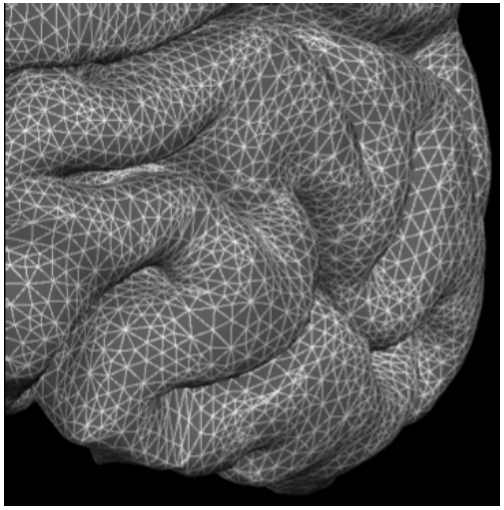
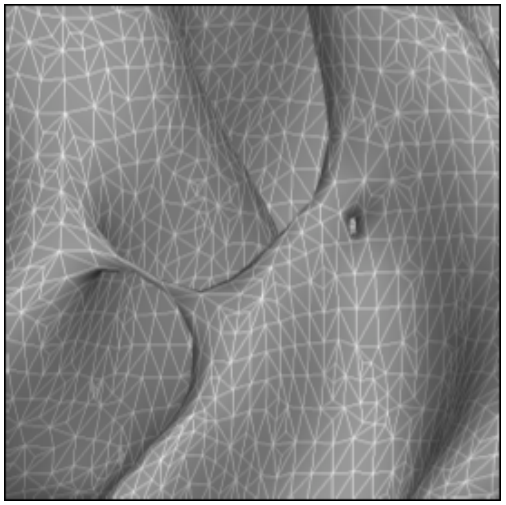
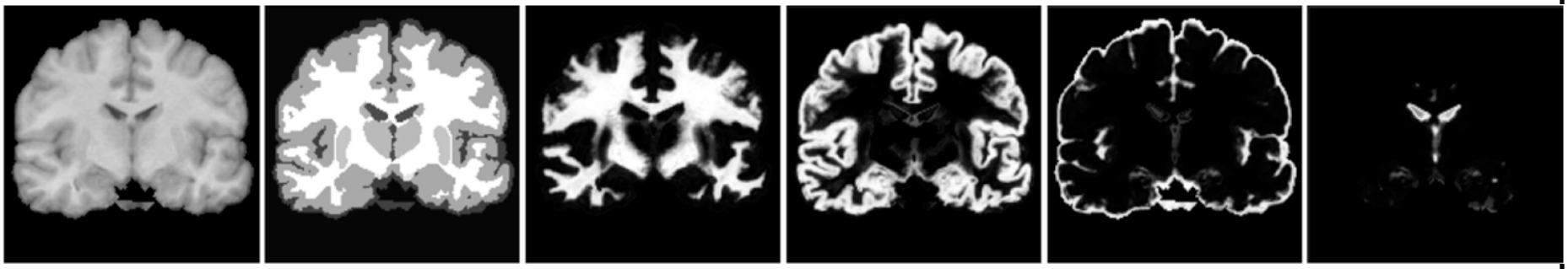
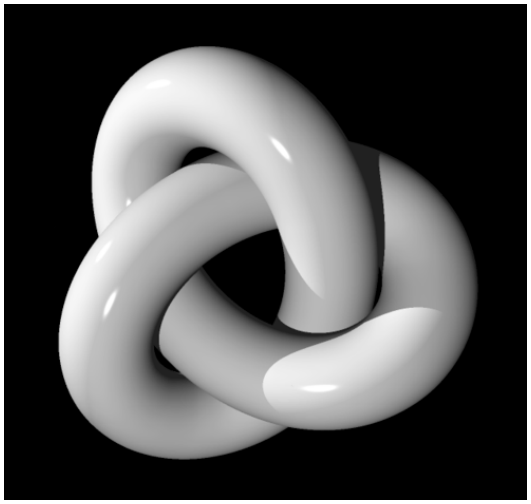


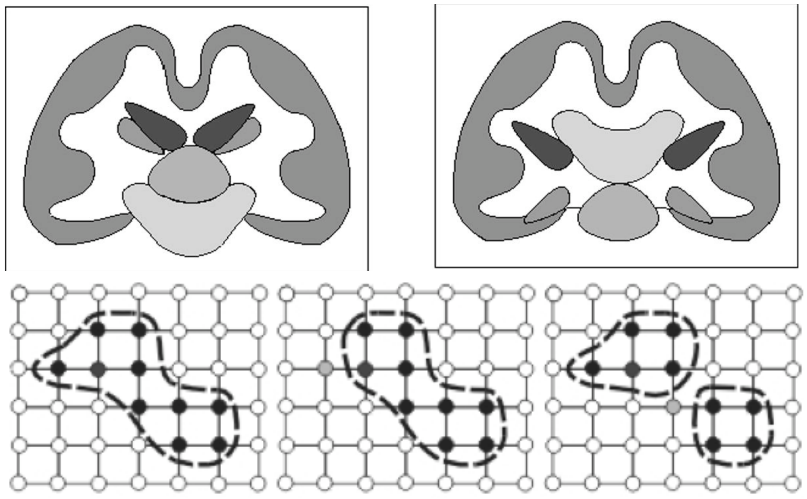
Brain images and topology

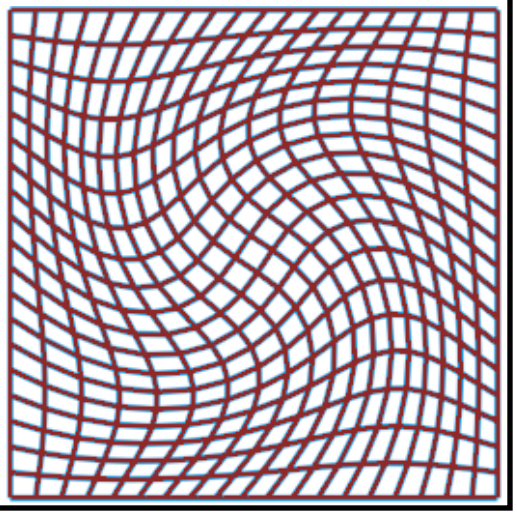
arno klein
arno@binarybottle.com
molecular imaging
& neuropathology
columbia university











