Registration and Its Medical Applications

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Syllabus

- Registration problem
  - Definitions, examples
  - Main components
- Medical image registration
  - Modalities (X-ray, US, MR, CT, PET, SPECT)
  - Applications
- Registration methods
  - Point-based methods
  - Surface fitting methods
  - Automatic methods
- Computer integrated surgery

Image Registration

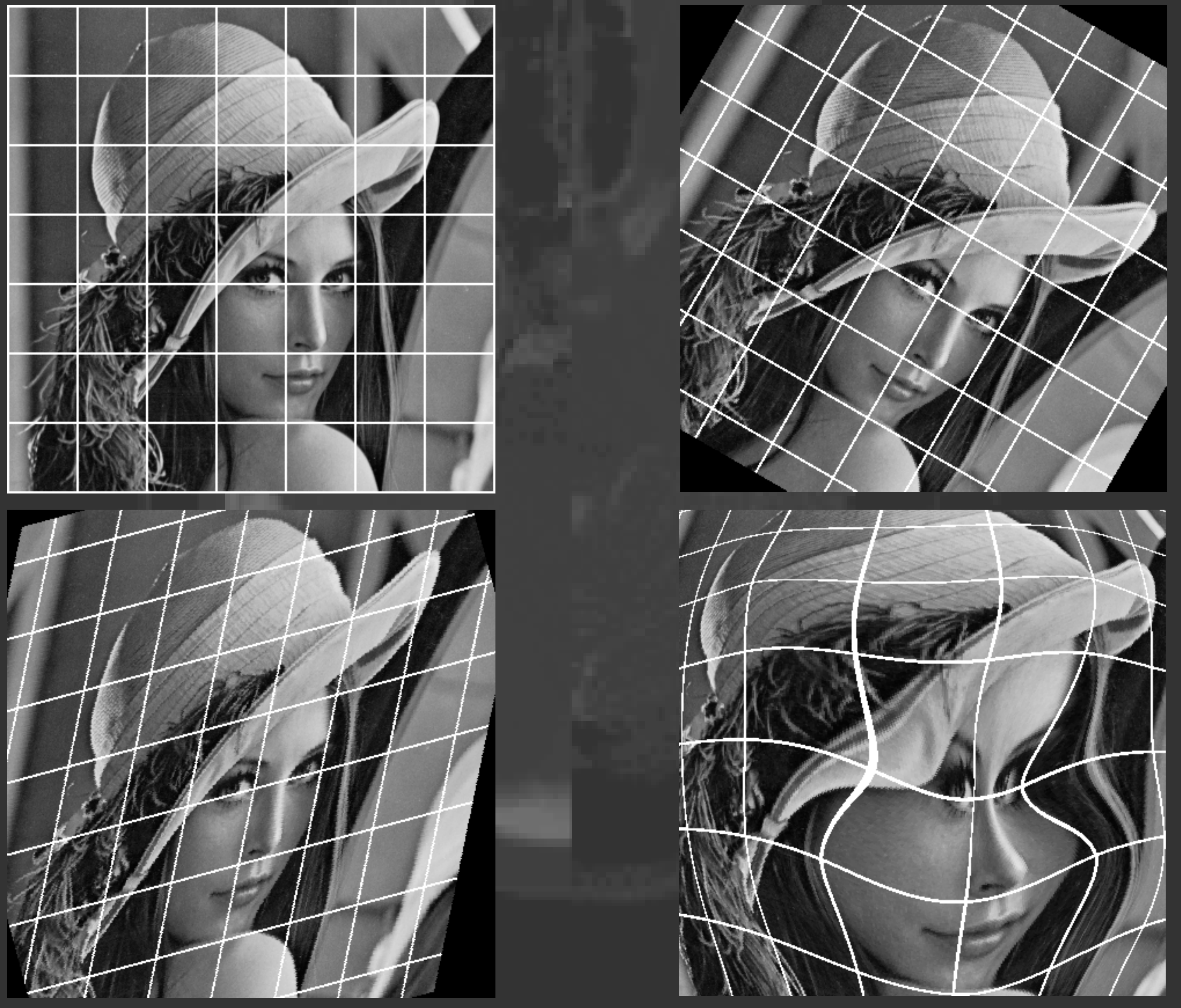
Task:

To find geometrical correspondence between images.

Terms:

- *image registration*
- *image matching*
- *image fusion*

Image Transformations

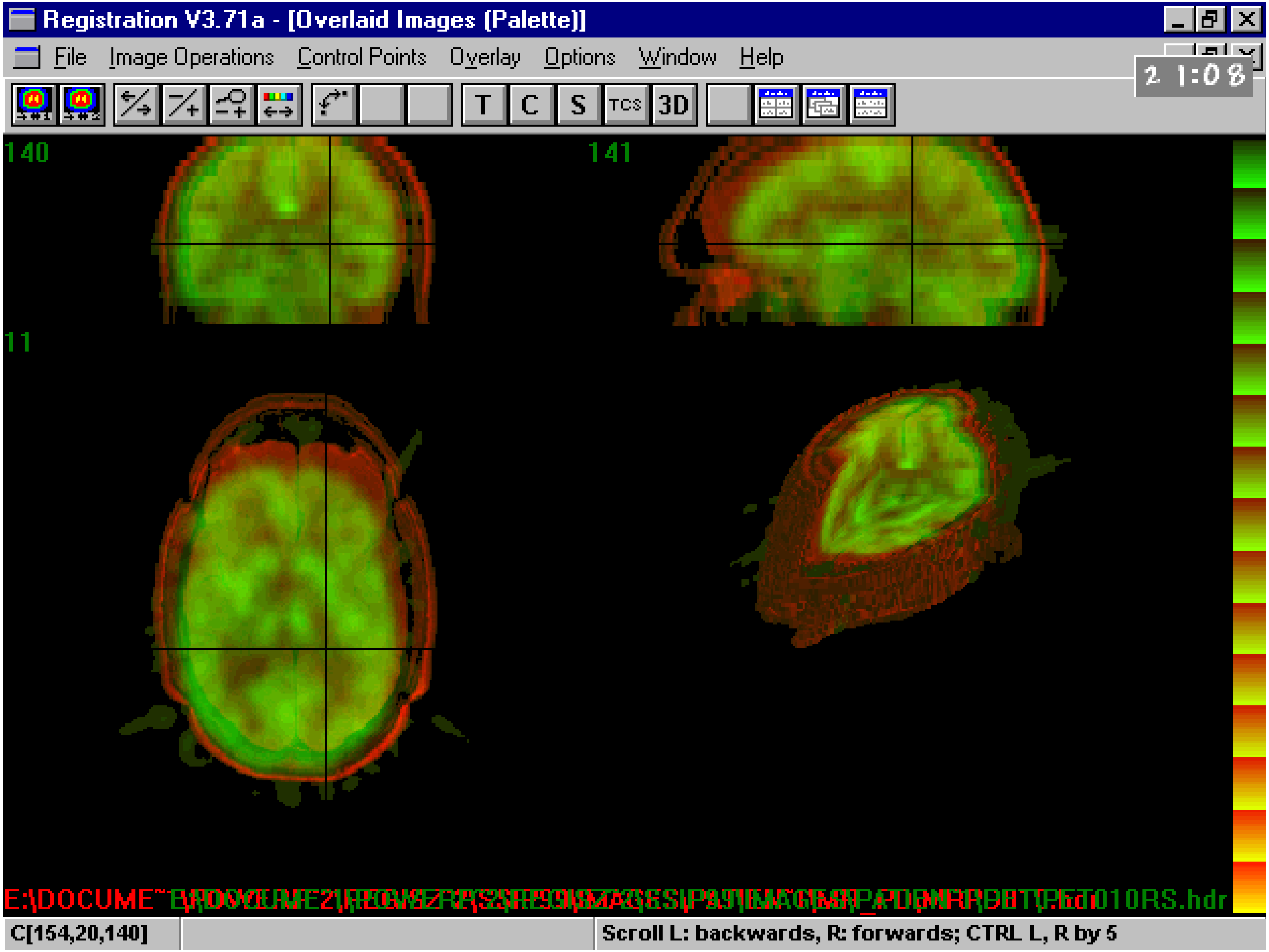


Registration (General)

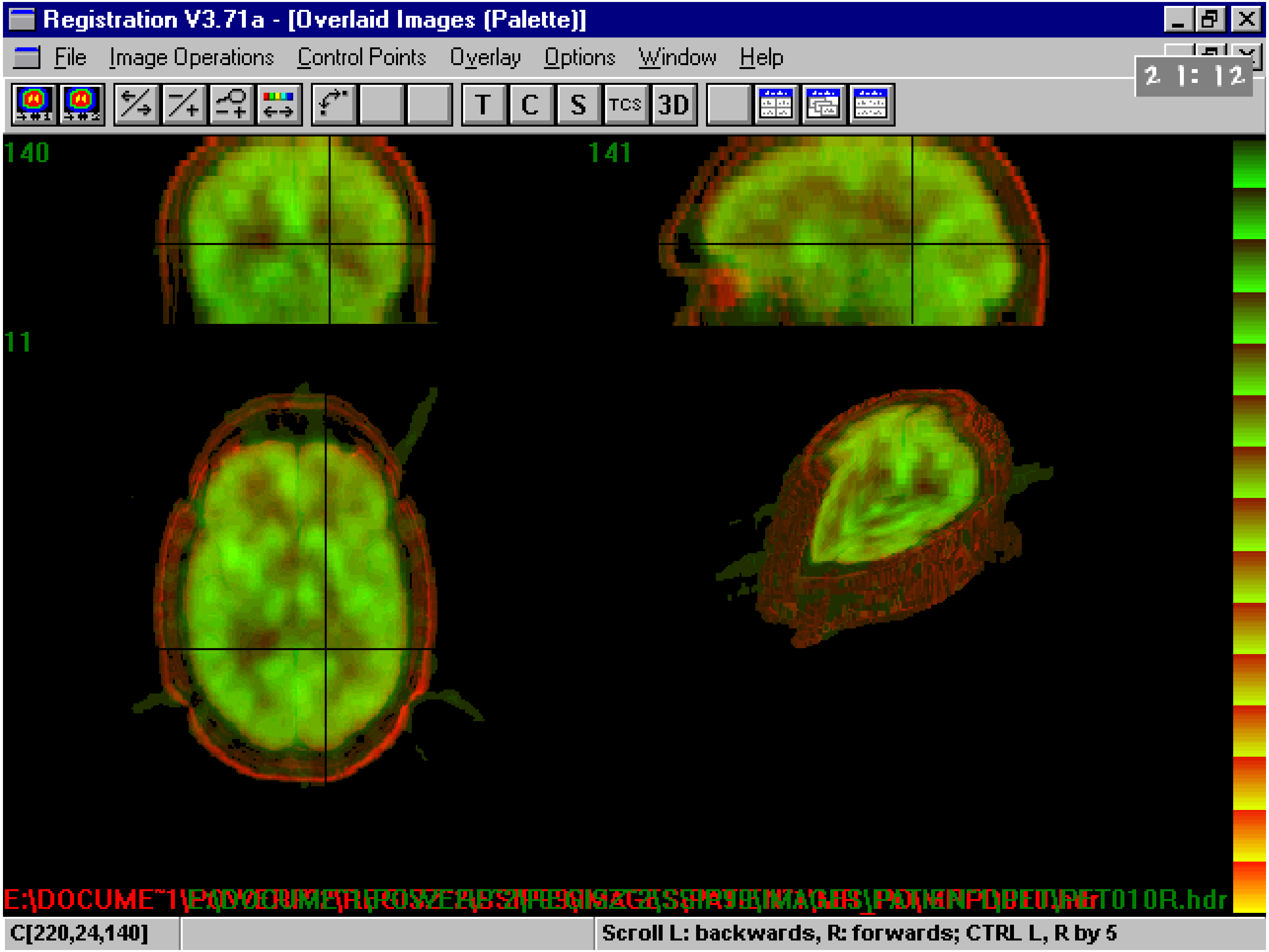
Task:

Combine (spatial) *information contents* coming from the same or different *sources*.

- Images,
- 2-D or 3-D models of objects,
- Spatial positions.



