Image Registration 1:

Spring 2021

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Handouts & Lecture Notes

- **Report in Scientific American (June 2014):**

  "In each study, however, those who wrote out their notes by hand had a stronger conceptual understanding and were more successful in applying and integrating the material than those who used [sic] took notes with their laptops."

  The Pen Is Mightier Than the Keyboard

  P. A. Mueller, D. M. Oppenheimer, *Psychological Science,* Vol 25,Issue 6, pp. 1159 – 1168, April-23-2014.

- **Handouts are to aid note taking, not a total replacement for note taking**
- **Podcasts, slides, pdfs etc on BlackBoard**

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Overview

- What is registration?
- Why registration?
- Example biomedical image data
- Breakdown of image registration problem

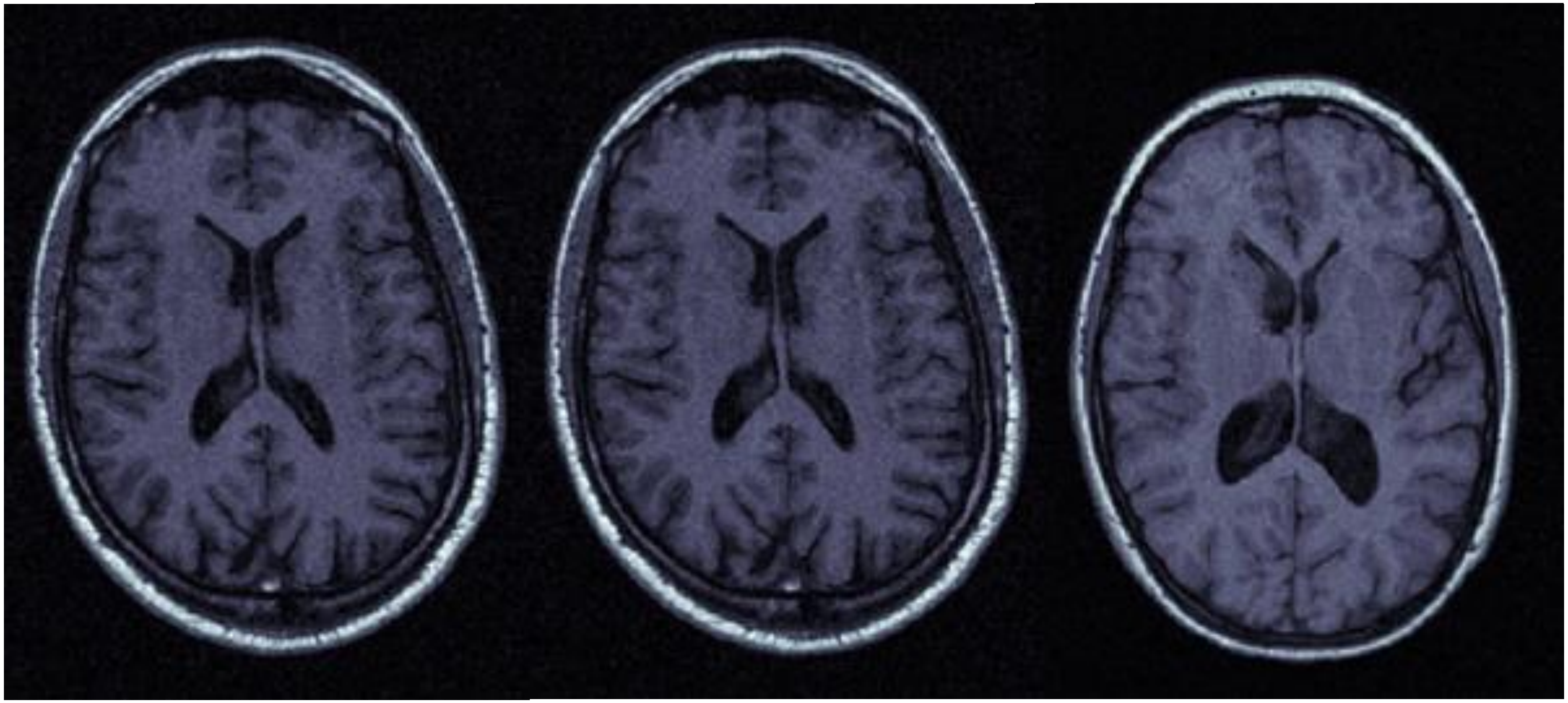
    Image matching

    Representing warps & regularisation

    Optimisation

What is Non-Rigid Registration? (NRR)

Source Image **Target Image**



- **Warp** source image to look like target image
- **Warp**: spatial deformation

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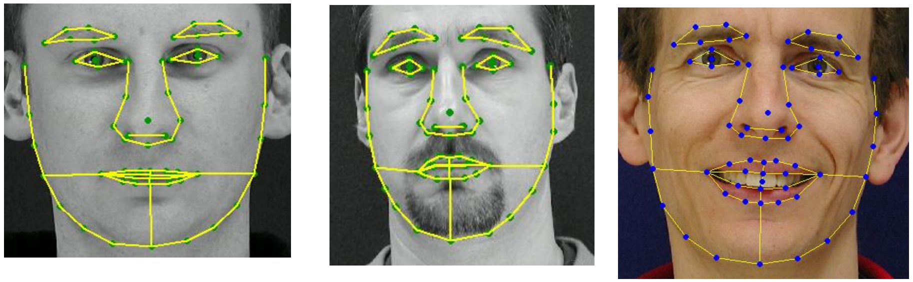
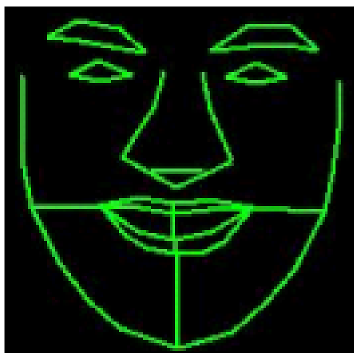
Landmark Based Registration

Annotated Images



Frame of mean shape



Original image

Frame of mean shape

- **Interpolate movement of landmarks to warp image patch**

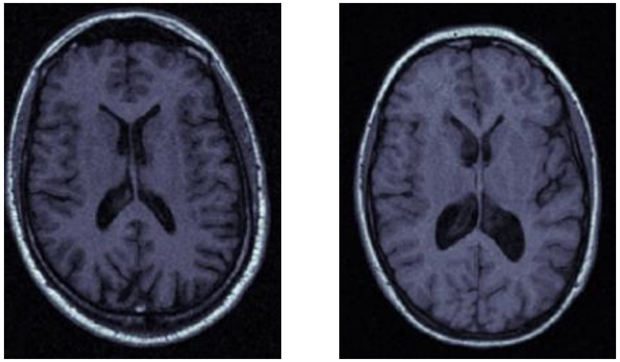
  [In AAM case, it was done using barycentric coordinates and triangulation]

- **If we could do it *without* landmarks, only have to annotate one image to build shape & appearance model**
- **Manual annotation not always possible or feasible**
- **Registration just using images => automatic model building**

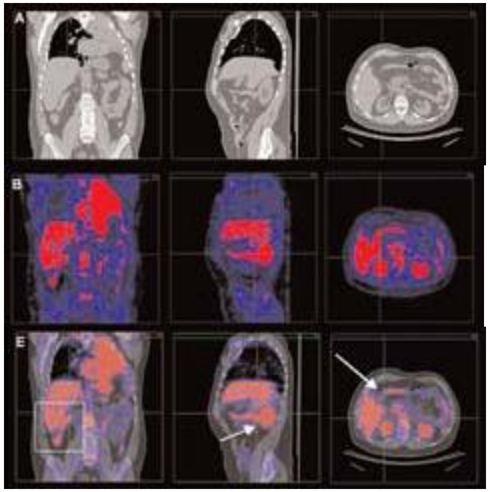
Why do we need to do registration?

