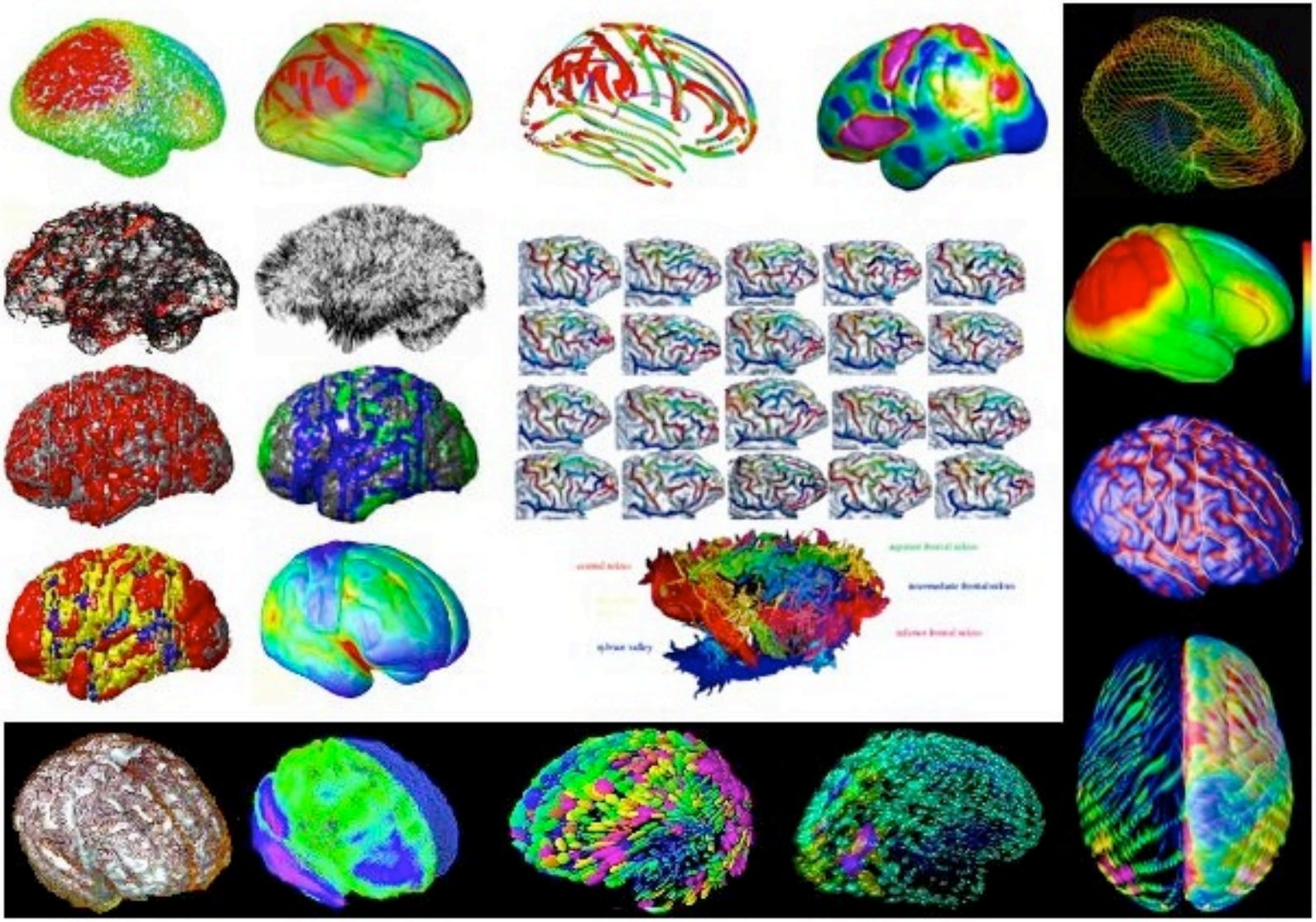
Nonlinear Registration and Brain Labeling

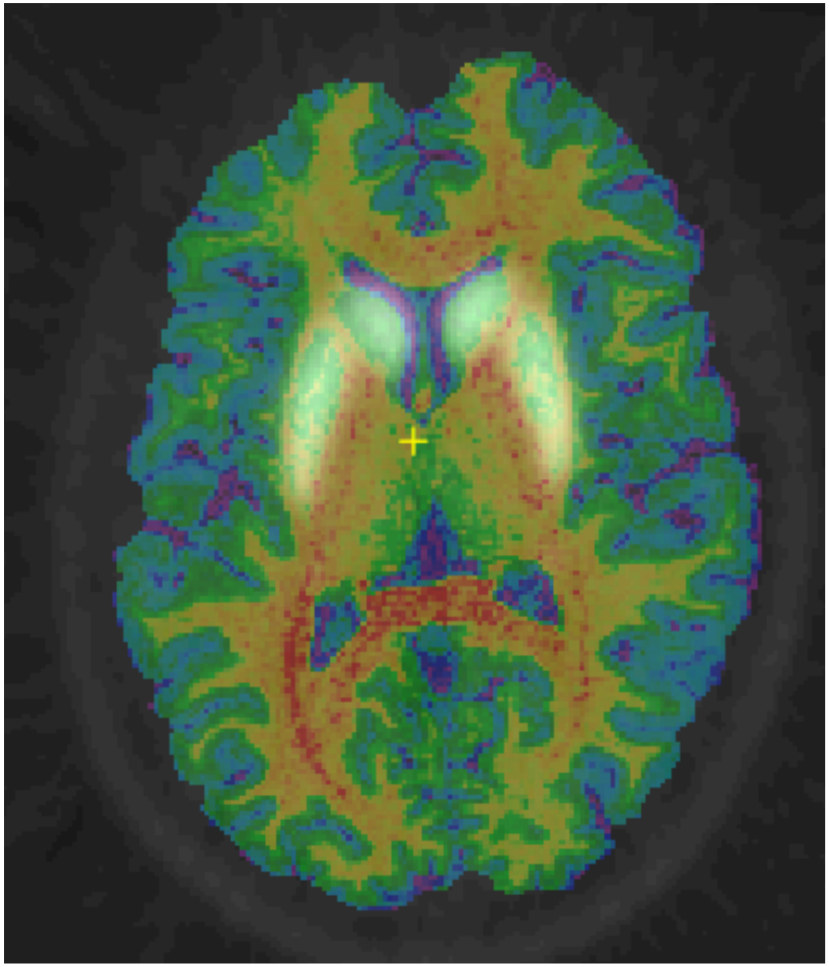


UCLA (LONI), INRIA, Timone U., NIMH, Cornell U., Columbia U.