Registration V3.71a - [Overlaid Images (Palette)]
File Image Operations Control Points Overlay Options Window Help
2 1:08
T C S TCS 3D
140
141
11
C[154,20,140]
Scroll L: backwards, R: forwards; CTRL L, R by 5


Registration V3.71a - [Overlaid Images (Palette)]
File
Image Operations
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Scroll L: backwards, R: forwards; CTRL L, R by 5

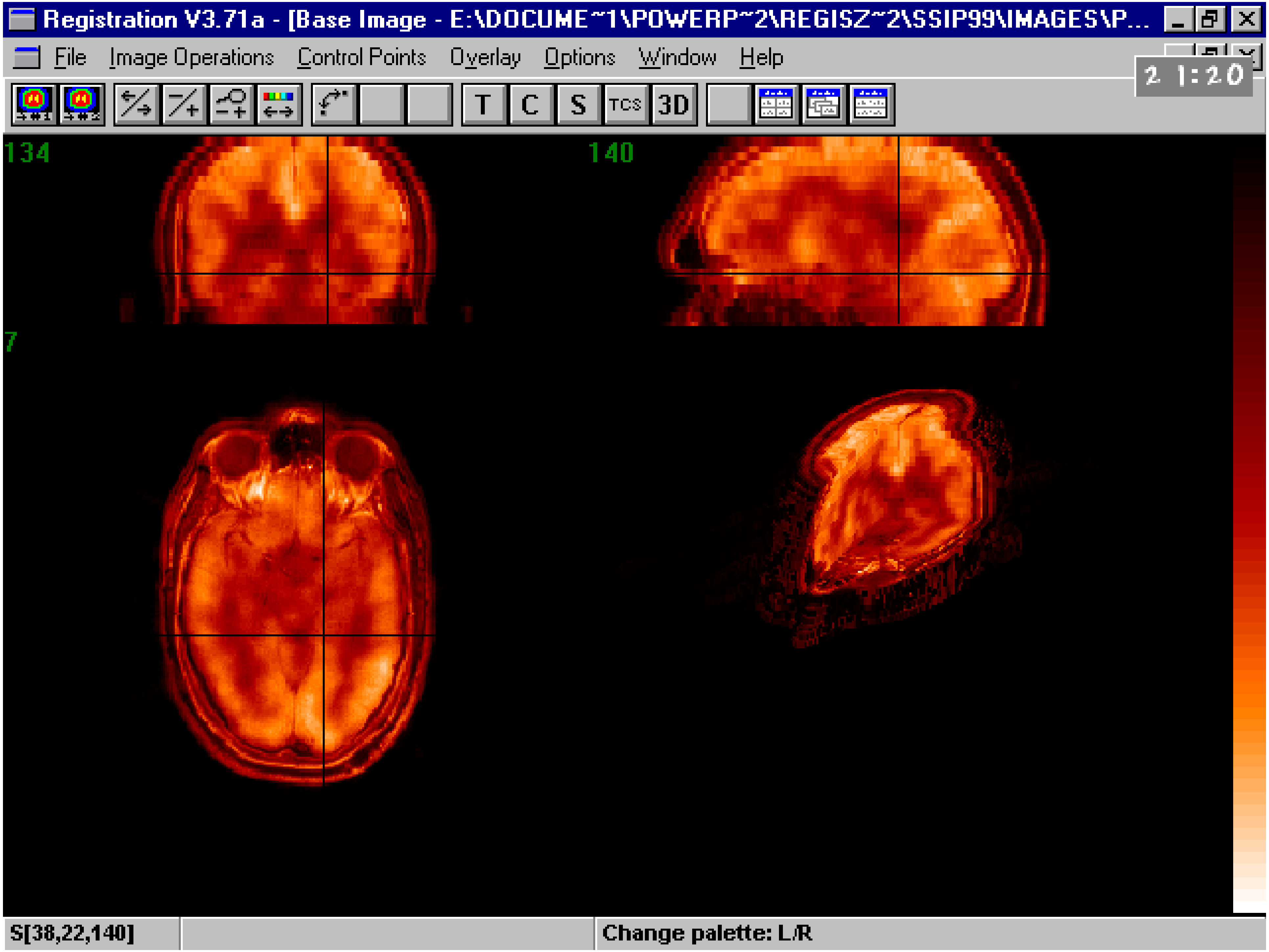

Registration V3.71a - [Base Image - E:\DOCUME~1\POWERP~2\REGISZ~2\SSIP99\IMAGES\P...
File Image Operations Control Points Overlay Options Window Help
2 1:20
T C S TCS 3D
134
140
7
S[38,22,140]
Change palette: L/R