- Automatic model building
- Registering two images:
  - Aligns common structures
  - Dense (pixel by pixel or voxel to voxel) correspondence
- Compare information from two different images
- Combine information from two different images

3D equivalent of the 2D pixel



Comparing MR brain images



3D CT image

3D PET image

Combined

Biomedical Image Data

- **Vast amount of 2D, 3D, 4D (3D+time) data available**
  - **Routine patient scans (diagnosis & disease progression)**
  - **Research studies (multimodality & population studies)**
  - **Human NeuroScanning Project (whole brain, sectioned)**

Various Registration Scenarios:

- **Same individual, same modality (Intra-subject)**
  - **Patient movement, organ movement, pre & post intervention**
- **Same individual, different modality**
  - **Movement between scans, functional versus structural imaging**

  e.g. PET vs CT
- **Population studies, many individuals (Inter-subject)**
  - **Atlas construction, variation/similarity between subjects**
- **Histological sections (2D slices from 3D object)**

Correspondence Problem

- **Intra(same)-subject case:**

  Identify real correspondence between different images

- **Inter(different)-subject case:**

  Meaningful anatomical correspondence between different individuals

  Correspondence between individual and some anatomical atlas

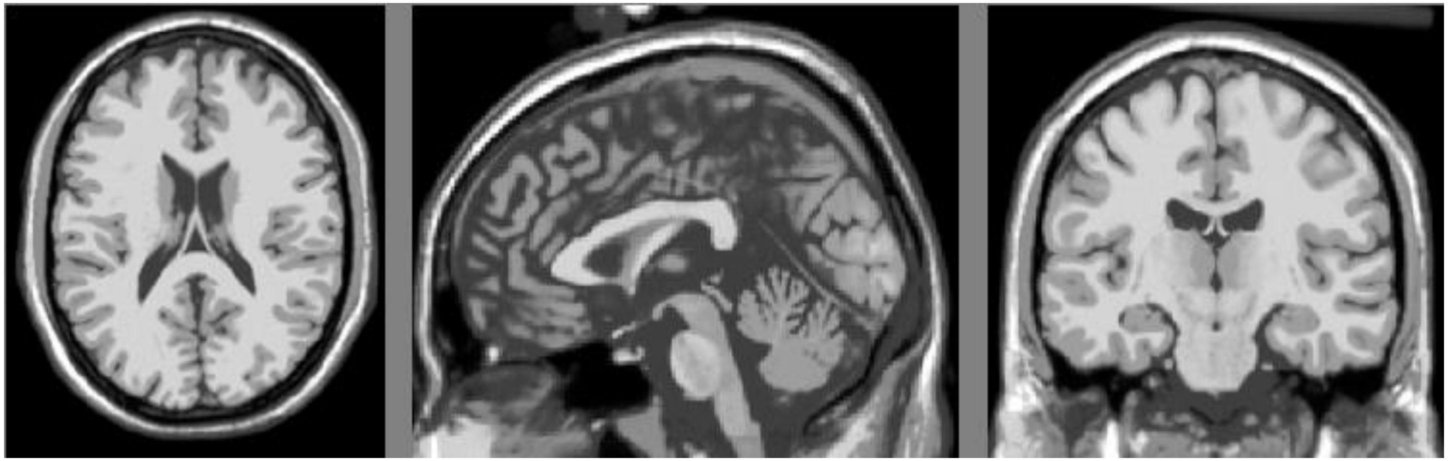
- **Histological case:**

  Reconstruct real correspondence distorted by preparation

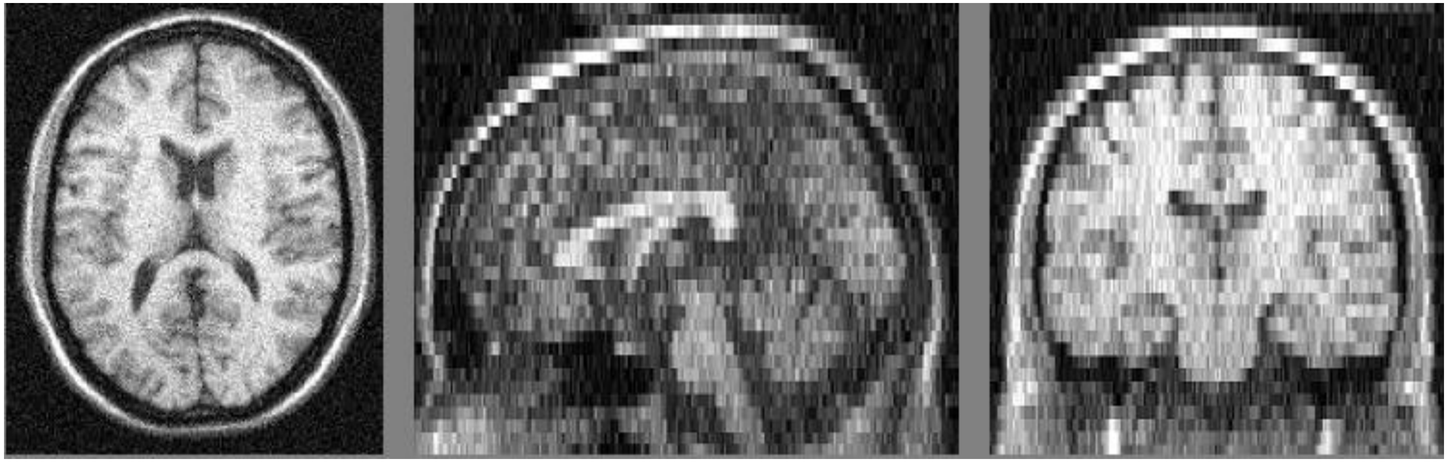
Unslicing the loaf!

Example Biomedical Images

Same individual, same modality



Pre-Operative MR, 1.5 Tesla



Intra-Operative MR, 0.15 Tesla

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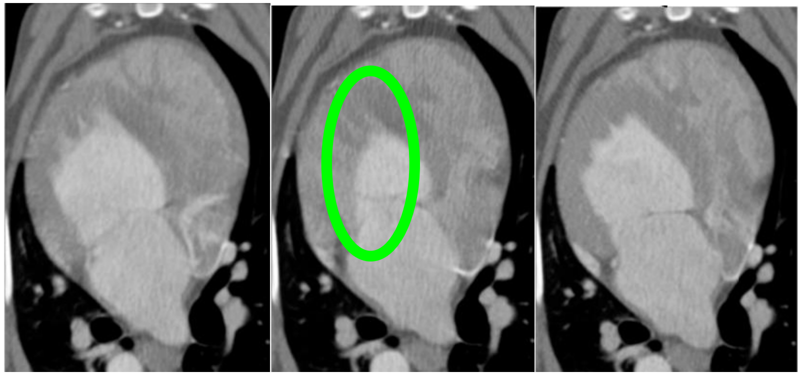
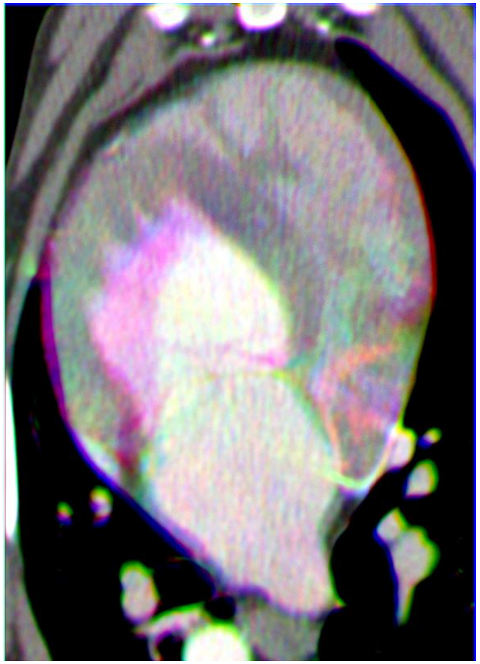
Same individual, same modality

Marcin Wierzbicki, Maria Drangova, Gerard Guiraudon, Terry Peters, *Validation of dynamic heart models obtained using non-linear registration for virtual reality training, planning, and guidance of minimally invasive cardiac surgeries*, Medical Image Analysis, 8(3),2004, Pages 387-401.