linear registration

same subject, different image type

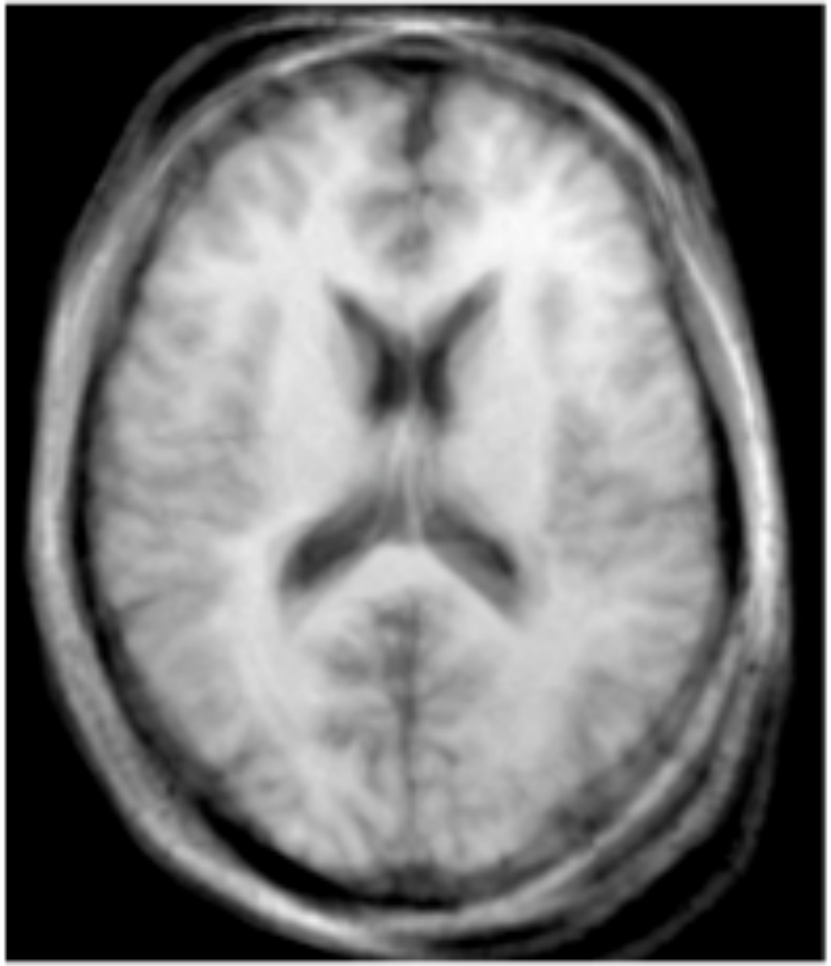
MRI



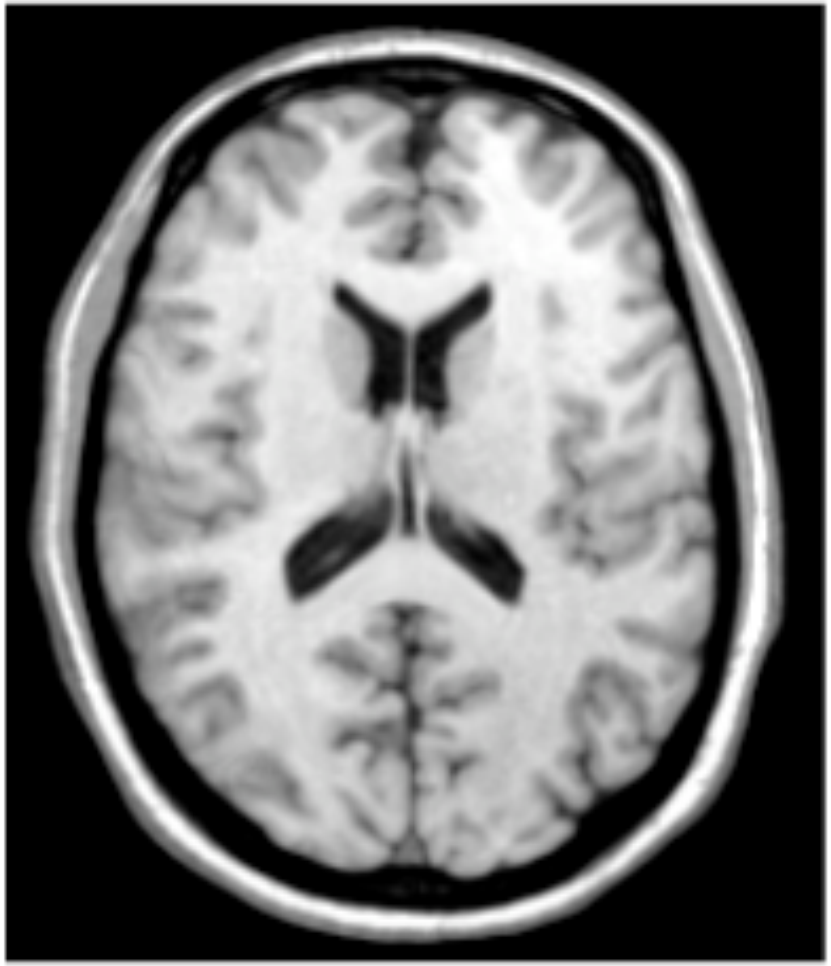
MRI + PET

linear vs. nonlinear

different subject, same image type



linear



nonlinear

registration / image mapping

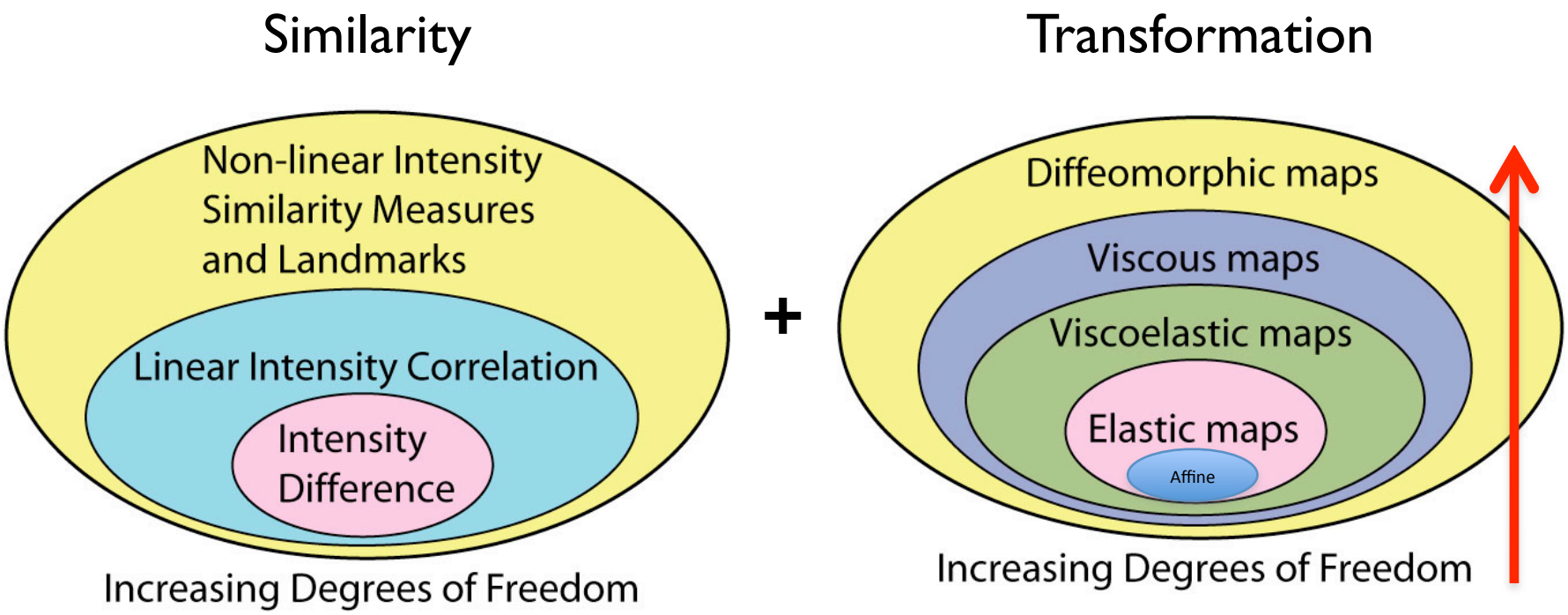
1. **Similarity** metric: SSD, MSD, (n)CR, (n)CC, MI,...
2. **Transformation** model: affine, piecewise linear, nonlinear,...
3. Regularization method: multi-resolution/scale, Gaussian blur,...
4. Optimization strategy: simplex, gradient descent,...
5. Interpolation type: nearest-neighbor, trilinear, cubic, sinc,...

comparative evaluation: http://www.mindboggle.info/papers/

Algorithm	Deformation	≃dof	Similarity	Regularization
FLIRT	linear, rigid-body	9, 6	norm. CR	
AIR	5th-order polynomial warps	168	MSD (opt. intensity scaling)	incremental increase of polynomial order; MRes: sparse-to-fine voxel sampling
ANIMAL	local translations	69K	CC	MRes, local Gaussian smoothing; stiffness parameter weights mean deformation vector at each node
ART	FFD based on cubic splines (non-parametric, homeomorphic)	7M	norm. CC	MRes median and low-pass Gaussian filtering
Diffeomorphic Demons	non-parametric, diffeomorphic displacement field	21M	SSD	MRes: Gaussian smoothing
FNIRT	cubic B-splines	30K	SSD	membrane energy* MRes: down- to up-sampling; number of basis components
IRTK	cubic B-splines	1.4M	norm. MI	none used in the study; MRes: control mesh and image
JRD-fluid	viscous fluid: variational calculus (diffeomorphic)	2M	Jensen-Rényi divergence	compressible viscous fluid governed by the Navier-Stokes equation for conservation of momentum; MRes
ROMEO	local affine (12 dof)	2M	displaced frame difference	first-order explicit regularization method, brightness constancy constraint MRes: adaptive multigrid (octree subdivision), Gaussian smoothing
SICLE	3-D Fourier series (diffeomorphic)	8K	SSD	small-deformation linear elasticity, inverse consistency MRes: number of basis components
SyN	bi-directional diffeomorphism	28M	CC	MRes Gaussian smoothing of the velocity field, transformation symmetry
SPM5:				
"SPM2-type" Normalization	discrete cosine transforms	1K	MSD	bending energy, basis cutoff
Normalization	discrete cosine transforms	1K	MSD	bending energy, basis cutoff
Unified Segmentation	discrete cosine transforms	1K	generative segmentation model	bending energy, basis cutoff
DARTEL Toolbox	finite difference model of a velocity field (constant over time, diffeomorphic)	6.4M	multinomial model ("congealing")	linear-elasticity; MRes: full-multigrid (recursive)

Table 1

similarity & transformation



after Avants, et al. 2008

similarity

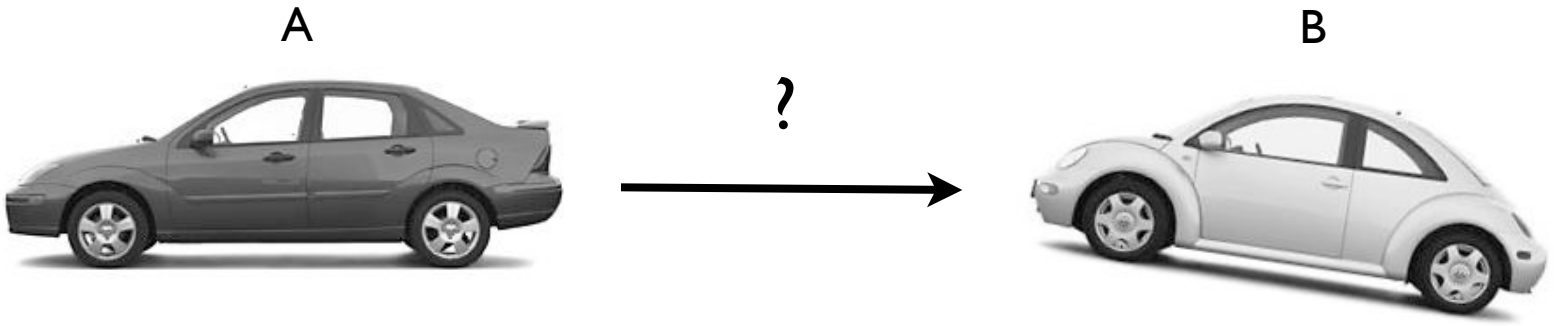
example: mutual information

Mutual information (MI) is a measure of the amount of information one variable contains about another.
The MI of two images describes the amount of information in the joint histogram of the images.

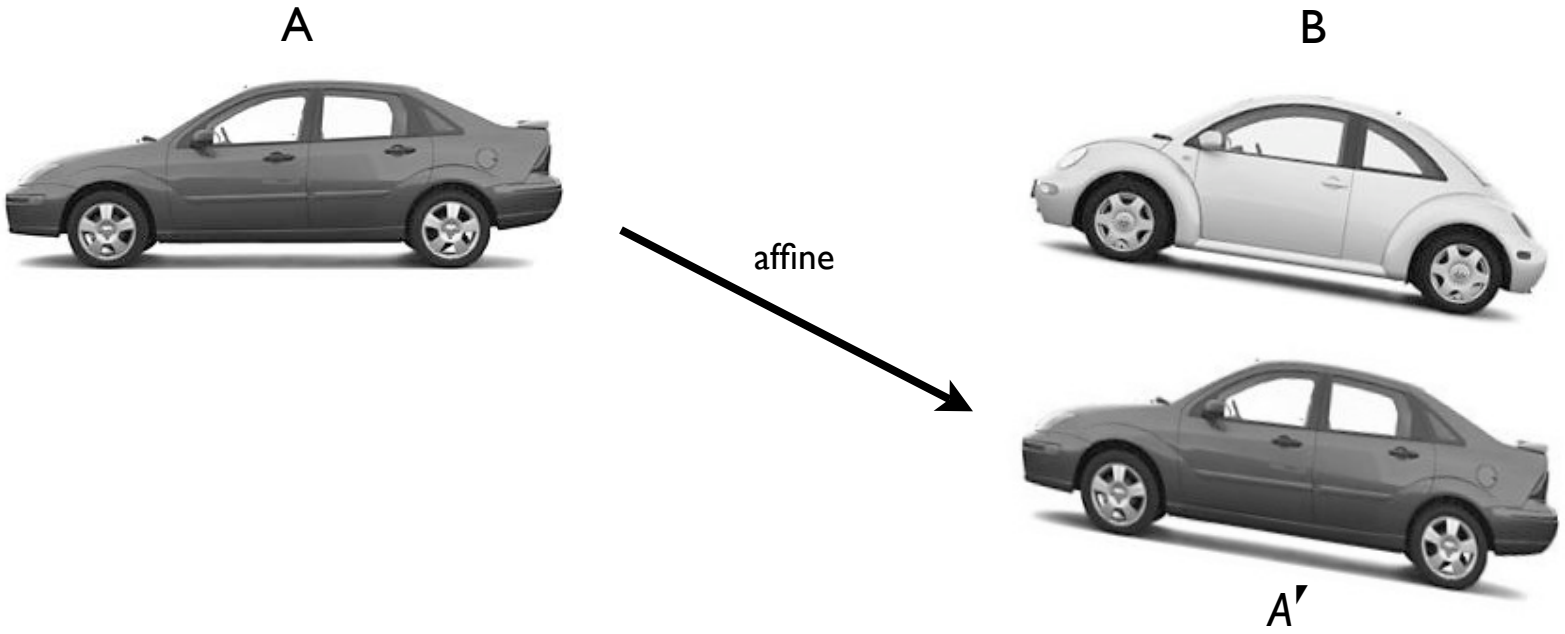
$$
\begin{aligned}
Q_{\mathrm{mi}}(T) &= H(A) + H(B) - H(A, T(B)) \\
Q_{\mathrm{nmi}}(T) &= \frac{H(A) + H(B)}{H(A, T(B))} \\
H(A) &= \sum_i p_A(g_i) \log(p_A(g_i)) \\
H(A, T(B)) &= \sum_{i,j} p_{AT(B)}(g_i, gj) \log(p_{AT(B)}(g_i, g_j)),
\end{aligned}
$$

where $p_A(g_i)$ denotes the probability of intensity g_i to occur at a given point in A and $p_{AT(B)}(g_i, gj)$ denotes the probability of coincidence of intensity g_i in image A and g_j in the transformed image $T(B)$; i, j loop over all possible gray values.