Image Mosaicking

Vision Research Lab, UCSB

Vision Research Lab, UCSB

Image Mosaicking

Vision Research Lab, UCSB

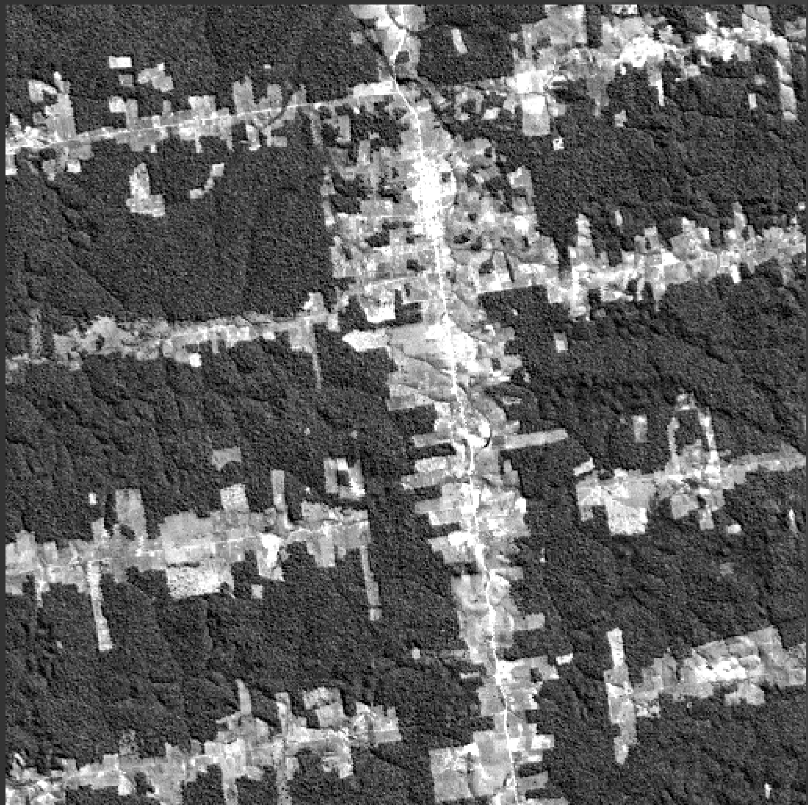
Image Mosaicking

A.A. Goshtasby

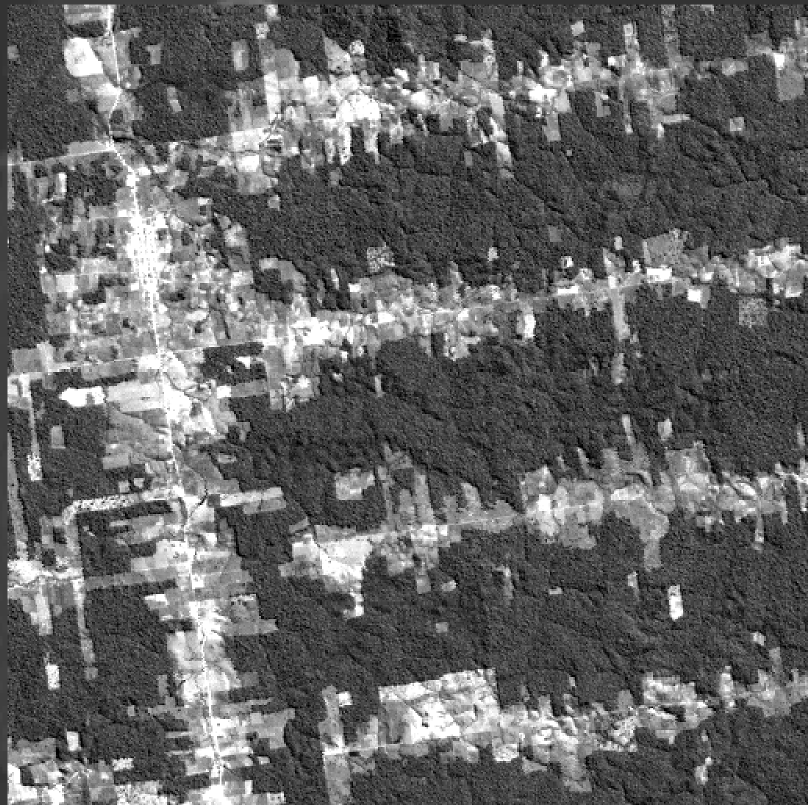
Image Mosaicking

A.A. Goshtasby

Amazonian Deforestation Progress



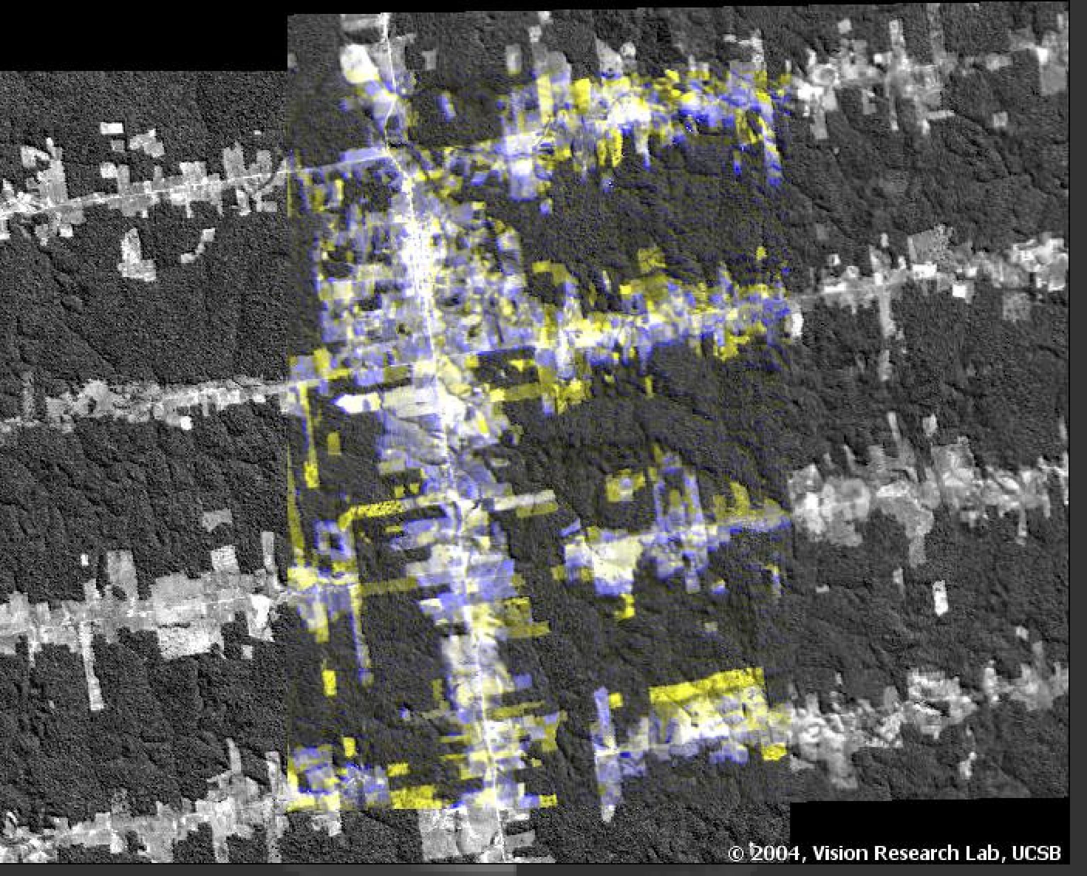
1992



1994

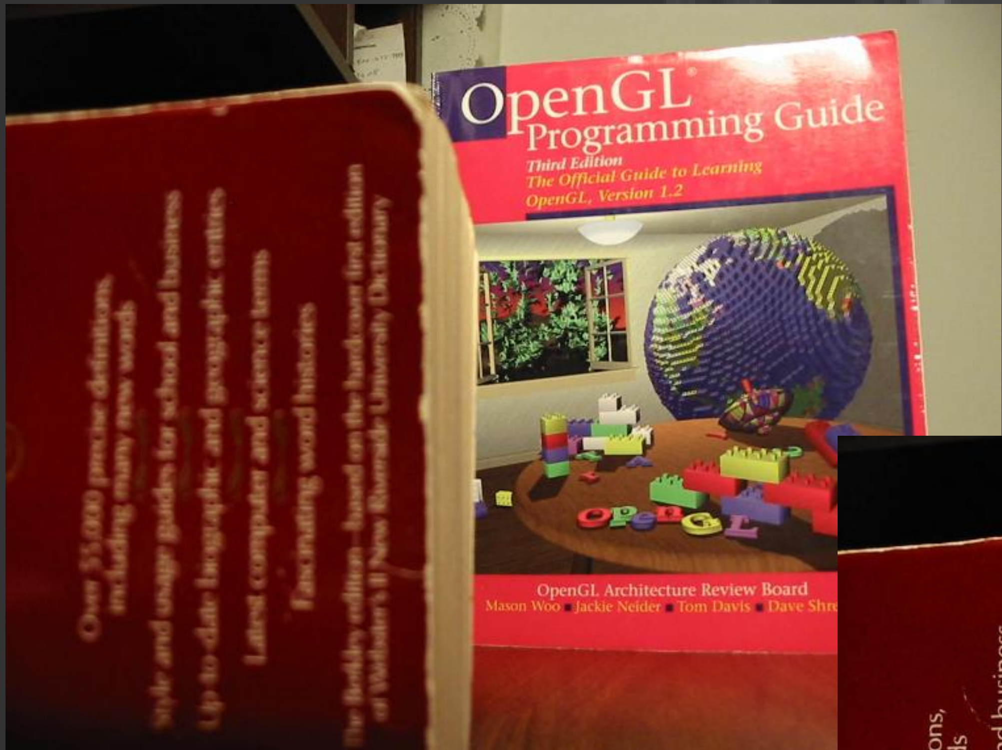
Vision Research Lab, UCSB

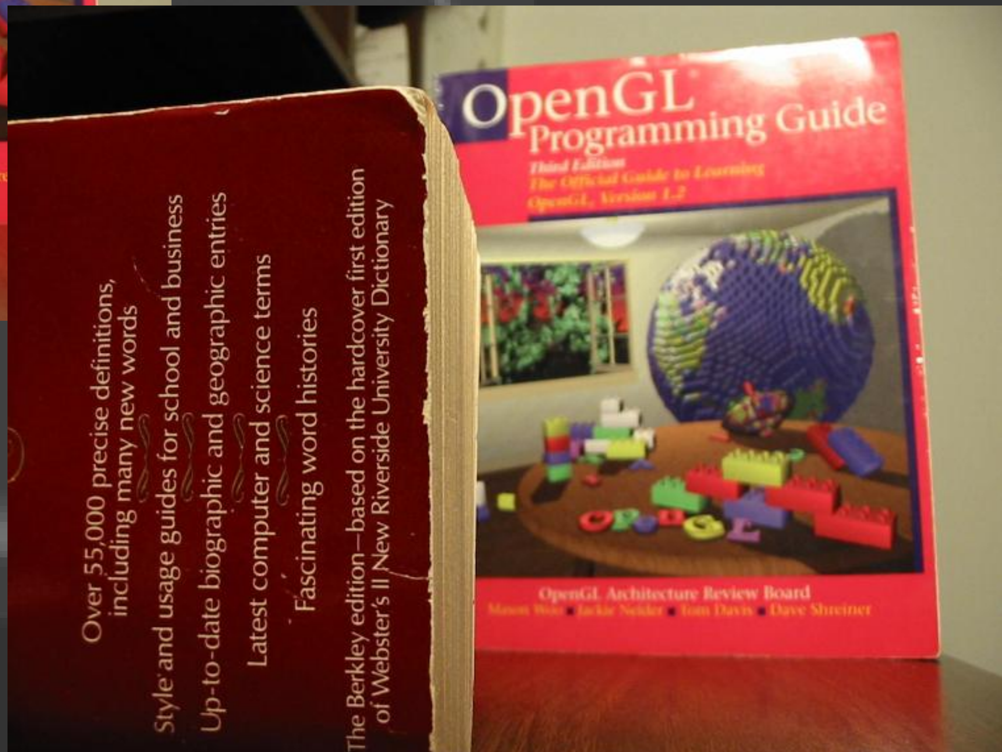
Amazonian Deforestation Progress



Vision Research Lab, UCSB

Multi-Focus Images





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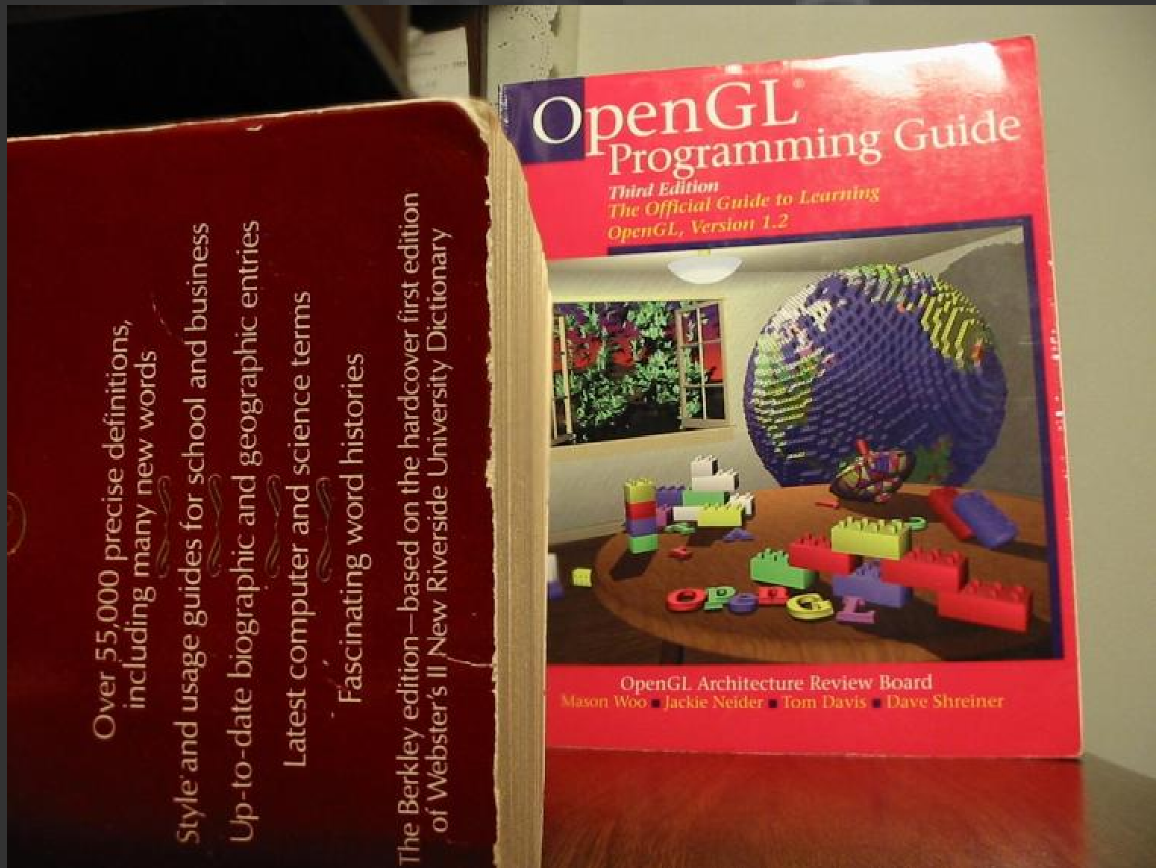
Multi-Focus Images



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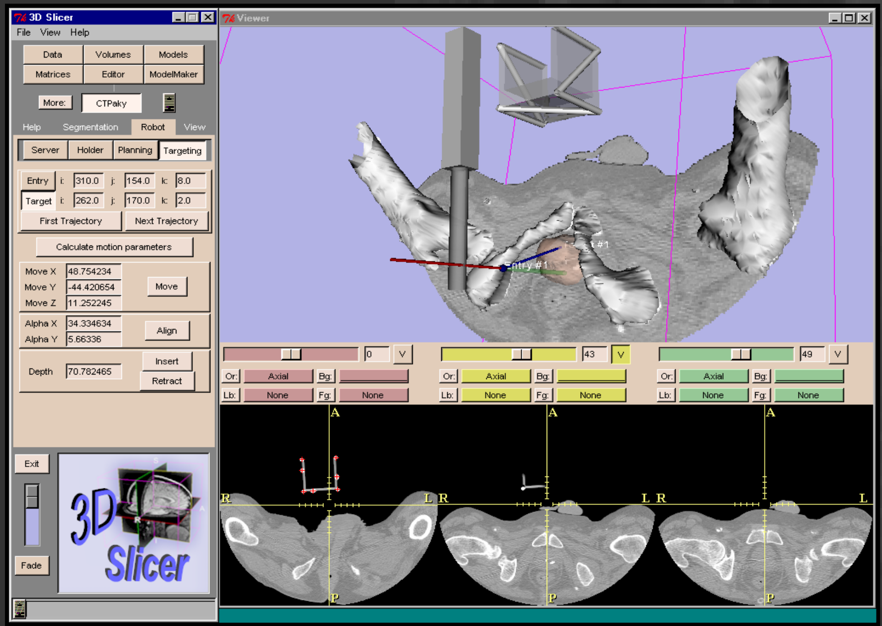
Surgery planning and execution

- Model - Modality
- Modality - Patient



Prostate biopsy project, Johns Hopkins University, Baltimore, MD, USA

Major research areas

- Computer vision and pattern recognition
  - segmentation, motion tracking, character recognition
- Medical image analysis
  - tumor detection, disease localization, classification of microscopic images
- Remotely sensed data processing
  - geology, agriculture, oceanography, oil and mineral exploration, forestry
- …

Variations Between Images

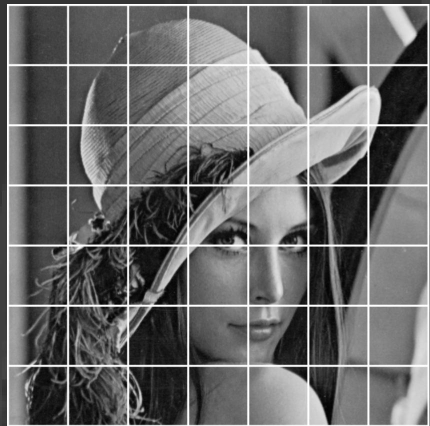
- Corrected distortions (easier)
  - Distortion which can be modeled (e.g. geometric differences due to viewpoint changes).
- Uncorrected distortions (medium)
  - Distortions which are difficult to model (e.g. lighting and atmospheric conditions, shadows).
- Variations of interest (harder)
  - Differences we would like to detect (e.g. Object movements or growth).

Main Components

- Search space
  - Type of geometric transformation.
- Feature space
  - What features to use to find the optimal transformation.
- Similarity measure
  - Defines how similar two images are.
- Search strategy
  - How to find the global optimum of the similarity measure.

Search Space

Original image



Rigid-body transformation

2D: 3 parameters
3D: 6 parameters

Affine transformation

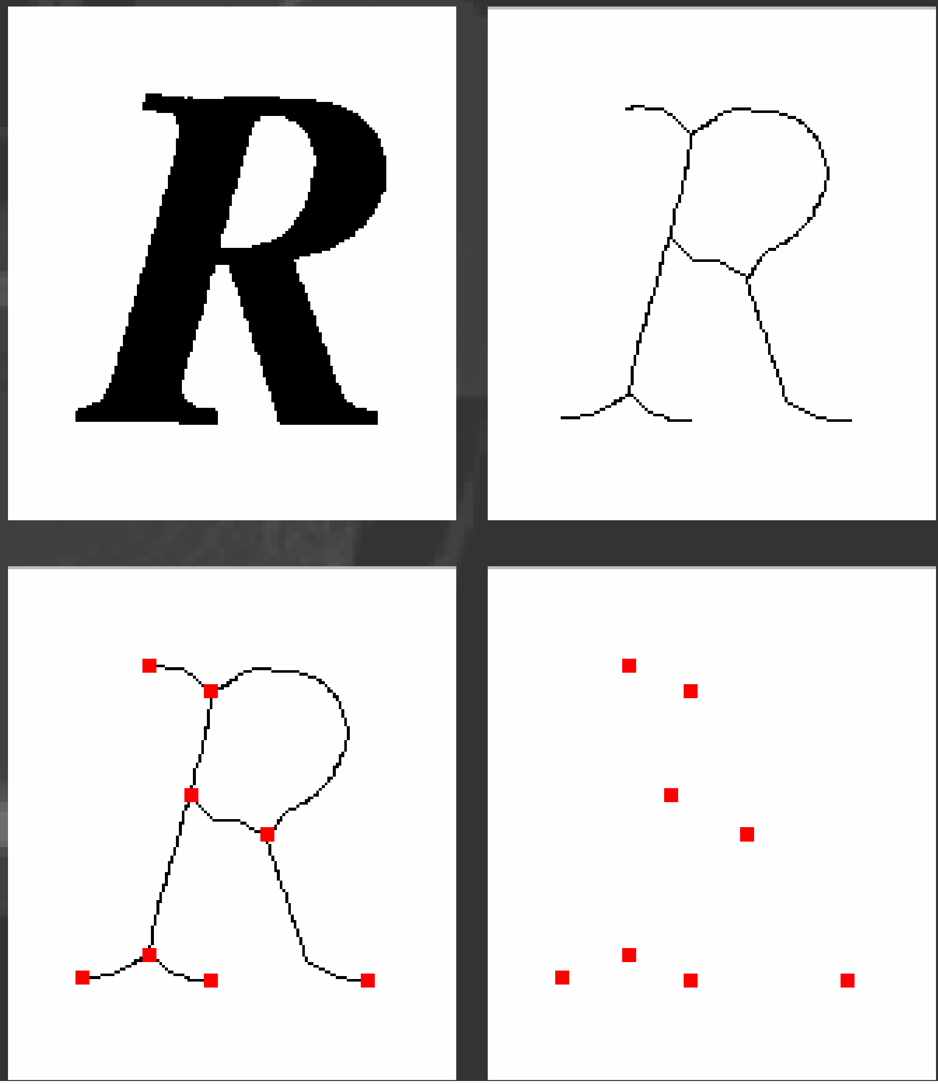
2D: 6 parameters
3D: 12 parameters

Nonlinear transformation

2D,3D: as many parameters as desired.