2D slices from sequence of 3D images



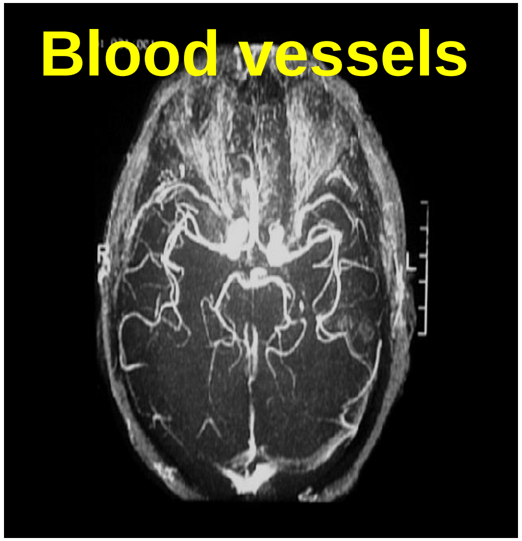
3 frames overlaid and colour-coded to show movement between frames

- Innate organ motion, or motion between scans

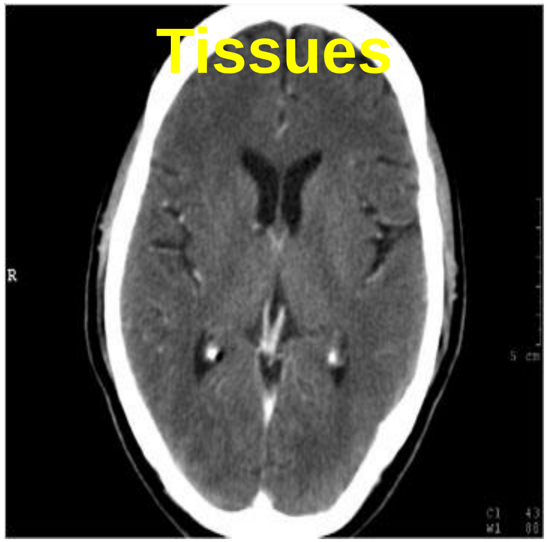
Multimodal Imaging

ANATOMICAL/ STRUCTURAL

Magnetic Resonance



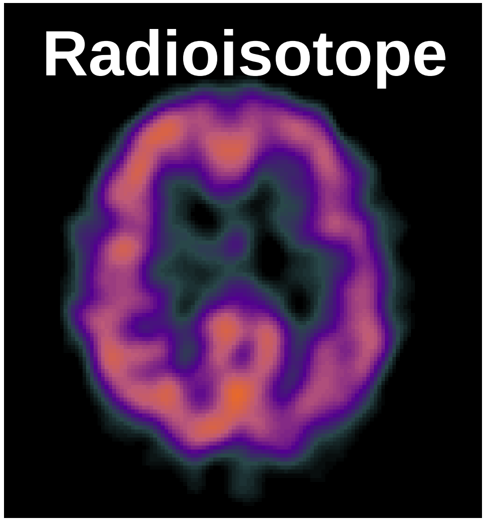
Angiography



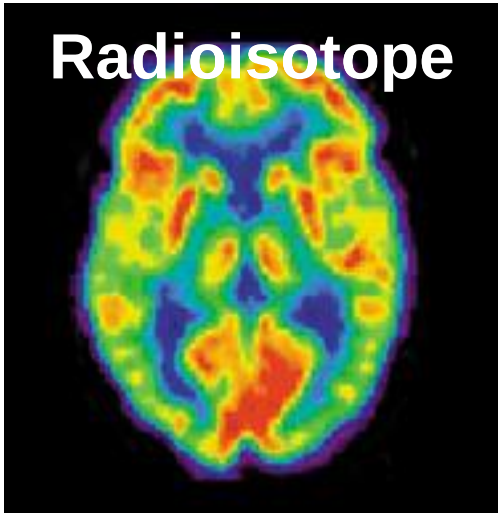
Computed Tomography

FUNCTIONAL

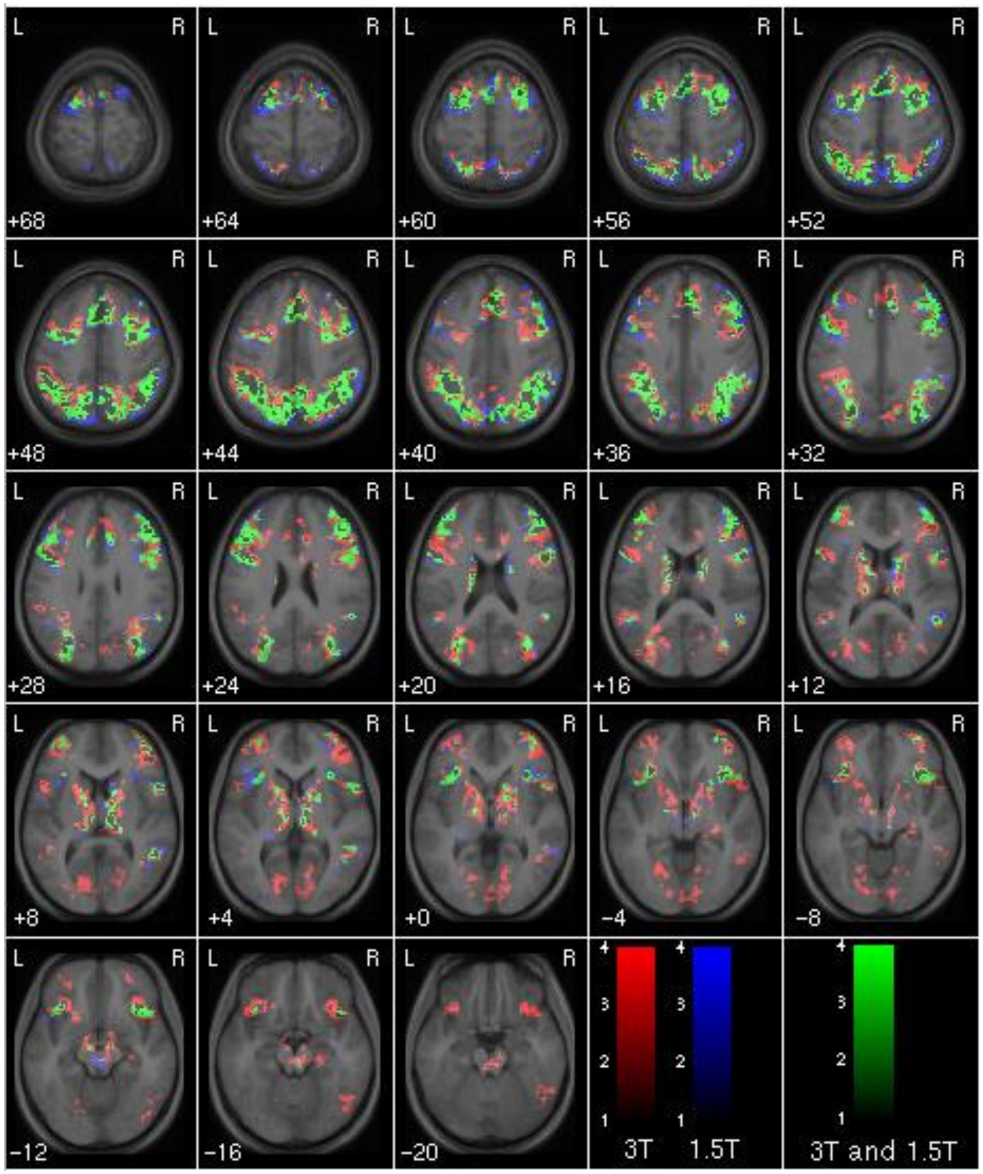
SPECT:
Single
Photon
Emission
Computed
Tomography



PET:
Positron
Emission
Tomography

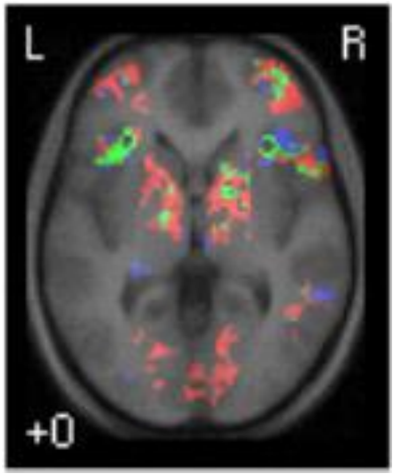


Data Fusion:



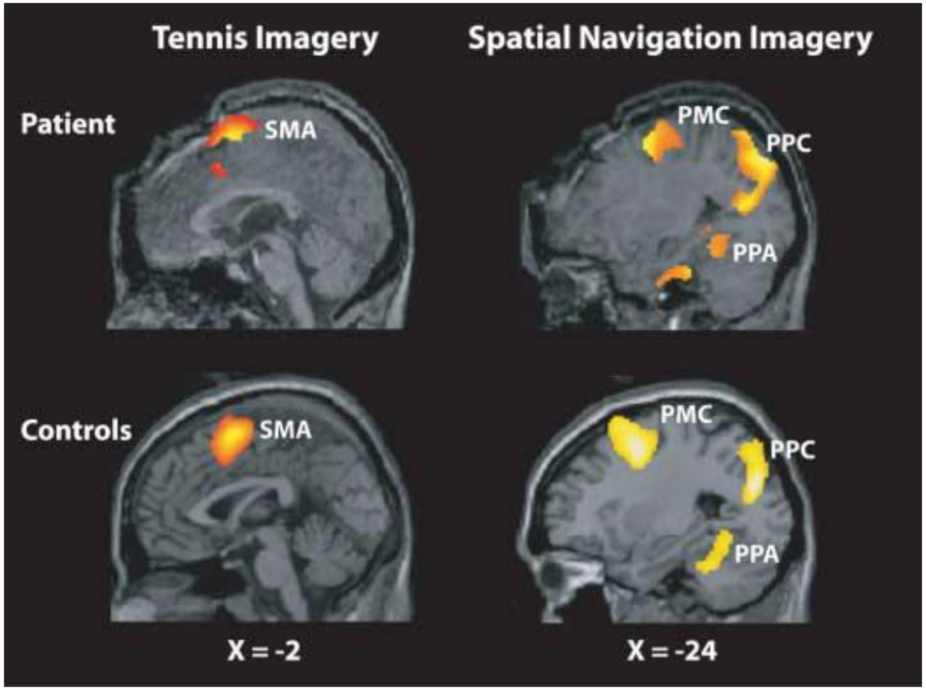
Functional (fMRI) overlaid on Anatomical MRI:

Link activation to specific anatomical structures



ASIDE: fMRI & Mind-Reading!

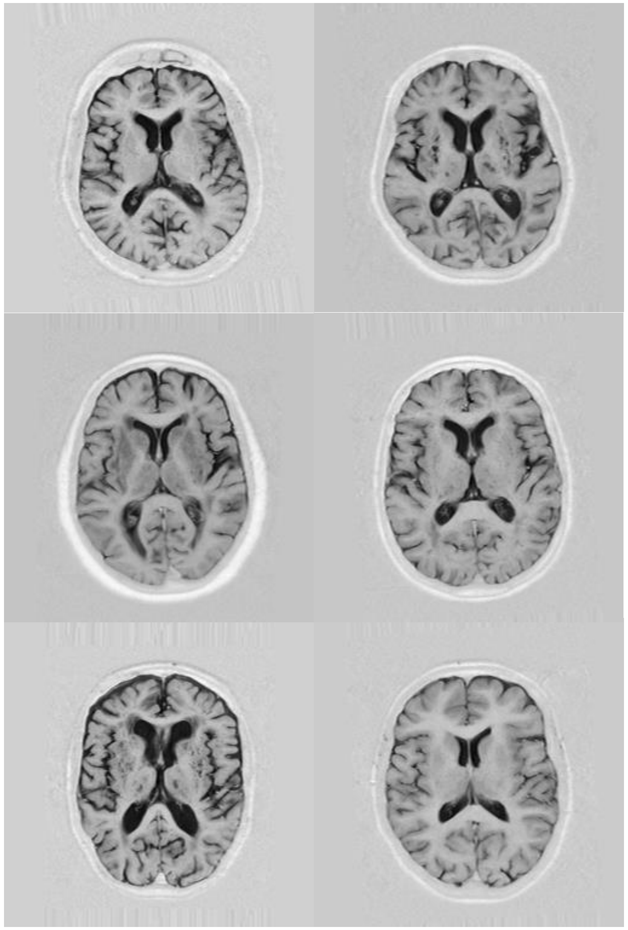
- **Patients in persistent vegetative states (PVS)**
- **Show brain activity & can answer yes/no questions**

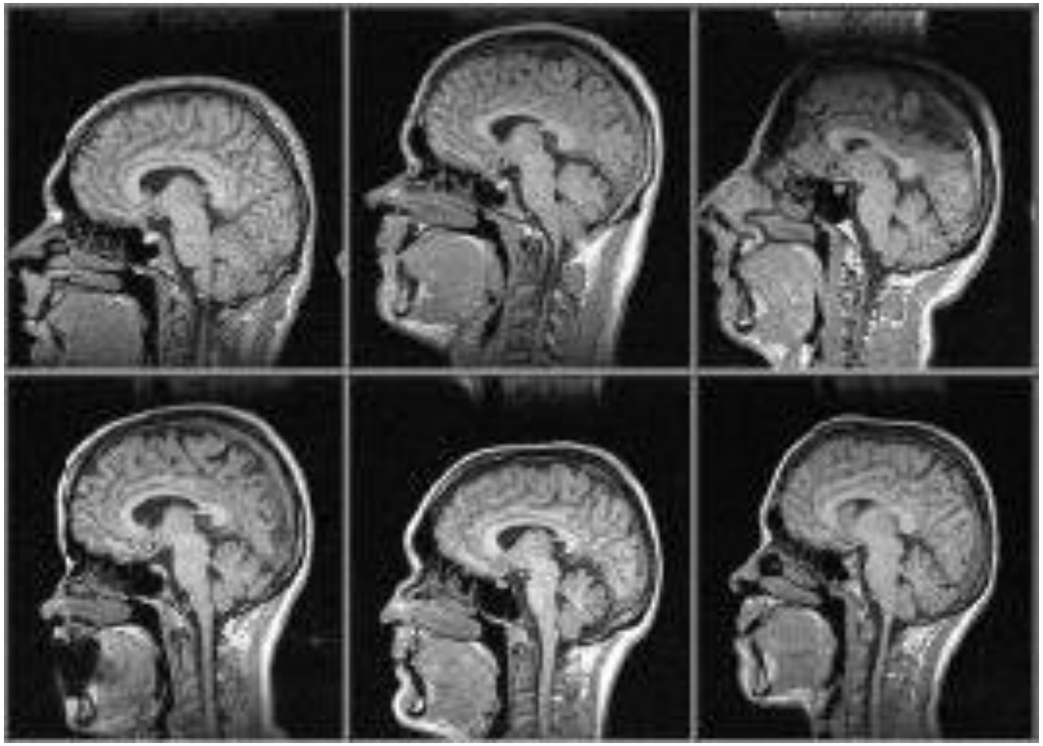


Owen et al. , *Detecting Awareness in the Vegetative State* Science 8 September 2006

- **Scott Routley able to answer that he was not in pain**
- **Raises important ethical issues……………….**

Population Studies





- **Normal and abnormal anatomical variation**

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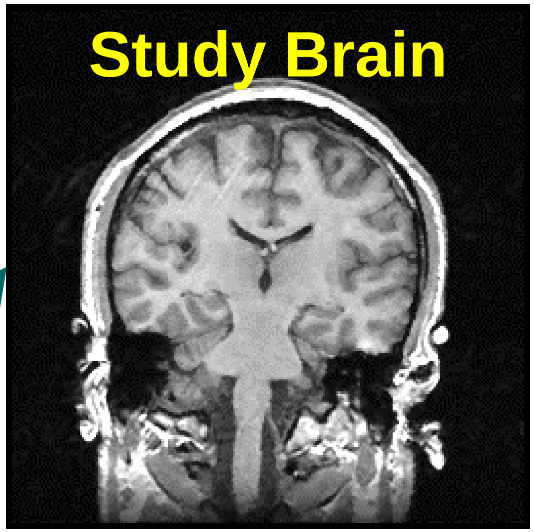
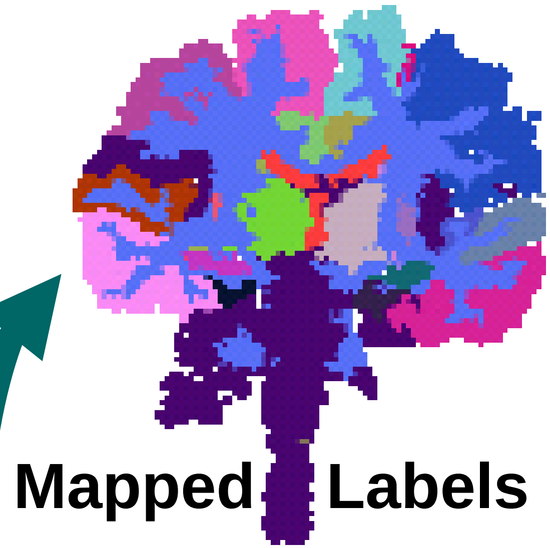
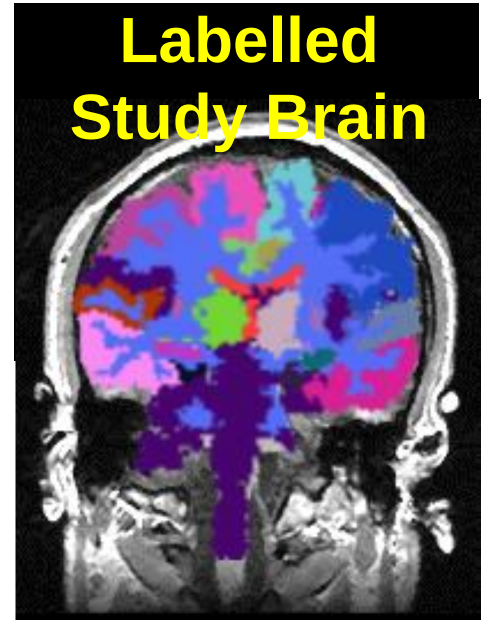
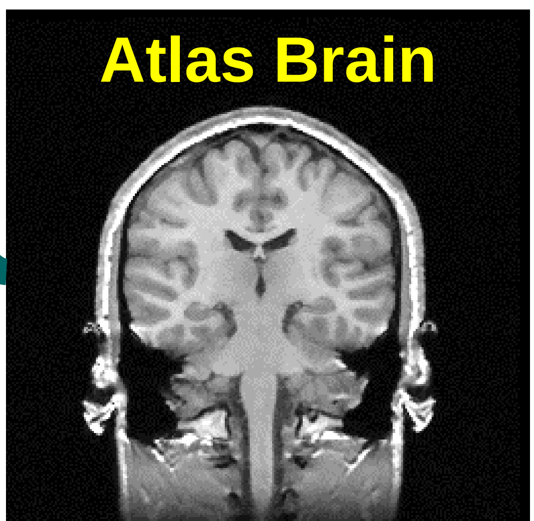
Individual to Atlas