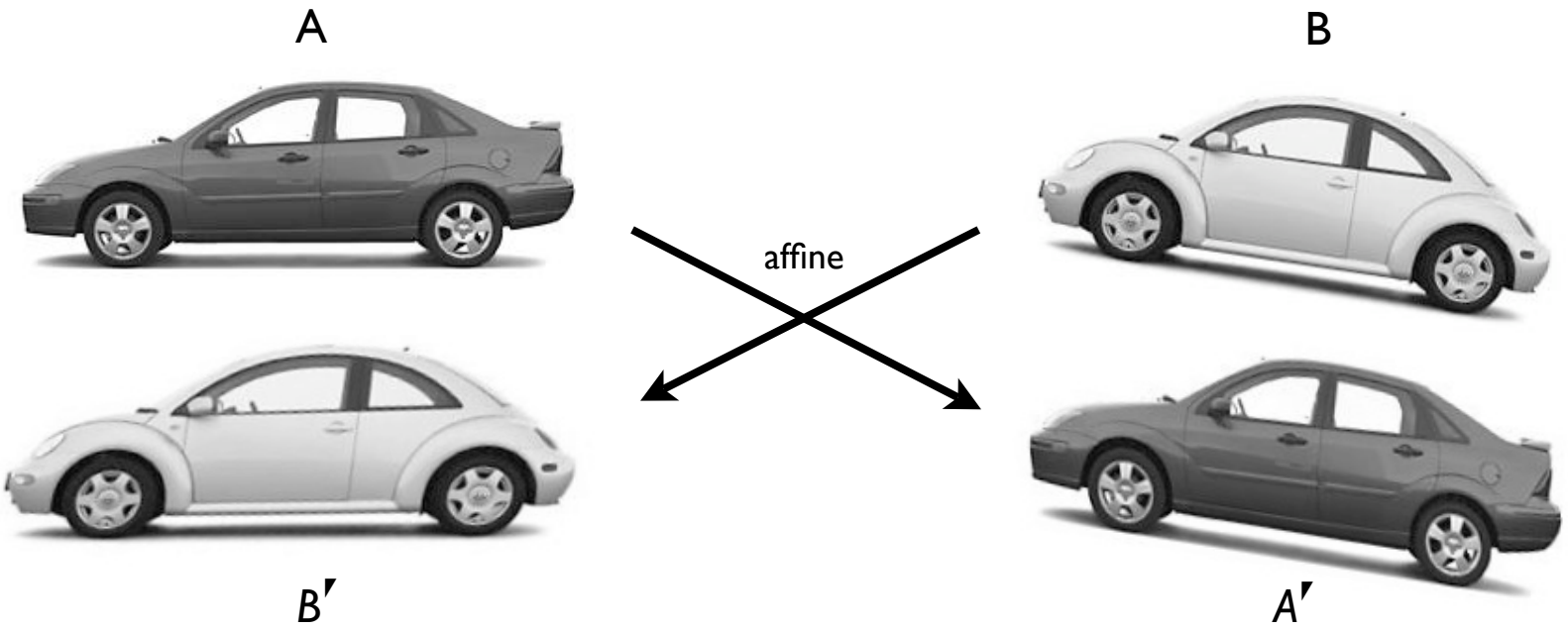
affine transformation



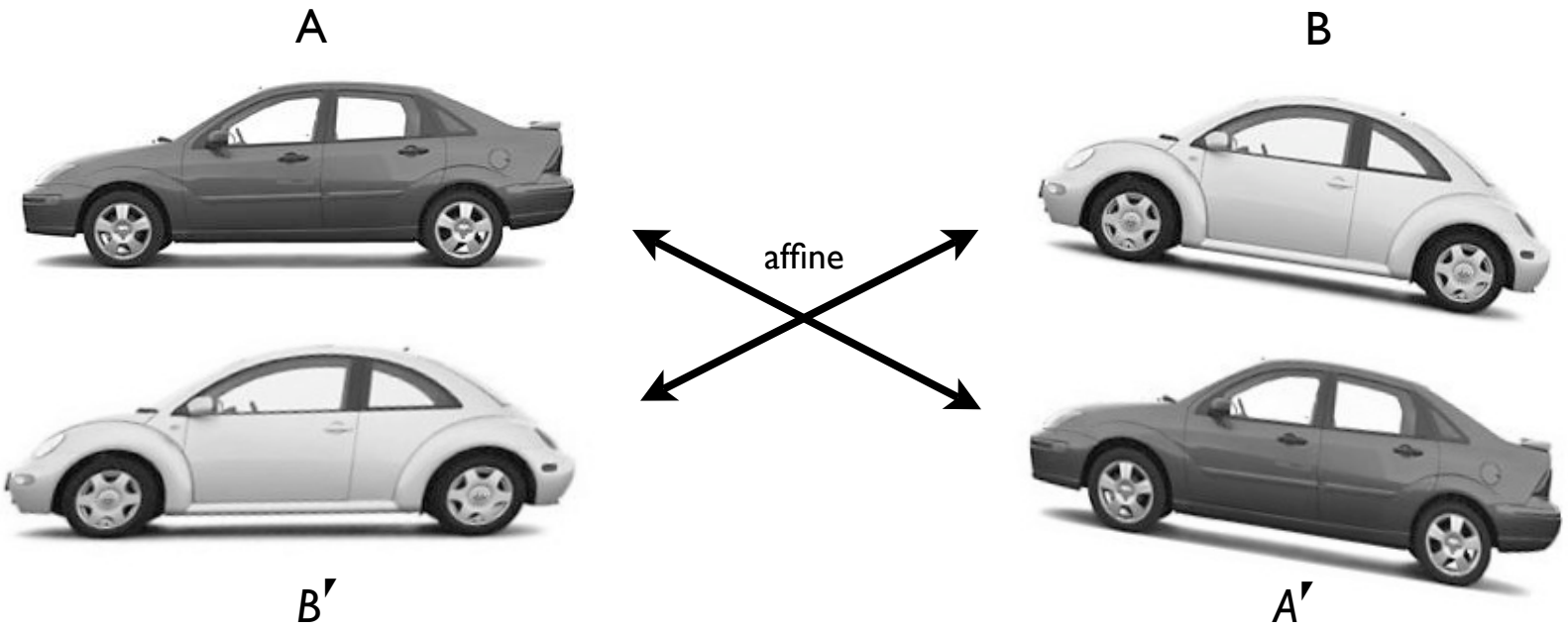
affine transformation



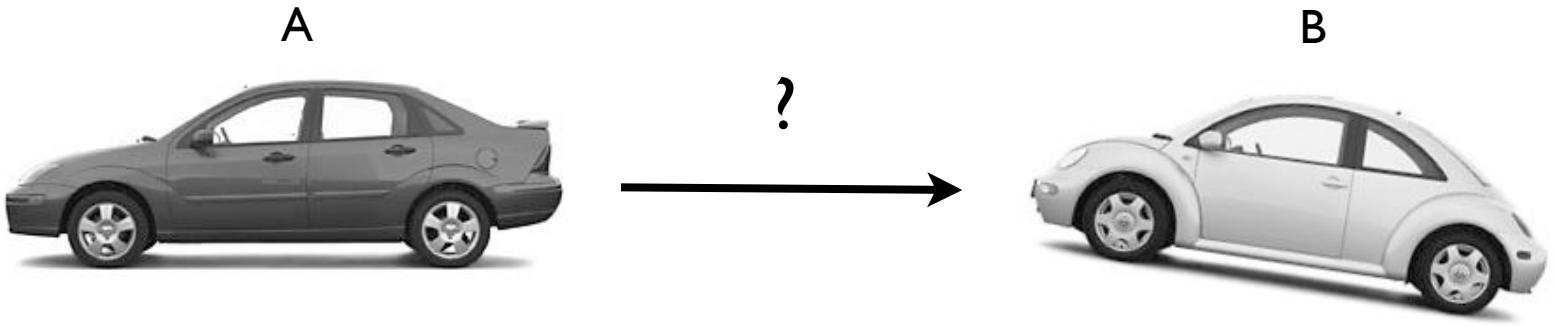
affine transformation



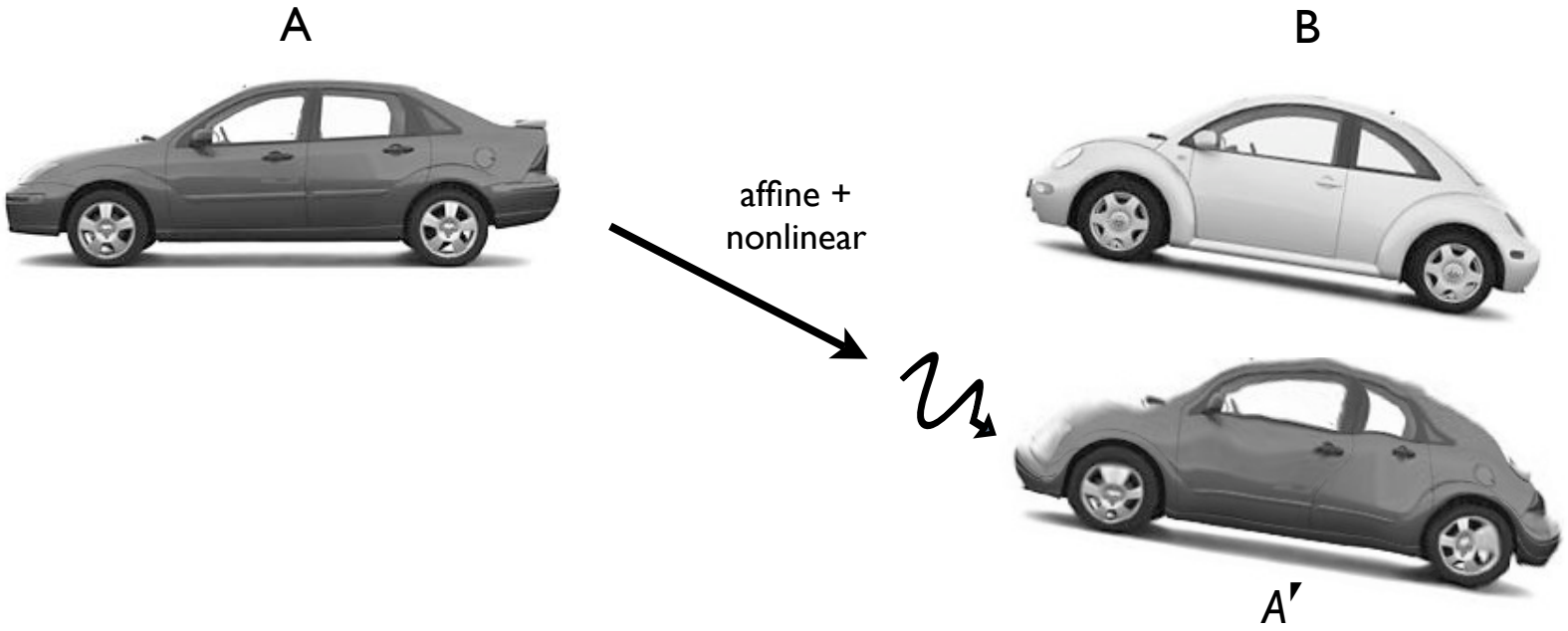
affine transformation
(forward and reverse)