Feature Space

- Goal:
  - Reduce amount of data,
  - by extracting relevant features.
- Features:
  - Geometric (e.g. points, edges, surfaces).
  - Image intensities (e.g. the whole image).



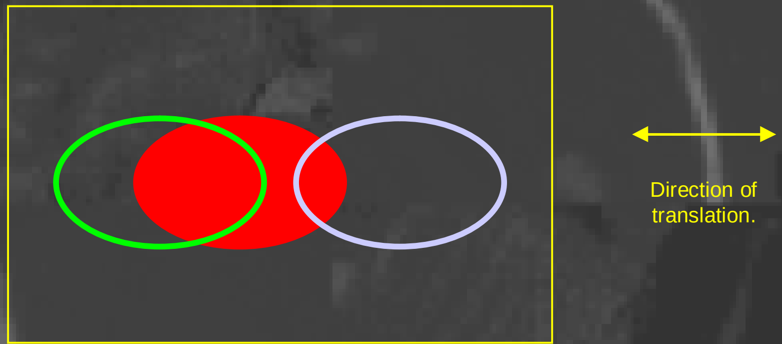
Similarity Measure

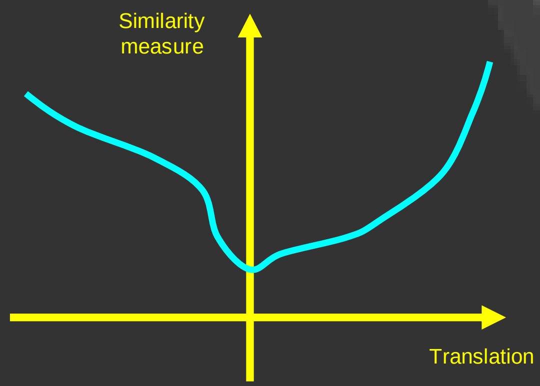
- Geometric features
  - Distance measures (e.g. minimization of Euclidean distance).

- Image intensity-based
  - Based on intensity differences (e.g. absolute/squared sum of intensity differences, sign changes of the difference image).
  - Correlation-based (cross-correlation, correlation coefficient).
  - Based on the co-occurrence matrix of the image intensities (e.g. joint entropy, mutual information).

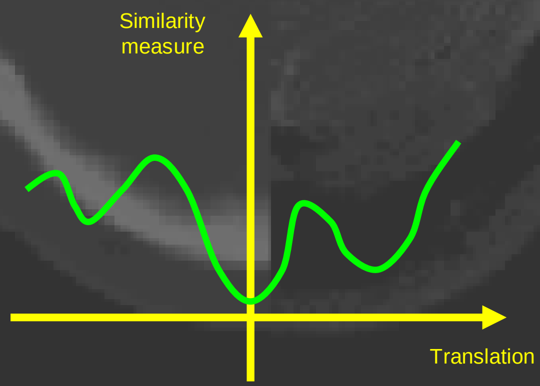
Similarity Measure

- Example: 1D transformation

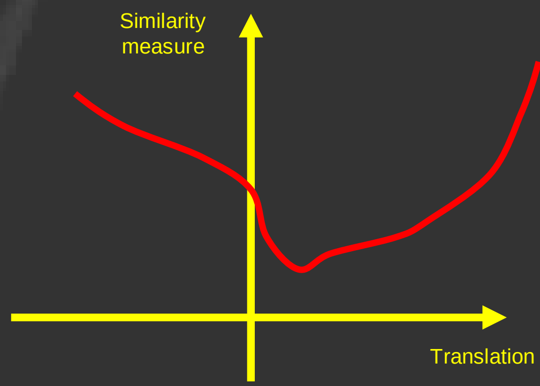




Good: global optimum at correct position, no other local optima.



Good but hard: many local optima, but the global one is at correct position.



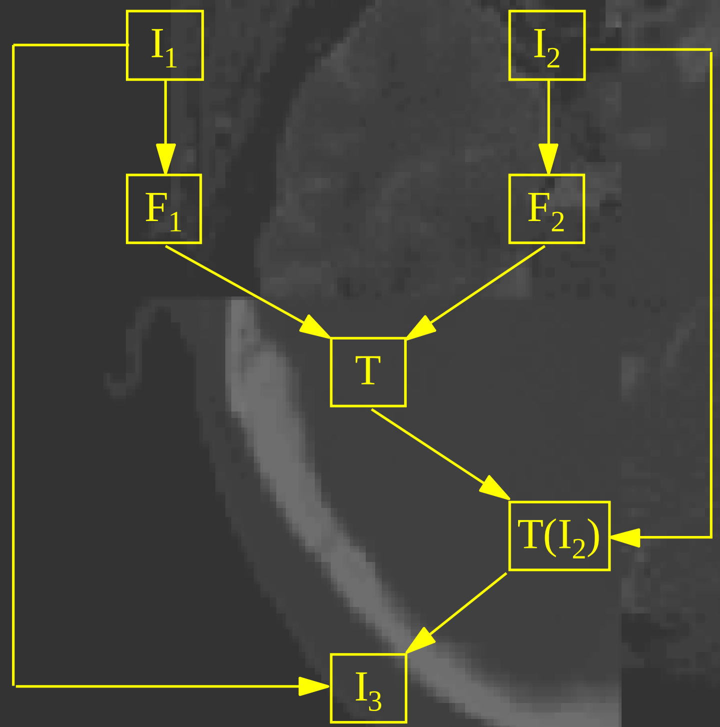
BAD: global optima at wrong position!

Search Strategy

- Direct methods
- ‘Coarse to fine’ search
- Multiresolution pyramid
- Dinamic programming methods
- Relaxation methods
- Heuristic search, genetic algorithms
- ...

Optimization is a bigger research field than registration itself!

Registration Process



Feature extraction

Determining the optimal transformation

Applying the transformation

Image fusion

Medical image registration

Matching all the data available for a patient

- provides better diagnostic capability,
- better understanding of data,
- improves surgical and therapy planning and evaluation.

Medical image registration

Potential medical applications

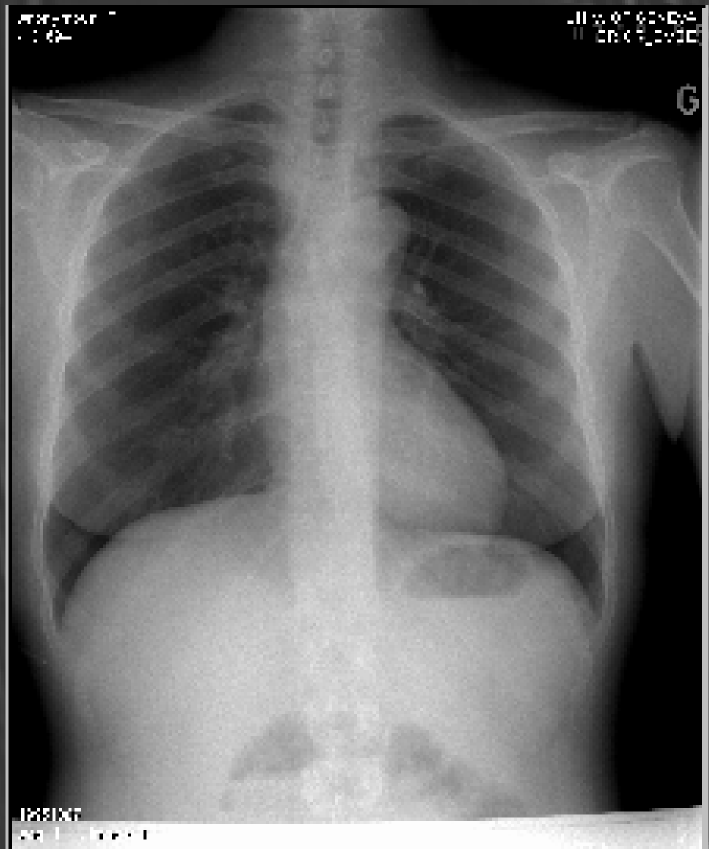
- Combining information from multiple imaging modalities (e.g., functional information to anatomy).
- Monitoring changes in size, shape, or image intensity over time intervals (few seconds to years).
- Relating preoperative images and surgical plans to the physical reality of the patient (image-guided surgery, treatment suite during radiotherapy).
- Relating an individual's anatomy to a standardized atlas.

Imaging Modalities

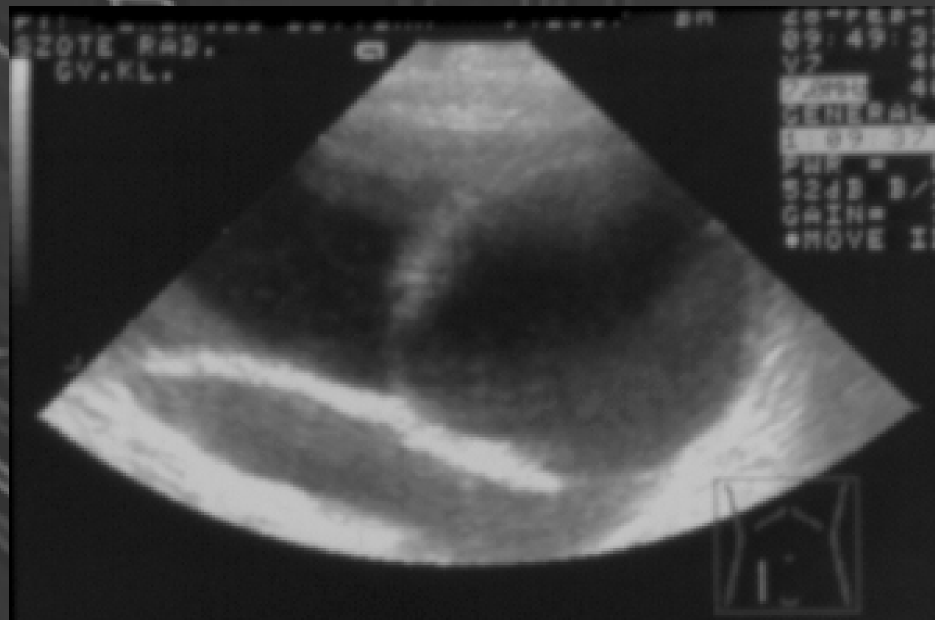
- 2D imaging
  - Anatomical
    - X-ray
    - US
  - Functional
    - Gamma camera
- 3D imaging
  - Anatomical
    - MR
    - CT
  - Functional
    - SPECT
    - PET

