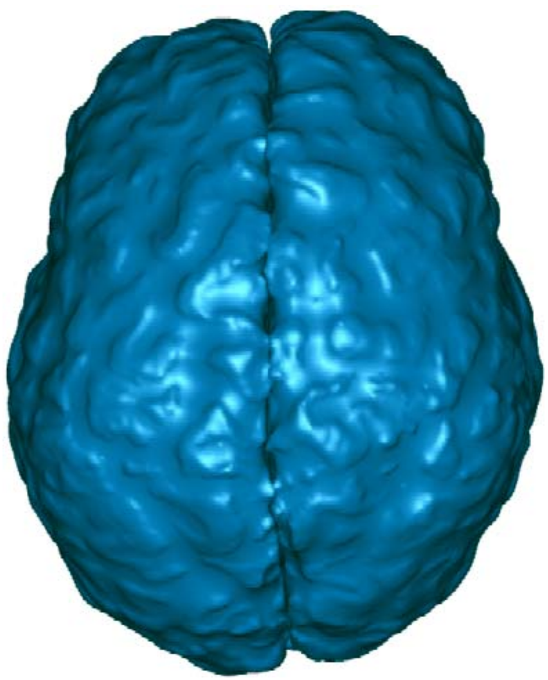
- Move surface $\phi = 0$ outward by a time parameter T
- Move surface inward by same amount of time
- Governing equation:

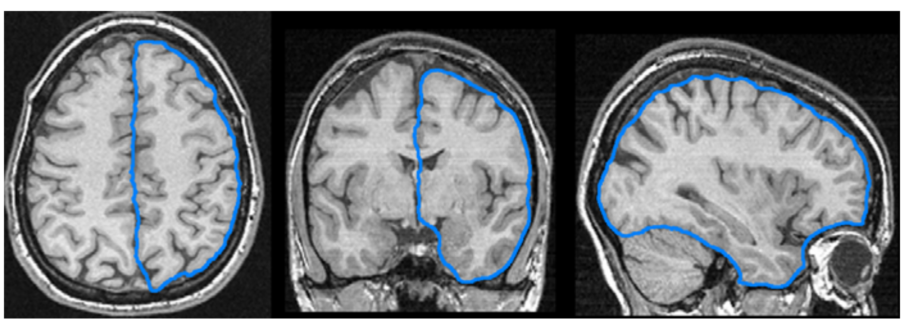
$$\begin{cases} \phi_t + V(t)|\nabla \phi| = 0 \\ \phi(x,0) = \phi_0 \end{cases}$$

where

$$V(t) = \begin{cases} 1 & for \quad t \le T \\ -1 & for \quad T \le t \le 2T \end{cases}$$

Outer hull surface computation





- Move surface $\phi = 0$ outward by a time parameter T
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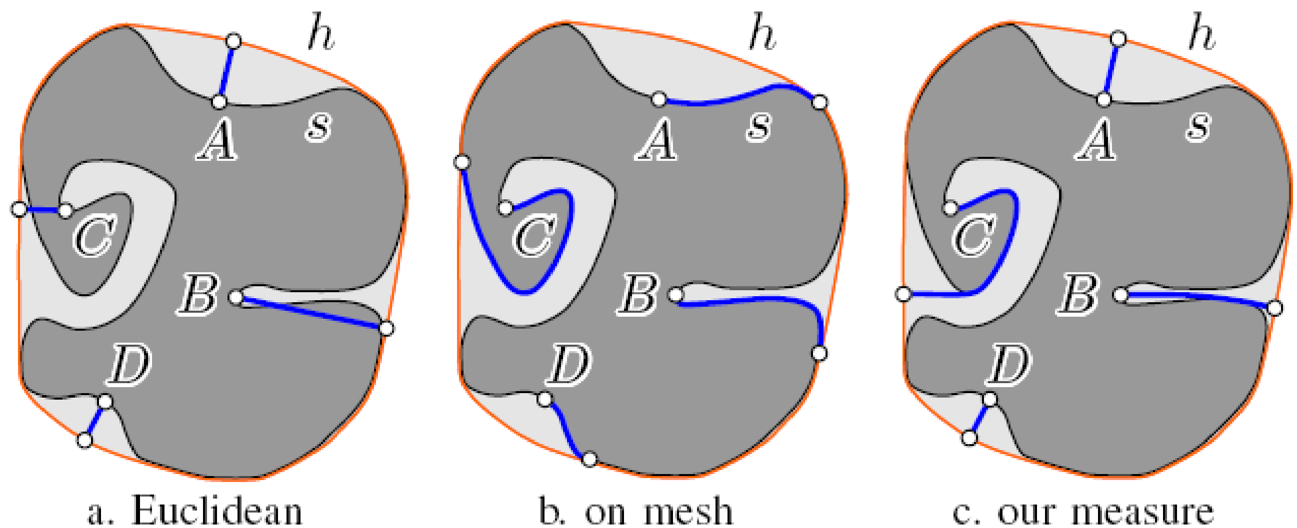
$$\begin{cases} \phi_t + V(t)\left|\nabla \phi\right| = 0 \\ \phi(x,0) = \phi_0 \end{cases}$$

where

$$V(t) = \begin{cases} 1 & for \quad t \le T \\ -1 & for \quad T \le t \le 2T \end{cases}$$

