Registration of images

Václav Hlaváč

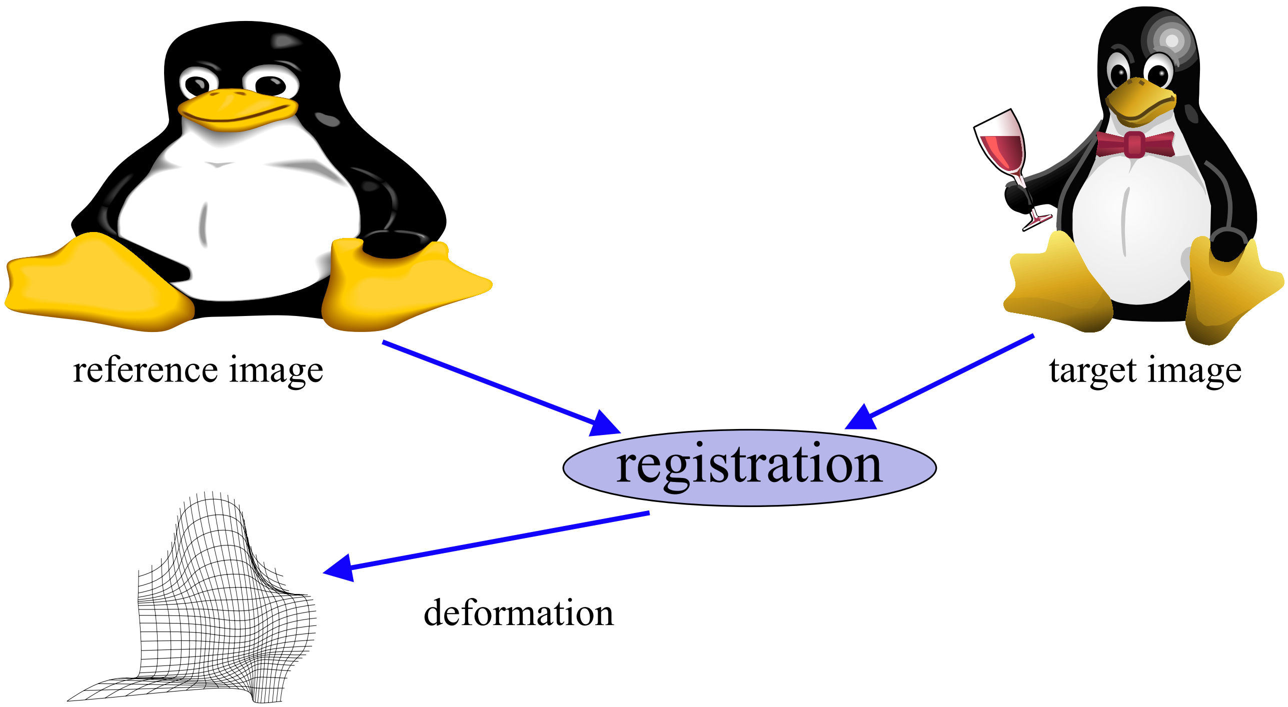
Czech Technical University in Prague
Czech Institute of Informatics, Robotics and Cybernetics
160 00 Prague 6, Jugoslávských partyzánů 1580/3, Czech Republic
http://people.ciirc.cvut.cz/hlavac, vaclav.hlavac@cvut.cz
also Center for Machine Perception, http://cmp.felk.cvut.cz

Courtesy: Presentations of A. Brun, M. Brady, J. Kybic, Aiming Lu

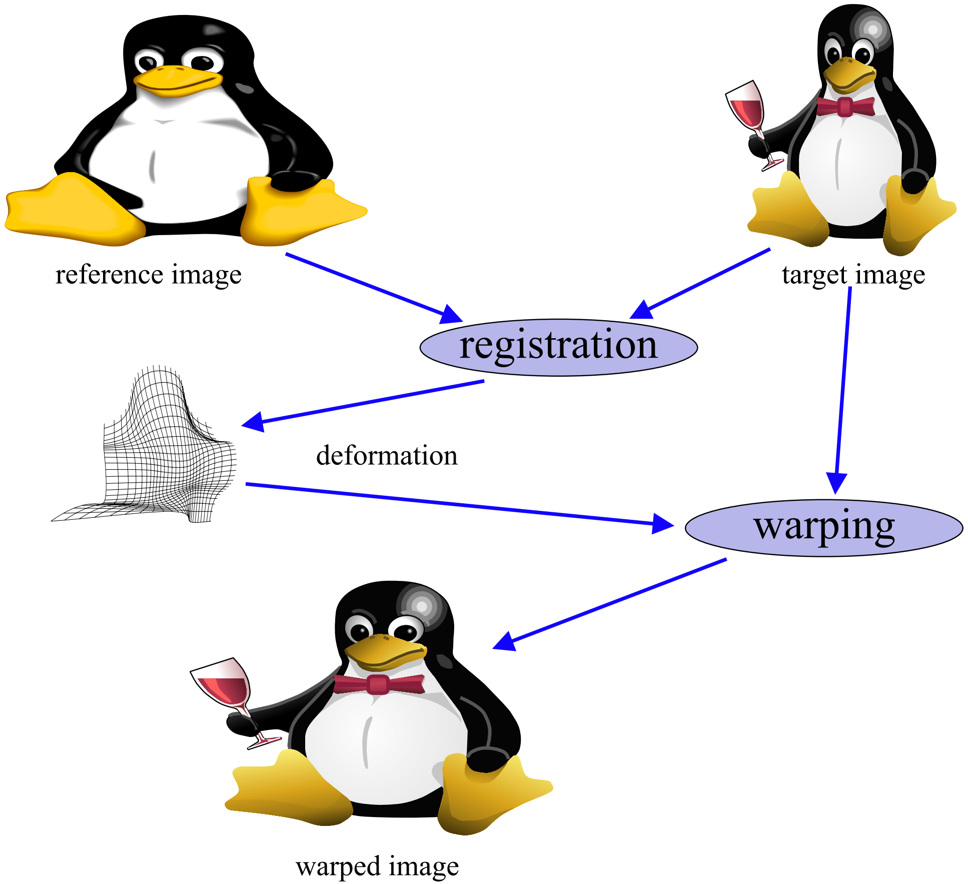
Image registration, the lecture plan

- Image registration: What is it? Motivation.
- Medical imaging examples.
- Image registration, (ill-posed) task formulation, flowchart, 3 steps, rigid vs. non-rigid registration.
- Image registration: intensity-based; landmark-based, feature-based.
- Image similarity measure.
- Practical optimization (covered elsewhere).

Motivation to the image registration (1)



Motivation to the image registration (2)



Registration – What is it?

Matching – “Two regions in the image (two instances of the object) resembling or corresponding one to the another.”

- Matching is a core of all three following concepts.
- Corresponding regions have to be found in the source and target data.

Registration – “To adjust so as to be properly aligned.”

- Geometric (and possibly photometric) alignment of one image with another, i.e. process of transforming different sets of data into one coordinate system.
- Images may be of same or different modalities (e.g. MR, CT).
- It is needed to be able to compare or integrate the data obtained from different measurements.

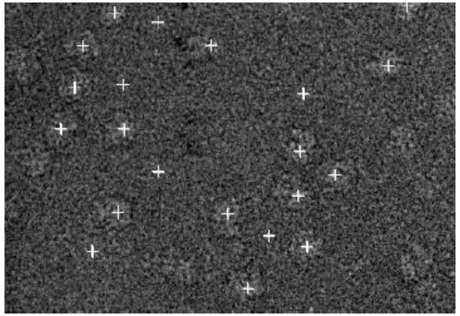
Fusion – “Something new is created by a mixture of qualities, ideas, or things.”

Warping – “Become or cause to become bent or twisted out of shape, typically as a result of the effects of heat or dampness.”

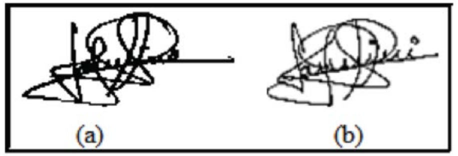
Courtesy: Centre for Image Analysis, Uppsala University

Registration – Where is it used?

- **Photography** – Stitching photos together, panoramic images
- **Astronomy** – Stitching photos together and fusion of different wavelengths, modalities, e.g. optical, radar.
- **Chemistry** – Finding similar images of molecules



- **Signature comparison**



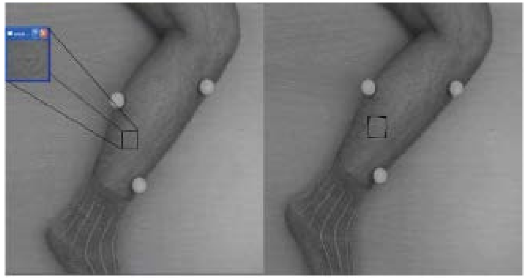
- **Human motion analysis** – temporal alignment of prototypical postures, e.g. gesture understanding
- **Stereo and shape from motion** – correspondence between key point
- **Video stabilization** – correspondence between key point

Image registration, the lecture plan

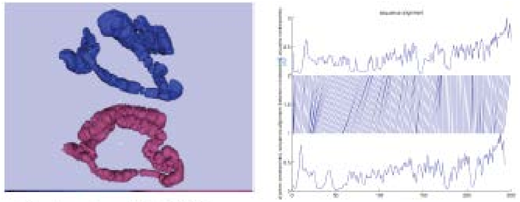
- Image registration: What is it? Motivation.
- Medical imaging examples.
- Image registration, (ill-posed) task formulation, flowchart, 3 steps, rigid vs. non-rigid registration.
- Image registration: intensity-based; landmark-based, feature-based.
- Image similarity measure.
- Practical optimization (covered elsewhere).