2D Imaging

X-ray



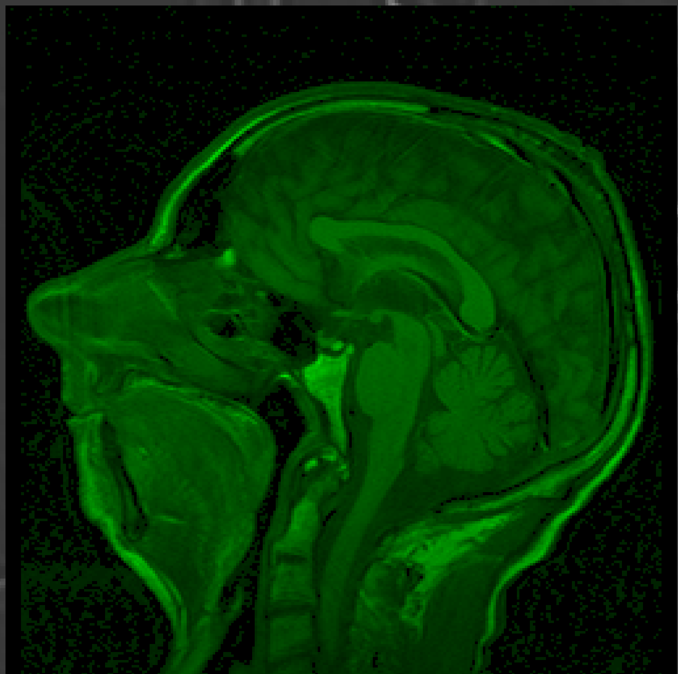
Ultrasound



3D Anatomical Imaging

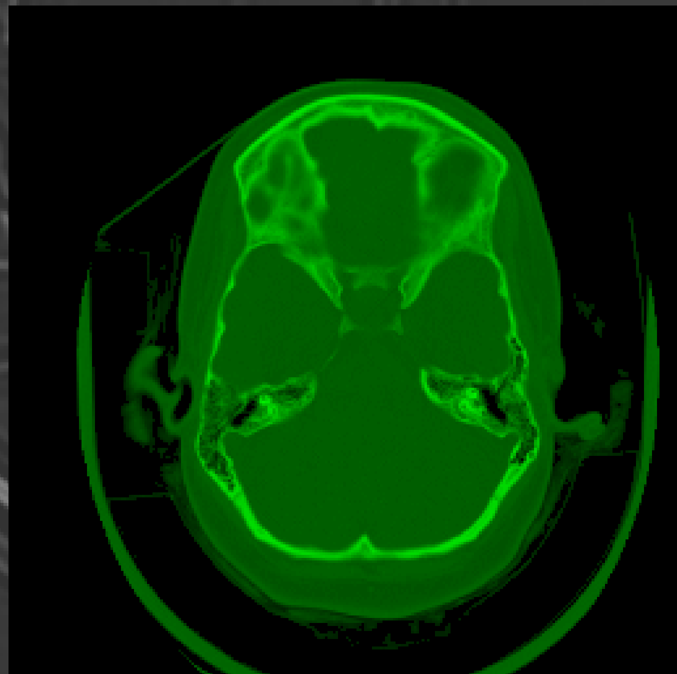
Magnetic Resonance

256x256



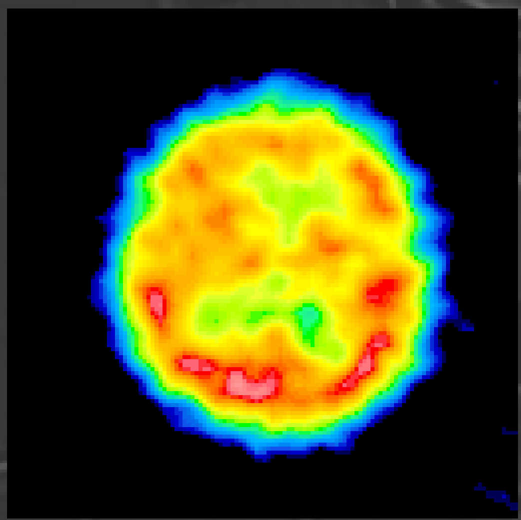
Computed Tomography

512x512

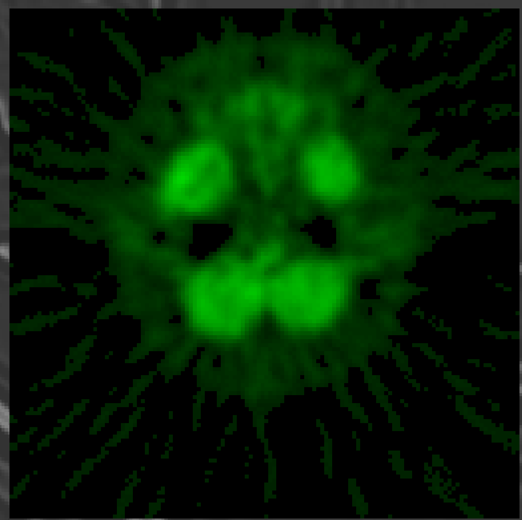


3D Functional Imaging

SPECT
(Single Photon Emission Computed Tomography)
64x64



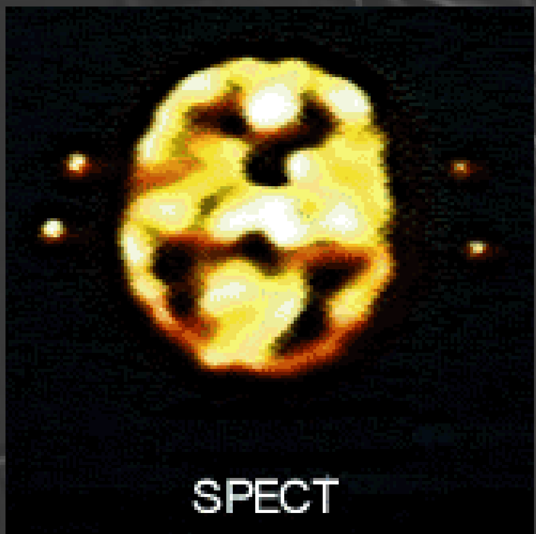
PET
(Positron Emission Tomography)
128x128



Type of Features

- Extrinsic (artificial)
  - Stereotactic frames
  - Head and dental fixation devices
  - Skin markers

Accurate, uncomfortable for the patient, non-retrospective.



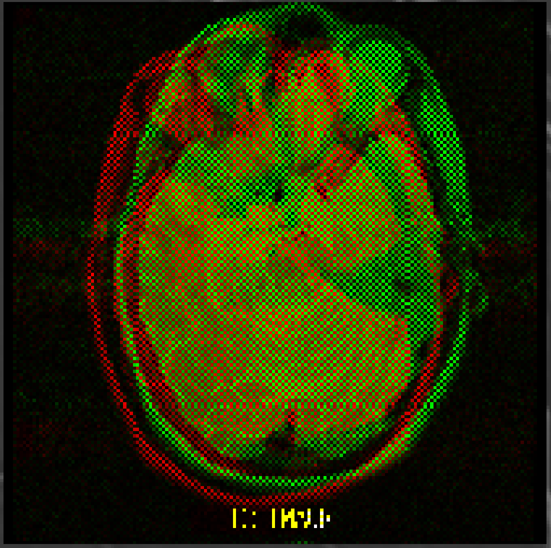
- Intrinsic
  - Anatomic areas (points, surfaces)
  - Geometric features
  - Image intensities

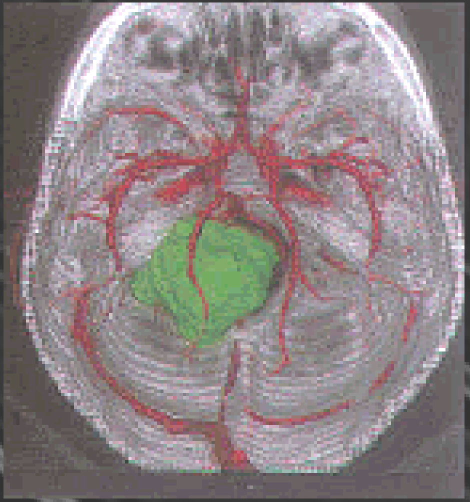
Accurate, comfortable, retrospective.

Modalities

- Unimodality
  - Time series
  - Different protocol settings
  - Atlas matching

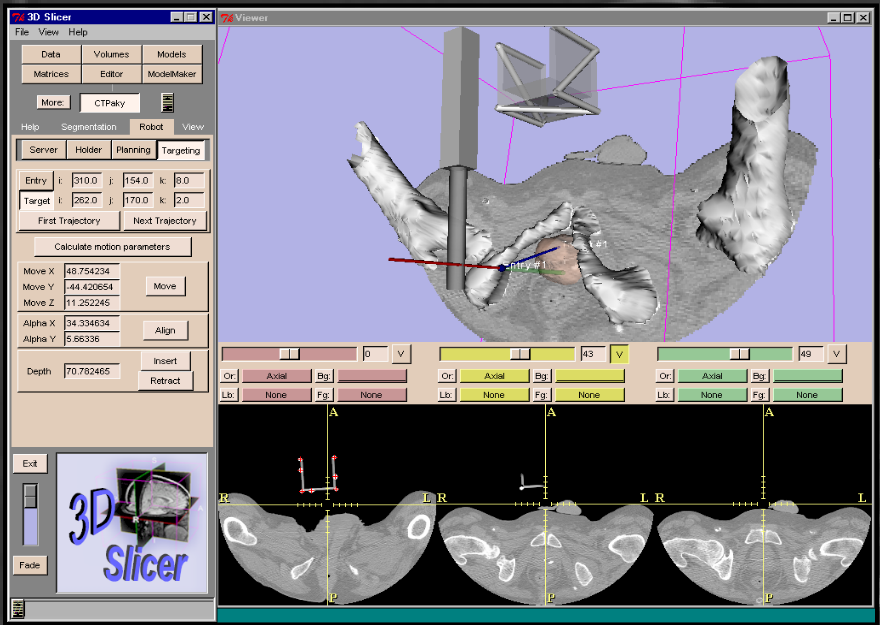
- Multimodality
  - Complementary image contents





Modalities

- Model - Modality
- Modality - Patient



Prostate biopsy project, Johns Hopkins University, Baltimore, MD, USA

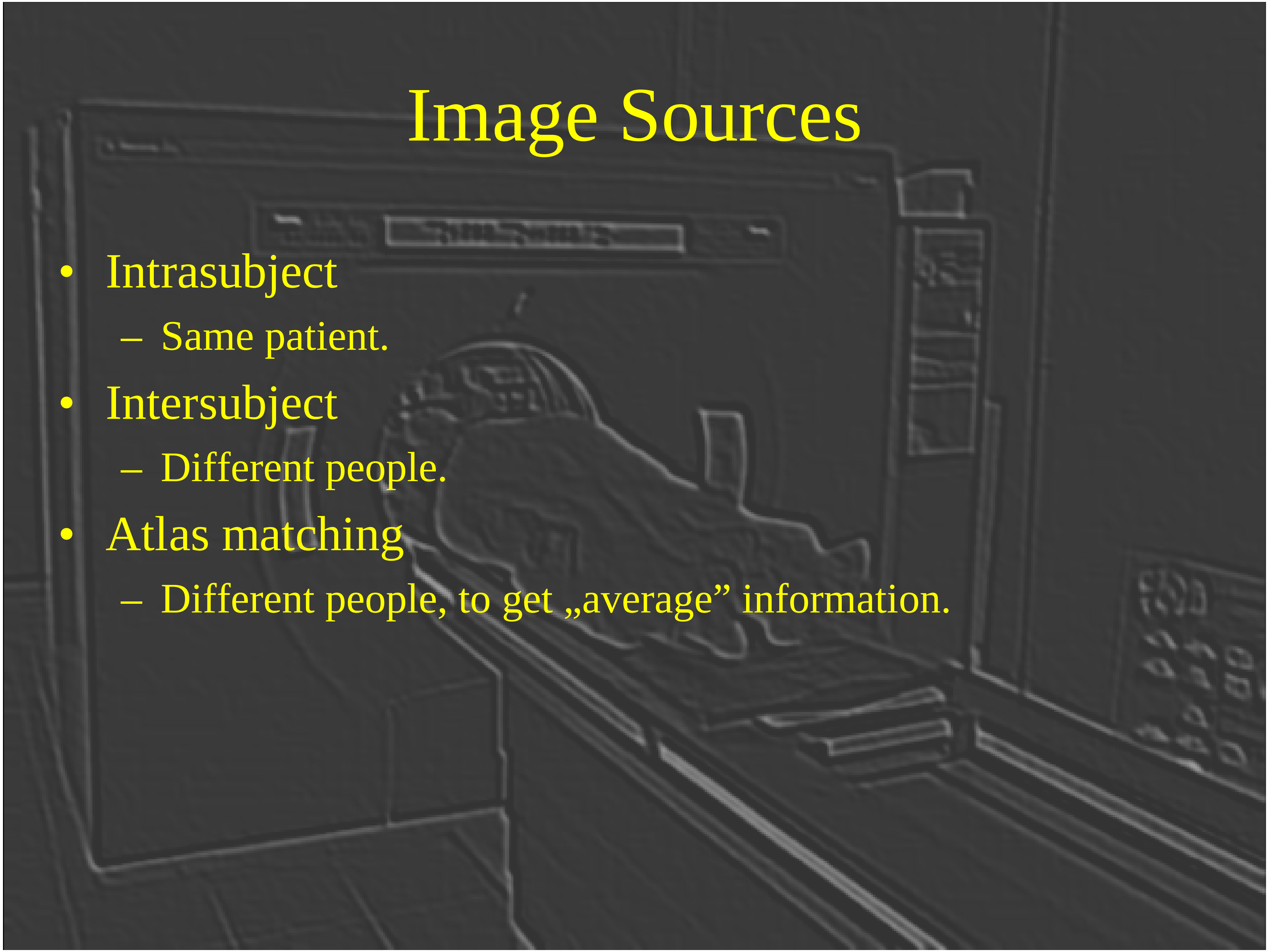


Image Sources

- Intrasubject
  - Same patient.
- Intersubject
  - Different people.
- Atlas matching
  - Different people, to get „average” information.