$$\Psi(x) = \min\{\phi(x,2T), \phi(x,0)\}$$

Difference between the Depth Measurements



- Previous work:
  - Euclidean distance to the outer hull

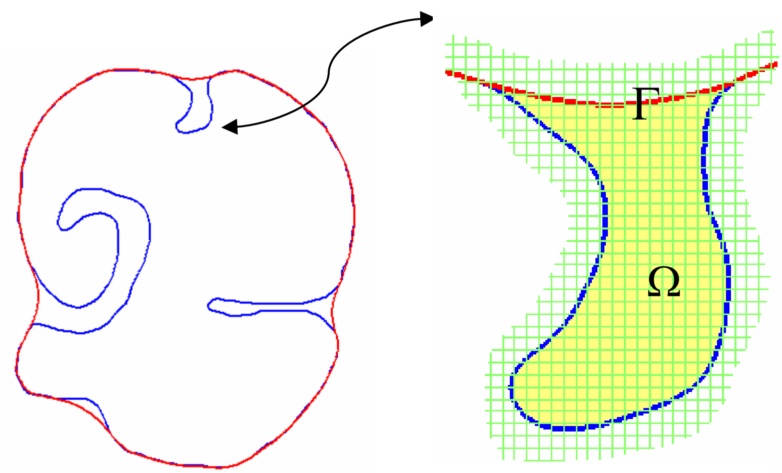
    $d(C) \cong d(D)$
  - Geodesic distance on surface

    $d(A) \cong d(B)$

- Propose a new geodesic depth measure of the pial surface s to the outer hull surface h

  $d(C) > d(B) > d(A) \cong d(D)$

2D Geodesic Depth Computation



- **Depth Calculation :**

  Calculate the geodesic distance to the outer hull surface (red) for all grids in the CSF region.

  Use Fast Marching Method

  or Fast Sweeping Method

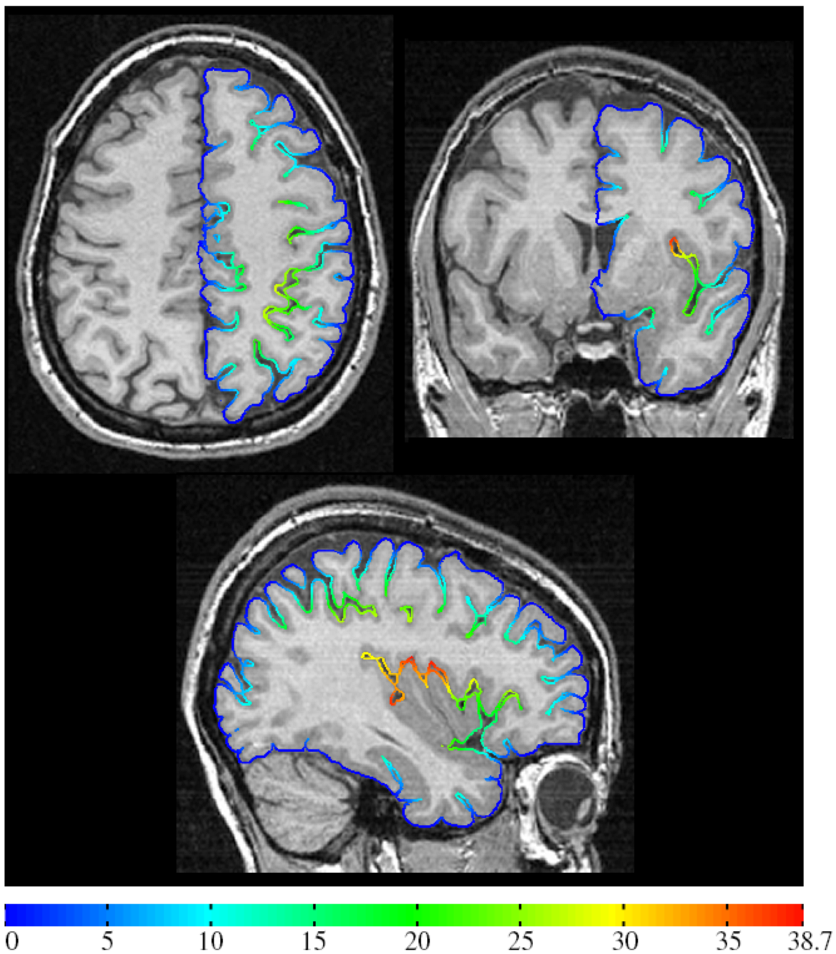
$$\sqrt{u_x^2 + u_y^2} = 1 \qquad for \quad u \in \Omega$$

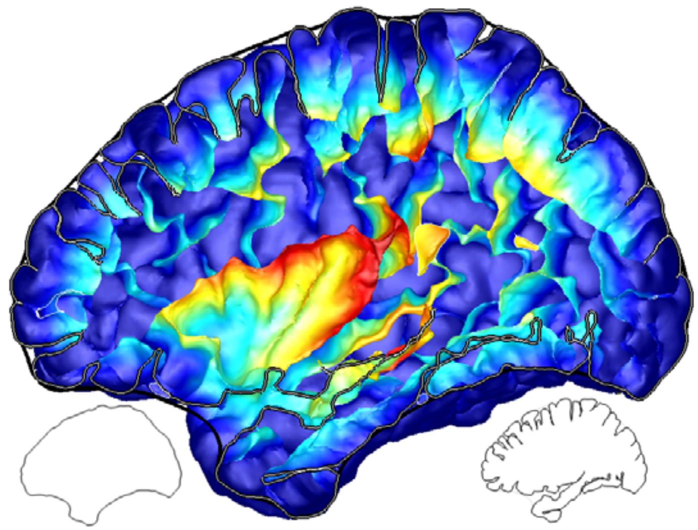
$$u(x, y) = g(x, y) \quad for \quad u \in \Gamma$$

- **Interpolation**

  Do bilinear interpolation to the points on the blue curve.