Brain images and topology

Brain image processing

Feature extraction

Surface construction

Deformation and registration

Topology and brain images

Brain image processing

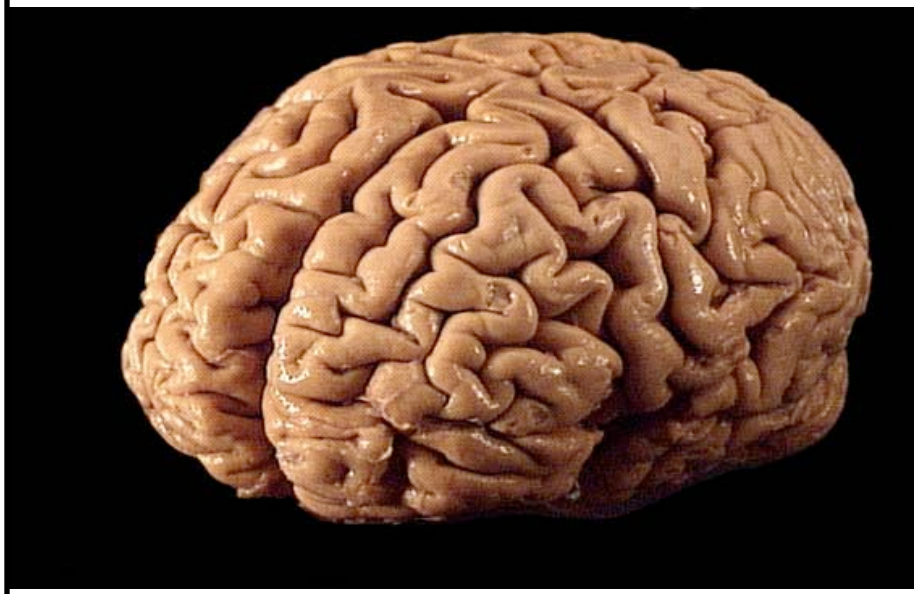
Feature extraction

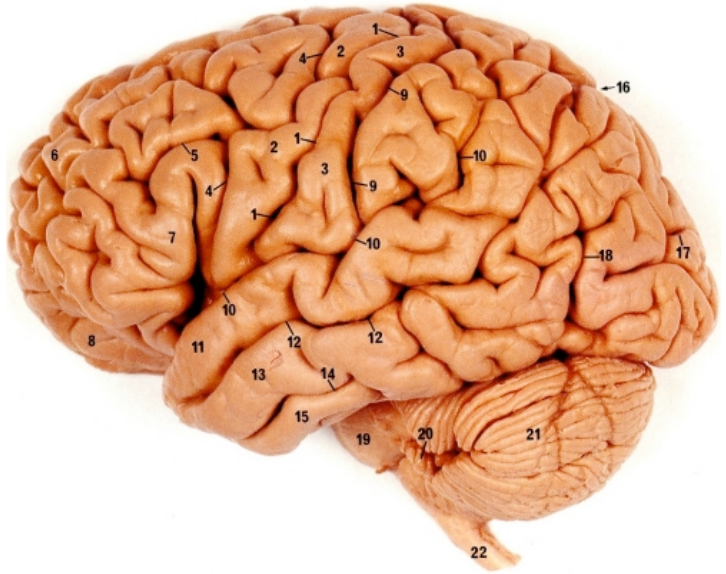
Surface construction

Deformation and registration

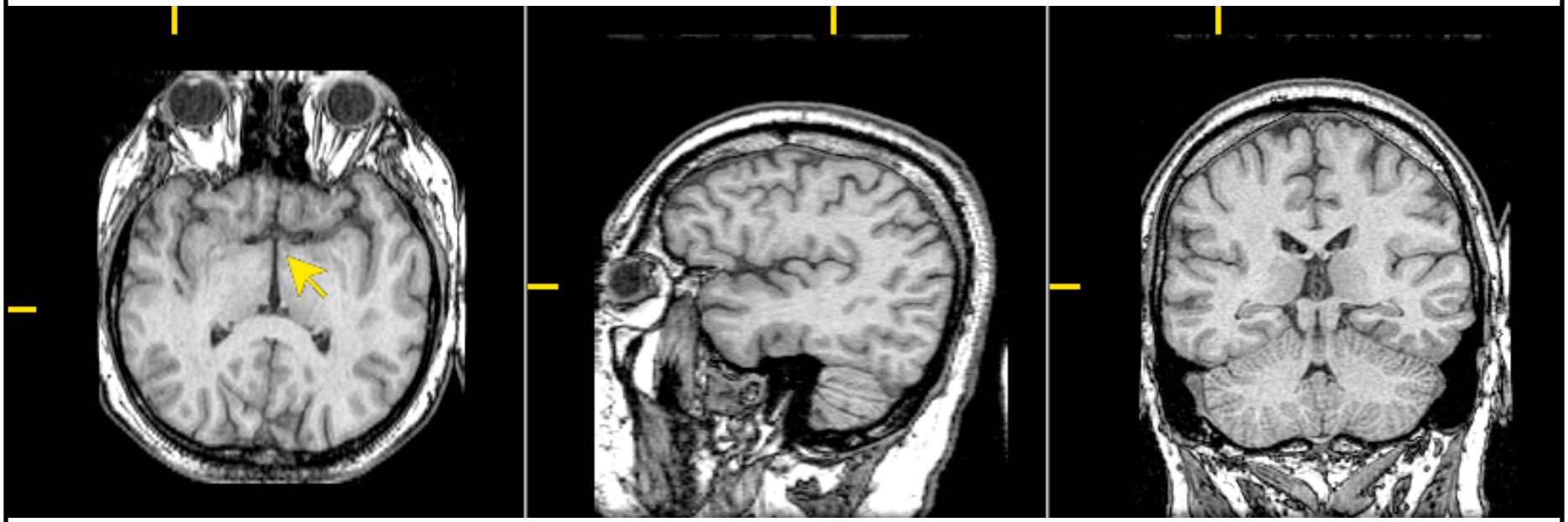
Topology and brain images

human brains

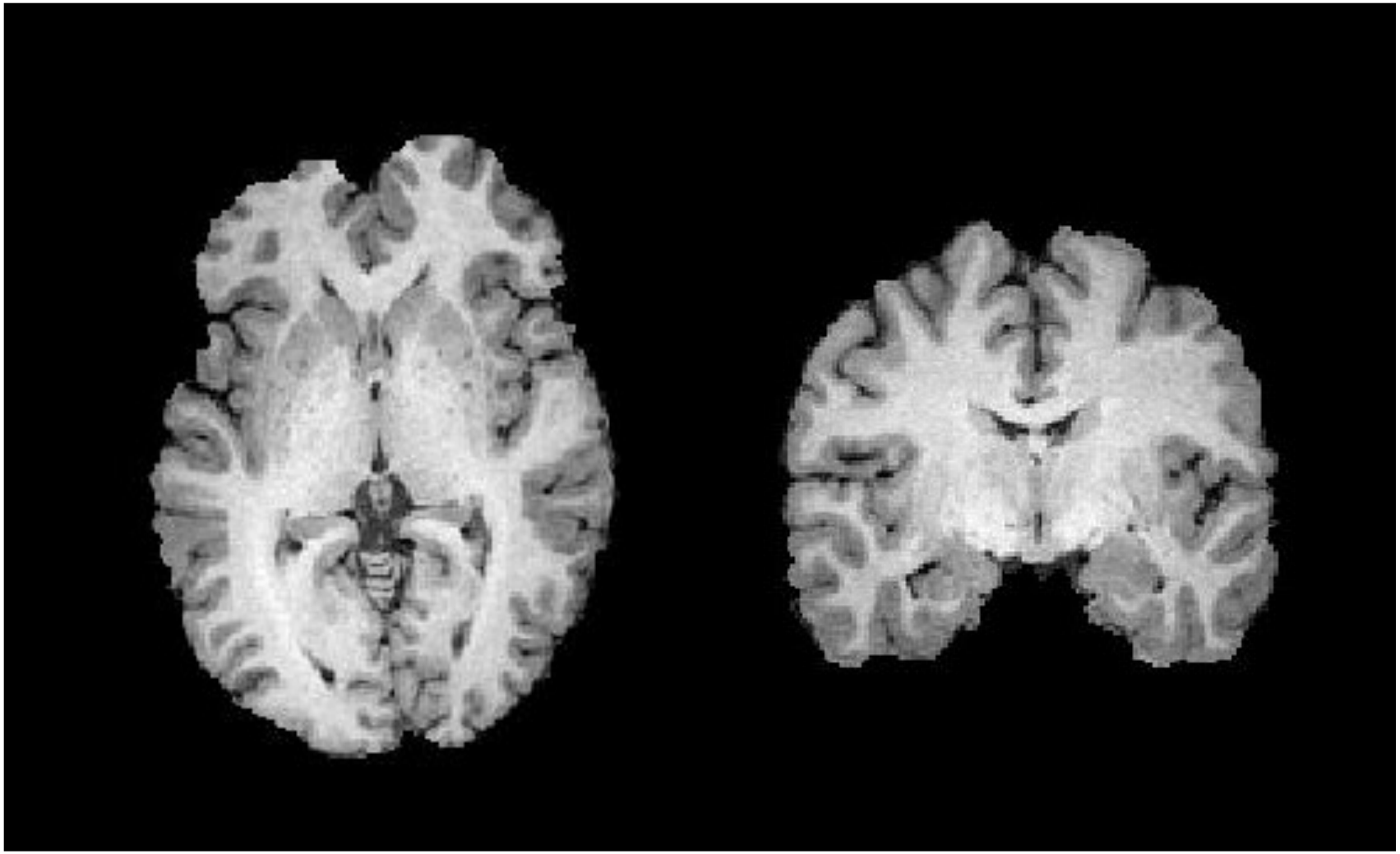


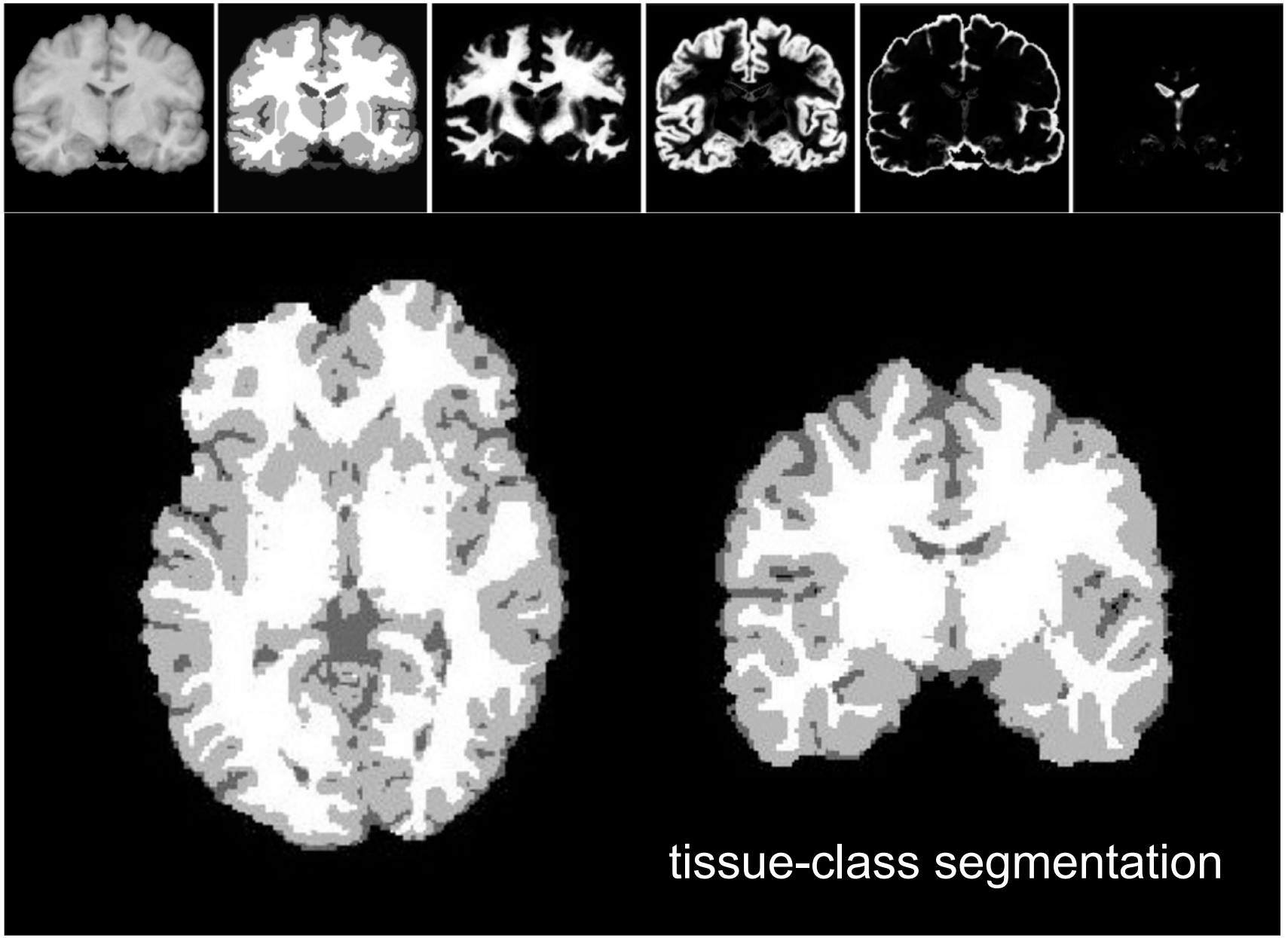


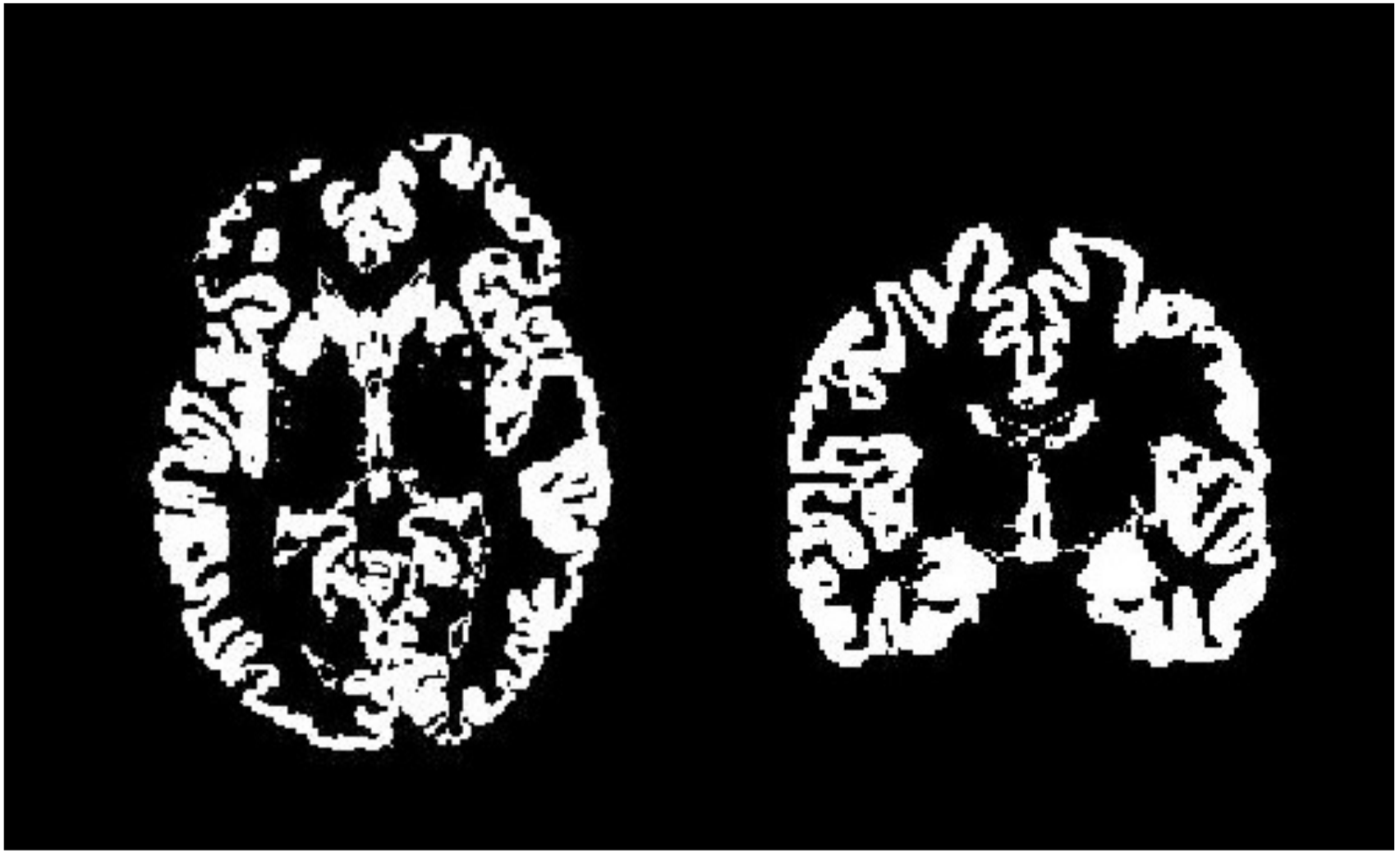
brain MRI volume



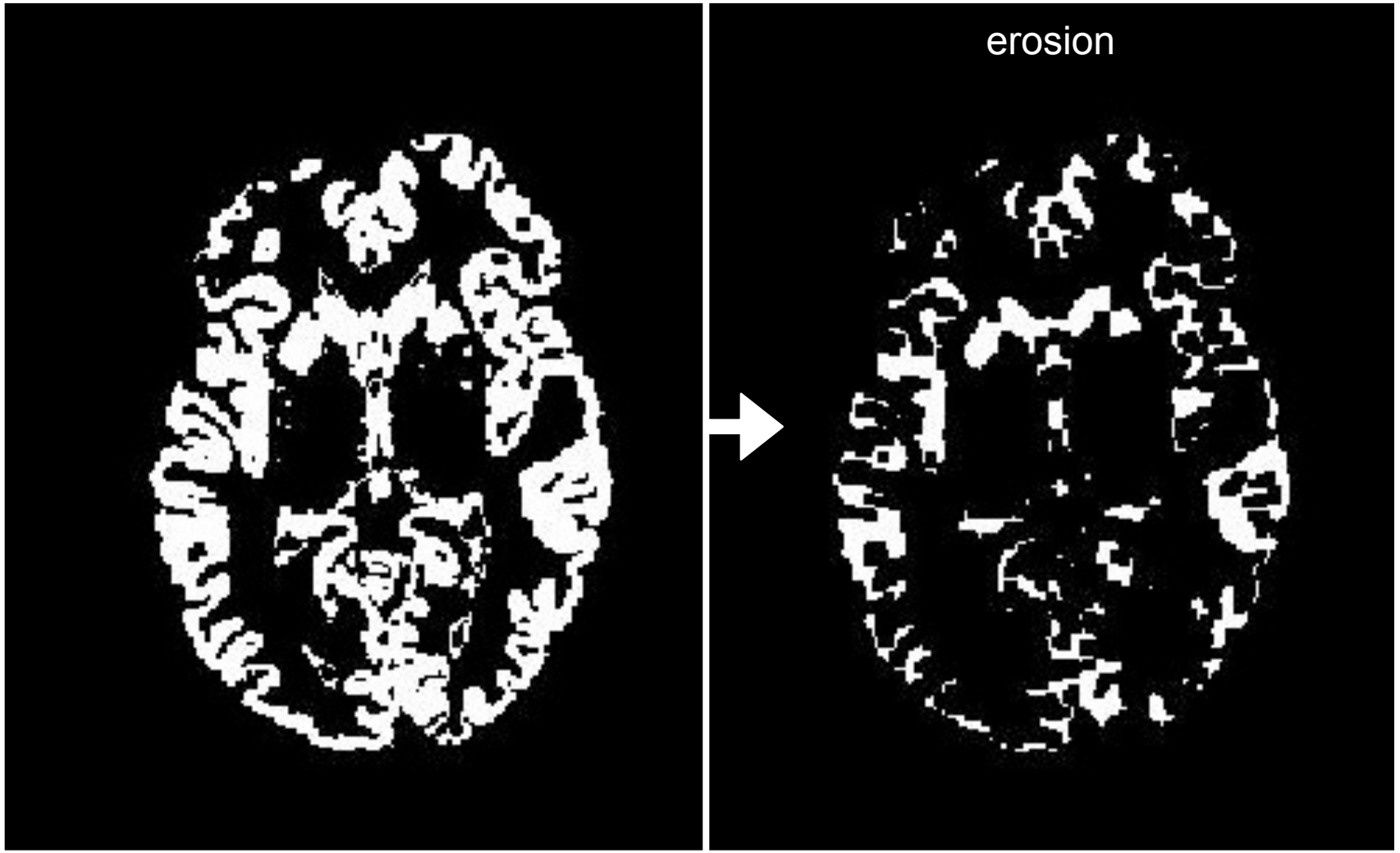
skull-stripping



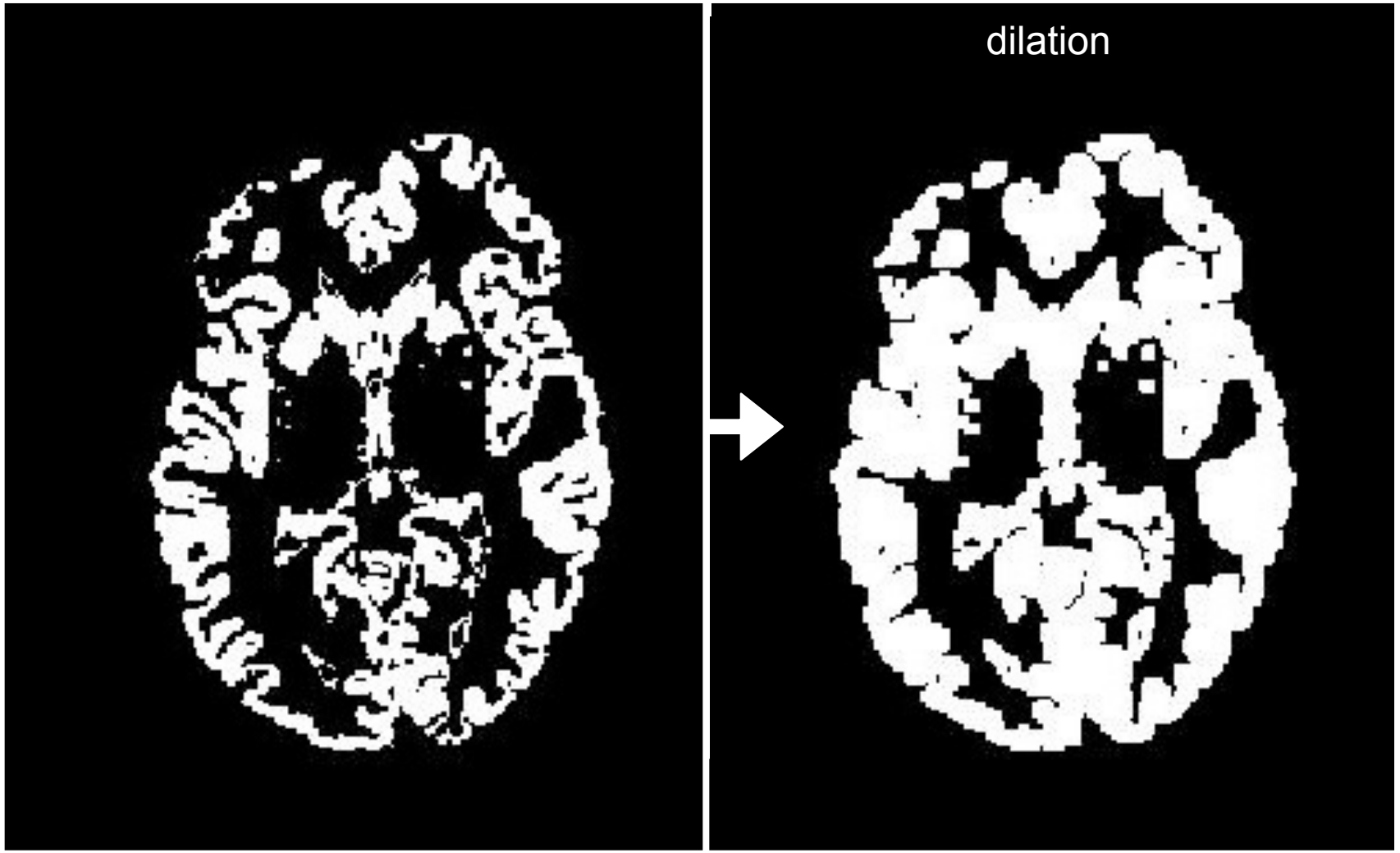

tissue-class segmentation



morphological image processing



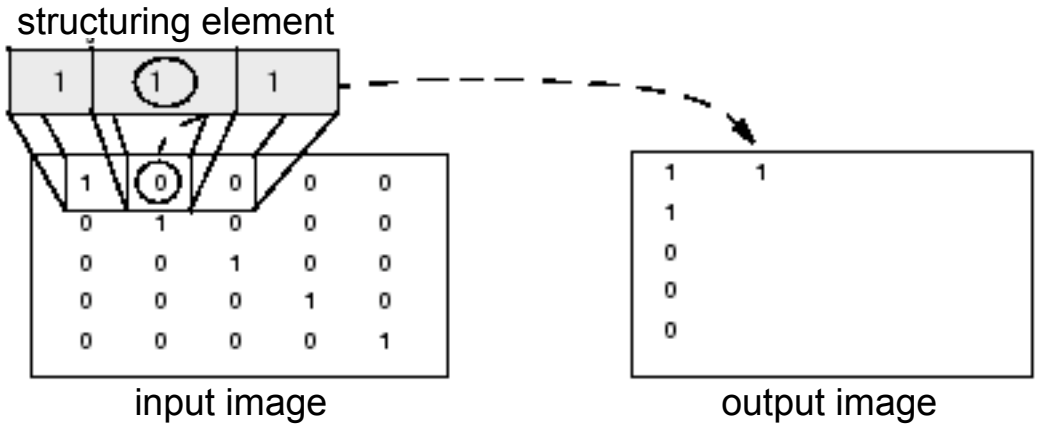
morphological image processing

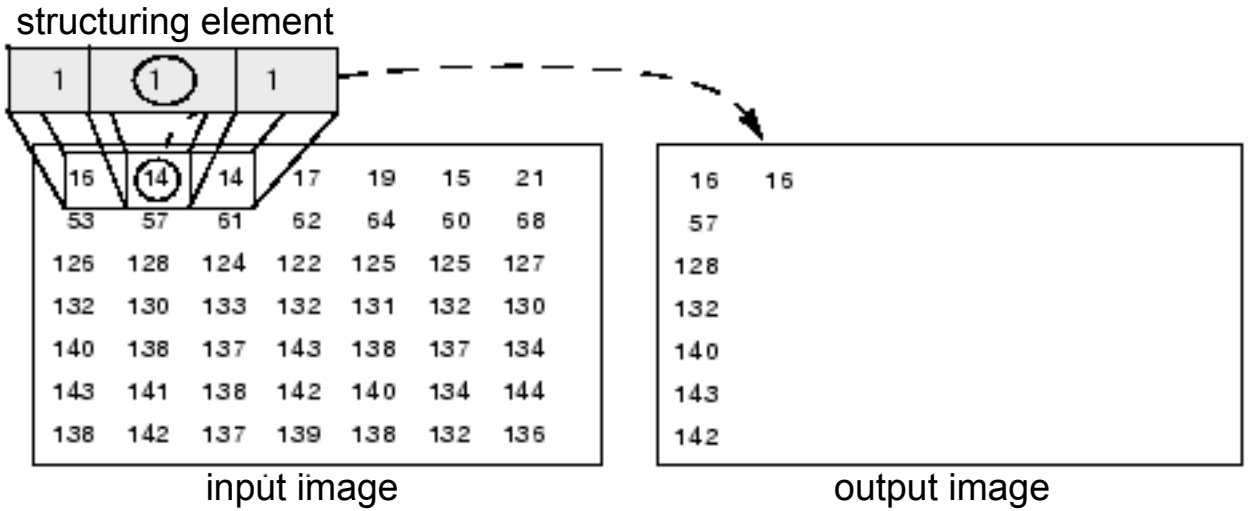


morphological image processing

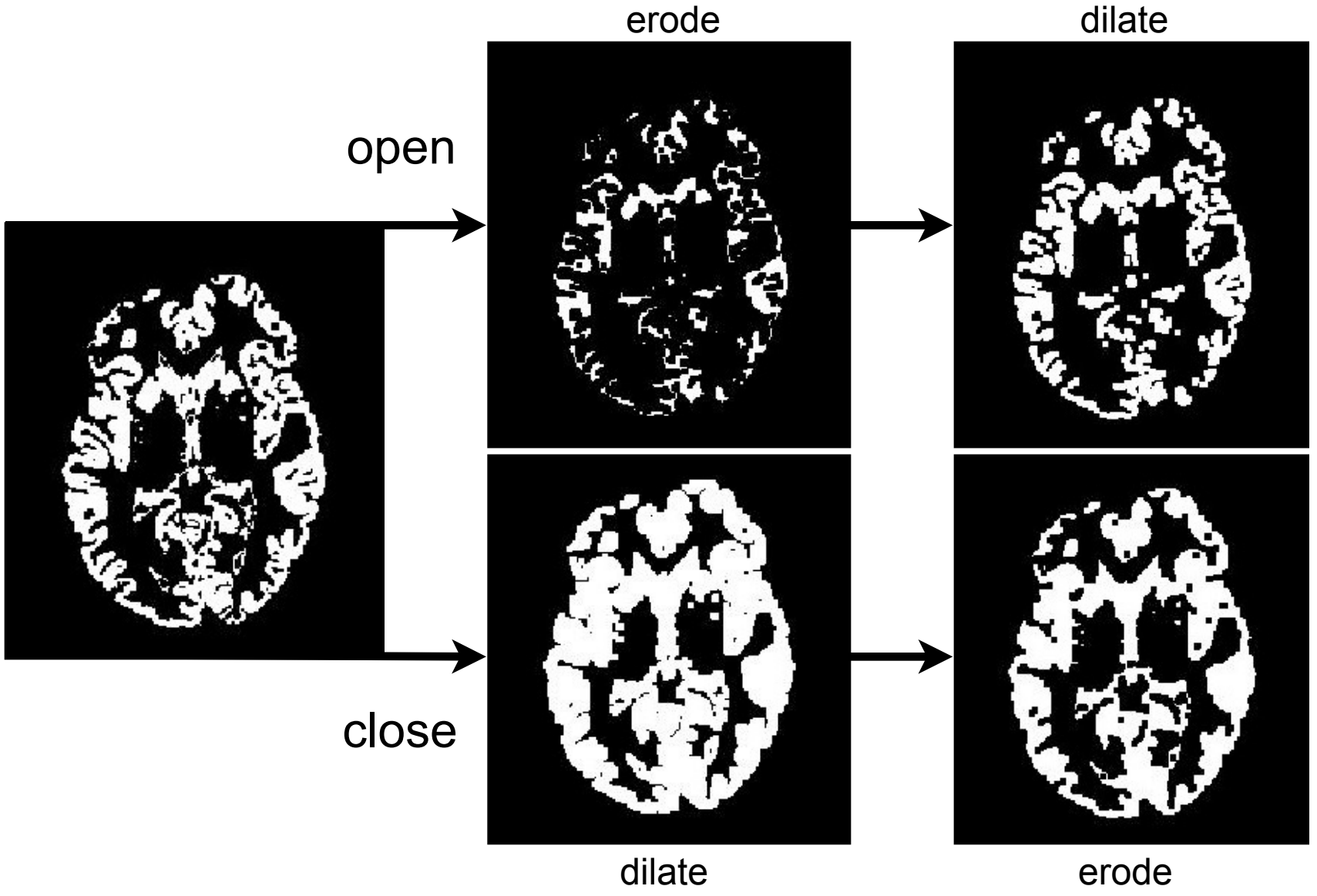
Dilation example

maximum value in neighborhood

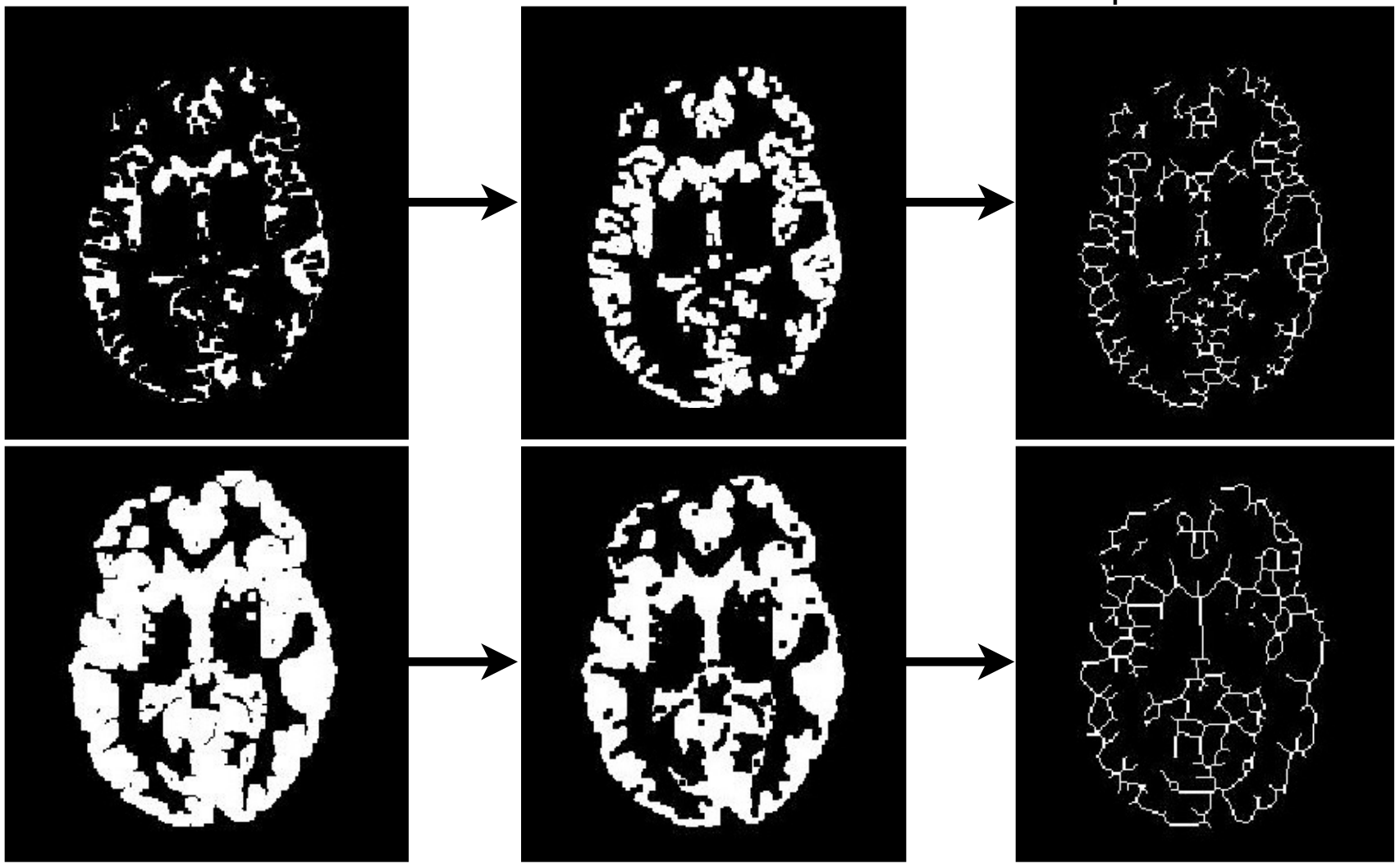




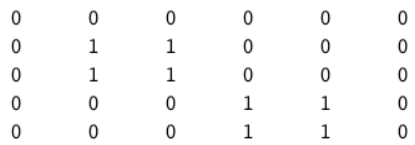
morphological image processing



morphological image processing



pixel connectivity



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0	0	0	1	1	0
0	0	0	1	1	0

pixel connectivity

0	0	0	0	0	0
0	1	1	0	0	0
0	1	1	0	0	0
0	0	0	1	1	0
0	0	0	1	1	0

0	0	0	0	0	0
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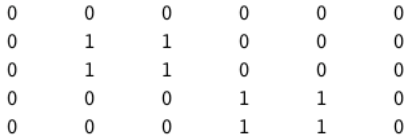
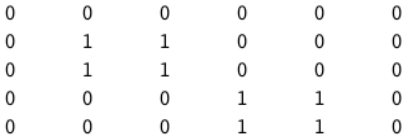
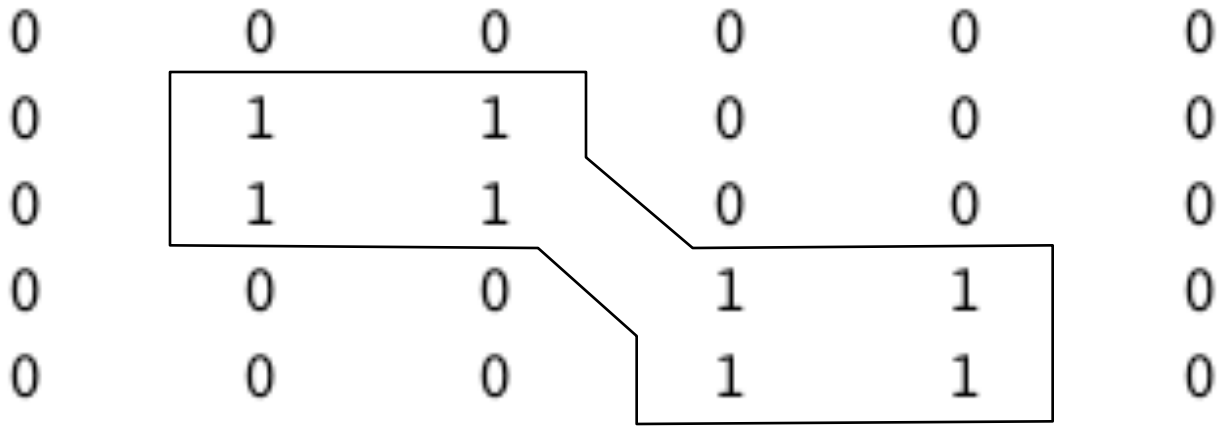
pixel connectivity



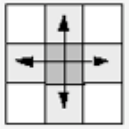
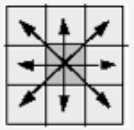




0	0	0	0	0	0
0	1	1	0	0	0
0	1	1	0	0	0
0	0	0	1	1	0
0	0	0	1	1	0

pixel connectivity

0	0	0	0	0	0
0	1	1	0	0	0
0	1	1	0	0	0
0	0	0	1	1	0
0	0	0	1	1	0

Two-Dimensional Connectivities		
4-connected	Pixels are connected if their edges touch. This means that a pair of adjoining pixels are part of the same object only if they are both on and are connected along the horizontal or vertical direction.	
8-connected	Pixels are connected if their edges or corners touch. This means that if two adjoining pixels are on, they are part of the same object, regardless of whether they are connected along the horizontal, vertical, or diagonal direction.	
Three-Dimensional Connectivities		
6-connected	Pixels are connected if their faces touch.	
18-connected	Pixels are connected if their faces or edges touch.	
26-connected	Pixels are connected if their faces, edges, or corners touch.	

flood filling

0	0	0	0	0	0	0	0
0	1	1	1	1	1	0	0
0	1	0	0	0	1	0	0
0	1	0	0	0	1	0	0
0	1	0	0	0	1	0	0
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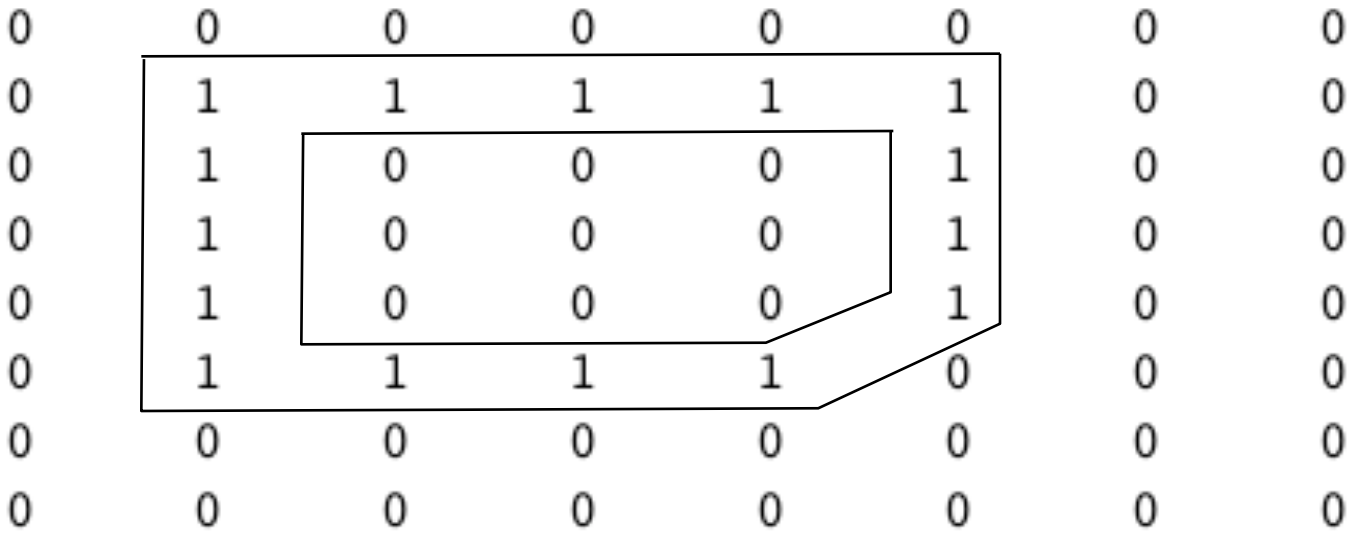
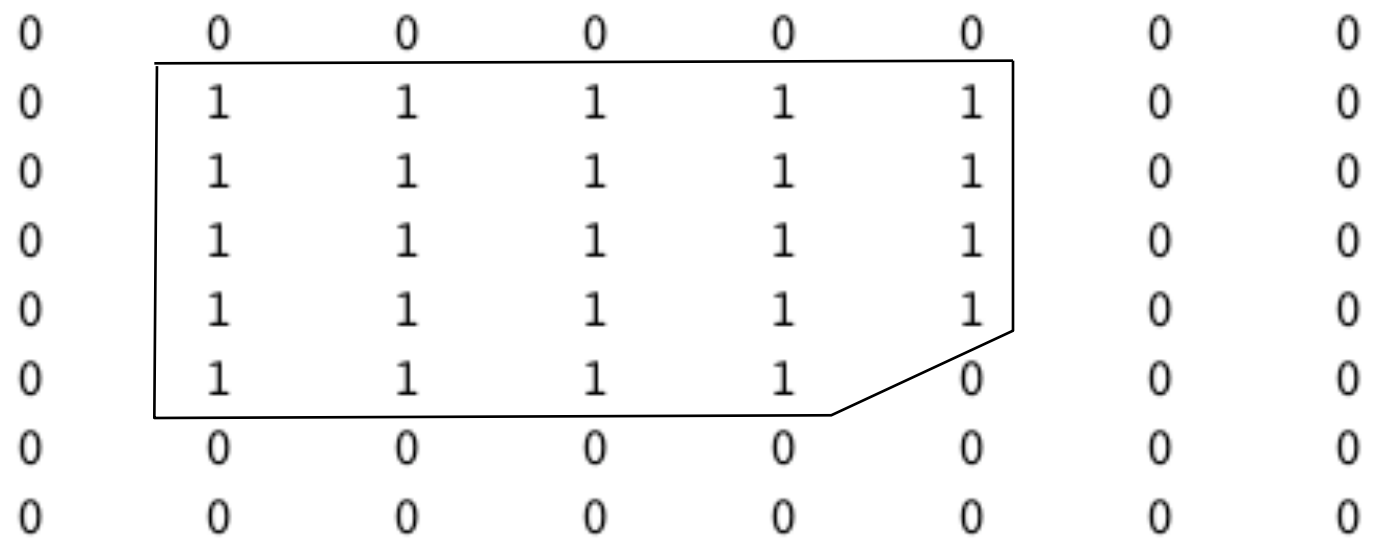
0	0	0	0	0	0	0	0