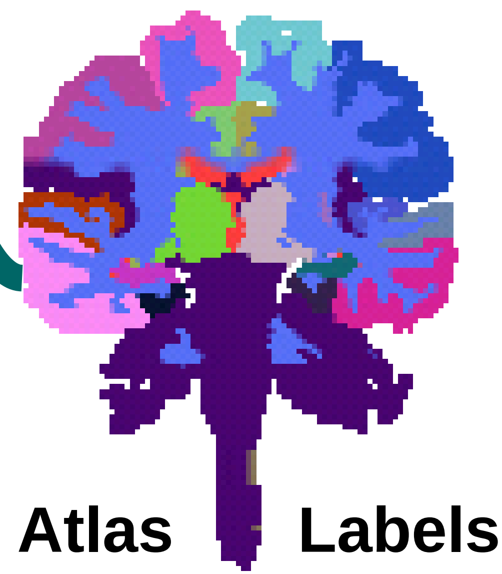
Courtesy of J-P. Thirion, INRIA

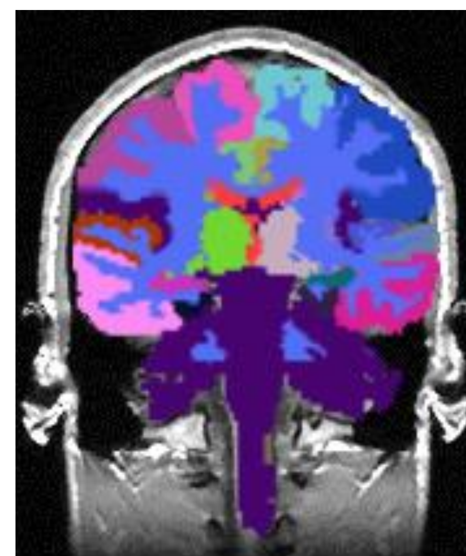




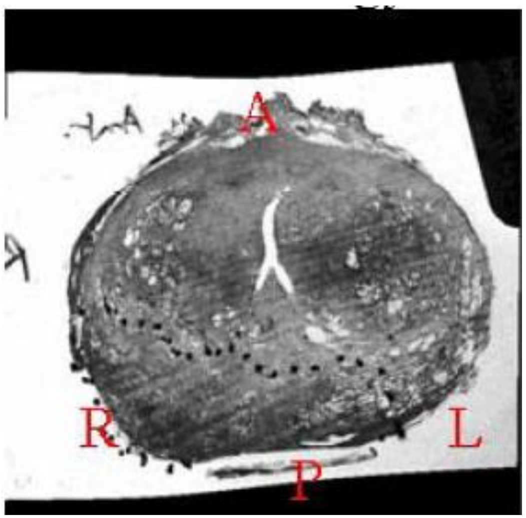




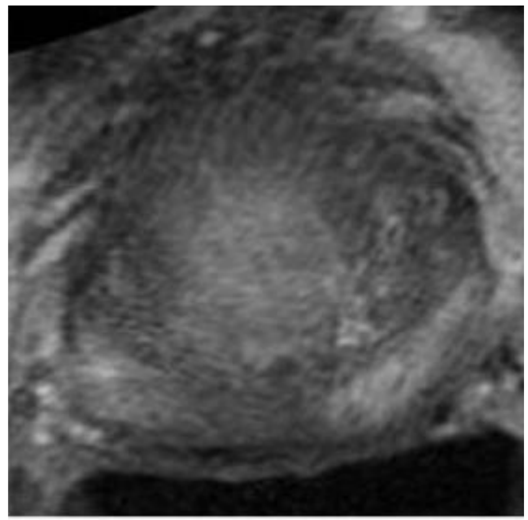




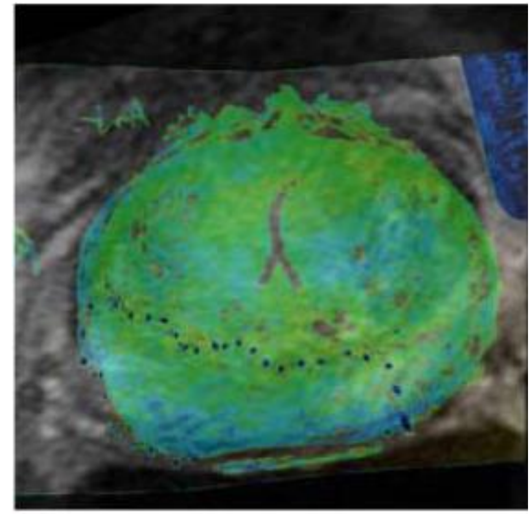
Histological Sections: Removed prostates



