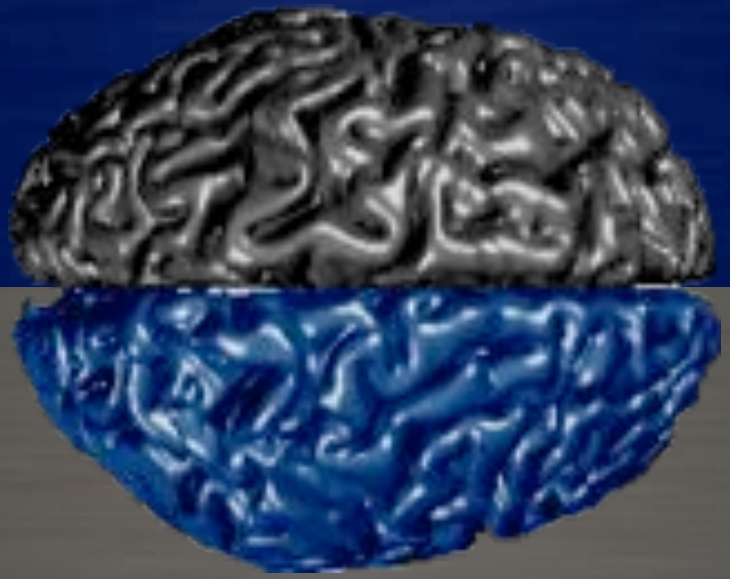
Surface Modeling & Analysis of Structural MRI Data



Rachel A. Yotter

Klinik für Psychiatrie
Friedrich-Schiller-Universität Jena

Outline

Introduction to surface meshes

- Motivation, Advantages

Pre-Processing for Group Analysis

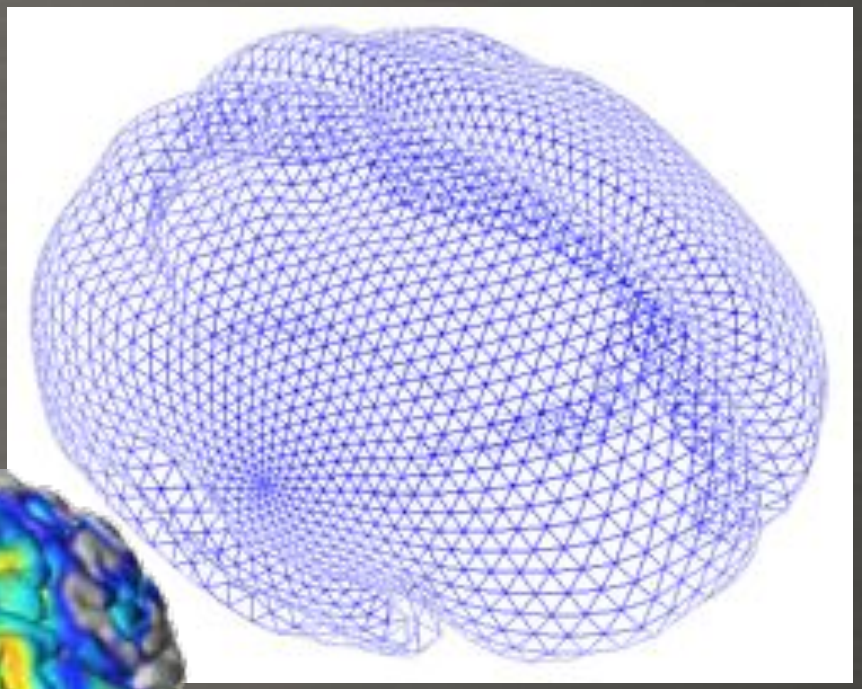
- Volumetric Data → Surface Mesh
- Spherical mapping
- Surface-based registration

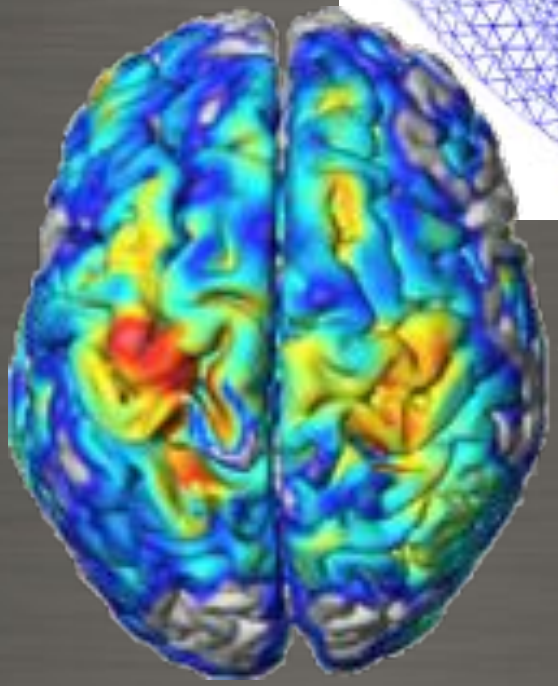
Surface Analysis

- Metrics: curvature, thickness, gyrification index, fractal dimension
- Research Highlights

Intro: What is a Cortical Surface Mesh?

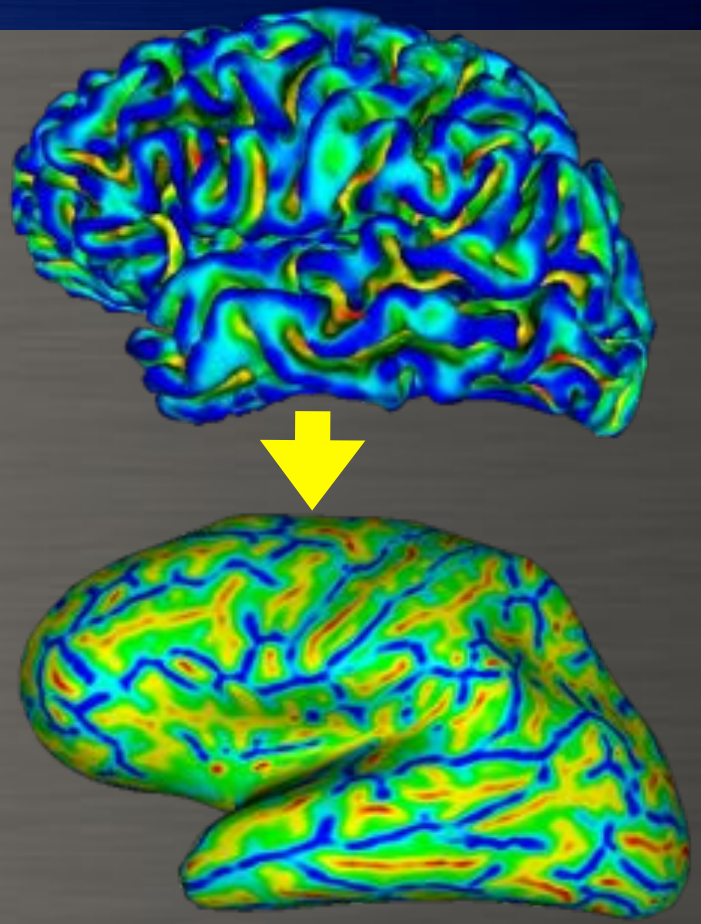
- List of triangular polygons
- Allows point-wise analysis





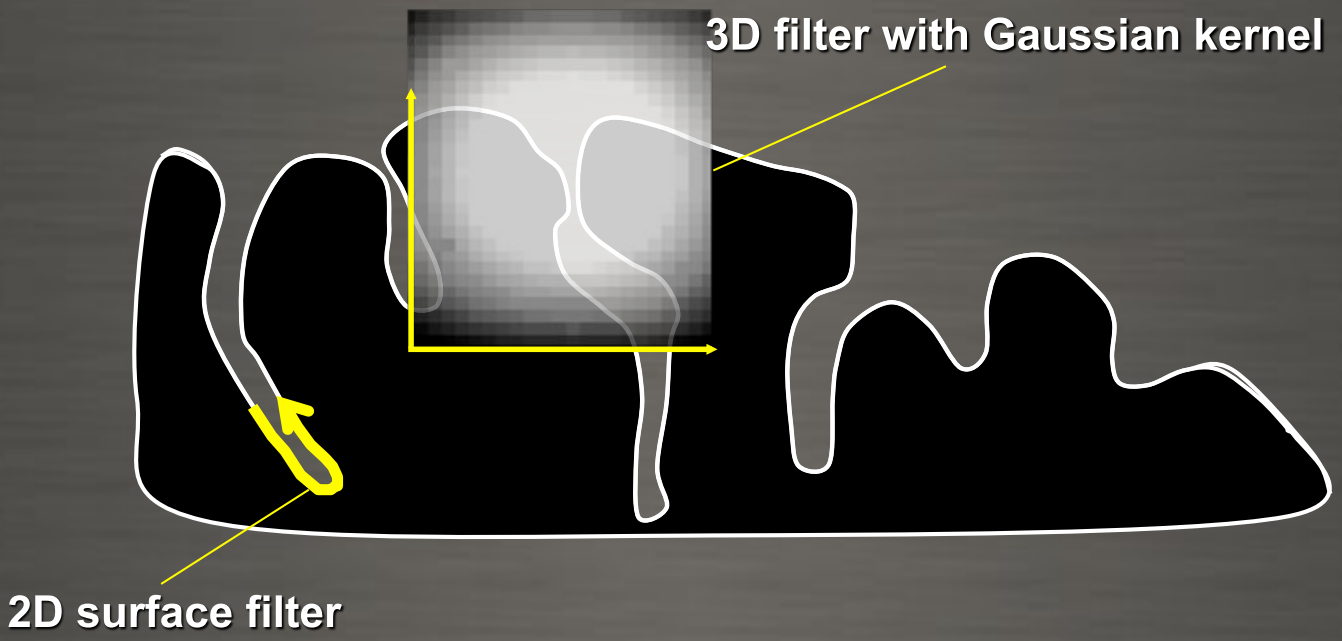
Intro: Motivation & Advantages

- Certain analyses are easier and more accurate
- Visualization
  - Surface maps (* spherical mapping)
  - Inflated surfaces
- More accurate intersubject registration
- New possibilities
  - Normalization
  - Smoothing (* next slide)
  - Surface averaging
  - Curvature
  - Gyrification index
  - Complexity
  - Spherical harmonic analysis – shape, databases, complexity, etc