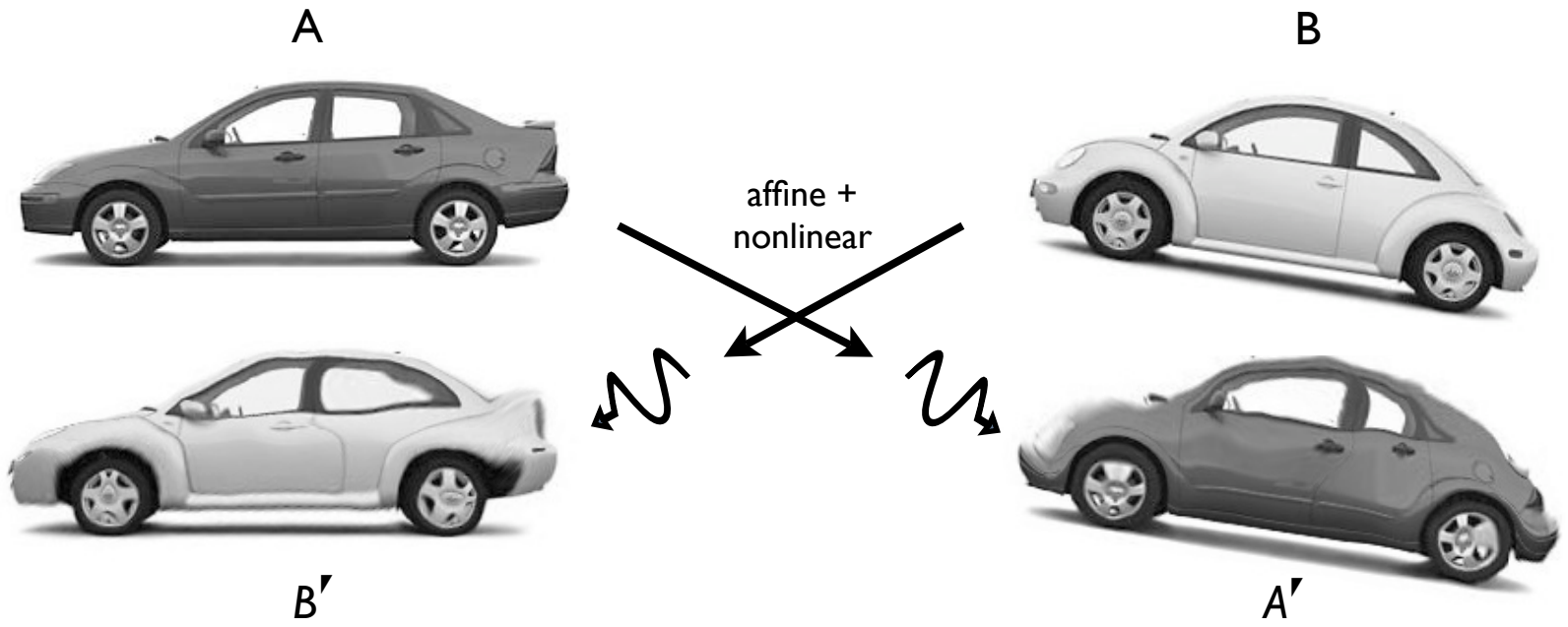
nonlinear transformation



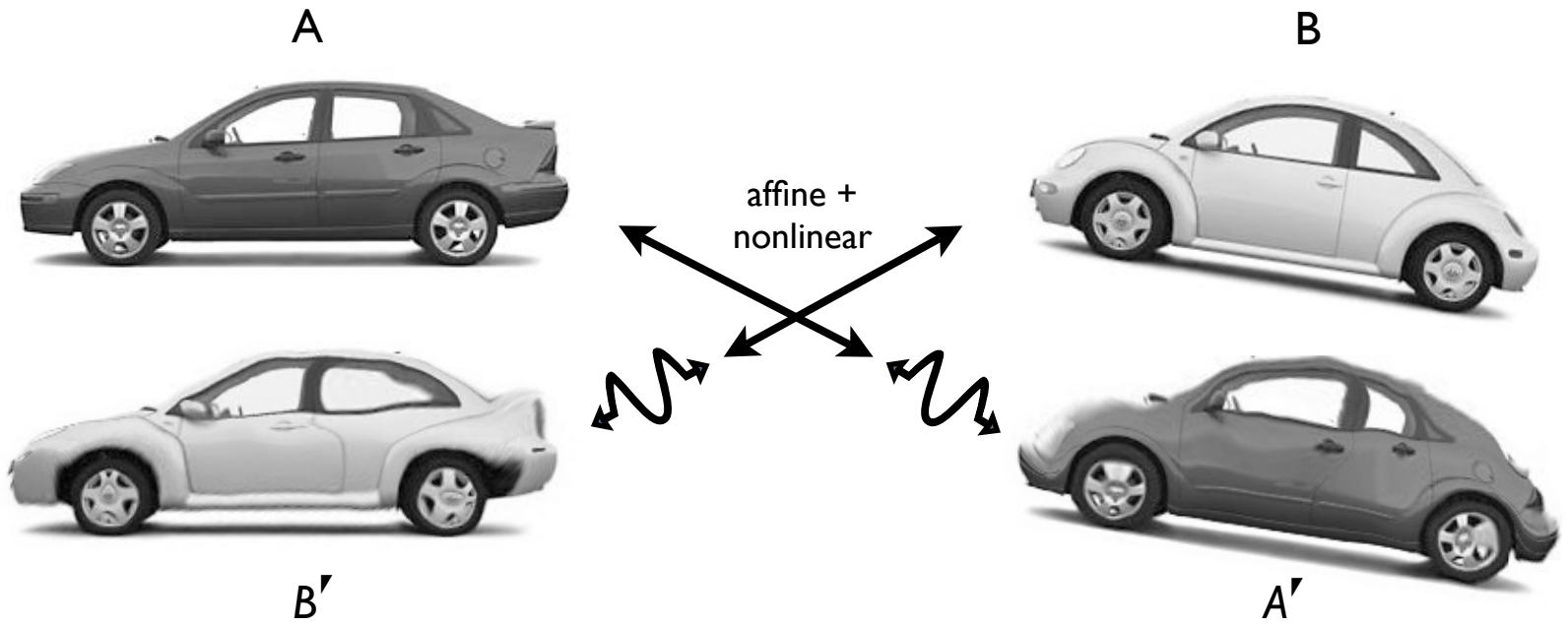
nonlinear transformation



nonlinear transformation

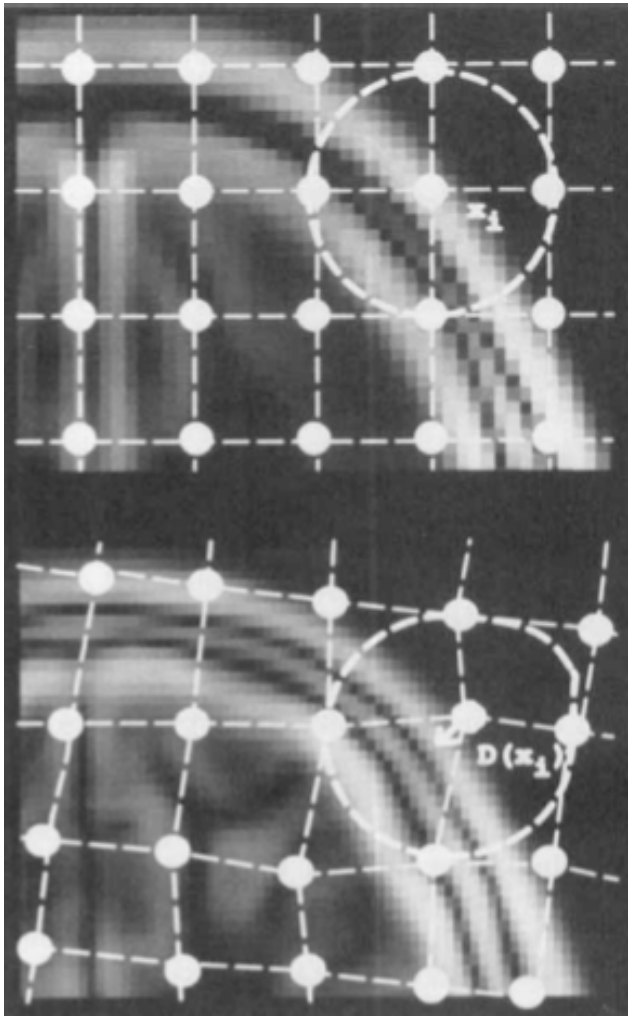


nonlinear transformation (bidirectional)



nonlinear brain image registration

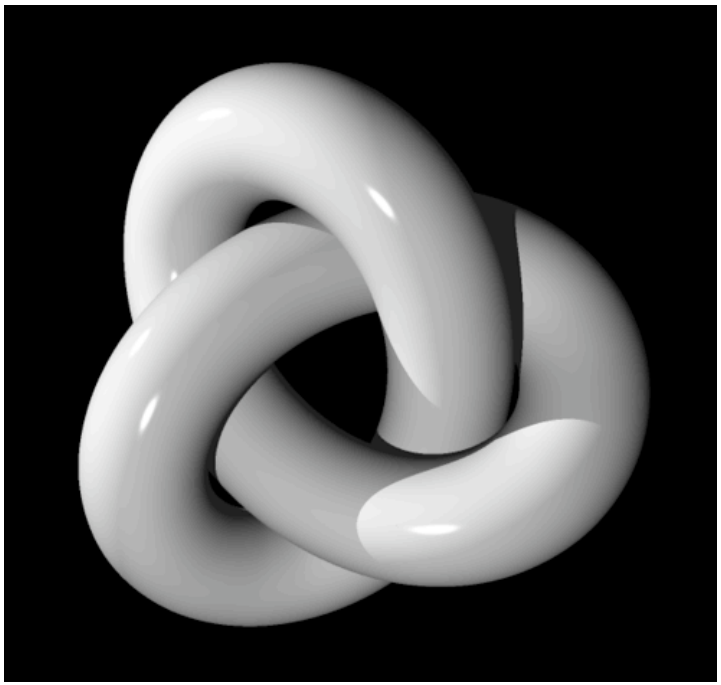
example: local translations (ANIMAL), FFD (ART, IRTK, FNIRT, etc.)



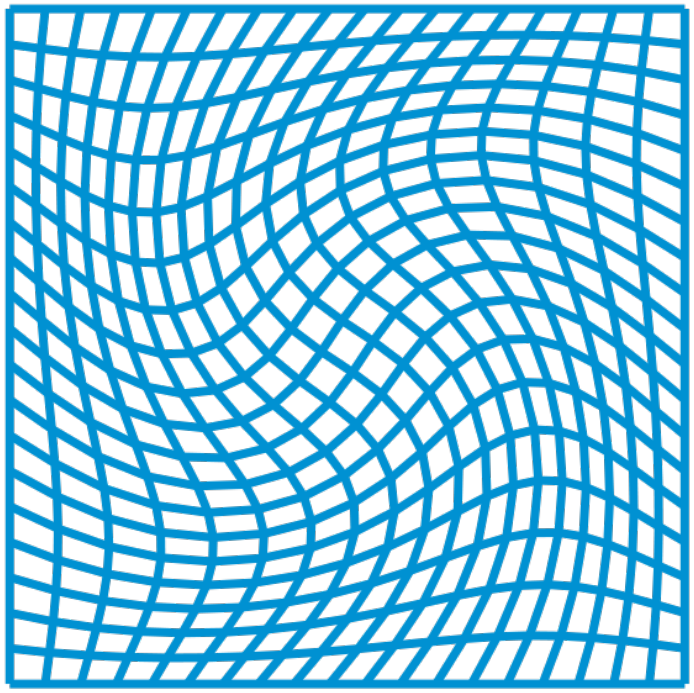
ANIMAL:
optimization of three translational parameters to maximize the neighborhood correlation for each node

nonlinear brain image registration

example: bidirectional diffeomorphism



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



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

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.

nonlinear brain image registration

example of bidirectional diffeomorphism: symmetric normalization (SyN)

transformation model

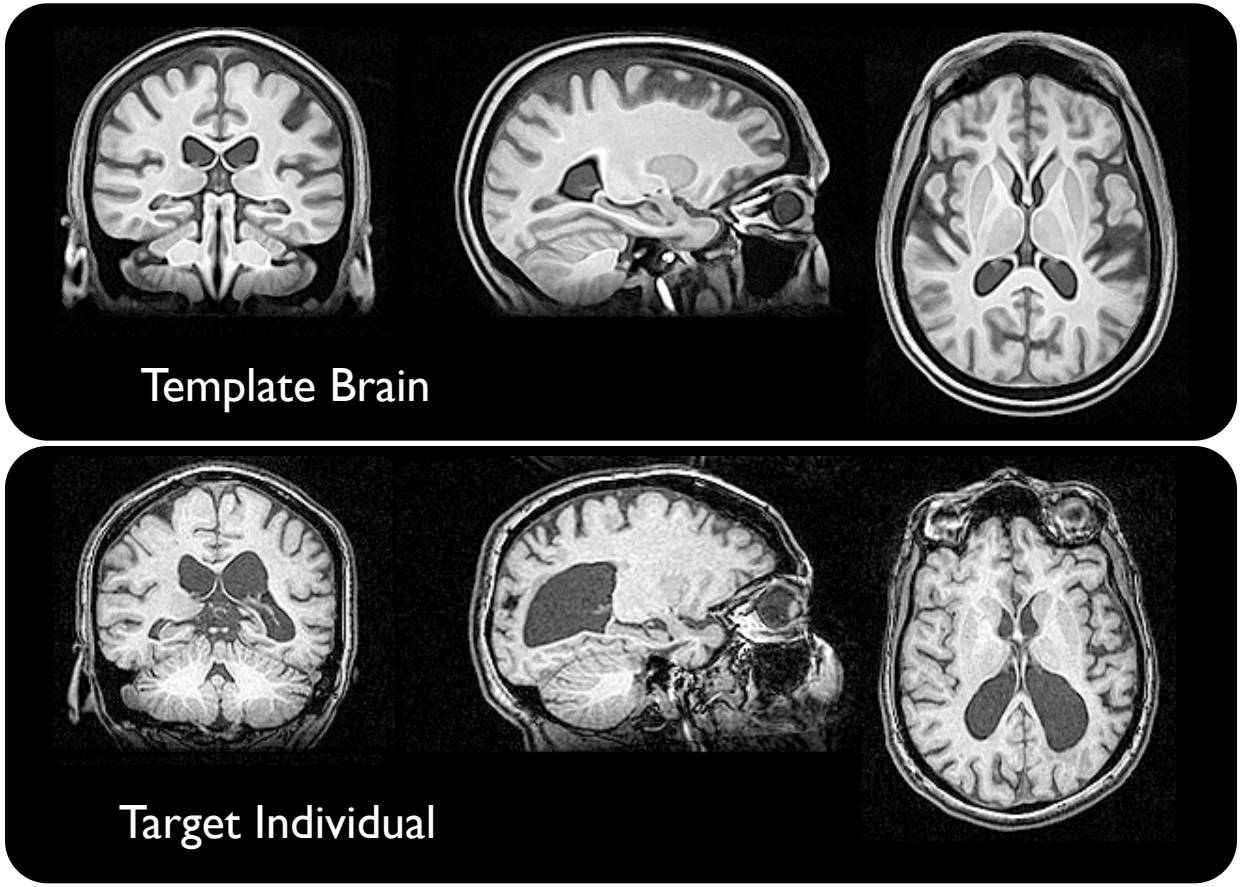
similarity metrics

$$\int_0^1 < Lv(x,t), v(x,t) > dt + w_1 SSD(I,J) + w_2 MI(I,J) + w_3 \sum_i LM_i(I,J)$$

diffeomorphic regularization + intensity difference + mutual information + landmark guidance