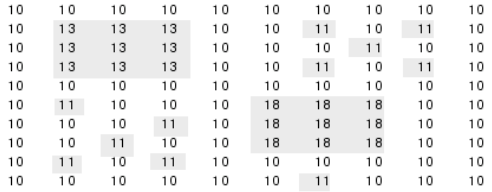
flood filling

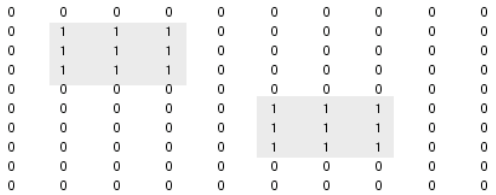


flood filling



peaks & valleys





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10	13	13	13	10	10	11	10	11	10
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10	10	10	11	10	18	18	18	10	10
10	10	11	10	10	18	18	18	10	10
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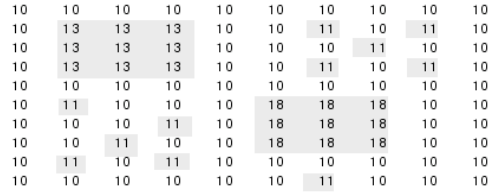
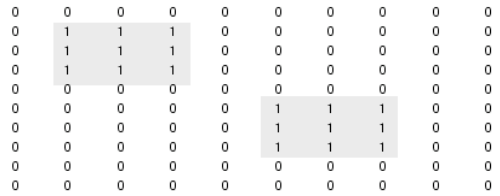
10	10	10	10	10	10	11	10	10	10



peaks & valleys



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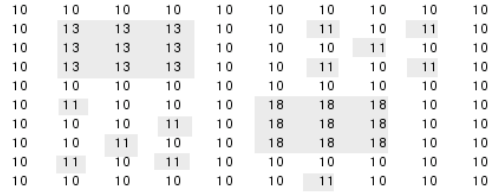
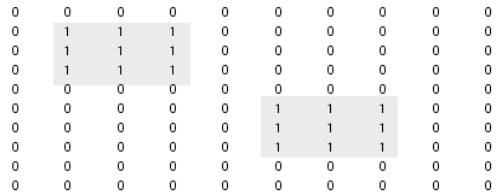


peaks & valleys



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0	0	0	0	0	1	1	1	0	0
0	0	0	0	0	1	1	1	0	0
0	0	0	0	0	0	0	0	0	0
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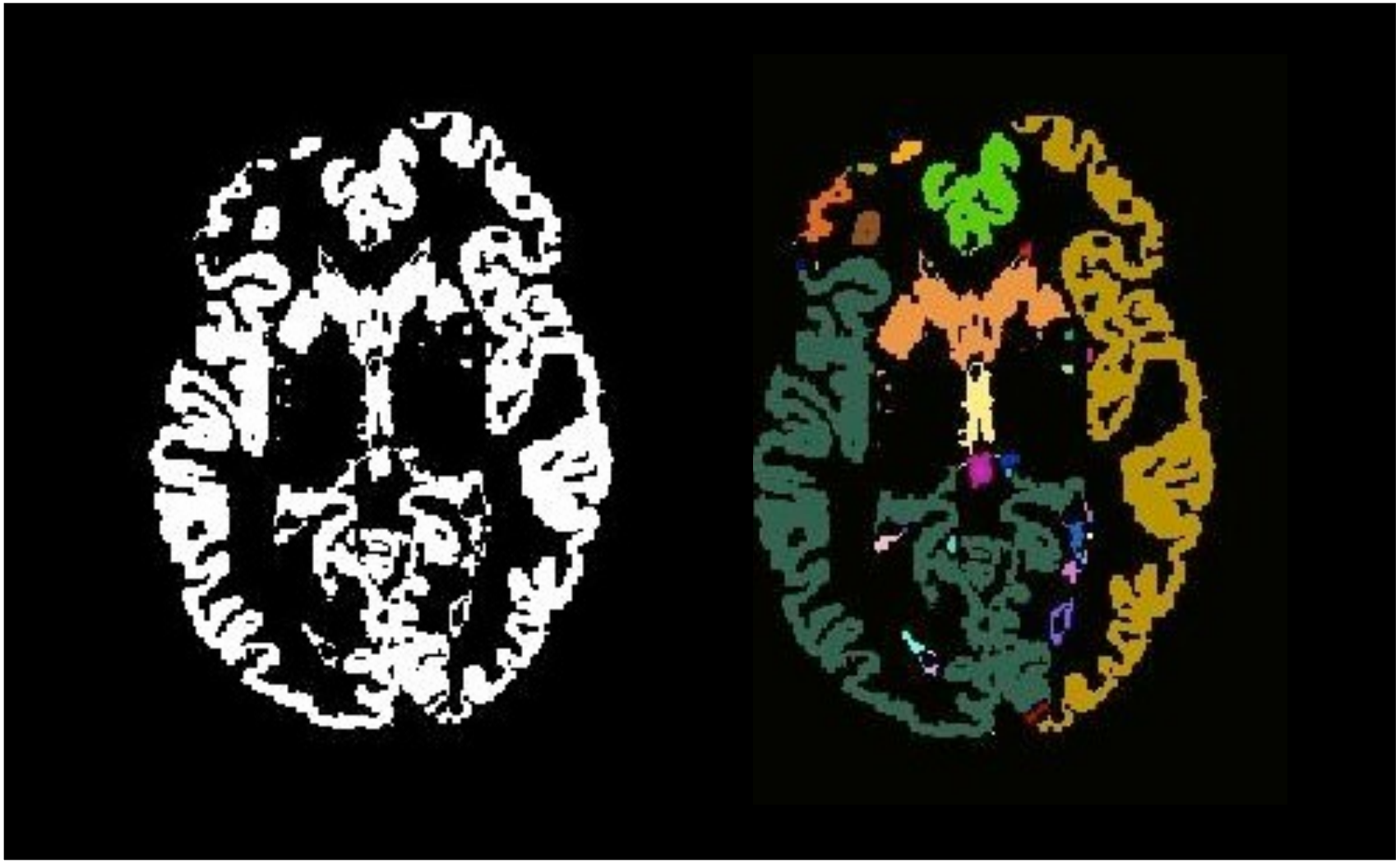
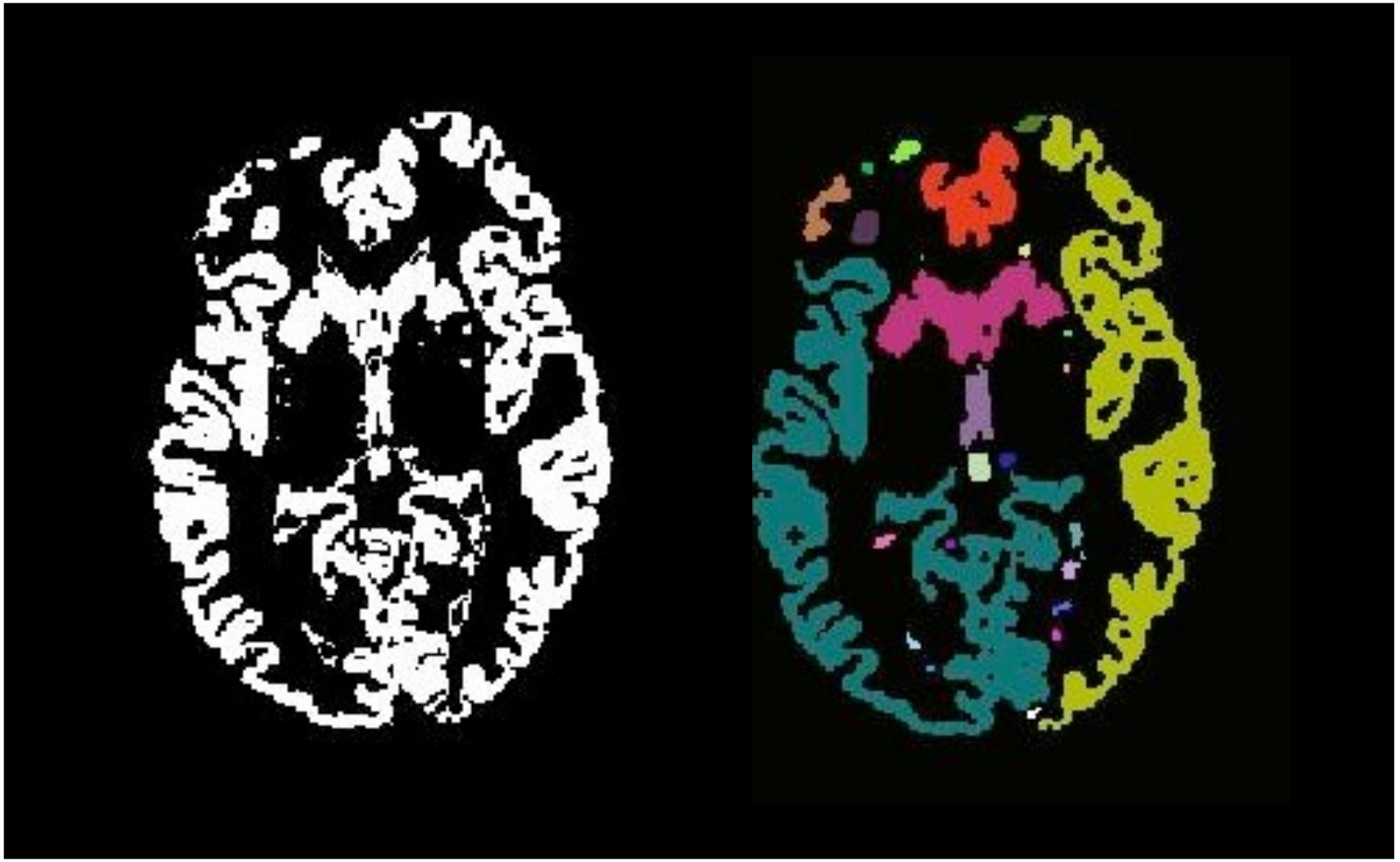
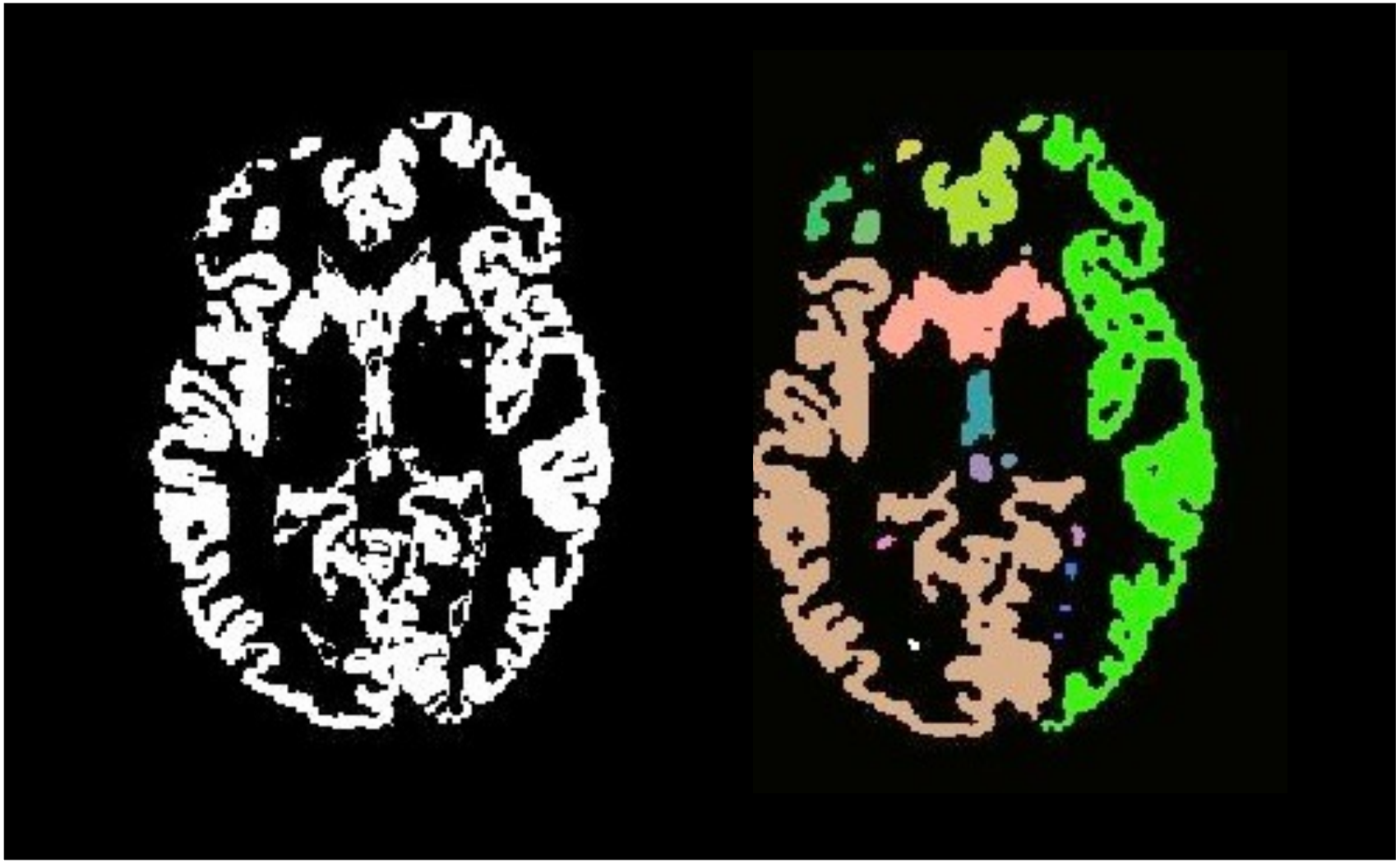
labeling connected objects



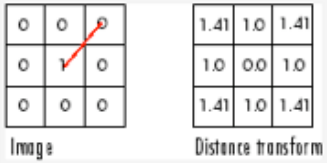
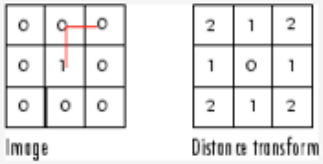
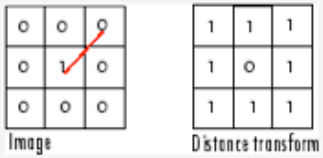
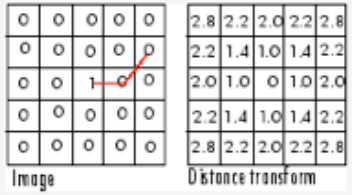
labeling connected objects



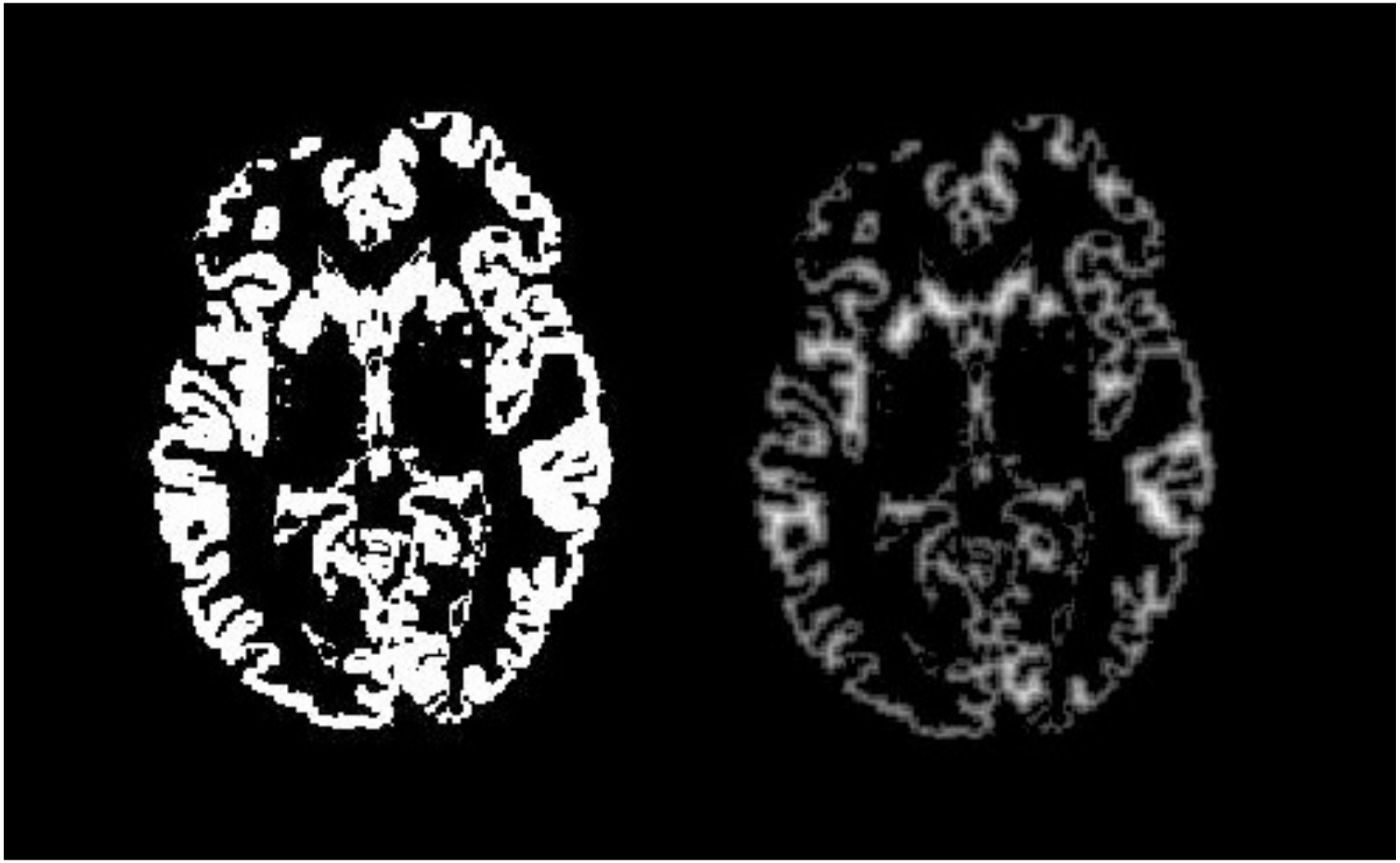
labeling connected objects



distance transforms

Distance Metric	Description	Illustration
Euclidean	The Euclidean distance is the straight-line distance between two pixels.	
City Block	The city block distance metric measures the path between the pixels based on a 4-connected neighborhood. Pixels whose edges touch are 1 unit apart; pixels diagonally touching are 2 units apart.	
Chessboard	The chessboard distance metric measures the path between the pixels based on an 8-connected neighborhood. Pixels whose edges or corners touch are 1 unit apart.	
Quasi-Euclidean	The quasi-Euclidean metric measures the total Euclidean distance along a set of horizontal, vertical, and diagonal line segments.	

distance transforms



distance transforms

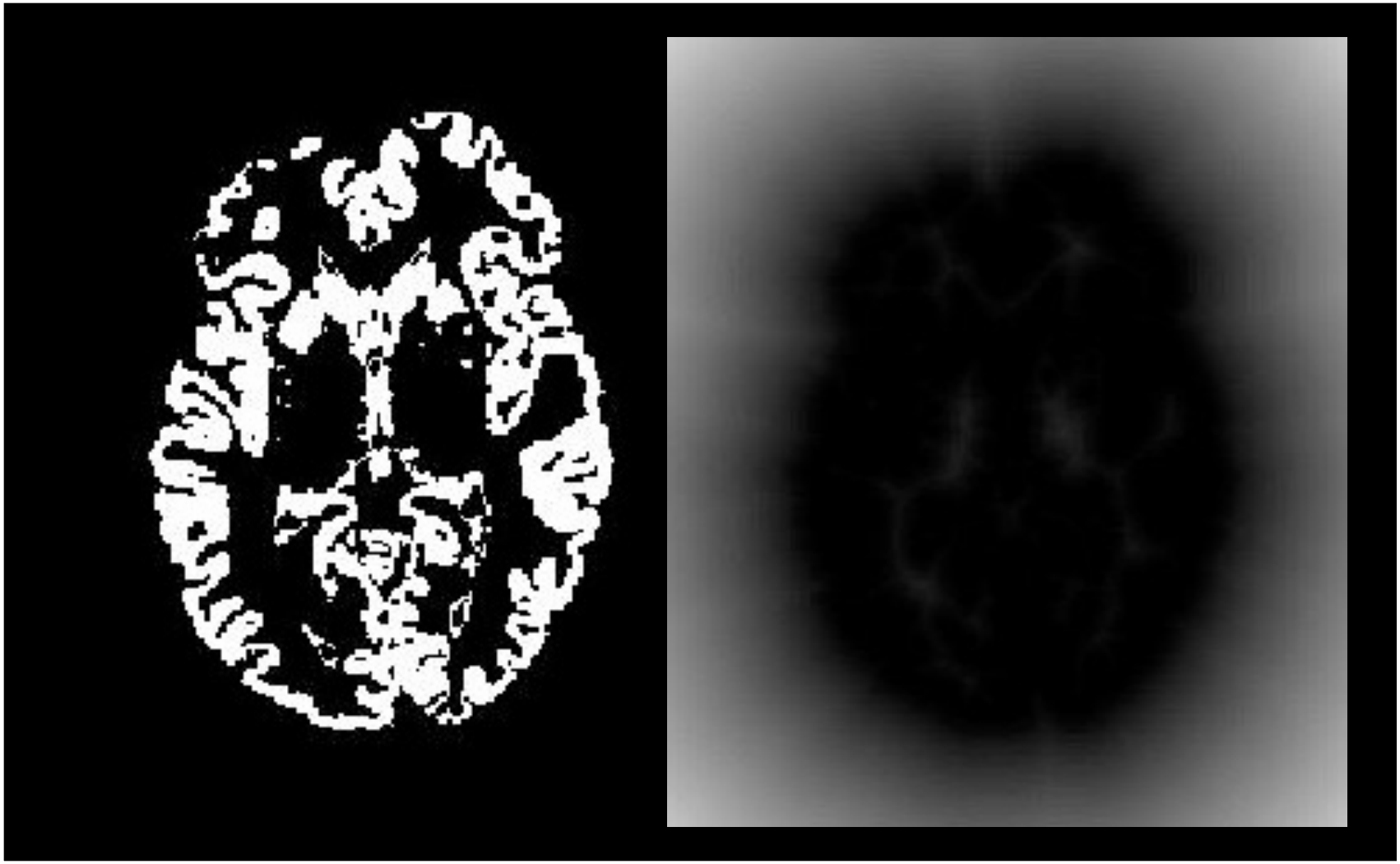
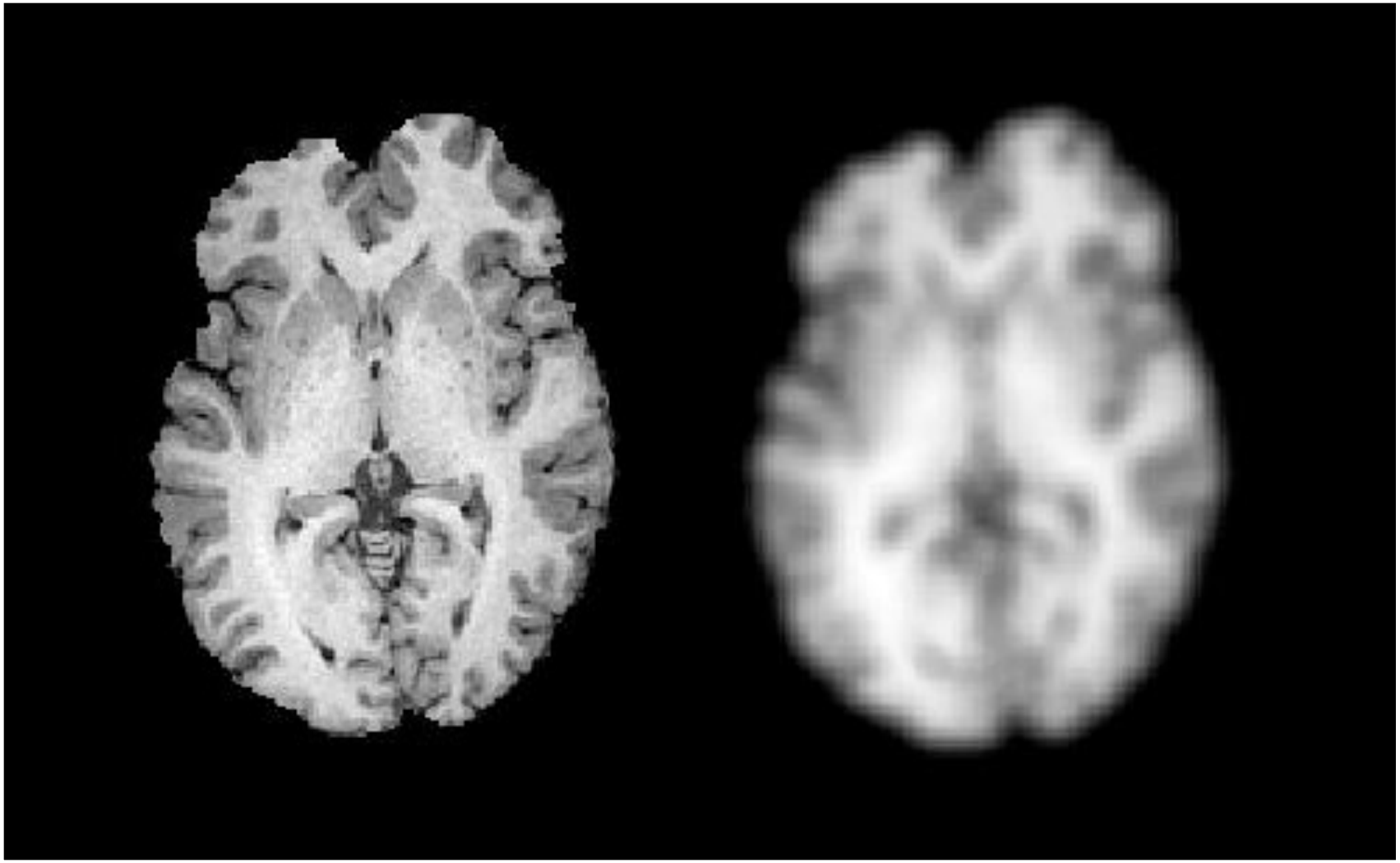