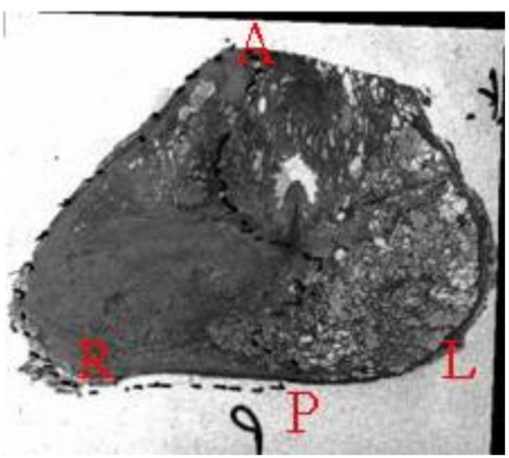
Histological section of prostate

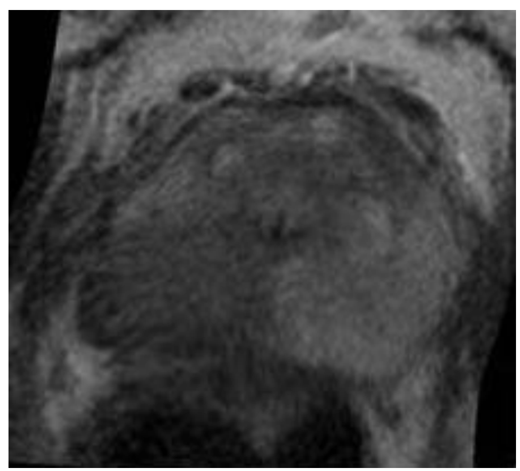


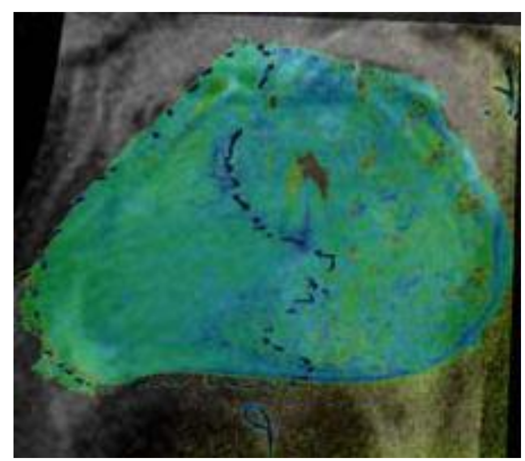
Registered MR image



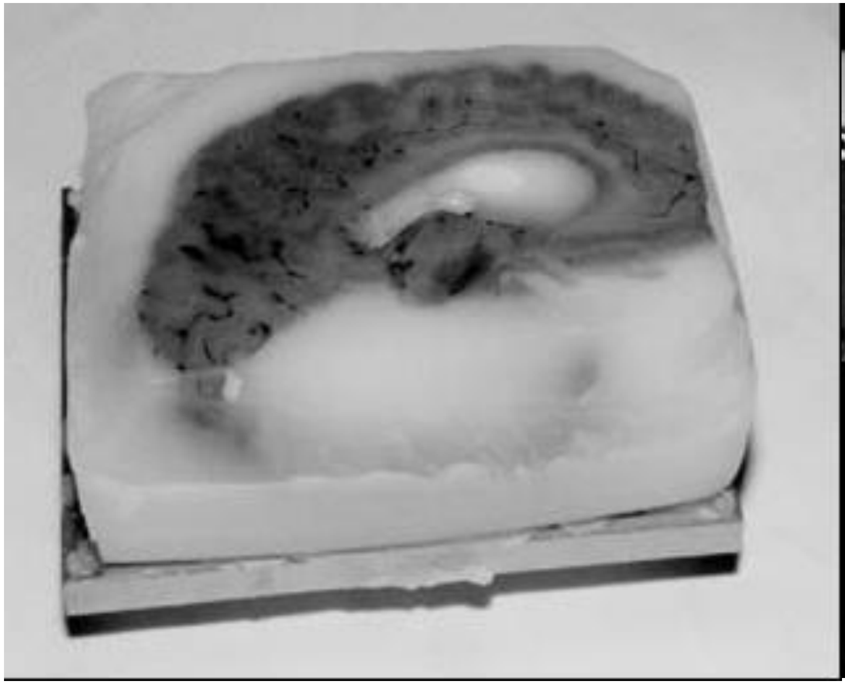
Superimposed

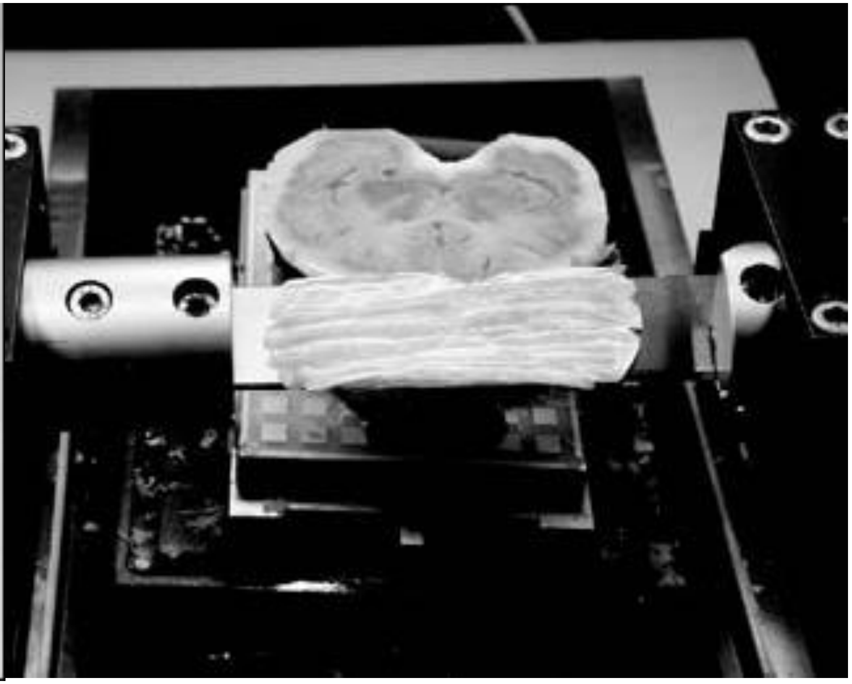






Example: Histological sections





Whole human brain embedded in paraffin wax

Microtome

- Stretched, dried, wax removed, stained, mounted
- Distortion occurs during this process

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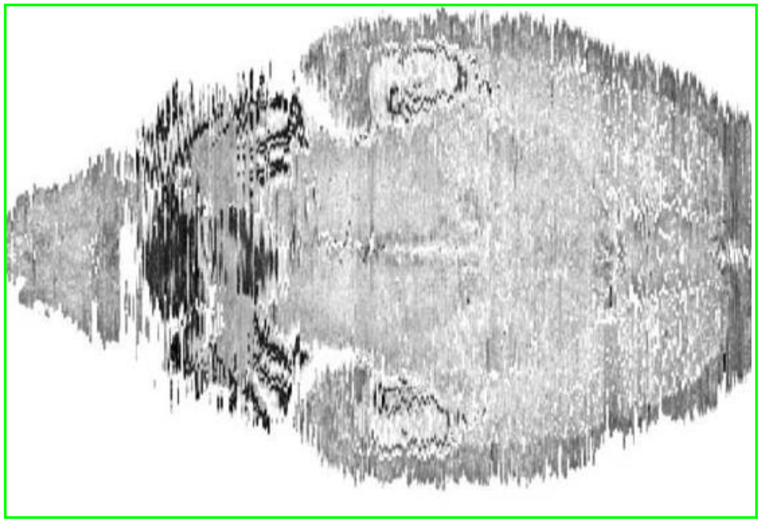
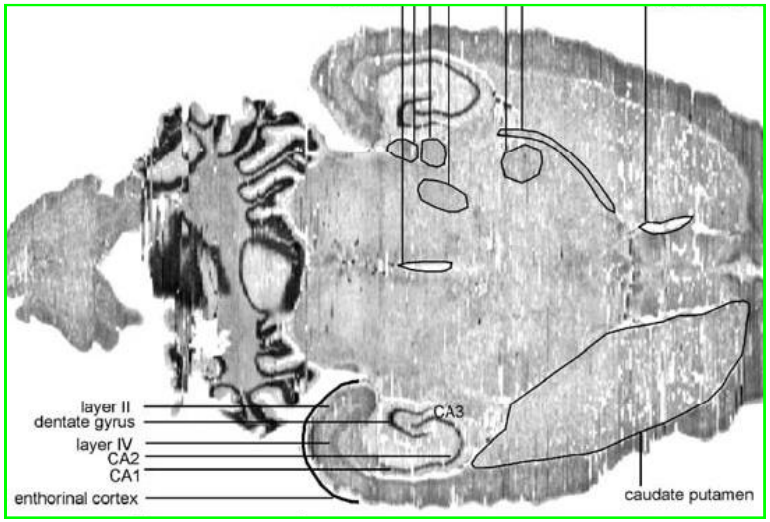
Histological Sections: Rat Brain

Modersitzki, Schmitt and Wirtz,
Registration of Histological Serial Sectionings,
Mathematical Models for Registration and Applications to Medical Imaging



Before registration



After volume preserving registration

- **Artificial slice of reconstructed 3D rat brain from histological sections**

Basic Structure of Pairwise Registration Algorithms

Pairwise Registration Algorithm

- **Two images, source and target** **(also called moving & reference, moving & stationary , template & reference etc etc etc!)**
- **Warp one image into the frame of the other**
- **Assess image matching**
- **Optimize the match**

Three Main Questions:

- **How do we measure image match/image difference?**
- **How do we represent image warping?**
- **How do we find the optimum match?**

Image Matching

Two main strands:

- **Geometric Matching:**

  Extract sparse features (manually or automatically) :

  points, lines, edges, ridge lines, surfaces etc

  Register extracted features

  Problems: manual annotation, matching features, interpolating/extrapolating the paired features