Registration in medical imaging

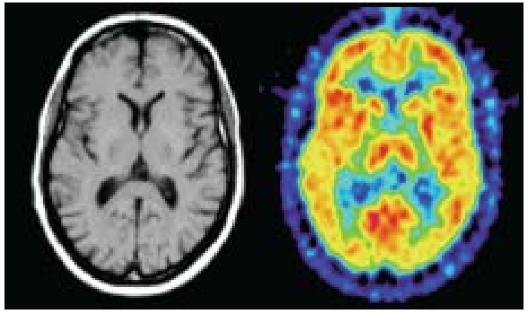
- Study skin changes over time
- Colonoscopy
- Pre surgery vs. post surgery
- Fusion of different modalities as
  - CT-MRI,
  - CT - ultrasound,
  - PET-CT, etc.
- . . . and many more



Holmberg et al. 2008

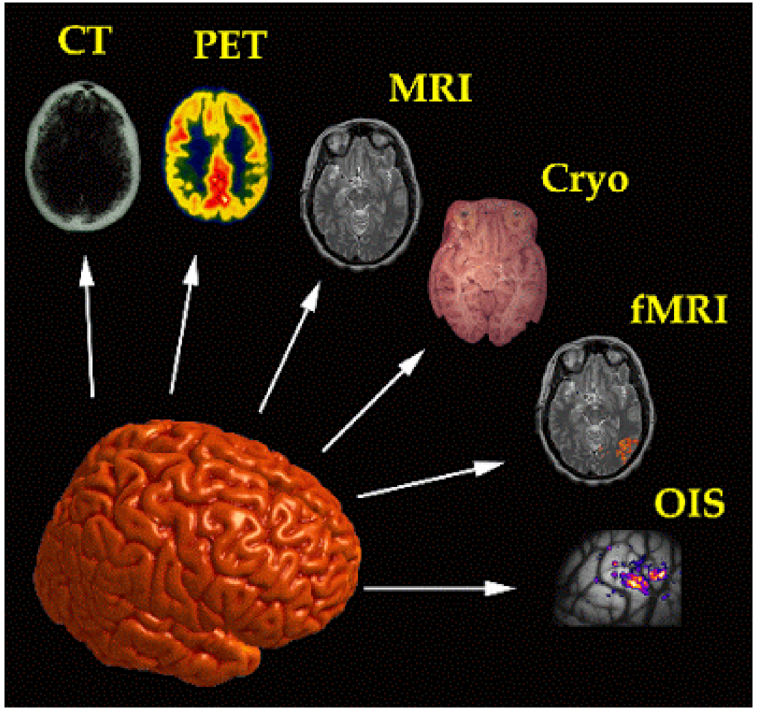


Nain et al. 2002



Courtesy, images:
Centre for Image Analysis, Uppsala University

Brain imaging, modalities to be registered



- CT – Computer Tomography
- PET – Positron Emission Tomography
- MRI – Magnetic Resonance Imaging
- Cryo – Cryogenic Electron Microscopy
- fMRI – functional MRI
- OIS – Ophthalmic Imaging Systems

Registration domains in medical imaging

Outer dimension = different spatial and temporal dimensions

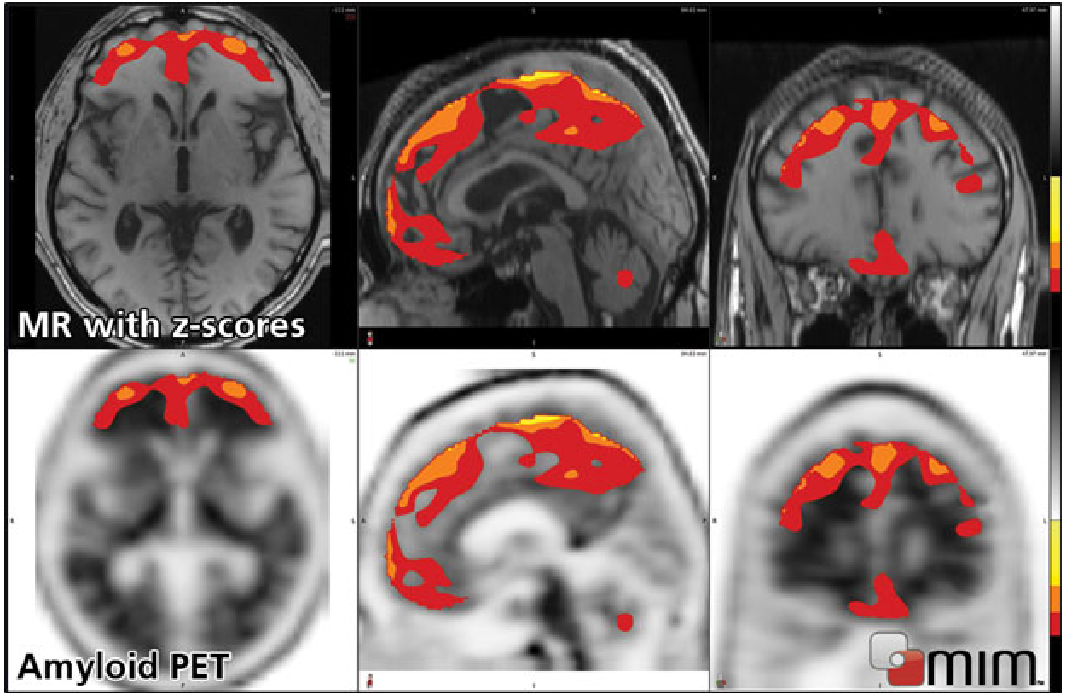
- 1-D (e.g. colonoscopy)
- 2-D (photos, MRI slices, ultrasound, ...)
- 3-D (MRI-, PET- and CT volumes, ...)
- 4-D (Volumes + time, e.g. a beating heart)
- 5-D (Volume + beating heart + breathing)

Inner dimensions = inside each pixel/voxel

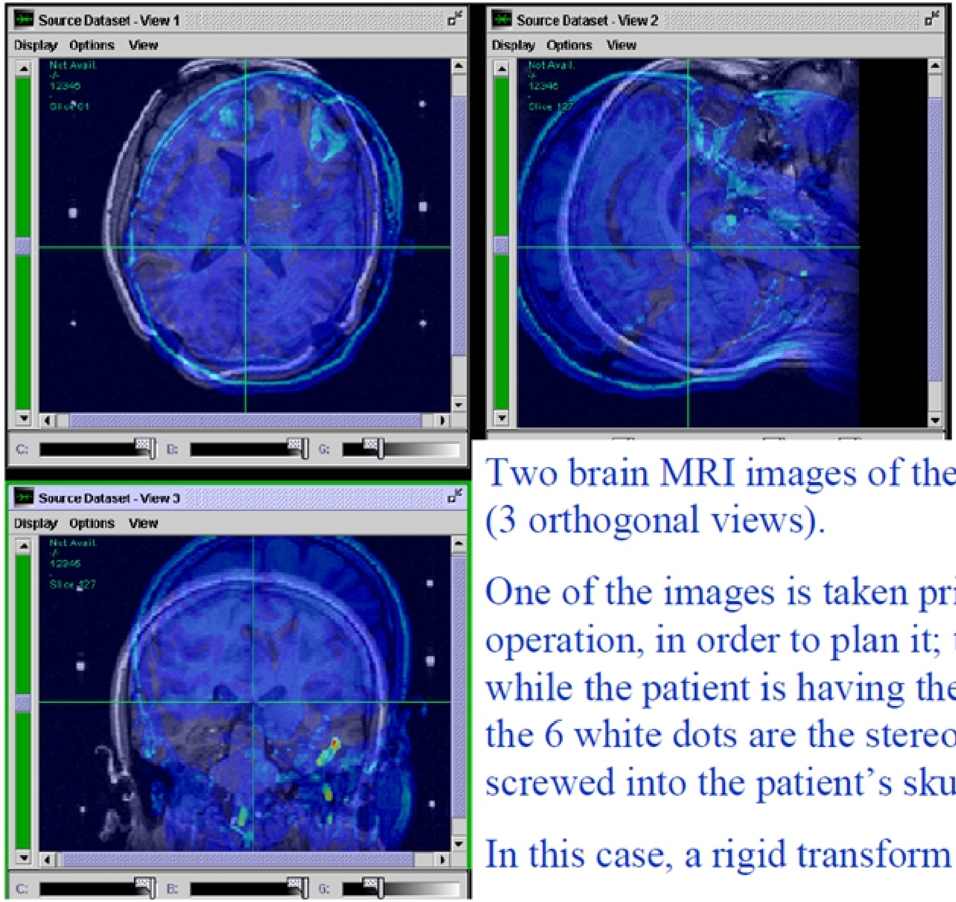
- Grayscale or color and other wavelengths
- Feature images (edges, corners, ...)

Registration cues in medical imaging

- Edgels, corners, eyes, interest points, . . .
- Color, texture, similarity measures, . . .
- Fiducials and frames, screws needed
- Skin markers – less painful
- Anatomical landmarks
- Expert knowledge



MRI, same patient, different time (1)

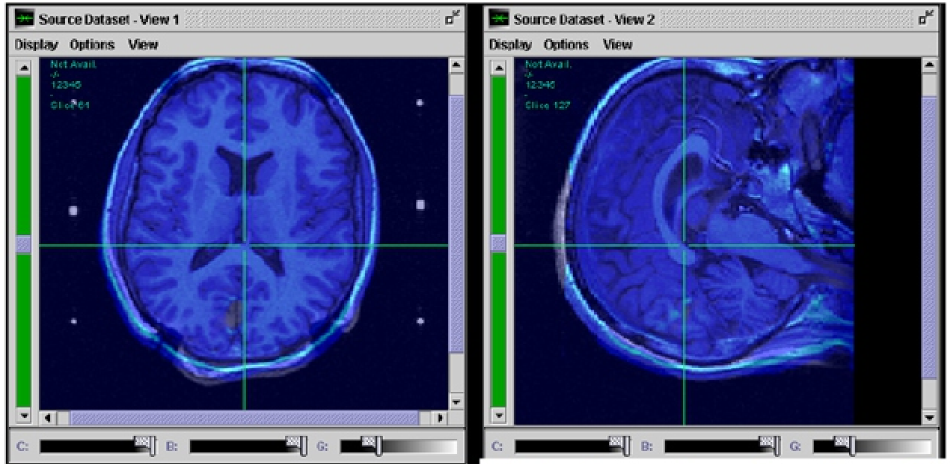


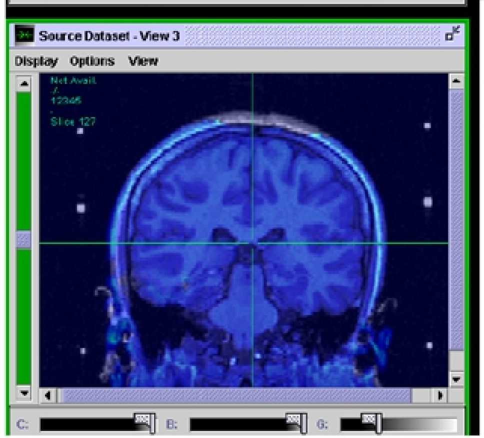
Two brain MRI images of the same patient (3 orthogonal views).

