Segmentation of Medical Images

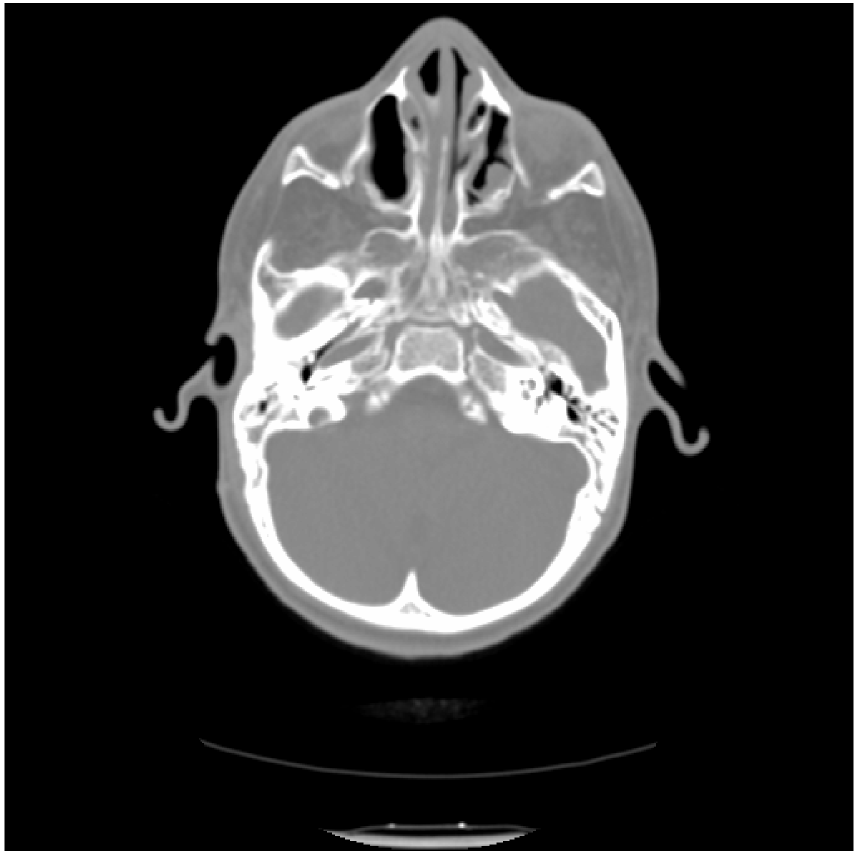
László Nyúl

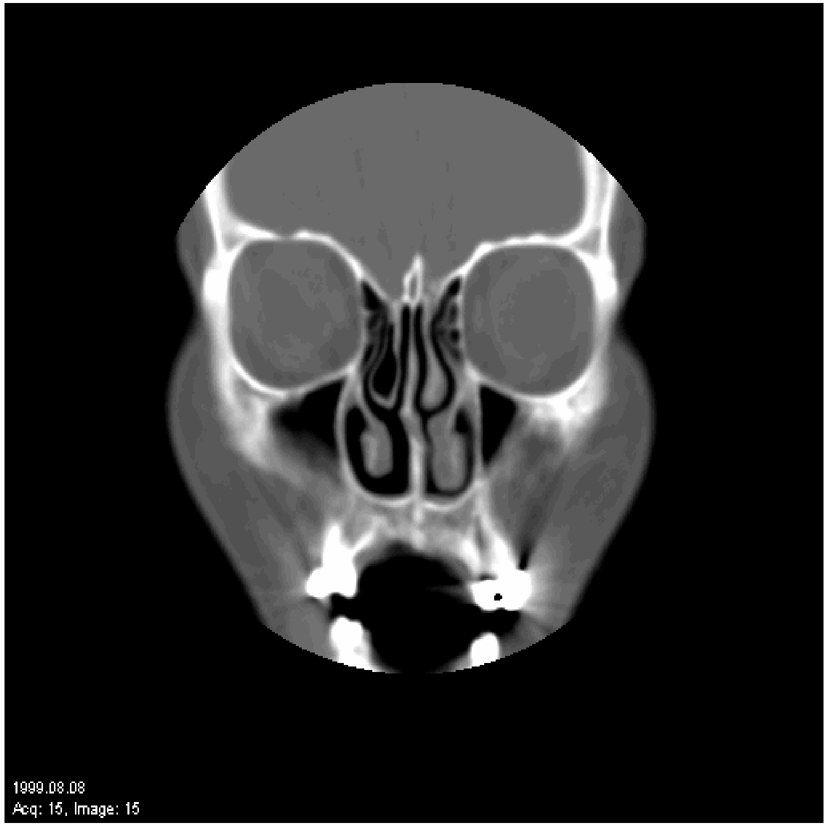
Department of Image Processing and Computer Graphics
University of Szeged

nyul@inf.u-szeged.hu

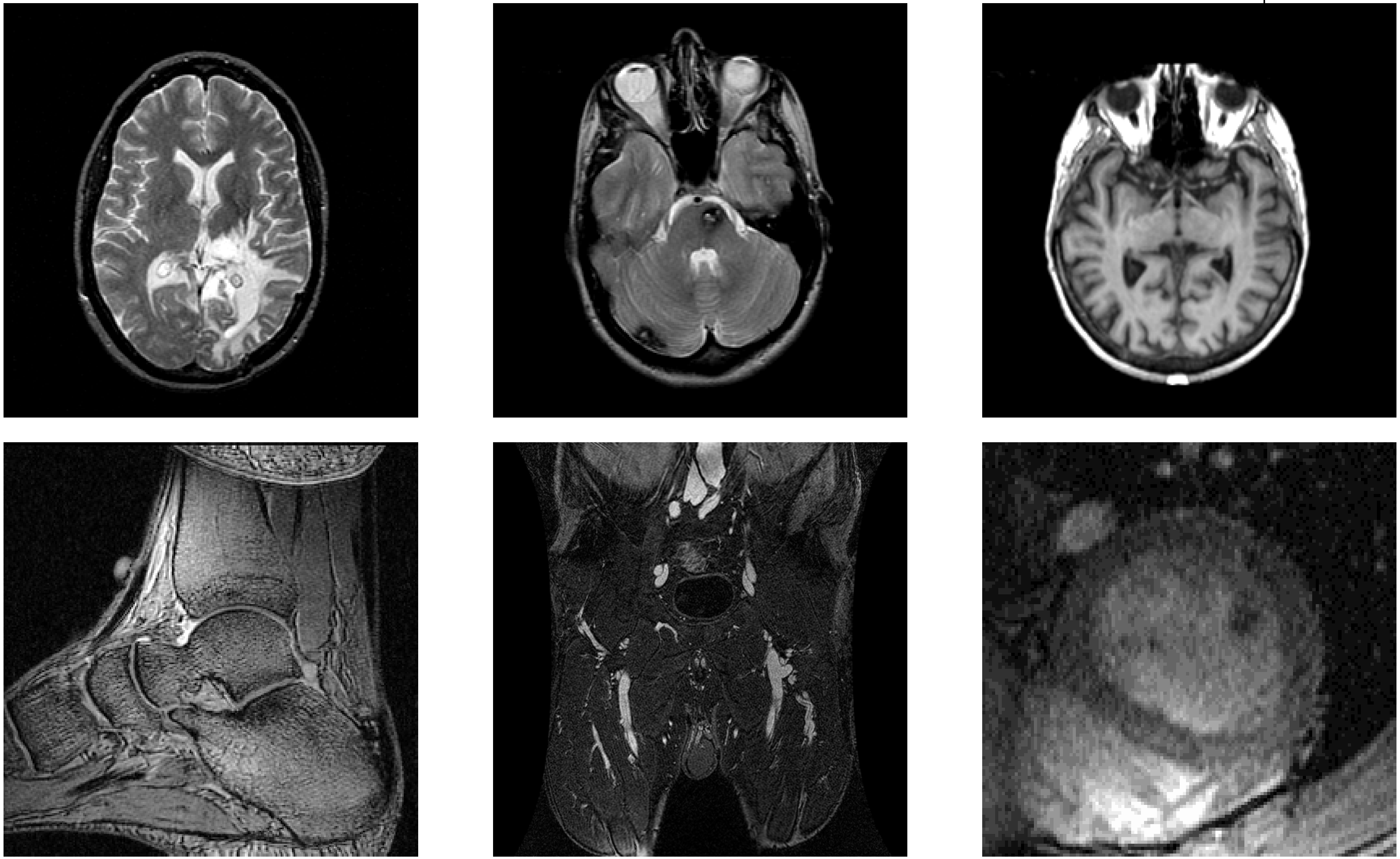
X-ray radiography

Computerized Tomography (CT)

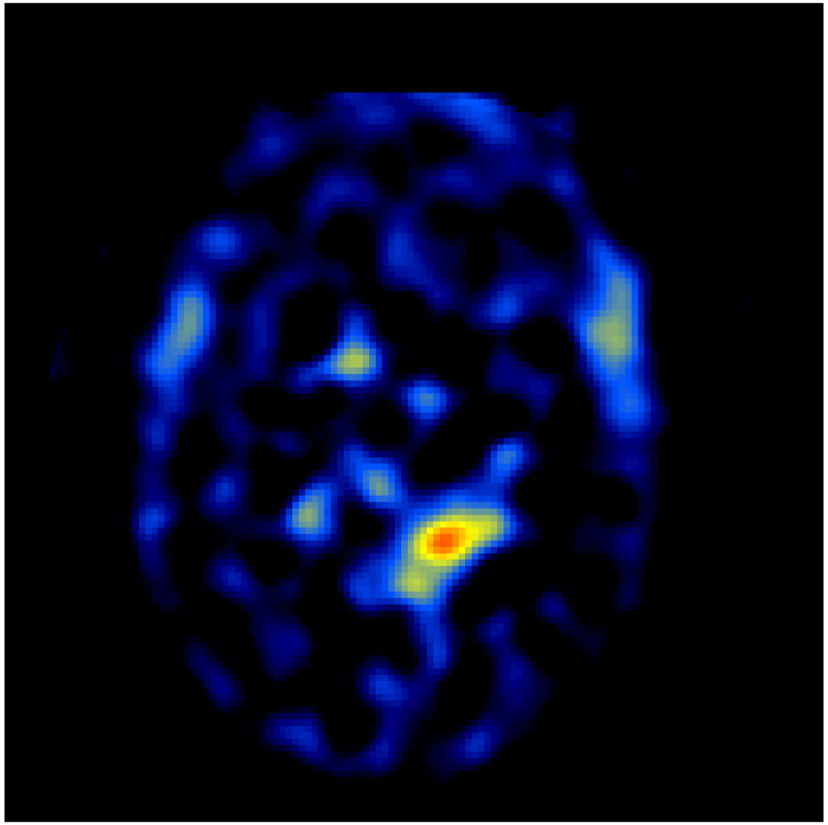


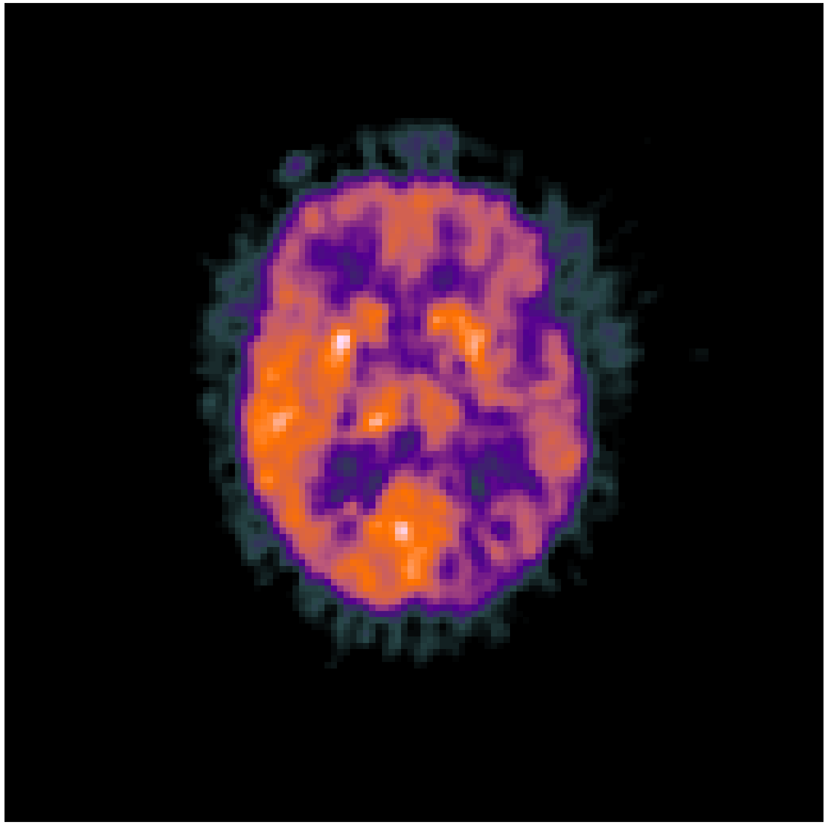


Magnetic Resonance Imaging (MRI)

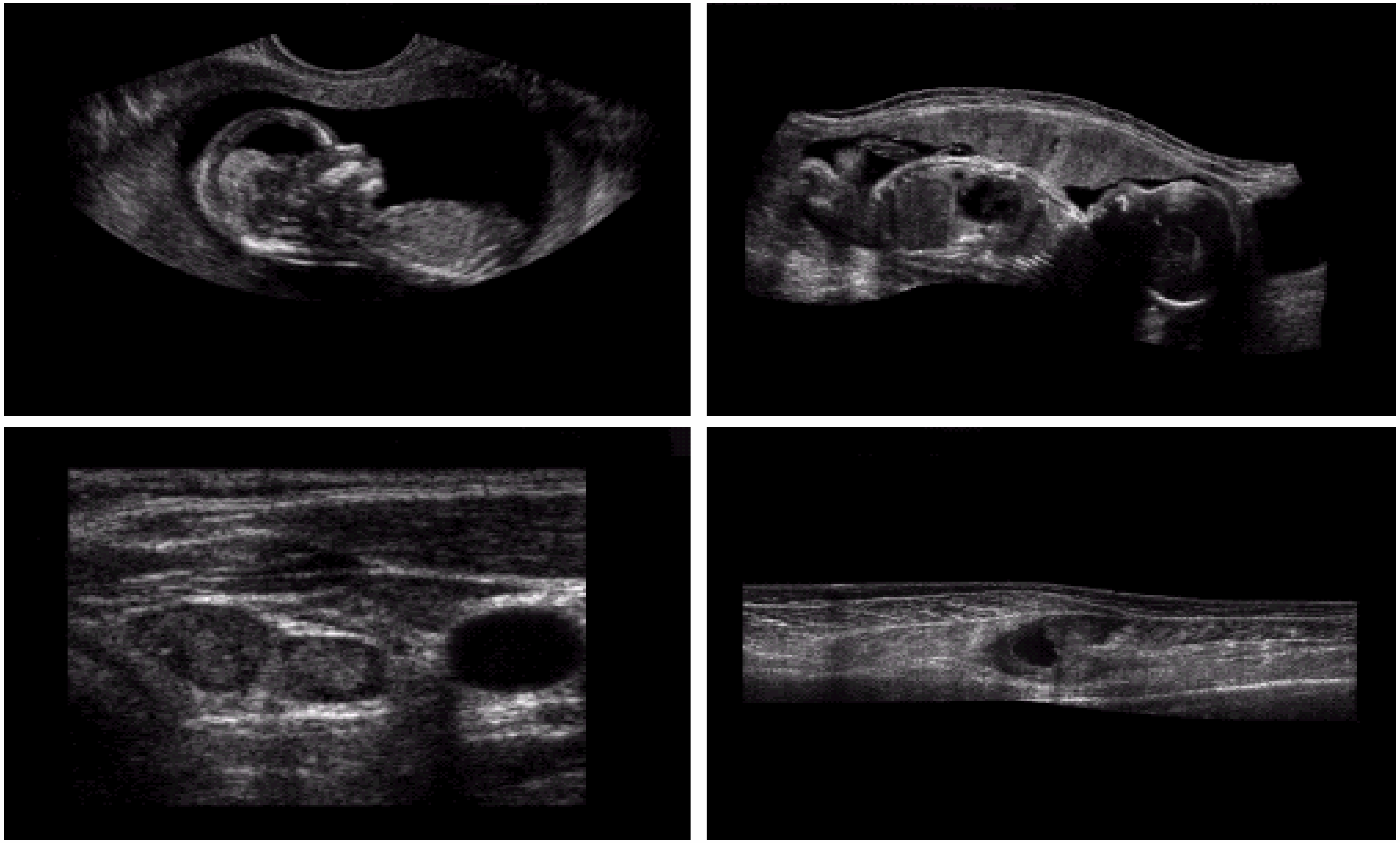


Single Photon Emission CT (SPECT)
Positron Emission Tomography (PET)

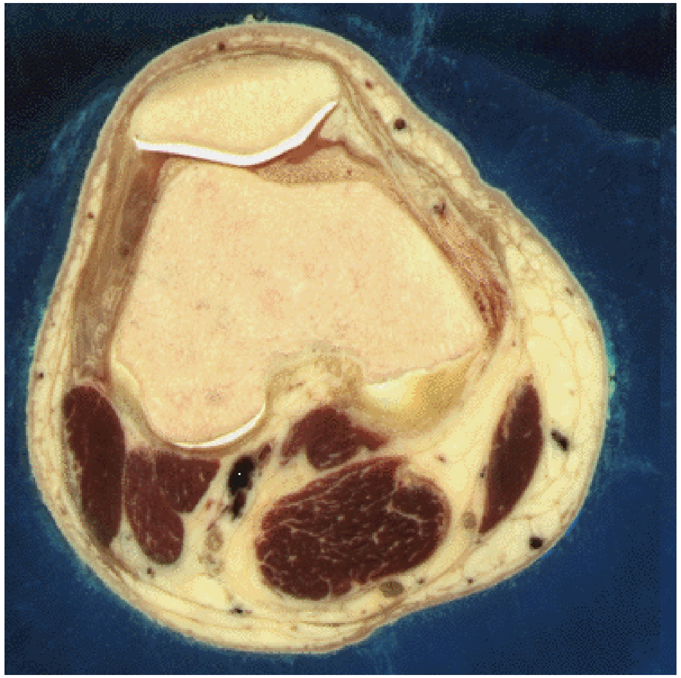


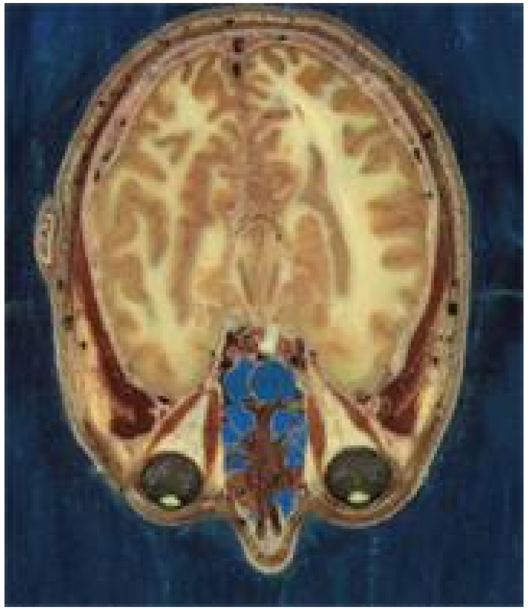


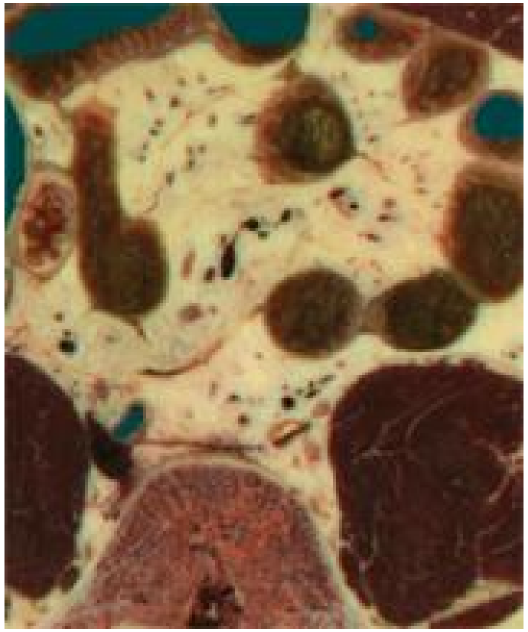
Ultrasound Imaging



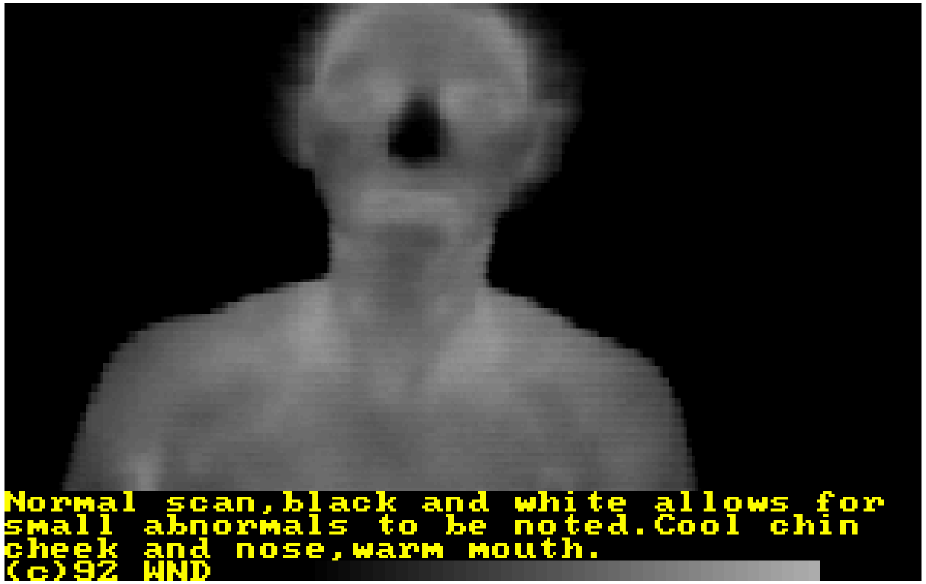
Cryo-section Photographs



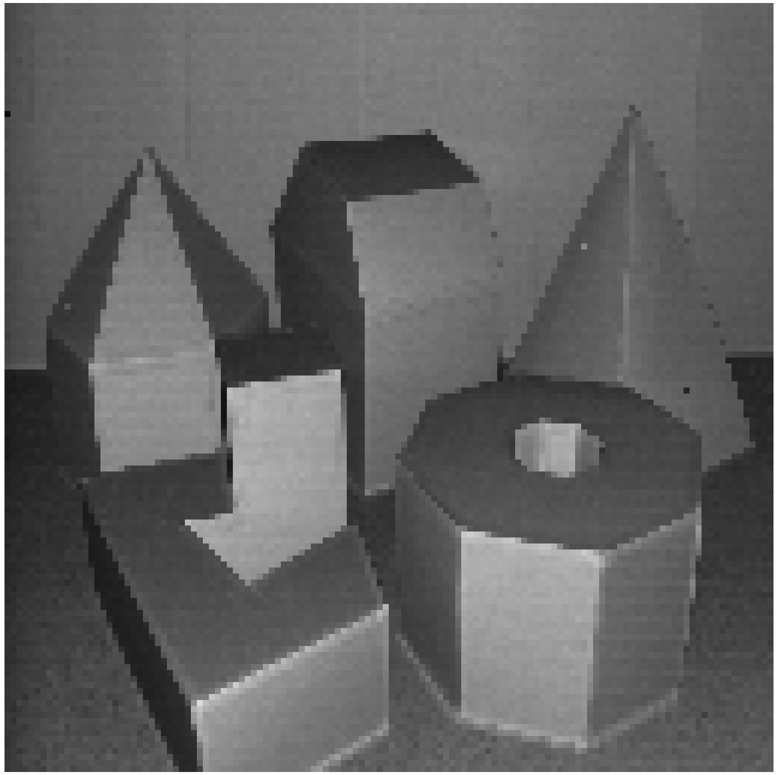




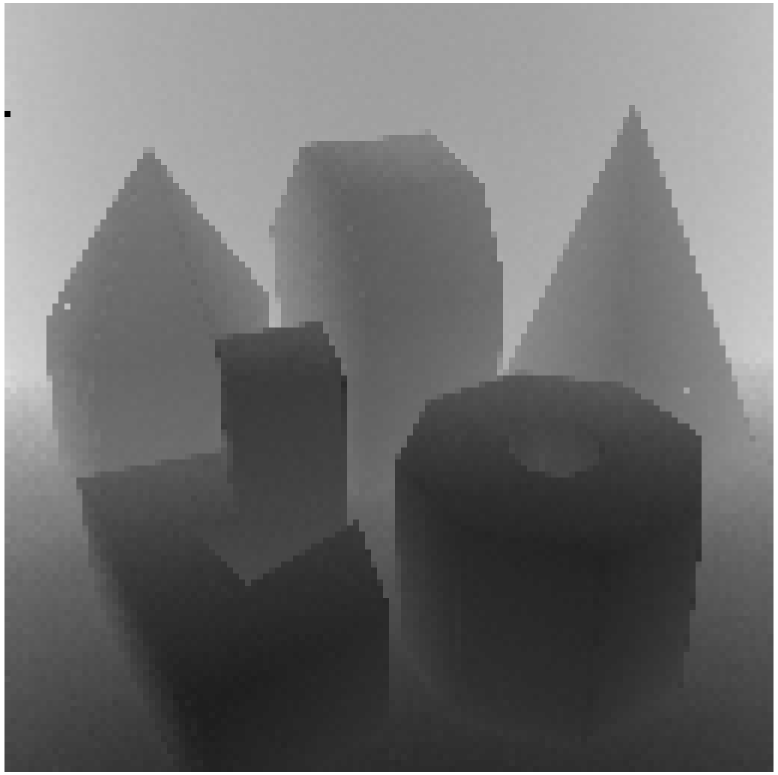
Thermographic Images



Range Images



Reflection image



Range image

Purpose of 3D Imaging

- IN: multiple multimodality images (CT, MR, PET, SPECT, US, …)

- OUT: information about an object/object system (qualitative, quantitative)

Sources of Images

- 2D: digital radiographs, tomographic slices
- 3D: a time sequence of 2D images of a dynamic object, a stack of slice images of a static object
- 4D: a time sequence of 3D images of a dynamic object
- 5D: a time sequence of 3D images of a dynamic object for a range of imaging parameters (e.g., MR spectroscopic images of heart)

Operations

- Preprocessing: for defining the object information
- Visualization: for viewing object information
- Manipulation: for altering object information
- Analysis: for quantifying object information