image filters



Brain image processing

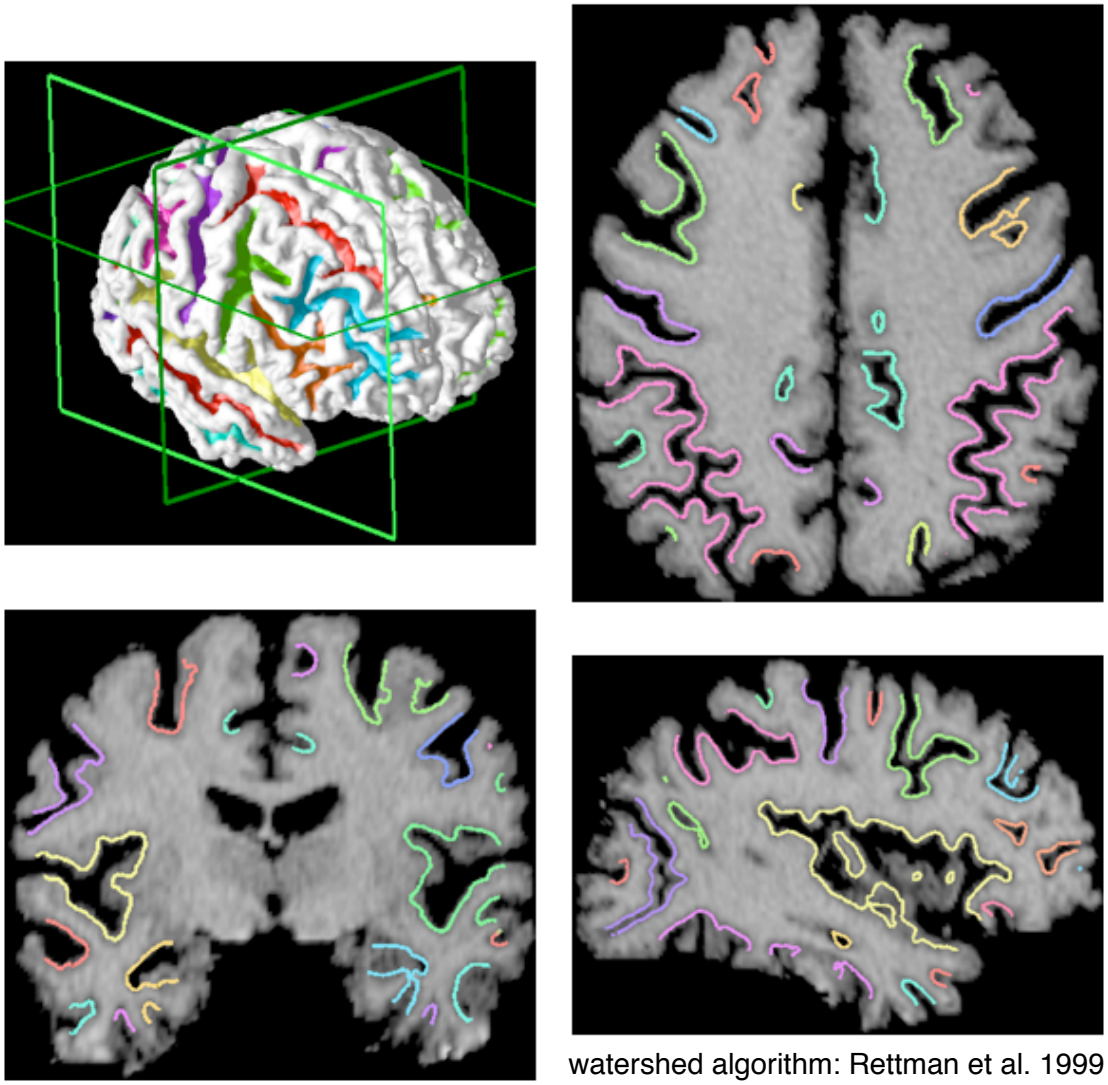
Feature extraction

Surface construction

Deformation and registration

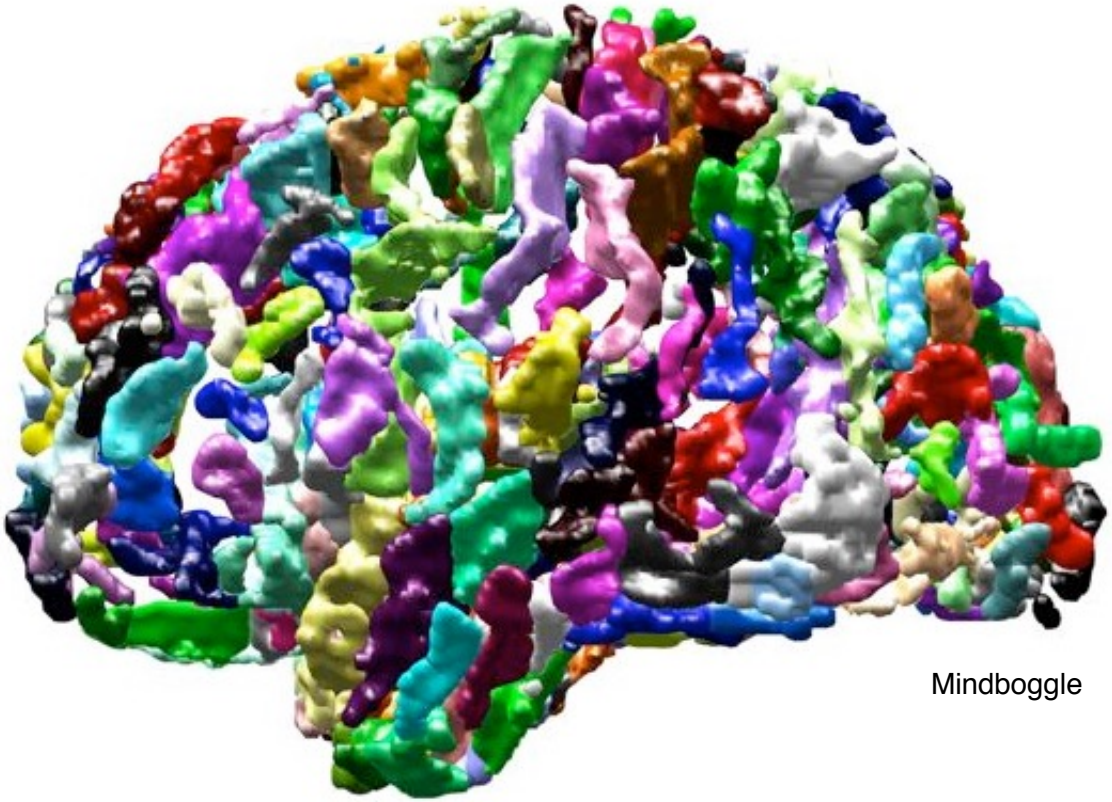
Topology and brain images

feature extraction: watershed algorithm



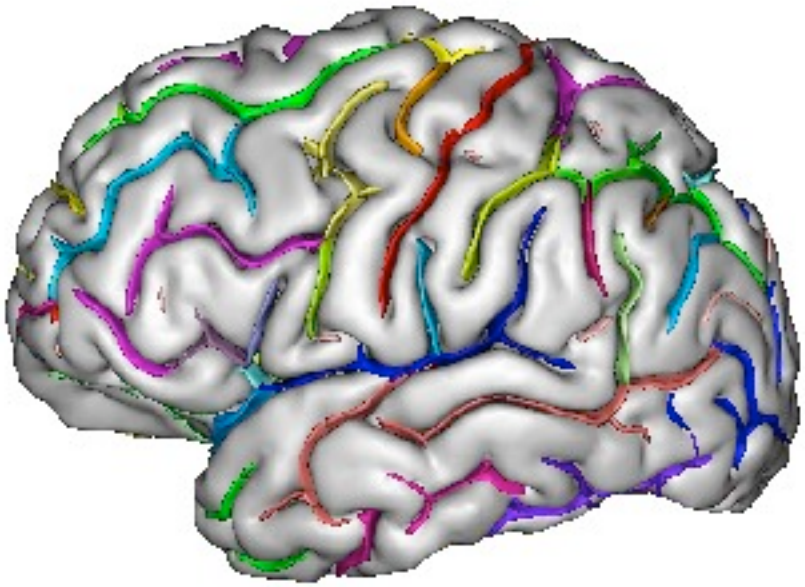
watershed algorithm: Rettman et al. 1999

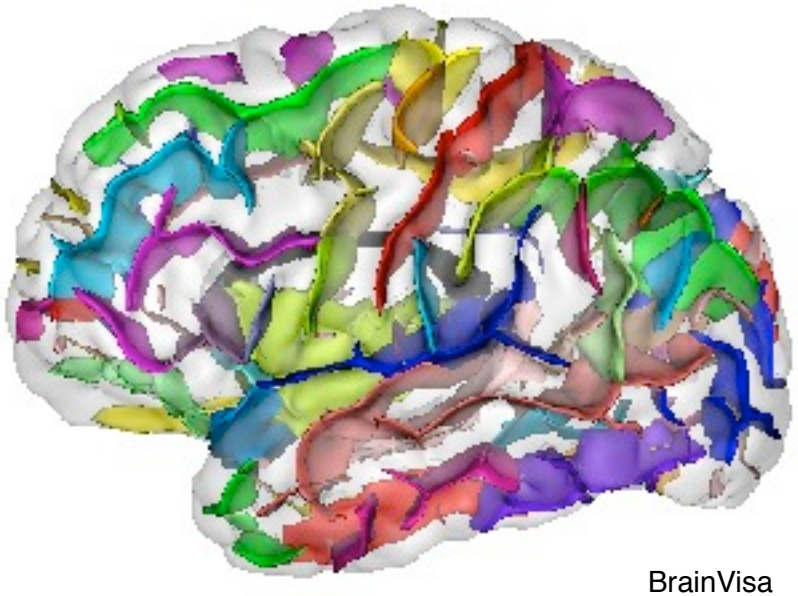
feature extraction: combinatoric matching