3D Geodesic Depth Computation

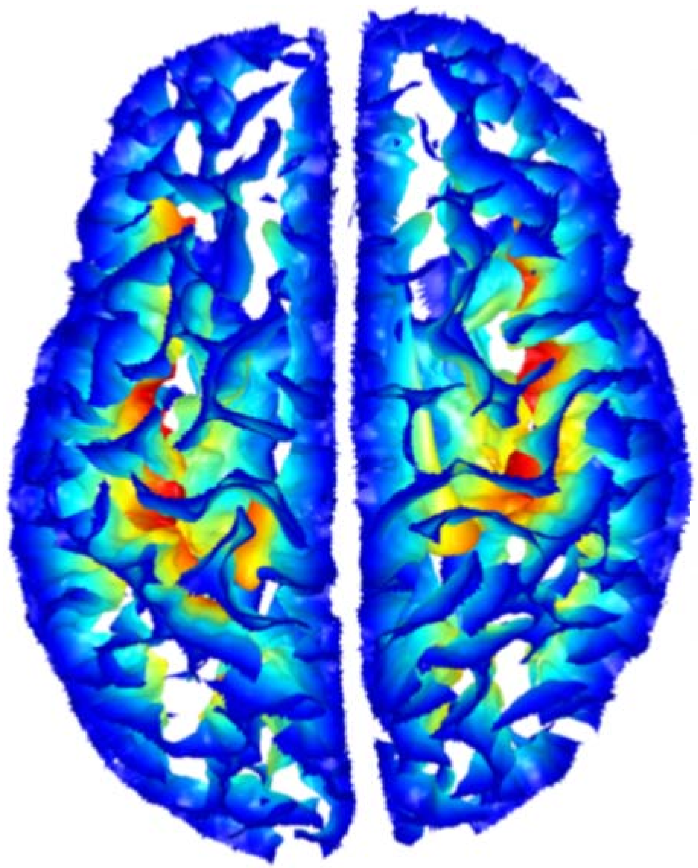




- **Interpolation**

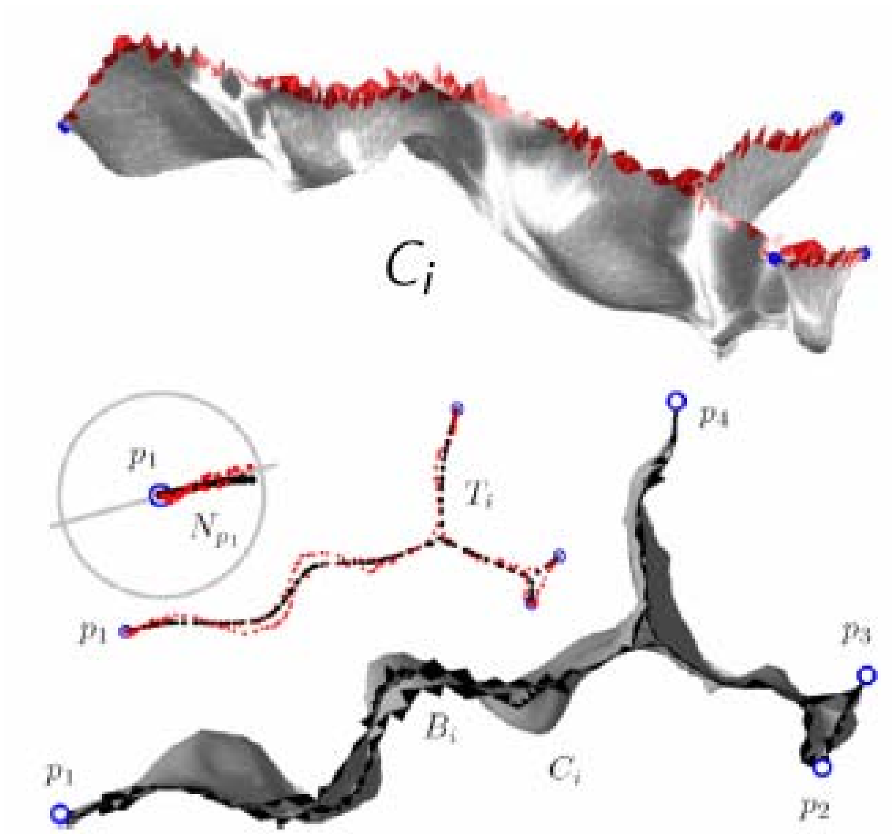
  Do trilinear interpolation to the barycenter of triangulated mesh.