One of the images is taken prior to the operation, in order to plan it; the second while the patient is having the operation: the 6 white dots are the stereotactic frame screwed into the patient's skull.

In this case, a rigid transform suffices

MRI, same patient, different time (2)

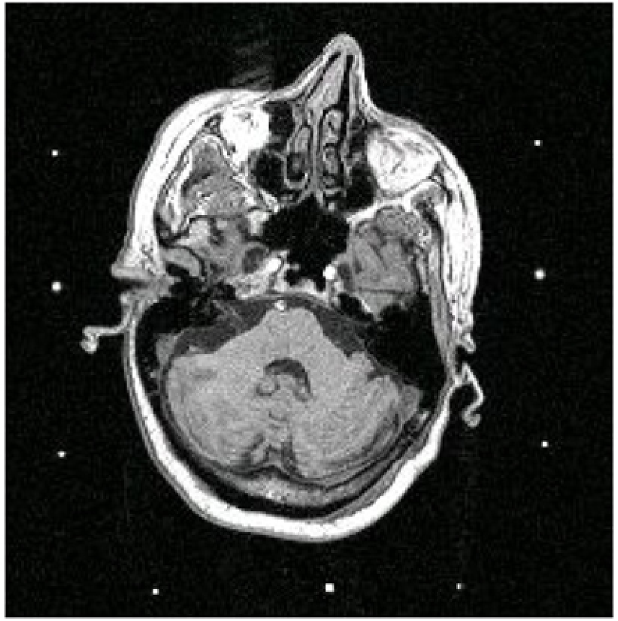




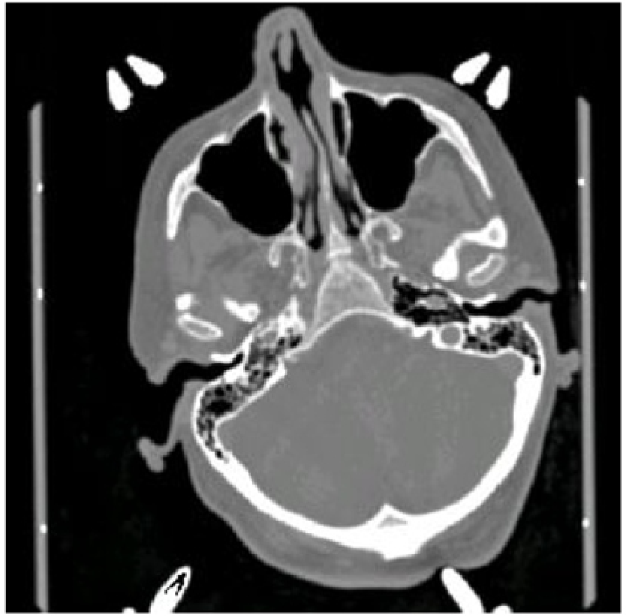
This shows the situation after the pre-op and inter-op images have been aligned.

Typically, a rigid registration algorithm applied to brain images will be accurate to 1/10 of a voxel and 0.1 degrees of rotation

MRI-CT image fusion

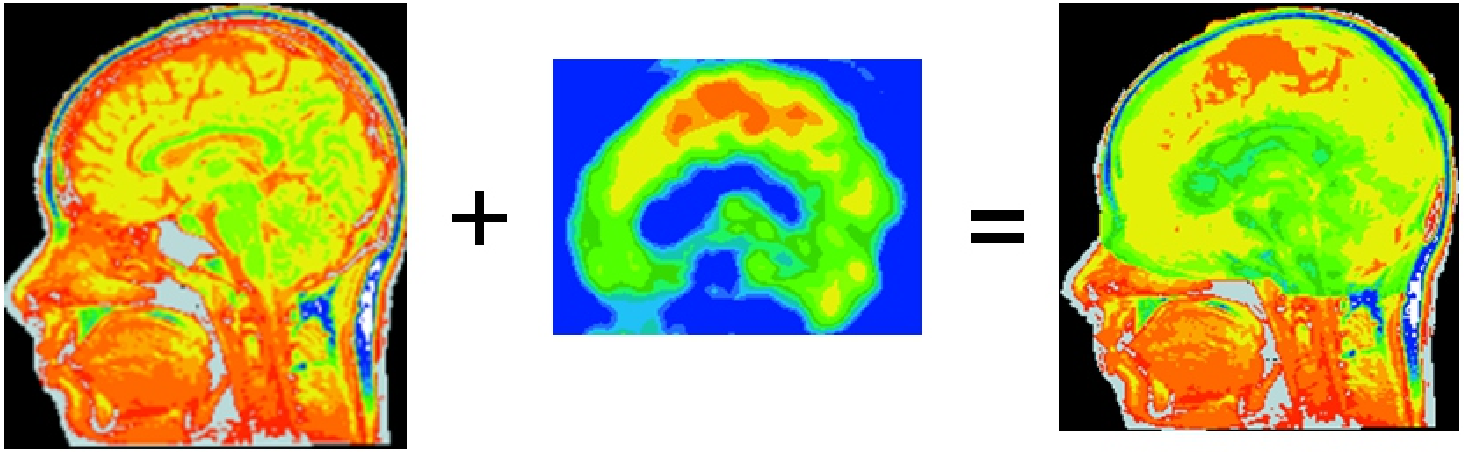


MRI image volume: soft tissue – show presence of a tumour



Computed tomography (CT), shows bony structures – very accurate

MRI + SPECT fusion



MR SPECT registered

Image alignment, example

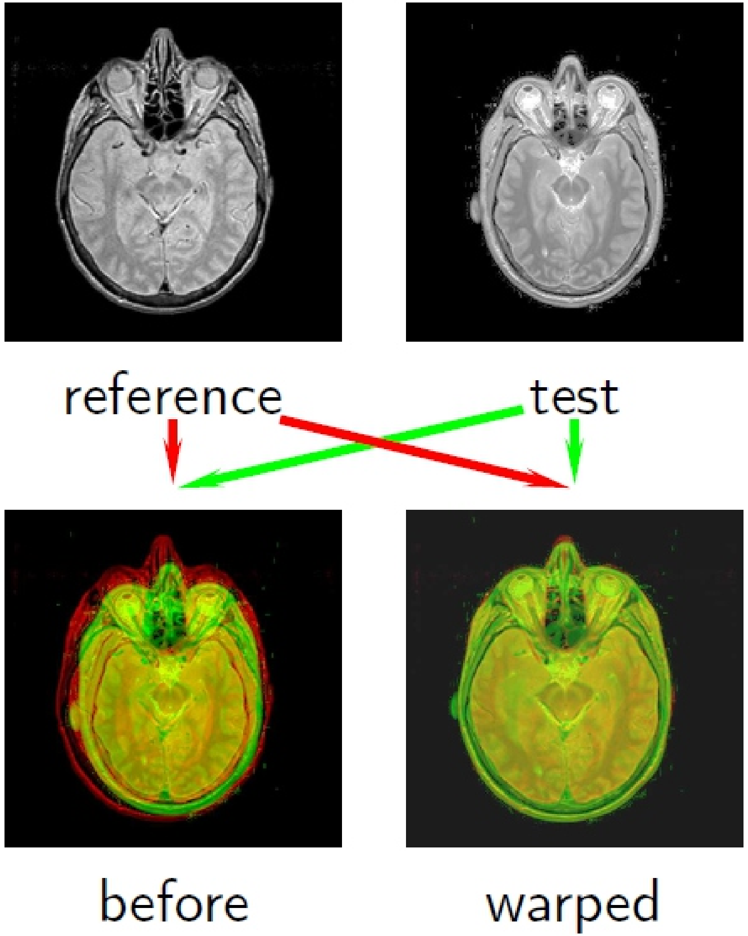


Image registration, the lecture plan

- Image registration: What is it? Motivation.
- Medical imaging examples.
- Image registration, (ill-posed) task formulation, flowchart, 3 steps, rigid vs. non-rigid registration.
- Image registration: intensity-based; landmark-based, feature-based.
- Image similarity measure.
- Practical optimization (covered elsewhere).

Image registration is an ill-posed task

- Reminder:

  An ill-posed problem has more degrees of freedom compared to available data.

- In registration:

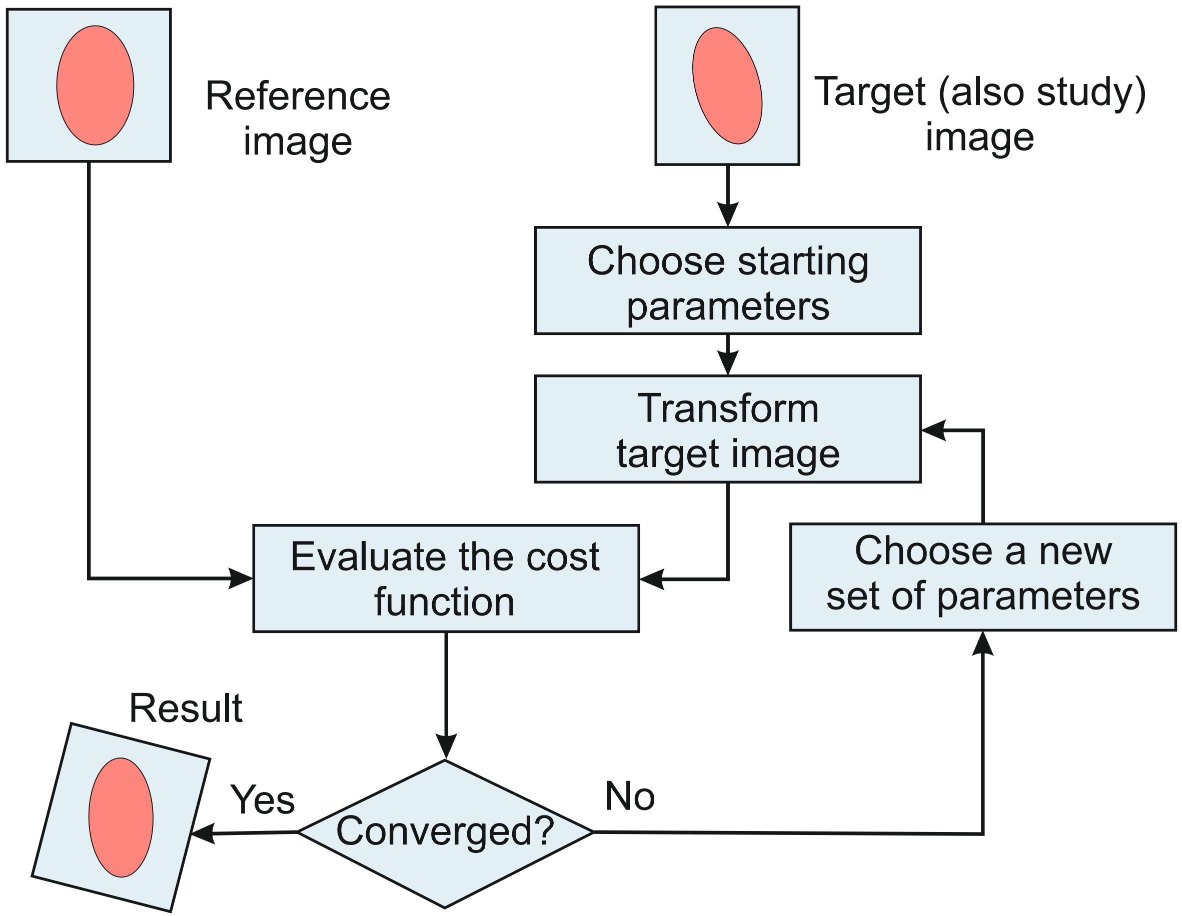
  If the reference image I_a has a total number of N pixels and the target image I_b has M pixels, then we need to find $2 * N$ coordinate values given $N + M$ values of input data.

- Consequently finding the best correspondence function φ (i.e. the transformation)

  $\begin{bmatrix} x_b \\ y_b \end{bmatrix} = \varphi\left(\begin{bmatrix} x_a \\ y_a \end{bmatrix}\right)$ is an Ill-posed problem!

- Solution: Restrict the set of admissible transformations φ.

Image registration flowchart

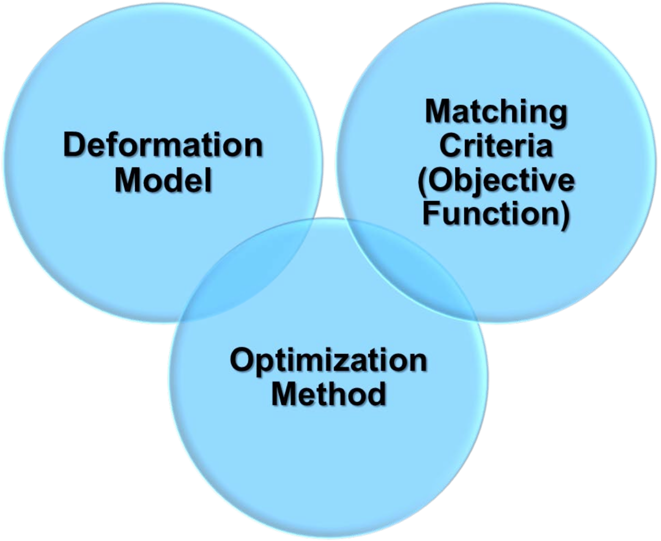


How to perform image registration?

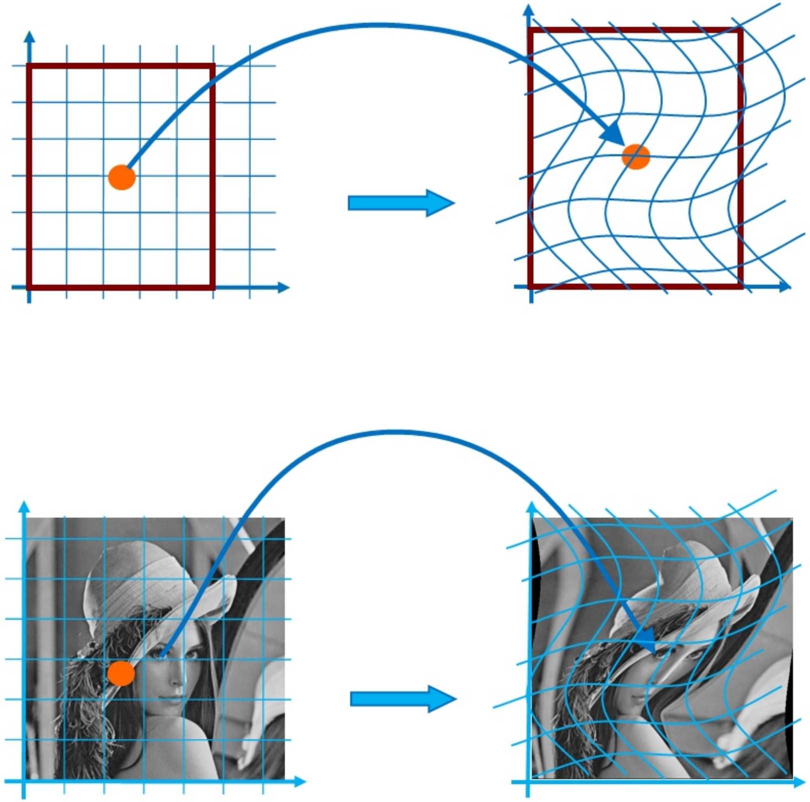
1. Understand the deformation model. Define the set of allowed transformations (correspondence functions, deformations) φ.

2. Define a useful functional to measure similarity (also matching criteria, objective function) in a consequent optimization.

3. Find and perform a practical optimization procedure.

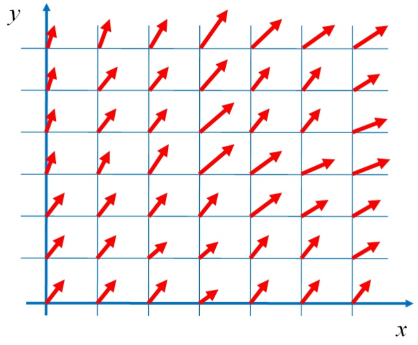


Deformation model illustration (1)

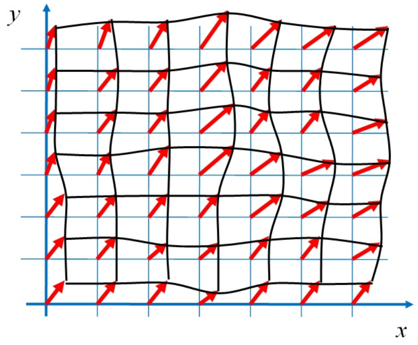


Deformation model illustration (2)

Estimated shifts per correspondence



Estimated deformation field



What is (2D) image registration?

- It is assumed that two images are given, the reference image $I_a(x, y)$ and the target image $I_b(x, y)$, where x, y are coordinates of pixels.
- The known correspondences among pixels assumed to be known too.
- $\varphi()$ is a 2D spatial (geometric) transformation.
- $g()$ is a 1D intensity transformation.
- The goal is to find such $\varphi()$ and $g()$ that the images are best matched,

$$I_b(x, y) \doteq g(I_a(\varphi(x, y)))$$

- Generalization to 3D (voxels) is easy.

Rigid vs. non-rigid registration

Rigid registration

- Landmark based
- Edgels / surface based
- Pixel / voxel intensity based
- Information theory based

Non-rigid registration
(also deformable registration)

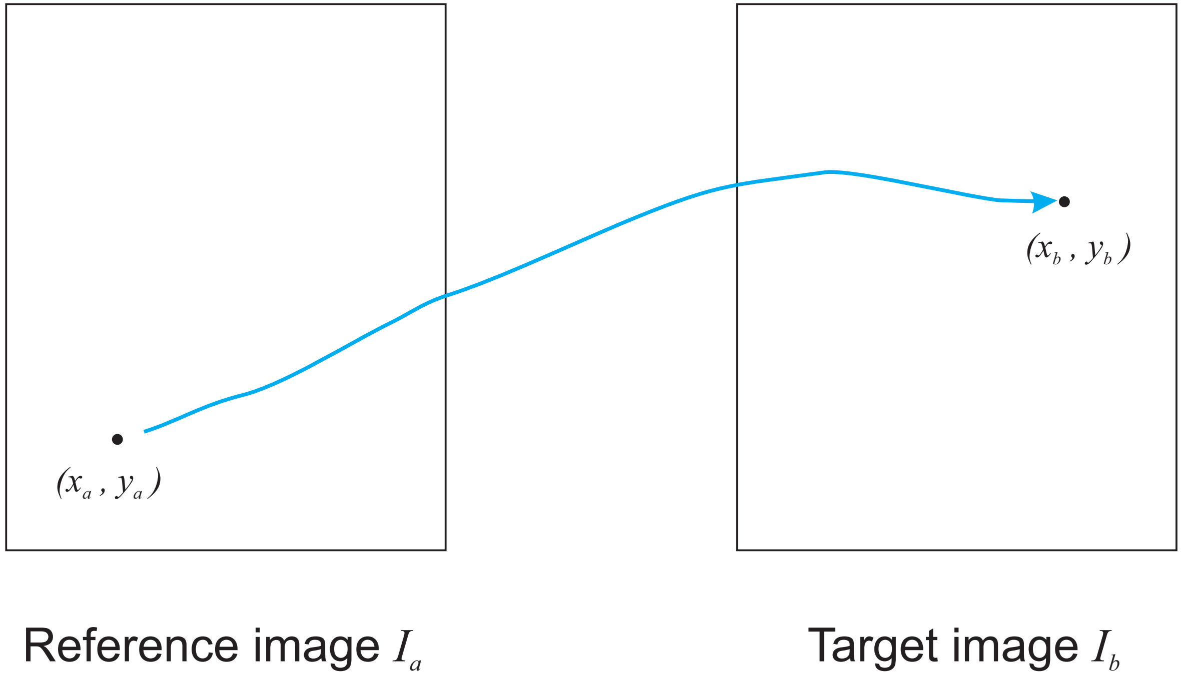
- Registration using basis functions
- Registration using curves surfaces (e.g. splines)
- Physics based, e.g. elastic, fluid, optical flow, etc.