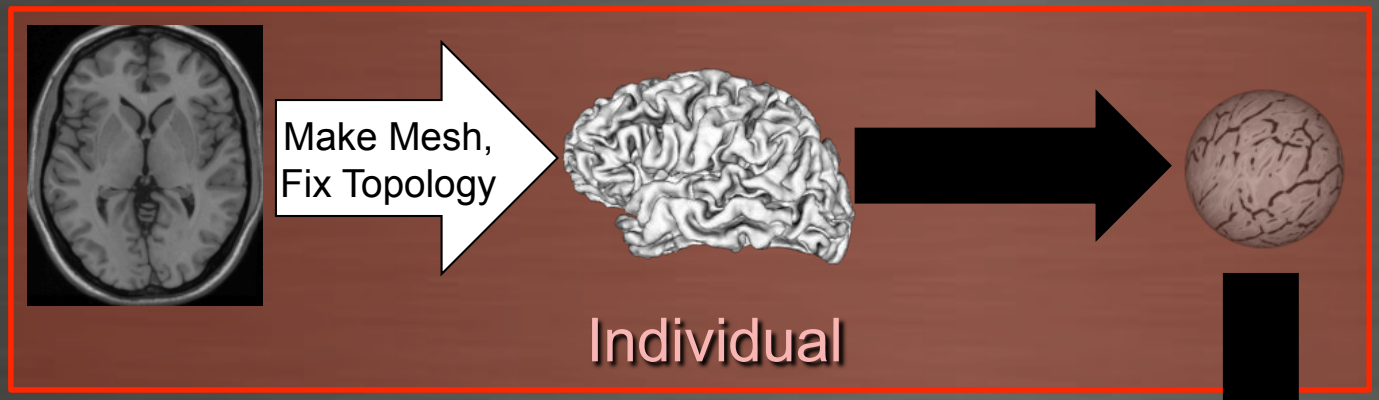


Intro: Surface Smoothing

Geodesic distances >> Euclidean distances



Pre-Processing: Surface Meshes

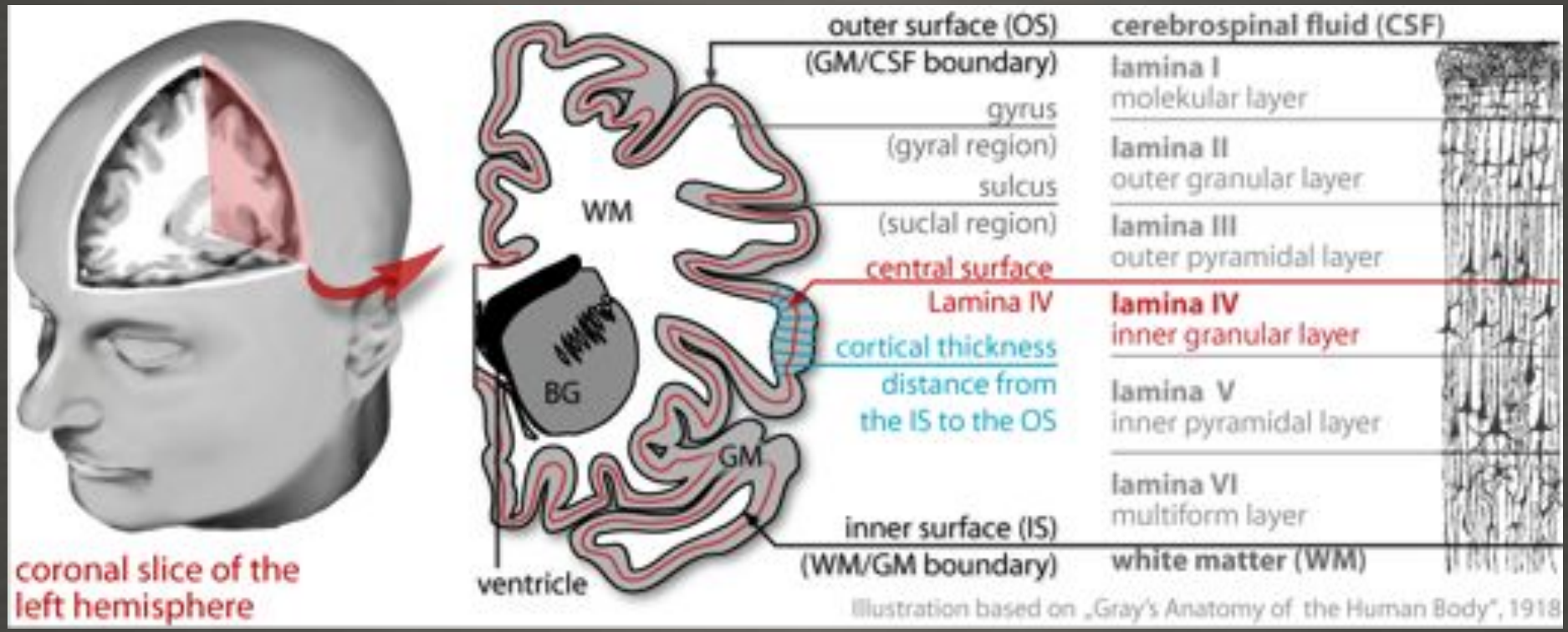


0. Segmentation
1. Make topologically correct mesh
   - Homeomorphic with a sphere

Pre-Processing: Building the Surface

Two main approaches

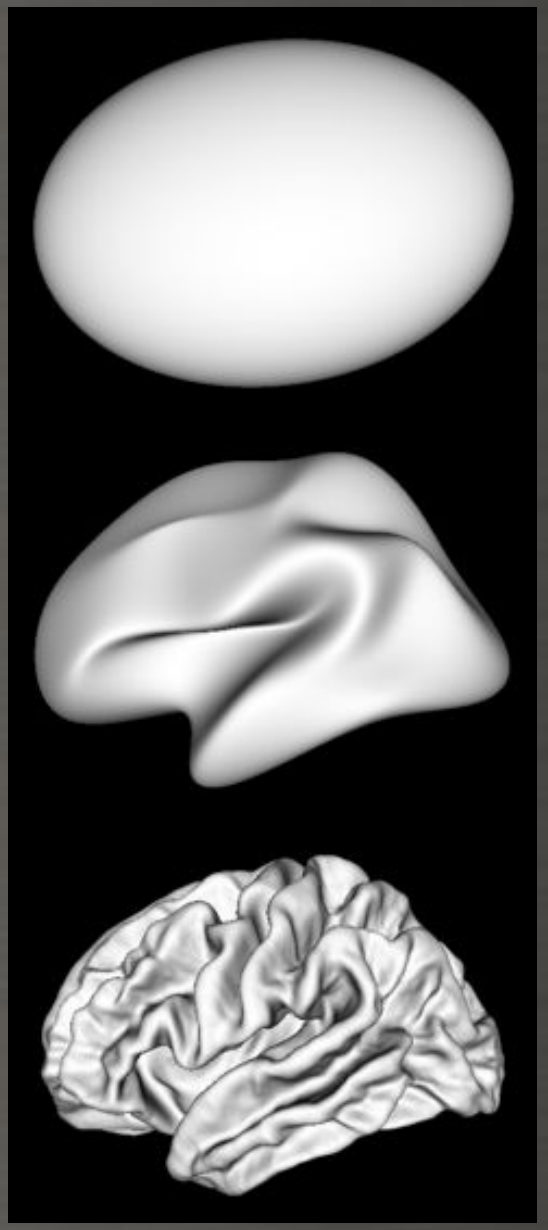
- Deformable Surfaces
- Marching Cubes



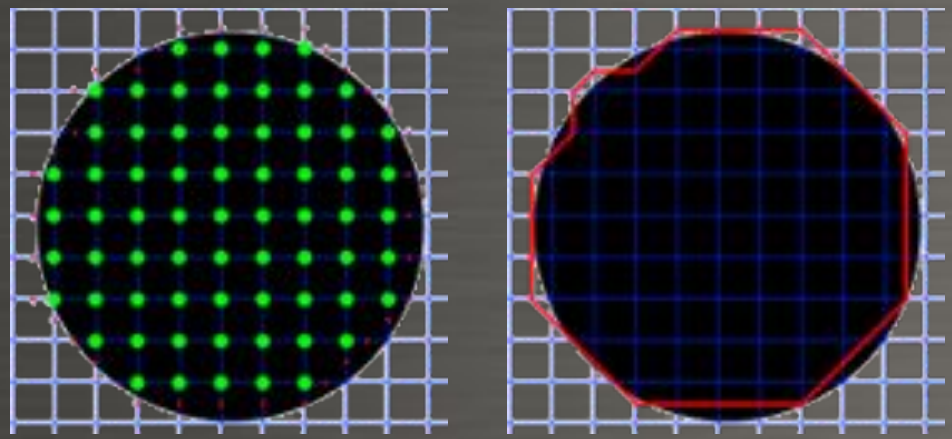
Pre-Processing: Deformable Surfaces

Start with sphere or simple shape, then deform to the GM/WM intensity boundary

- Potential problems:
  - Slow, depending on equation
  - May not reach full sulcal depths
  - Self-intersections possible
- Software: CLASP