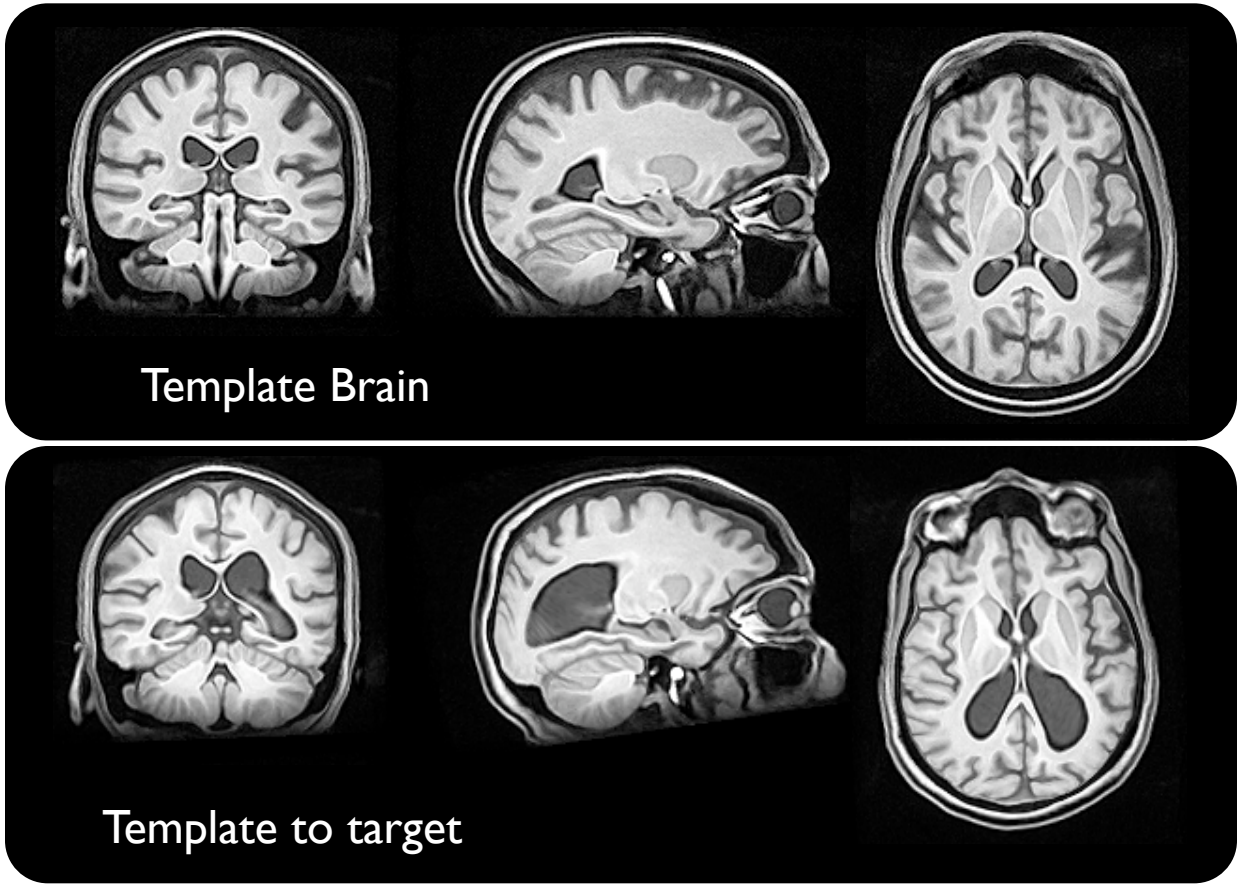
(*L* is the linear operator regularizing the velocity.)

template registration



Avants, et al. 2008

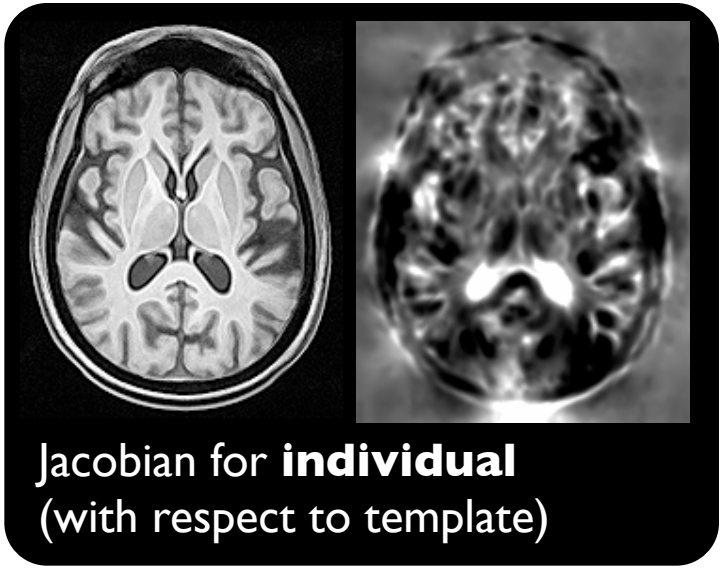
template registration

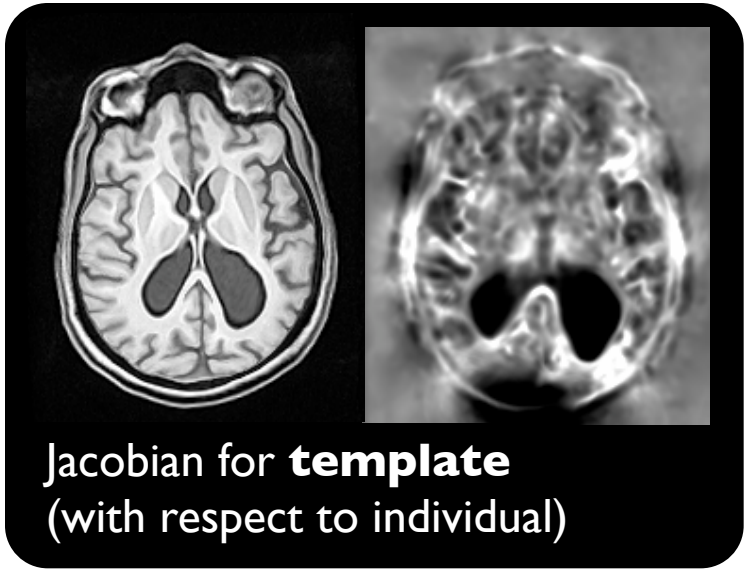


Avants, et al. 2008

precise, but accurate?