- The operations are independent

Preprocessing Operations

- Volume of interest (VOI)

  converts a given scene to another scene of smaller scene domain (ROI) and/or intensity range (IOI)

- Filtering

  converts a given scene to another scene by suppressing unwanted information and/or enhancing wanted information

Preprocessing Operations

- Interpolation

  converts a given scene to another scene of specified level and orientation of discretization

- Registration

  converts a given scene/structure to another scene/structure by matching it with another given scene/structure

- Segmentation

  converts a given set of scenes to a structure/structure system

Image Segmentation

- Purpose: to extract object information from scenes and represent it as a structure/structure system
- Consists of
  - Recognition
    - Determine roughly the objects' whereabouts in the scene
    - humans >> computer algorithms
  - Delineation
    - Determine the objects' precise spatial extent and graded composition
    - computer algorithms >> humans
    - Manual delineation specifying graded composition is impossible
- Needed for most (3D) imaging operations

Challenges in Medical Imaging

- Subject of imaging
  - Human beings
- Side effects, health hazards of the acquisition
  - Contrast agents
  - Radiation
  - Invasive techniques
- Data handling
  - Privacy

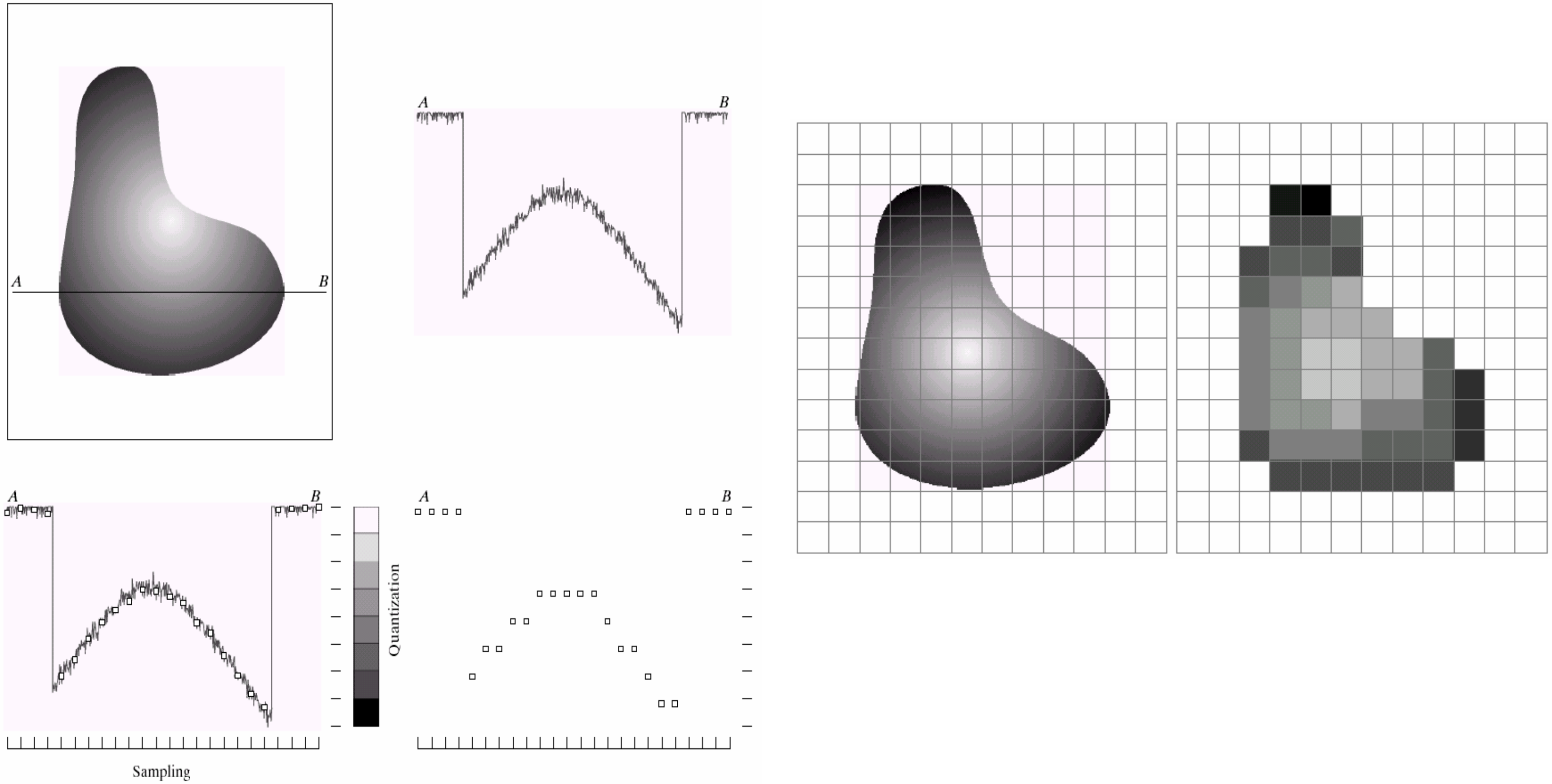
Challenges in Medical Imaging

- Image processing
  - Grey-level appearance of tissues
  - Characteristics of imaging modality
  - Geometry of anatomy
    - Organs are of different size and shape
    - Normal vs. diseased
    - Objects may change between acquisitions
  - Automated processing is desirable
- Evaluation
  - No ground truth available! L

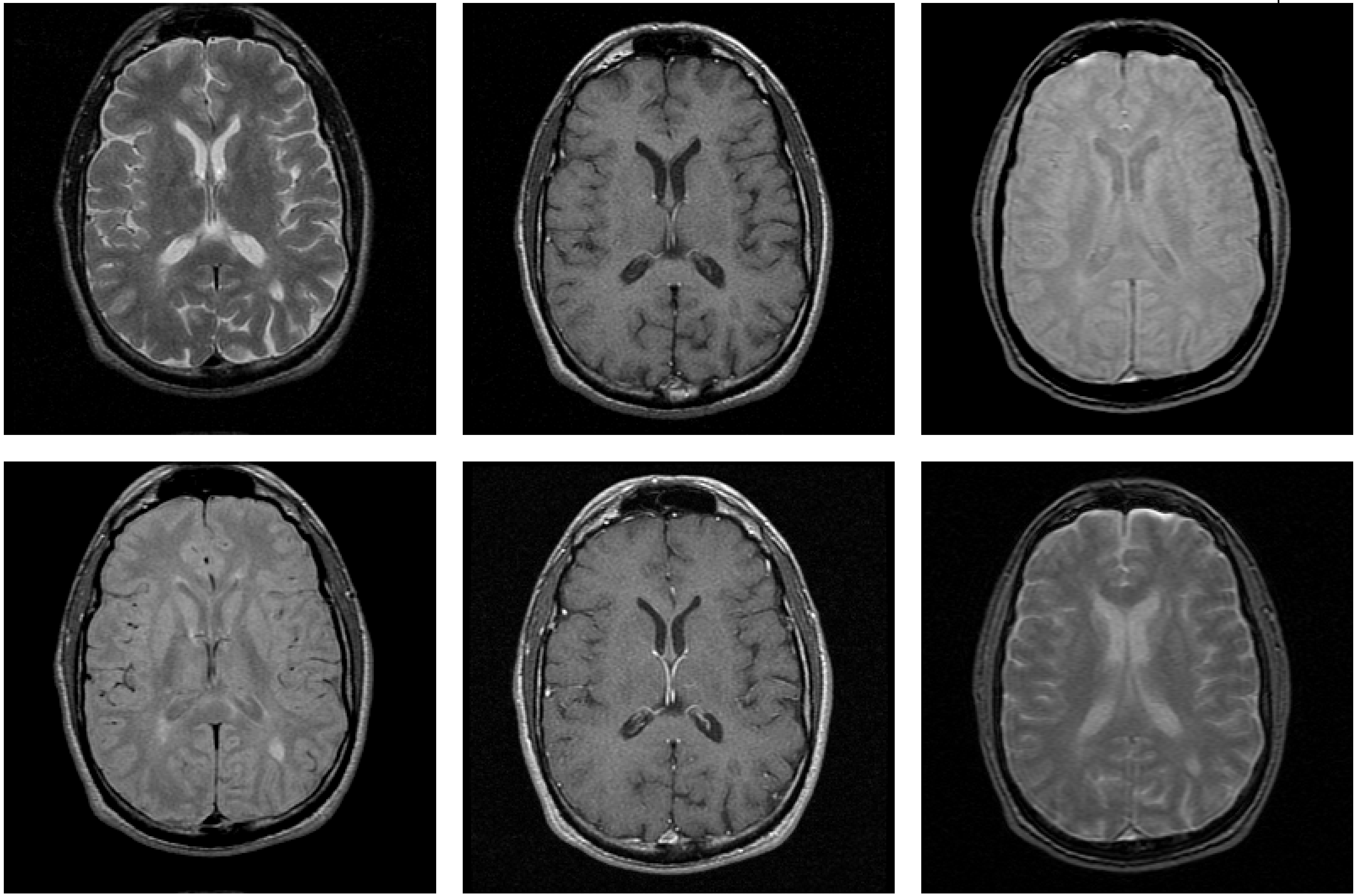
Limitations of Acquisition Techniques

- Resolution
  - Spatial
  - Temporal
  - Density
- Tissue contrast
- Noise distribution, shading
- Partial volume averaging
- Artifacts
- Implants

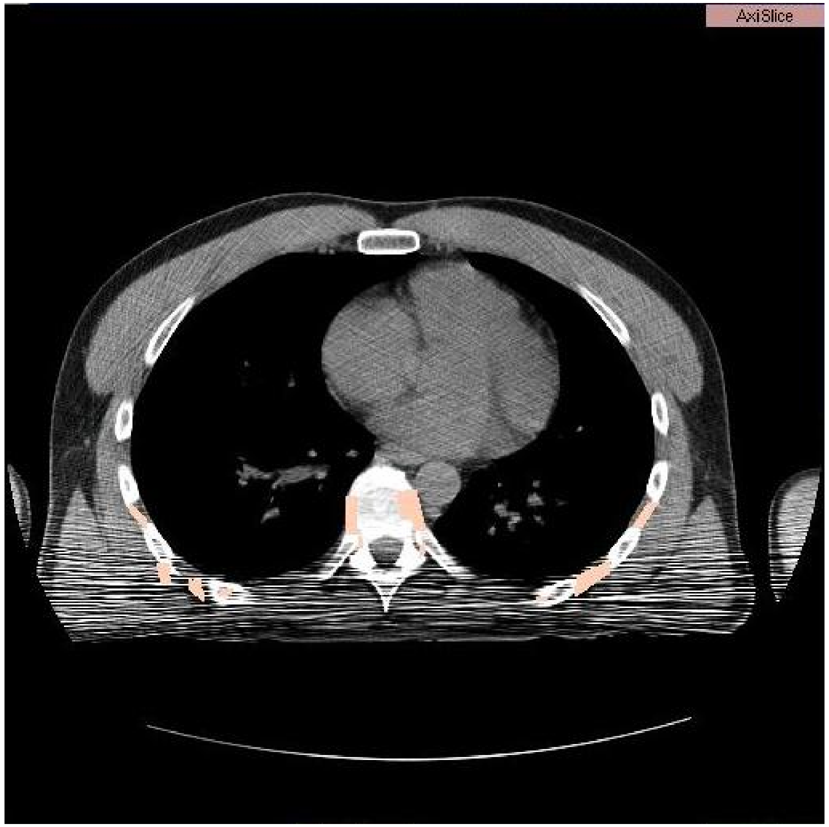
Noise and Sampling Errors

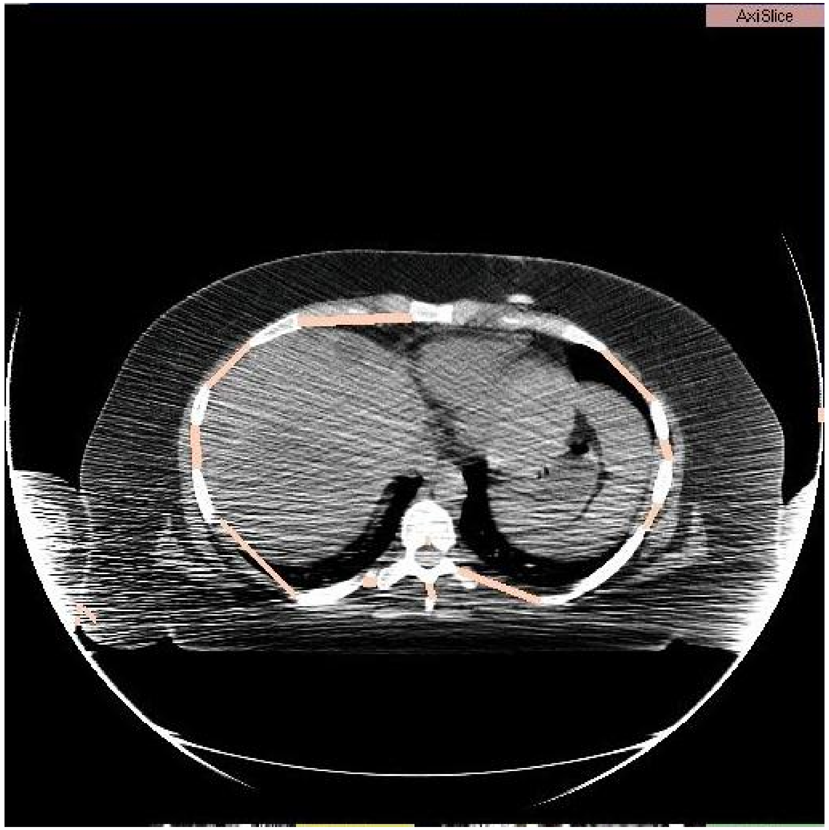


Different Tissue Contrast



Artifacts



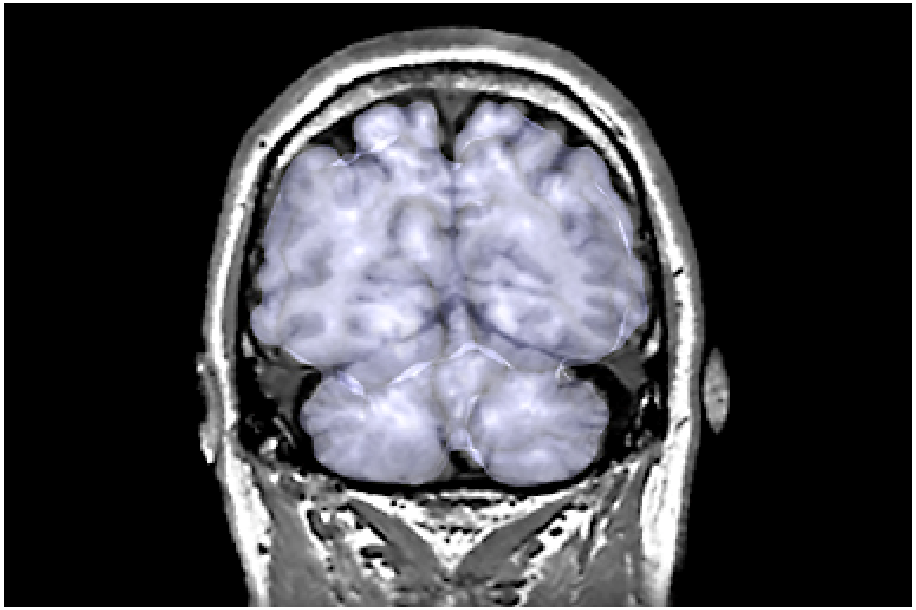


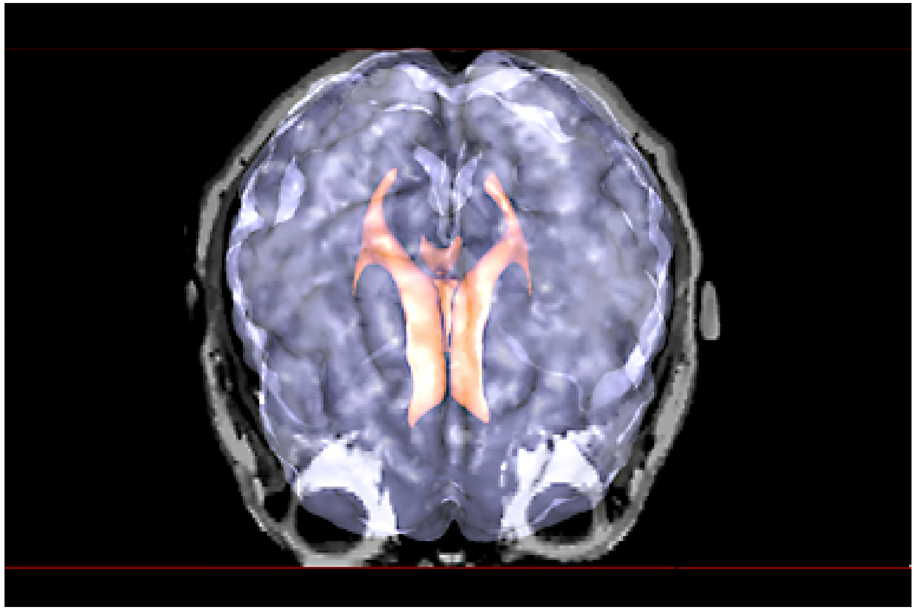
Applications of Image Segmentation in Medicine

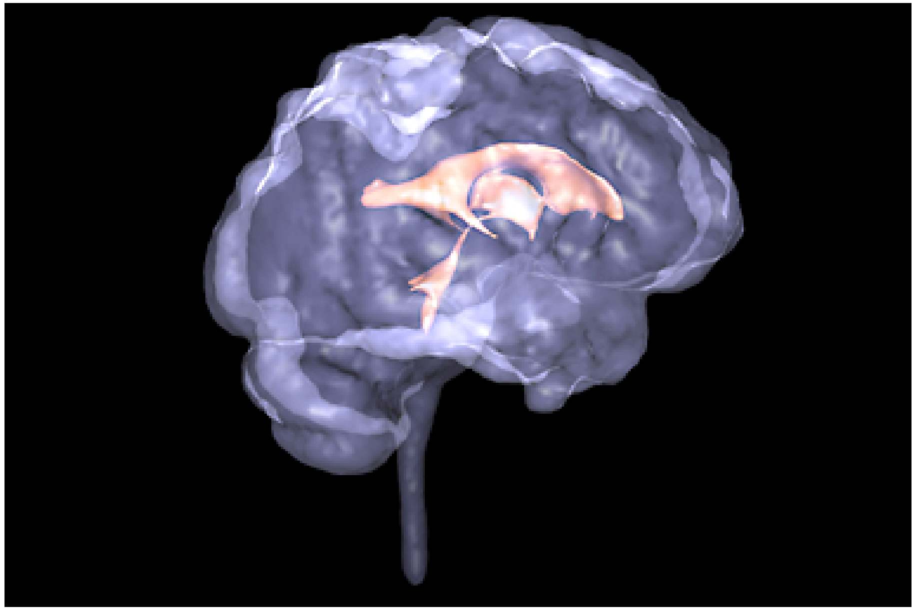
- Visualization, qualitative analysis
- Quantitative analysis

- Neurological studies
- Radiotherapy planning
- Diagnosis
- Research
- Implant design
- Image guided surgery
- Surgical planning and simulations
- Therapy evaluation and follow up
- …

Brain and the Ventricles







Regions to Segment

- Target regions for
  - quantification and measurements
  - radiation treatment
  - needle insertion, biopsy
  - surgical resection
- Regions to avoid by
  - radiation
  - needle
  - drill
  - surgical knife

Computer Aided Diagnosis (CAD)

- The computer can store, process, compare, and present (visualize) data
- The computer may even make suggestions

The physician has to make the final judgment!

Image Segmentation

- Consists of
  - Recognition
    - humans >> computer algorithms
  - Delineation
    - computer algorithms >> humans
    - Manual delineation specifying graded composition is impossible

- Aim: exploit the synergy between the two (humans and computer algorithms) to develop practical methods with high
  - PRECISION: reliability/repeatability
  - ACCURACY: agreement with truth
  - EFFICIENCY: practical viability

Approaches to Recognition

- Automatic
  - Knowledge- and atlas-based artificial intelligence techniques used to represent object knowledge
  - Preliminary delineation needed to form object hypotheses
  - Map geometric information from scene to atlas

Approaches to Recognition

- Human assisted
  - Often a simple human assistance is sufficient as a recognition aid:
    - Specification of “seed” points in the object
    - Indication of a box enclosing the object
    - Click of a mouse button to accept a real object or reject a false object

Approaches to Delineation

- Boundary-based
  - Work with boundaries (contours, surfaces)
  - Output boundary description of objects
- Region-based
  - Work with regions (pixels, voxels and patches)
  - Output regions occupied by objects
- Hybrid
  - Combine boundary-based and region-based methods

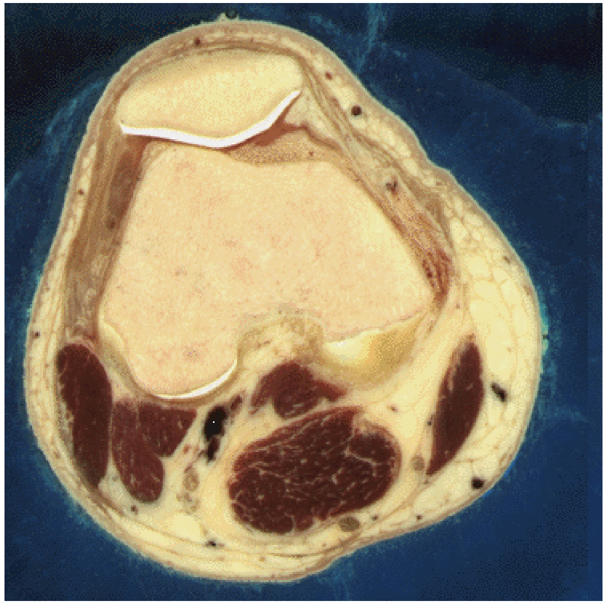
Approaches to Delineation

- Hard (crisp)
  - Each voxel in the output has a label of belonging either to object or background

- Fuzzy
  - Each voxel in the output has a membership value in both object and background

Boundary-based Segmentation Methods

- Align model boundary with object boundary using image features (edges)
- Requires initialization near solution to avoid becoming stuck in local minima
- Pixel information inside the object is not considered



Pre-processing (creating boundaries)

- Feature detection
  - Points
  - Lines
  - Edges
  - Corners
  - Junctions

−1	−1	−1
−1	8	−1
−1	−1	−1

−1	−1	−1
2	2	2
−1	−1	−1

Horizontal

−1	−1	2
−1	2	−1
2	−1	−1

+45°

−1	2	−1
−1	2	−1
−1	2	−1

Vertical

2	−1	−1
−1	2	−1
−1	−1	2

−45°

- Contour following
- Edge linking
- Canny edge-detector

Iso-surfacing

- Produce a surface that separates regions of intensity > threshold from those < threshold
- Digital surfaces
  - Voxels
  - Voxel faces
  - Polygonal elements

0	20	30	10	15
20	50	80	20	10
30	70	40	10	20
16	15	20	60	15
10	15	20	30	20

Gradient operators

−1	0
0	1

0	−1
1	0

Roberts

−1	−1	−1
0	0	0
1	1	1

−1	0	1
−1	0	1
−1	0	1

Prewitt

−1	−2	−1
0	0	0
1	2	1

−1	0	1
−2	0	2
−1	0	1

Sobel

0	1	1
−1	0	1
−1	−1	0

−1	−1	0
−1	0	1
0	1	1

Prewitt

0	1	2
−1	0	1
−2	−1	0

−2	−1	0
−1	0	1
0	1	2

Sobel

Creating Edges From Image Gradient

Degree of “edginess”

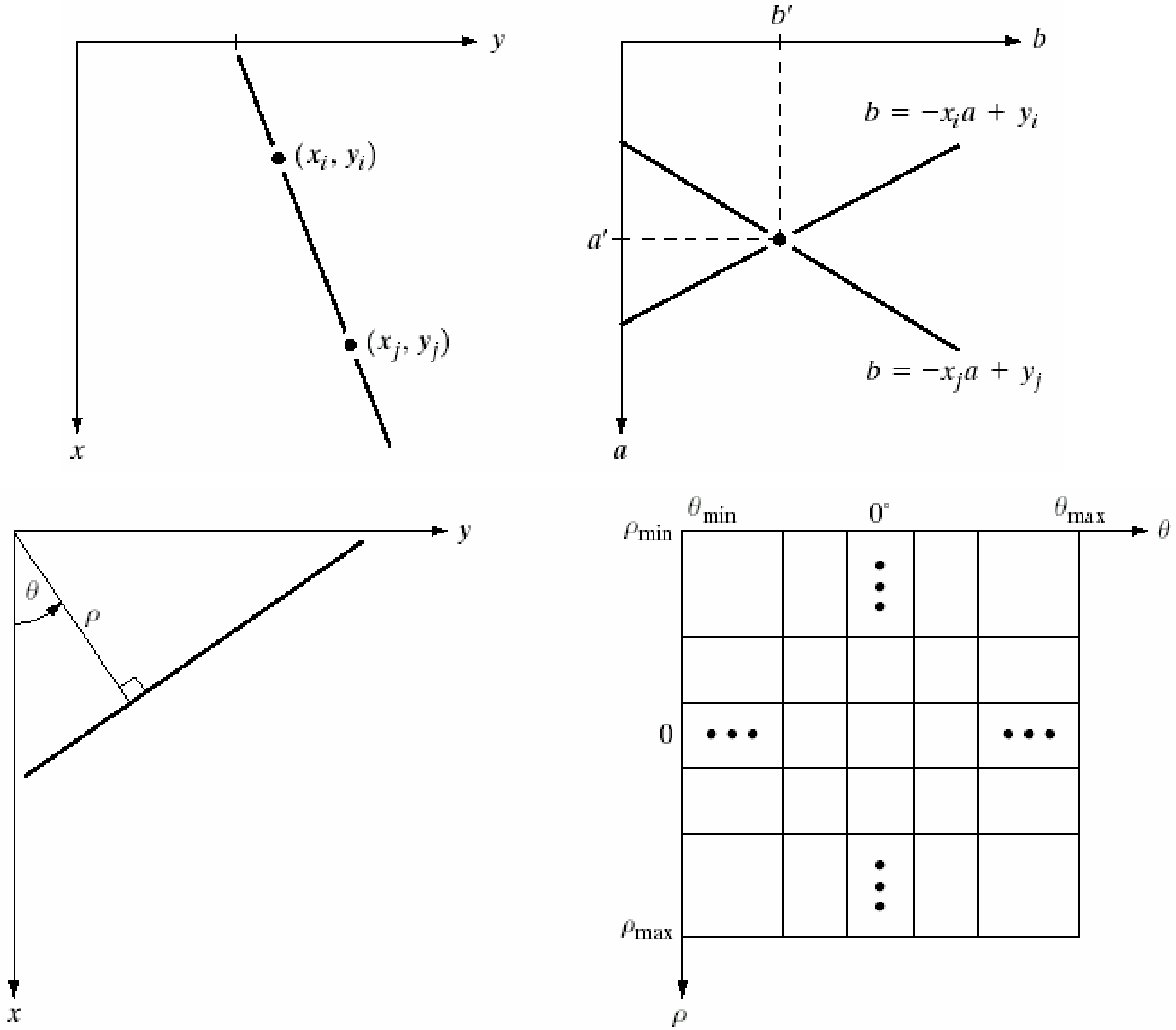
$$\mu_{Edge}(g(x,y)) = 1 - \frac{1}{1 + \frac{\sum_N |g(x,y) - g(i,j)|}{\Delta}}$$