Non-rigid (deformable) image registration

- Non-linear.
- Many different parameterizations.
- Too much flexibility in the transformation and its parameters can lead to undesirable results.

- Fundamental task in medical image processing
- Typical uses:
  - Longitudinal studies, where temporal structural or anatomical changes are investigated.
  - Matching of images from different patients.
  - Multi-modal registration, i.e. matching images of the same patient acquired by different imaging technologies.

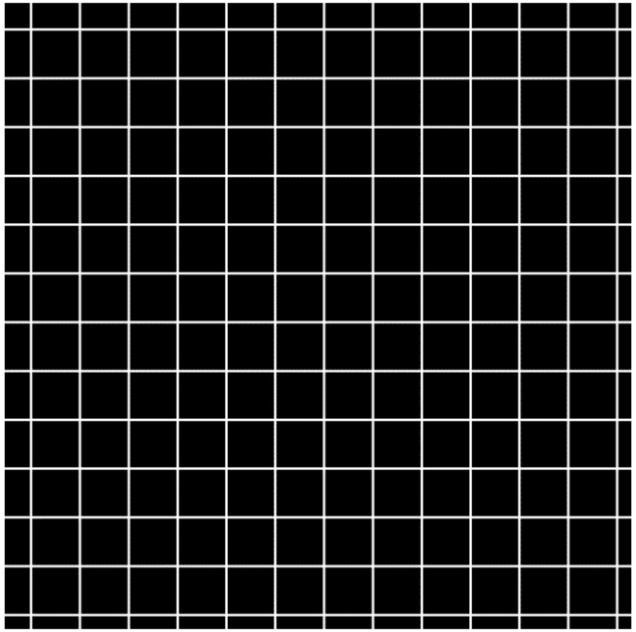
Correspondence function φ, illustration



$$\begin{bmatrix} x_b \\ y_b \end{bmatrix} = \varphi\left(\begin{bmatrix} x_a \\ y_a \end{bmatrix}\right)$$

Image warping, illustration, 0 %

Deformation grid



Brain image warping

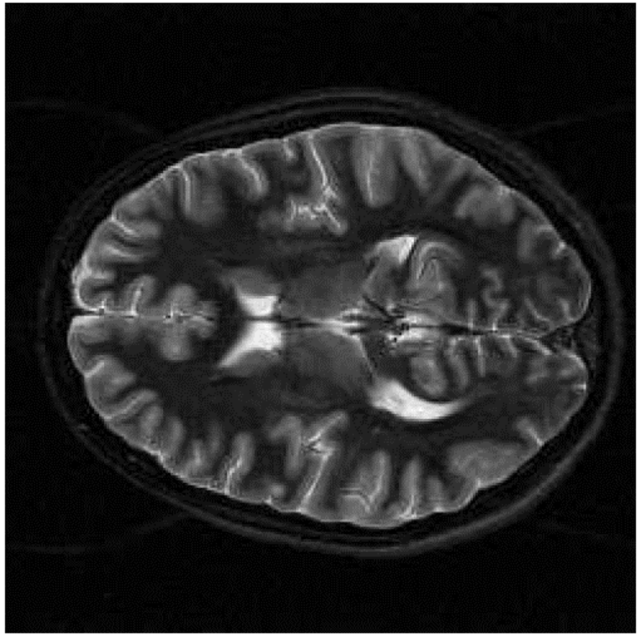
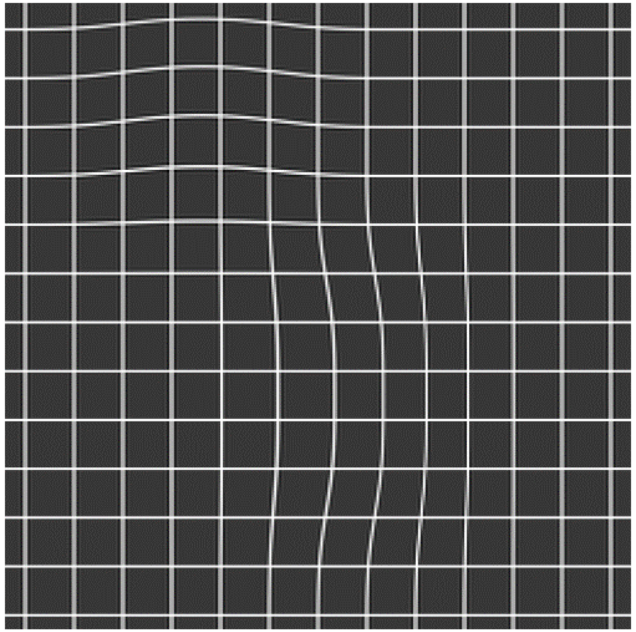


Image warping, illustration, 25 %

Deformation grid



Brain image warping

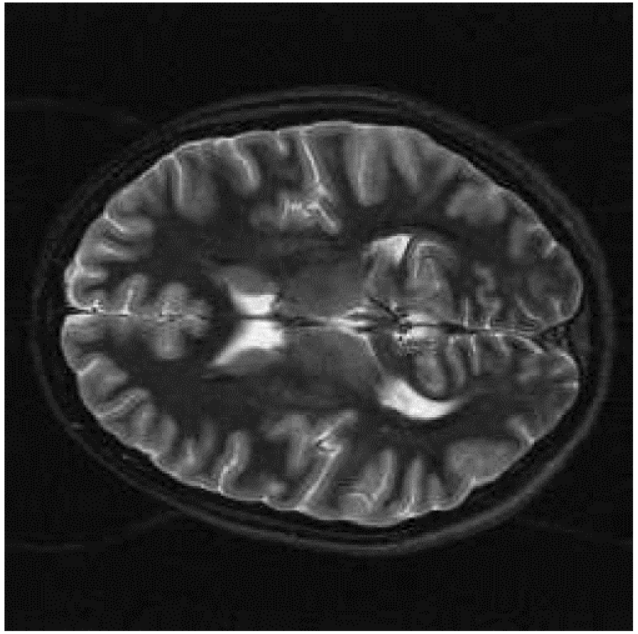
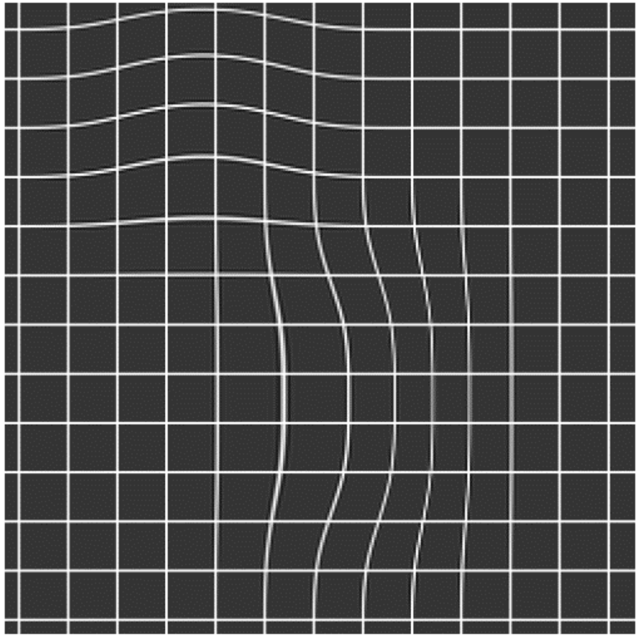


Image warping, illustration, 50 %

Deformation grid



Brain image warping

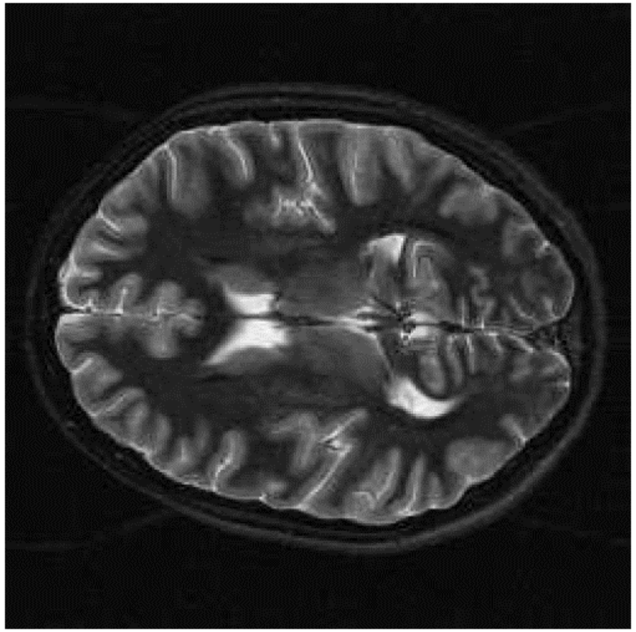
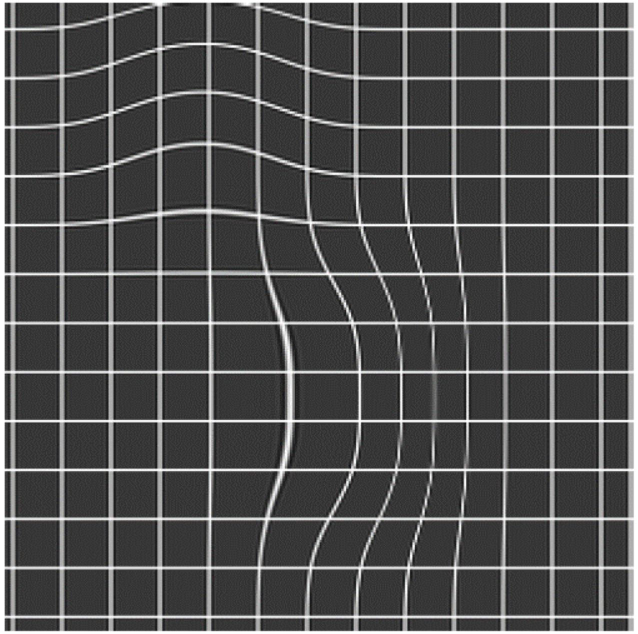