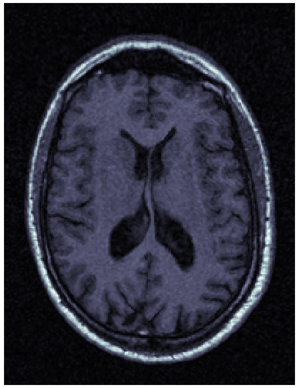
- **Intensity-Based Registration:**

  pixel-by-pixel comparison warped & stationary images

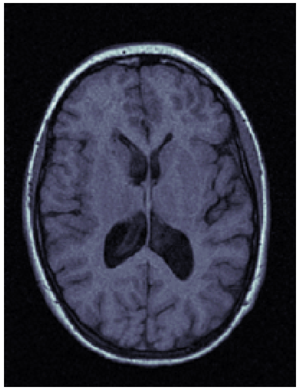
  Agrees with our intuition about matching

  Makes maximal use of available image information

Image & Warped Image: Matching



$\mathcal{I}_1(\underline{X})$



$\mathcal{I}_2(\underline{X})$

- **Both defined on same pixellated grid:** $\underline{X} = \{\underline{p}_\mathrm{a}\}$
- **Pixel-by-pixel comparison:**
  $\mathcal{I}_1(\underline{p}_\mathrm{a})$ versus $\mathcal{I}_2(\underline{p}_\mathrm{a})$

- **Sum of Absolute Differences (SAD):** $\sum_\mathrm{a} \left|\mathcal{I}_1(\underline{p}_\mathrm{a}) - \mathcal{I}_2(\underline{p}_\mathrm{a})\right|$
- **Sum of Squared Differences (SSD):** $\sum_\mathrm{a} \left(\mathcal{I}_1(\underline{p}_\mathrm{a}) - \mathcal{I}_2(\underline{p}_\mathrm{a})\right)^2$
- **Both assume best match = same values**
- **If this is not the case, correlation or mutual information**
- **Resampling the images onto common pixel grid?**

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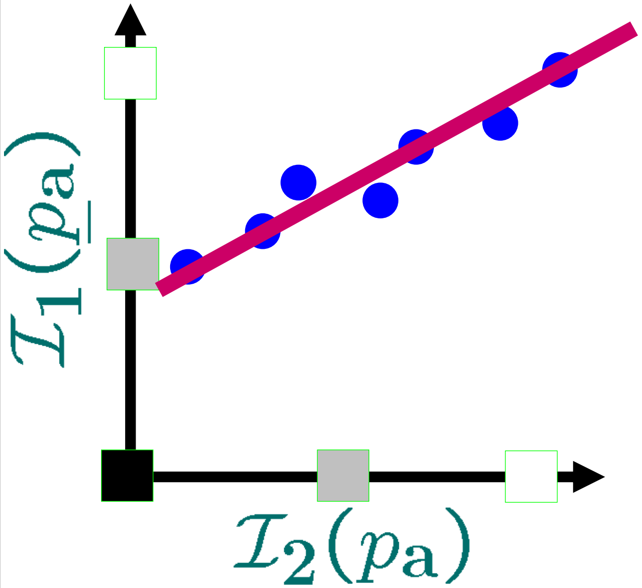
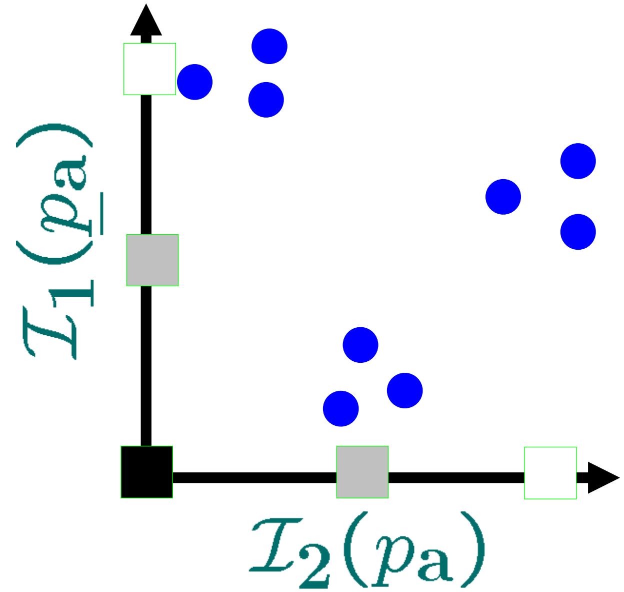
Correlation & Mutual Information





Subtract mean of each image

$$\hat{\mathcal{I}}(\underline{p}_{\mathrm{a}}) = \mathcal{I}(\underline{p}_{\mathrm{a}}) - \frac{1}{\mathrm{n_p}} \sum_{\mathrm{b}} \mathcal{I}(\underline{p}_{\mathrm{b}})$$

Normalised cross-correlation

$$\frac{\sum_{\mathrm{a}} \hat{\mathcal{I}}_1(\underline{p}_{\mathrm{a}}) \hat{\mathcal{I}}_2(\underline{p}_{\mathrm{a}})}{\sqrt{\sum_b (\hat{\mathcal{I}}_1(\underline{p}_b))^2 \sum_c (\hat{\mathcal{I}}_2(\underline{p}_c))^2}}$$

Tries to make joint distribution a straight line

Mutual Information (Viola, 1995):

Useful when no simple ordering relation between intensities:

multi-modality registration

Tries to make joint distribution as peaky as possible

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Mutual Information & Entropy

- **Histogram, bins:** $\{\mathrm{i}\}$ **probabilities:** $\{\mathrm{P_i}\}, \sum_{\mathrm{i}} \mathrm{P_i} = 1$
- **Entropy:** $\mathrm{E} = -\sum_{\mathrm{i}} \mathrm{P_i} \log \mathrm{P_i}$

Single bin: E = 0
Else E>0

Mutual Information:

- **Entropy of distribution of pixel values for image 1**
- **Entropy of distribution of pixel values for image 2**
- **minus entropy of joint 2D histogram**

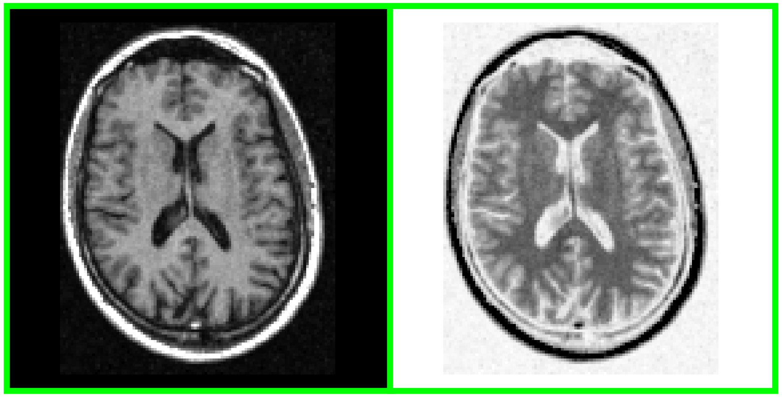
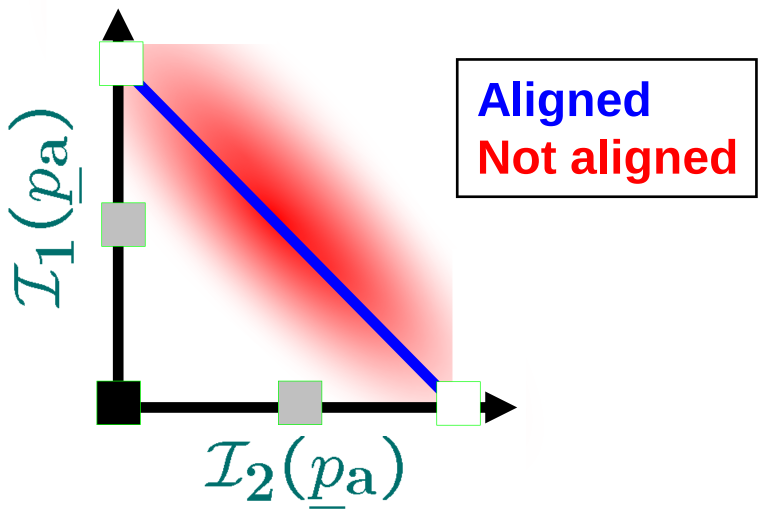
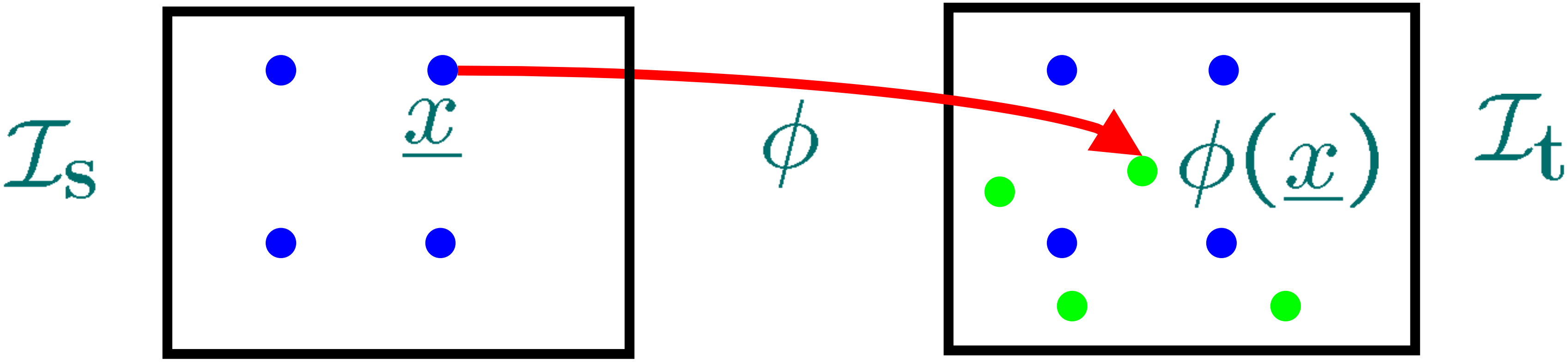