Hough Transform

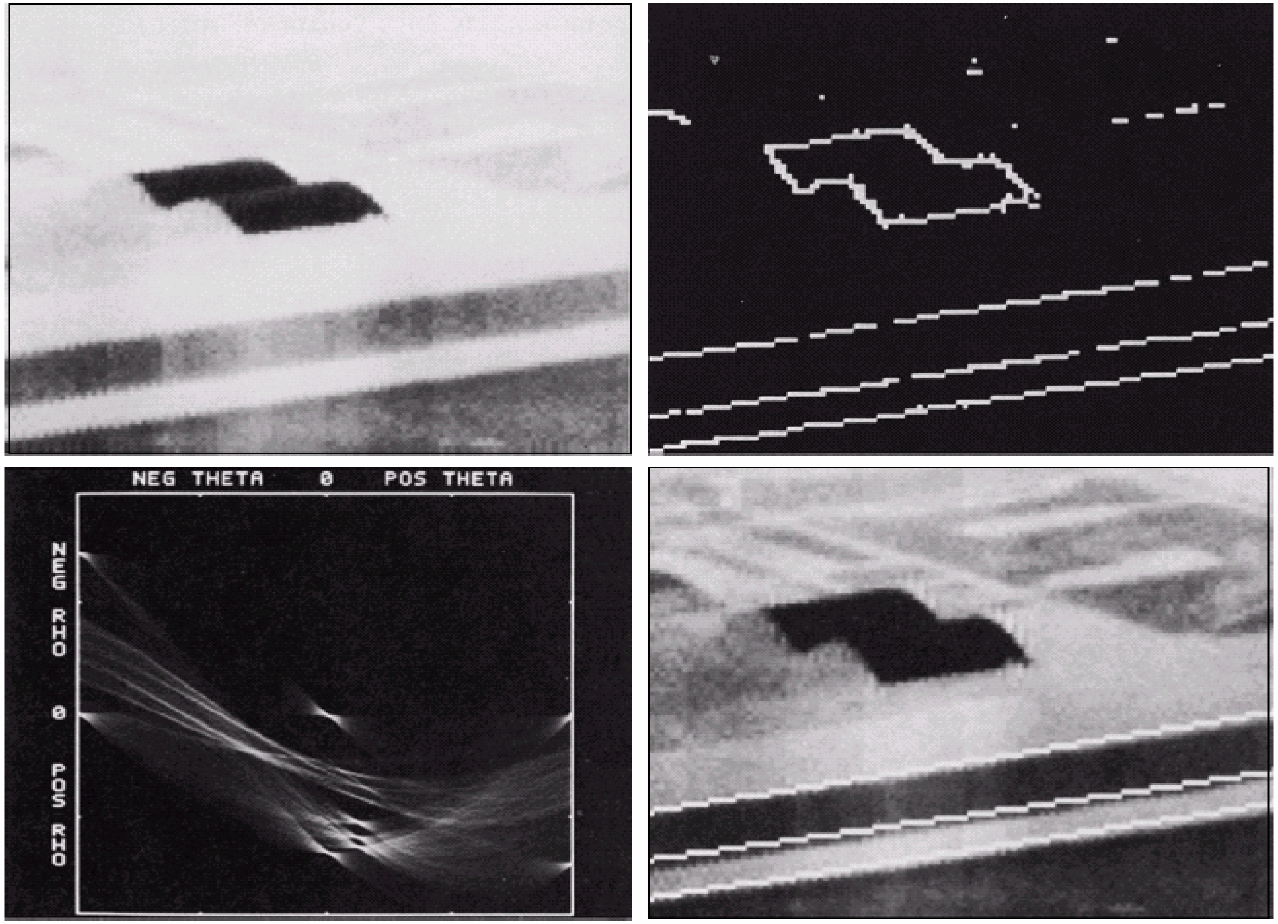
- Locate curves described by a few parameters
- Edge points are transformed into the parameter space and a cumulative map is created
- Local maximum corresponds to the parameters of a curve along which several points lie

- Straight lines
- Circles

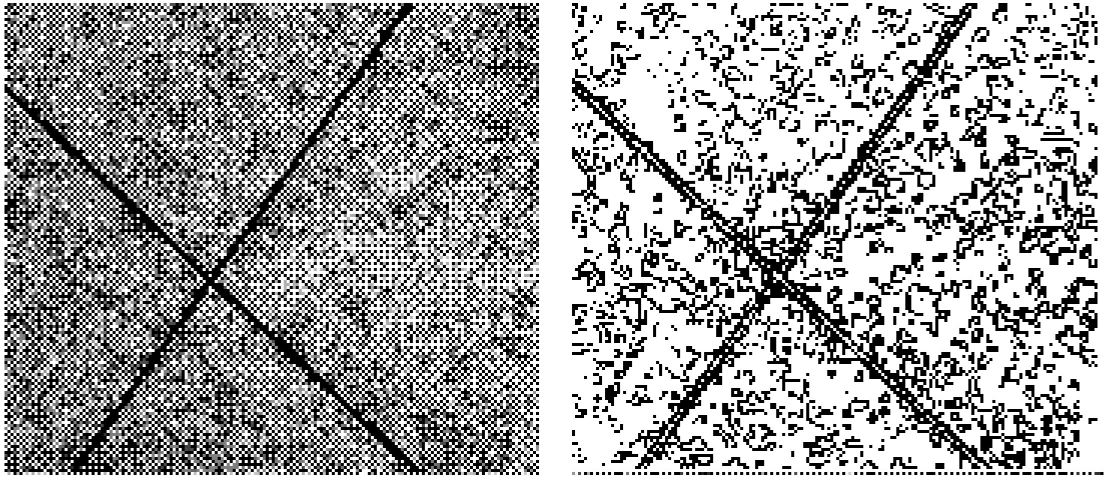
Parameterization of a Line



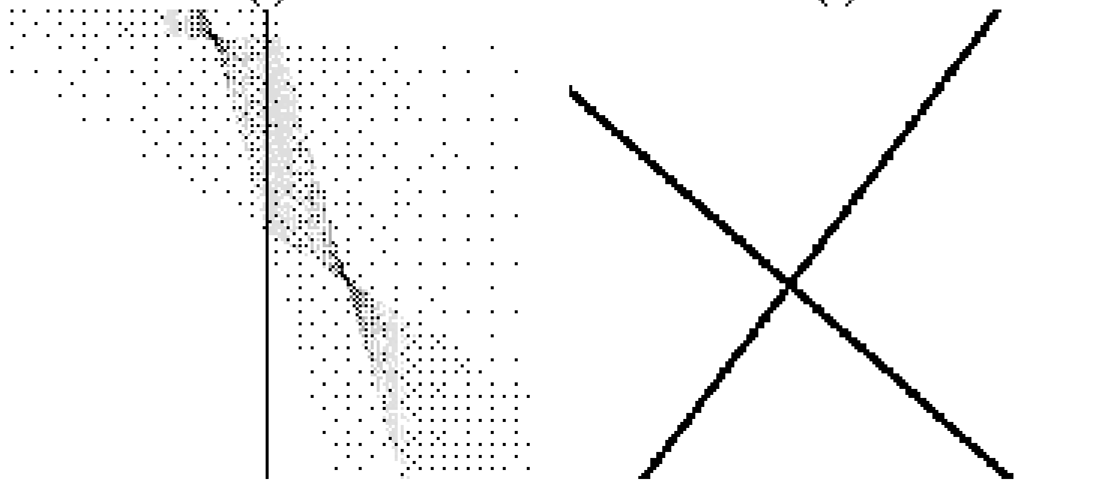
Detecting Lines via Hough Transform



Detecting Lines via Hough Transform

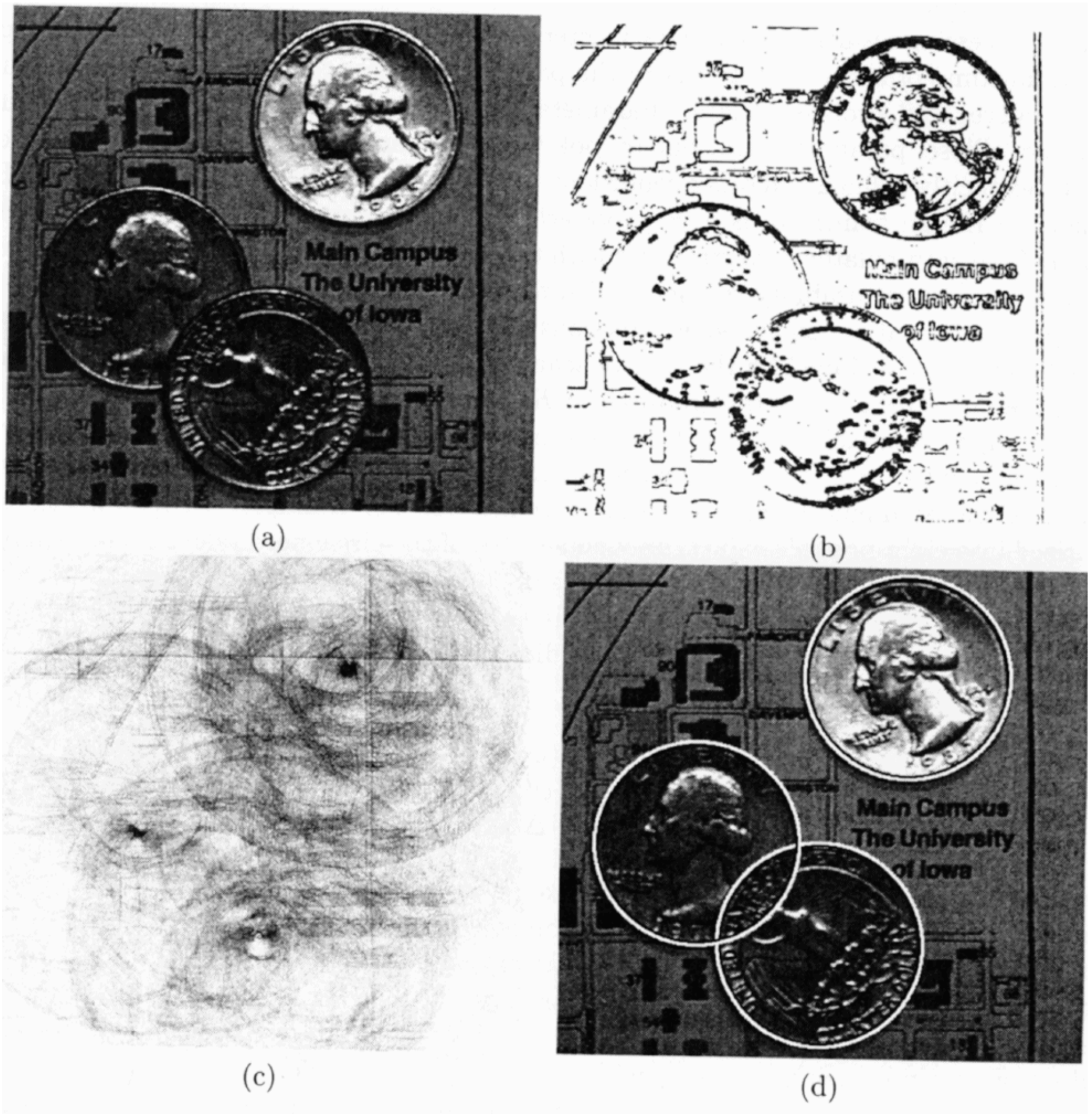


(a) (b)

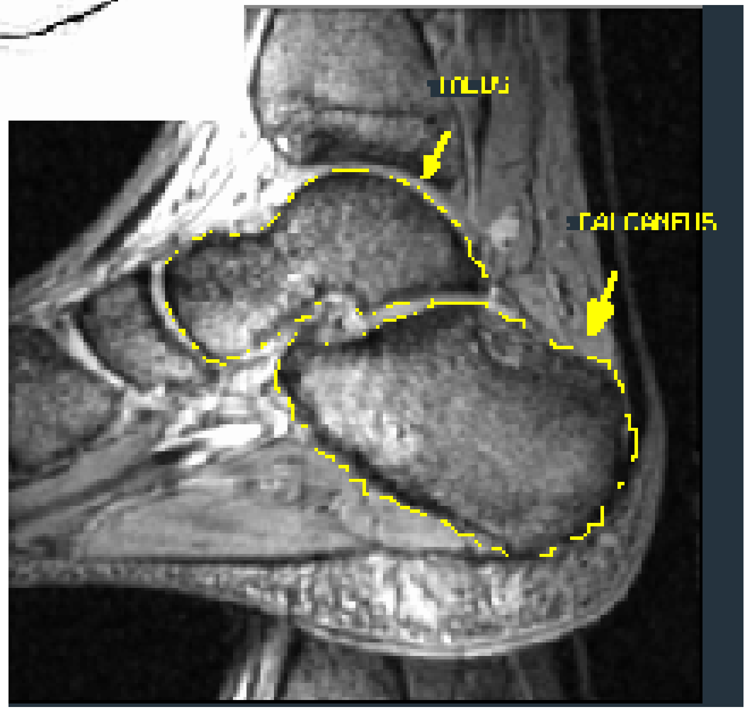


(c) (d)

Detecting Circles via Hough Transform



Live Wire Segmentation of the Knee and the Ankle



- Live wire
- Live lane
- Live wire 3D

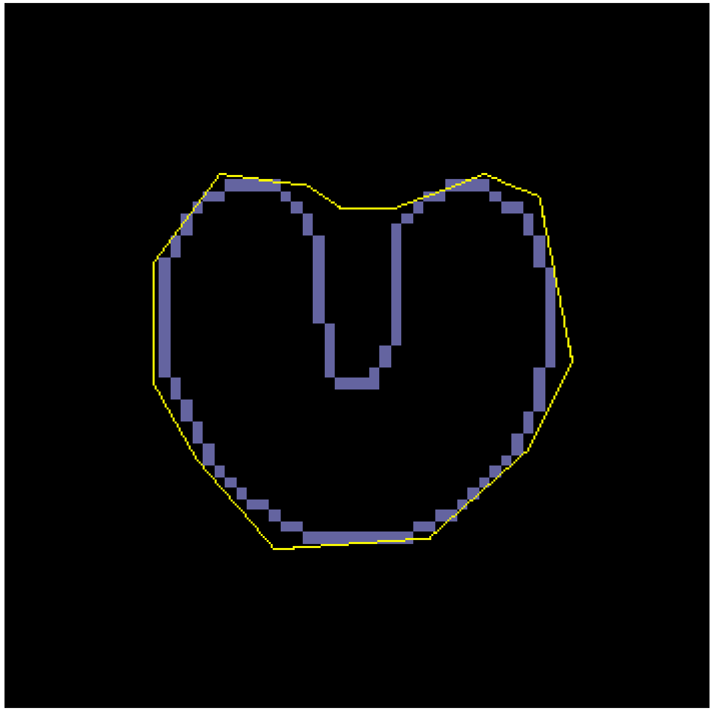
Deformable Boundaries

- Active/dynamic contour, snake
- Active surface
- Active shape model (ASM)
- Active appearance model (AAM)

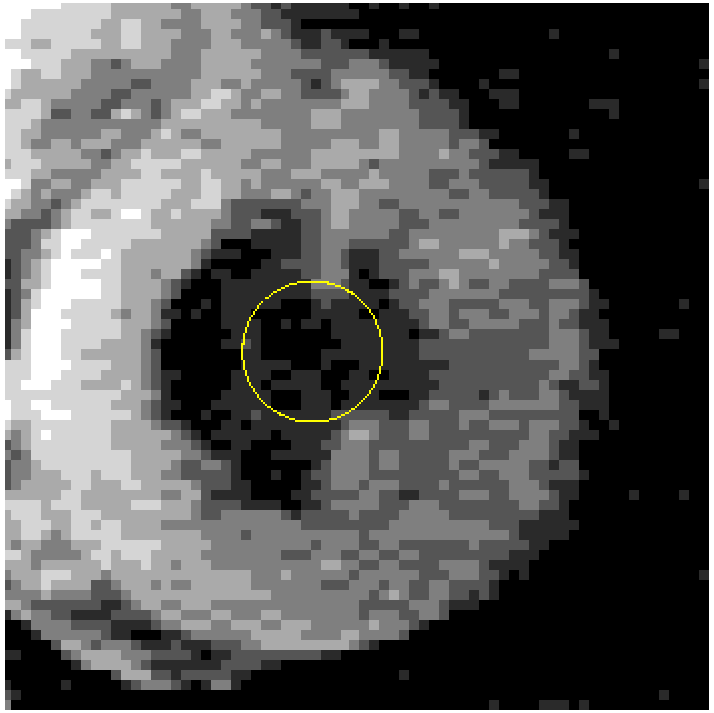
- Aim: minimize an energy functional with internal and external energy content

- Challenges
  - Tuning the effects of the energy components
  - Handling topology changes during evolution

Active Contour

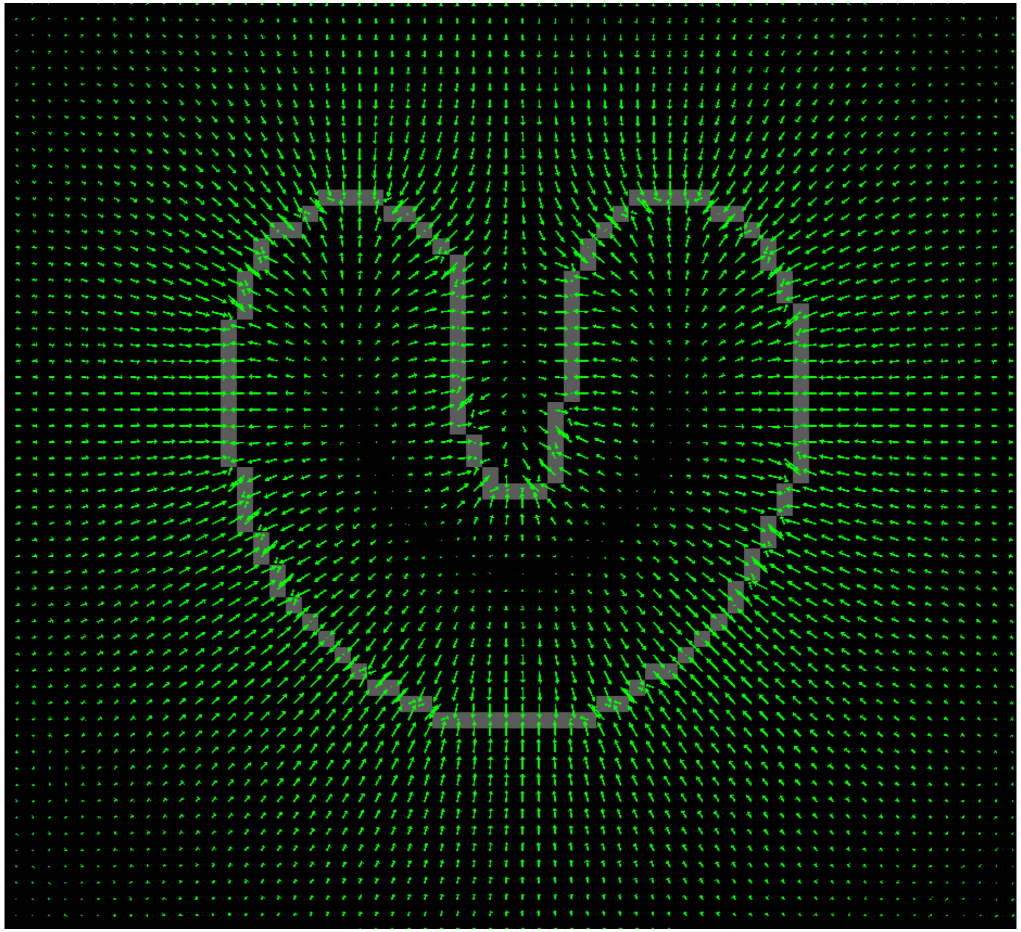


shrink wrap

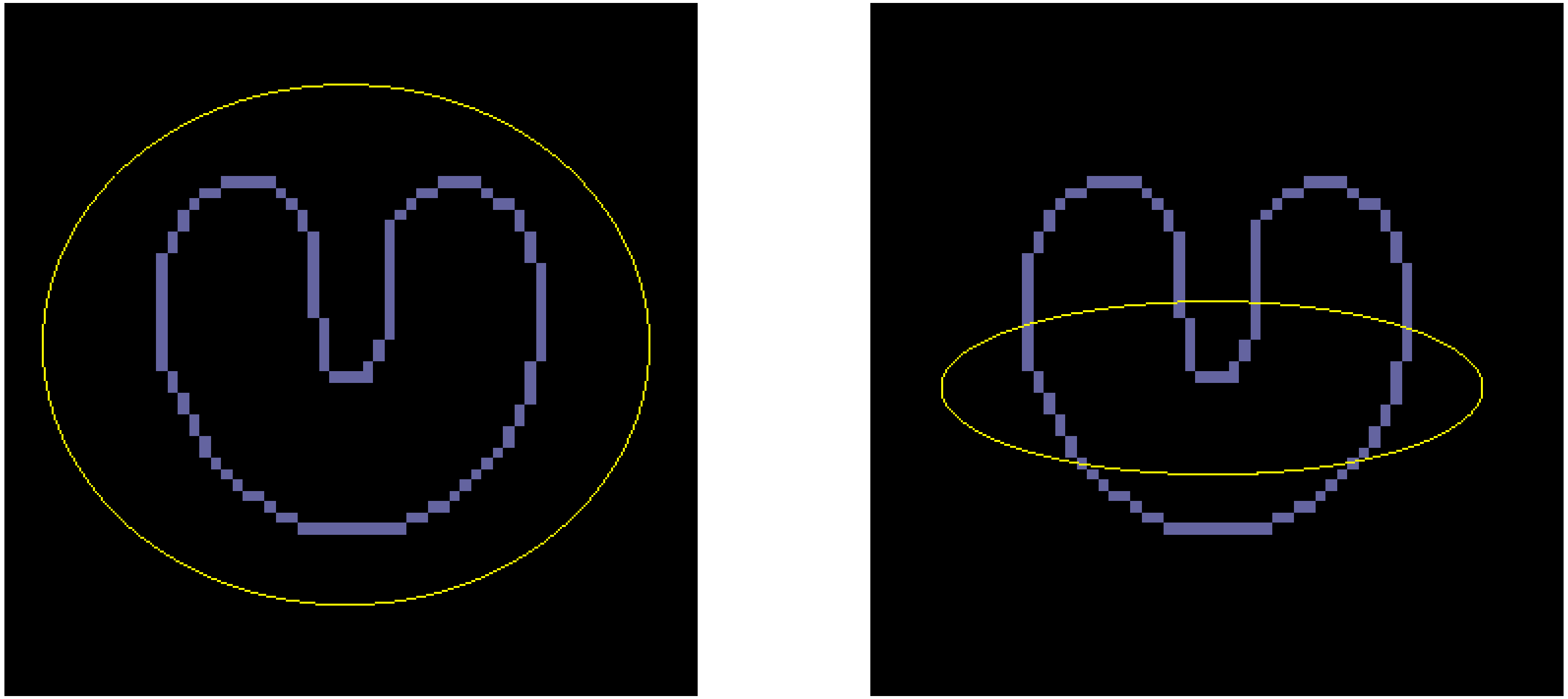


balloon

Gradient Vector Field



Active Contour with GVF



Deformable Surfaces in 3D

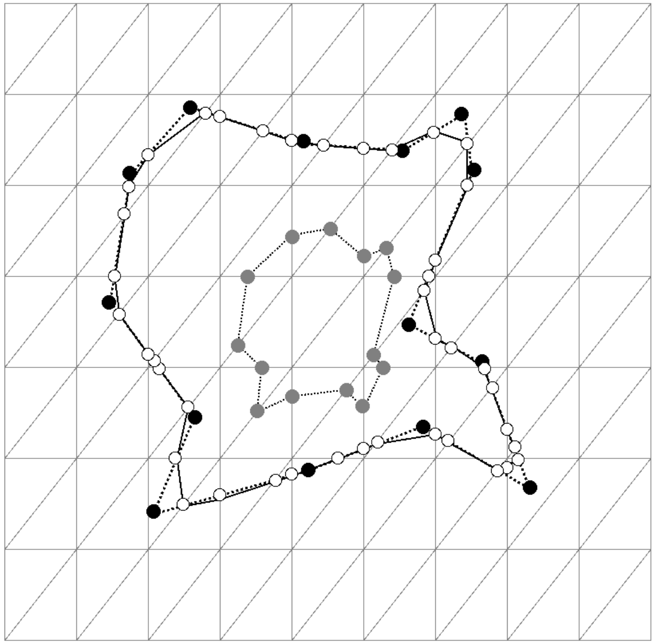
- Transition from 2D to 3D is not trivial!