Image warping, illustration, 75 %

Deformation grid



Brain image warping

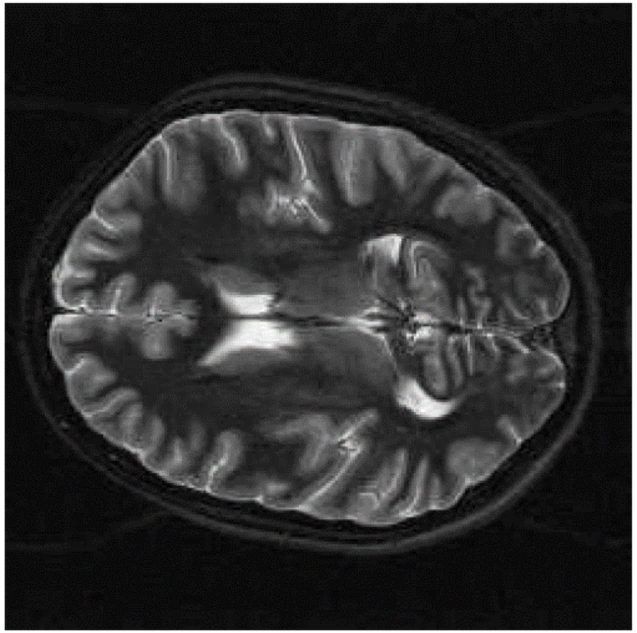
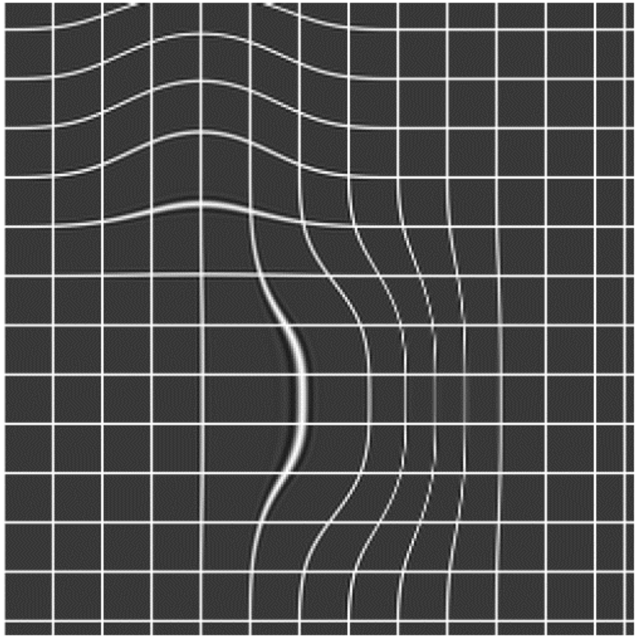


Image warping, illustration, 100 %

Deformation grid



Brain image warping

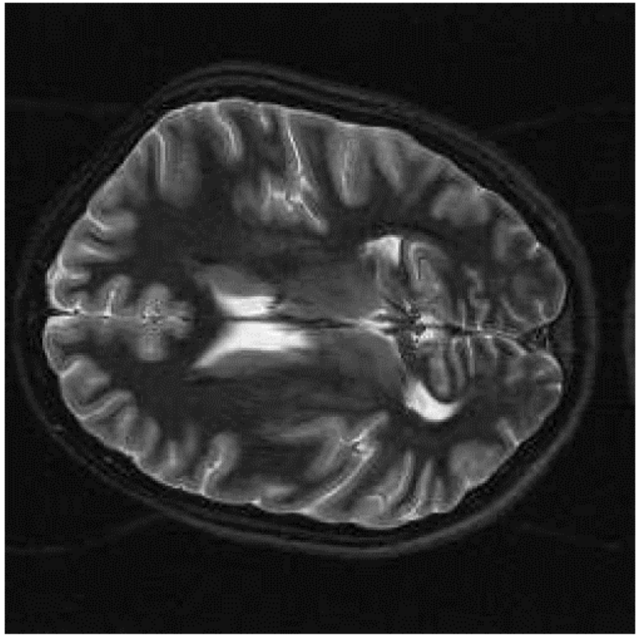
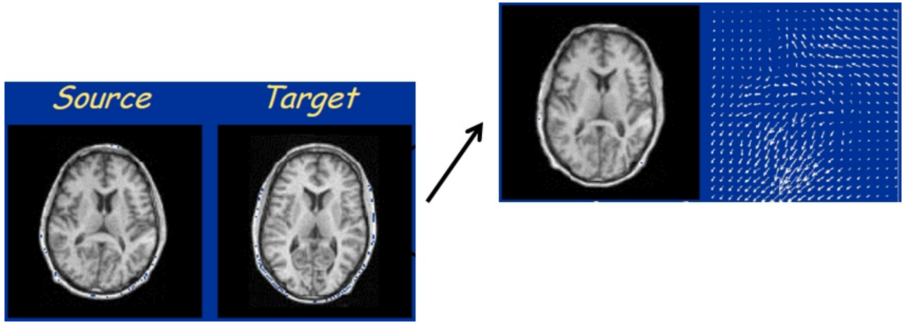


Image registration, the lecture plan

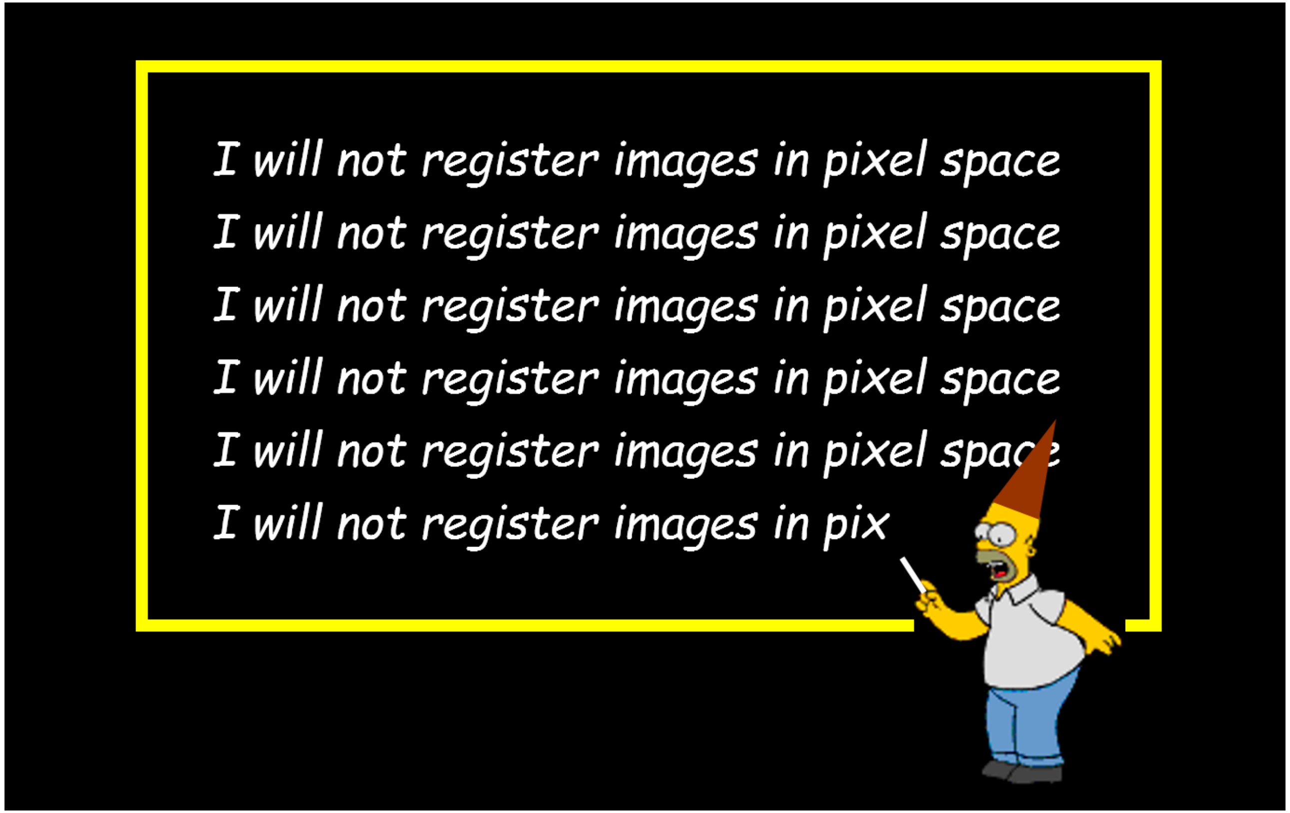
- Image registration: What is it? Motivation.
- Medical imaging examples.
- Image registration, (ill-posed) task formulation, flowchart, 3 steps, rigid vs. non-rigid registration.
- Image registration: intensity-based; landmark-based, feature-based.
- Image similarity measure.
- Practical optimization (covered elsewhere).