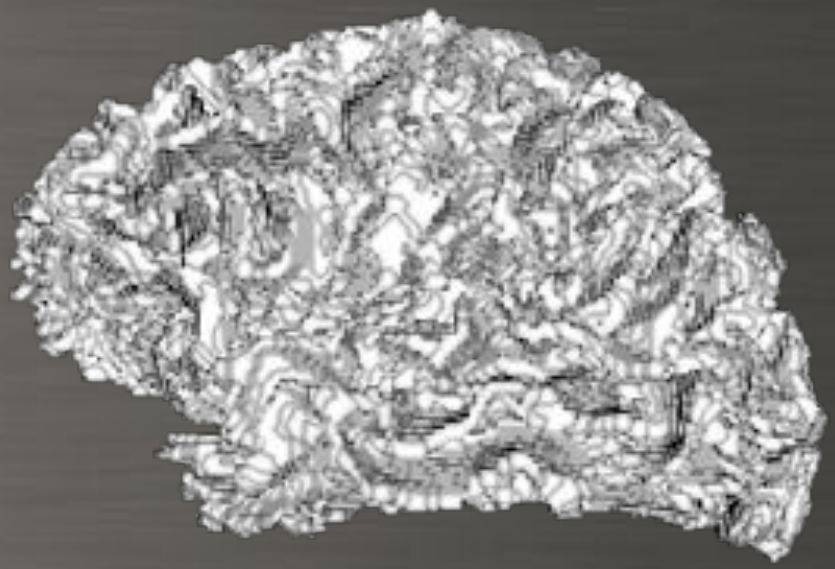


Pre-Processing: Marching Cubes



256 possible configurations

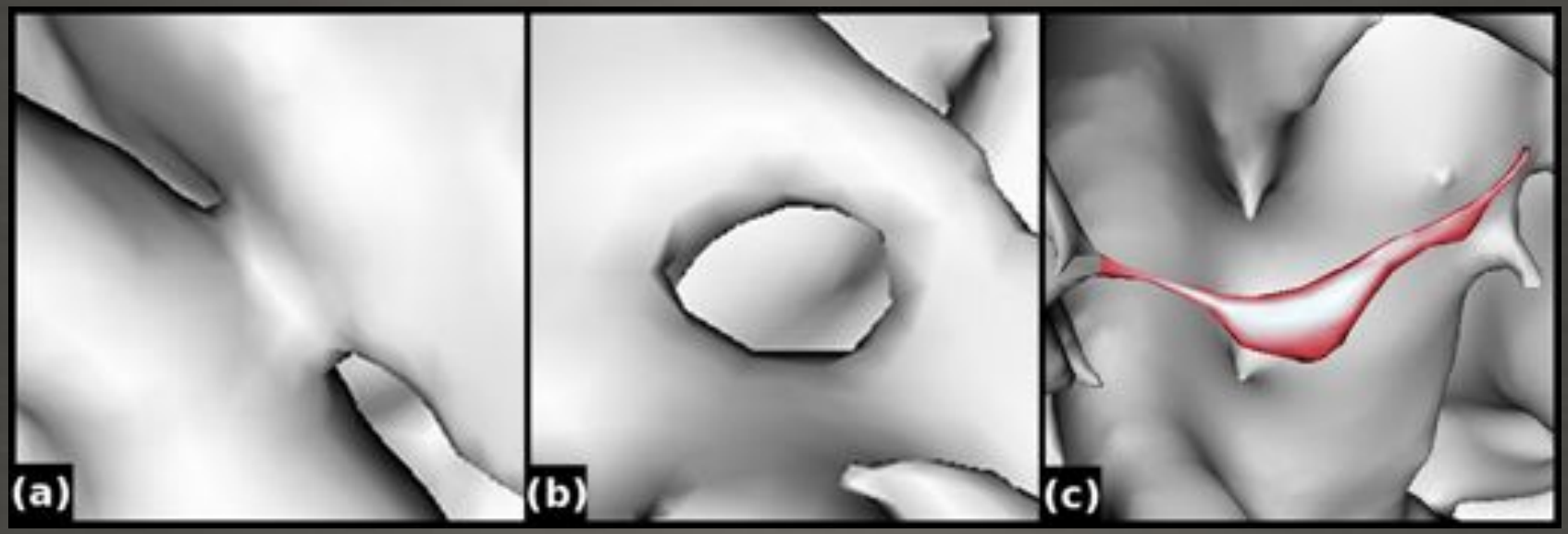
15 unique cubes



- Preserves geometry, but creates topological defects
- Software: FreeSurfer, CARET, BrainVisa (with modifications)

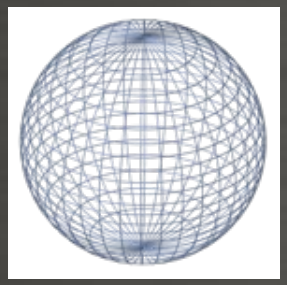
Picture sources: http://www.exaflop.org/docs/marchcubes/ & http://en.wikipedia.org/wiki/Marching_cubes

Pre-Processing: Topological Defects & Artifacts



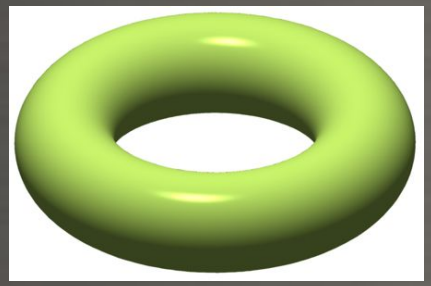
Goal: Euler Characteristic = 2

EC = Vertices – Edges + Faces



Sphere

2

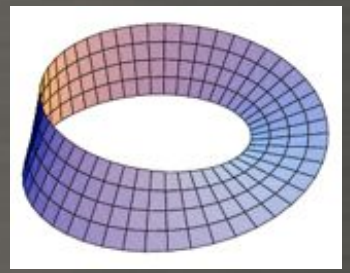


Torus

0

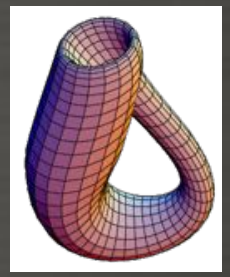
Double Torus

-2



Möbius Strip

0



Klein Bottle

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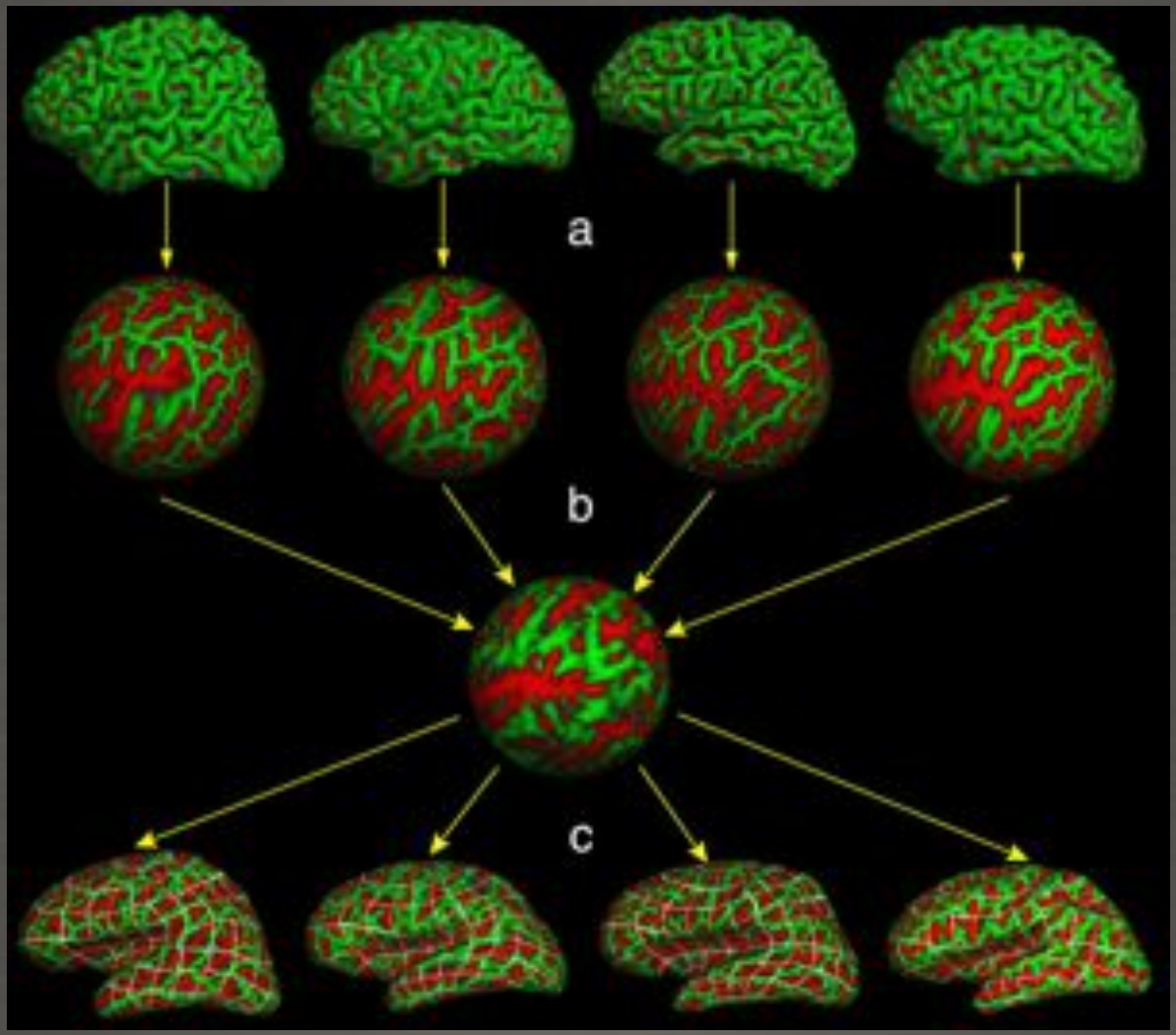
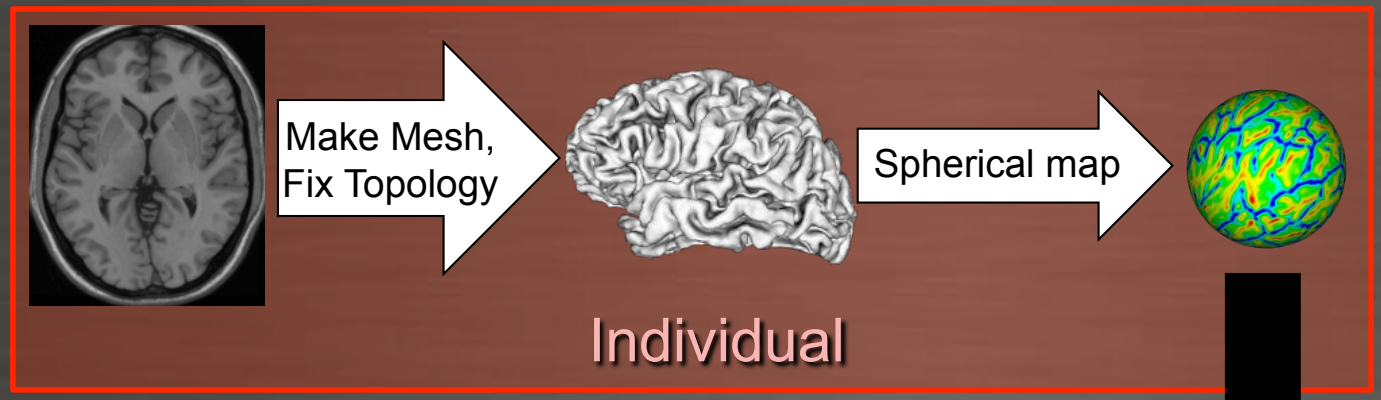
Picture source: http://en.wikipedia.org/wiki/Euler_characteristic