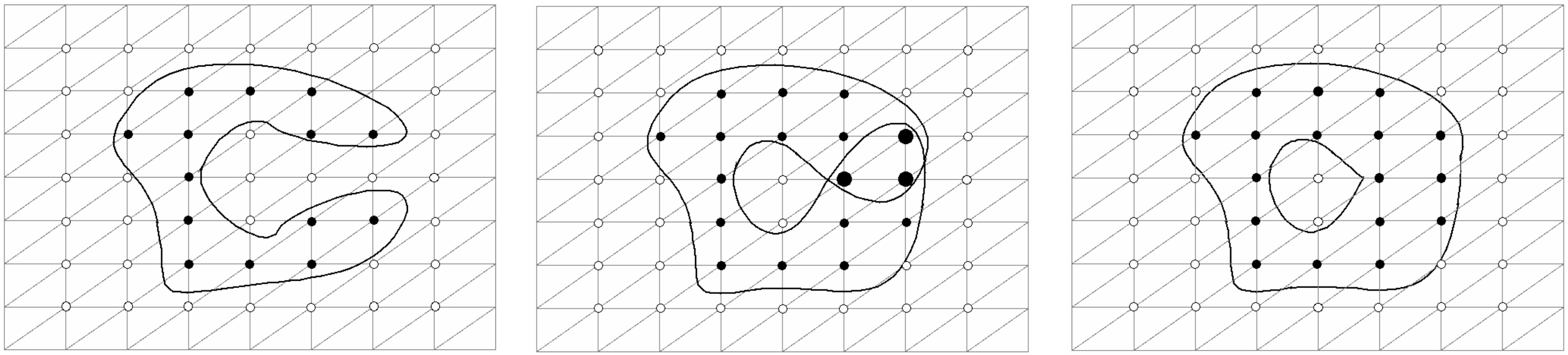
- 2D contour as polygon (vertices, edges)
- 3D surface as polyhedron (vertices, edges, faces)

- Self-crossing
- Topology changes

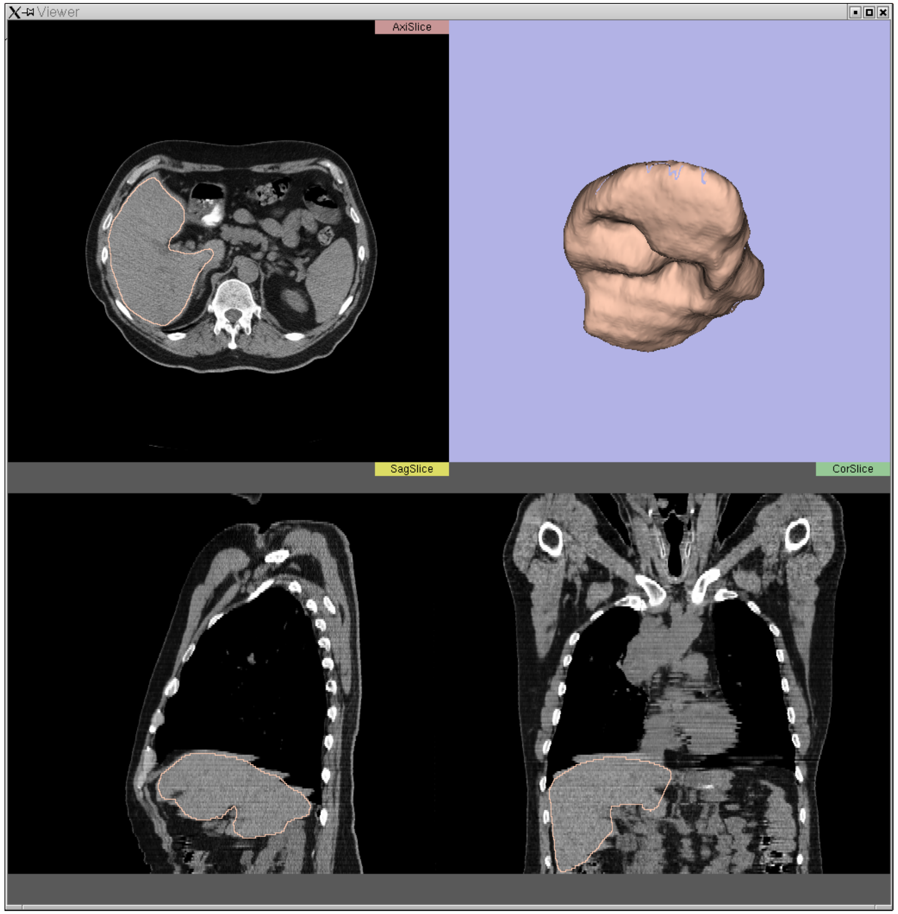
- Topology adaptive snakes (T-snakes)

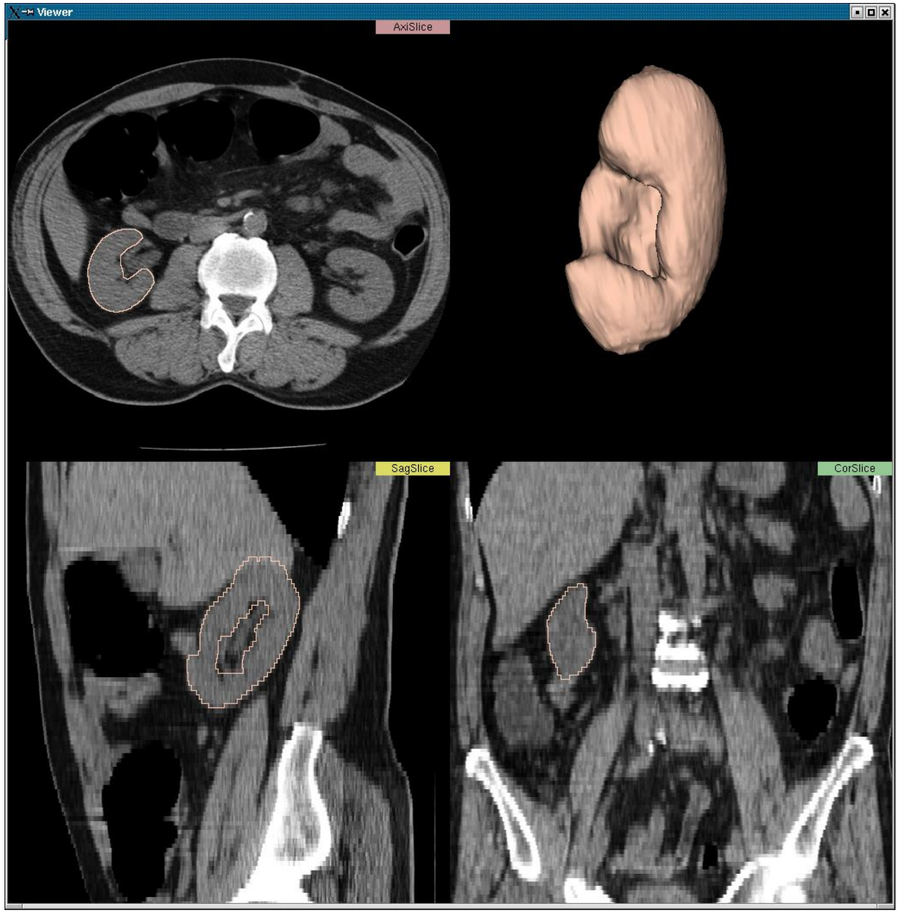
Affine cell image decomposition (ACID)





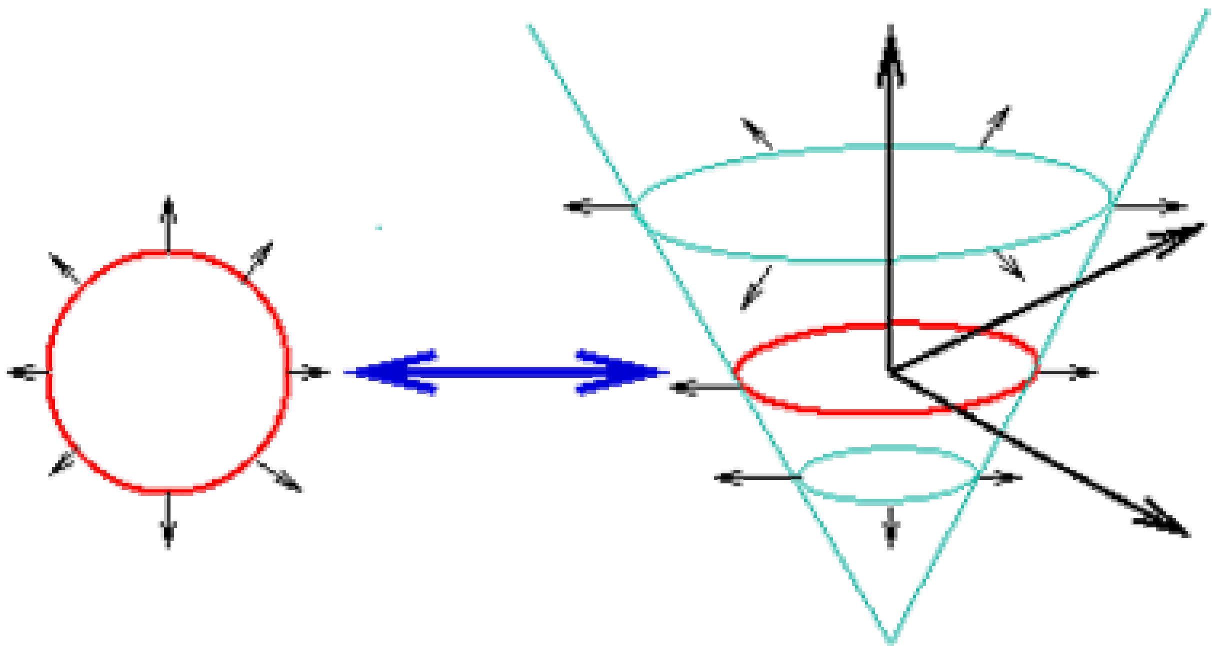
Active Surface Segmentations of the Liver and the Right Kidney



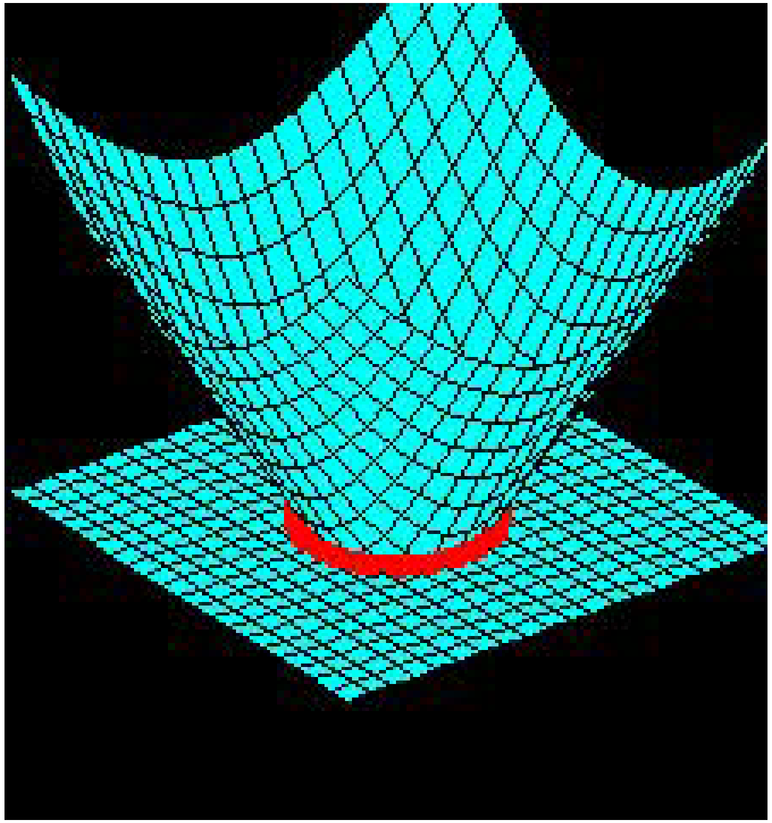


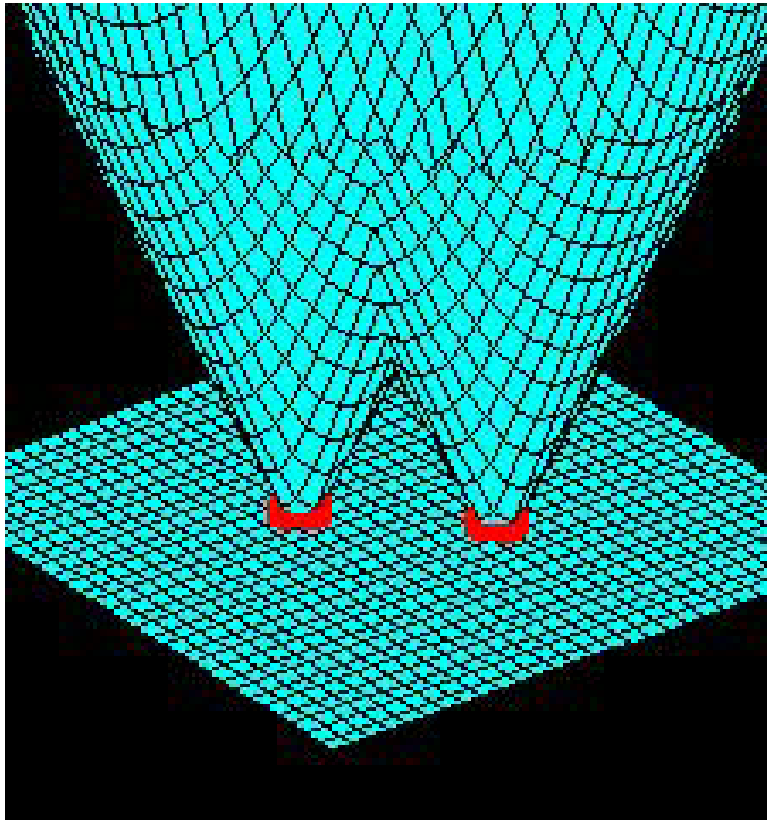
Level-set and Fast Marching Methods

- Contour/surface is represented as the zero level set of some evolving implicit function

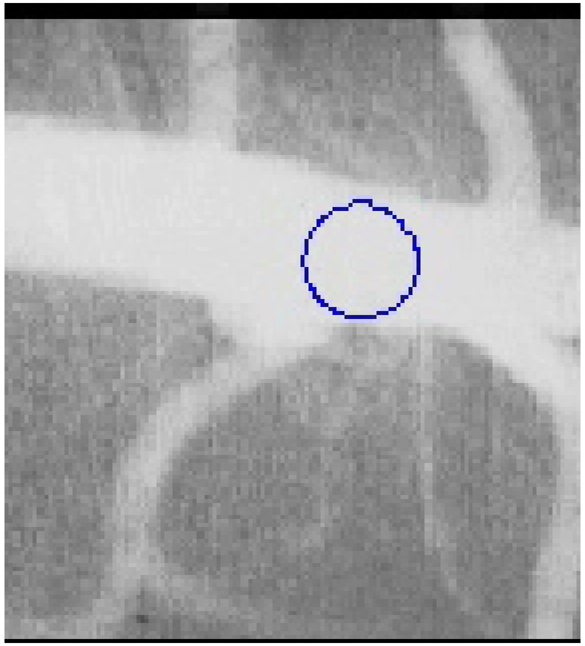


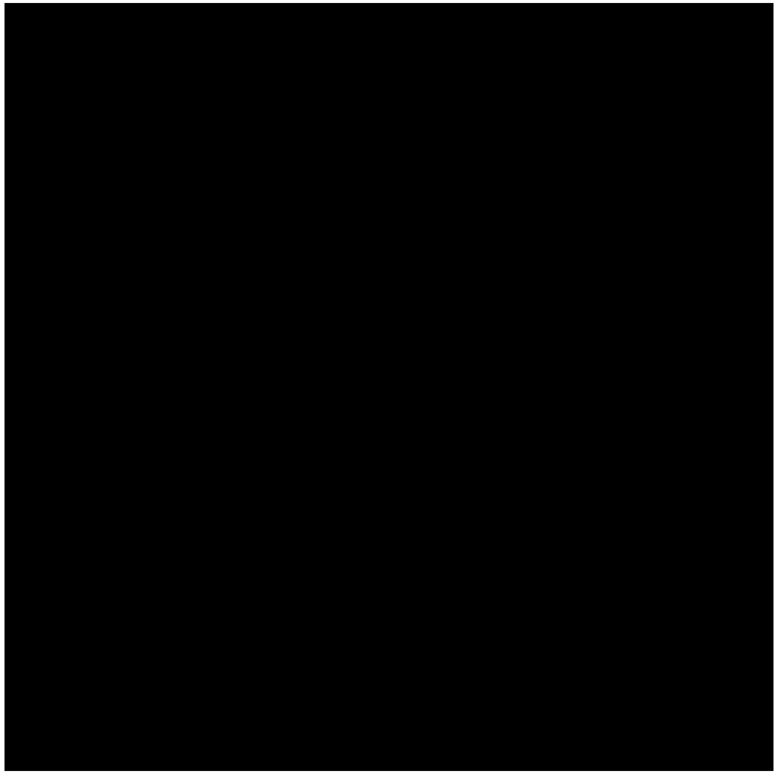
Evolving Level Set Functions





Segmenting Vessels and Gray Matter using Level-sets





Region-based Segmentation Methods

- Image pixels are assigned to object or background based on homogeneity statistics
- Advantage is that image information inside the object is considered
- Disadvantage is lack of provision for including shape of object in decision making process

Thresholding

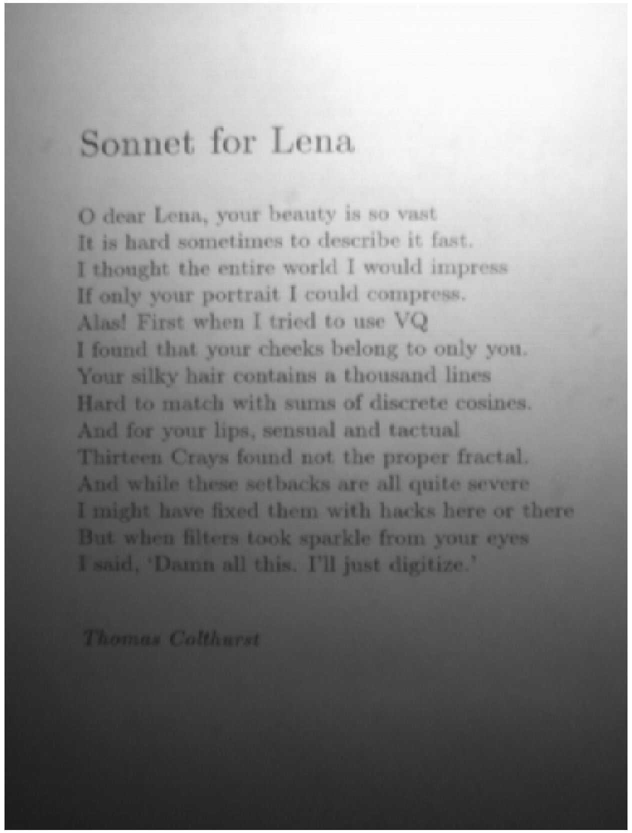
- General form: $T = T\{\, \boldsymbol{x}, A(\boldsymbol{x}), f(\boldsymbol{x}) \,\}$

  - Global: $T = T\{\, f(\boldsymbol{x}) \,\}$
  - Local: $T = T\{\, A(\boldsymbol{x}), f(\boldsymbol{x}) \,\}$
  - Adaptive / dynamic: $T = T\{\, \boldsymbol{x}, A(\boldsymbol{x}), f(\boldsymbol{x}) \,\}$

  - Single threshold
  - Band thresholding
  - Hysteresis thresholding

- Dozens of strategies for determining thresholds

Thresholding

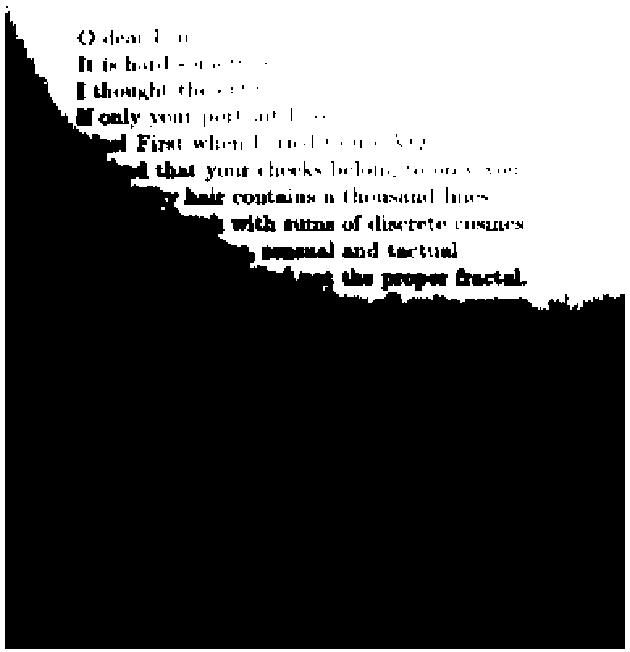


Sonnet for Lena

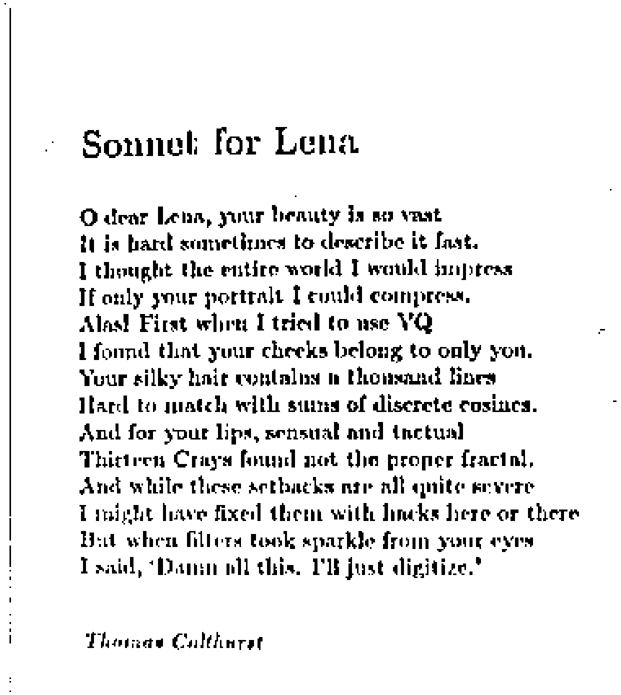
O dear Lena, your beauty is so vast
It is hard sometimes to describe it fast.
I thought the entire world I would impress
If only your portrait I could compress.
Alas! First when I tried to use VQ
I found that your cheeks belong to only you.
Your silky hair contains a thousand lines
Hard to match with sums of discrete cosines.
And for your lips, sensual and tactual
Thirteen Crays found not the proper fractal.
And while these setbacks are all quite severe
I might have fixed them with hacks here or there
But when filters took sparkle from your eyes
I said, 'Damn all this. I'll just digitize.'

Thomas Colthurst

Original image



Global thresholding



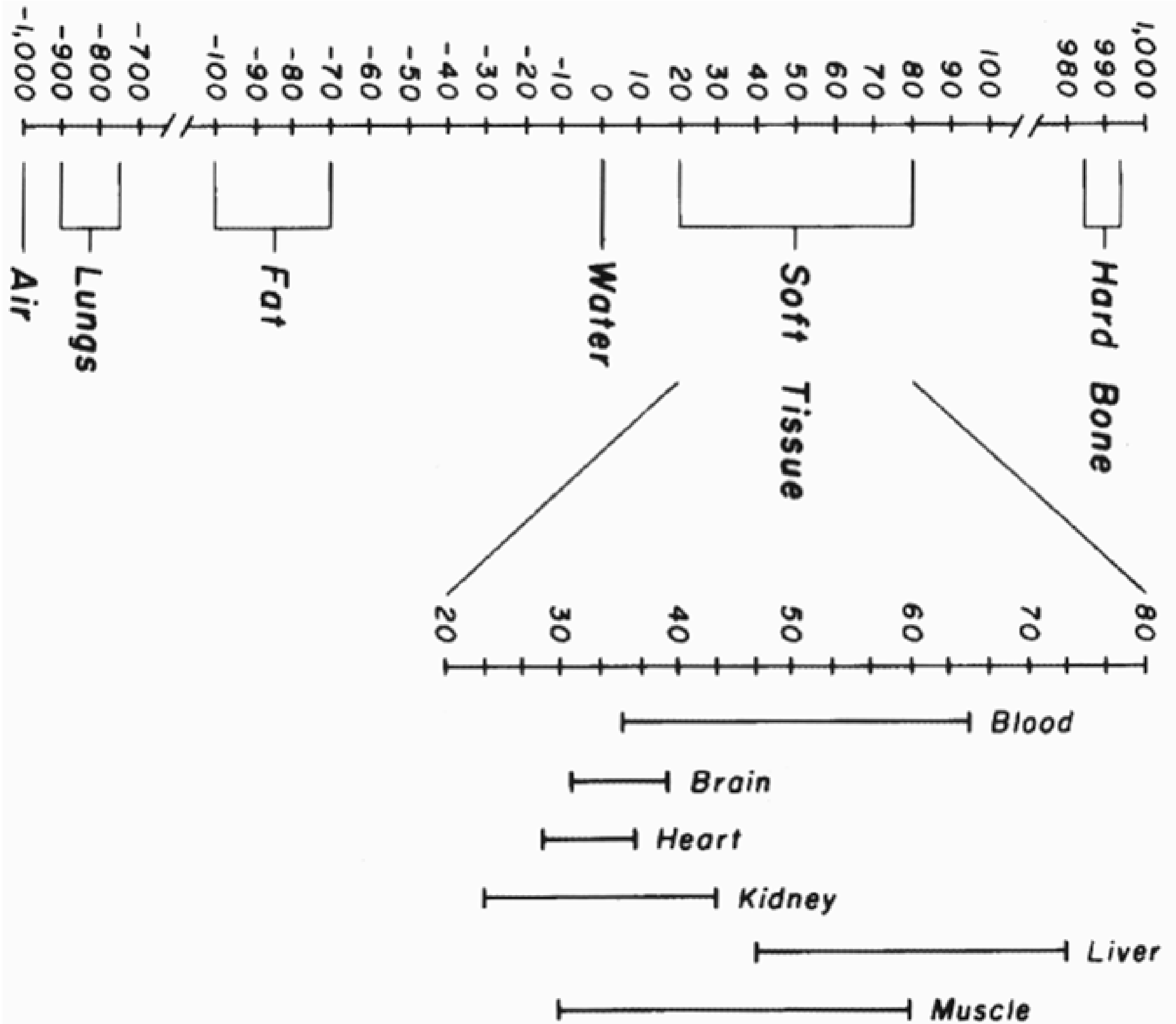
Sonnet for Lena

O dear Lena, your beauty is so vast
It is hard sometimes to describe it fast.
I thought the entire world I would impress
If only your portrait I could compress.
Alas! First when I tried to use VQ
I found that your cheeks belong to only you.
Your silky hair contains a thousand lines
Hard to match with sums of discrete cosines.
And for your lips, sensual and tactual
Thirteen Crays found not the proper fractal.
And while these setbacks are all quite severe
I might have fixed them with hacks here or there
But when filters took sparkle from your eyes
I said, 'Damn all this. I'll just digitize.'