Intensity-based image registration methods

- These are based on pointwise comparisons between pixels in the reference and the target image. This is performed by a sliding local window.
- Prior preprocessing of the images as denoising, edge filters, interest point filters can be used where appropriate.
- Correspondence is based on (di)similarity measures as
  - Mean squared error (MSE) = Sum of squared differences (SSD). *Dissimilarity.*
  - Normalized cross-correlation. *Similarity.*
  - Mutual information. *Similarity.*

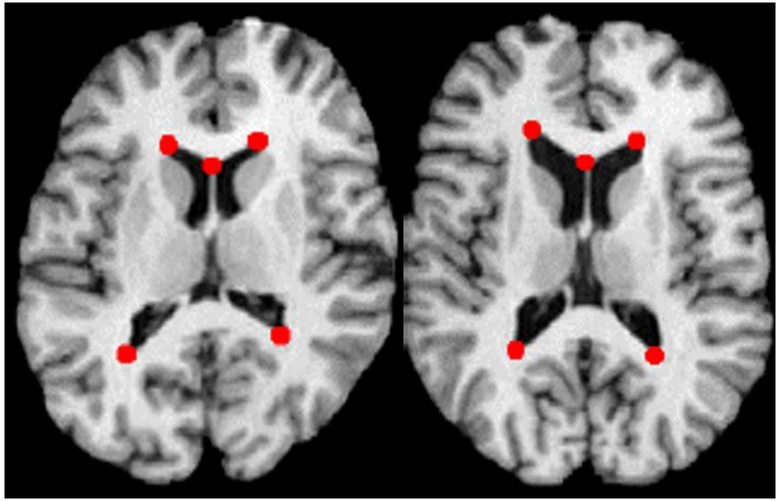


Practitioner's advice, if possible



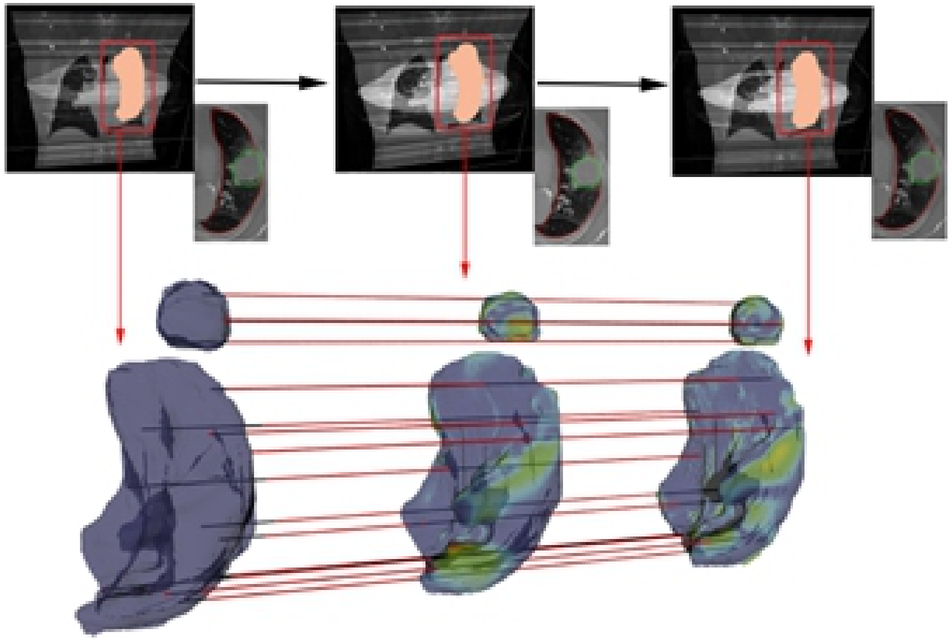
Landmark-based image registration methods

- Manually defined landmarks serve to infer the deformation.
- Landmarks
  - Extrinsic landmarks, artificial objects attached to, e.g., a patient.
  - Intrinsic landmarks, e.g. obvious anatomical structures.
- Translation is estimated from landmark centroids shifts.



Feature-based image registration methods

- Correspondence is sought automatically between image features as interest points, regions, lines, contours.
- Similarity metric between feature values is needed.



Free-form deformations

- The general idea is to deform an image by manipulating a regular grid of control points that are distributed across the image at an arbitrary mesh resolution.
- Control points can be moved and the position of individual pixels between the control points is approximated from the positions of surrounding control points.

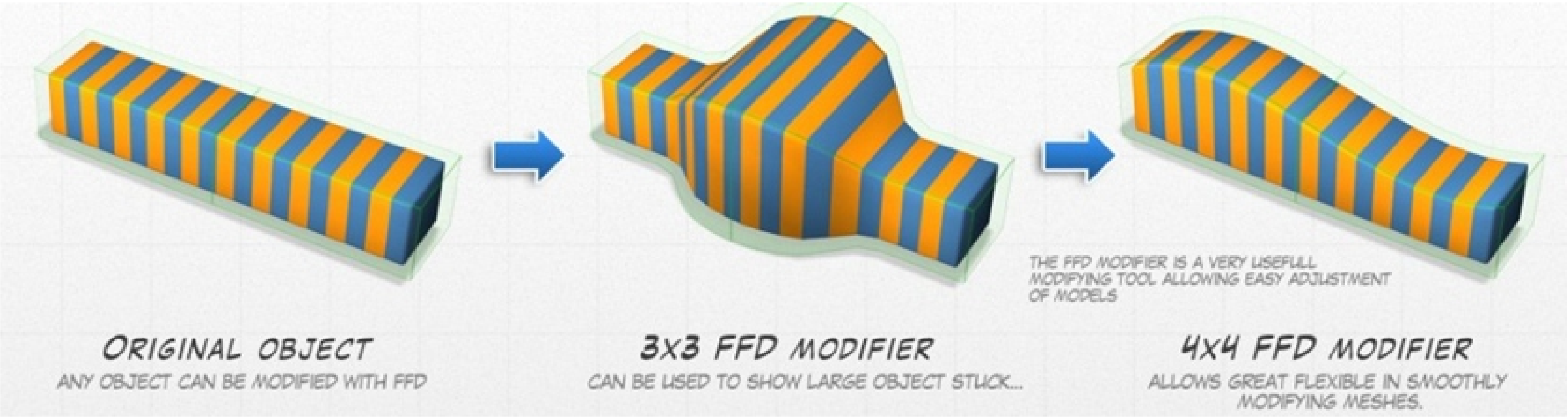


Image registration, the lecture plan

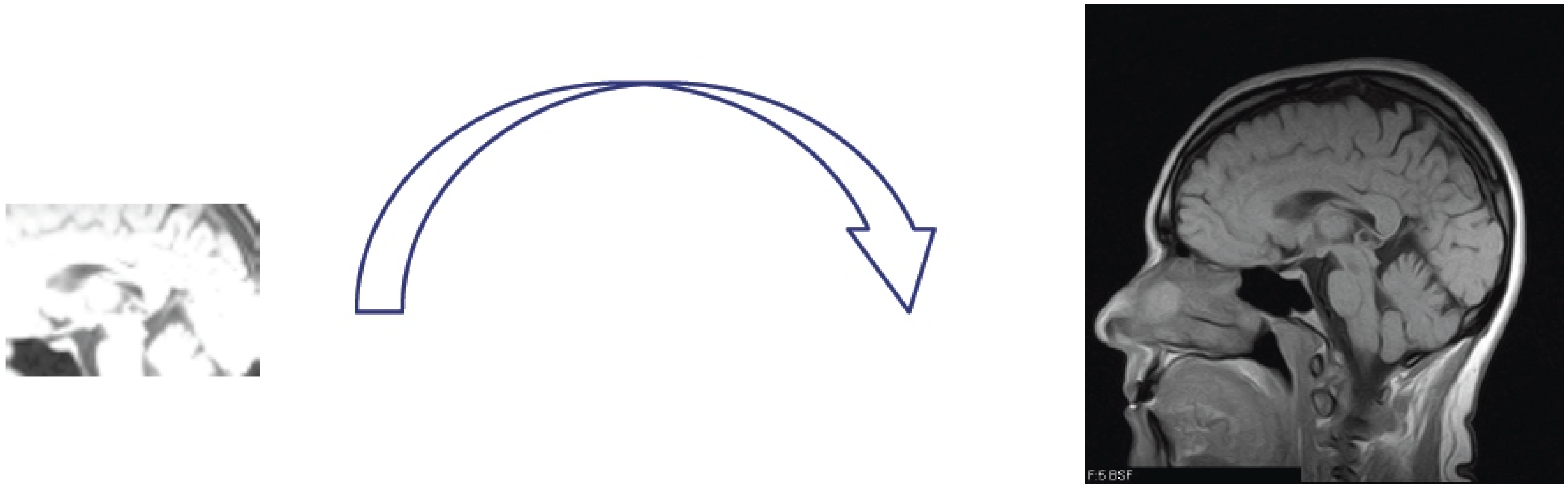
- Image registration: What is it? Motivation.
- Medical imaging examples.
- Image registration, (ill-posed) task formulation, flowchart, 3 steps, rigid vs. non-rigid registration.
- Image registration: intensity-based; landmark-based, feature-based.
- Image similarity measure.
- Practical optimization (covered elsewhere).

Mean squared error

- Mean squared error $MSE = \sum_{x,y}(I_a(x,y) - I_b(x,y))^2$
- Advantages:
  - Simple and intuitive.
  - Positive differences do not cancel negative differences.
  - Ensures exact intensity matching.
- Disdvantages:
  - Sensitivity to outliers.
  - Linear mean squares will not be the best fit for data that is not linear.
  - Images must have almost the same brightness and contrast.
  - Does not work if modalities differ.

Correlation coefficient (1)

- How can this template be found in the image?



- Linear intensity changes are common in practice.
- Mean squared error (MSE) may not work in such cases. The correlation does.

Correlation coefficient (2)

The (Pearson's) correlation coefficient ρ of the two random variables is the covariance of two variables divided (normalized) by their standard deviations σ.