Pre-Processing: Spherical Mappings

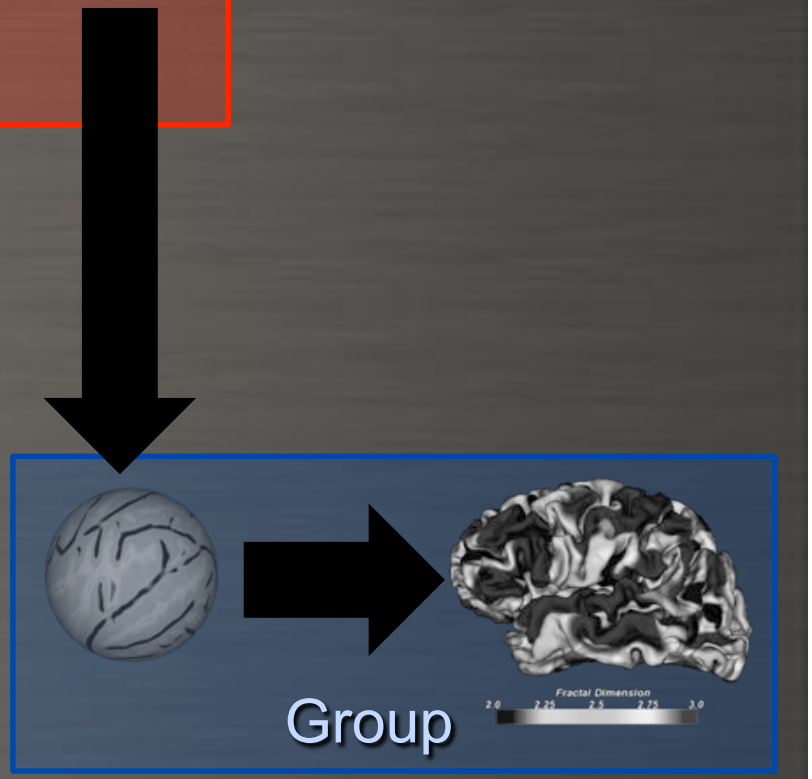
A Surface-Based Coordinate System



Picture source: http://surfer.nmr.mgh.harvard.edu/



2. Create a spherical map



Pre-Processing: Spherical Mapping

Ideal mapping – Isometric

- Conserves polygon areas & angles
- Impossible to achieve for brain surfaces

Mapping Strategies

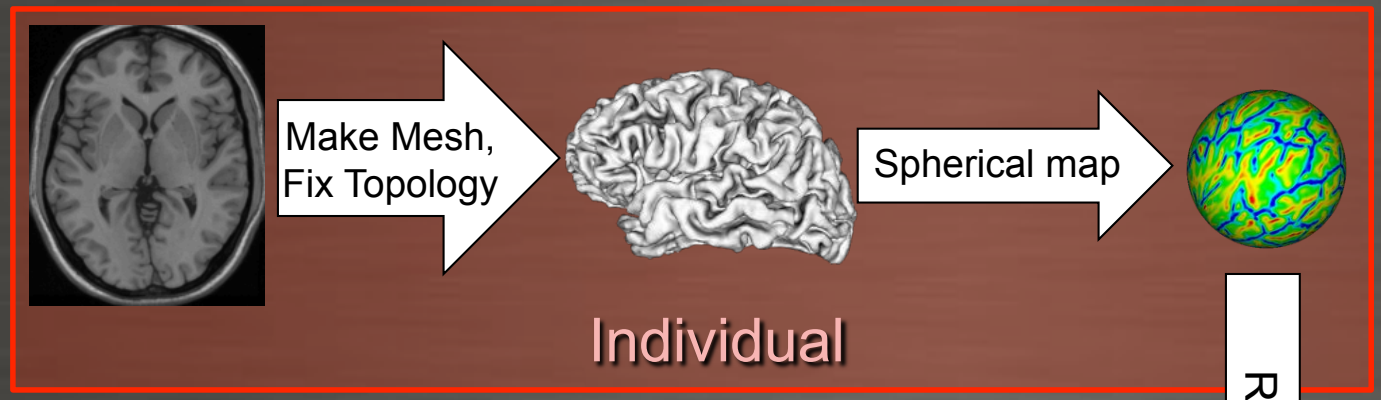
- Optimize one metric at the expense of others
- A non-linear optimization problem
- Angles – a “conformal” mapping; Laplace-Beltrami
- Areas – our method
- Edge lengths – usually minimize energy function

Why does the spherical mapping matter?

Changes re-parameterization quality

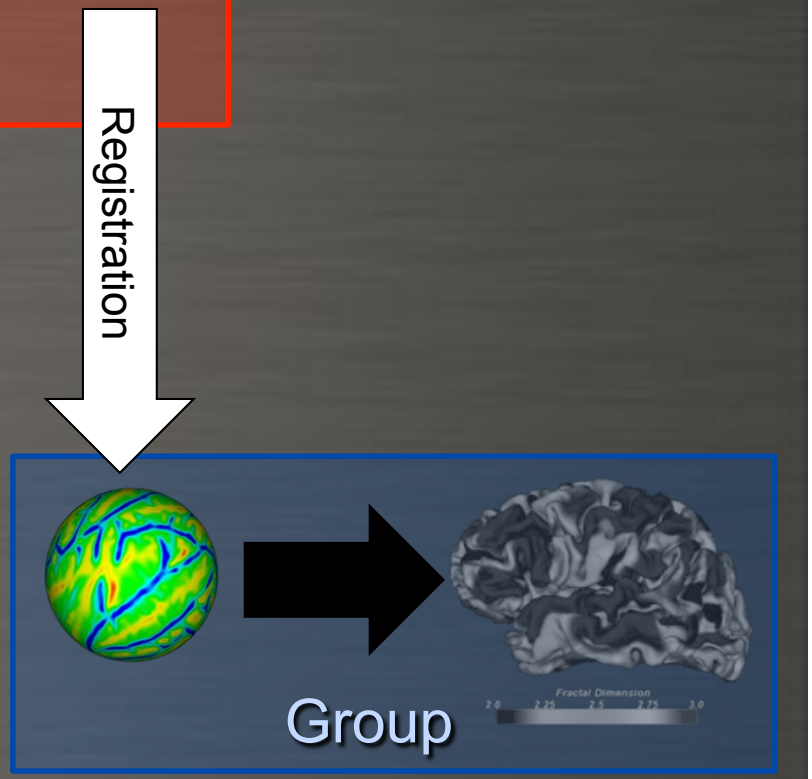
Table S1. Mean distance error and Hausdorff distances for 20 central surface meshes. *IC: Isometric Correction; LB: Laplace-Beltrami; SI1: Surface Inflation Method #1; SI2: Surface Inflation Method #2.*

			Mean Distance Error (μm)		Hausdorff Distance (mm)	
CS	IC	Resolution	Forward	Reverse	Forward	Reverse
LB		128	0.02038	426.82	0.000270	6.0328
	✓	128	0.02101	259.42	0.000264	4.1298
		256	0.02040	165.20	0.000368	4.4069
	✓	256	0.02100	91.69	0.000342	2.5390
		512	0.02040	65.53	0.000488	3.3872
	✓	512	0.02095	37.86	0.000447	1.4294
		1024	0.02040	29.13	0.000682	2.7374
	✓	1024	0.02100	18.26	0.000592	0.7993
SI1		128	0.02091	359.94	0.000311	7.0888
	✓	128	0.02070	276.59	0.000240	4.2255
		256	0.02090	142.24	0.000352	5.5824
	✓	256	0.02080	96.18	0.000342	2.2132
		512	0.02085	61.29	0.000452	4.0242
	✓	512	0.02085	39.41	0.000479	1.3857
		1024	0.02090	28.76	0.000643	2.6968
	✓	1024	0.02074	18.97	0.000649	0.8308
SI2		128	0.02073	283.32	0.000263	3.2064
	✓	128	0.02071	267.63	0.000257	4.0592
		256	0.02075	101.32	0.000371	1.8592
	✓	256	0.02085	94.13	0.000328	2.5713
		512	0.02080	41.45	0.000532	1.2474
	✓	512	0.02080	38.72	0.000418	1.4165
		1024	0.02075	19.84	0.000635	0.7925
	✓	1024	0.02072	18.68	0.000593	0.7781