Thomas Colthurst

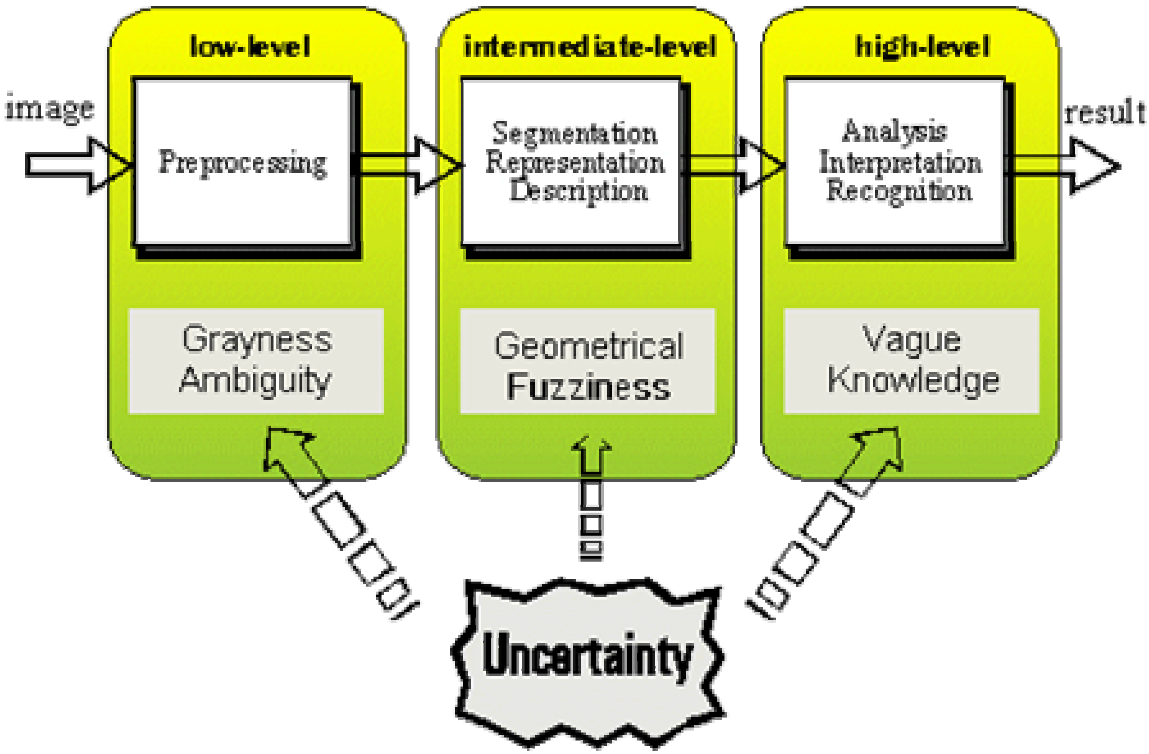
Local thresholding

Hounsfield Unit Ranges for CT

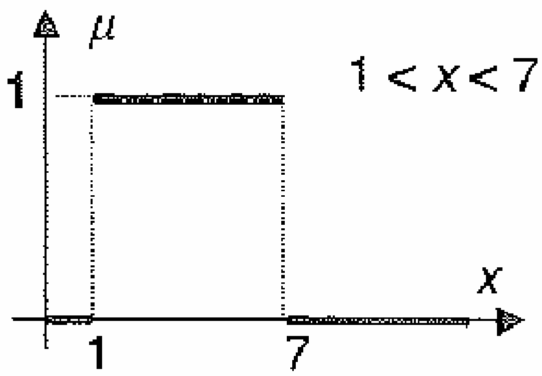


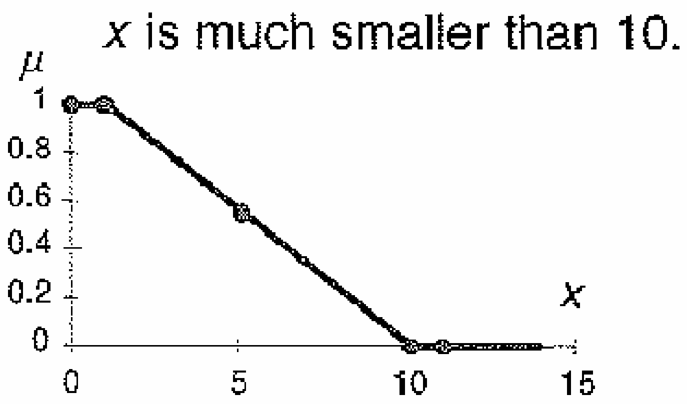
Fuzzy Image Processing

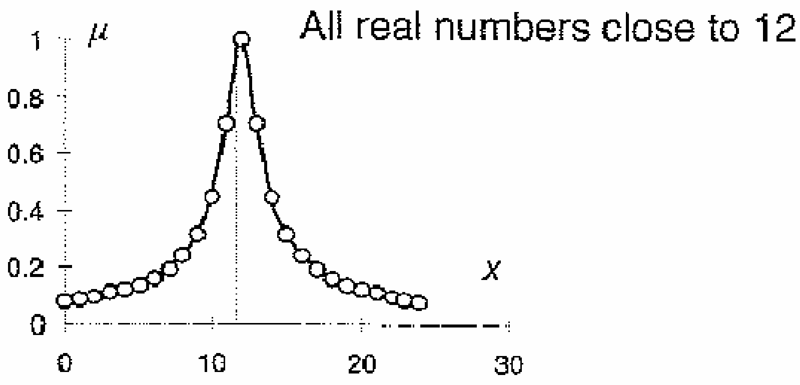
- Why Use Fuzzy Image Processing?



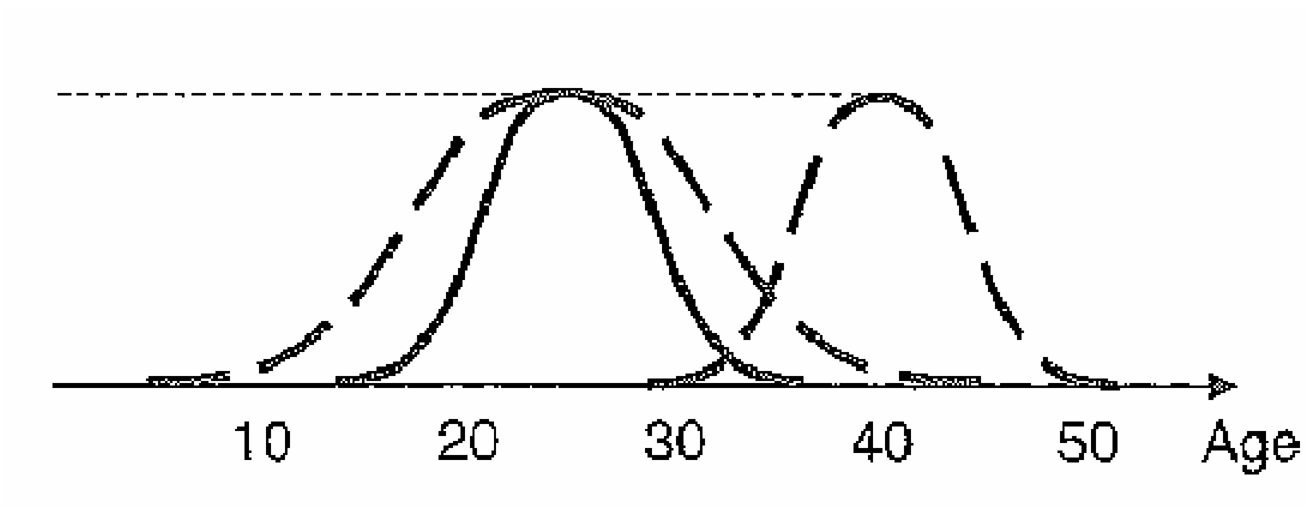
Membership functions



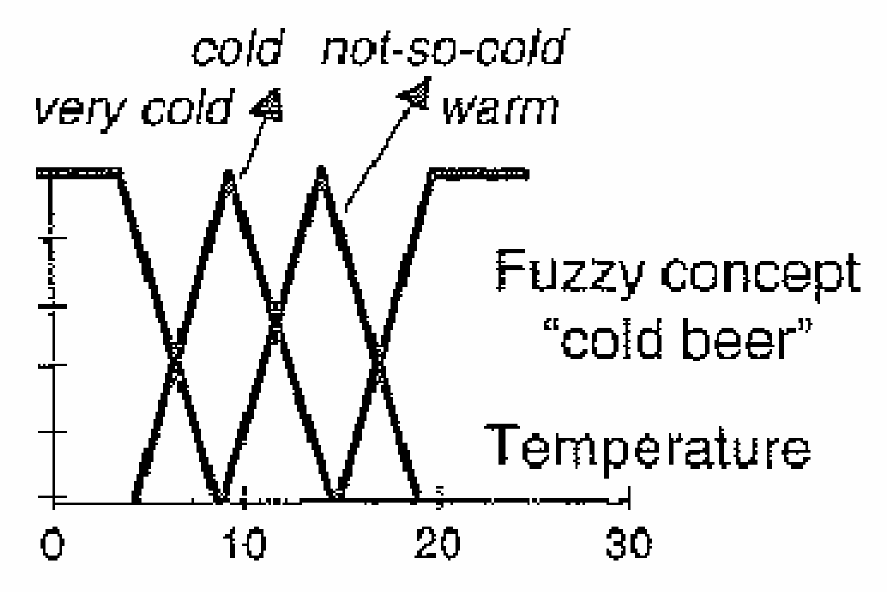




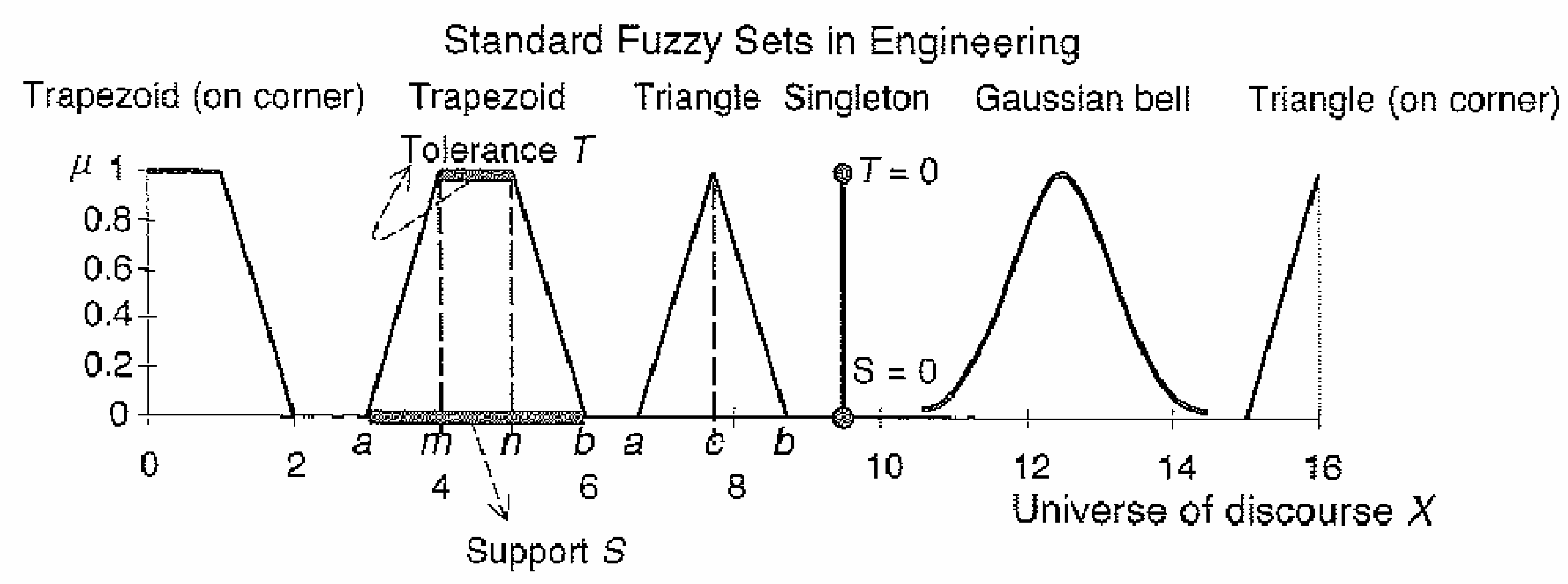
„young person"



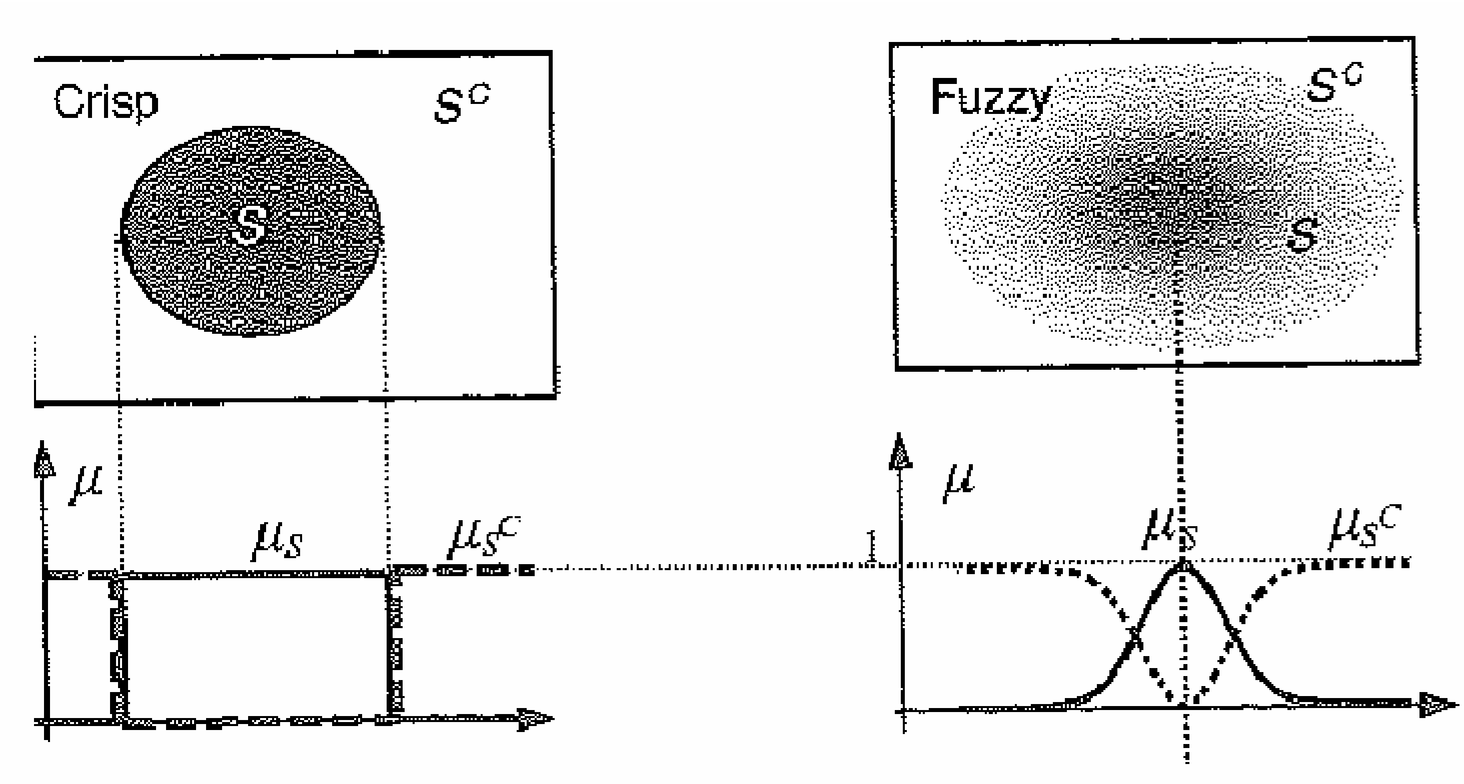
„cold bear”


cold
not-so-cold
very cold
warm
Fuzzy concept
“cold beer”
Temperature
0
10
20
30

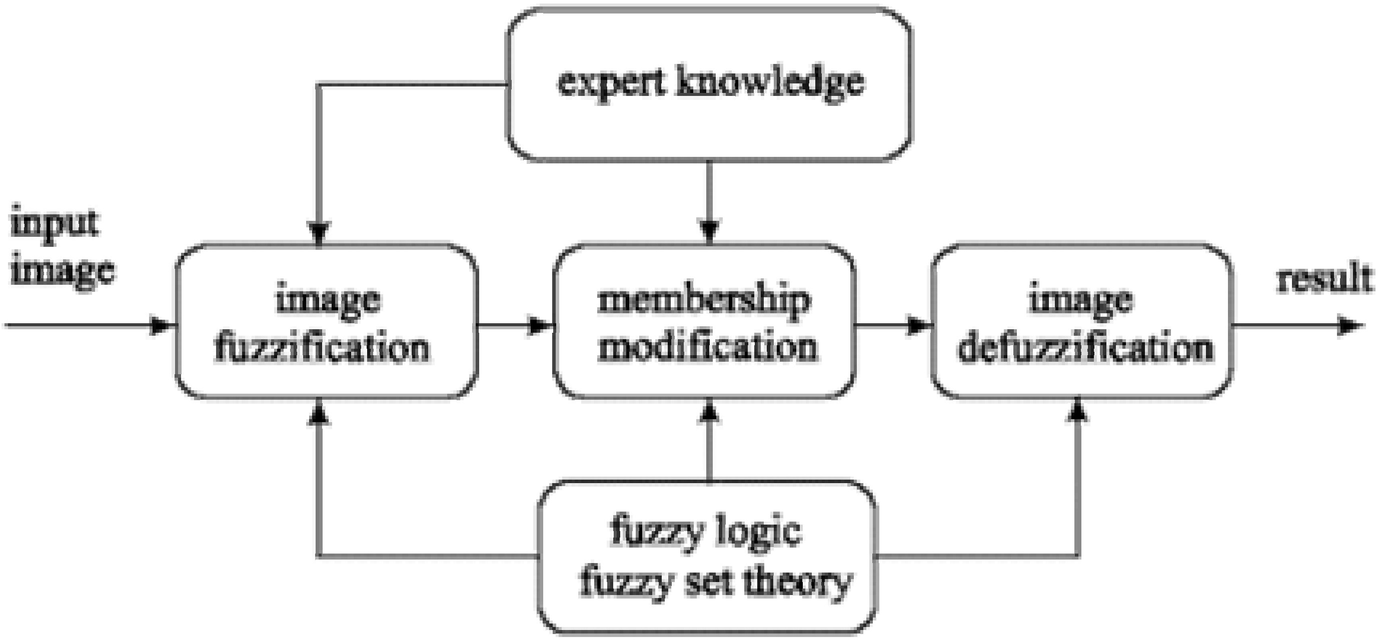
Typical shapes of membership functions



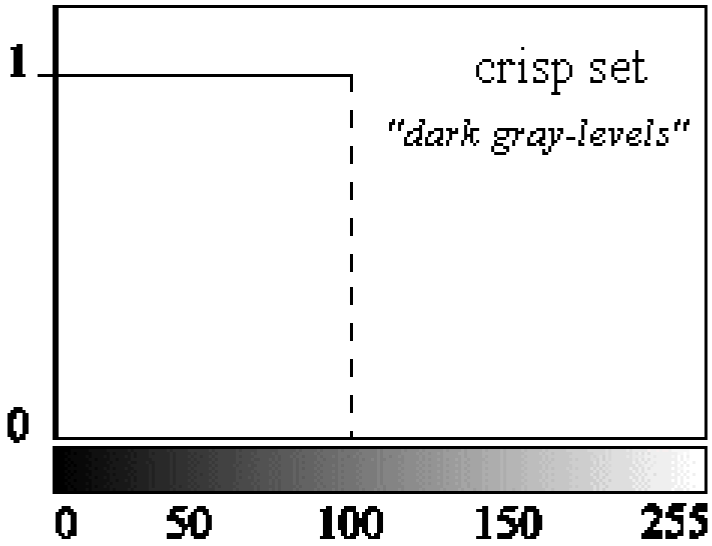
Set and its complement

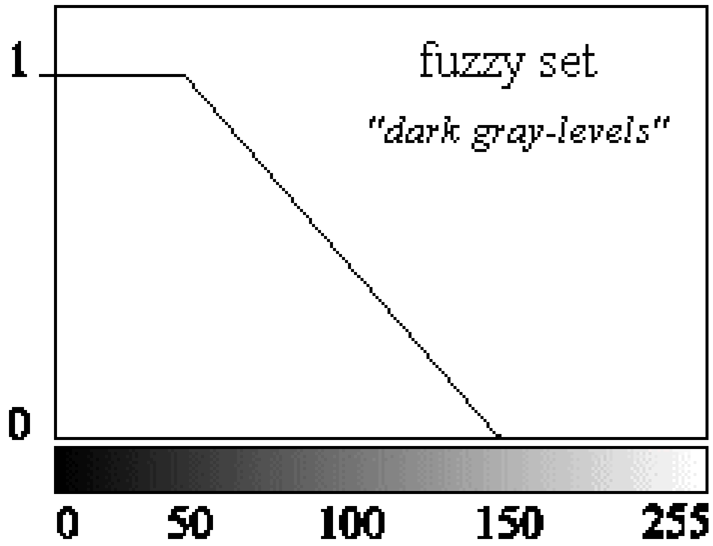


General Structure of Fuzzy Image Processing

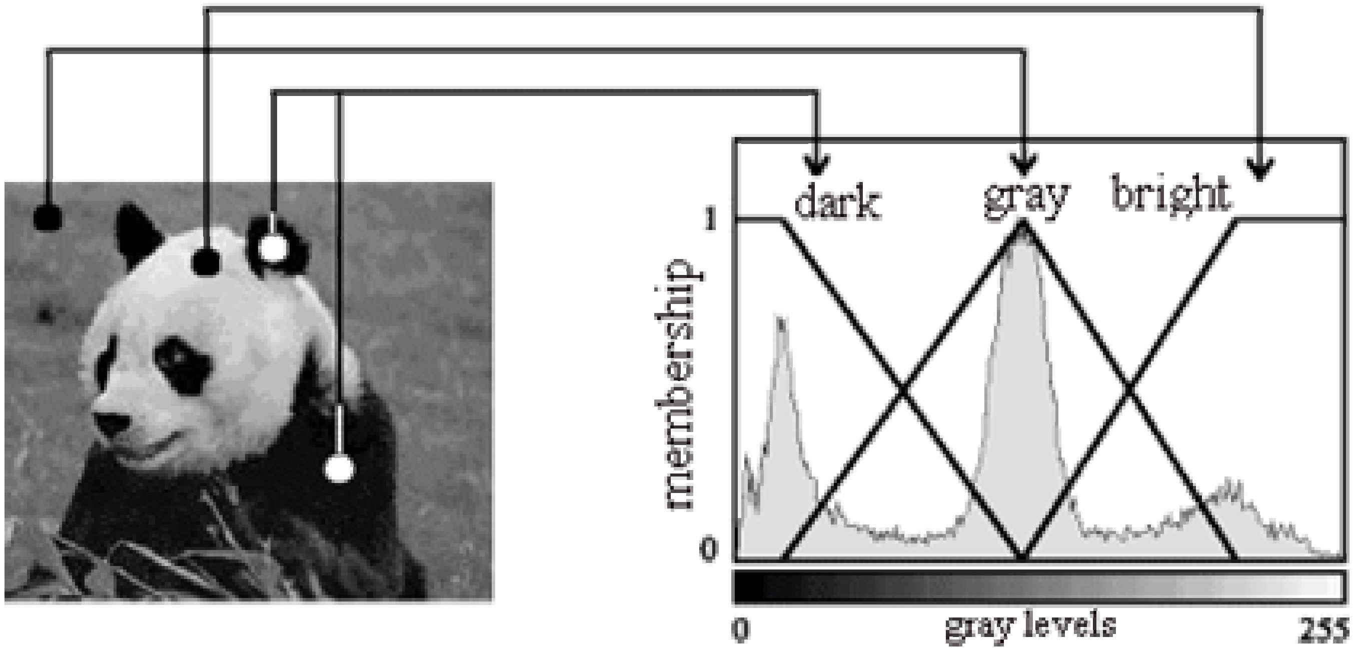


Representing "dark gray-levels" with sets

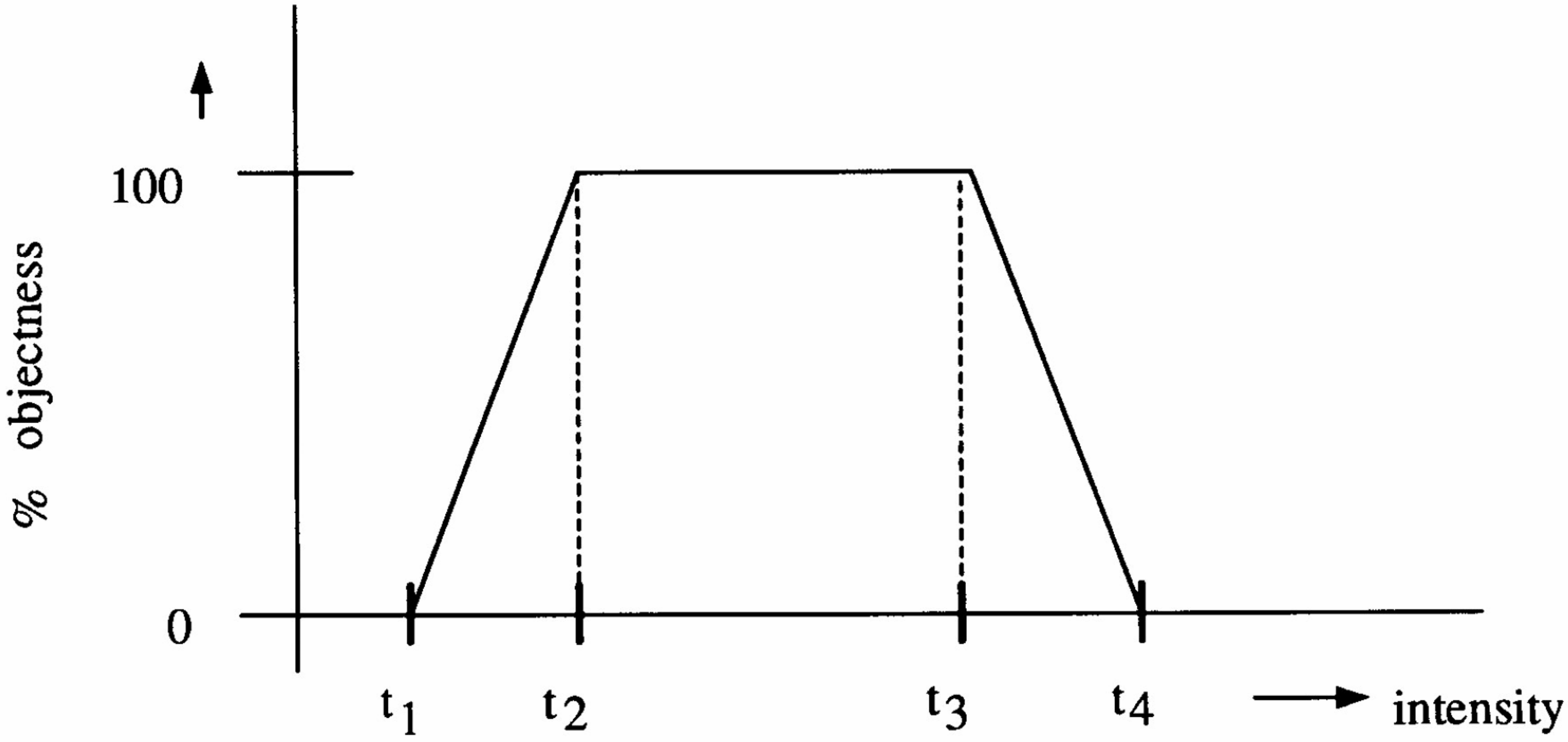




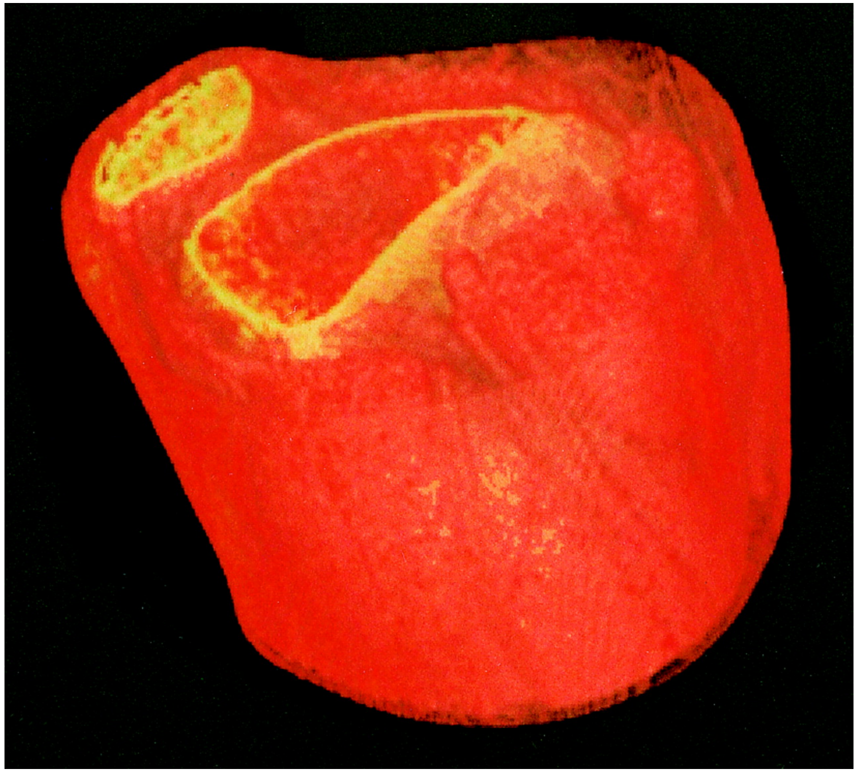
Histogram Fuzzification with Three Membership Functions