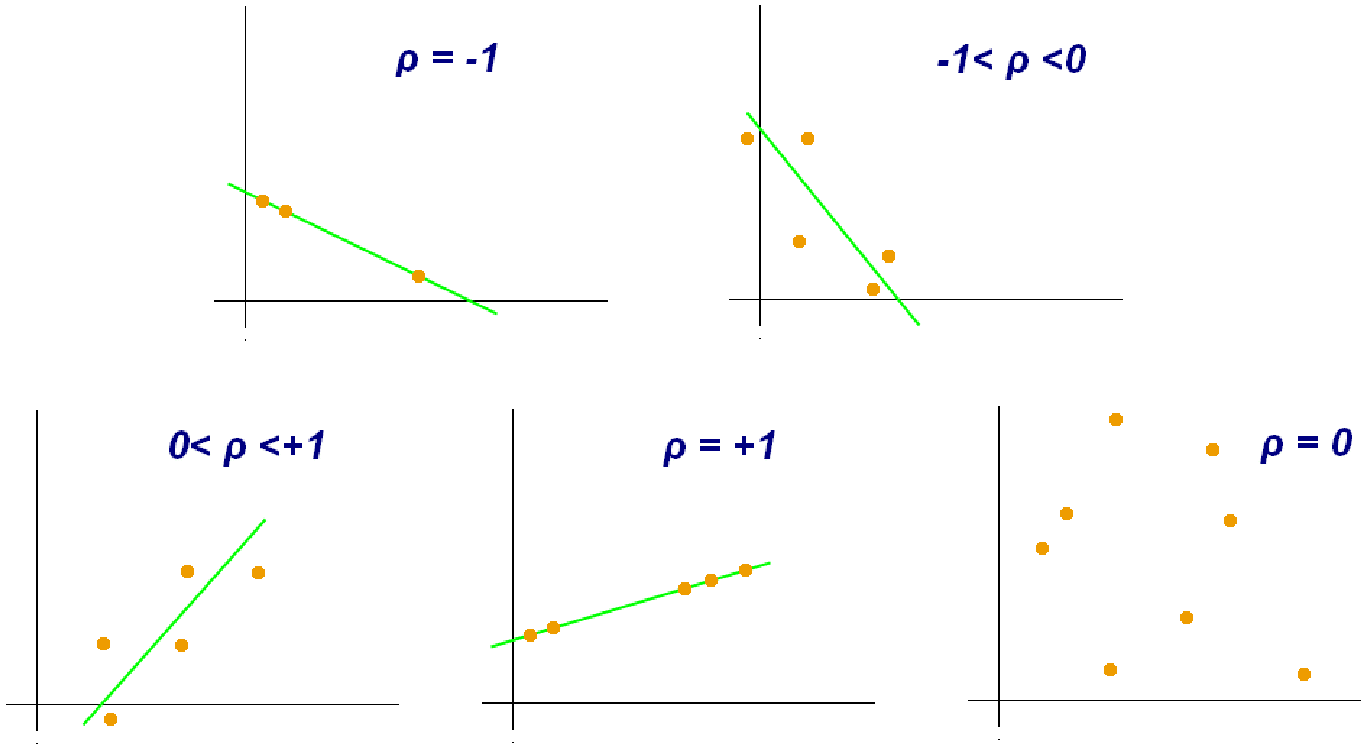
In the case of images I_a (the reference image) and I_b (the target image),

$$\rho = \frac{E((I_a - \mu_a)(I_b - \mu_b))}{\sigma_a \, \sigma_b},$$

where E expresses the expectation of a probability distribution and μ is the population mean. If f is the discrete probability density of the distribution X then

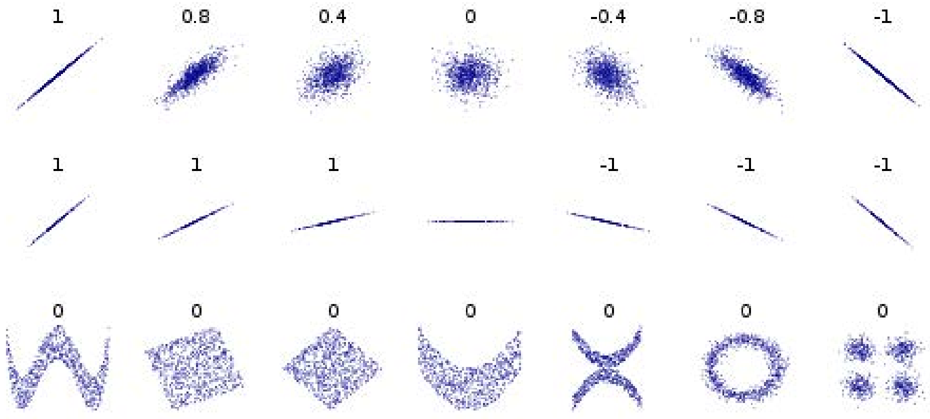
$$E(X) = \sum_{x \in X} x \, f(x)$$

Correlation coefficient (3)



Examples of scattered diagrams with different values of the correlation coefficient σ. Source Wikipedia.

Correlation coefficient (4)



Several sets of (x, y) points, with the correlation coefficient of x and y for each set. Note that the correlation reflects the non-linearity and direction of a linear relationship (top row), but not the slope of that relationship (middle row), nor many aspects of nonlinear relationships (bottom row).

N.B.: The figure in the center column has a slope of 0 but in that case the correlation coefficient is undefined because the variance of Y is zero.

Source Wikipedia.

Correlation coefficient (5)

- Advantages:
  - Corrects for linear intensity changes, which is common in practice.
  - It is efficient to evaluate.
  - Can be generalized to non-scalar signals using the “Canonical Correlation Analysis”, see overview paper, tutorial.
- Disdvantages:
  - There is the underlying assumption about Gaussian distributions due to the Central limit theorem.
  - Does not work for (very) different modalities.

Mutual information (1)

- The mutual information of two discrete random variables X and Y is based on the joint probability distribution $p(X, Y)$, which is approximated by the joint histogram in practice.
- The mutual information is defined as

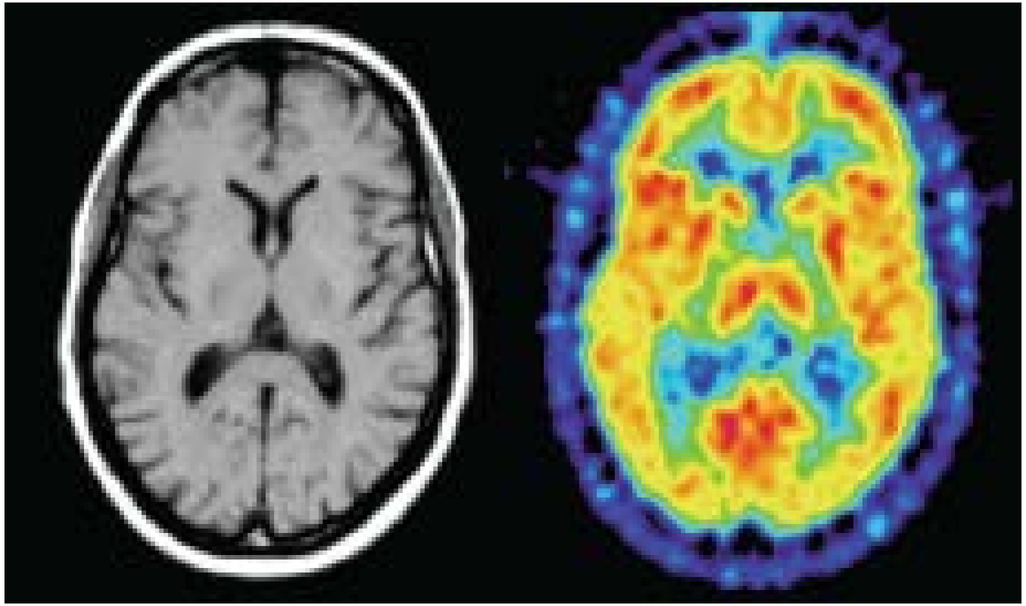
$$I(X;Y) = \sum_{y \in Y} \sum_{x \in X} p(x,y) \log \left(\frac{p(x,y)}{p(x)\, p(y)} \right) ,$$

where $p(x)$, $p(y)$ are marginal probability density functions.

- The mutual information measures the information that X and Y share. It tells how much knowing one of these variables reduces uncertainty about the other.

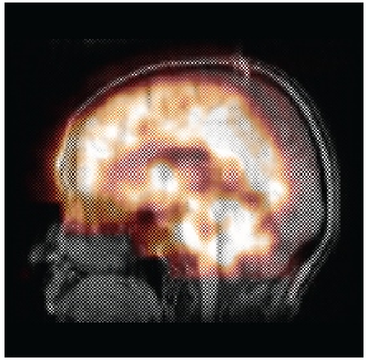
Mutual information (2), use for alignment

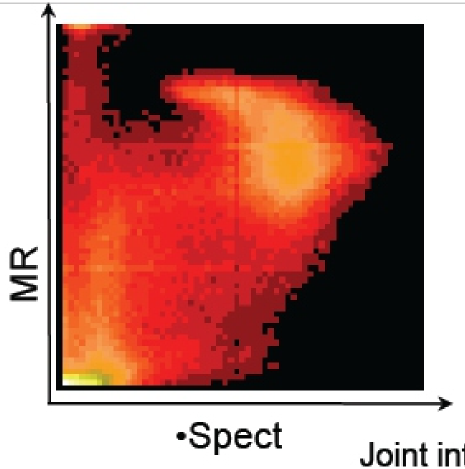
- The MI registration criterion states that the images I_a, I_b are geometrically aligned when $I(a, b)$ is maximal.
- For example, let I_a be an MR-scan (left in the figure) and I_b a SPECT-scan (right in the figure). If we know the MR intensities, the uncertainty of the SPECT intensities is minimal when the scans are aligned.



Mutual information (3), MR and Spect alignment

Before registration

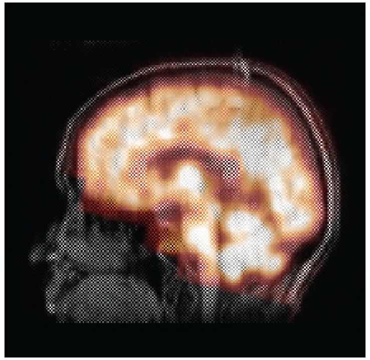


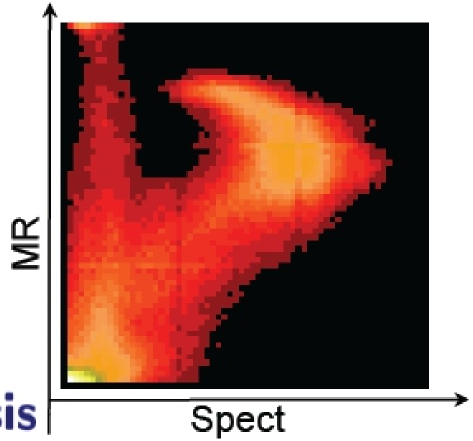


Joint intensity histogram

MI = 0.357

After registration





MI = 0.446

Analysis

Mutual information (4)

- Advantages:
  - Rather general approach.
  - Works for different modalities.
  - Works for non-scalar signals, e.g. RGB images.
- Disdvantages:
  - Can be tricky to implement.
  - Slower evaluation as compared to MSE and correlation.

Image registration, the lecture plan

- Image registration: What is it? Motivation.
- Medical imaging examples.
- Image registration, (ill-posed) task formulation, flowchart, 3 steps, rigid vs. non-rigid registration.
- Image registration: intensity-based; landmark-based, feature-based.
- Image similarity measure.
- Practical optimization (covered elsewhere). Most commonly, the gradient descent method.