Interactivity

- Manual

  Decent visualization software is necessary. Labour intensive.

- Semi-automatic (interactive)

  Reliable, fast, but trained user might be required.

  - User initializes (e.g. point selection, segmentation).
  - User decides (accept/reject).
  - Combined together.

- Automatic
  - Easy to use.
  - Usually accurate, but visual inspection is necessary.
  - Can take a lot of time (especially in nonlinear cases).

Registration Algorithms

- Point-based methods,
  - Reliable, fast, but trained user might be required.
- Contour/surface fitting methods,
- Automatic volume fitting based on voxel similarity measures.

Point Pair Selection

- Interactive
  - Selection of point pairs
    - Might require trained user,
    - Can be hard (e.g. in 3D), or even impossible (MR – SPECT TRODAT),
    - Might take lot of time (few minutes – 10-30 minutes).
- Automatic
  - Feature extraction (e.g. corner points).
  - Number of points can be different.
  - Pairing is to be solved!

Interactive Point Pair Selection

Automatic Point Selection

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Point-Based Methods

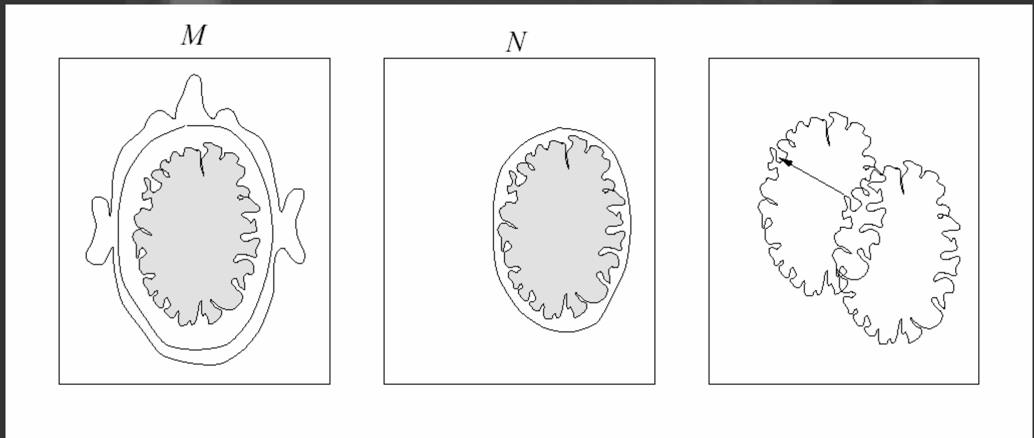
- Rigid-body, similarity transformation
  - SVD, unit quaternions, iterative search.
- Affine transformation
  - Least squares, SVD.
- Polinomial transformations
  - 2nd, 3rd, n-th order.
- Nonlinear transformations
  - Thin-plate spline, B-Spline, multiquadrics, RBF, etc.

Registration Algorithms

- Point-based methods,
- Contour/surface fitting methods,
- Automatic volume fitting based on voxel similarity measures.

Contour/Surface Fitting

- Extraction of same contours/surfaces
- Contour/surface distance definition
- Optimization (iterative method)
- Outliers problem



Distance definition

- Point-based

$$\mathcal{D}_p(T) = \sum_{i=1}^{K} \|\mathbf{x}_i - T(\mathbf{y}_i)\|^2,$$

- Contour/surface

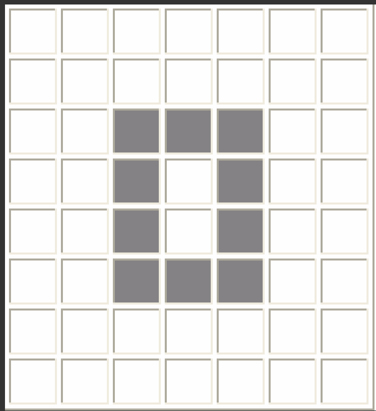
$$\mathcal{D}_s(T) = \sqrt{\sum_{i=1}^{K} \|\mathbf{x}_i - \mathcal{P}(T(Y), \mathbf{x}_i)\|^2}.$$

  – Closest point in the transformed Y point set.
  – Closest point in the triangulated surface mesh of the trasformed Y point set.
  – Etc.

Contour/Surface Methods

- Head-hat (Pelizzari, 1989)
- Hierarchical Chamfer Matching (Borgefors, Jiang, 1992)
- Iterative Closest Point (Besl, McKay, 1992)

Chamfer Matching



Original contour

X	X	X	X	X	X	X
X	X	X	X	X	X	X
X	X	0	0	0	X	X
X	X	0	X	0	X	X
X	X	0	X	0	X	X
X	X	0	0	0	X	X
X	X	X	X	X	X	X
X	X	X	X	X	X	X

Chamfer initialization

X	X	X	X	X	X	X
X	X	X	X	X	X	X
X	X	0	0	0	3	6
X	4	0	3	0	3	6
8	4	0	3	0	3	6
8	4	0	0	0	3	6
8	4	3	3	3	4	7
8	7	6	6	6	7	8

Forward scan

8	7	6	6	6	7	8
7	4	3	3	3	4	7
6	3	0	0	0	3	6
6	3	0	3	0	3	6
6	3	0	3	0	3	6
6	3	0	0	0	3	6
7	4	3	3	3	4	7
8	7	6	6	6	7	8

Backward scan

8	7	6	6	6	7	8
7	4	3	3	3	4	7
6	3	0	0	0	3	6
6	3	0	3	0	3	6
6	3	0	3	0	3	6
6	3	0	0	0	3	6
7	4	3	3	3	4	7
8	7	6	6	6	7	8

Distance map with the target contour

8	7	6	6	6	7	8
7	4	3	3	3	4	7
6	3	0	0	0	3	6
6	3	0	3	0	3	6
6	3	0	3	0	3	6
6	3	0	0	0	3	6
7	4	3	3	3	4	7
8	7	6	6	6	7	8

Distance: 46

8	7	6	6	6	7	8
7	4	3	3	3	4	7
6	3	0	0	0	3	6
6	3	0	3	0	3	6
6	3	0	3	0	3	6
6	3	0	0	0	3	6
7	4	3	3	3	4	7
8	7	6	6	6	7	8

Distance: 35

8	7	6	6	6	7	8
7	4	3	3	3	4	7
6	3	0	0	0	3	6
6	3	0	3	0	3	6
6	3	0	3	0	3	6
6	3	0	0	0	3	6
7	4	3	3	3	4	7
8	7	6	6	6	7	8

Distance: 18

Registration Algorithms

- Point-based methods,
- Contour/surface fitting methods,
- Automatic volume fitting based on voxel similarity measures.
  - Easy to use.
  - Usually accurate, but visual inspection is necessary.
  - Can take a lot of time (especially in nonlinear cases).

Intensity differences

$$\mathrm{SSD} = \frac{1}{N} \sum_{x_A \in \Omega_A} \left| A(x_A) - B^T(x_A) \right|^2 ,$$

$$\mathrm{SAD} = \frac{1}{N} \sum_{x_A \in \Omega_A} \left| A(x_A) - B^T(x_A) \right|$$

- Optimal when the noise is Gaussian.
  - For unimodality registration.
  - Unimodality problems
    - Noise is not Gaussian in MR.
    - Contrast agents can cause big intesity differences.

Correlation techniques

$$\mathrm{C} = \frac{1}{N} \sum_{x_A \in \Omega^T_{A,B}} A(x_A) \cdot B^T(x_A)$$

$$\mathrm{CC} = \frac{\sum_{x_A \in \Omega_A} \left(A(x_A) - \bar{A}\right) \cdot \left(B^T(x_A) - \bar{B}\right)}{\sqrt{\sum_{x_A \in \Omega_A} \left(A(x_A) - \bar{A}\right)^2 \cdot \sum_{x_A \in \Omega_A} \left(B^T(x_A) - \bar{B}\right)^2}}$$

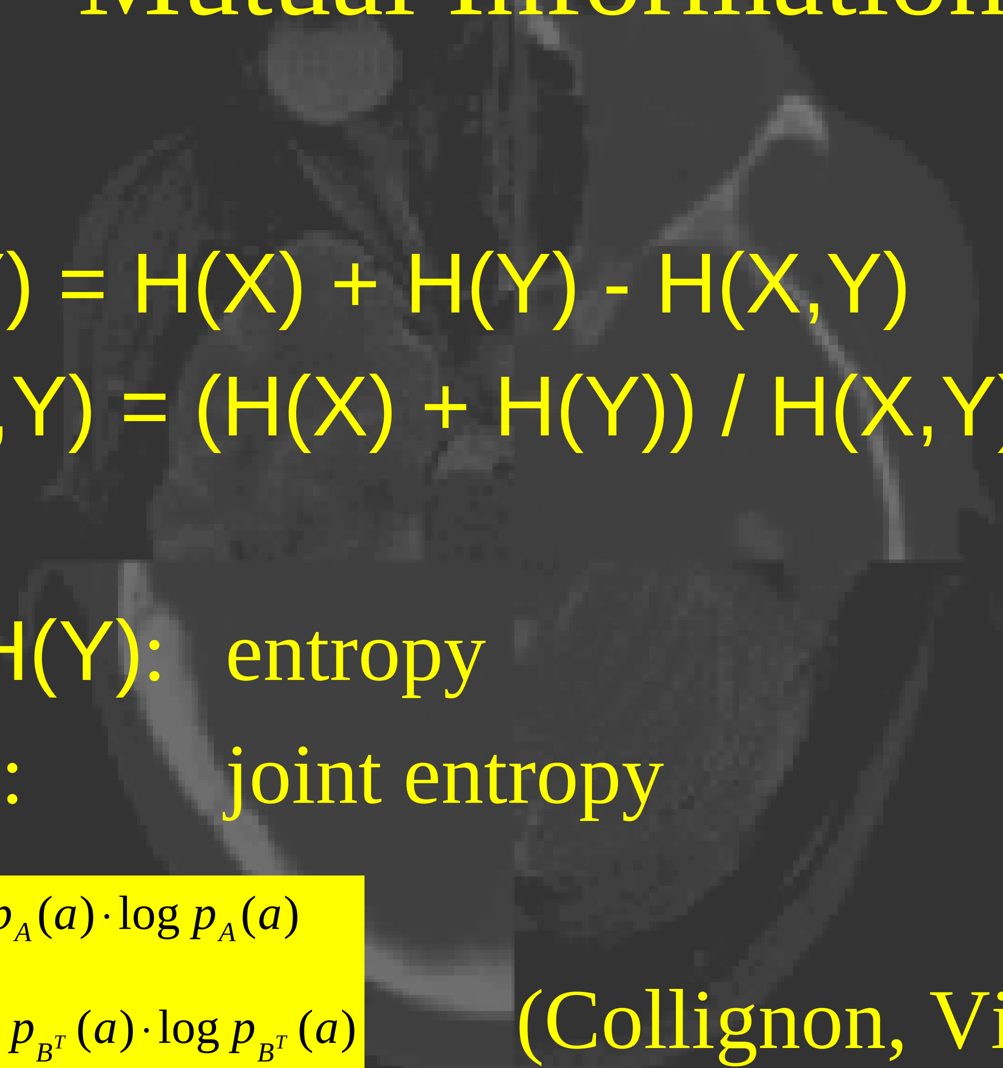
- Optimal when the relationship is linear between intensities of the images.
  - For unimodality registration.

Partitioned Image Uniformity

$$PIU = \sum_a \frac{n_a}{N} \cdot \frac{\sigma(a)}{\mu(a)} \qquad n_a = \sum_{\Omega_a} 1 \qquad \mu(a) = \frac{1}{n_a} \cdot \sum_{x_A \in \Omega_a} B^T(x_A) \qquad \sigma(a) = \sum_{x_A \in \Omega_a} \left(B^T(x_A) - \mu(a)\right)^2$$

- Assumed: an intensity value describes a tissue type well in both images.
- For MR-PET registration (Woods, 1992)
  - Remove parts outside of brain from PET.
  - Transform MR intensity scale to 256 values.
  - Maximizes the uniformity of the intensities from PET paired with intensities of MR.