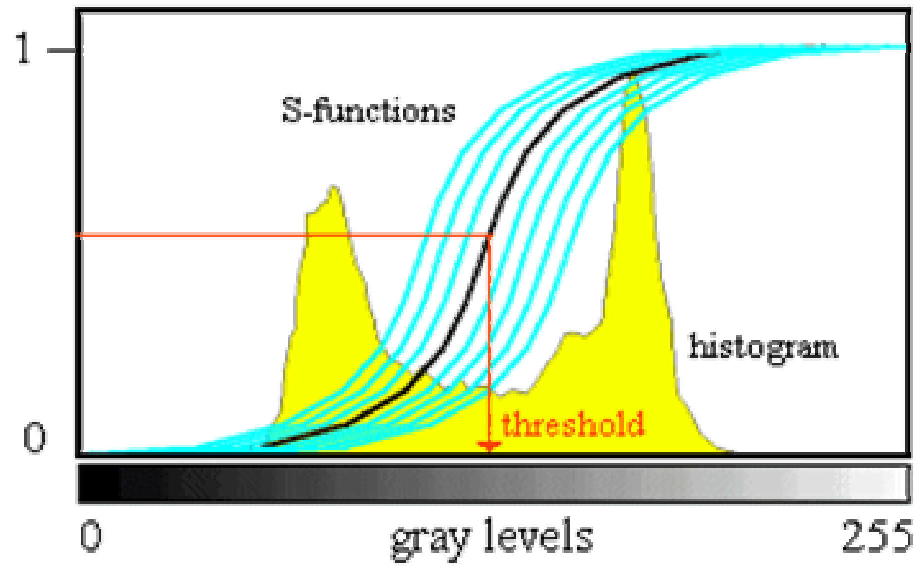
Fuzzy thresholding



Example of fuzzy thresholding



Thresholding Using Fuzziness



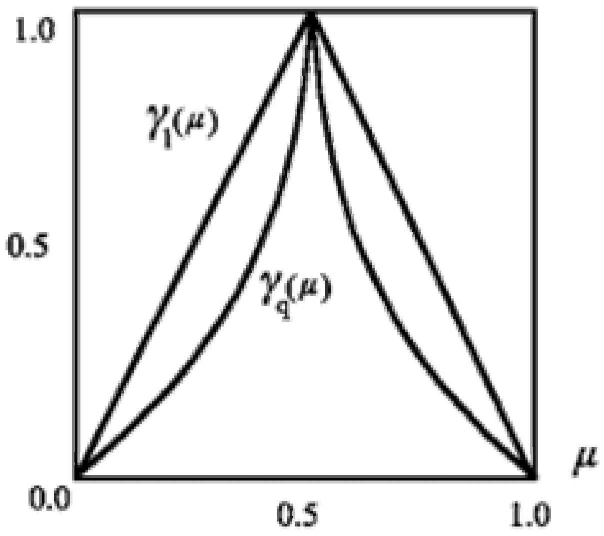
Measures of Fuzziness

- Linear index of fuzziness for an image of size MxN:

$$\gamma_1 = \frac{2}{MN}\sum_m \sum_n \min\left(\mu_{mn}, 1-\mu_{mn}\right)$$

- Quadratic index of fuzziness:

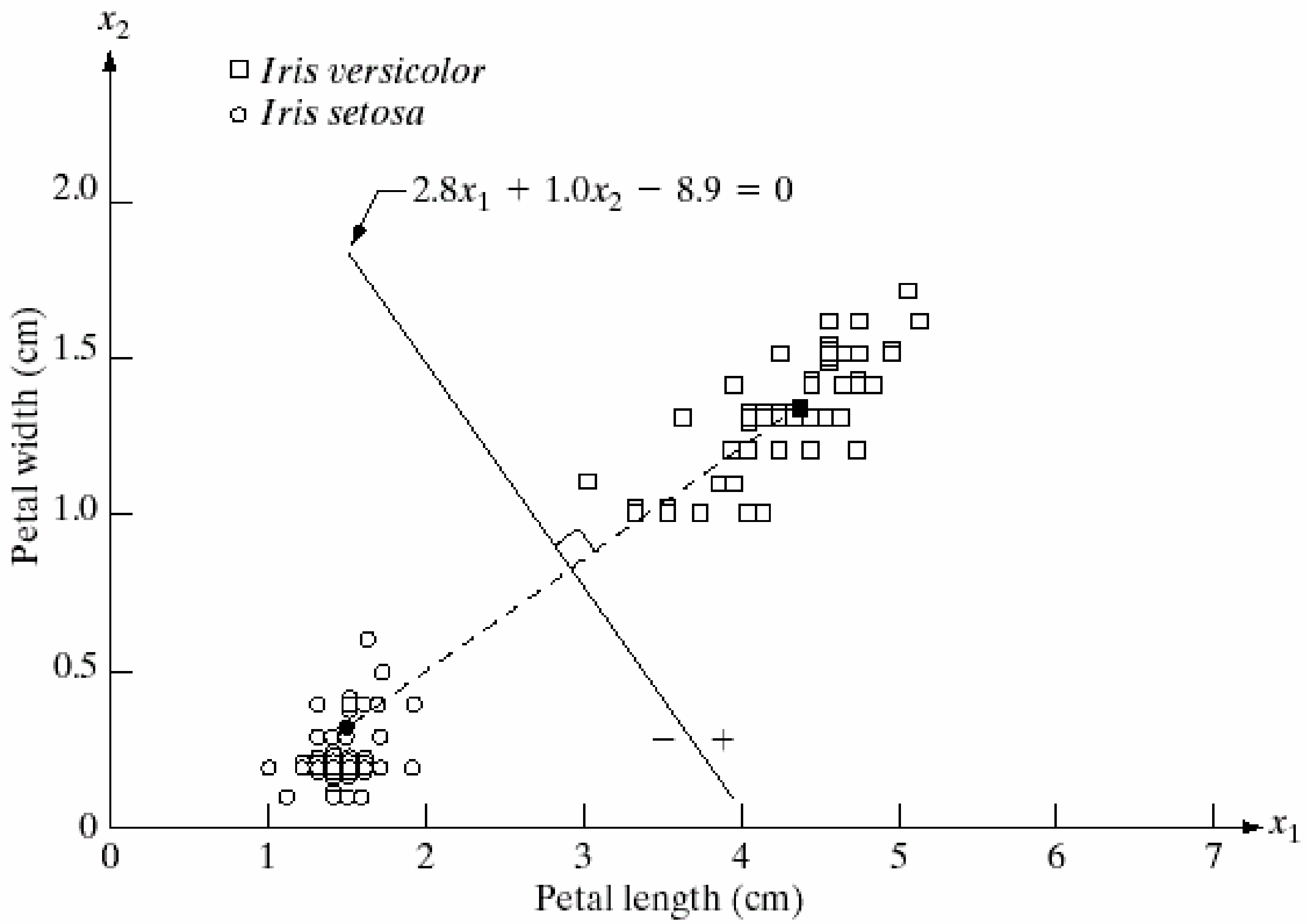
$$\gamma_q = \frac{2}{\sqrt{MN}}\left[\sum_m \sum_n \left\{\min\left(\mu_{mn}, 1-\mu_{mn}\right)\right\}^2\right]^{\frac{1}{2}} .$$



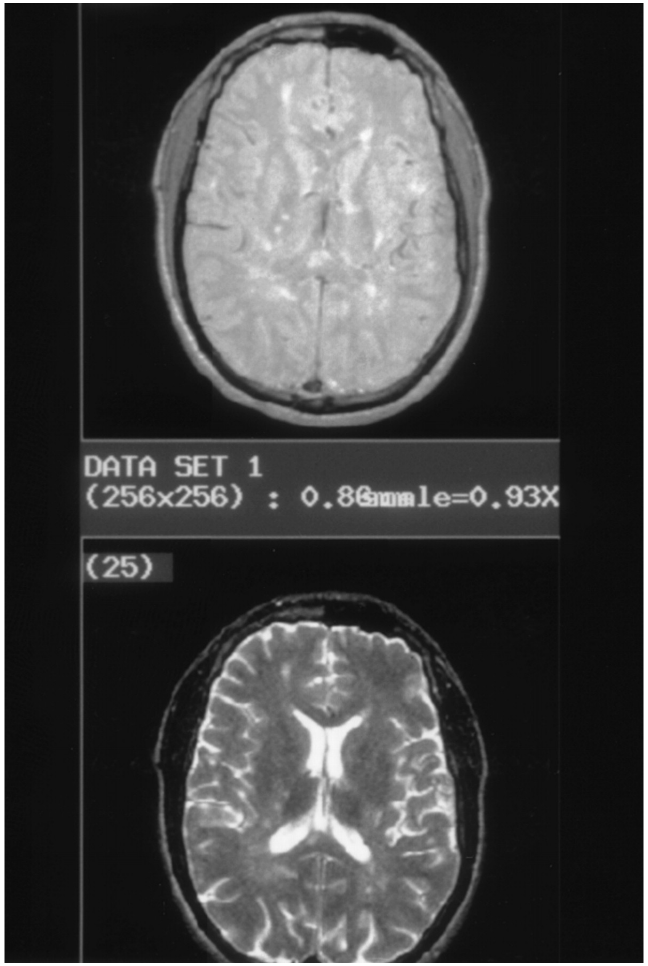
- Fuzzy entropy:

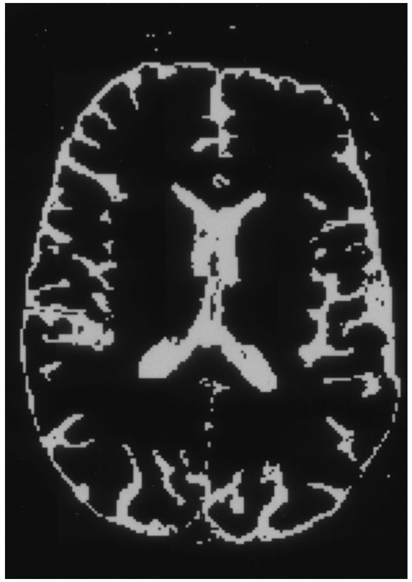
$$H_{\log}(X) = \frac{1}{MN\ln 2}\sum_m \sum_n S_n\left(\mu_{mn}\right), \qquad S_n\left(\mu_{mn}\right) = -\mu_{mn}\ln\mu_{mn} - \left(1-\mu_{mn}\right)\ln\left(1-\mu_{mn}\right).$$

Clustering Techniques



Clustering using two features





k-nearest neighbors (kNN)

- Training: identify two sets of voxels X_O in object region and X_{NO} in background
- For each voxel *v* in input scenes, find its location *P* in feature space
- Find *k* voxels closest to *P* from sets X_O and X_{NO}
- If a majority of those are from X_O, *v* belongs to object, otherwise to background
- Fuzzy kNN is possible
  - if *m* out of *k* nearest neighbors of voxel *v* belongs to object, than we can assign $\mu(v)=m/k$ as the membership of *v* in the object

Algorithm 1 K-Means Clustering

1. Consider a set of n data points (feature vectors) to be clustered.
2. Assume the number of clusters, or classes, k, is known. $2 \leq k < n$.
3. Randomly select k initial cluster centre locations.
4. All data points are assigned to a partition, defined by the nearest cluster centre.
5. The cluster centres are moved to the geometric centroid (centre of mass) of the data points in their respective partitions.
6. Repeat from (4) until the overall objective function is smaller than a given tolerance, or the centres don't move to a new point.

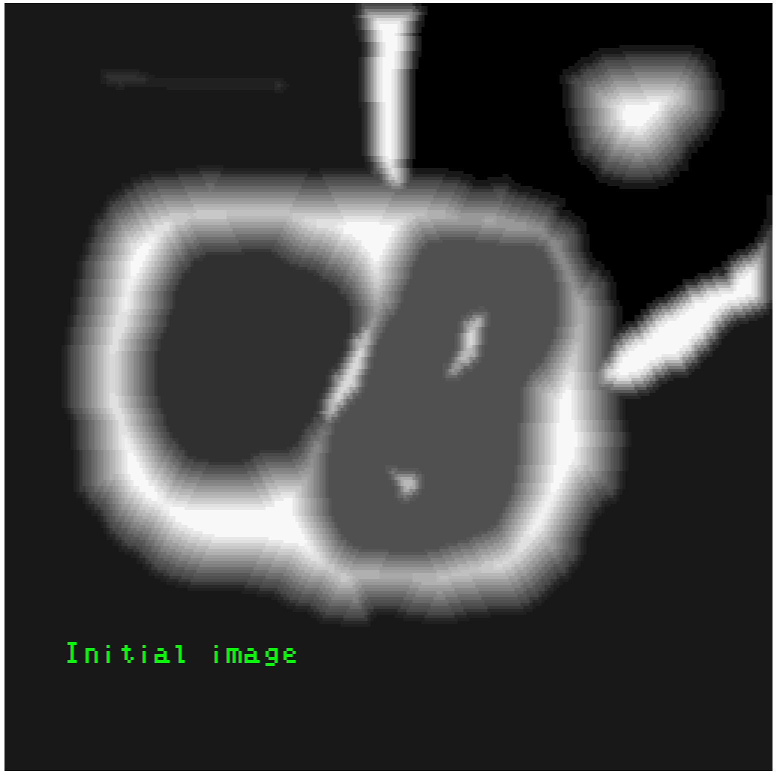
Algorithm 2 Fuzzy C-Means Clustering

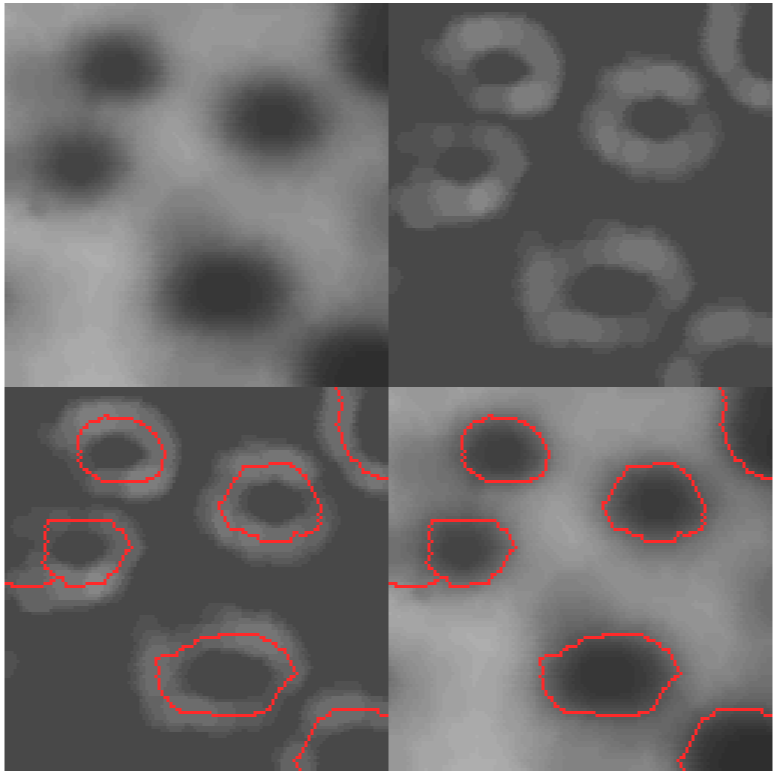
1. Consider a set of n data points (feature vectors) to be clustered, $\mathbf{x}_i$.
2. Assume the number of clusters, or classes, c, is known. $2 \leq c < n$.
3. Choose an appropriate level of cluster fuzziness, $m \in \mathbb{R}_{>1}$.
4. Initialise the $(n \times c)$ sized membership matrix U to random values such that $u_{ij} \in [0, 1]$ and $\sum_{j=1}^{c} u_{ij} = 1$.
5. Calculate the cluster centres $\mathbf{c}_j$ using $\mathbf{c}_j = \frac{\sum_{i=1}^{n}(u_{ij})^m \mathbf{x}_i}{\sum_{i=1}^{n}(u_{ij})^m}$, for $j = 1 \ldots c$.
6. Calculate the distance measures $d_{ij} = \left\|\mathbf{x}_i^{(j)} - \mathbf{c}_j\right\|$, for all clusters $j = 1 \ldots c$ and data points $i = 1 \ldots n$.
7. Update the fuzzy membership matrix U according to d_{ij}. If $d_{ij} > 0$ then $u_{ij} = \left[\sum_{k=1}^{c}\left(\frac{d_{ij}}{d_{ik}}\right)^{\frac{2}{m-1}}\right]^{-1}$. If $d_{ij} = 0$ then the data point $\mathbf{x}_j$ coincides with the cluster centre $\mathbf{c}_j$, and so full membership can be set $u_{ij} = 1$.
8. Repeat from (5) until the change in U is less than a given tolerance.

Region Growing

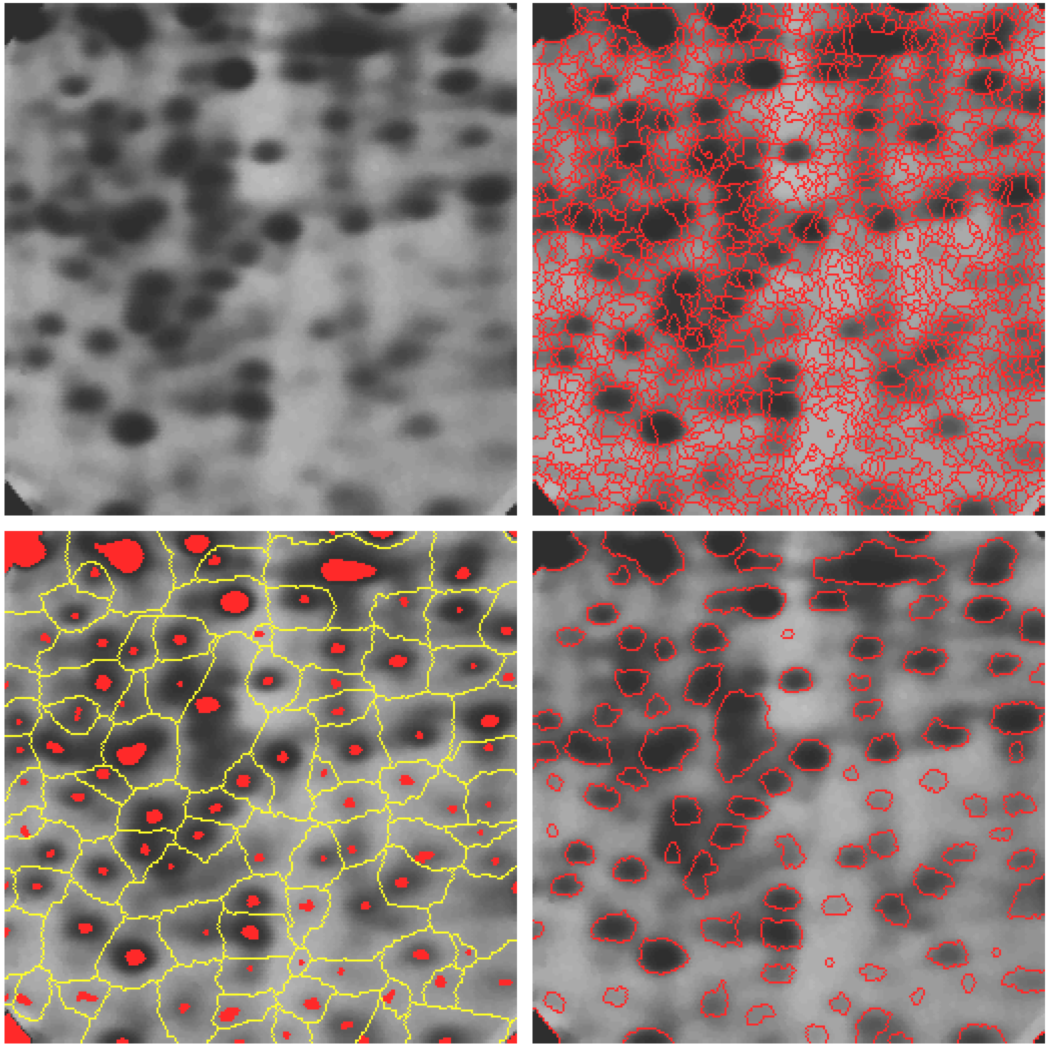
1. Specify a (set of) seed voxel(s) in the object and put them in a queue Q. Specify criteria C for inclusion of voxels (such as thresholds on voxel intensity and/or mean intensity and/or variance of growing region)
2. If Q is empty, stop, else take a voxel v from Q and output v
3. Find those neighbors X of v in scene which were not previously visited and satisfy C
4. Put X in Q and go to Step 2.