template registration
application 1: deformation-based morphometry

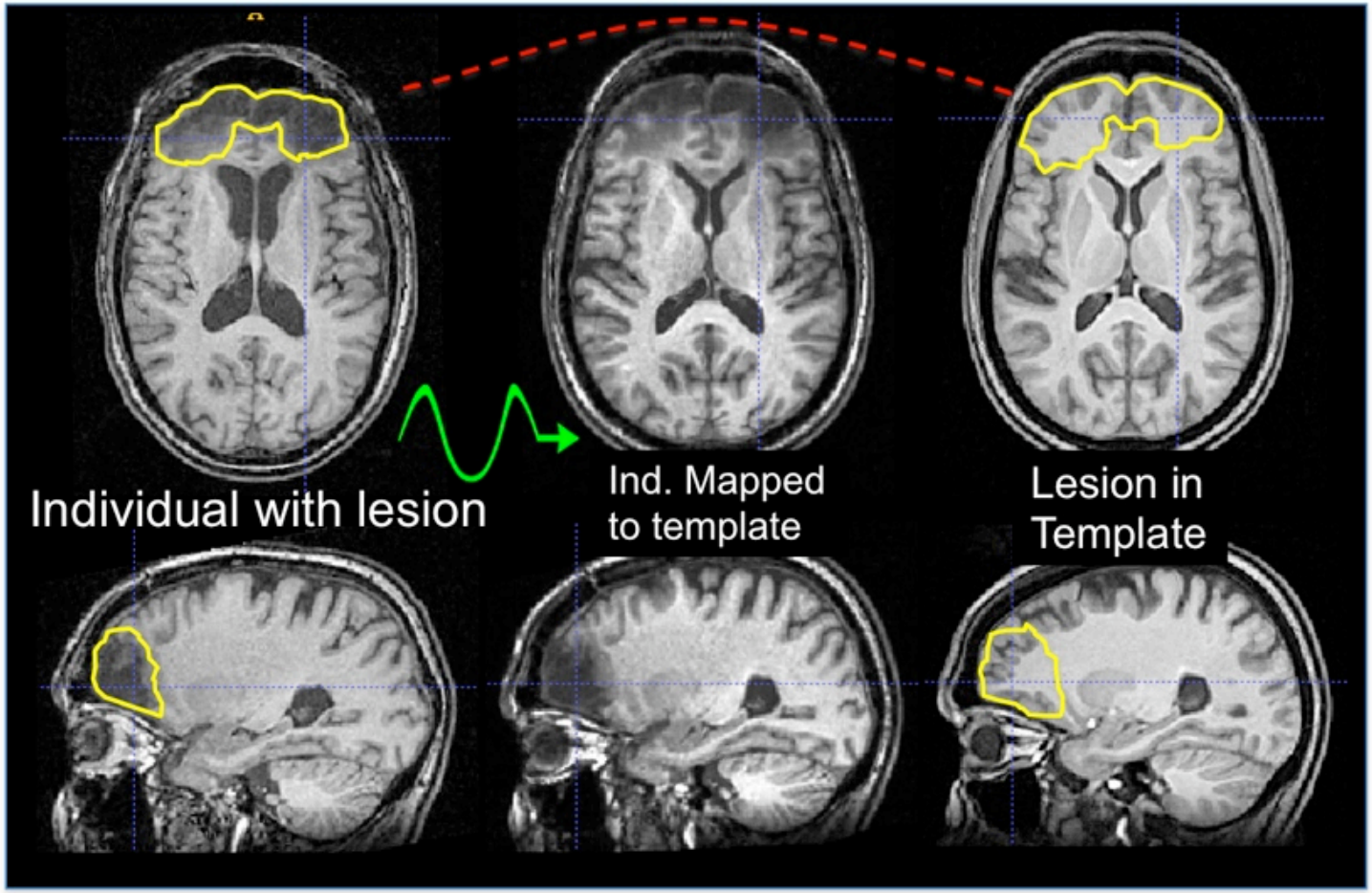




Avants, et al. 2008

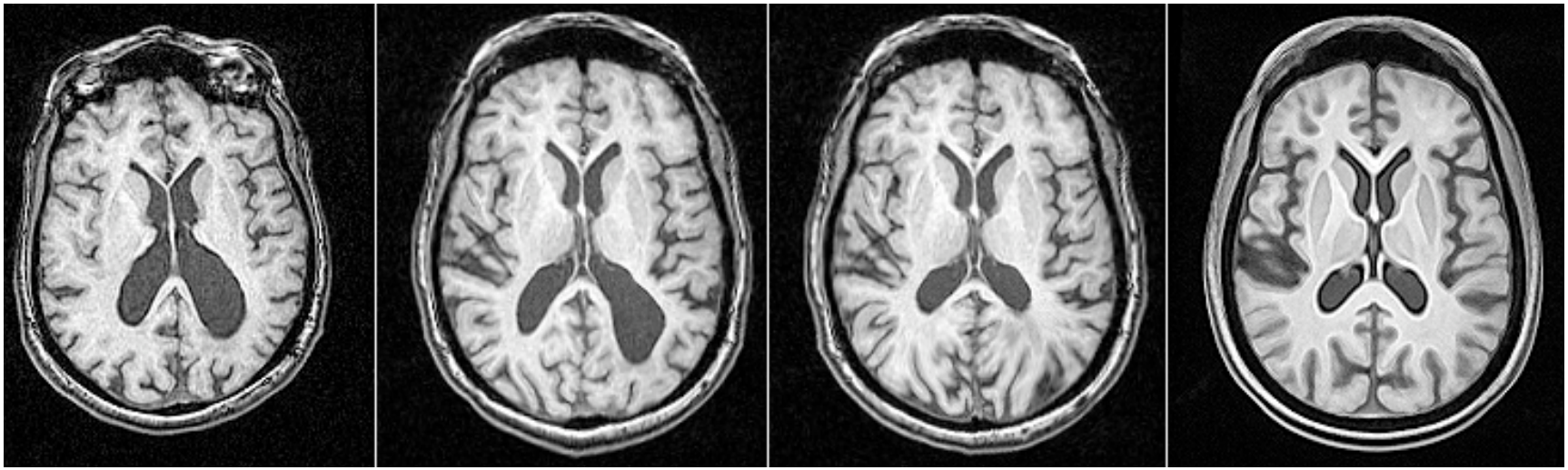
template registration

application 2: anatomical localization



Avants, et al. 2008

template registration
application 3: spatial normalization

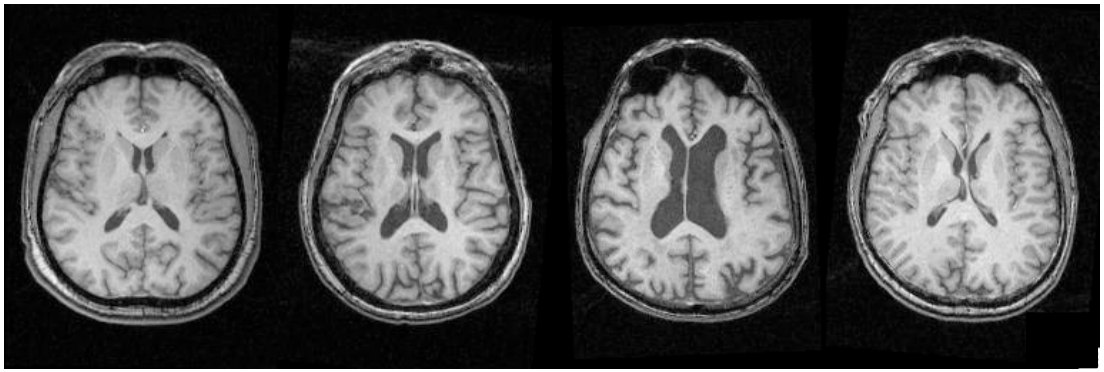


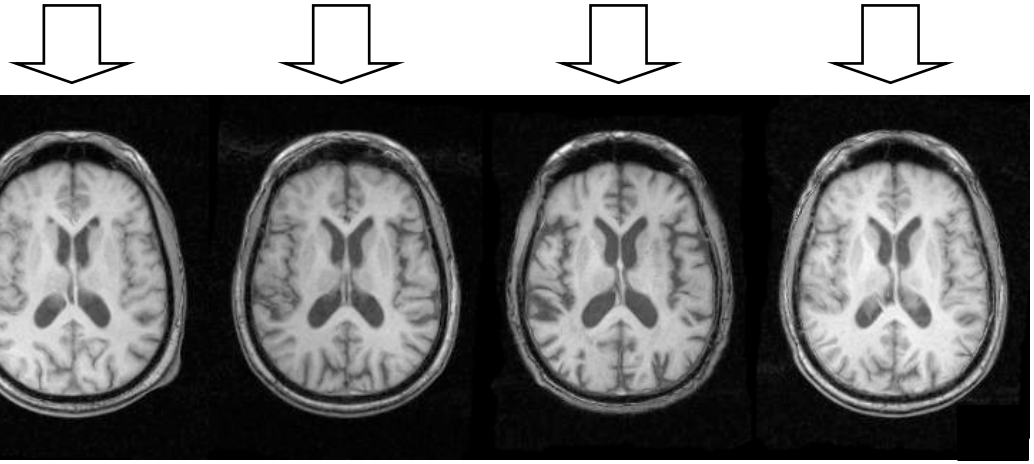
individual | default mapping to template | adjusted mapping to template | template

template registration

application 4: group analysis of data

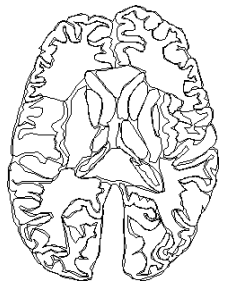
data (structure, function, etc.) in individual space





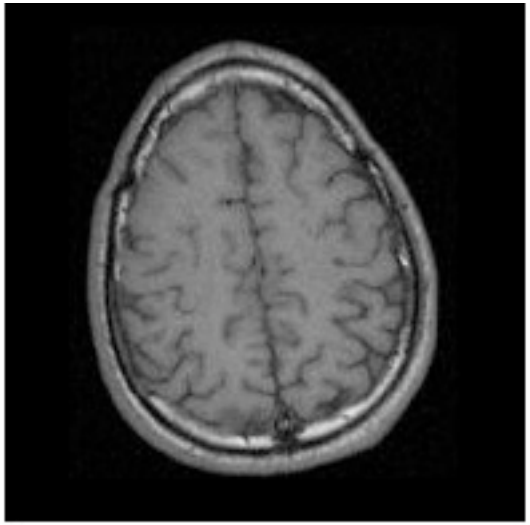
template image

individuals normalized to template space

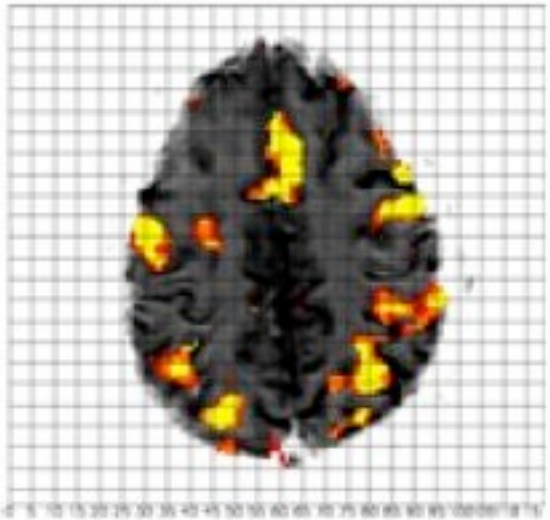


template labels

template registration
application 5: atlas-based anatomical labeling

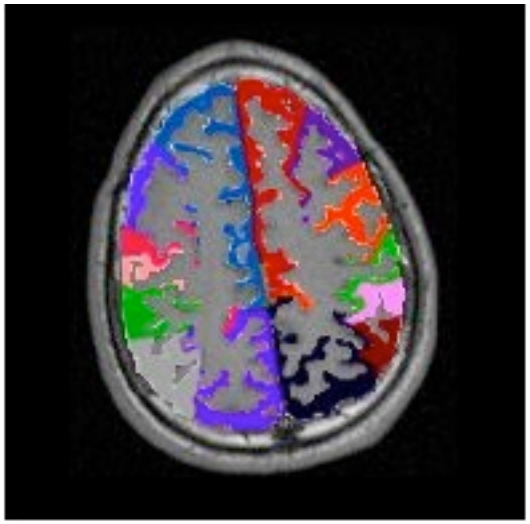


MRI

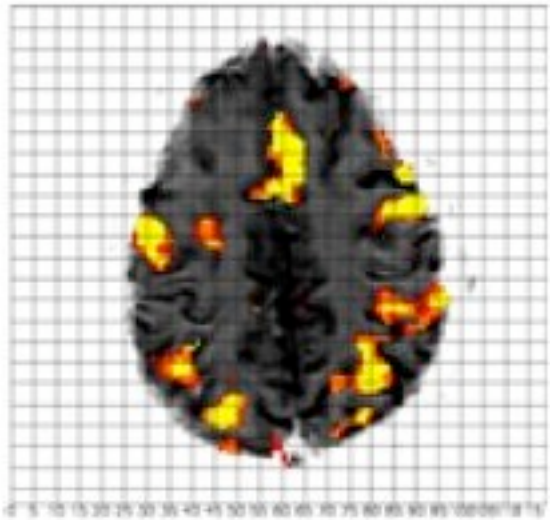


fMRI

template registration
application 5: atlas-based anatomical labeling

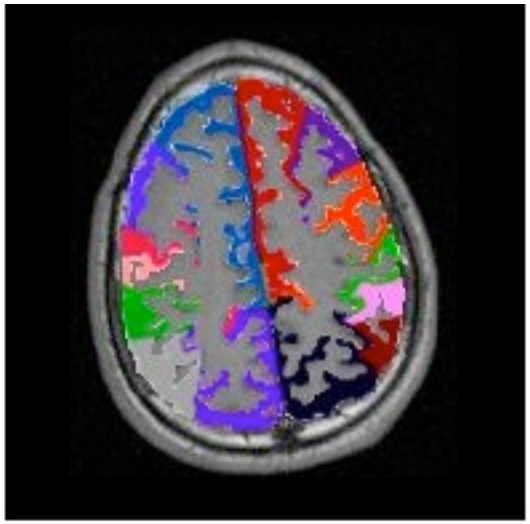


labeled MRI



fMRI

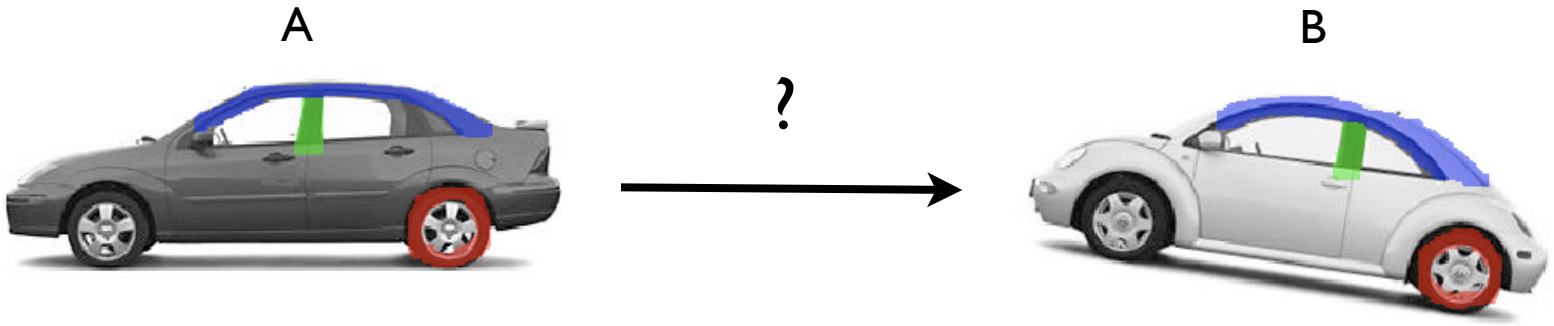
template registration
application 5: atlas-based anatomical labeling



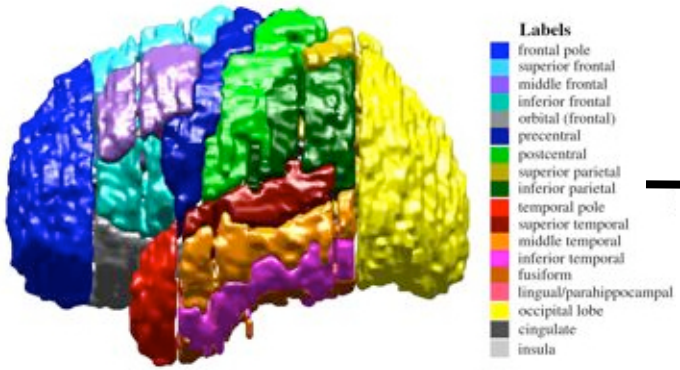
labeled MRI

labeled fMRI

template + labels = atlas

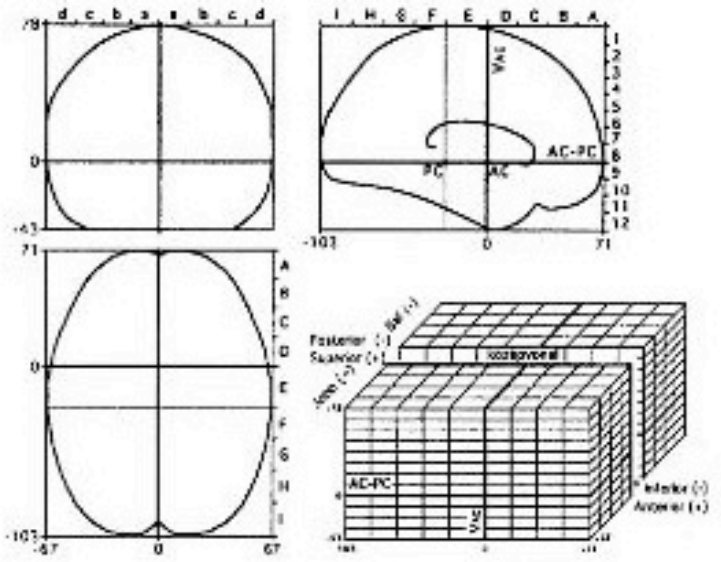


atlas labels



?