Mutual Information



MI(X,Y) = H(X) + H(Y) - H(X,Y)

NMI(X,Y) = (H(X) + H(Y)) / H(X,Y)

H(X), H(Y): entropy

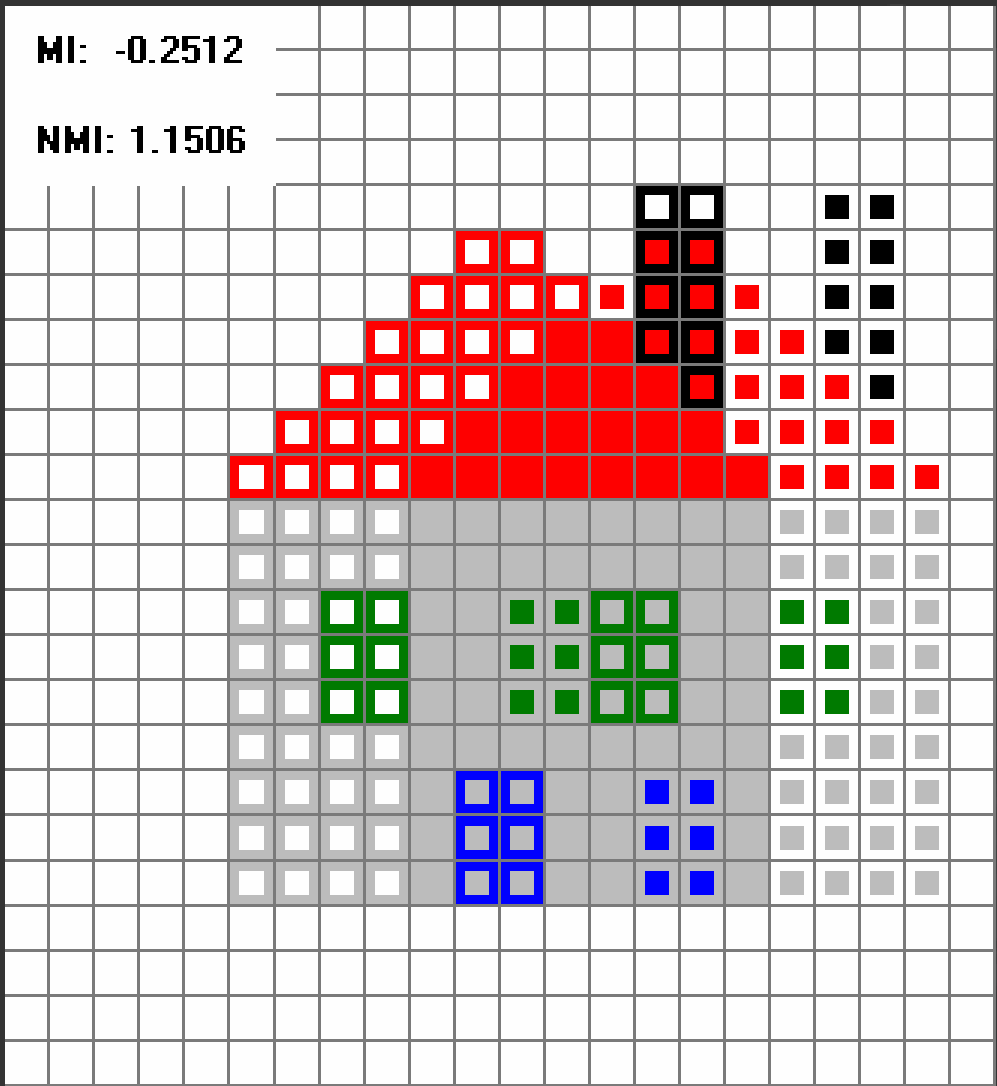
H(X,Y): joint entropy

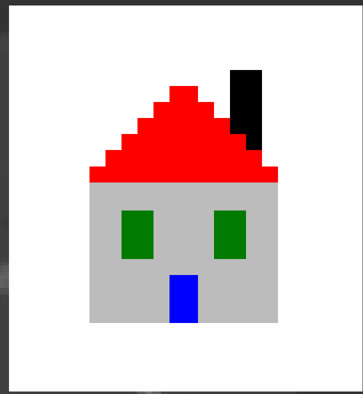
$$\mathrm{H(A)} = -\sum_a p_A(a) \cdot \log p_A(a)$$

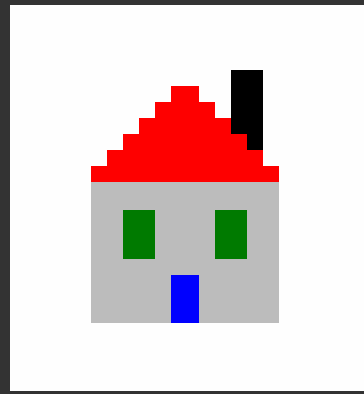
$$\mathrm{H(B^T)} = -\sum_a p_{B^T}(a) \cdot \log p_{B^T}(a)$$

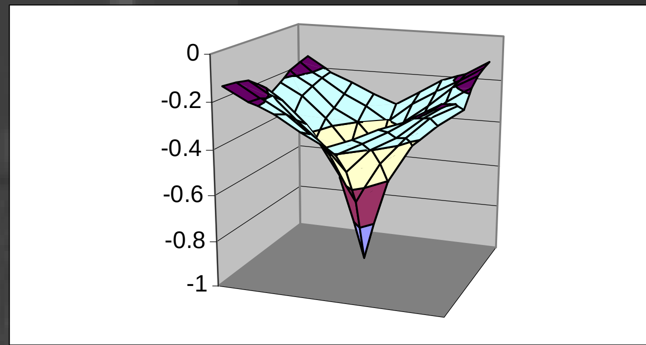
$$\mathrm{H(A, B^T)} = -\sum_a \sum_b p_{AB^T}(a,b) \cdot \log p_{AB^T}(a,b)$$

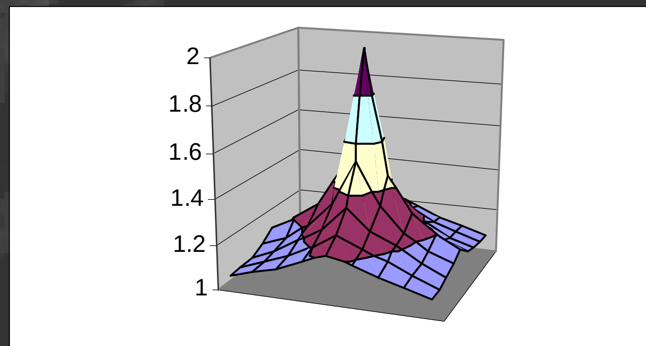
(Collignon, Viola 1995)