Watershed Algorithm



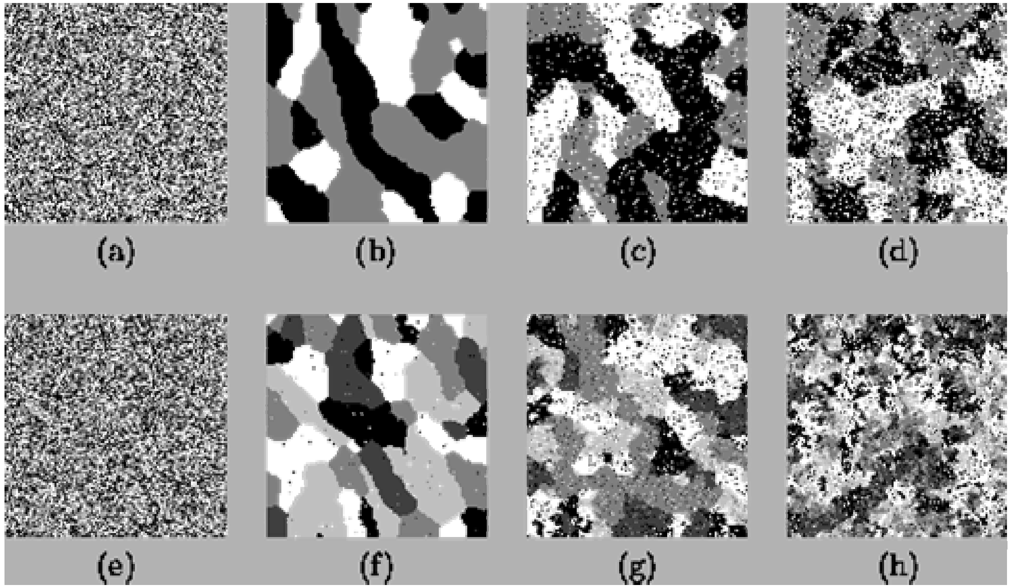


Using Markers to Overcome Over-segmentation

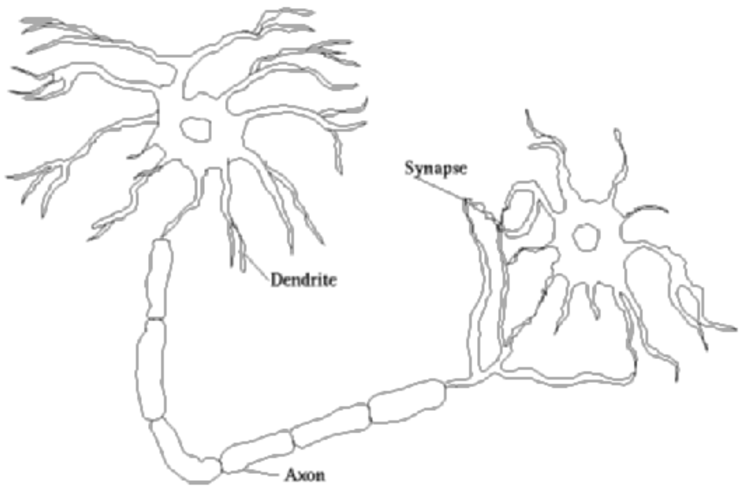


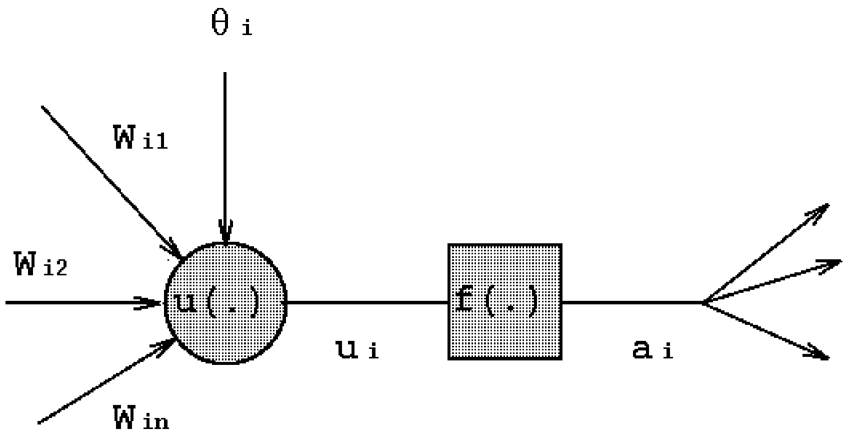
Markov Random Fields (MRF)

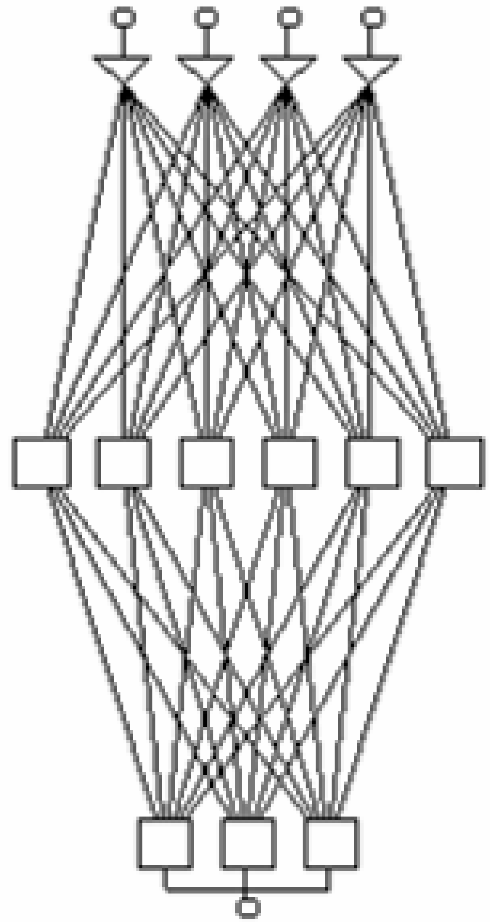
- MRF can be used to model
  - nonlinear interaction between features
  - spatial and temporal information
- Cliques
- Statistical processes



Artificial Neural Networks (ANN)







Object Characteristics in Images

- Graded composition

  heterogeneity of intensity in the object region due to heterogeneity of object material, blurring, noise, and background variation caused by the imaging device

- Hanging-togetherness (Gestalt)

  natural grouping of voxels constituting an object a human viewer readily sees in a display of the scene in spite of intensity heterogeneity

- Graded composition and hanging-togetherness are fuzzy properties

Fuzzy Sets and Relations

- Fuzzy subset: $\mathrm{A} = \{(x, \mathrm{m}_{\mathrm{A}}(x)) \mid x \in X\}$
- Membership function: $\mathrm{m}_{\mathrm{A}} : X \to [0,1]$
- Fuzzy relation: $\mathrm{r} = \{((x, y), \mathrm{m}_{\mathrm{r}}(x, y)) \mid (x, y) \in X \times X\}$

  $\mathrm{m}_{\mathrm{r}} : X \times X \to [0,1]$
- Fuzzy union and intersection operations (e.g., max and min)
- Similitude relation: reflexive, symmetric, transitive

Fuzzy Digital Space

- Fuzzy spel adjacency: how close two spels are spatially. Example:

$$m_a(c,d)=\begin{cases}\dfrac{1}{\left\|c-d\right\|}, & \text{if } \left\|c-d\right\| < \text{a small distance}\\ 0, & \text{otherwise}\end{cases}$$

- Fuzzy digital space: $\left(Z^n, \mathrm{a}\right)$

- Scene (over a fuzzy digital scene): $\mathrm{C} = \left(C, f\right)$

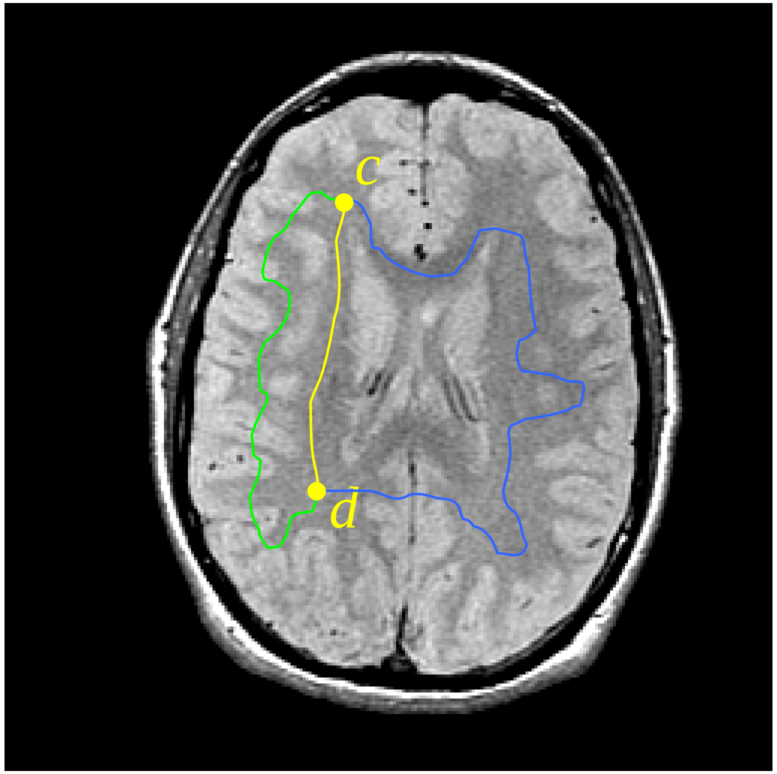
Fuzzy Connectedness

- Fuzzy spel affinity:

  how close two spels are spatially and intensity-based-property-wise (local hanging-togetherness)

$$\mu_k(c,d) = h(\mu_a(c,d), f(c), f(d), c, d)$$

- Path (between two spels)
- Fuzzy k-net
- Fuzzy k-connectedness (K)



Fuzzy Connected Objects

- Binary relation K_q

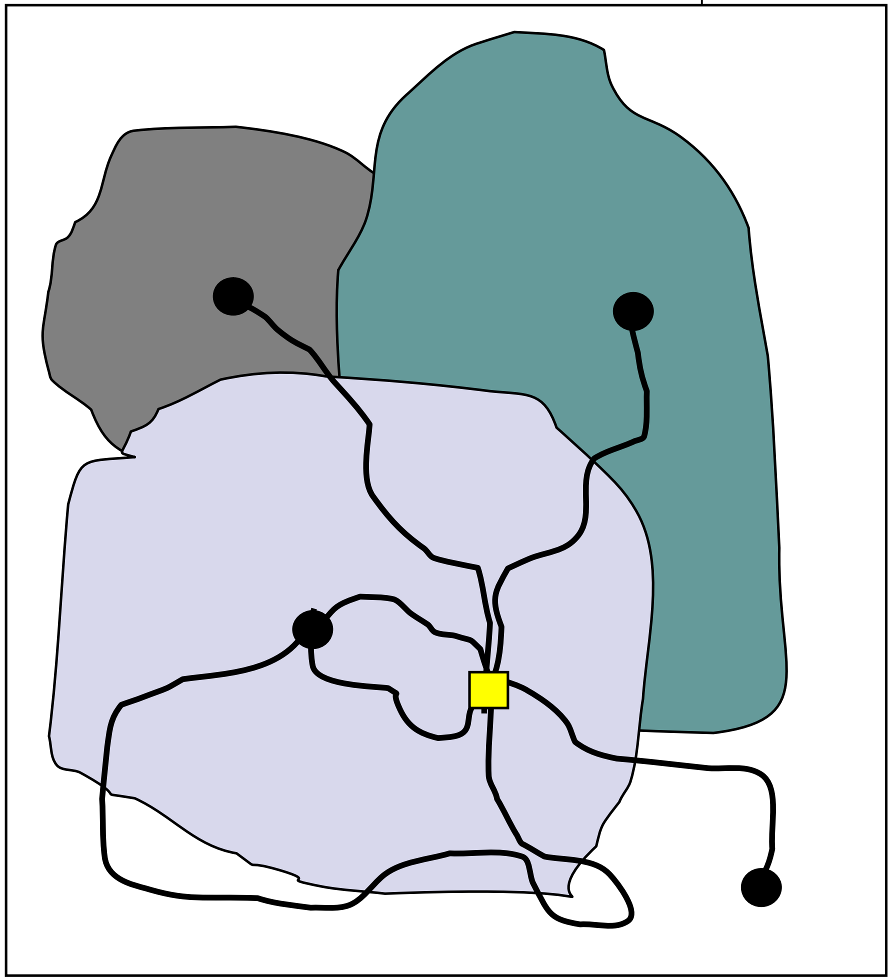
$$m_{K_q}(c,d) = \begin{cases} 1, & \text{if } m_k(c,d) \in q \\ 0, & \text{otherwise} \end{cases}$$

- Fuzzy k-component of strength q_x
- Fuzzy $k_{q\,x}$ object containing o

- Very important property: robustness

Fuzzy Connectedness Variants

- Multiple seeds per object
- Scale-based fuzzy affinity
- Relative fuzzy connectedness
- Iterative relative fuzzy connectedness
- Vectorial … fuzzy connectedness



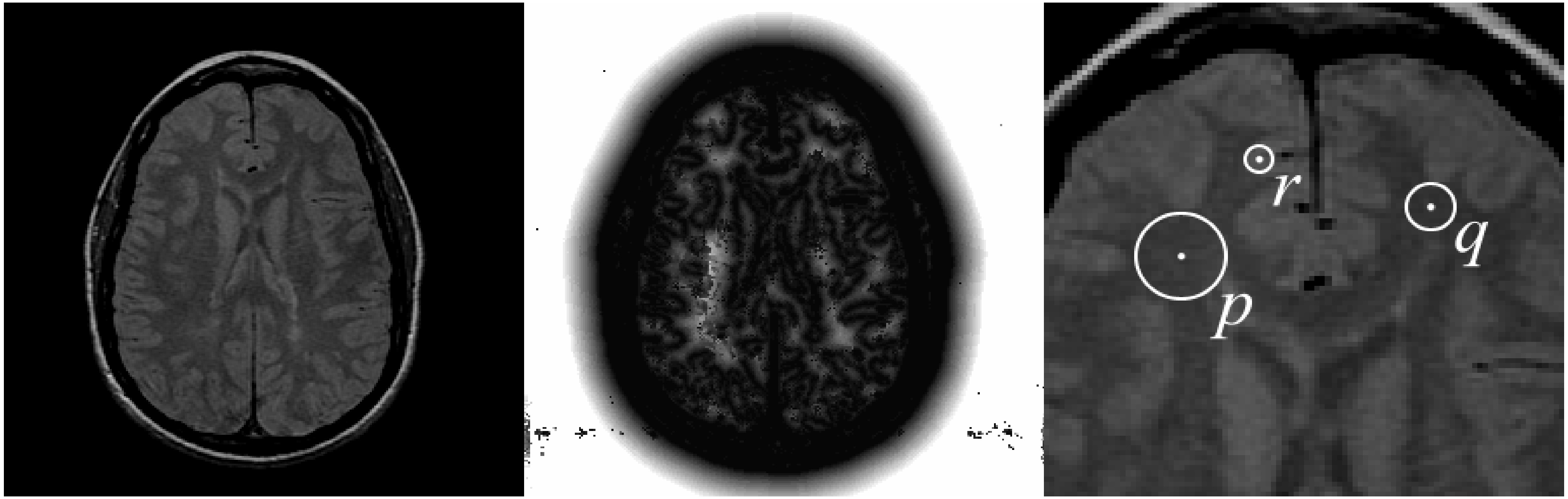
Scale-based Fuzzy Affinity

- spatial adjacency
- homogeneity
- object feature
- object scale

- global hanging-togetherness

Scale As Used in Fuzzy Connectedness

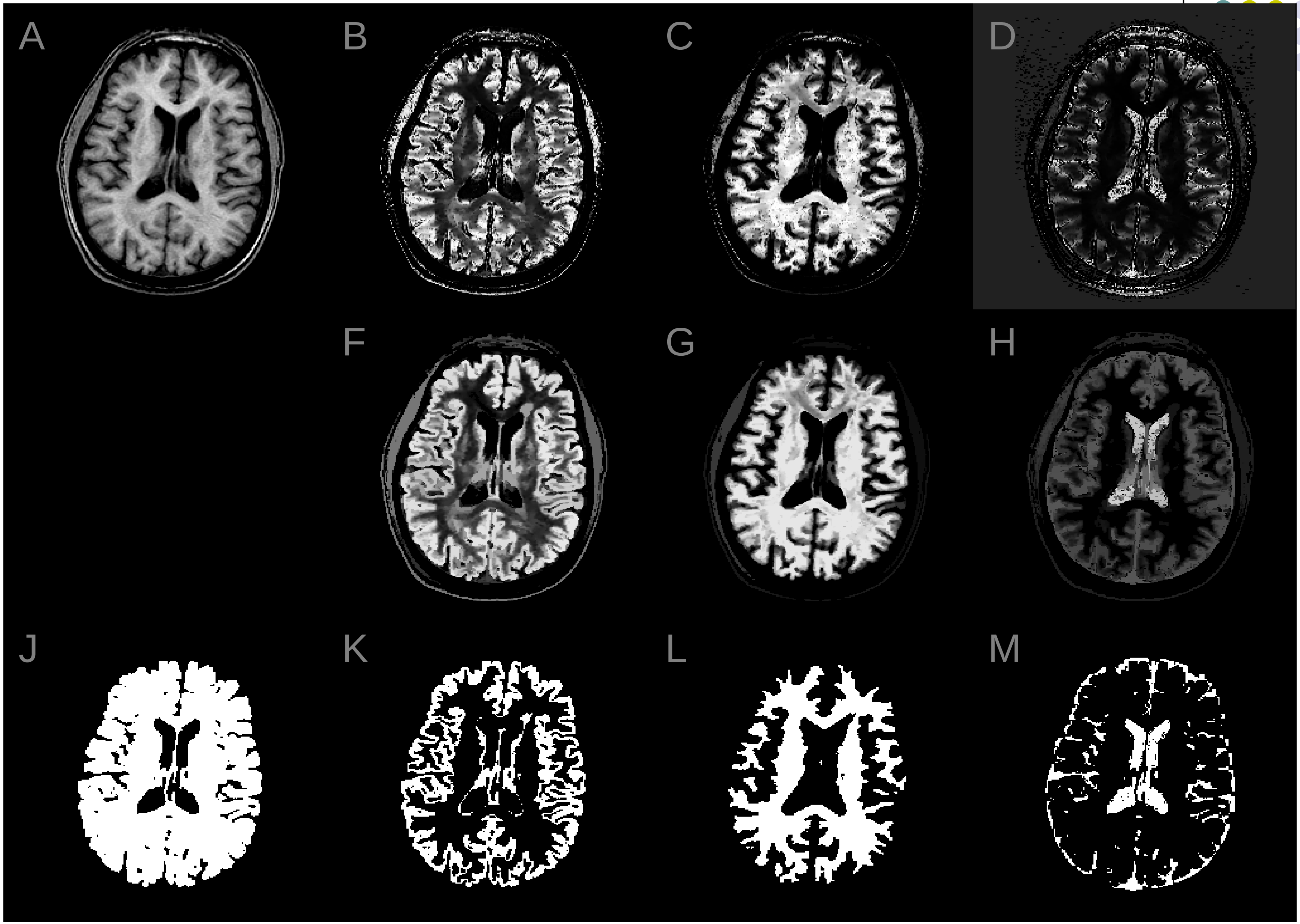
- "Scale" is the size of local structures under a pre-specified region-homogeneity criterion.
- In an image C at any voxel c, scale is defined as the radius r(c) of the largest ball centered at c which lies entirely within the same object region.
- The scale value can be simply and effectively estimated without explicit object segmentation.



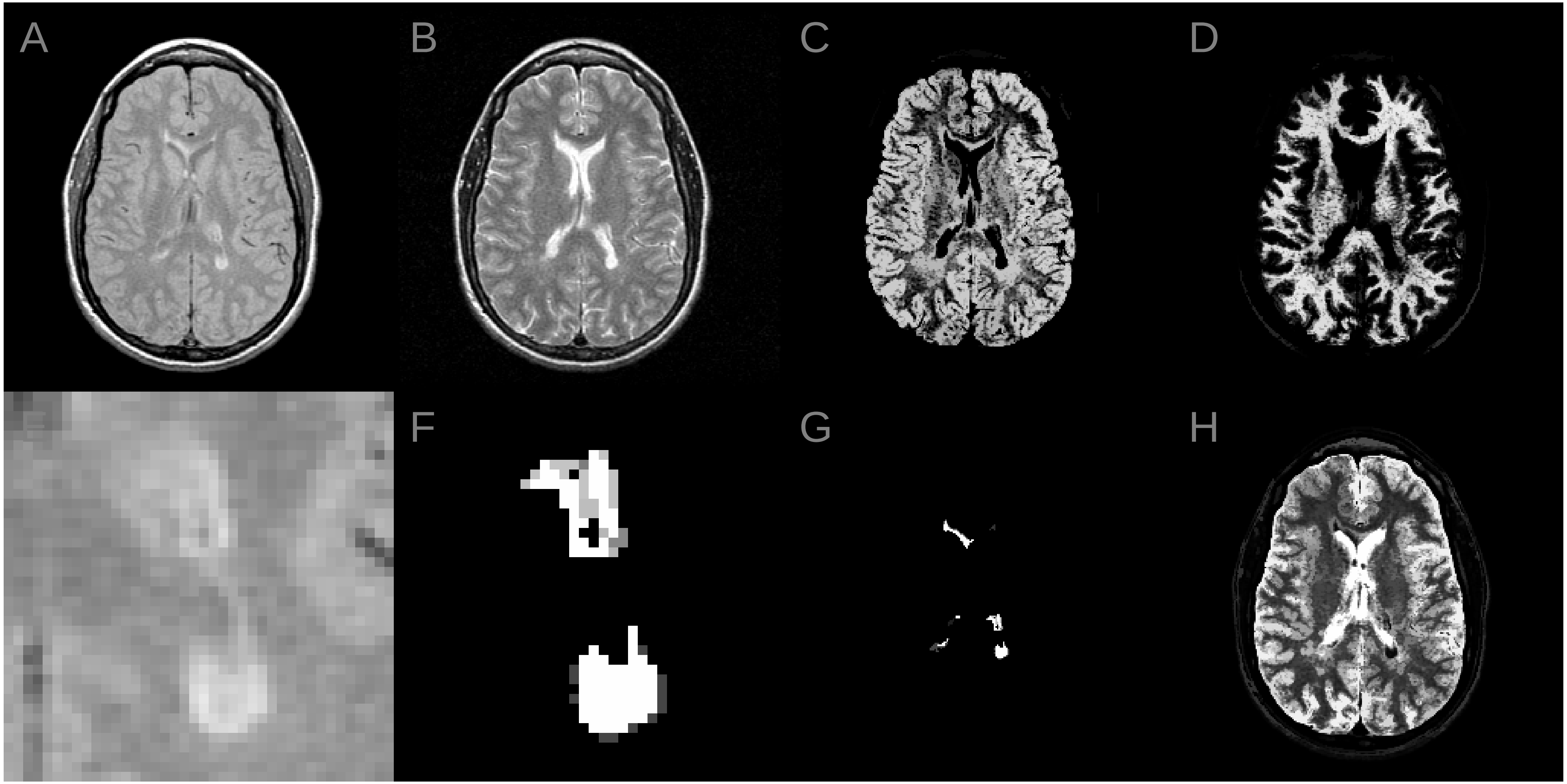
Applications with Fuzzy Connectedness Segmentation

- MR
  - Brain tissue segmentation
  - Brain tumor quantification
  - Image analysis in multiple sclerosis and Alzheimer's disease
- MRA
  - Vessel segmentation, artery-vein separation
- CT bone (skull, shoulder, ankle, knee, pelvis) segmentation
  - Kinematics studies
  - Measuring bone density
  - Stress-and-strain modeling
- CT soft tissue (fat, skin, muscle, lungs, airway, colon) segmentation
  - Detecting and quantifying cancer, cyst, polyp
  - Detecting and quantifying stenosis and aneurism
- Digitized mammography
  - Detecting microcalcifications
- Craniofacial 3D imaging
  - Visualization and surgical planning
- Visible Human Data

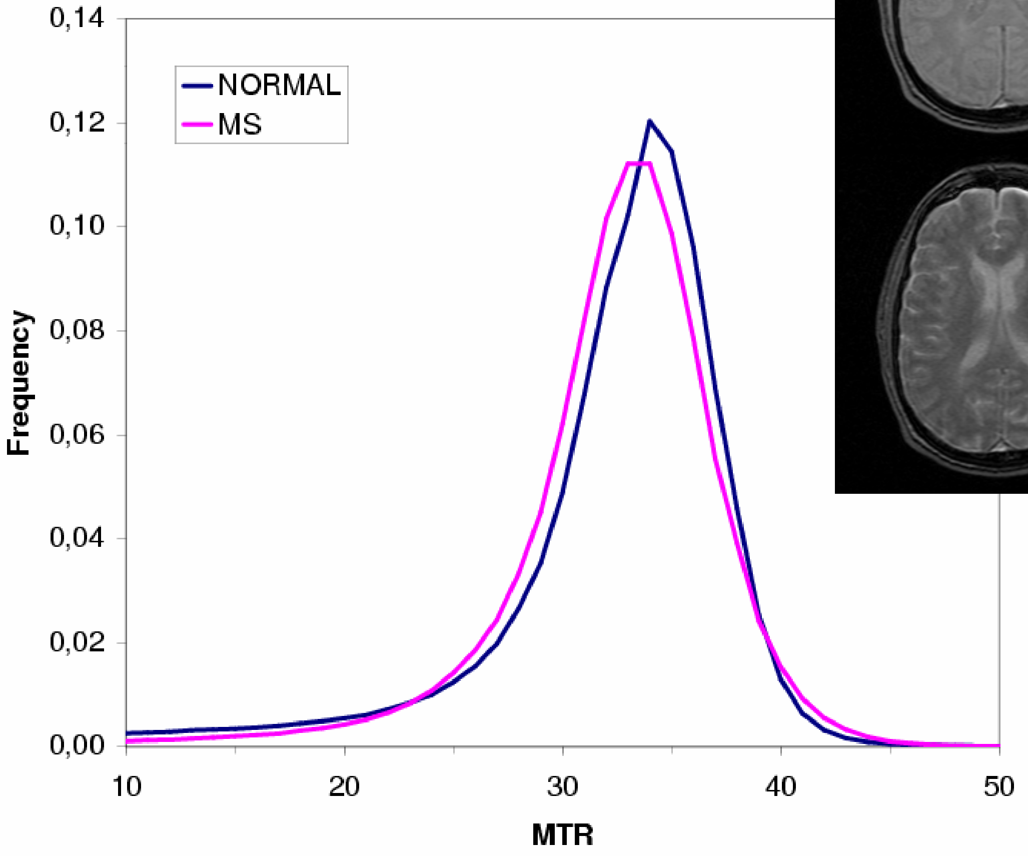
Brain Tissue Segmentation (SPGR)

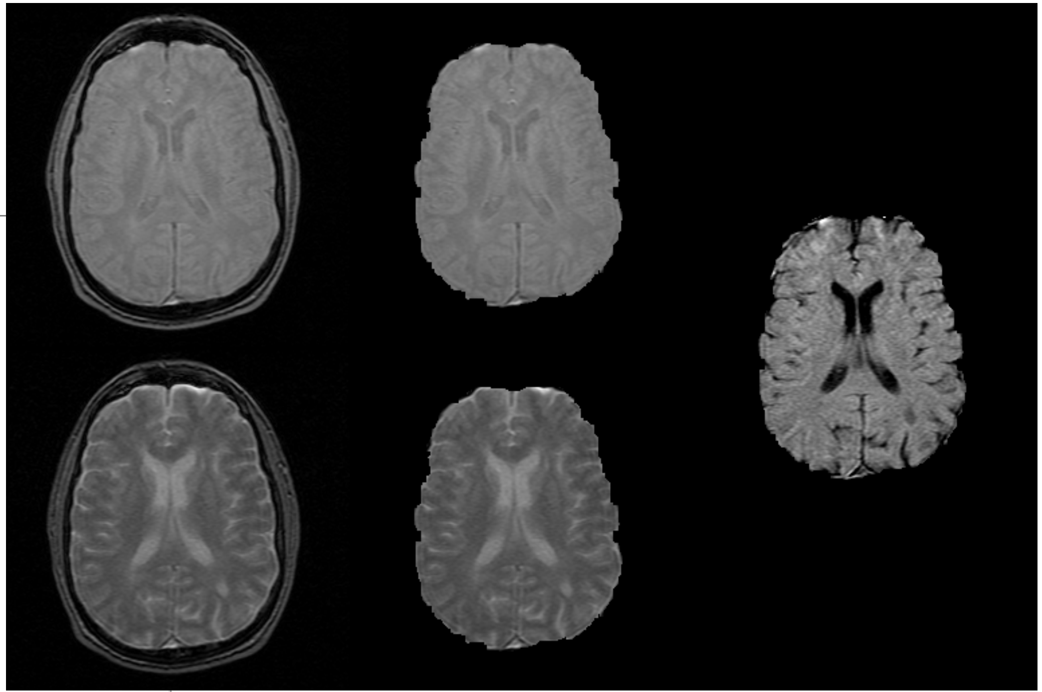


MS Lesion Quantification (FSE)