Mindboggle

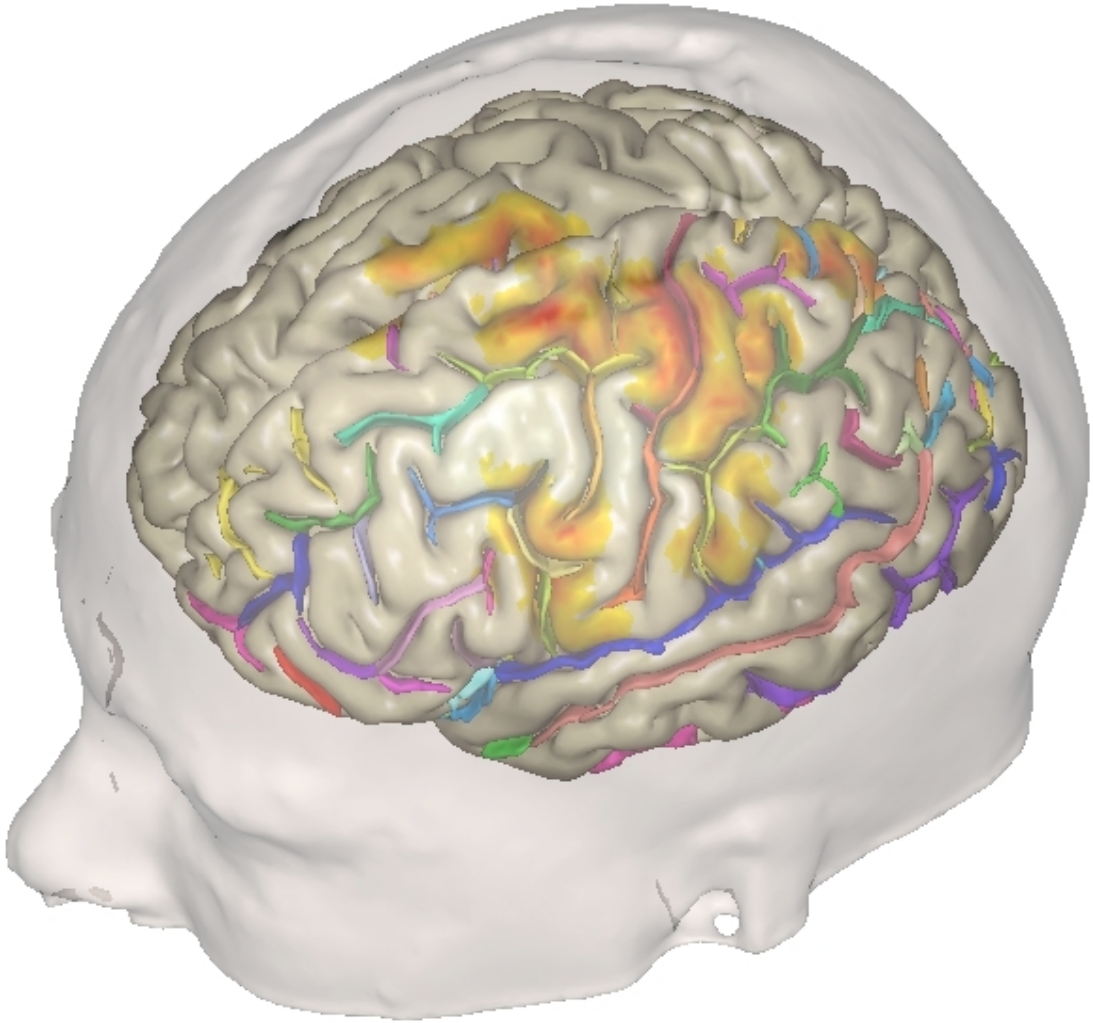
feature extraction: neural networks



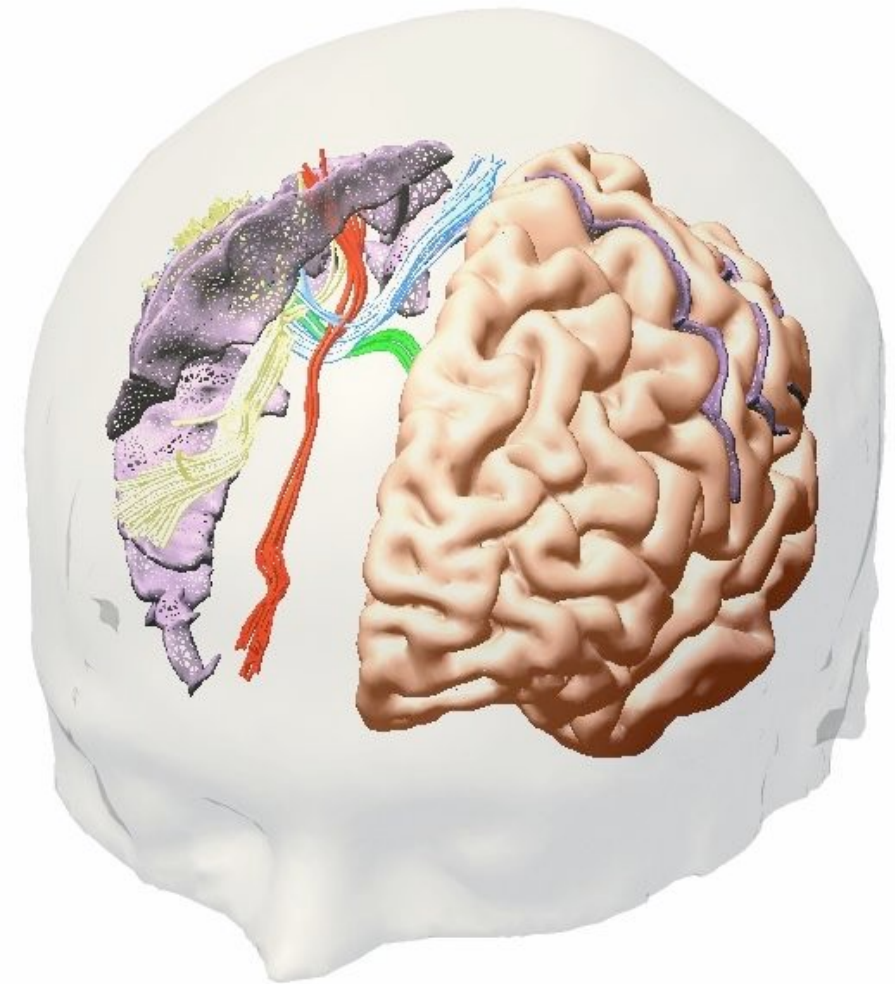


BrainVisa

features + activity data



features + connectivity data



Brain image processing

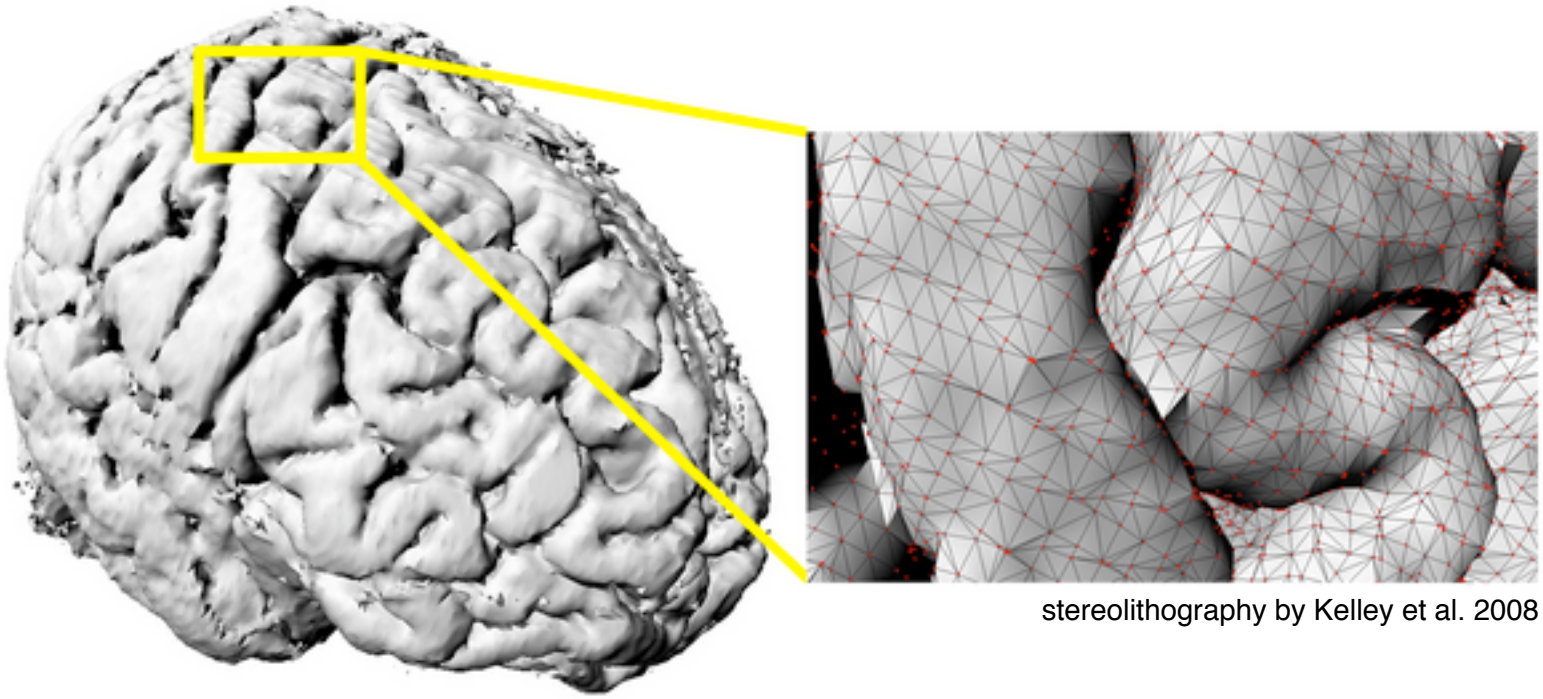
Feature extraction

Surface construction

Deformation and registration

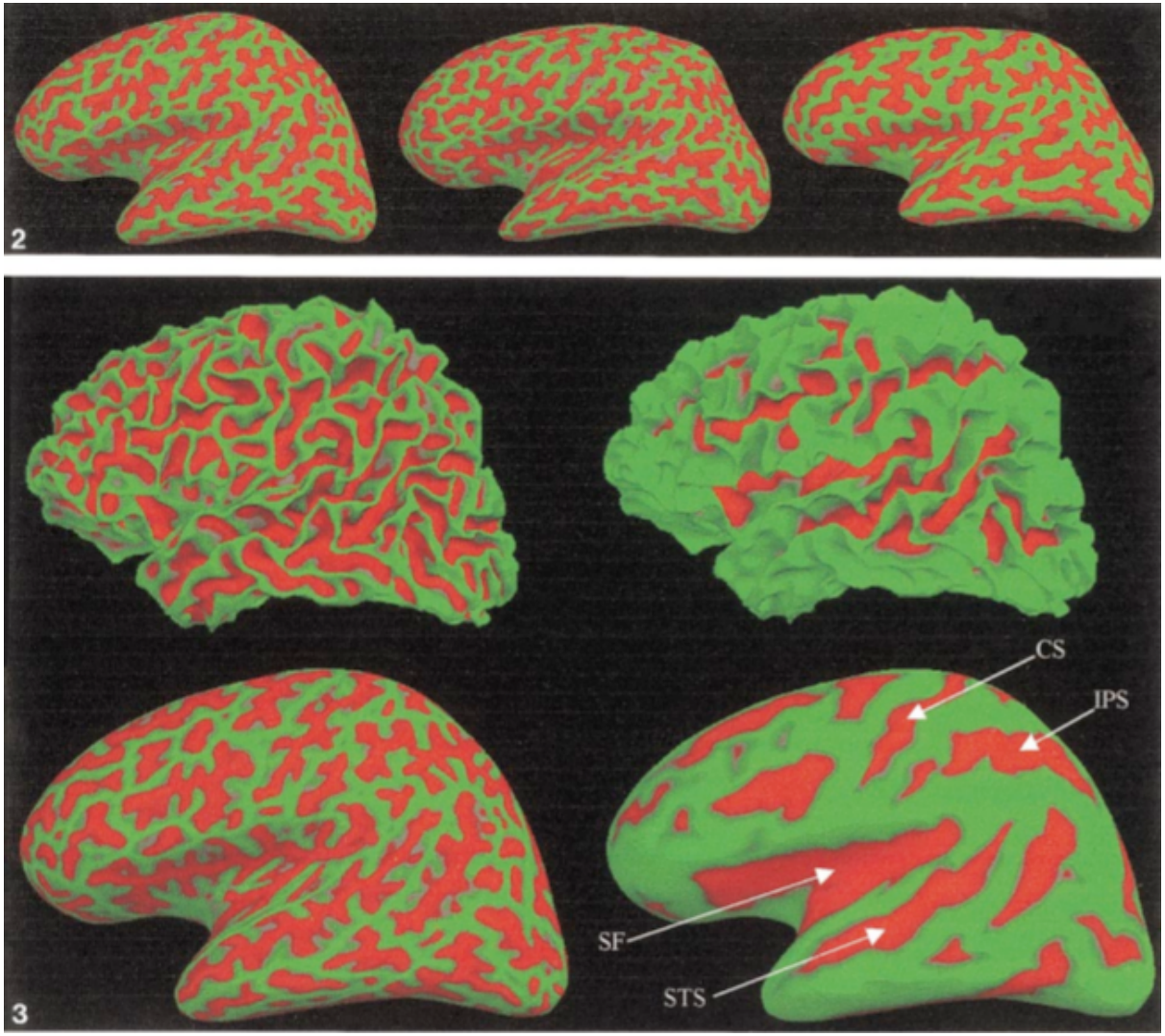
Topology and brain images

surface mesh construction



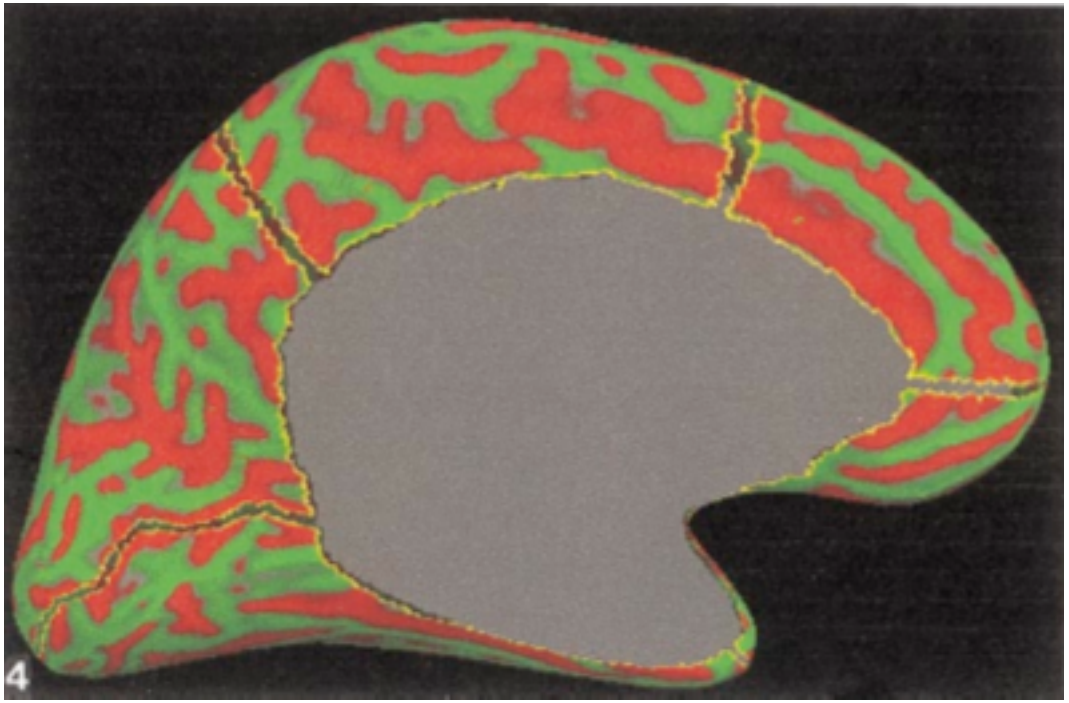
stereolithography by Kelley et al. 2008

inflated surfaces



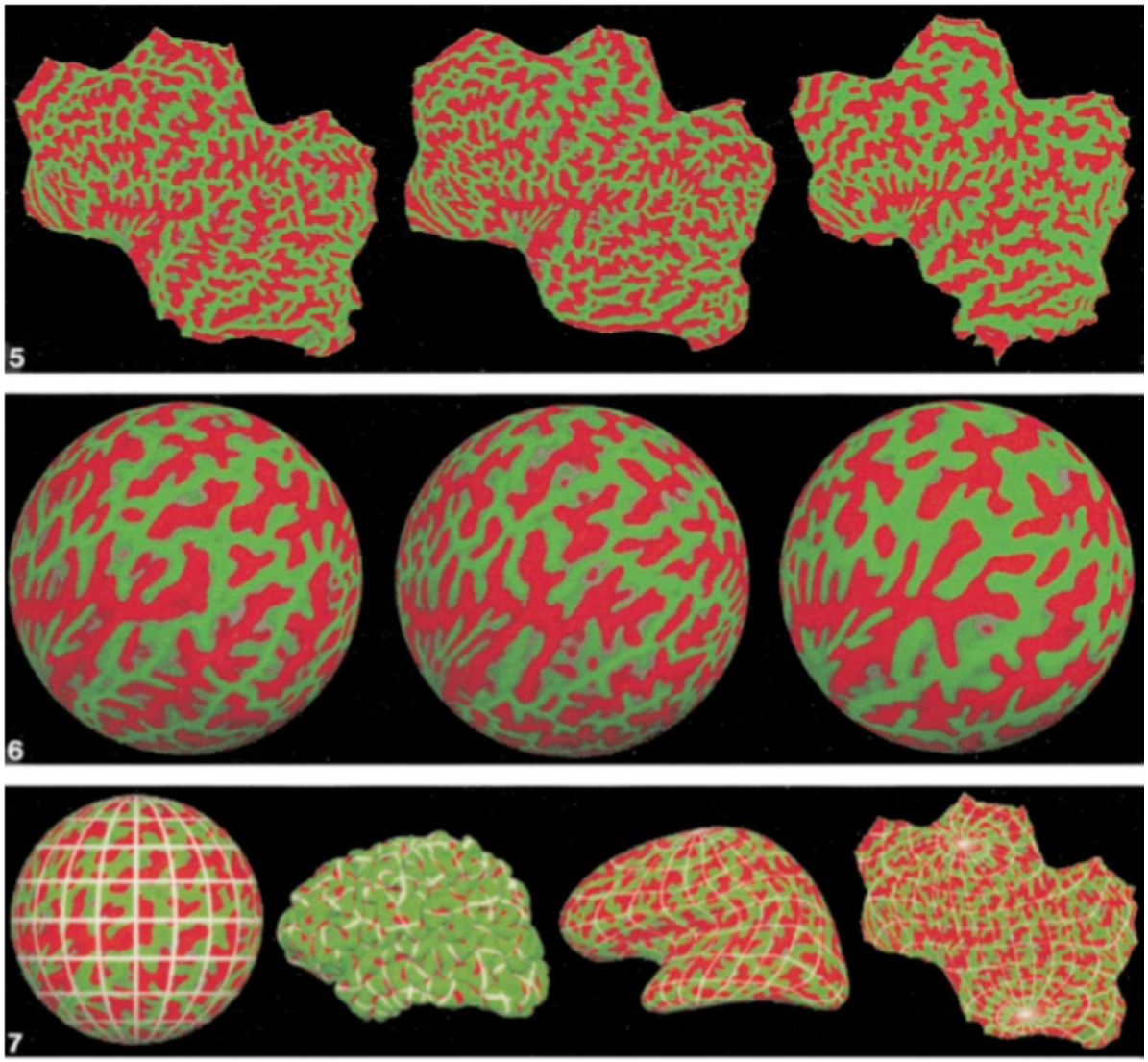
Freesurfer

cutting an inflated surface



Freesurfer

flattened and inflated surfaces



Freesurfer

Brain image processing

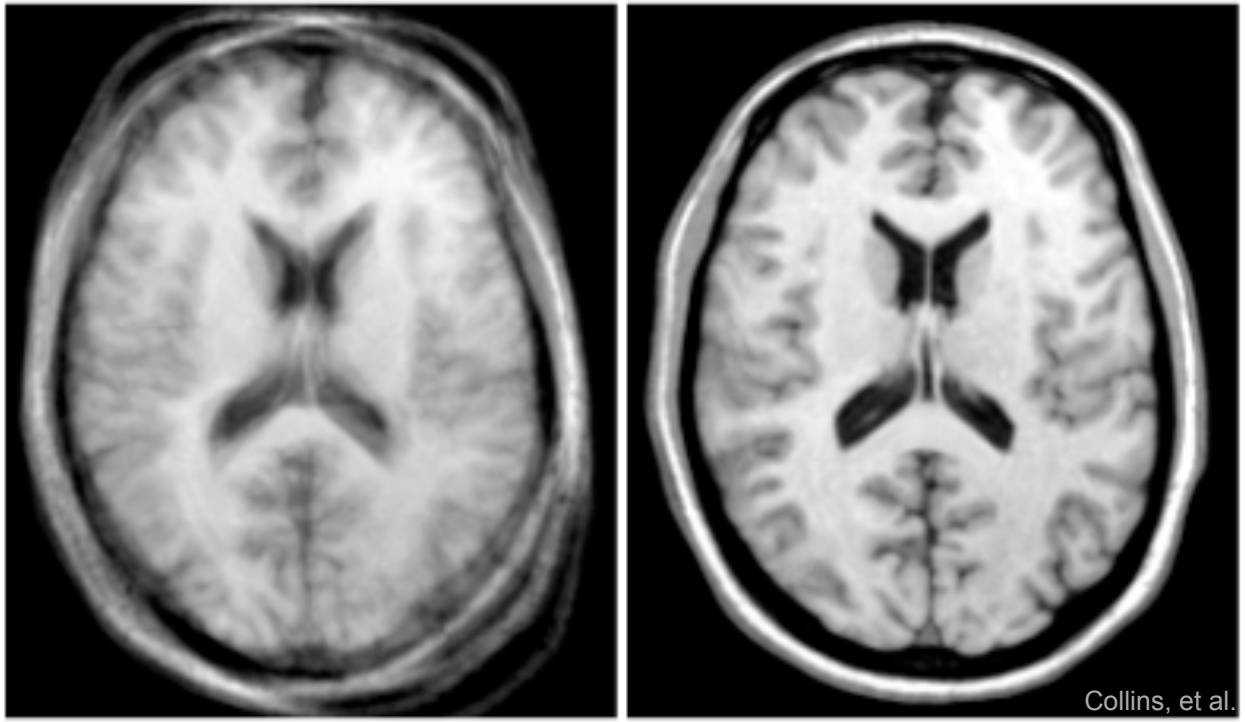
Feature extraction

Surface construction

Deformation and registration

Topology and brain images

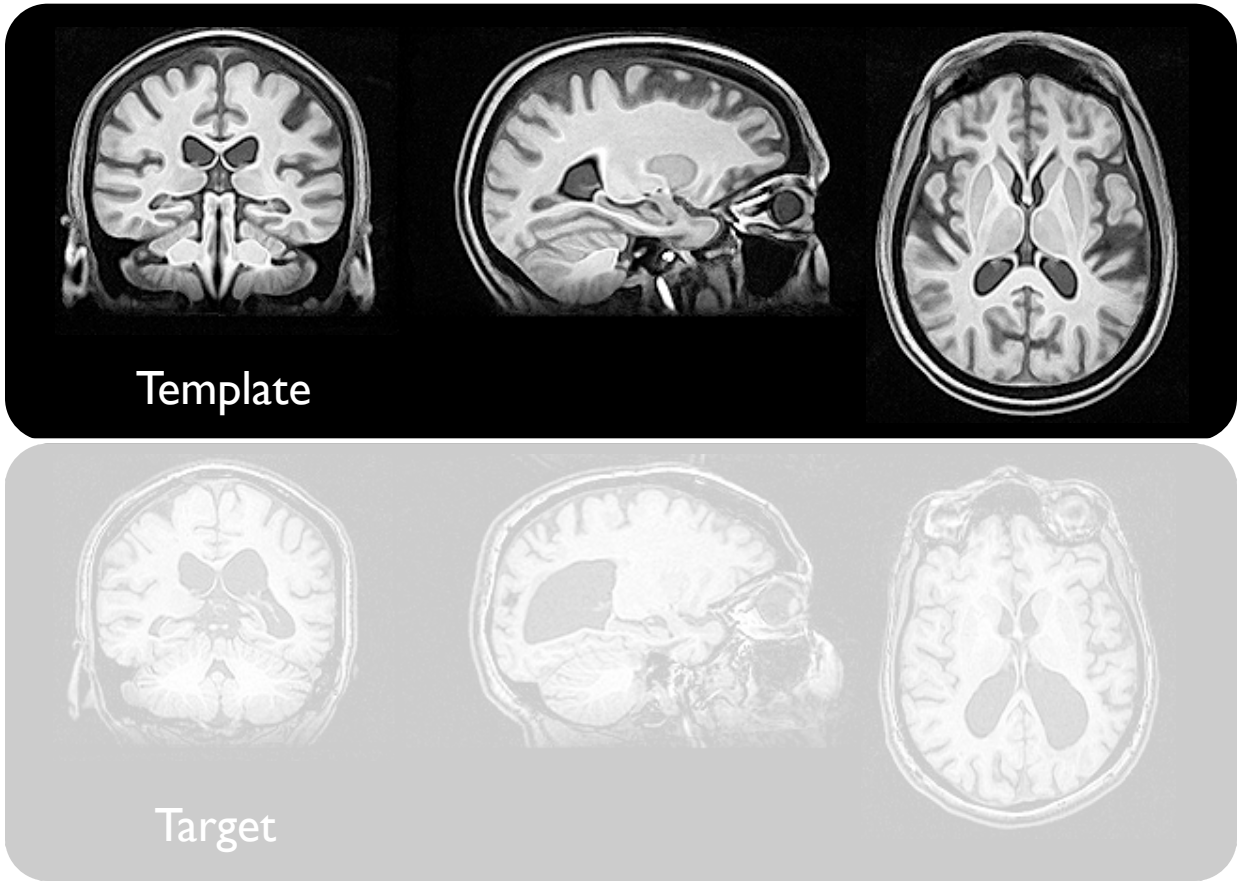
registration: establishing correspondences



linear nonlinear

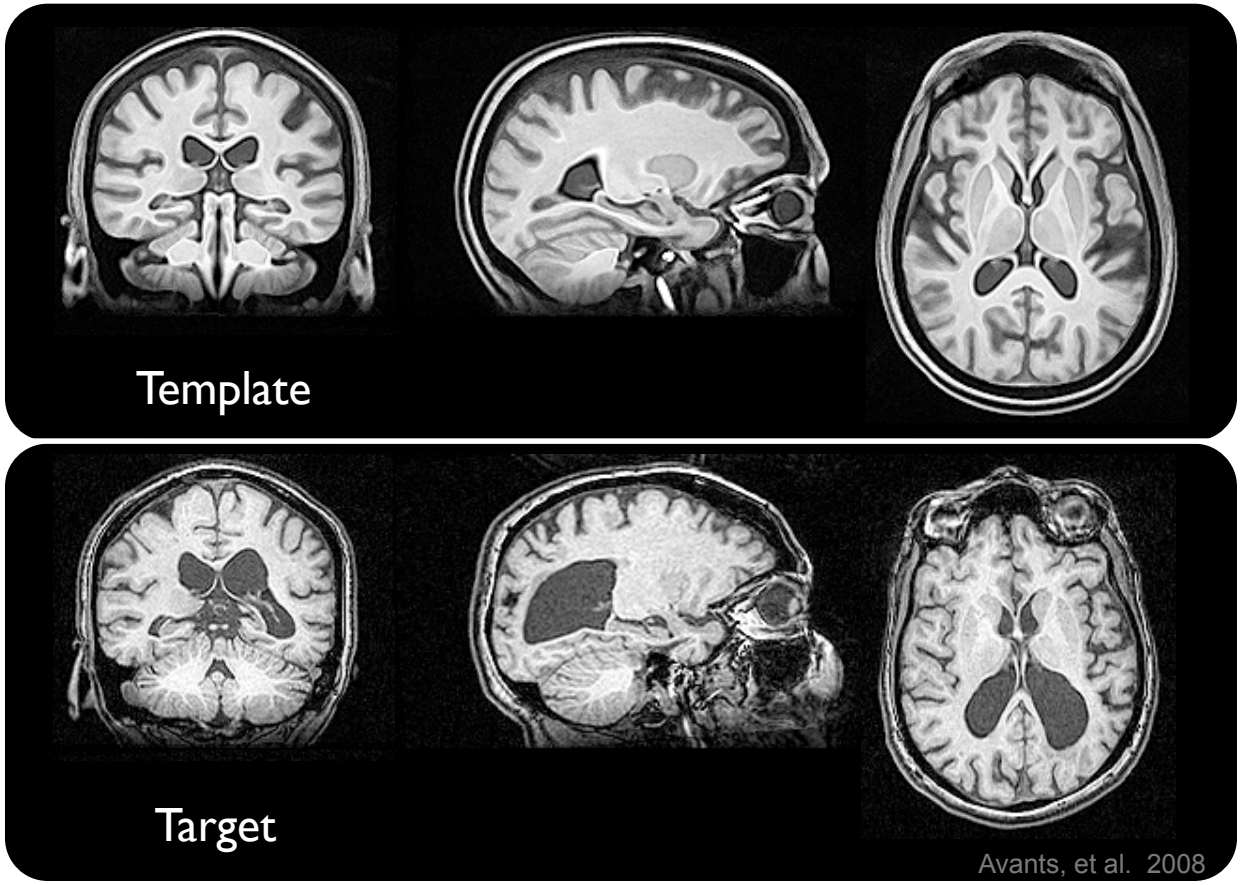
the correspondence problem

template registration



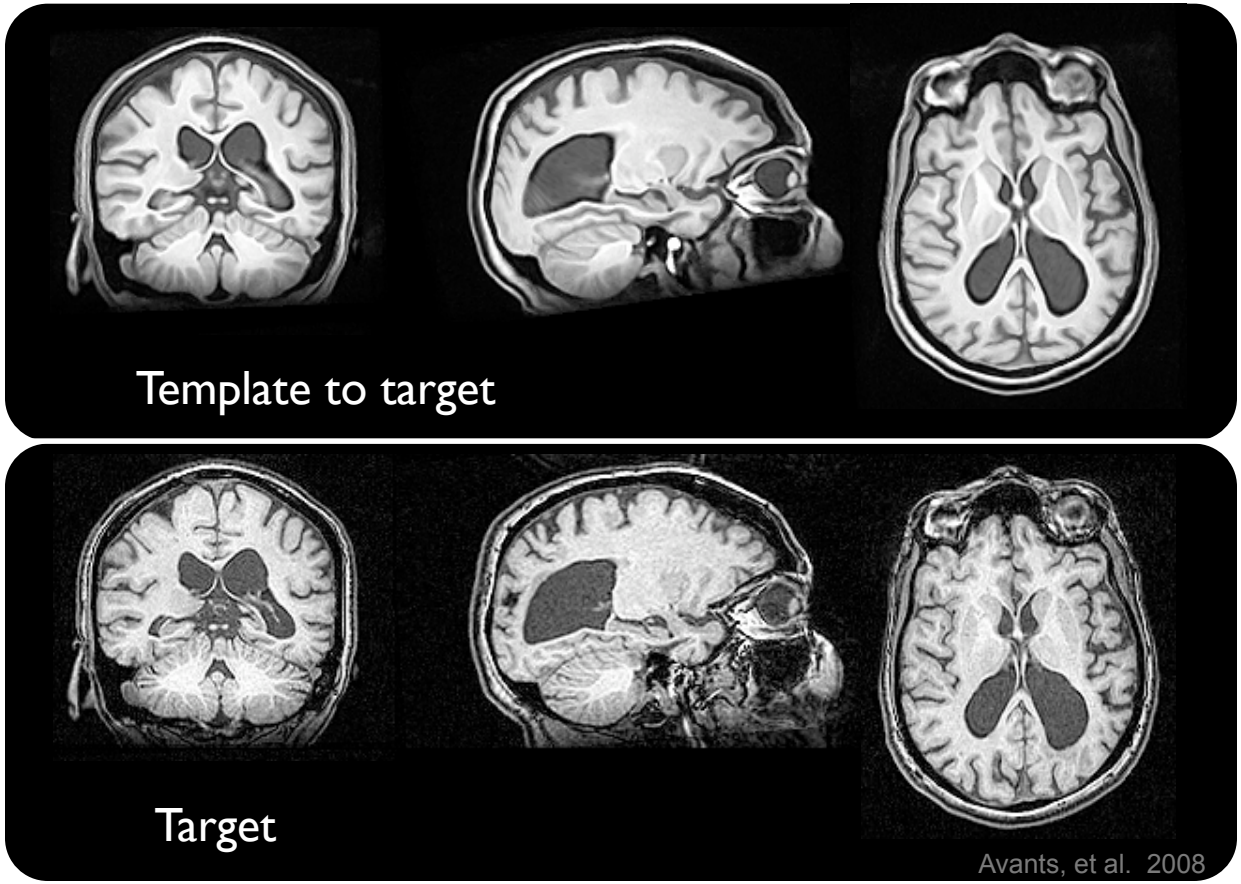
the correspondence problem

template registration



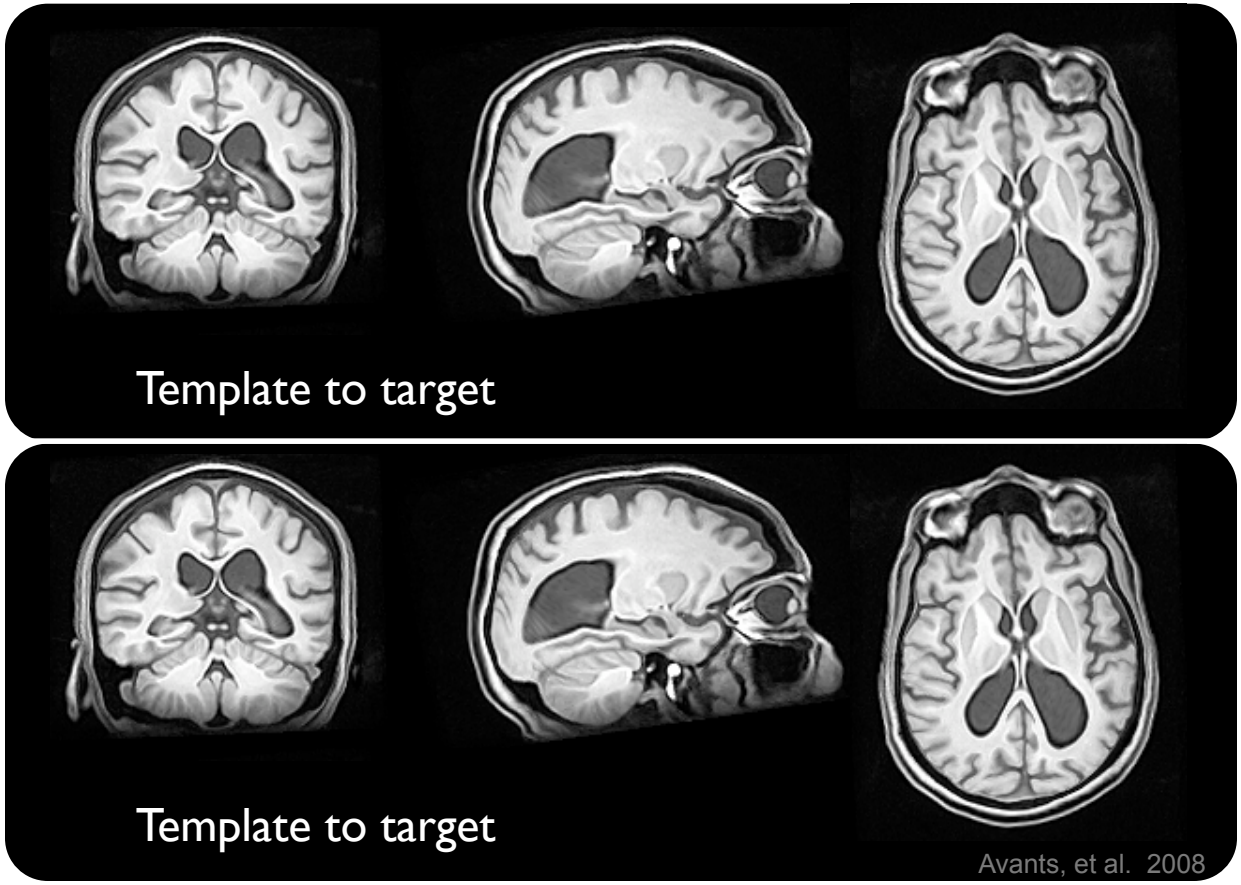
the correspondence problem

precise, but accurate?



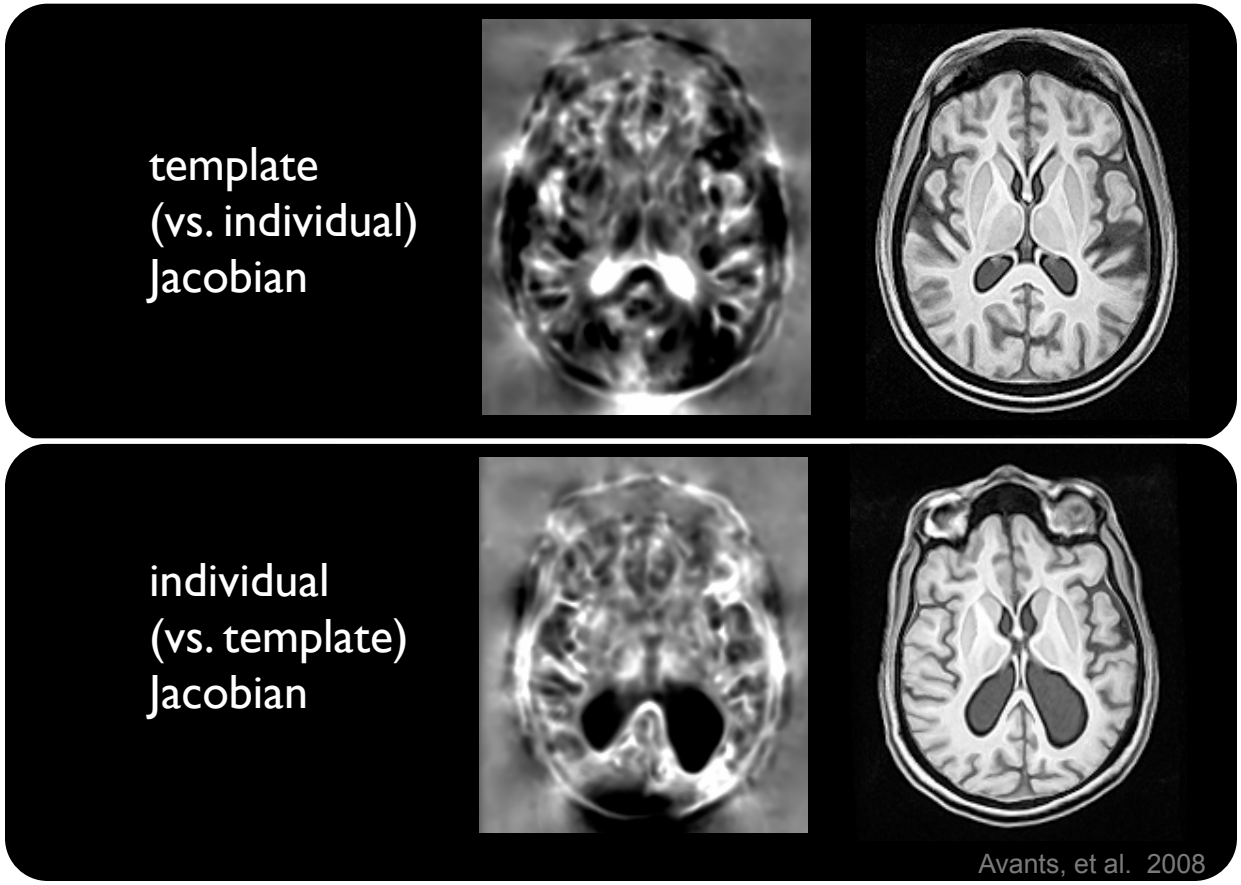
the correspondence problem

precise, but accurate?



registration application 1:

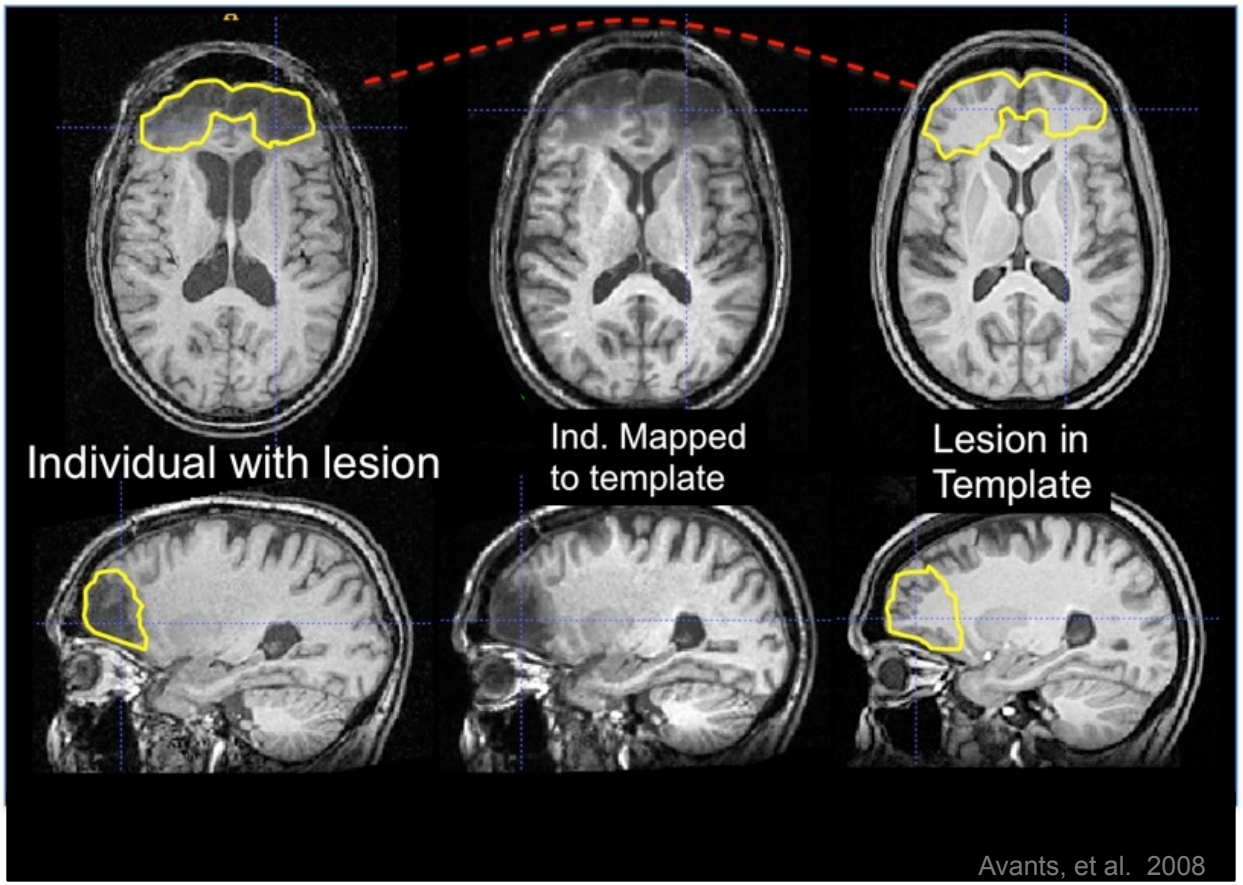
deformation-based morphometry



Jacobian matrix: representation of a differential, an $n \times n$ matrix of first order partial derivatives whose entry in the i-th row and j-th column is $\partial f_i / \partial x_j$. The Jacobian can be thought of as describing the amount of "stretching" that a transformation imposes.