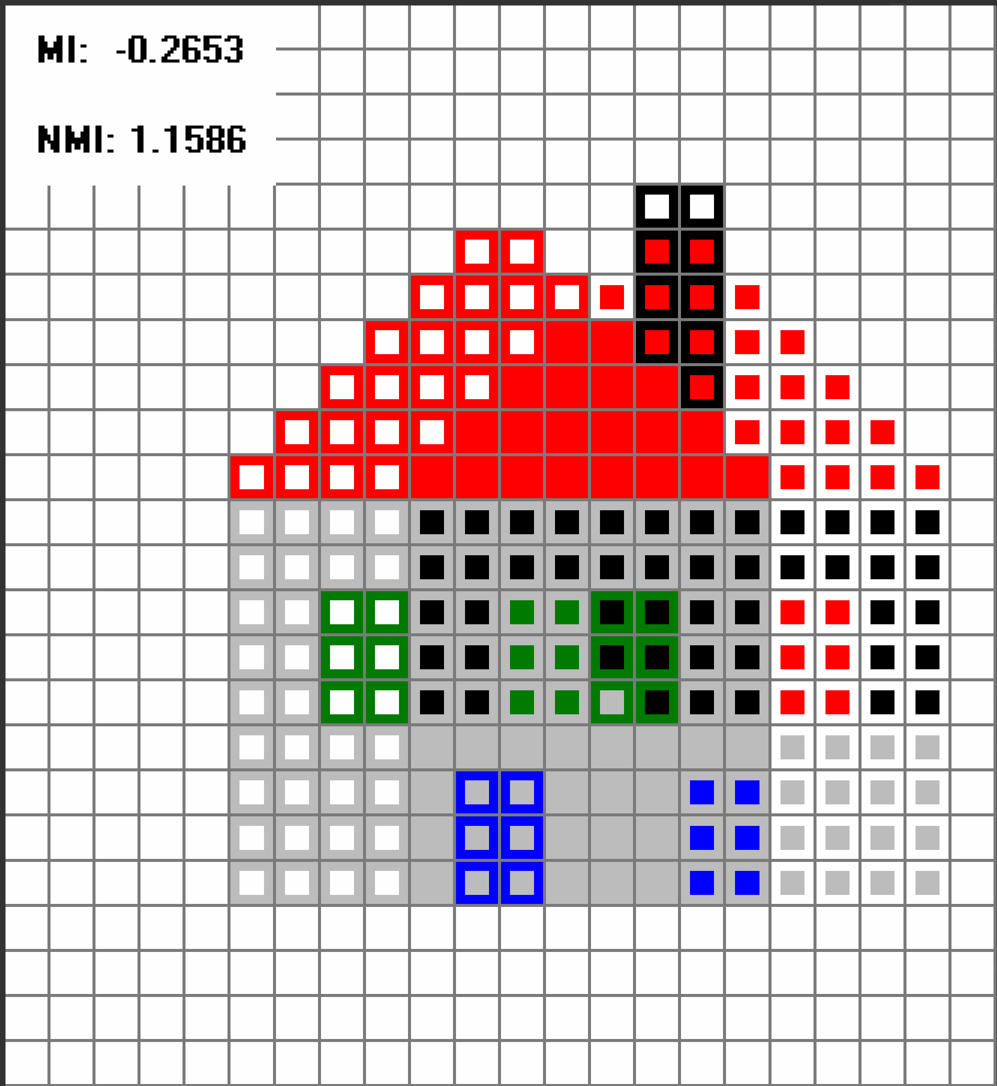

MI: -0.2512
NMI: 1.1506






0
-0.2
-0.4
-0.6
-0.8
-1


2
1.8
1.6
1.4
1.2
1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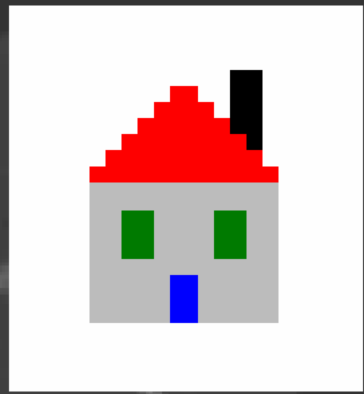
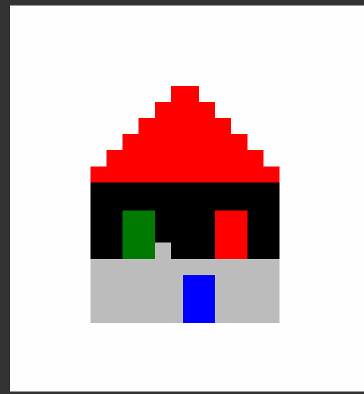
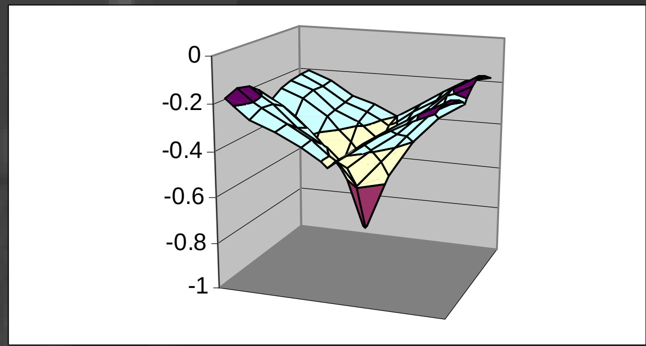
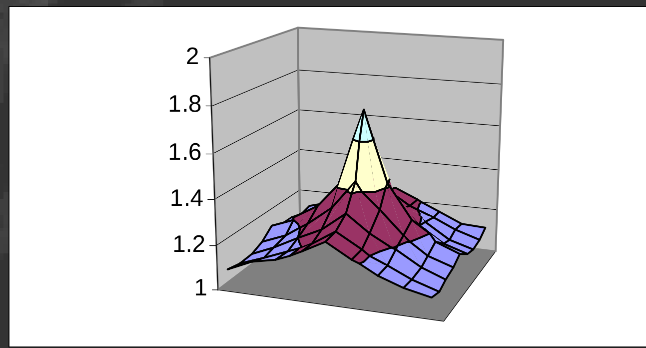
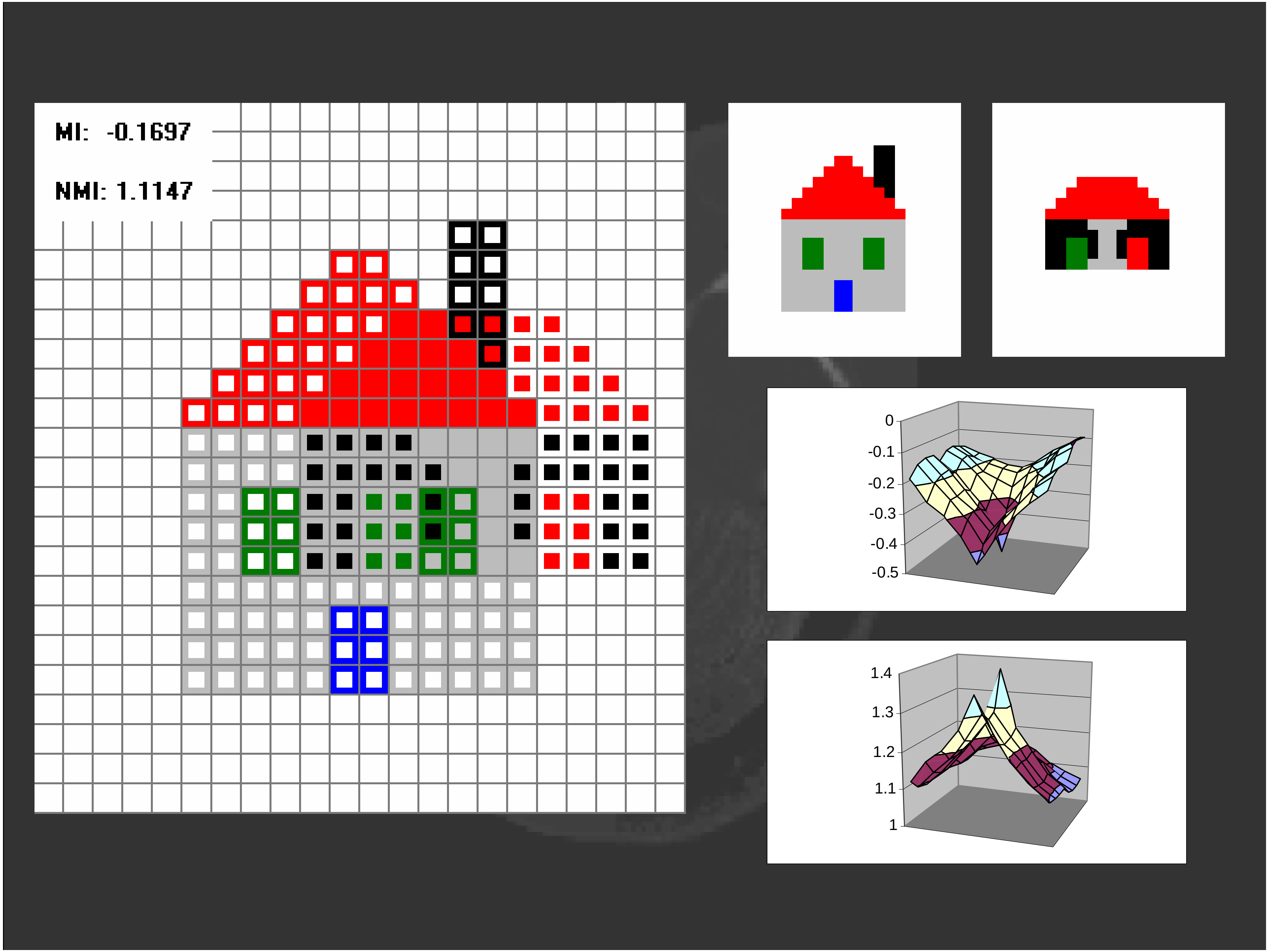
NMI: 1.1586






0
-0.2
-0.4
-0.6
-0.8
-1


2
1.8
1.6
1.4
1.2
1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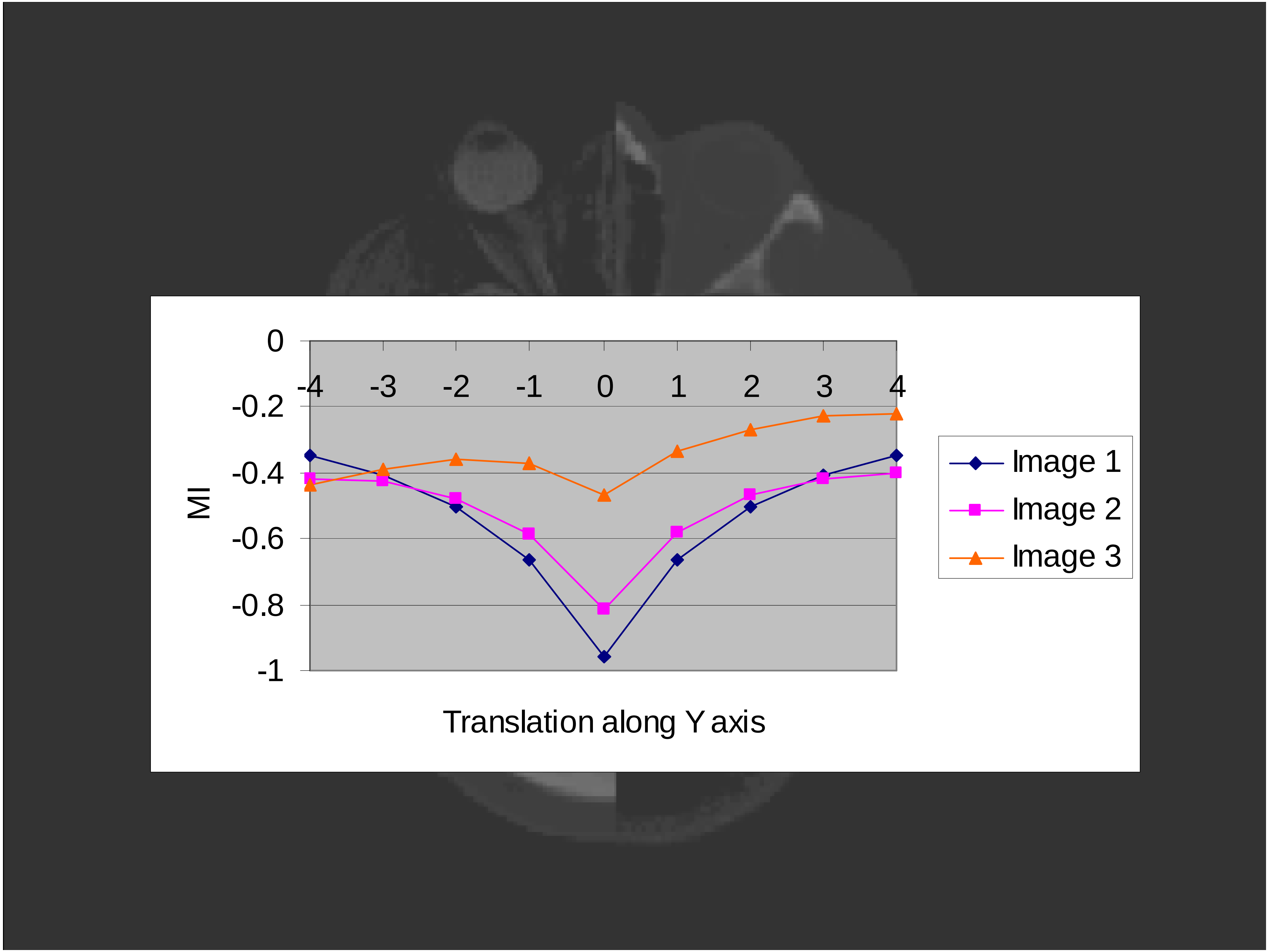
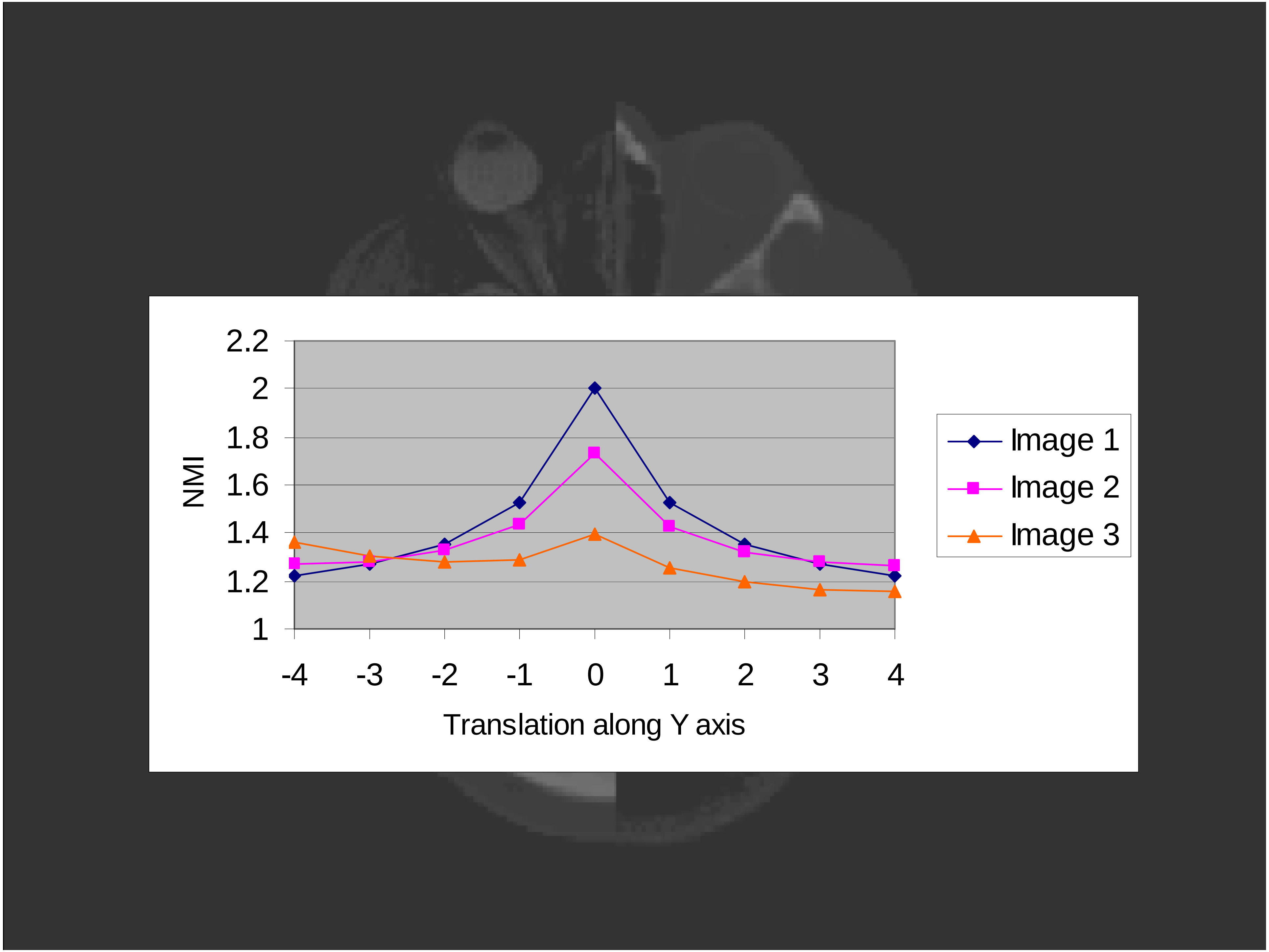
NMI: 1.1147
0
-0.1
-0.2
-0.3
-0.4
-0.5
1.4
1.3
1.2
1.1
1


0
-0.2
-0.4
-0.6
-0.8
-1
-4
-3
-2
-1
0
1
2
3
4
MI
Translation along Y axis
Image 1
Image 2
Image 3



2.2
2
1.8
1.6
1.4
1.2
1
NMI
-4
-3
-2
-1
0
1
2
3
4
Translation along Y axis
Image 1
Image 2
Image 3

Selected Surveys and Books

- General
  - Brown, L.G.: A survey of image registration techniques. ACM Computing Surveys 24 (1992) 325-376
  - Modersitzki, J.: Numerical Methods for Image Registration. Oxford University Press (2004)
  - Goshtasby, A.A.: 2-D and 3-D Image Registration for Medical, Remote Sensing, and Industrial Applications. Wiley and Sons (2005)
- Medical
  - Maintz, J.B.A., Viergever, M.A.: A survey of medical image registration. Medical Image Analysis 2 (1998) 1-36
  - Studholme, C.: Measures of 3D Medical Image Alignment. PhD Thesis, University of London (1997)
  - Hajnal, J.V., Hill, D.L.G., Hawkes, D.J. (eds.): Medical Image Registration. CRC Press (2001)
- Internet
  - http://vision.ece.ucsb.edu/registration/imreg/
  - http://www.imgfsr.com/