3. Surface registration and re-parameterization

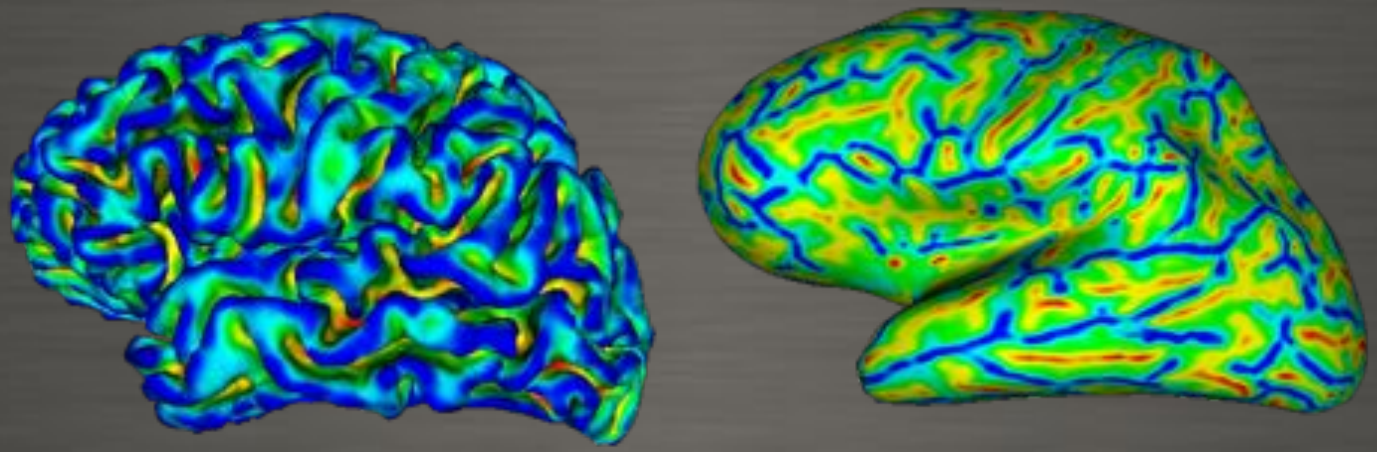
- Re-parameterized points correspond anatomically across subjects



Pre-Processing: Surface Registration

Step 1: Make a map (or maps)

curvature, sulcal depth, ??

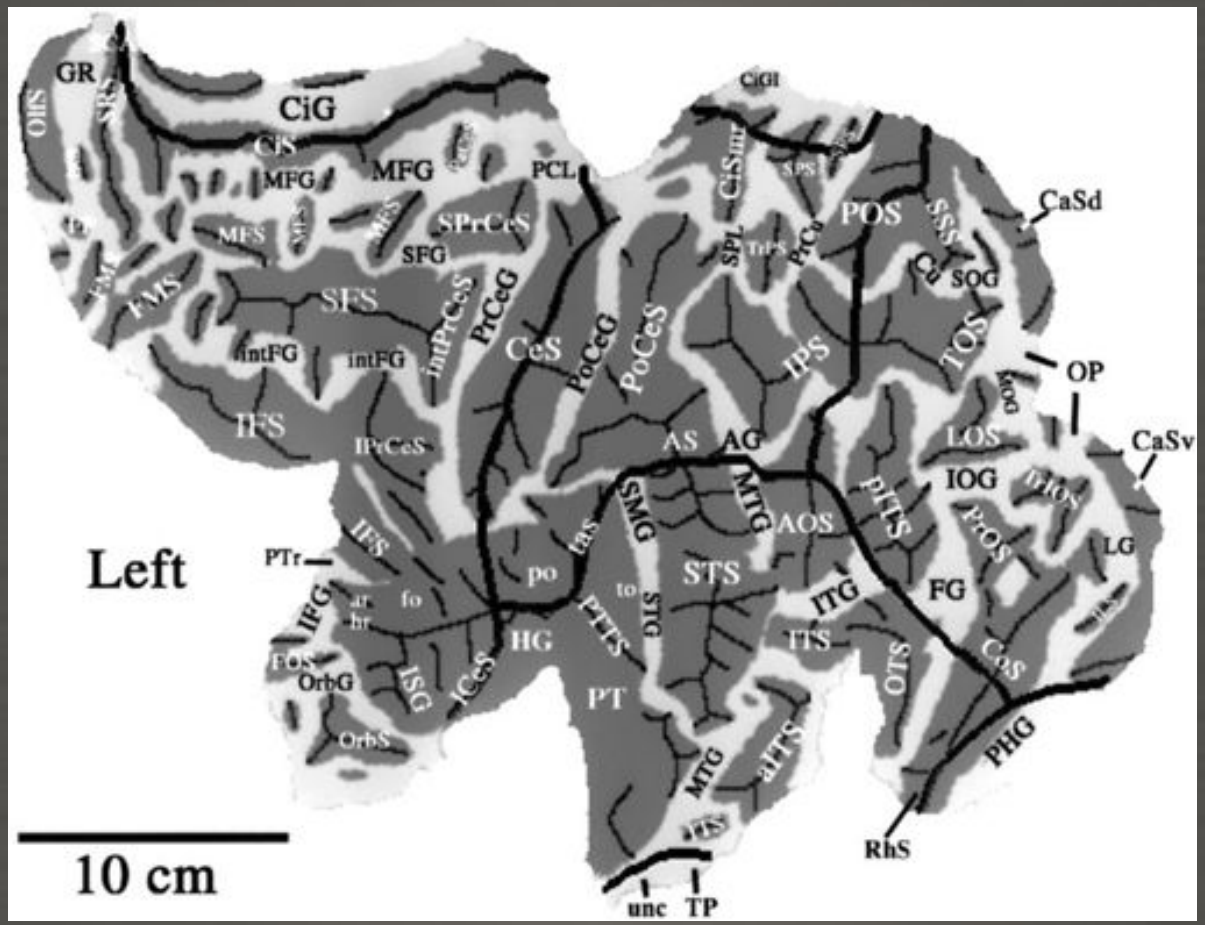


Step 2: Rough alignment

simple rotation, translation, scaling

Pre-Processing: Surface Registration

Step 3: Align to a (sulcal) atlas - Landmarks



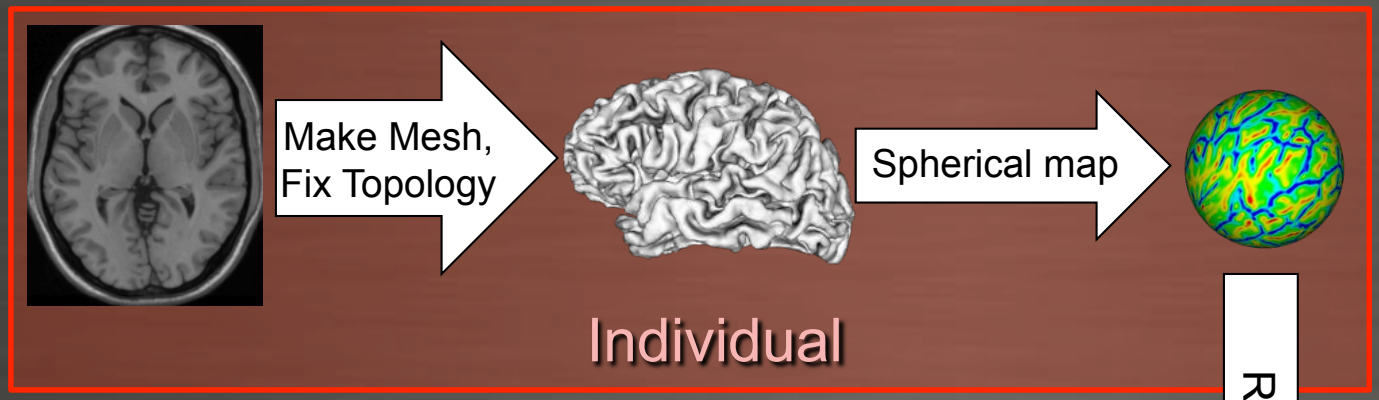
Picture source: van Essen, D.C., Drury, H.A., 1997. Structural and functional analyses of human cerebral cortex using a surface-based atlas. Journal of Neuroscience 17(18), 7079-7102

Pre-Processing: Surface Registration

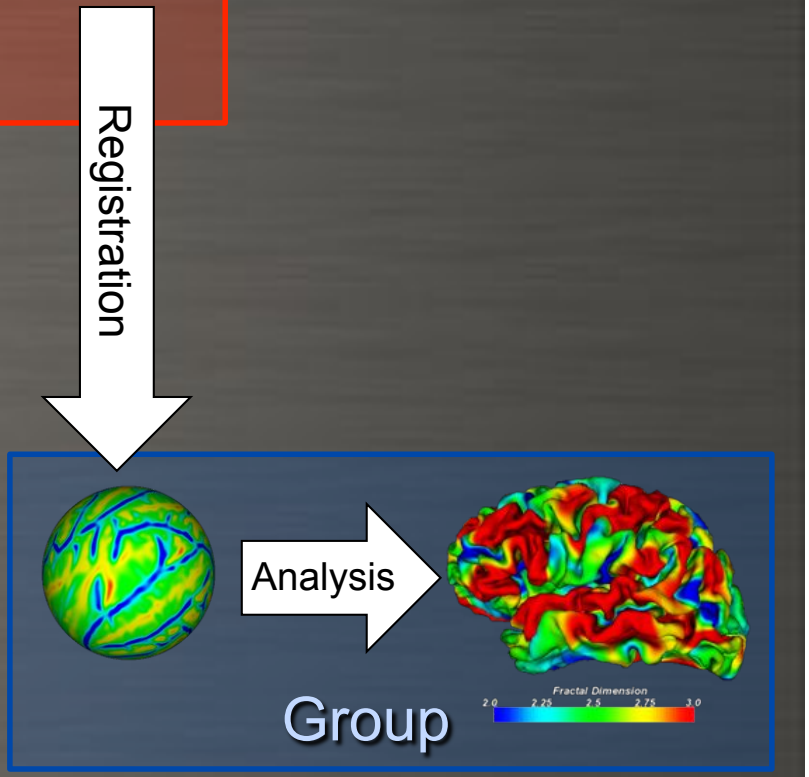
Step 4: Local alignment to reduce RMS error

- Elastic energy, fluid flow, diffeomorphisms
- Issue: deformations must be constrained to avoid flips

Analysis (Finally!)