individual atlases

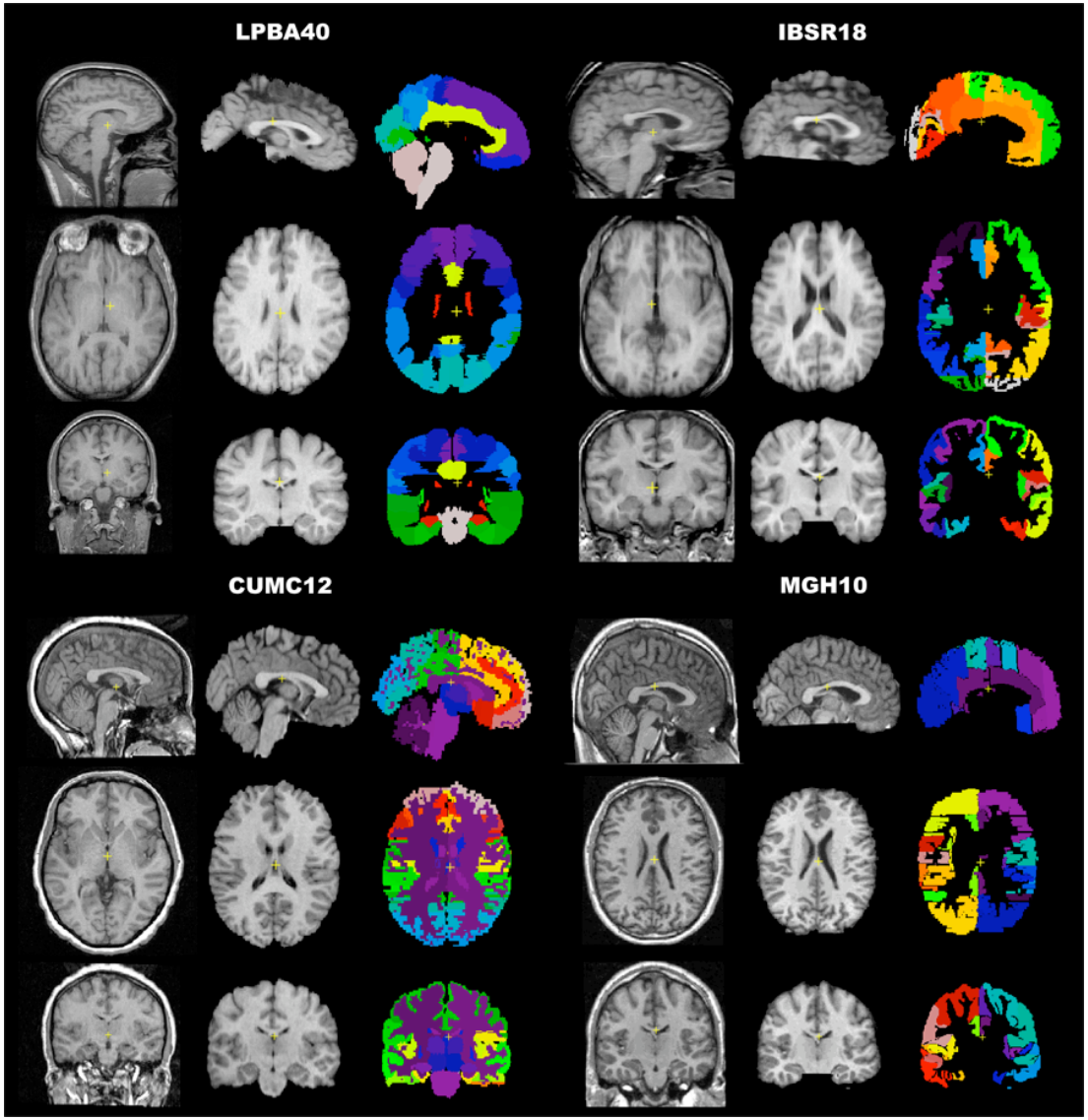


Talairach-Tournoux coordinate frame and variants (1967, 1988,...)

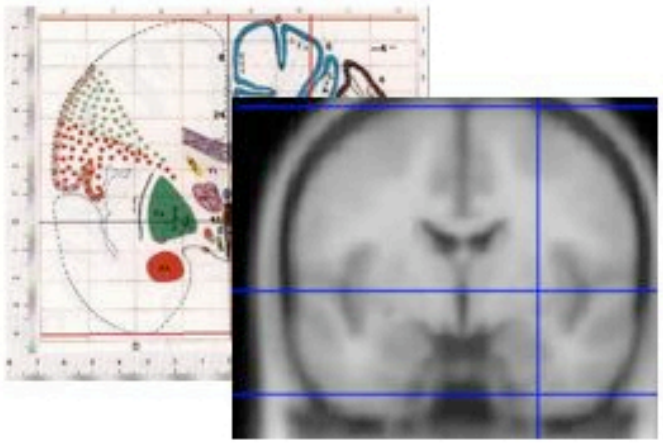
individual atlases

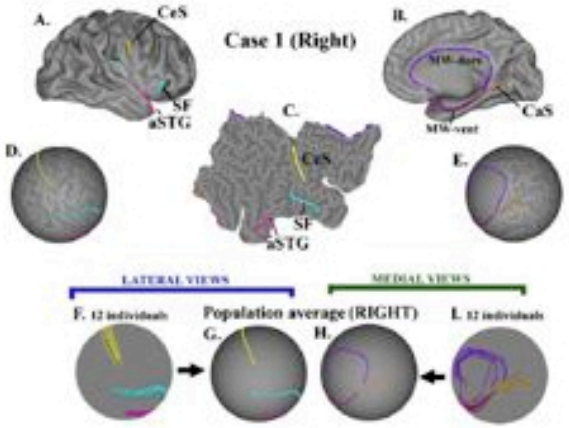
NIH Visible Human Male, Harvard's Whole Brain and SPL Atlases, vanEssen's CARET Atlas (top)

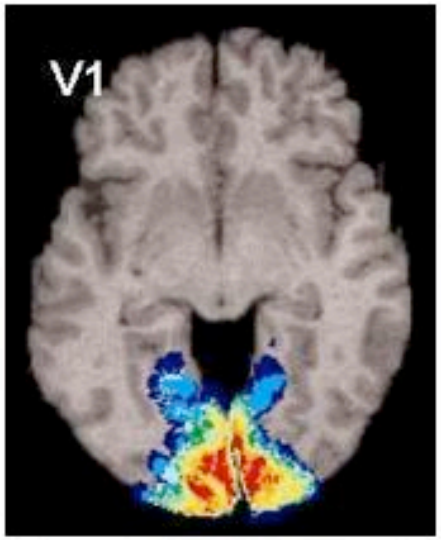
multiple individual atlases

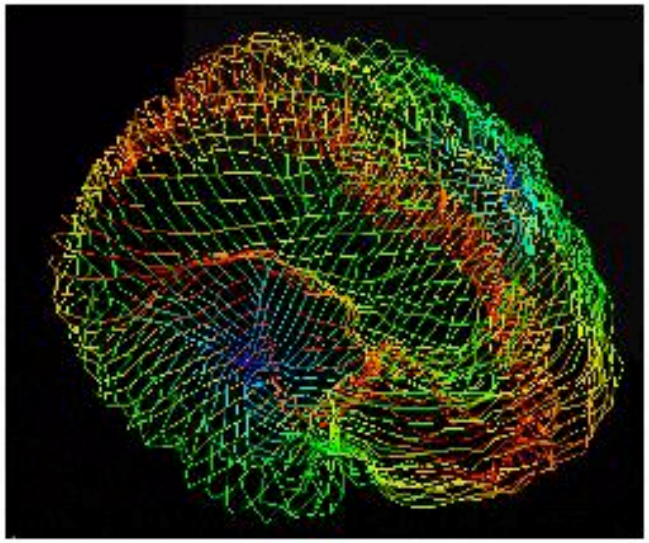


probabilistic atlases



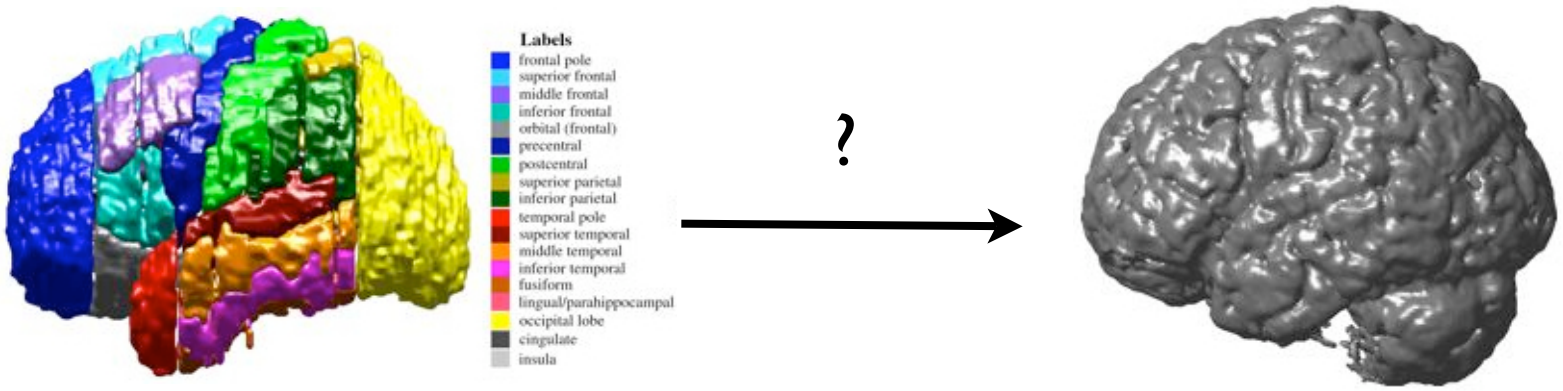




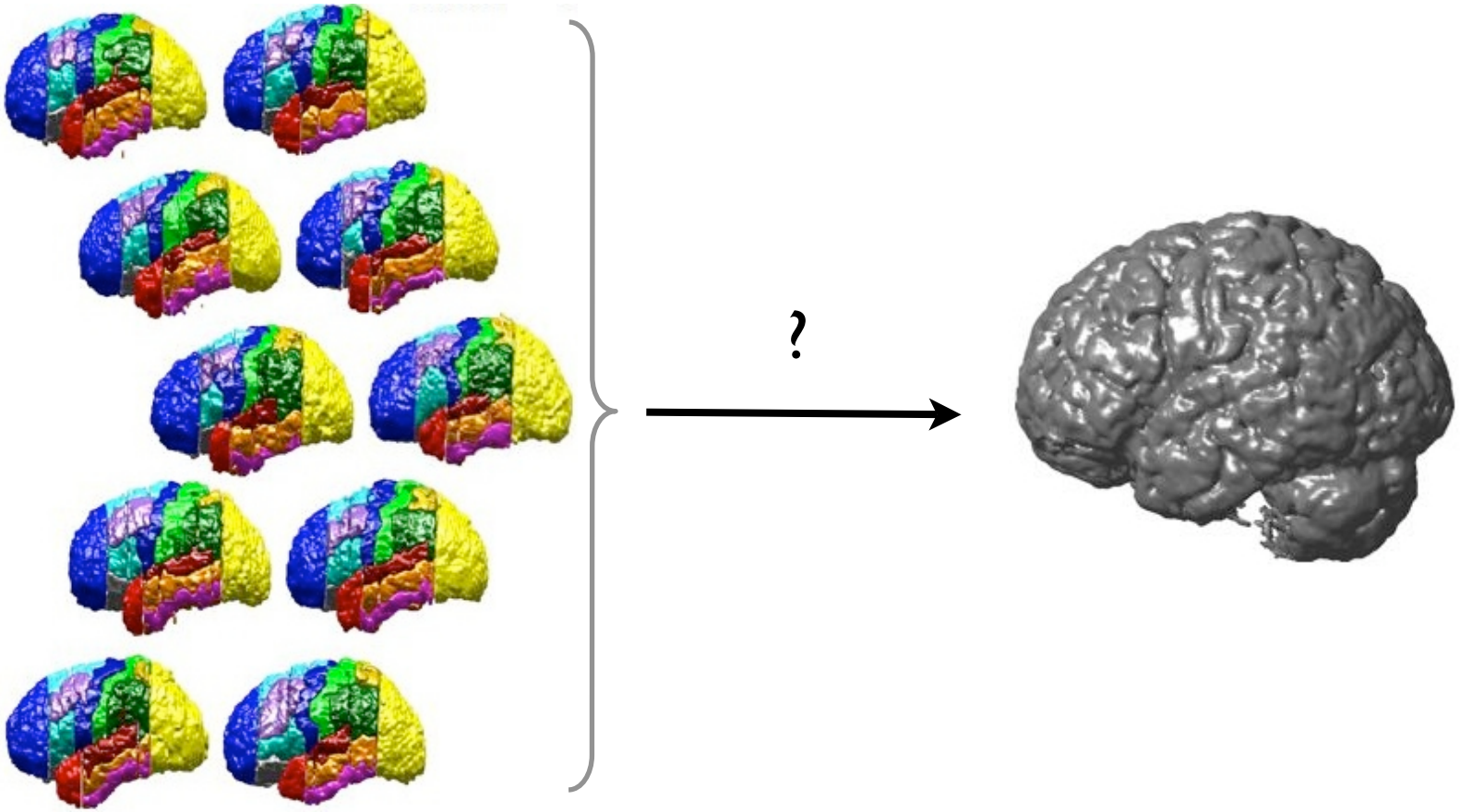


MNI Atlas, van Essen surface-based atlas, LONI deformable atlas , Zilles' probability map, (clockwise from upper left)