Extraction of Sulcal Region



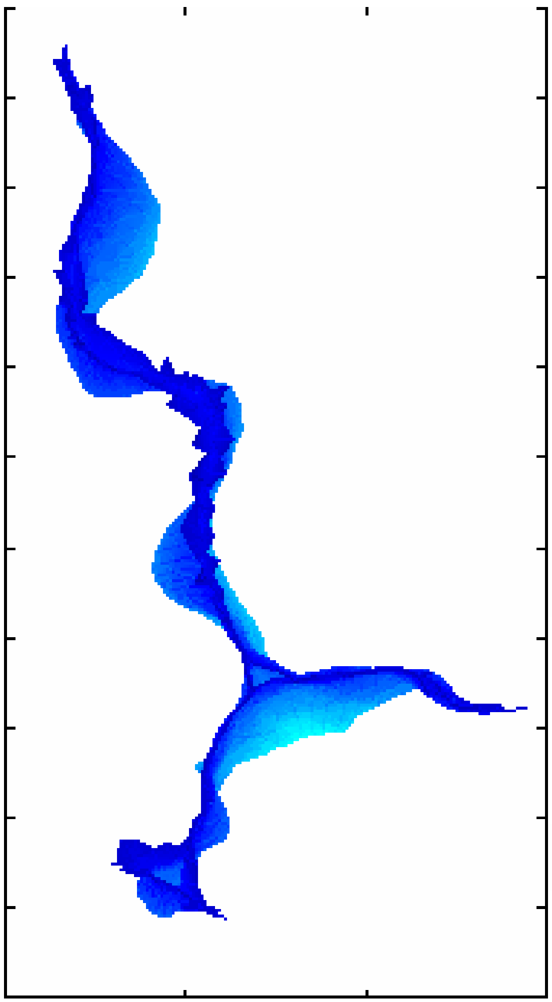
- Define the sulcal regions of the pial surface as those with a depth d larger than a depth threshold D
- In the literature, D is usually chosen 2-3 mm
- We use D = 2.5 mm
- Results in approximately 50 components per hemisphere

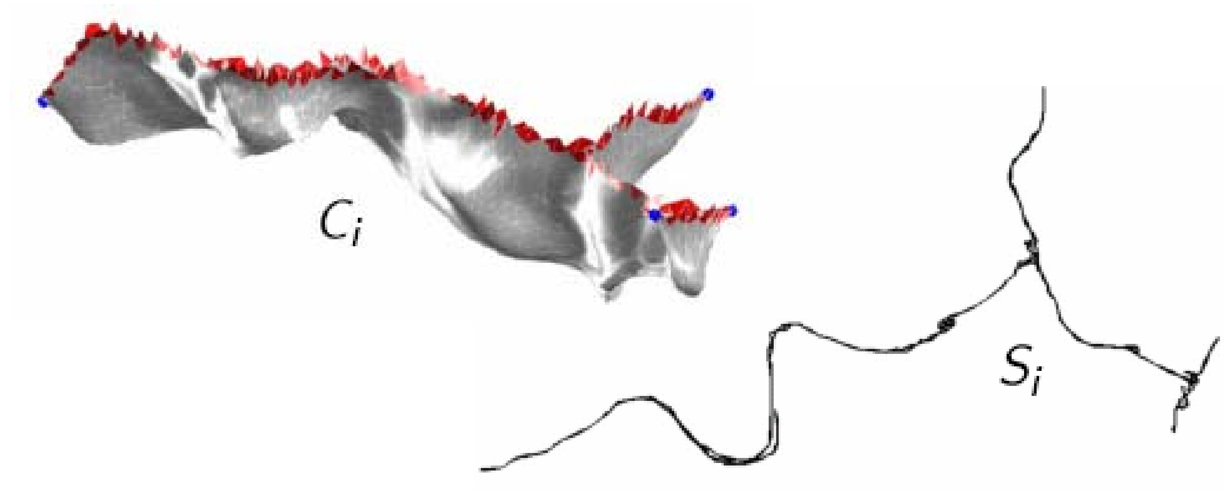
Sulcal Fundi Extraction



- For each barycenter of boundary triangles, we do the principle component analysis for points within a specified radius
- Identify 'endpoints' p_j of boundary of component C_i