3. Compute metrics in subject space
4. Re-parameterize metrics into group (registered) space



Surface-Based Analyses

Curvature

- Measure of convexity and concavity

Cortical Thickness

- Distance between GM/WM and pial surfaces

Gyrification Index

- A measure of convolution

Complexity

- Assume cortical surface is a fractal
- Measure self-similarity

Analyses using surface meshes

Complicated computation – what's the advantage?

Precision advantages:

- Better localization of fMRI data, at least along sulcal landmarks

New measurements:

- Cortical thickness, gyrification index, complexity

Neuroscience discoveries:

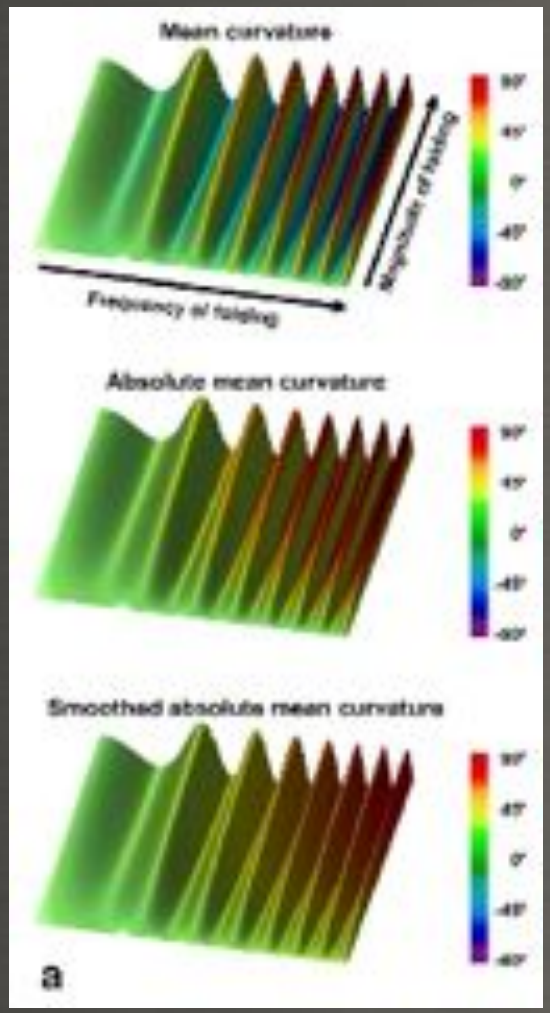
- Thickness and/or GI differences have been found for several disease states (schizophrenia, autism, Alzheimer's, etc), gender, development & ageing, experience (meditation), and IQ

Research Highlight: Schizophrenia & Gyrification

Gyrification Index

- Ratio of inner surface area to outer surface area
- Initially, measured manually from brain slices (Zilles et al., 1988) → 2D

Research Highlight: Schizophrenia & Gyrification



Surface-Based GI

- Full 3D measurement with ability to estimate local point-wise GI values
- Automatic, fast
- Luders et al., 2006; Shaer et al., 2008; many others

Research Highlight: Schizophrenia & Gyrification

Issues with Gyrification Index Measure

- Varying definition of the outer hull
- Often performed in 2D → may depend on slice direction & rater
- Normalization differences, dependence on noise
  - Example: “disorganized” subgroup tends to move more, introducing more noise and potentially increasing GI measure

Conflicting Results

- Findings of GI abnormalities for schizophrenia vary widely (see Yotter et al., 2011)

Research Highlight: Schizophrenia & Fractal Dimension

Potential Solution: Fractal Dimension

- Noise-resistant, no normalization, no outer hull definition
- Use spherical harmonic reconstructions to reduce re-sampling errors from the more standard box-counting approach

What are Spherical Harmonics?

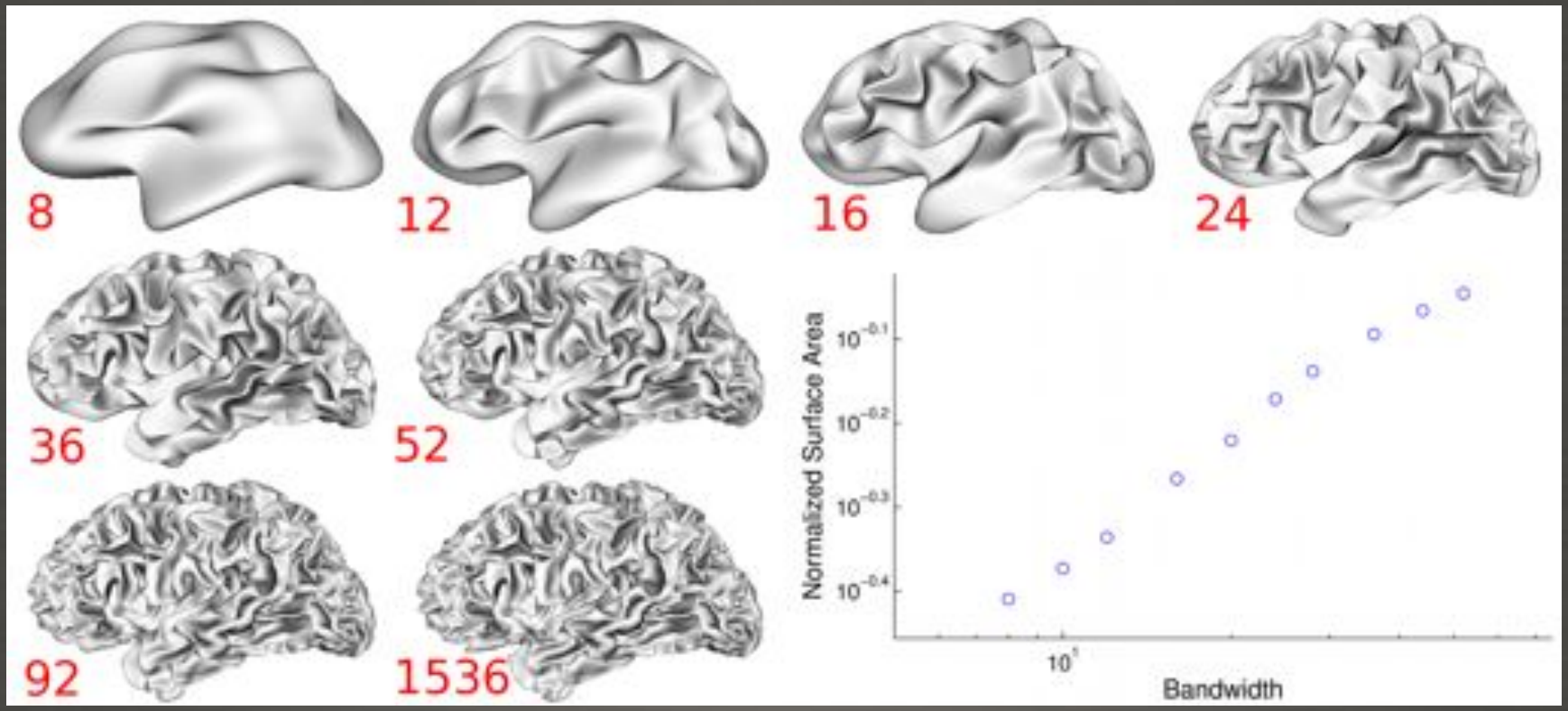
- Solution to Laplace's equation in spherical coordinates
- Essentially a Fourier transform on a spherical surface
- Solution using Legendre polynomials:

$$Y_\ell^m(\theta,\varphi) = N\, e^{im\varphi}\, P_\ell^m(\cos\theta),$$

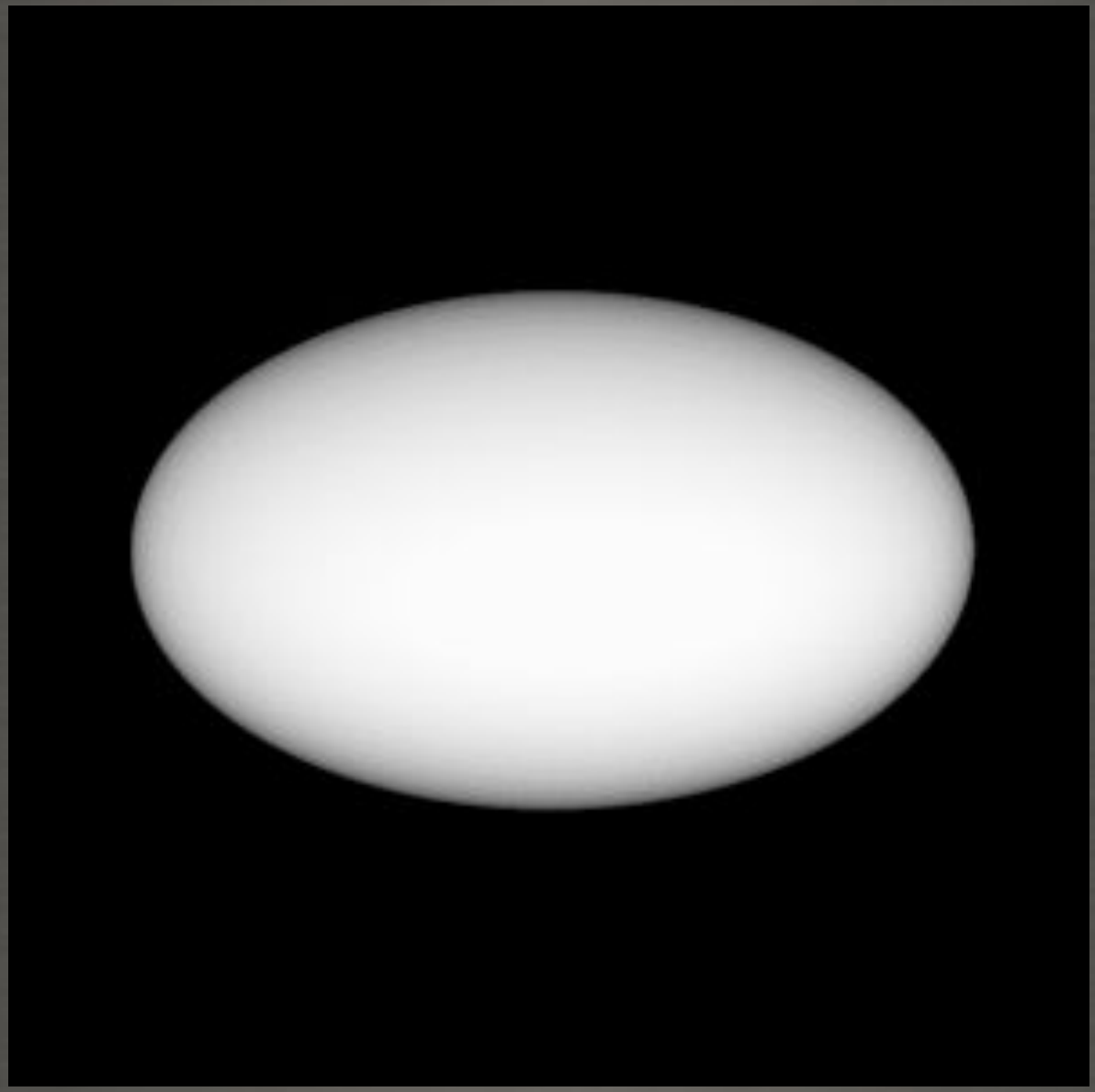
- General solution for ball centered at origin:

$$f(r,\theta,\varphi) = \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{\ell} f_\ell^m\, r^\ell\, Y_\ell^m(\theta,\varphi),$$

Research Highlight: Fractal Dimension

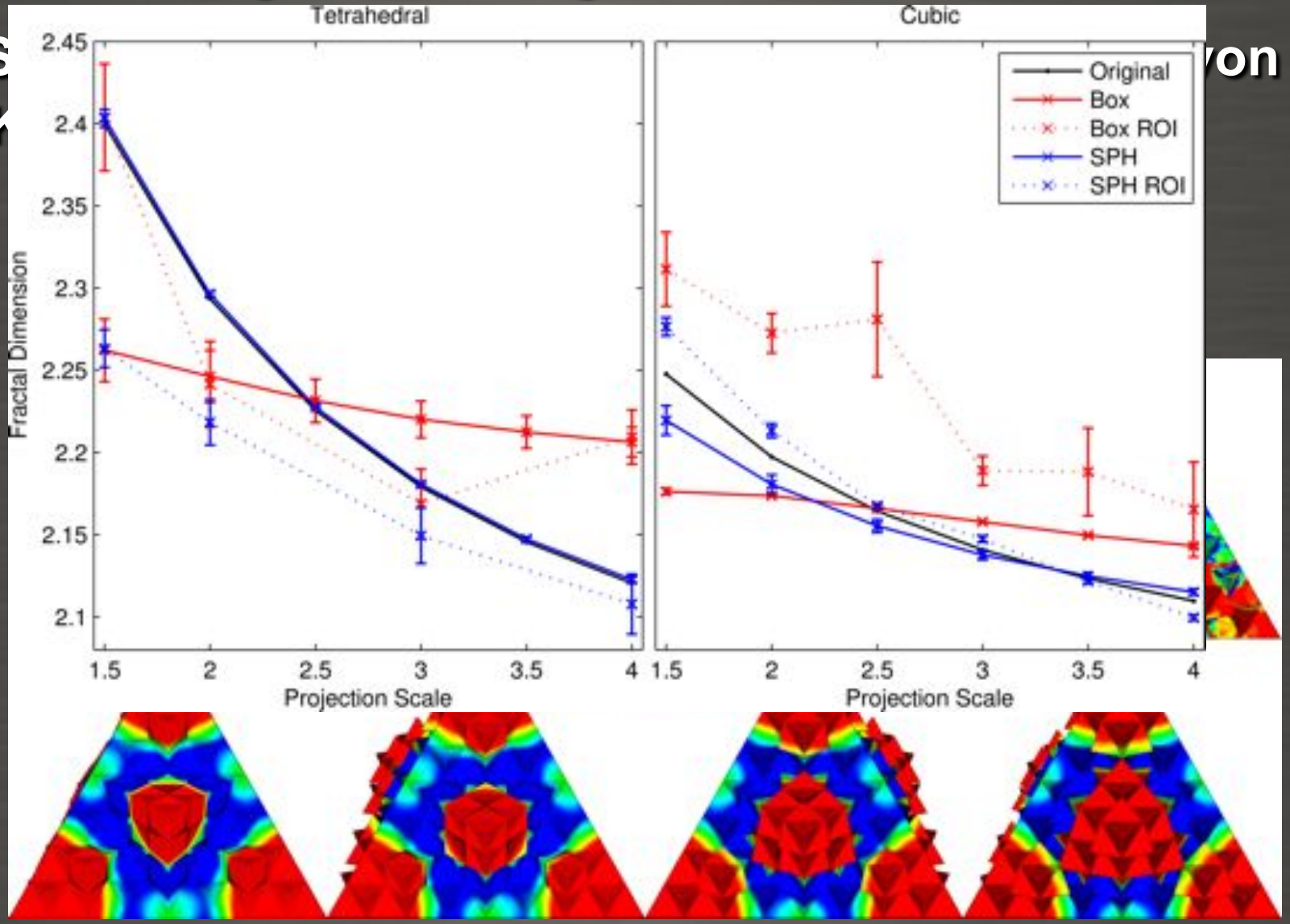


Research Highlight: Fractal Dimension



Research Highlight: Fractal Dimension

1. Local, regional, and global measurements
2. S… von K…

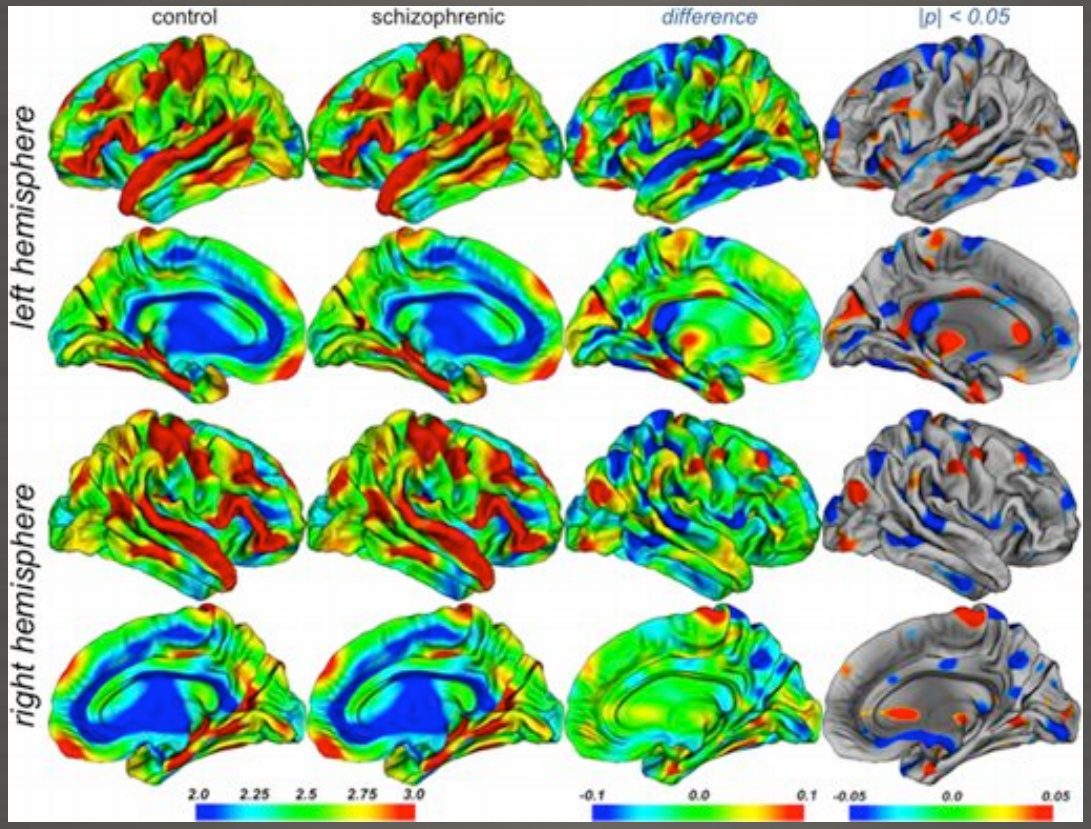


Research Highlight: Fractal Dimension

Application of new method to schizophrenia

Global right hemi < Global left hemi

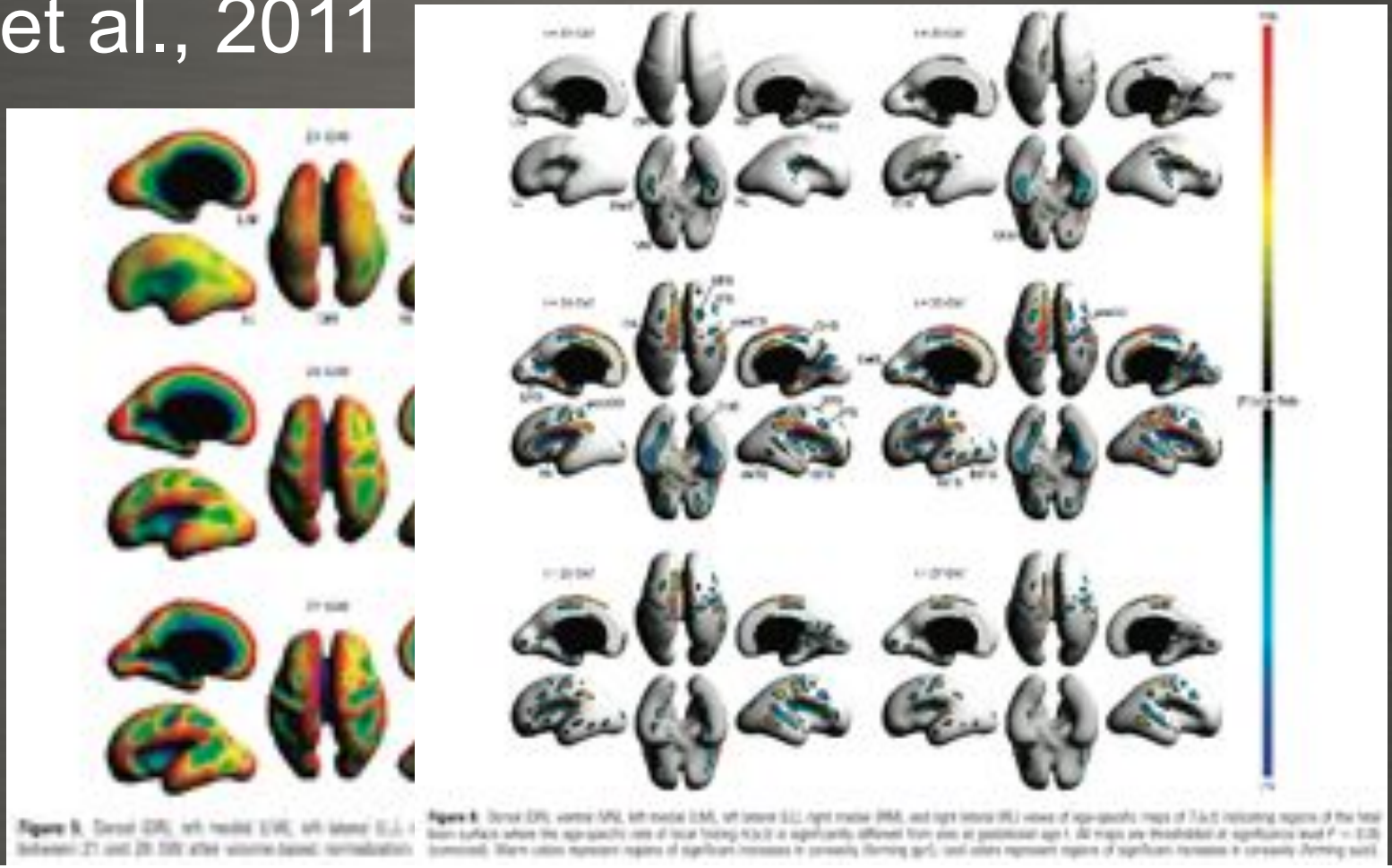
Otherwise... No significant differences



Research Highlight: Development

Cortical Curvature Analysis of Fetal Data

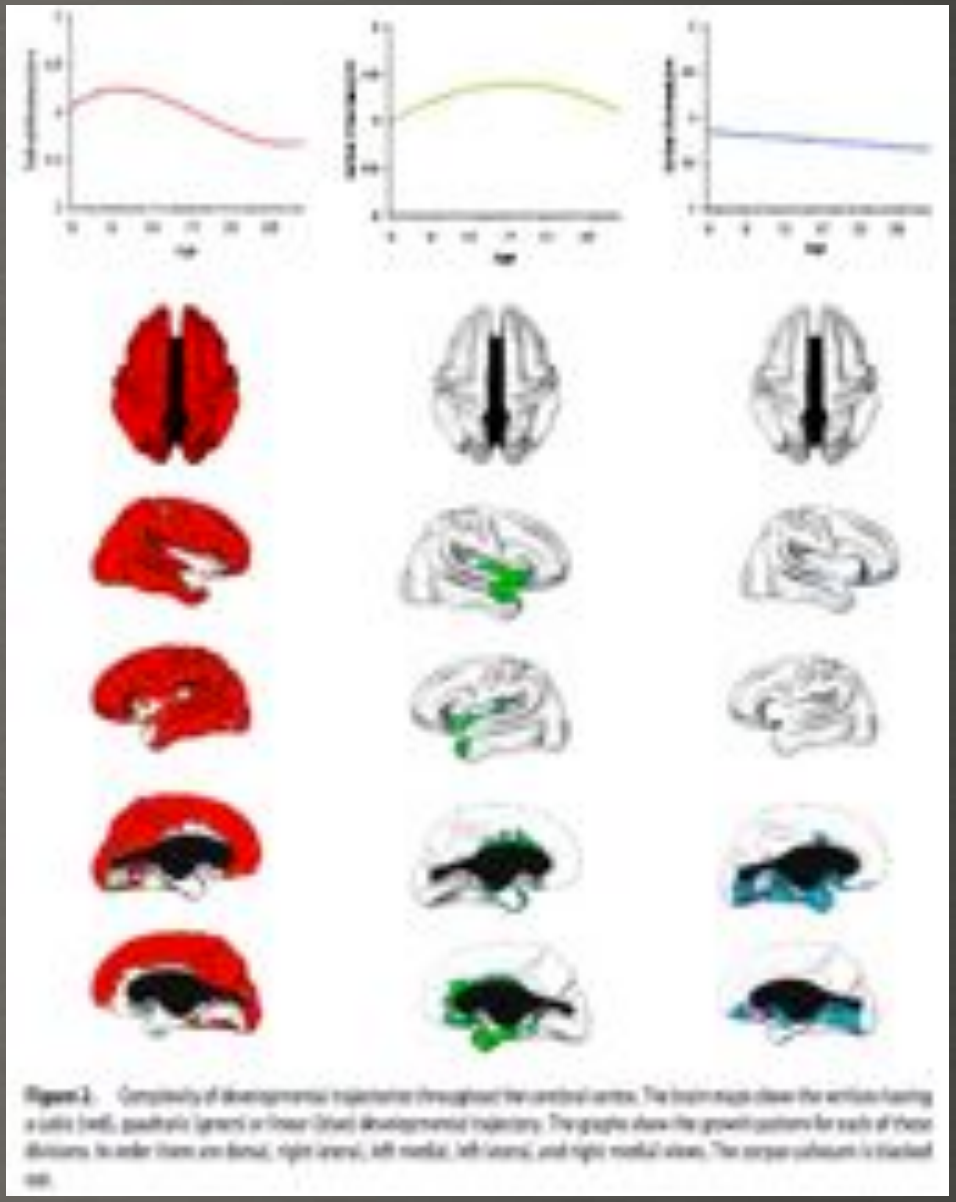
- Subjects: 21-28 gestational weeks (GW)
- Habas et al., 2011