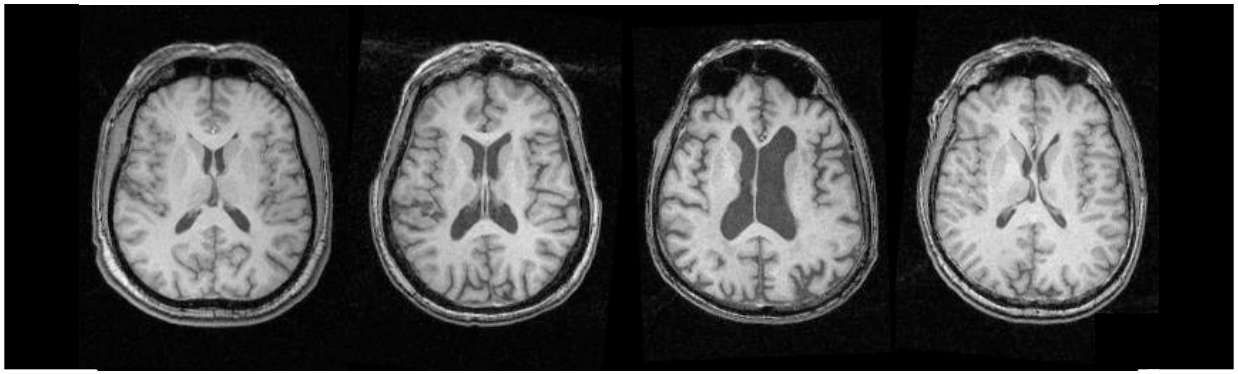
registration application 2:

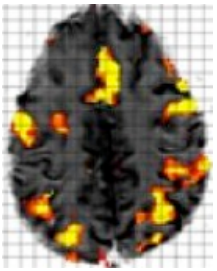
anatomical localization



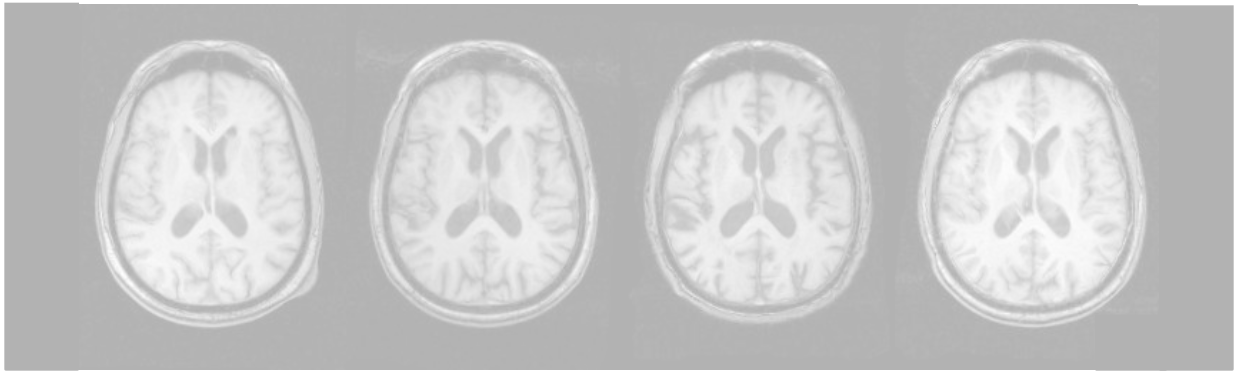
registration application 3:

group analysis of data





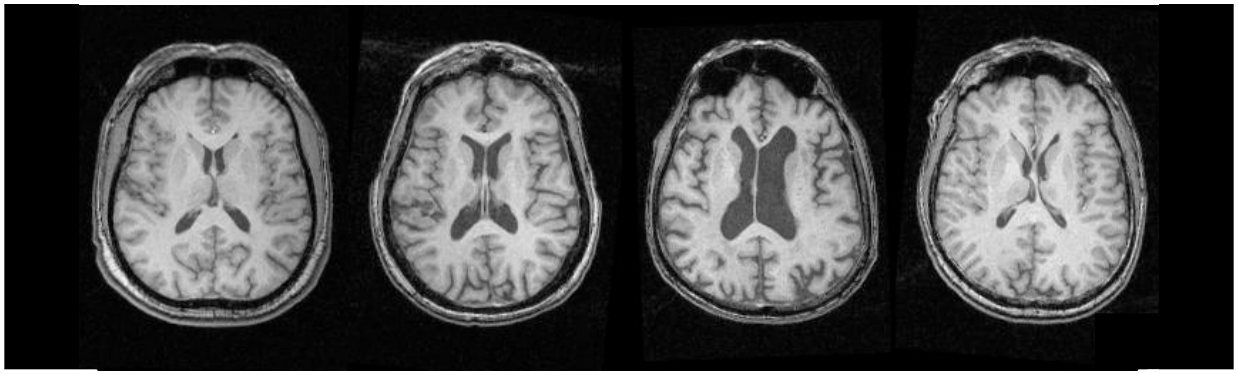
data (structure, function, physiology, landmarks) in individual space

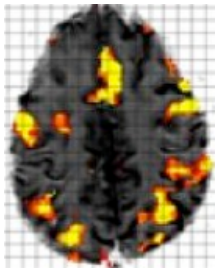


individuals normalized to template space

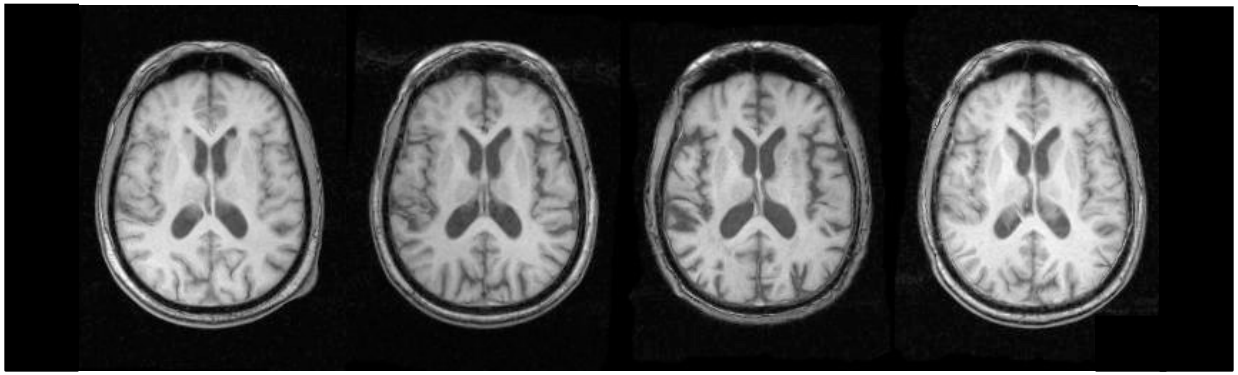
registration application 3:

group analysis of data





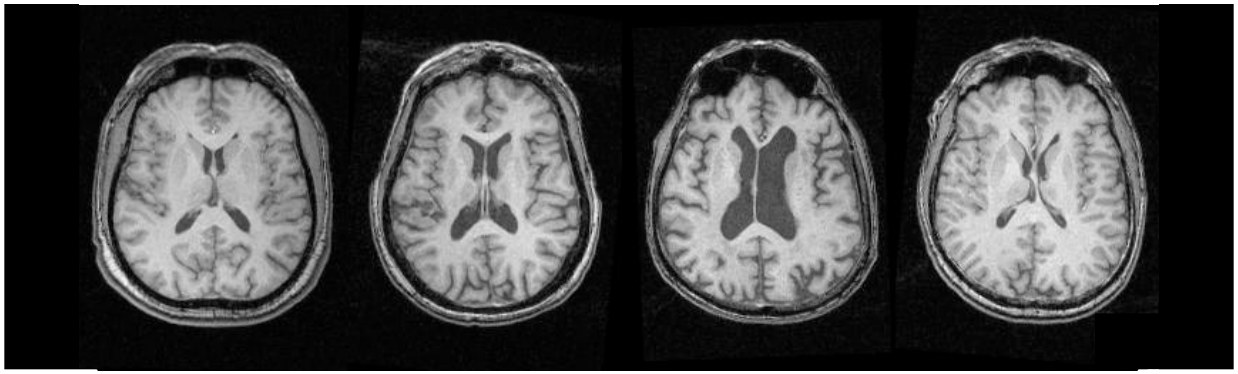
data (structure, function, physiology, landmarks) in individual space

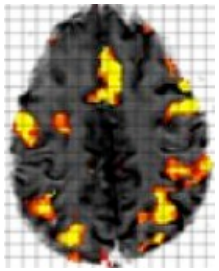


individuals normalized to template space

registration application 3:

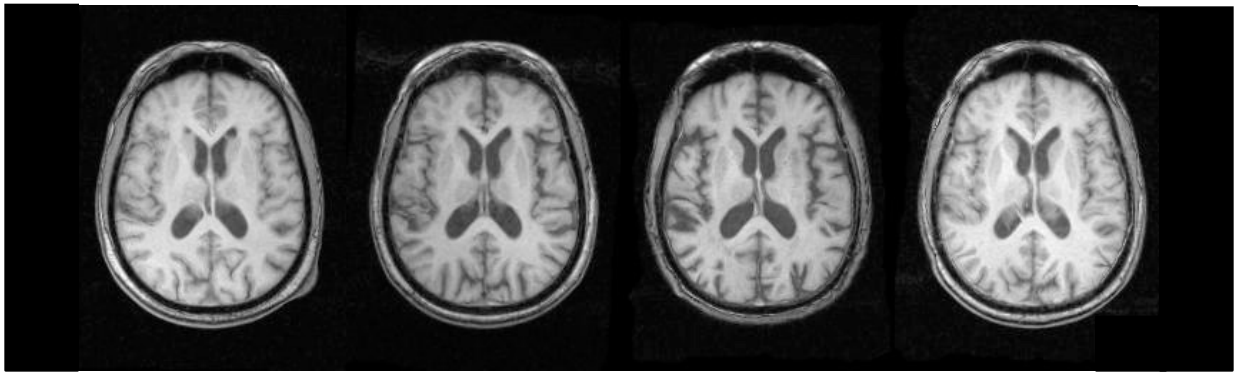
group analysis of data



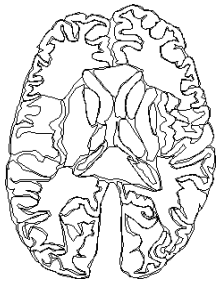


data (structure, function, physiology, landmarks) in individual space

template image



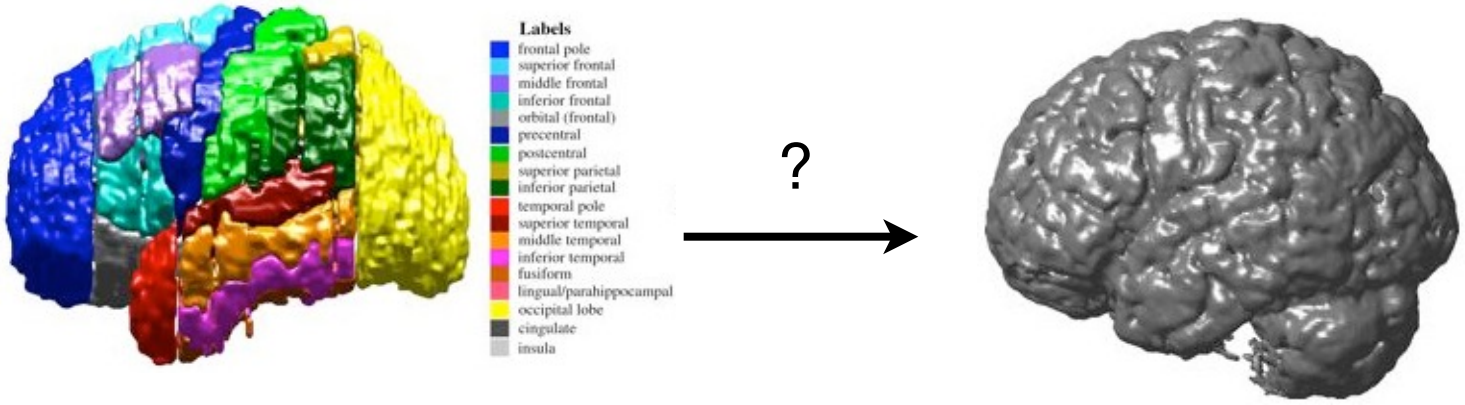
individuals normalized to template space



template labels

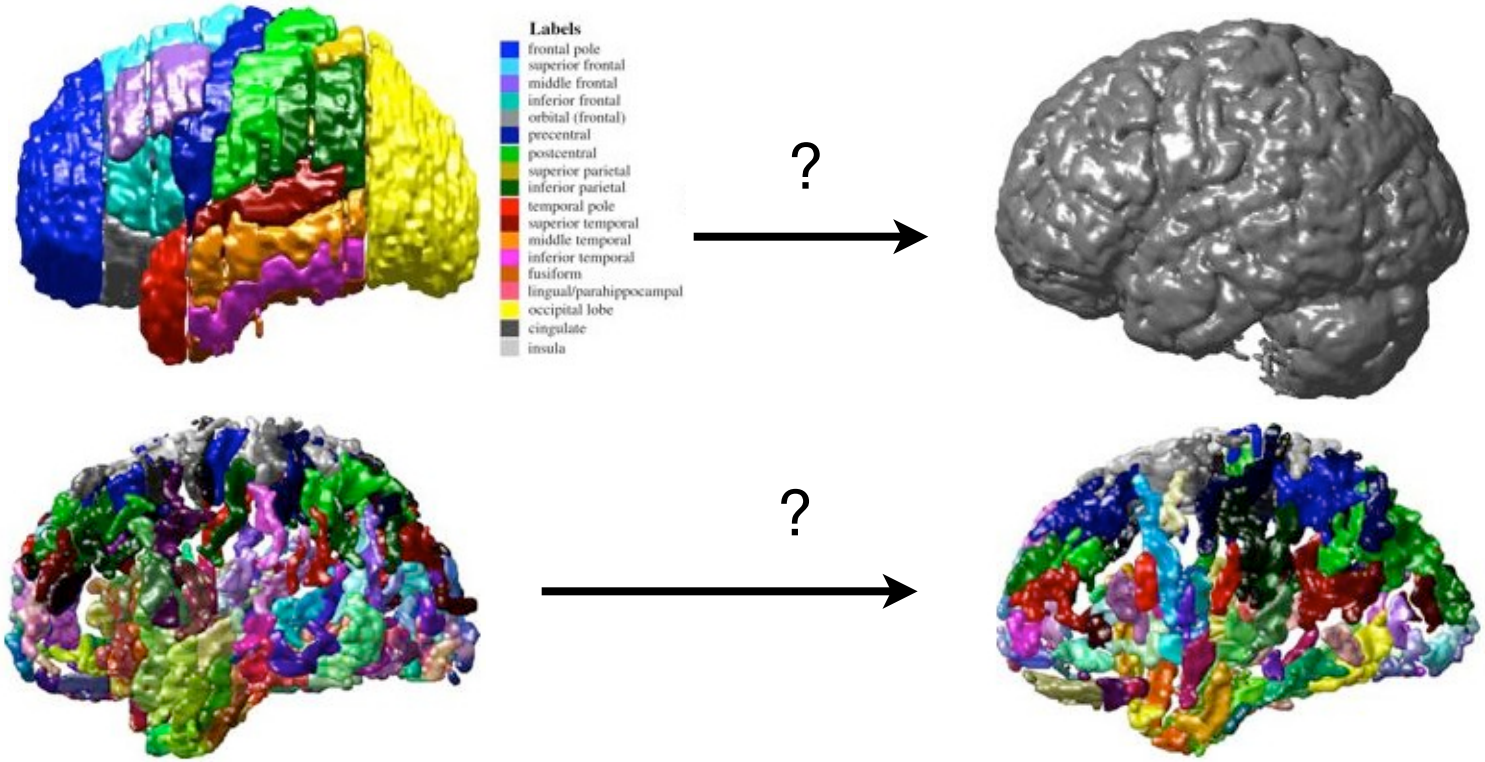
registration application 4:

atlas-based anatomical labeling



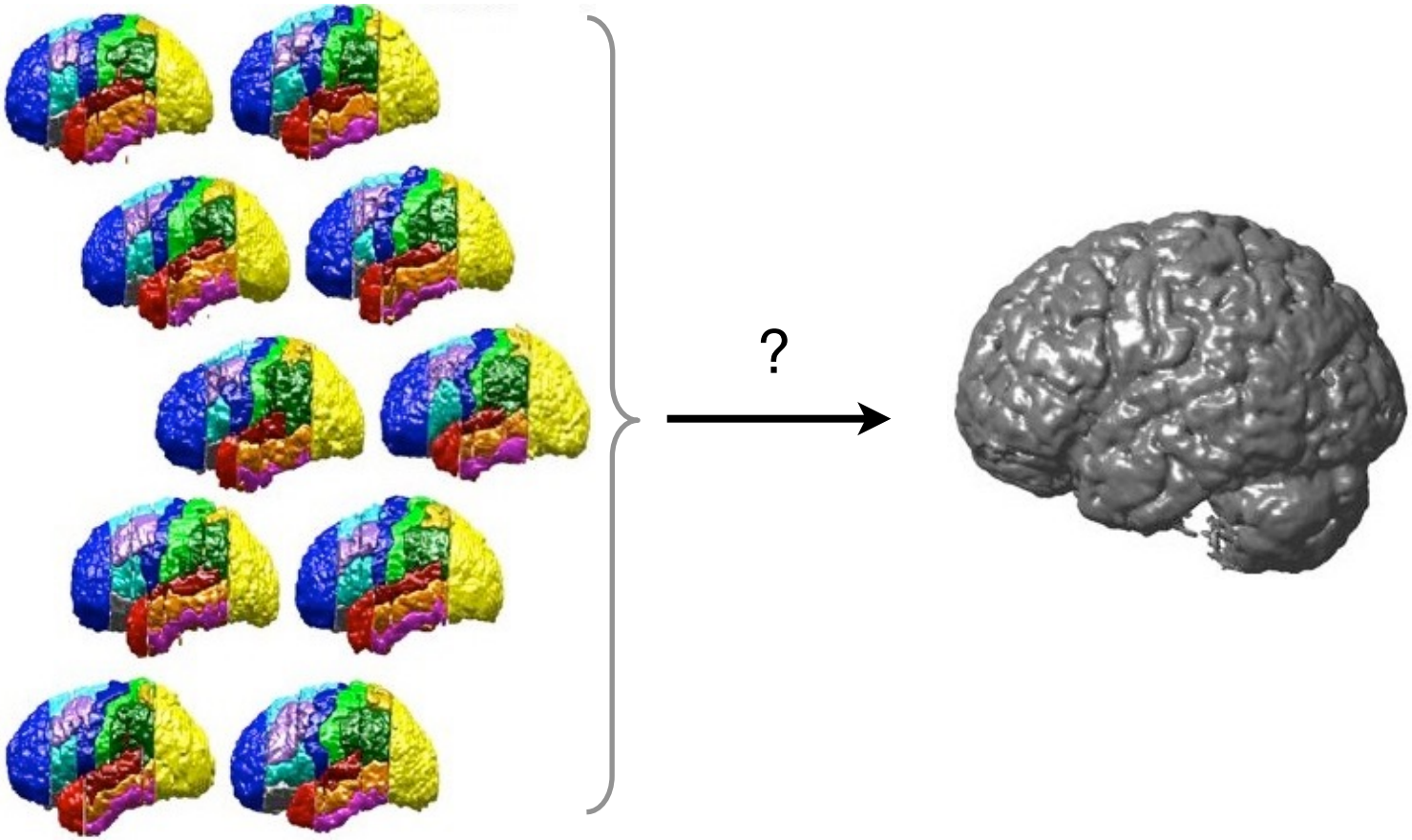
registration application 4:

atlas-based anatomical labeling

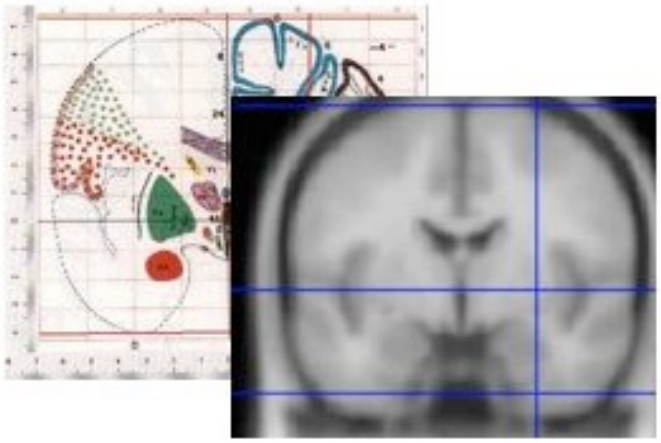


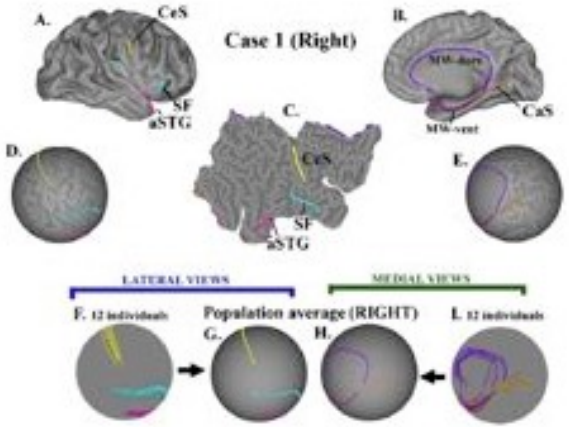
registration application 4:

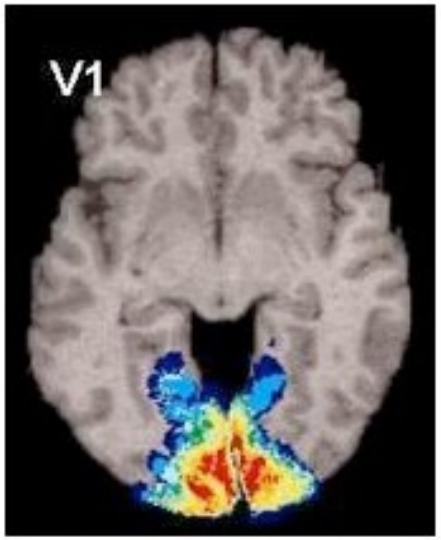
atlas-based anatomical labeling

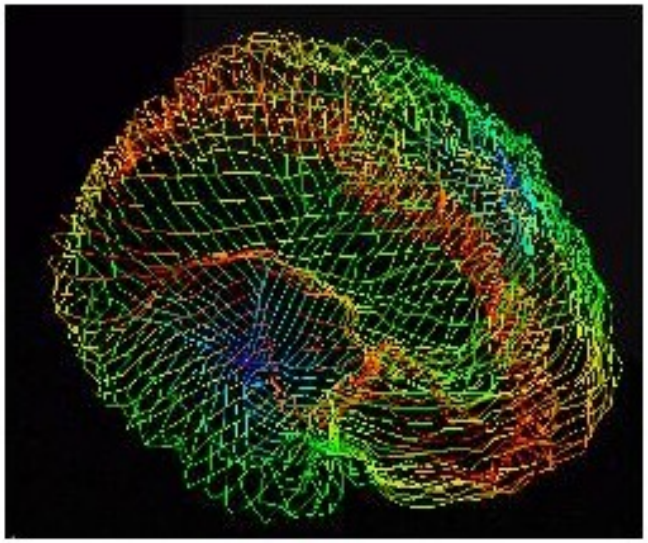


probabilistic atlases



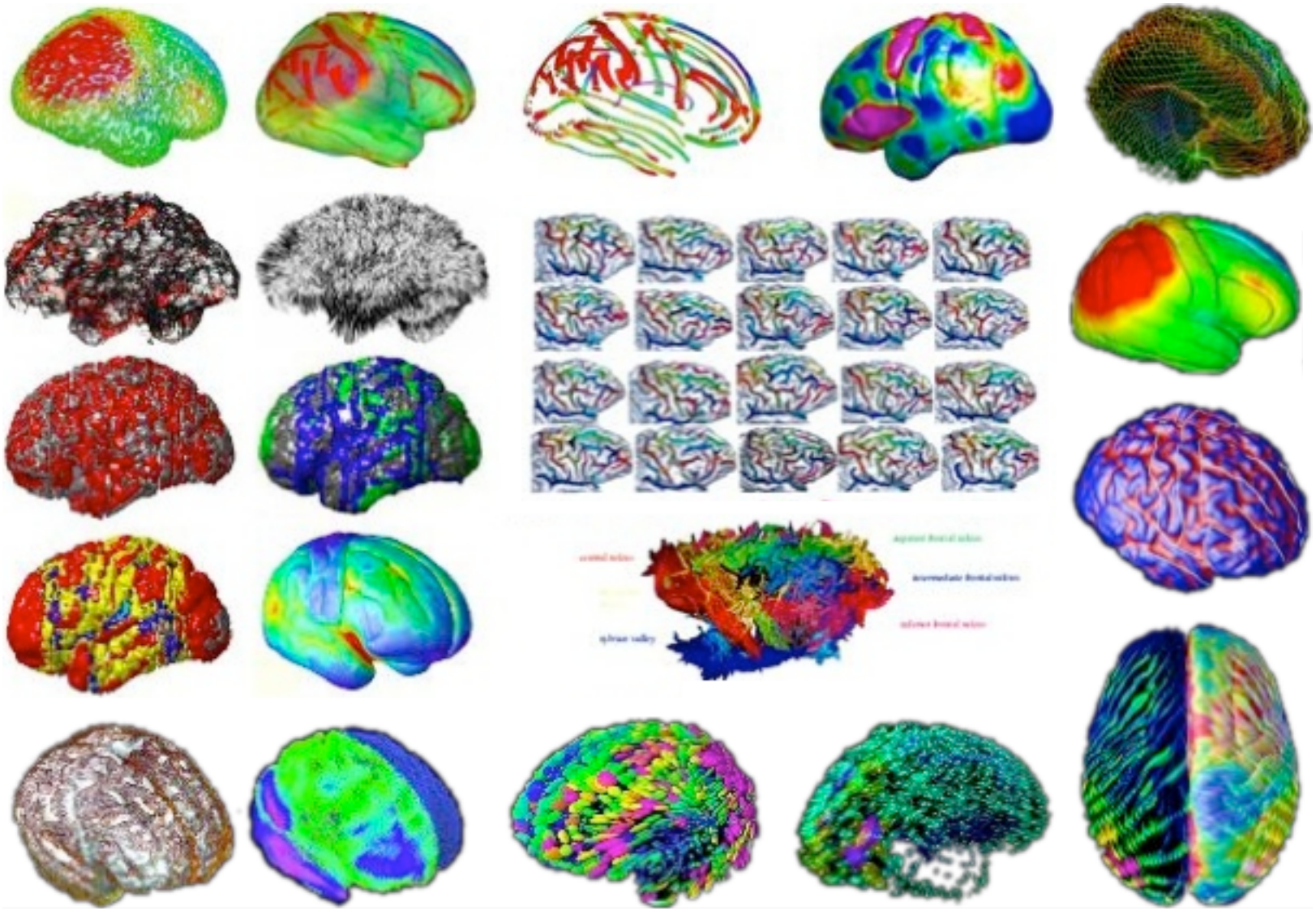






MNI Atlas, van Essen surface-based atlas, LONI deformable atlas , Zilles' probability map, (clockwise from upper left)

registration applications



What characterizes a registration algorithm?

Similarity metric: SSD, MSD, (n)CR, (n)CC, MI,...

Transformation: affine, piecewise linear, nonlinear,...

Regularization: multi-resolution/scale, Gaussian blur,...

Optimization: simplex, gradient descent,...

Interpolation: nearest-neighbor, trilinear, cubic, sinc,...

Algorithms

Software	Similarity metric	Transformation	DOF
FLIRT (linear)	nCR	linear, rigid-body	9, 6
AIR	MSD	5th-order polynomial warps	168
ANIMAL	CC	local translations	69,000
ART	nCC	FFD based on cubic splines (H, np)	7,000,000
Diffeomorphic Demons	SSD	displacement field (D, np)	21,000,000
FNIRT	SSD	cubic B-splines	30,000
IRTK	nMI	cubic B-splines	1,400,000
JRD-fluid	Jensen-Rényi divergence	viscous fluid; variational calculus (D)	2,000,000
ROMEO	displaced frame difference	local affine	2,000,000
SICLE	SSD	3-D Fourier series (D)	8,000
SyN	CC	bi-directional diffeomorphism (D)	28,000,000
SPM5 SPM2-type	MSD	discrete cosine transforms	1,000
Normalize	MSD	discrete cosine transforms	1,000
Unified Segment	generative segmentation model	discrete cosine transforms	1,000
DARTEL toolbox	multinomial model: congealing	FDM of viscosity field (Dc)	6,400,000

n = normalized
CC = cross-correlation
CR = correlation ratio
MI = mutual information
MSD = mean of squared differences
SSD = sum of squared differences

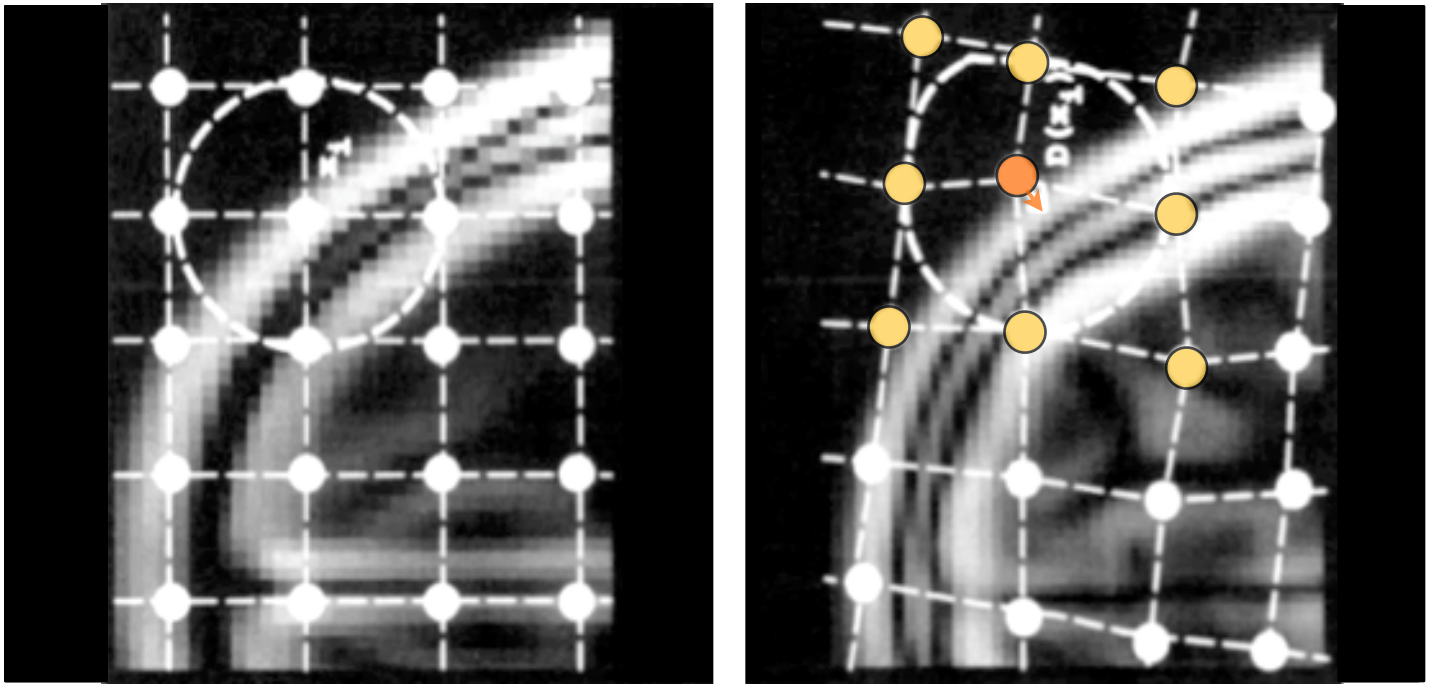
D = diffeomorphic
Dc = diffeomorphic, constant over time
FDM = finite difference model
FFD = free-form deformation
H = homeomorphic
np = nonparametric

Algorithms

Software	Regularization	Multi-resolution
FLIRT (linear)		
AIR	increase of polynomial order	sparse to fine voxel sampling
ANIMAL	stiffness parameter at each node	local Gaussian
ART		median- & low-pass Gaussian
Diffeomorphic Demons		Gaussian
FNIRT	membrane energy	down- to up-sampling; # basis components
IRTK	none used in study	control mesh
JRD-fluid	compressible viscous fluid	multi-resolution
ROMEO	explicit method; brightness constancy	adaptive multigrid (octree); Gaussian
SICLE	linear elasticity; inverse consistency	# basis components
SyN	transformation symmetry	xfm symmetry; Gaussian of velocity field
SPM5 SPM2-type	bending energy; basis cutoff	
Normalize	bending energy; basis cutoff	
Unified Segment	bending energy; basis cutoff	
DARTEL toolbox	linear elasticity	full multigrid (recursive)

Nonlinear registration example

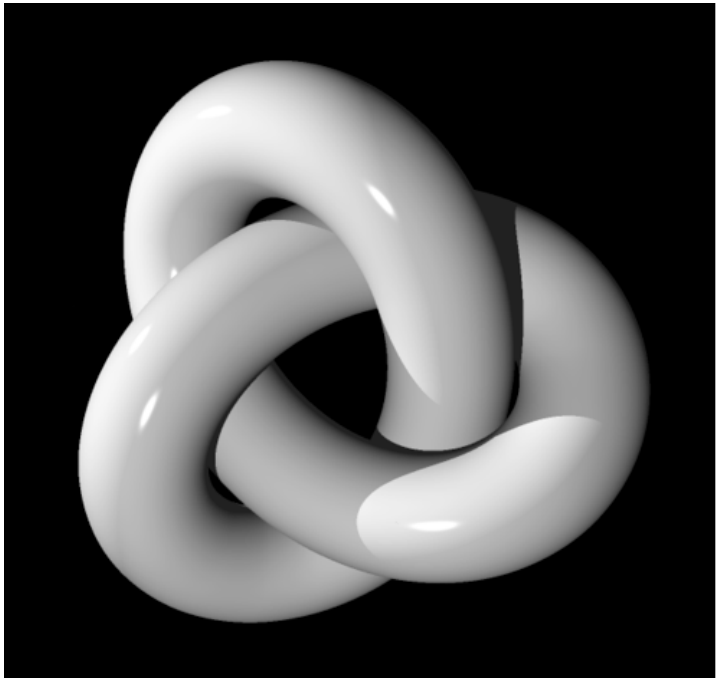
local translations, free-form deformations



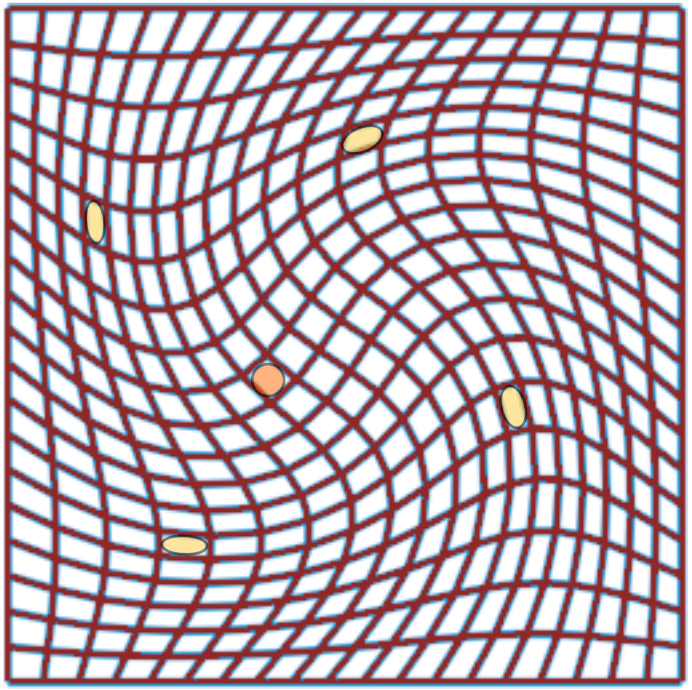
optimization of 3 translational parameters to maximize the neighborhood cross-correlation for each node (ANIMAL)

Nonlinear registration example

topological constraints: diffeomorphisms



homeomorphism: continuous mapping and inverse, but not deformation (trefoil knot, circle)



diffeomorphism: bijective map from manifold M to N and its inverse are differentiable

Brain image processing

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Deformation and registration

Topology and brain images

Topology correction

of segmented / extracted structures

Topology-preserving deformations

Topology of lesions, plaques, etc.

Topology of elevation map of brain folds

Topology of networks

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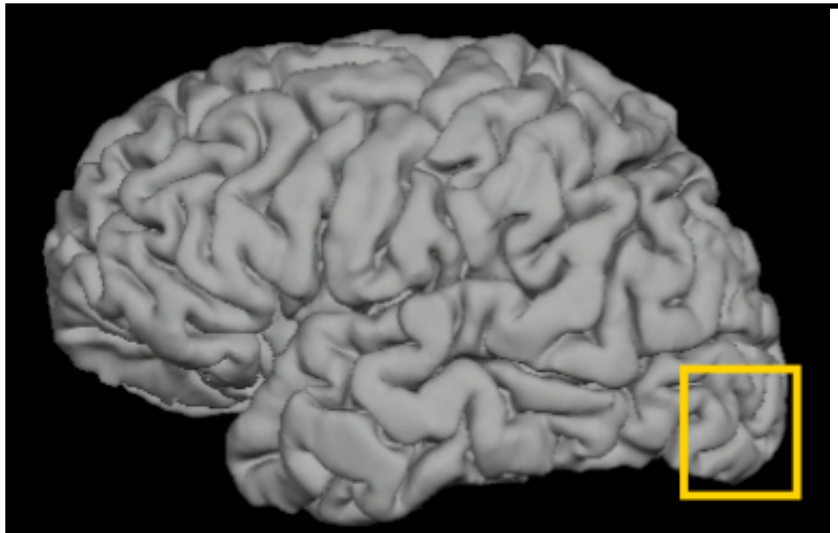
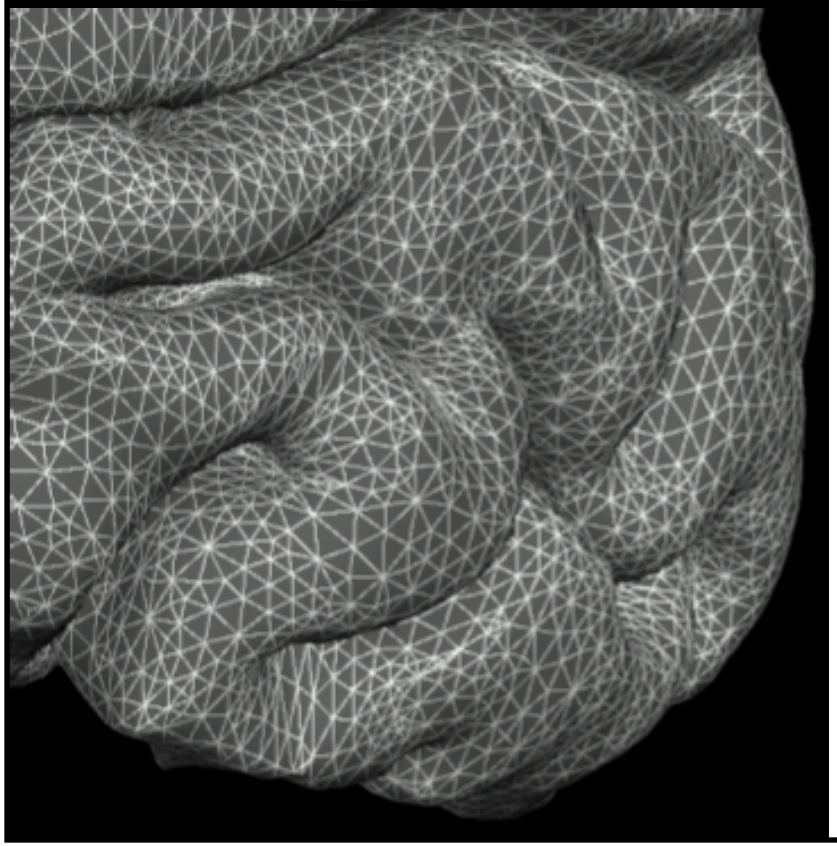
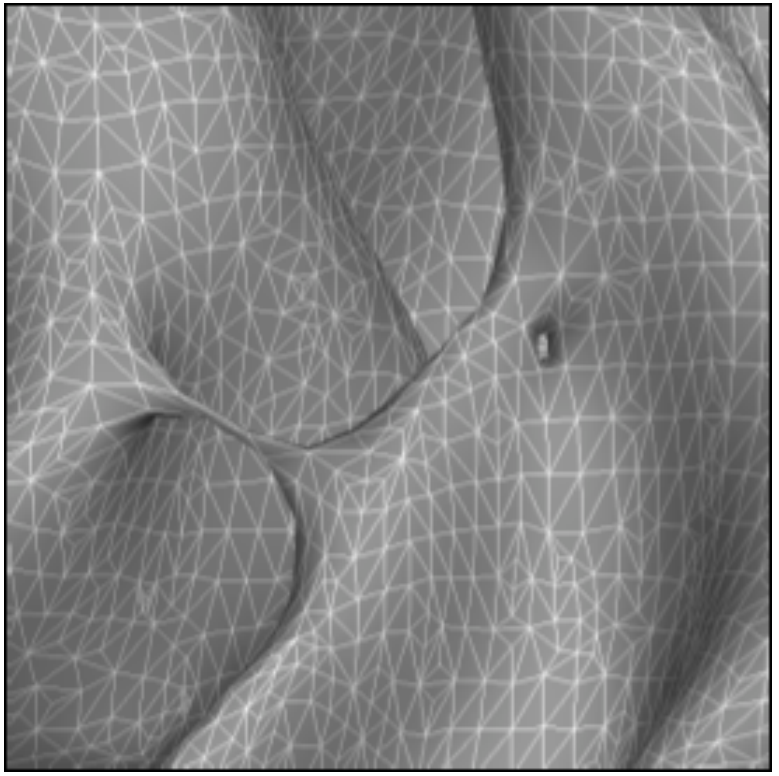
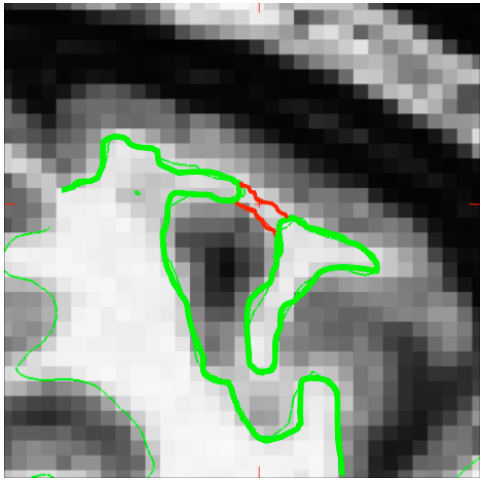
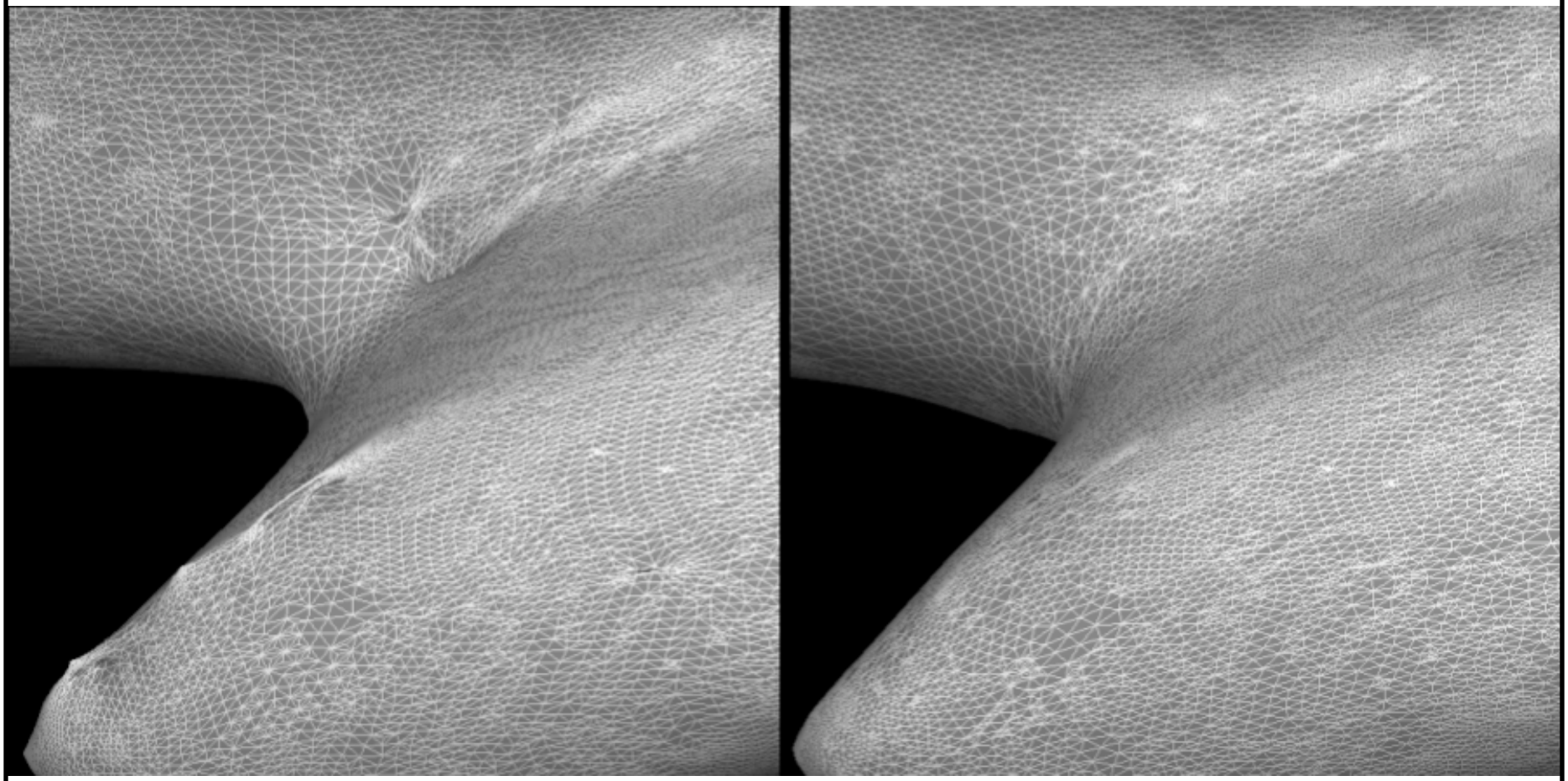