Sulcal Fundi Extraction

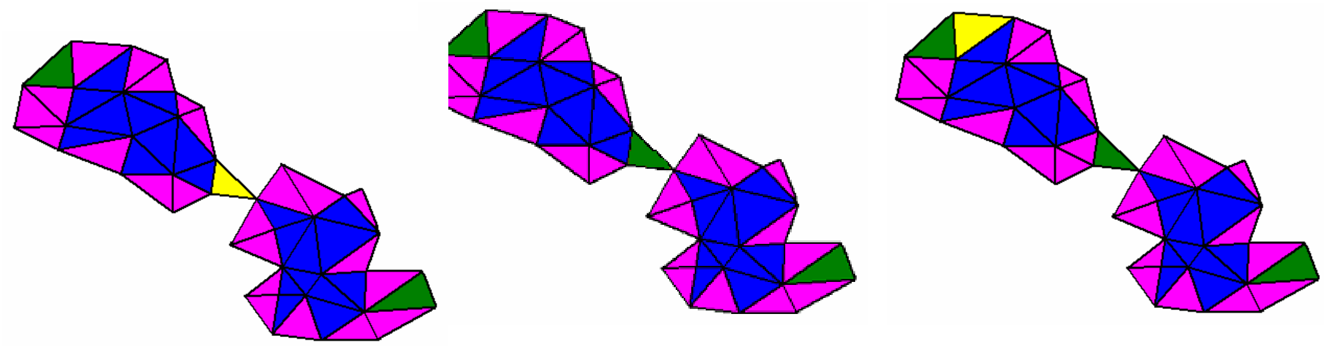




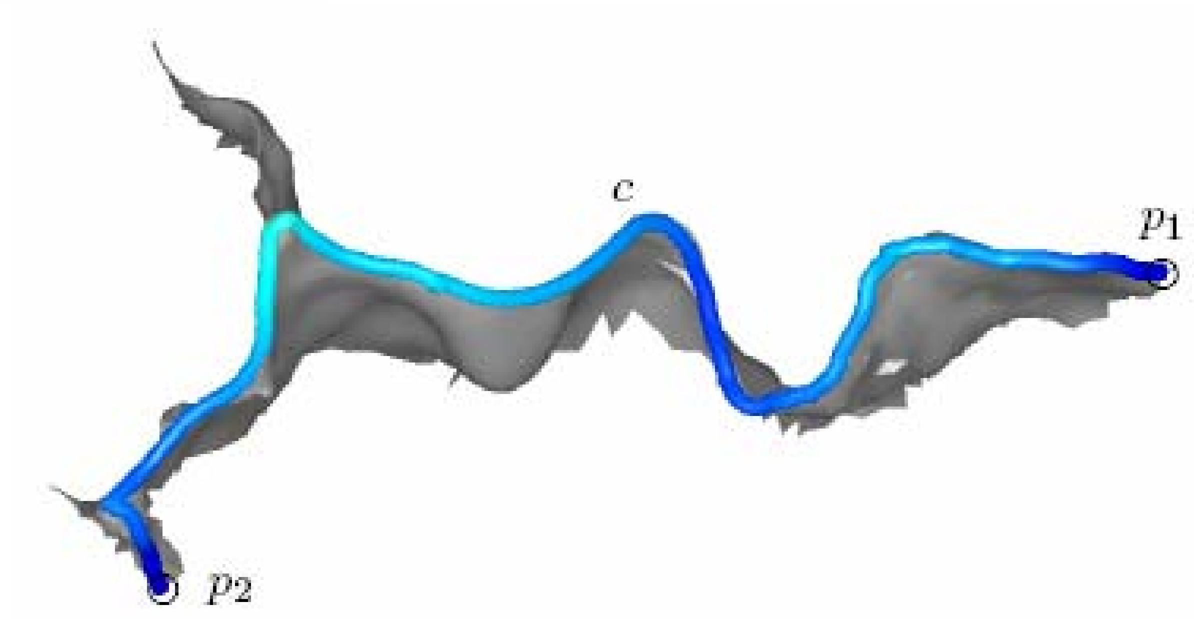
- Fix triangles corresponding to endpoints and run thinning algorithm to get the skeleton S_i of C_i as a connected set of triangles
- Minimum Spanning Tree of S_i typically has one long and several shorter branches