Research Highlight: Development

Cortical regions have varying development trajectories for GM thickness

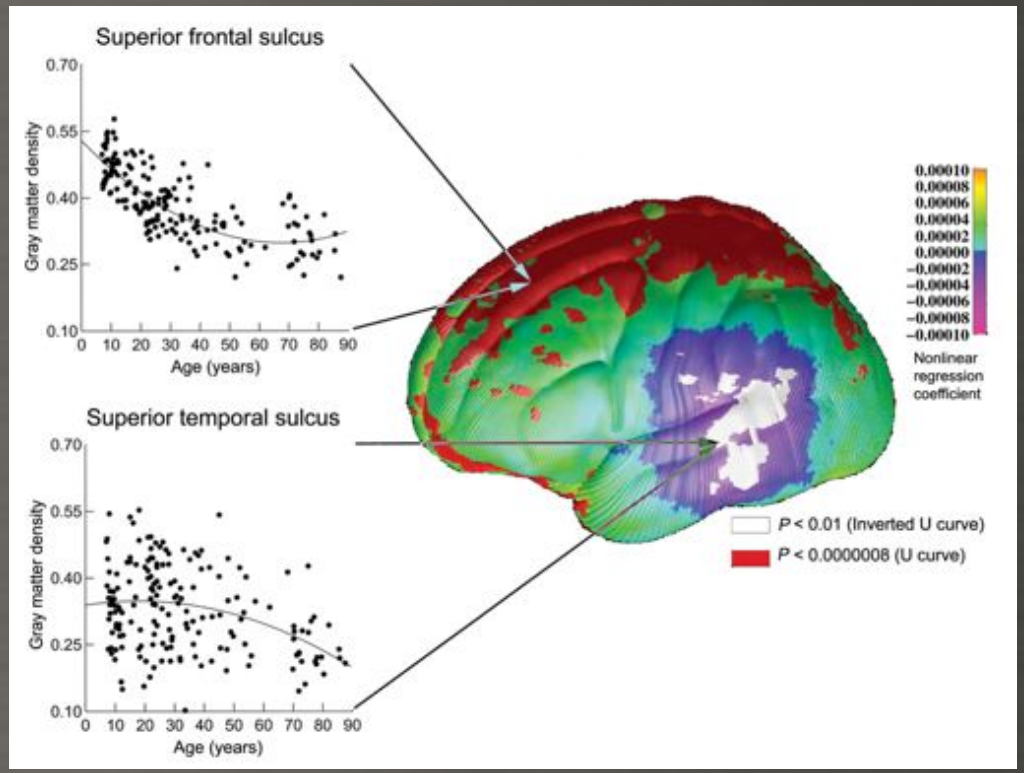
- Subjects: 3.5-33 yo
- Shaw et al., 2008



Research Highlight: Development

In some regions, GM thickness may increase in old age

- Subjects: 7-87 yo
- Sowell et al., 2003



Concluding Remarks

Advantages of Surface Meshes

- Improved registration accuracy
- New analysis approaches; many other possibilites not shown here
- Not discussed here but important: visualization, databases, shape analysis

Future Research Directions

- Especially relevant: application to development and cross-species differences
- Sensitive detection in other realms: schizophrenia, William's syndrome, IQ, gender, etc

Thank you for your attention!