Image & Inverse image



Sampling the Warped Image

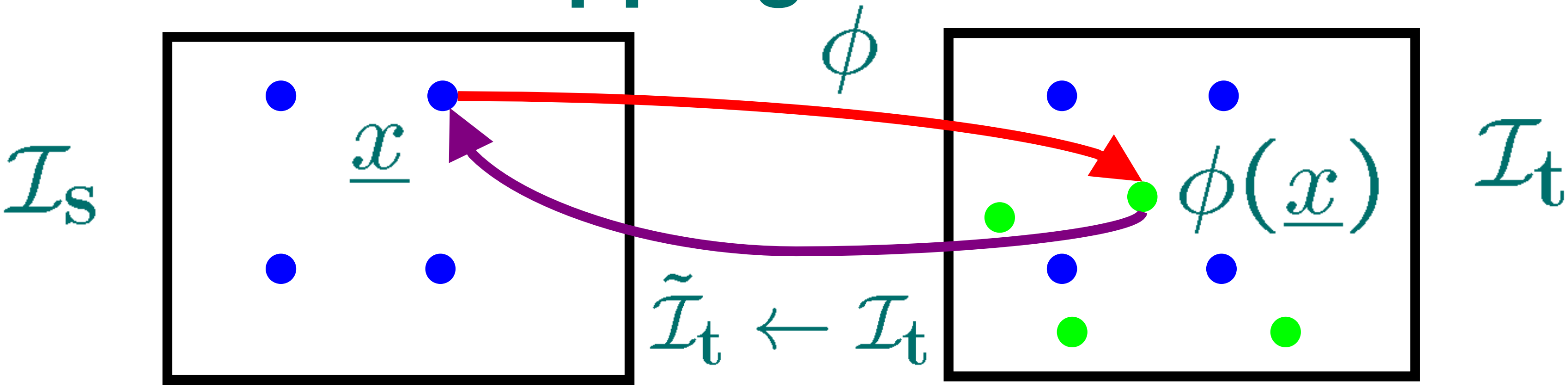
Push-Forward Mapping



- $\mathcal{I}_{\mathrm{s}}$ & $\mathcal{I}_{\mathrm{t}}$ **both defined on regular pixel grid** $\underline{X}$
- **Mapping:** $\phi : \underline{x} \mapsto \phi(\underline{x})$
- **Warped source:** $\tilde{\mathcal{I}}_{\mathrm{s}} : \tilde{\mathcal{I}}_{\mathrm{s}}(\phi(\underline{X})) \doteq \mathcal{I}_{\mathrm{s}}(\underline{X})$
- **Pixel-by-pixel comparison in frame of target image**
- **Comparing** $\tilde{\mathcal{I}}_{\mathrm{s}}(\phi(\underline{X}))$ **with** $\mathcal{I}_{\mathrm{t}}(\underline{X})$ **:**

  resample source from irregular grid to regular grid
- **Computationally expensive**

Pull-Back Mapping



- $\mathcal{I}_{\mathrm{s}}$ & $\mathcal{I}_{\mathrm{t}}$ **both defined on regular pixel grid** $\underline{X}$
- **Mapping:** $\phi : \underline{x} \mapsto \phi(\underline{x})$
- **Pixel-by-pixel comparison in frame of source image**
- **Warped target:** $\tilde{\mathcal{I}}_{\mathrm{t}} : \tilde{\mathcal{I}}_{\mathrm{t}}(\underline{X}) \doteq \mathcal{I}_{\mathrm{t}}(\phi(\underline{X}))$
- **Compare** $\mathcal{I}_{\mathrm{s}}$ **with** $\tilde{\mathcal{I}}_{\mathrm{t}}$
- **Computing** $\tilde{\mathcal{I}}_{\mathrm{t}}$ **:** $\mathcal{I}_{\mathrm{t}}(\underline{X}) \rightarrow \mathcal{I}_{\mathrm{t}}(\phi(\underline{X}))$

  resample target from regular grid to irregular grid
- **Computationally easier**

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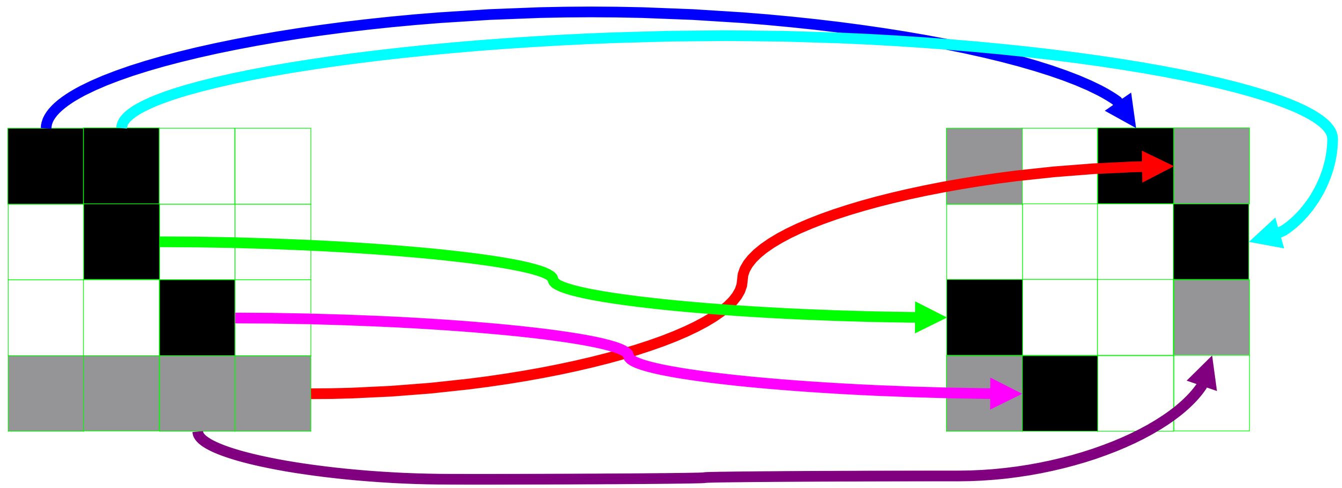
Image matching alone not enough



- **If we: Shuffle pixels in any fashion**
- **Add in intensity changes due to interpolation**
- **Result: Match almost anything to almost anything!**

Ideal Solution:

- **Retain proximity:**
  close in one image = close in the other
- **Deformation field $\phi(\underline{x})$ continuous and smooth**
- **No folds or tears**

Summary:

- **Why registration & example image data**

Pairwise Registration:

- **Image matching, single or multi modal cases**
- **Creating warped image**
- **Why image matching alone isn't enough!**

Next Lectures:

Warp Regularisation:

- **Parametric Warps:**

  Meshes, barycentric coordinates & splines

- **Non-Parametric Warps:**

  Dense deformation fields, elastic solids & fluids