multiple-atlas-based labeling

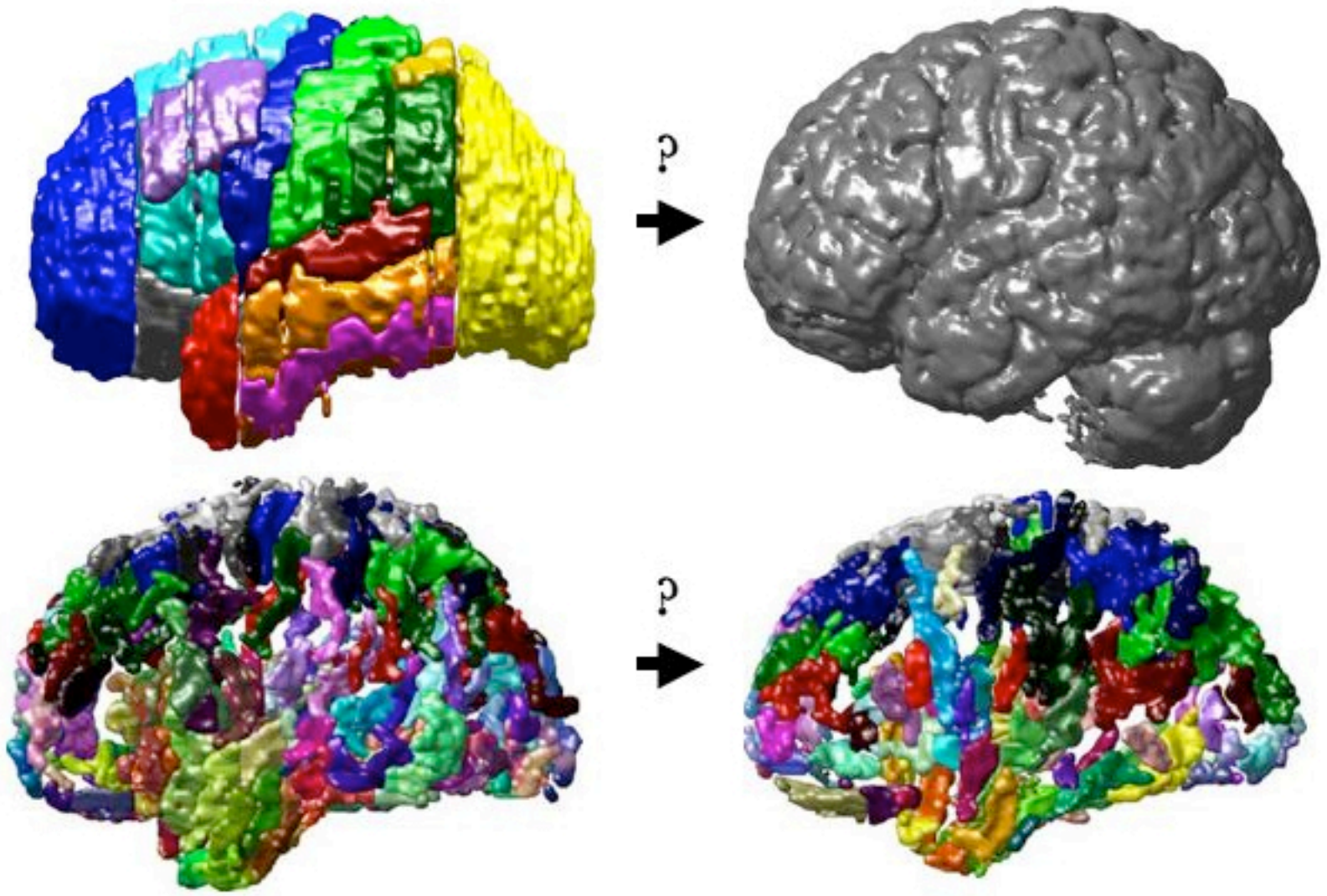


multiple-atlas-based labeling



alternative solution to the correspondence problem: feature-matching (ex: Mindboggle)

feature-based labeling



References

"Brain functional localization: a survey of image registration techniques"
IEEE Trans Med Imaging. 2007. 26(4): 427-451. (330 references!)

Malte Westerhoff's 2003 dissertation:
"Efficient Visualization and Reconstruction of 3D Geometric Models
from Neuro-Biological Confocal Microscope Scans"
http://www.diss.fu-berlin.de/diss/servlets/MCRFileNodeServlet/FUDISS_derivate_000000001196/

http://www.picsl.upenn.edu/ANTS/

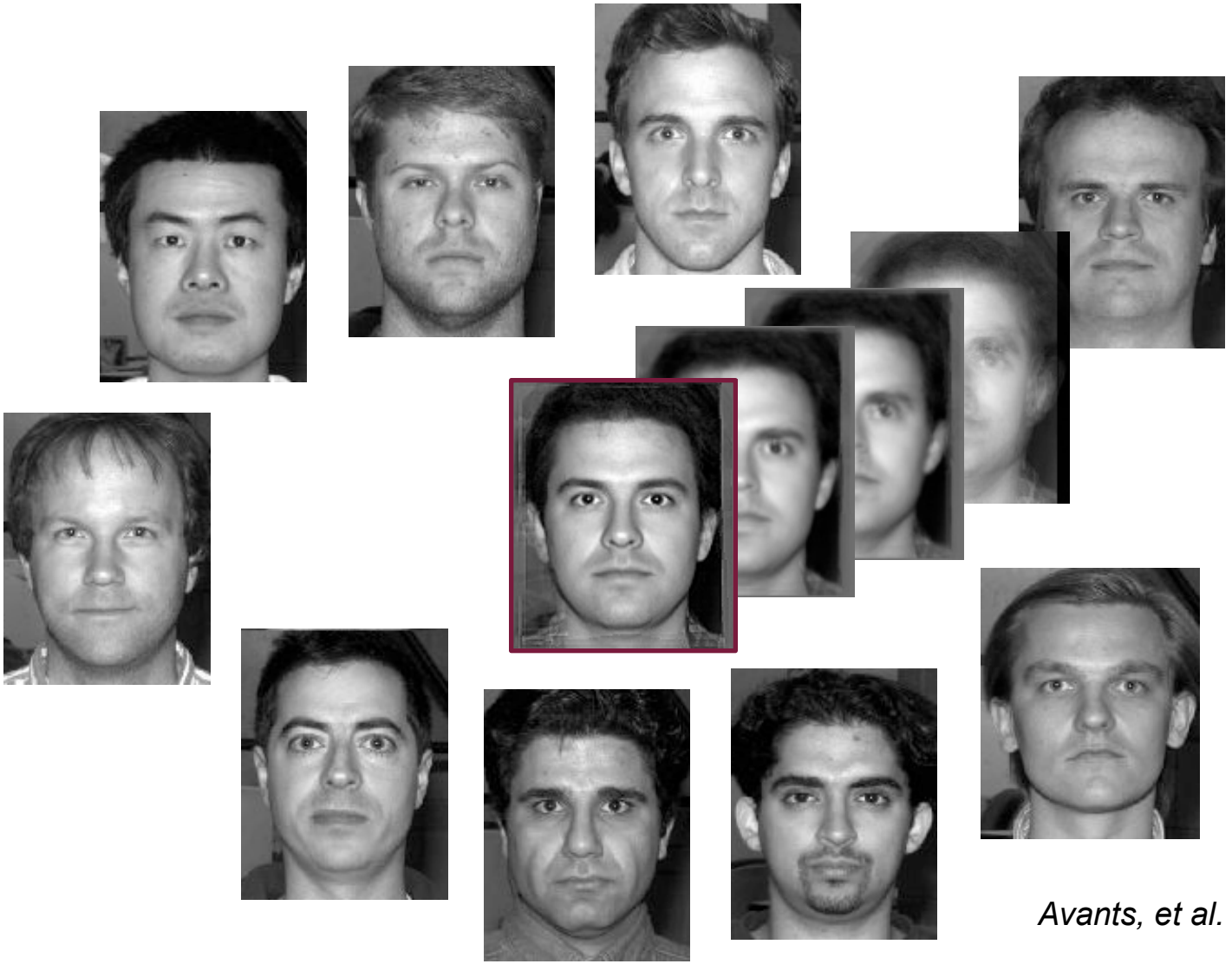
SyN: "ANTS Anatomy: Overview of ANTS Toolkit" keynote presentation
Brian Avants, et al., Penn Image Computing & Science Laboratory
University of Pennsylvania

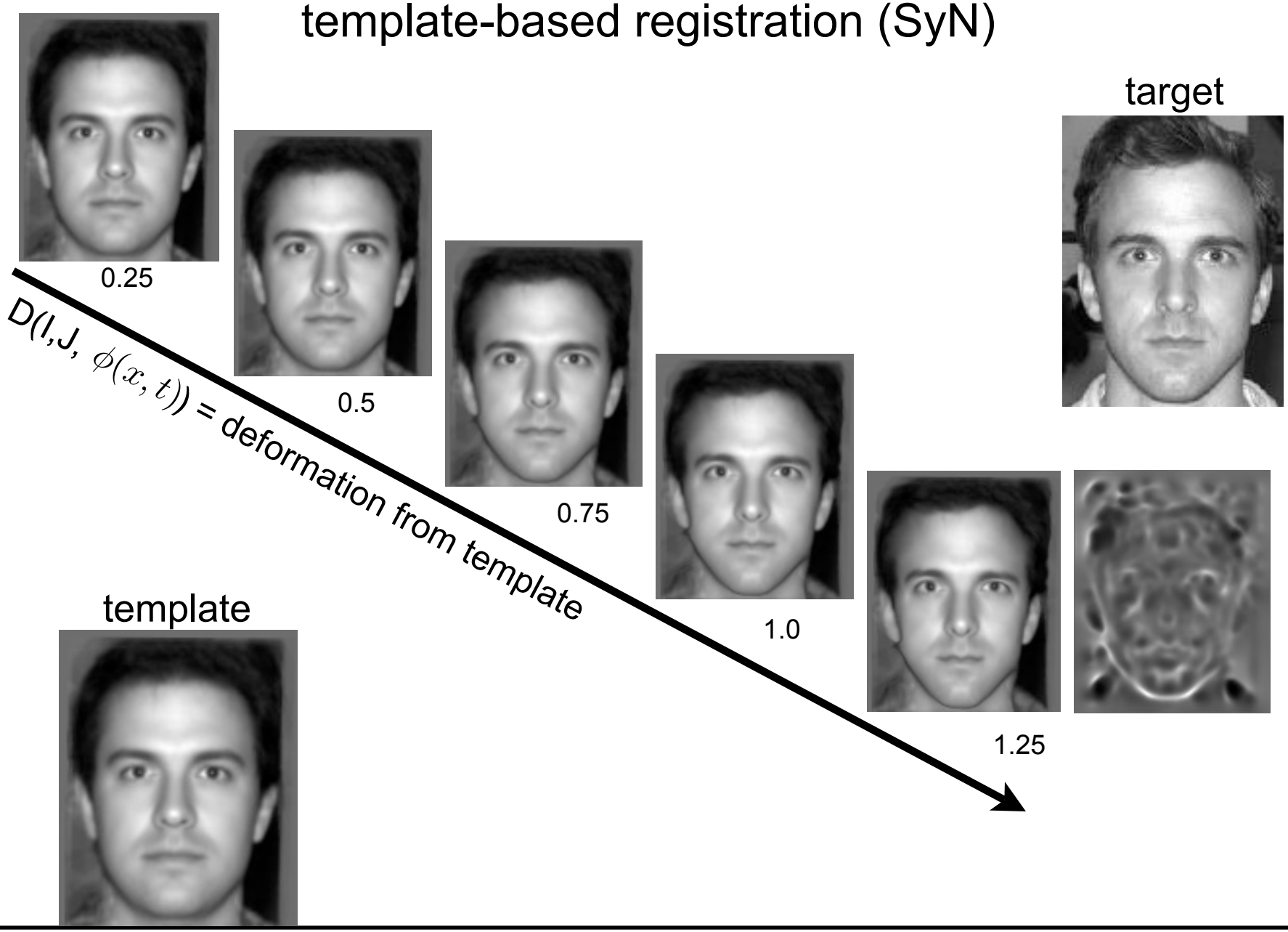
ANIMAL: http://dx.doi.org/10.1002/hbm.460030304 and chapter 9

http://www.mindboggle.info/papers/
http://www.mindboggle.info/talks/google_20070813/

Wikipedia: diffeomorphism, homeomorphism, etc.

template construction (SyN)



Avants, et al. NIMG

template-based registration (SyN)