Sulcal Fundi Extraction

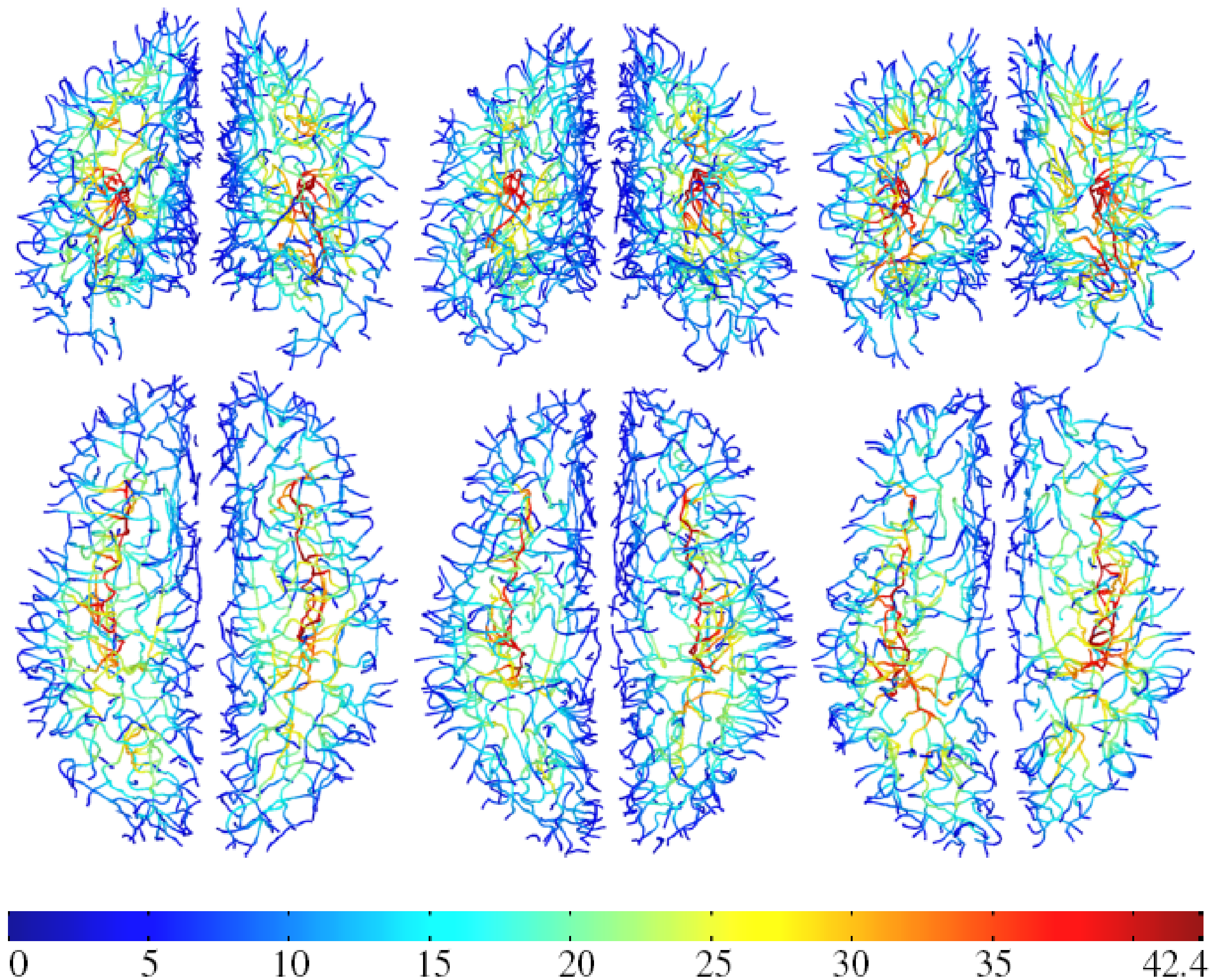
- Thinning Process



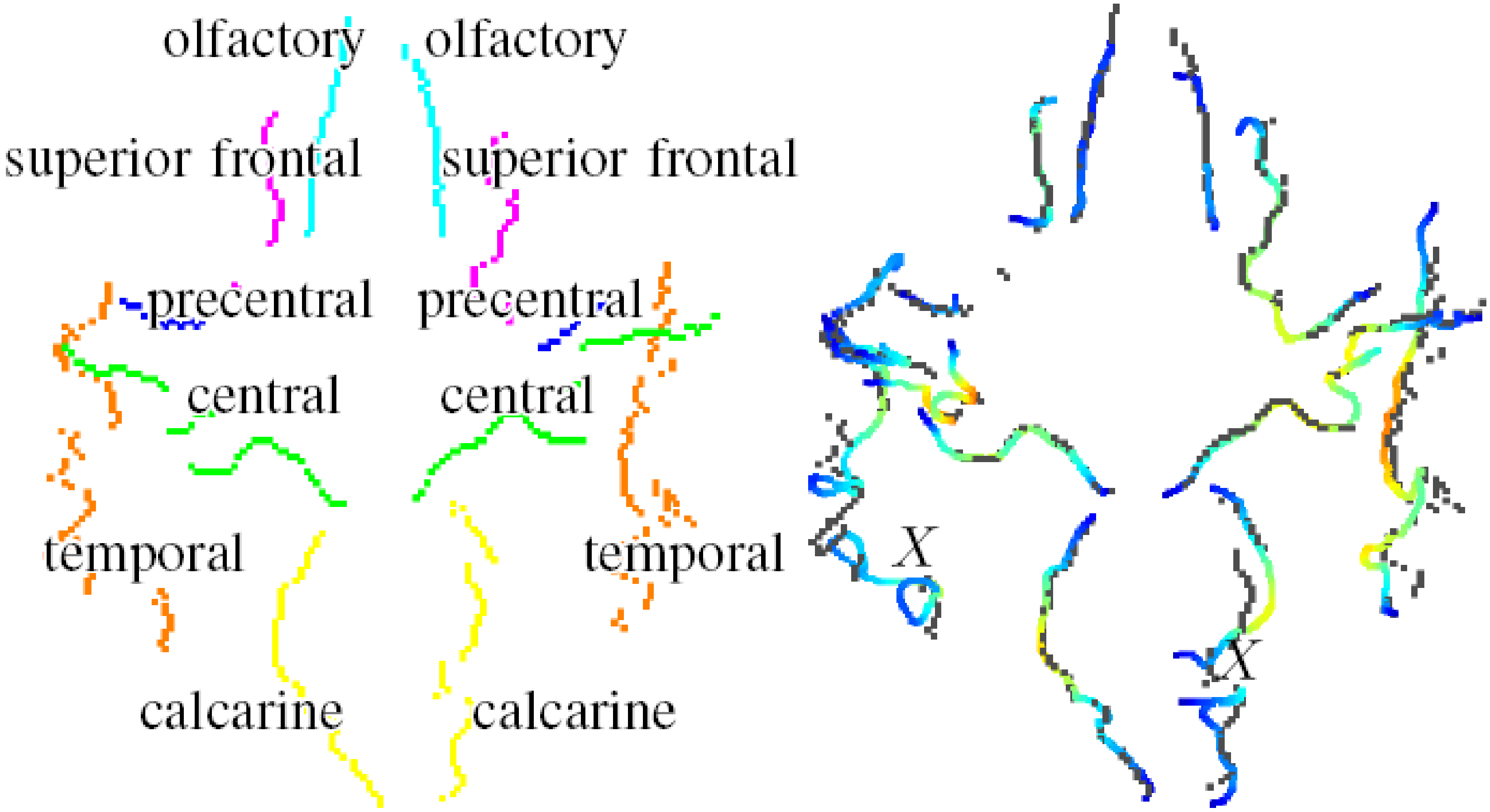
- Find the longest tree



Automatically extracted Sulcal Fundi



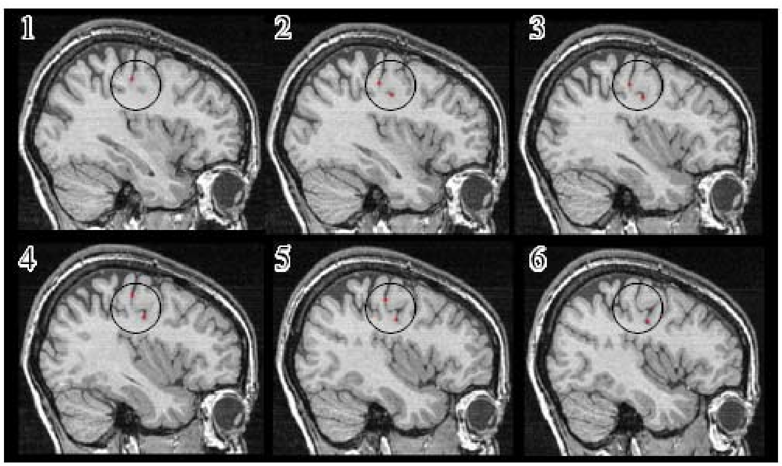
12 handmarked vs. automatic fundi

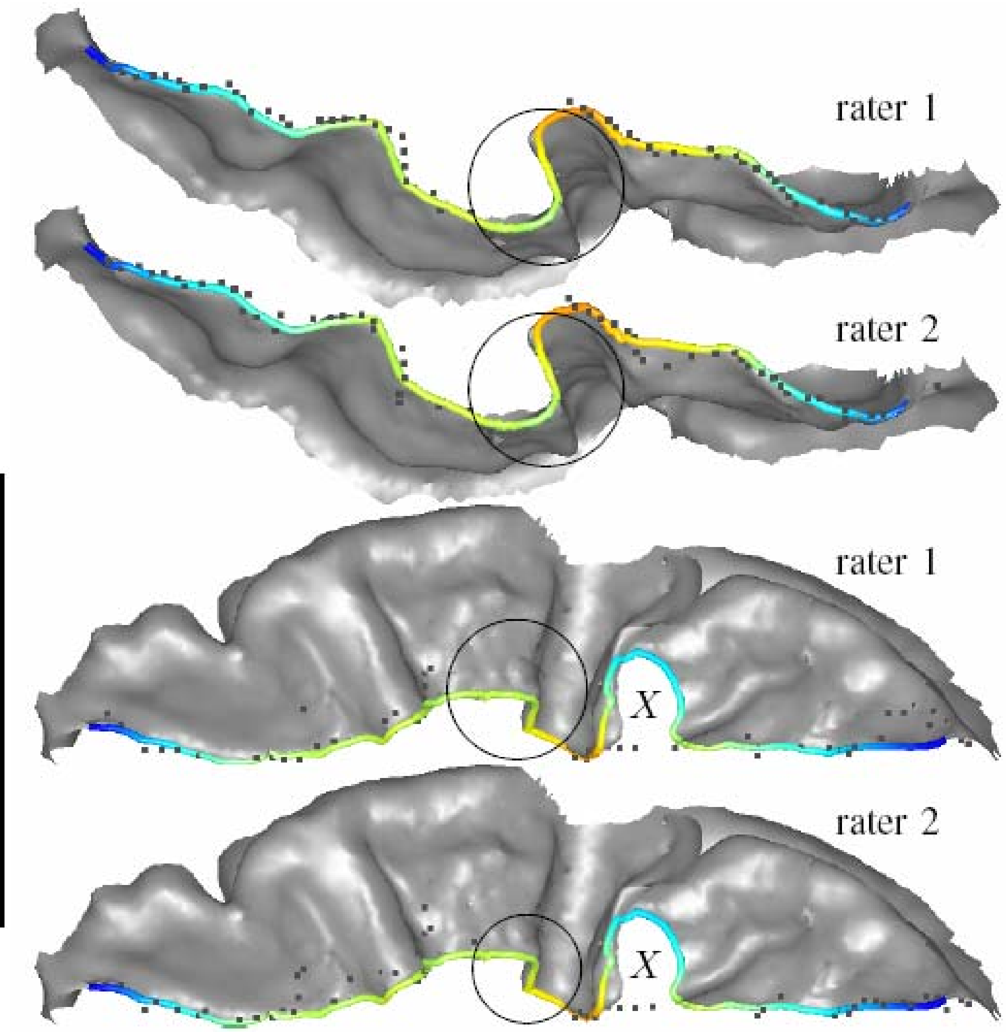


manually-labeled and automatically-labeled fundi

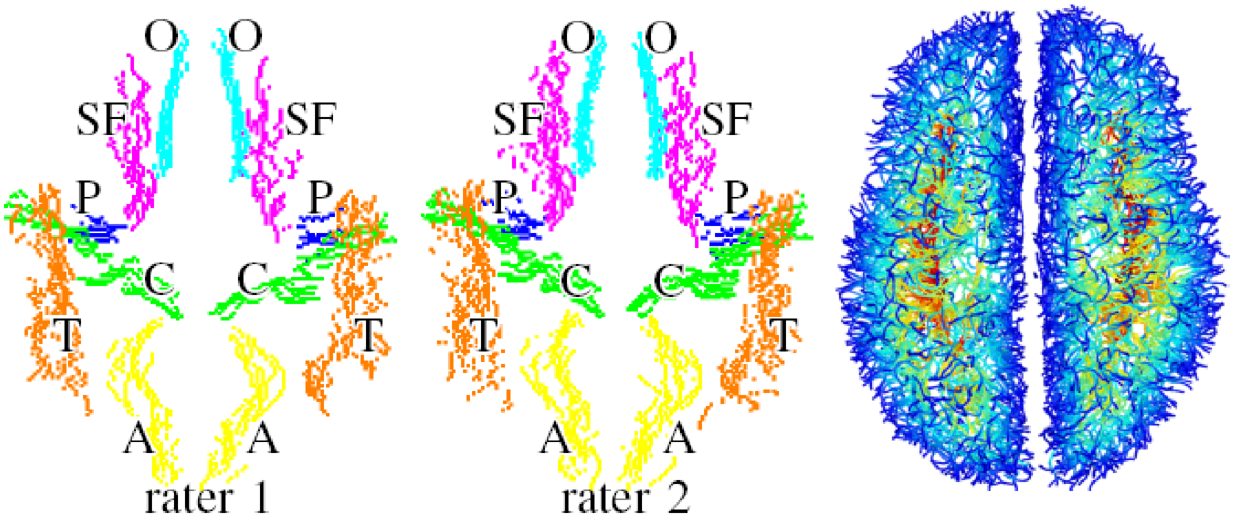
- **Central sulcus:**

  The automatically labeled sulcal fundus are continuous curves





Comparison on Six Brains