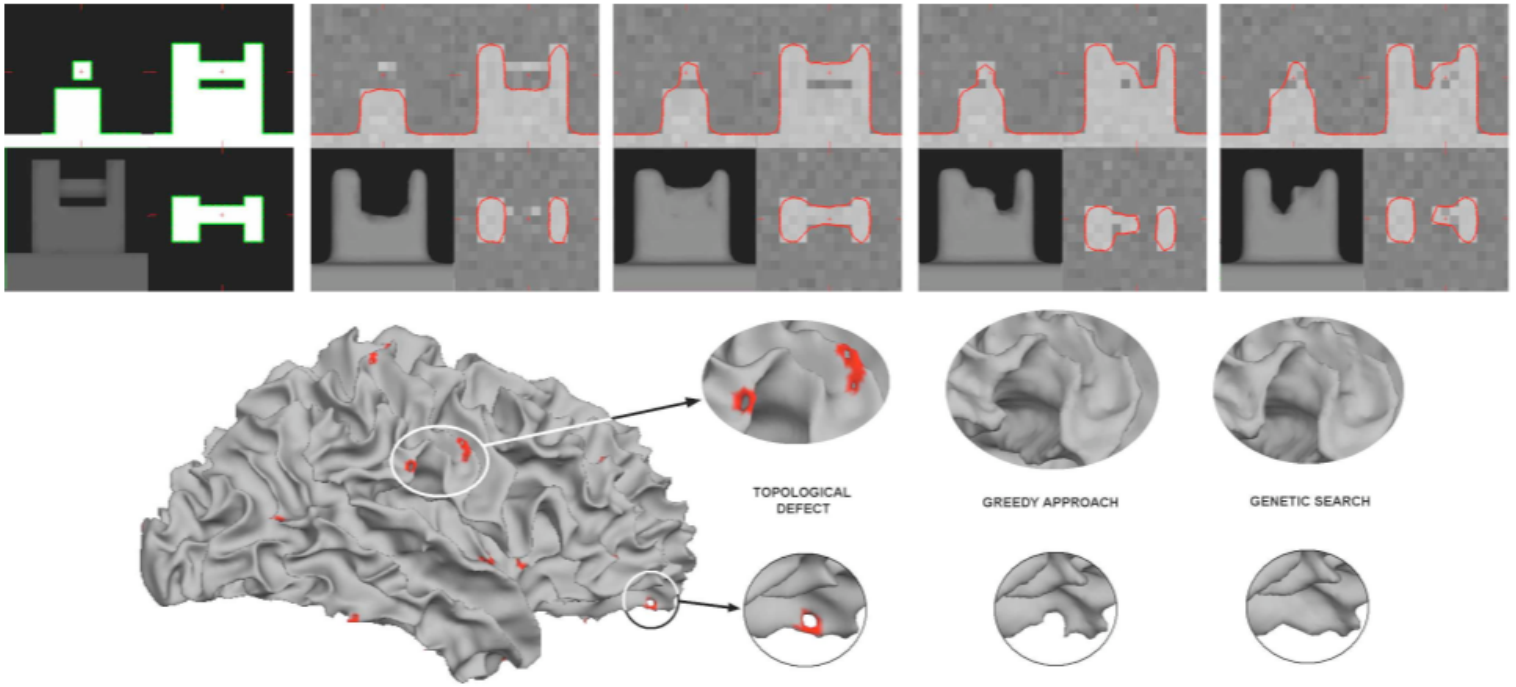


Freesurfer



Freesurfer

A Genetic Algorithm for the Topology Correction of Cortical Surfaces



Ségonne et al. 2005

Topology correction

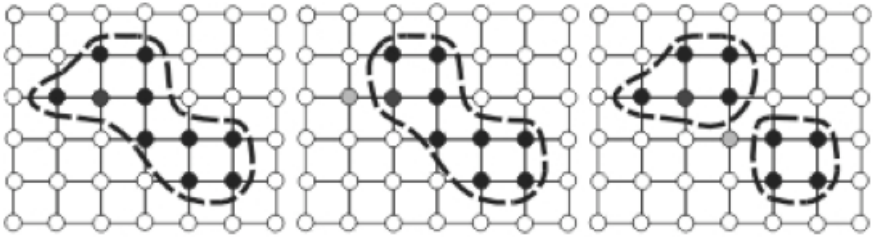
of segmented / extracted structures

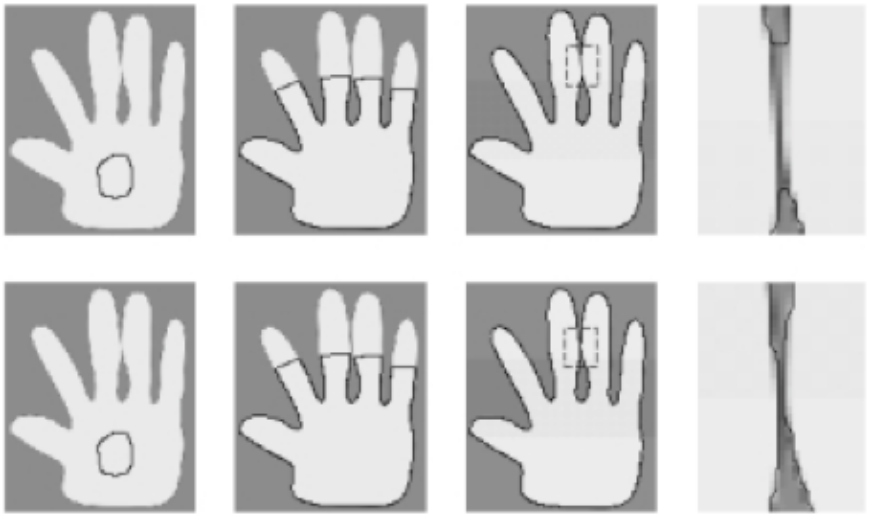
Topology-preserving deformations

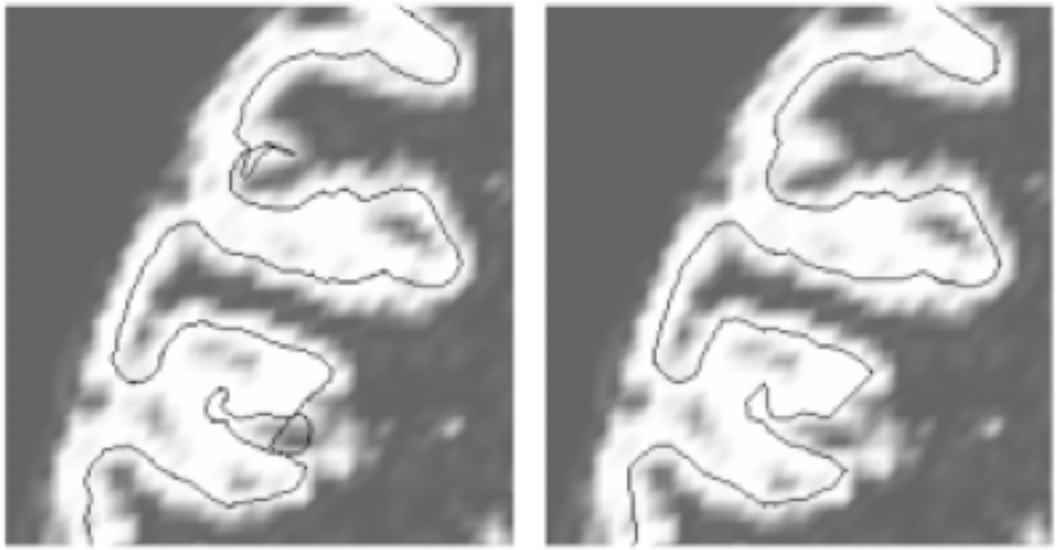
Topology of lesions, plaques, etc.

Topology of elevation map of brain folds

Topology of networks

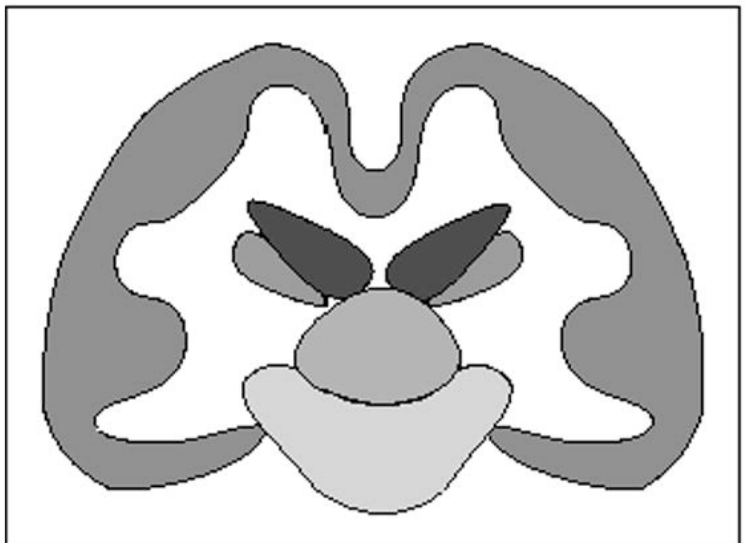


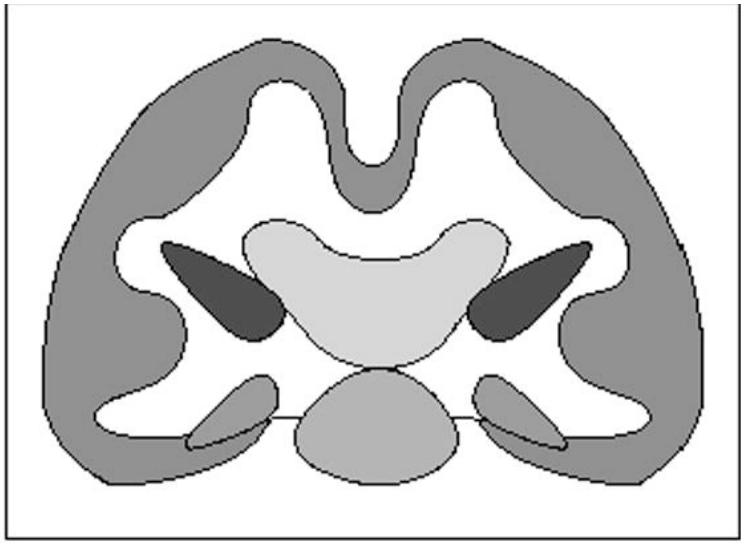




topology-preserving geometric deformation model: level set implementation

Xan et al. 2003





homeomorphic segmentation, topology of groups (unions) of structures

Bazin and Pham 2008

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Topology of networks

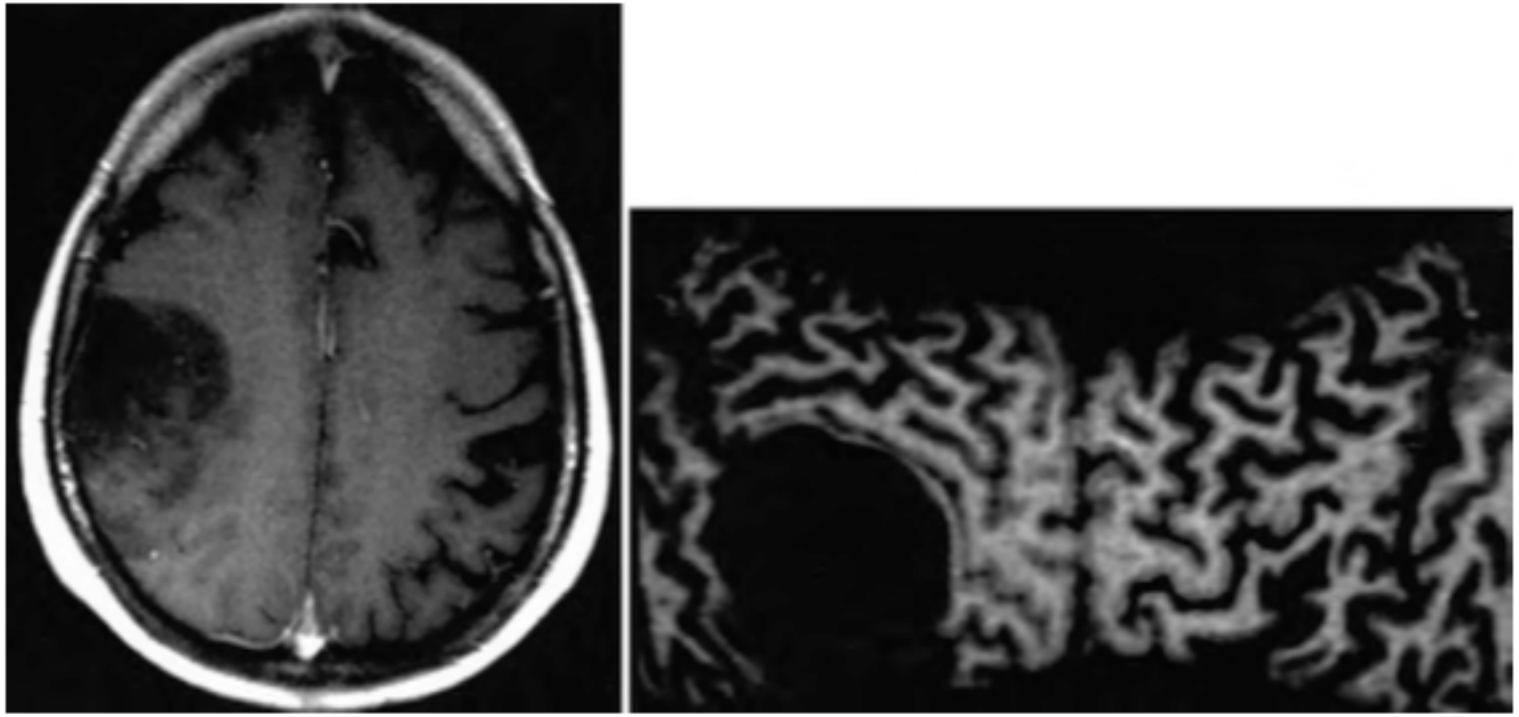

FIG. 4. Accurate localization of this large World Health Organization Grade III astrocytoma was not possible due to distortion and shifting of the frontoparietal gyri. *Left:* Sagittal MR image. The sulci are effaced and landmarks are not identifiable on sectional images. *Right:* A BSR image clearly demonstrating localization of the tumor in the parietal lobe and extension of the lesion as it infiltrates the postcentral gyrus. By depicting the entire extent of the tumor along the brain surface, infiltration of the precentral gyrus could be ruled out.

Brain Surface Reformatting for lesion localization

Hattingen et al. 2005

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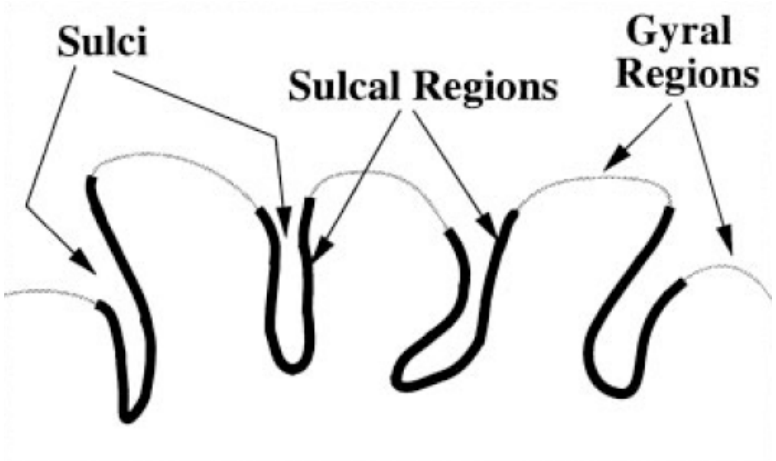
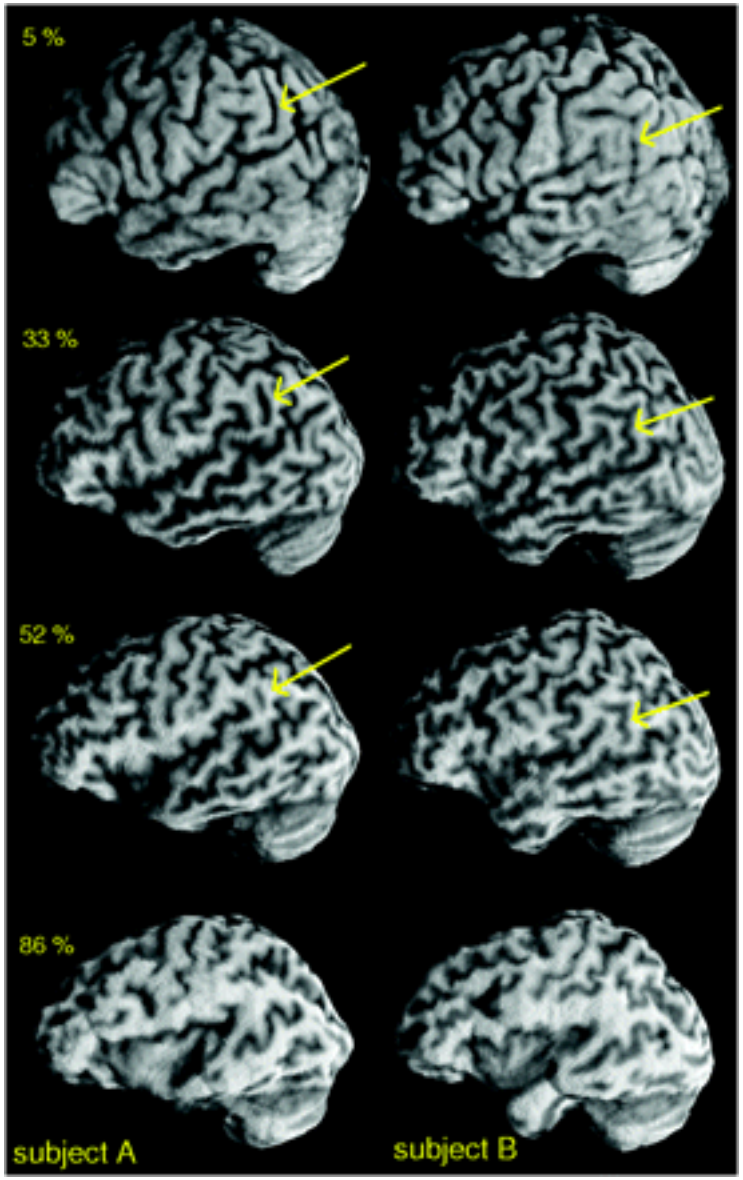
Topology of lesions, plaques, etc.

Topology of elevation map of brain folds

Topology of networks





complexity of sulcal pattern decreases with depth

Lohmann et al. 2008

Topology correction

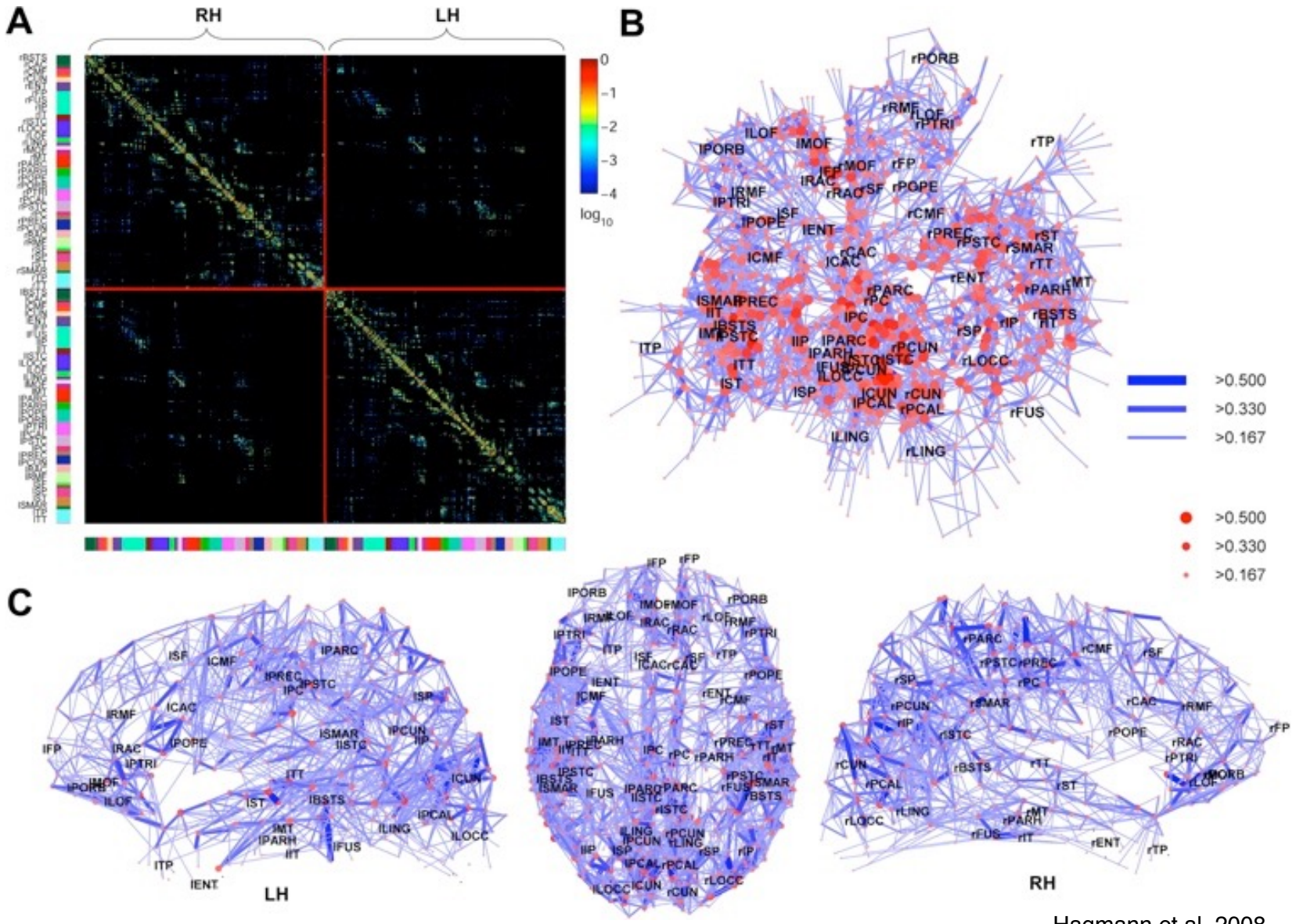
of segmented / extracted structures

Topology-preserving deformations

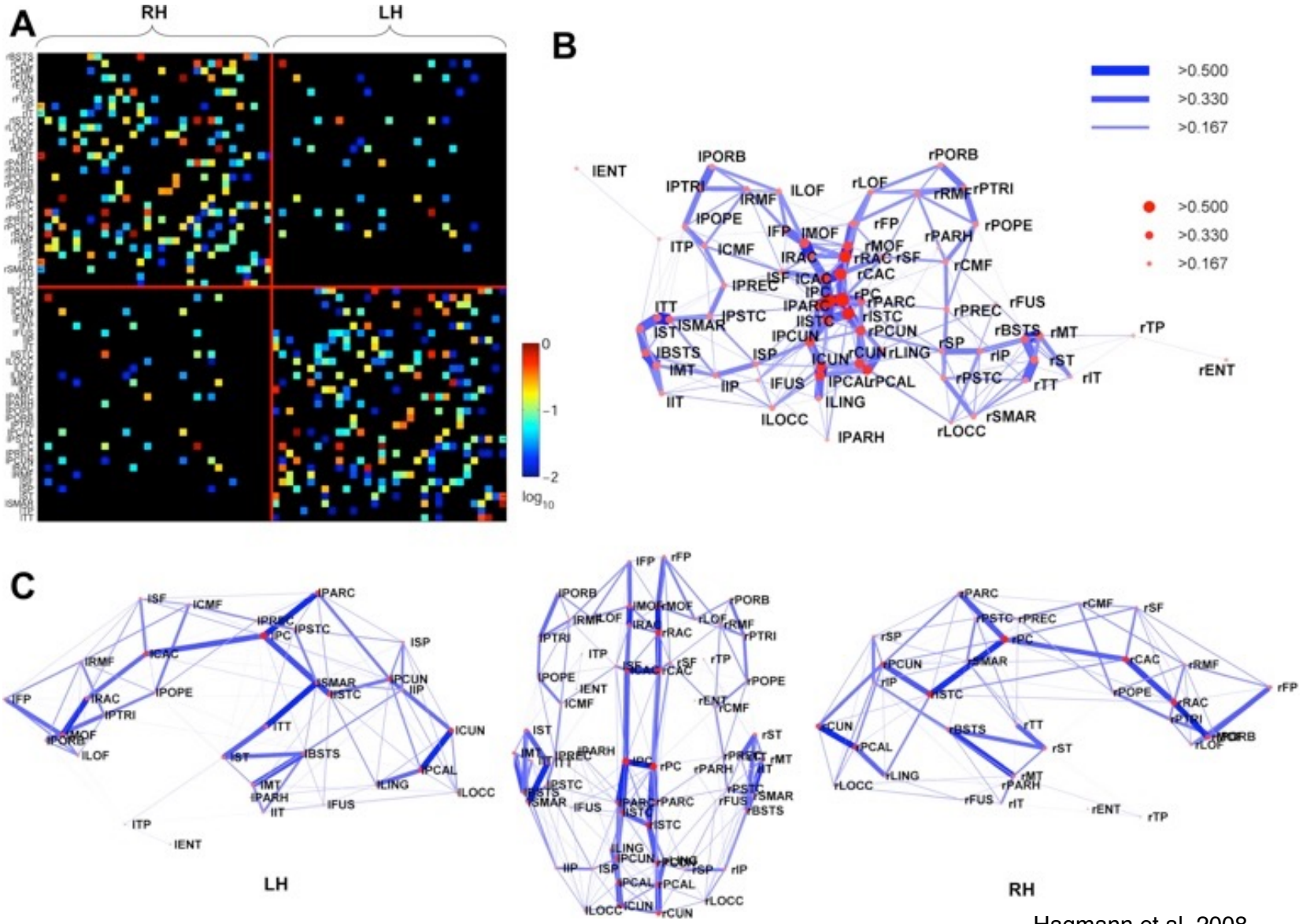
Topology of lesions, plaques, etc.

Topology of elevation map of brain folds

Topology of networks



Hagmann et al. 2008



Hagmann et al. 2008

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References

To download this lecture:
http://www.mindboggle.info/lectures/

Software packages illustrated:
Mindboggle, FreeSurfer, BrainVisa, CRUISE, etc.

Image processing examples
Matlab software environment: http://www.mathworks.com

Registration examples:
http://www.picsl.upenn.edu/ANTS/
ANIMAL: http://dx.doi.org/10.1002/hbm.460030304
Whole Brain Atlas