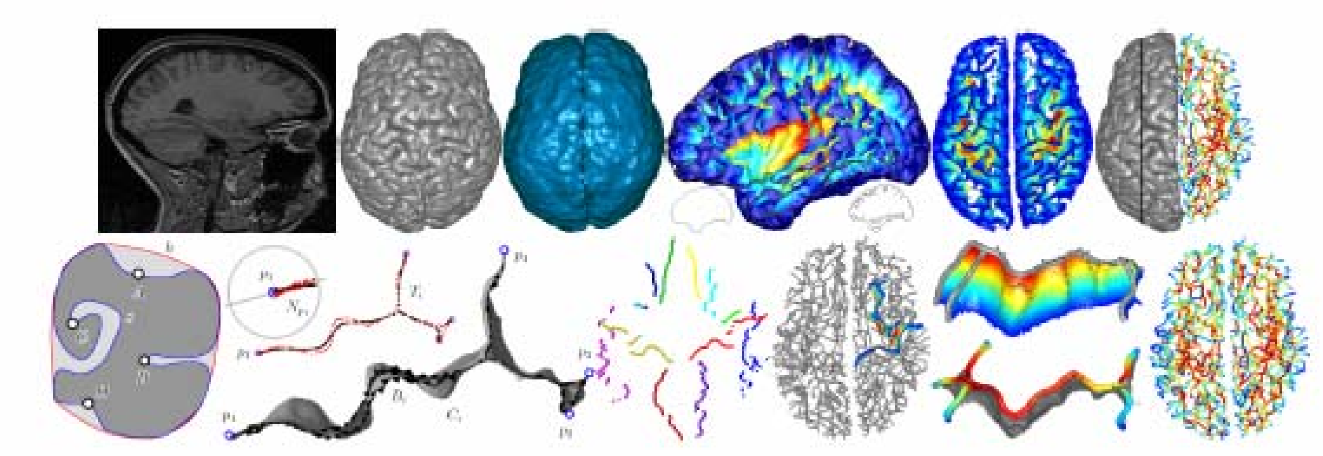
	calc.	cent.	olfa.	prec.	supe.	temp.
$\bar{n}$	54.5	63.5	45.7	15.5	48.4	82.0
σ_n	4.2	3.8	4.3	4.0	10.9	10.0
$\bar{r}$	1.0	1.1	1.0	1.8	2.5	2.4
σ_r	0.4	0.4	0.4	0.9	0.8	0.6
$\bar{m}$	86%	86%	87%	63%	52%	55%
σ_m	9%	9%	9%	28%	19%	11%

Open Questions & Future Plans

- Experts only agree on nomenclature for the major sulci (e.g. central and superior frontal)
- Secondary and tertiary sulcal patterns vary greatly from individual to individual
- Classification of our results into primary, secondary, tertiary sulcal fundi
- Automatic labeling of sulcal fundi
- Design surface warping based on the extracted sulcal fundi

Conclusion

- Sequence of geometric algorithms for automatic extraction of sulcal fundi from MR images
- Novel depth measure, high quality polyline representation of sulcal fundi
- Results are useful for downstream applications in computational neuroanatomy



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The End

Thank you for your attention!!

Questions??