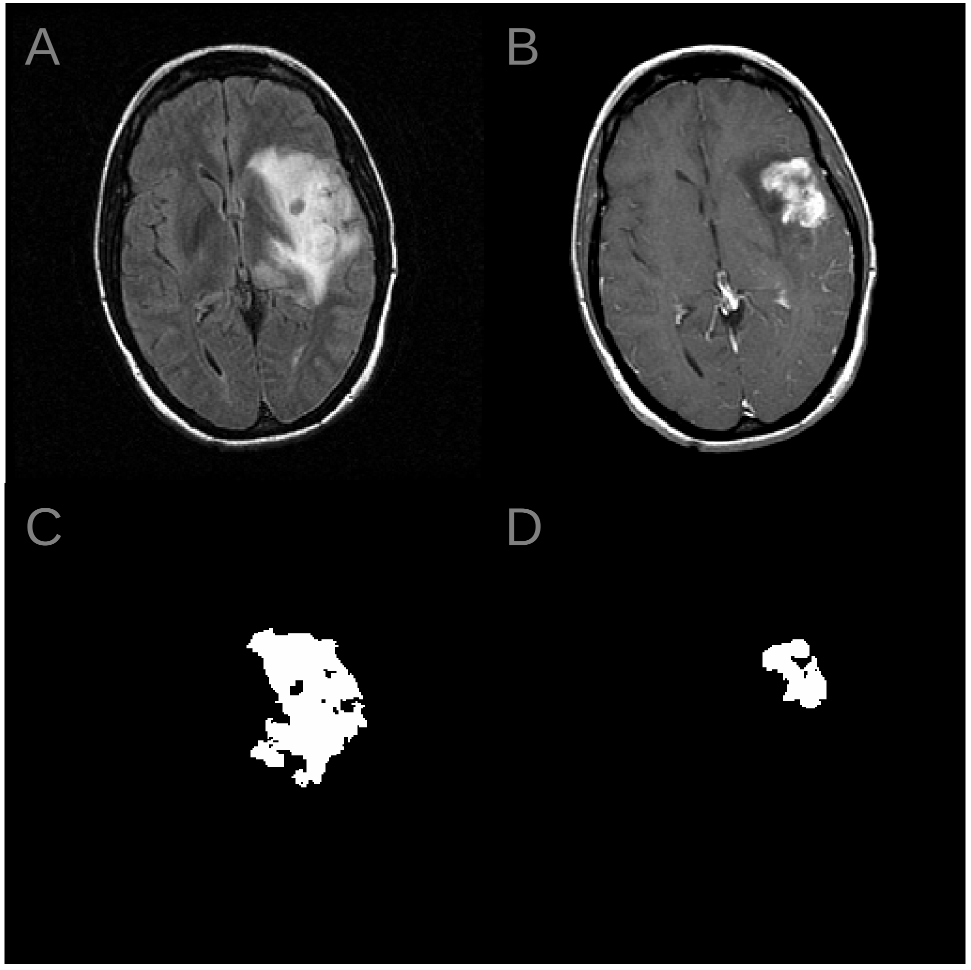


MTR Analysis





Brain Tumor Quantification



MRA Vessel Segmentation

Hybrid Segmentation Methods

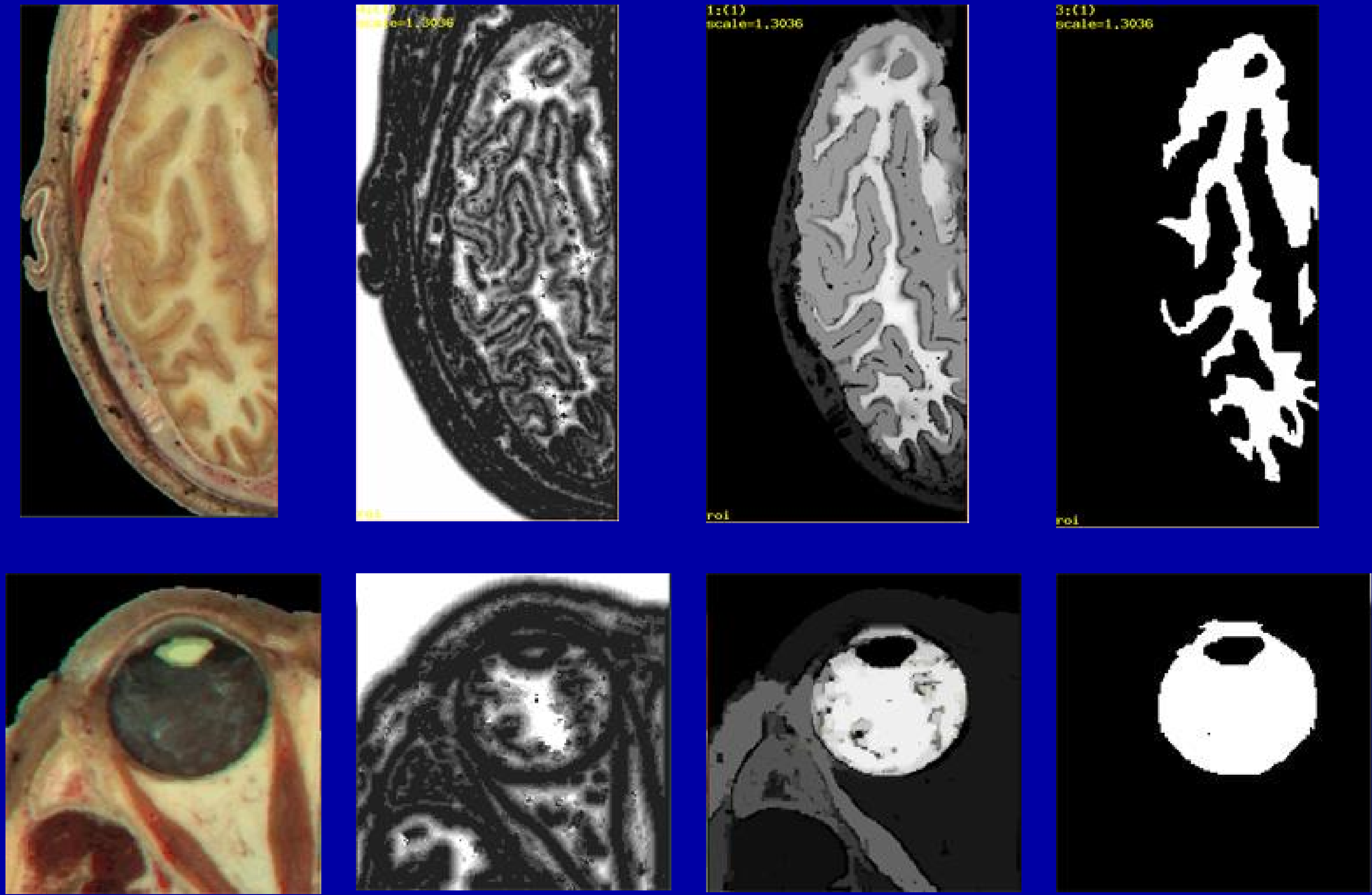
- Combine boundary-based and region-based methods
- Each well understood
- Utilize strengths of both, reduce exposure to weakness of either

- Advantage
  - More reliable
  - When the region-based method is trapped in a local minimum, the boundary-based method can drive it out

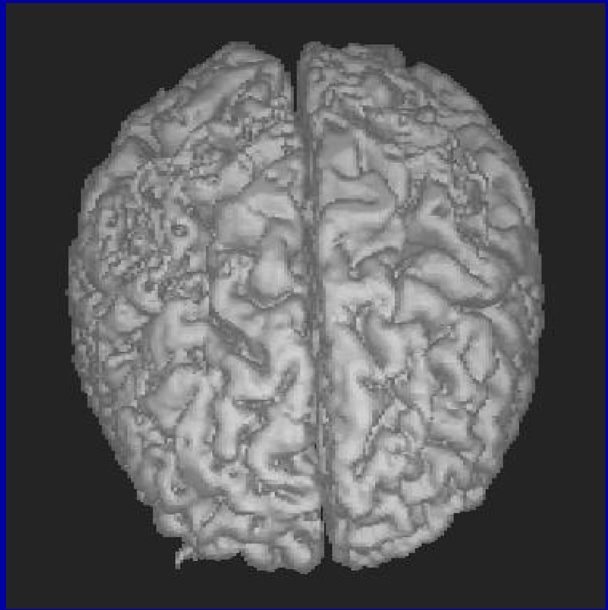
Fuzzy connectedness with Voronoi diagram

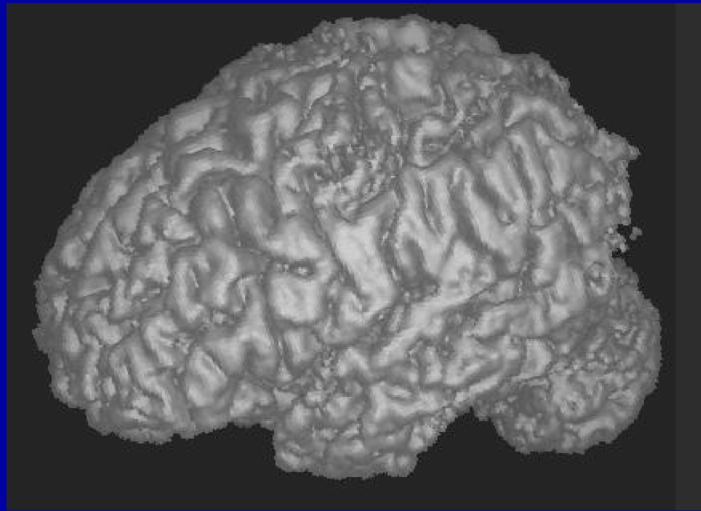
- Use fuzzy connectedness to generate statistics for homogeneity operator in a color space (e.g., RGB, HCV)
- Run Voronoi Diagram-based algorithm in multiple color channels
- *Identify connected components*
- *Use deformable model to determine final (3D) boundary*

Slides with hybrid segmentation examples borrowed from lecture notes of Celina Imielinska (Columbia University)

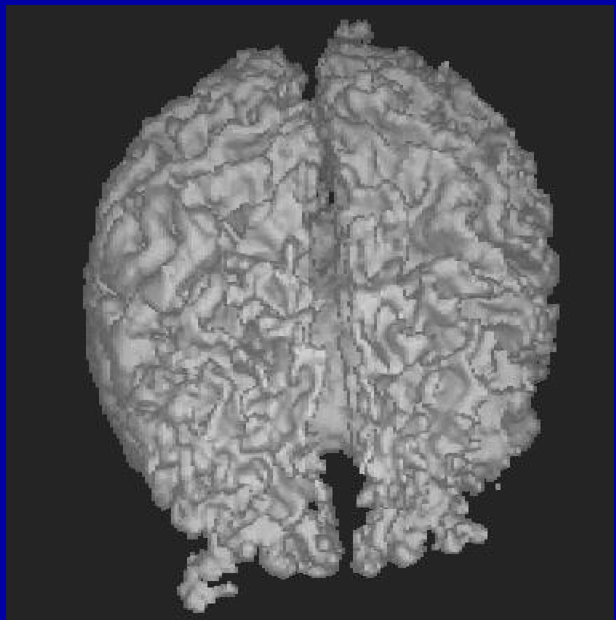

1:(1)
scale=1.3036
roi
3:(1)
scale=1.3036
roi

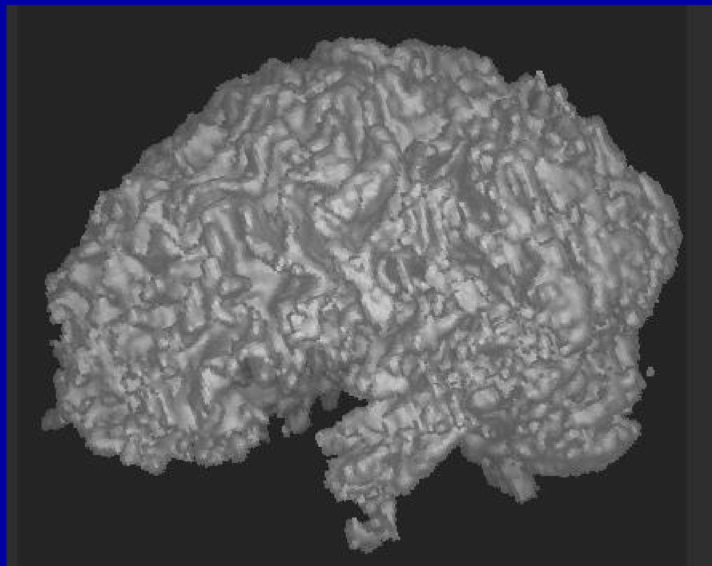
GM



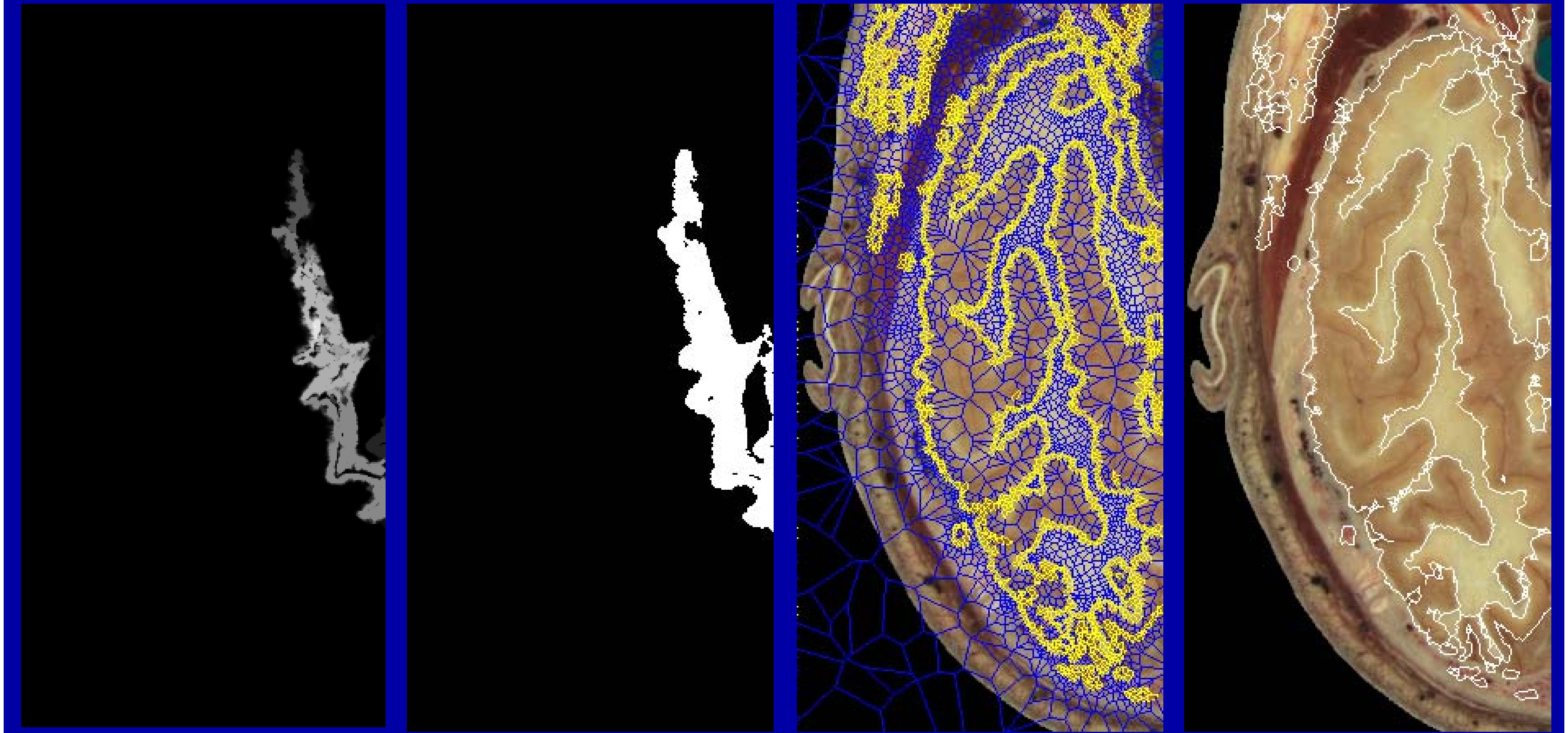


WM

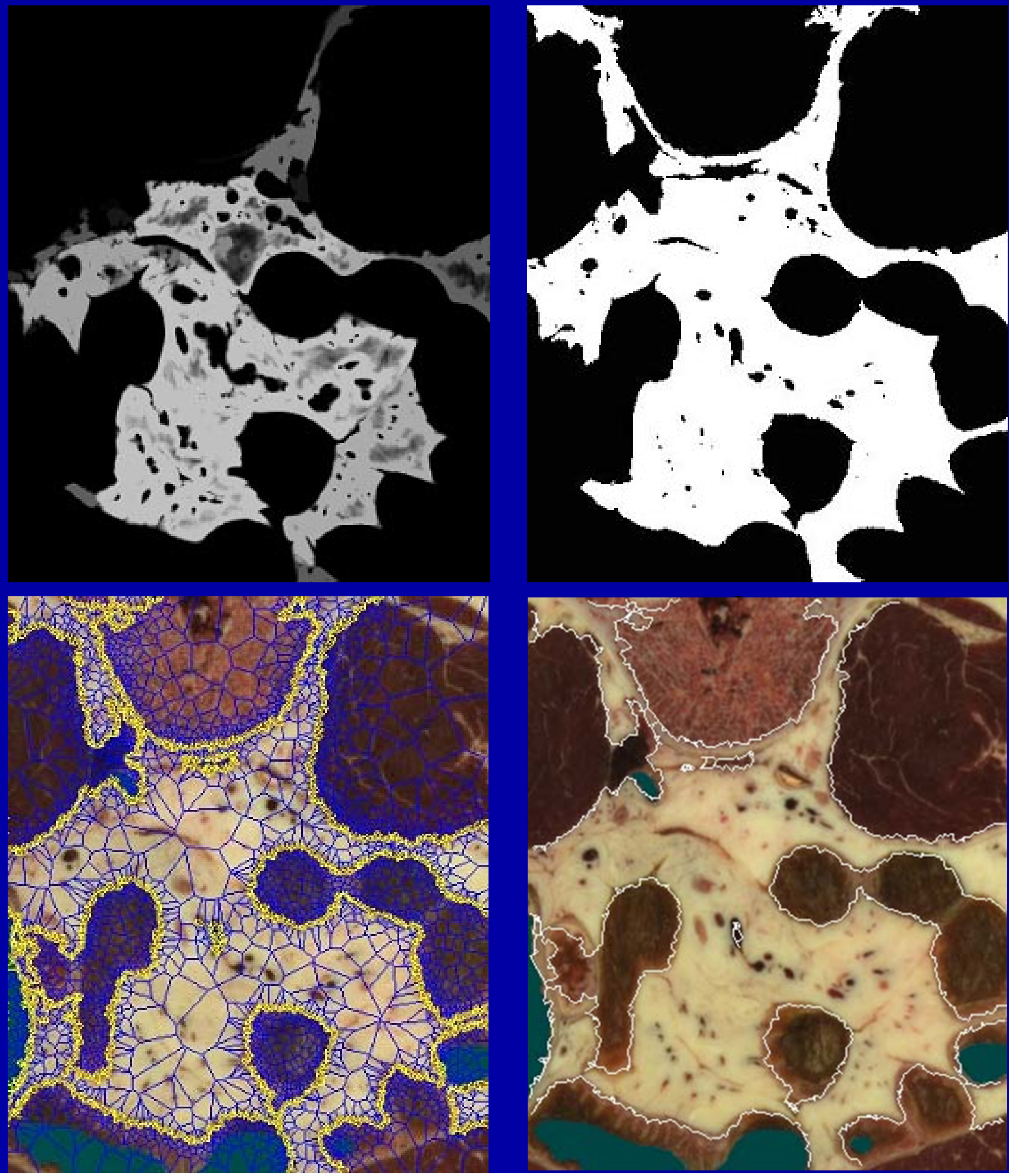


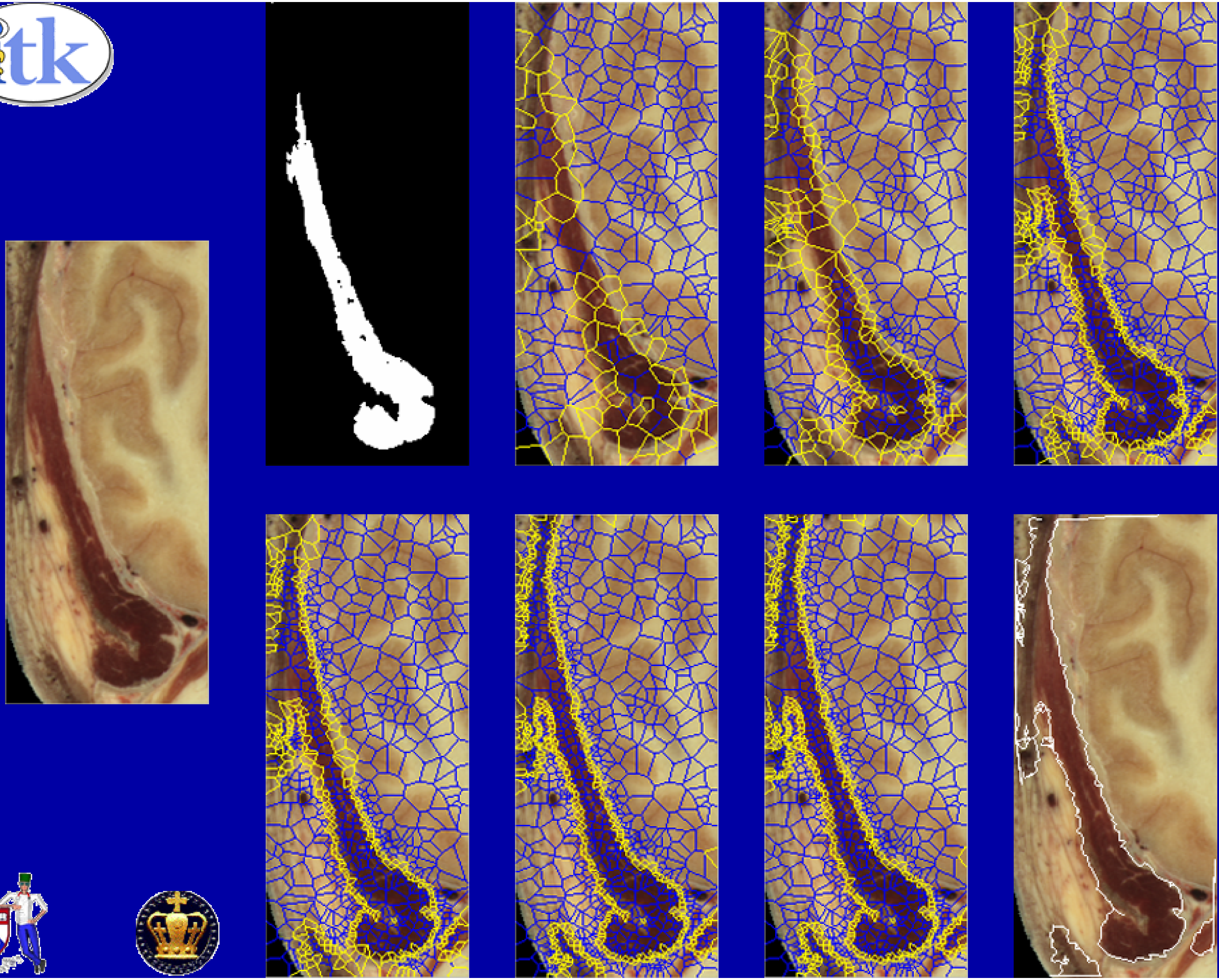


Fuzzy Connectedness with Voronoi Diagram

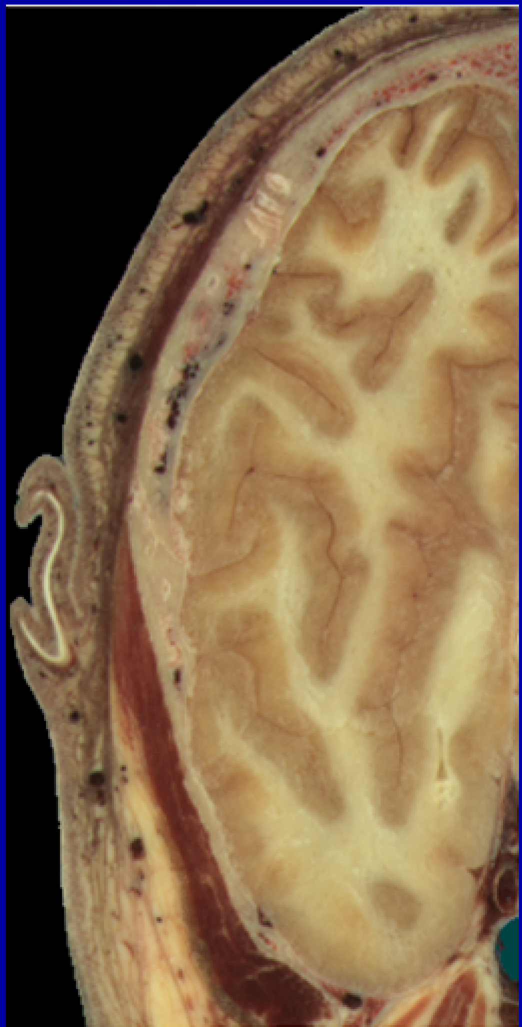


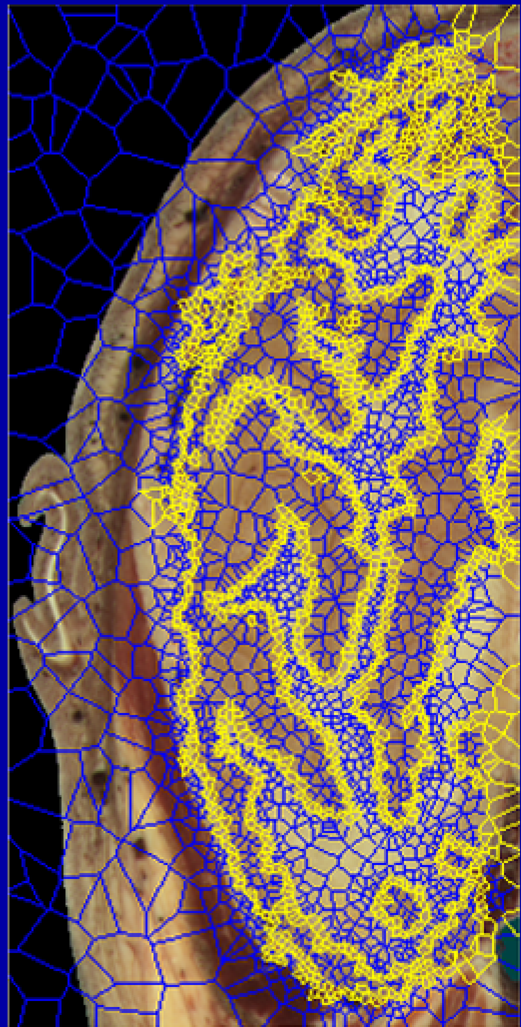
Fuzzy Connectedness with Voronoi Diagram

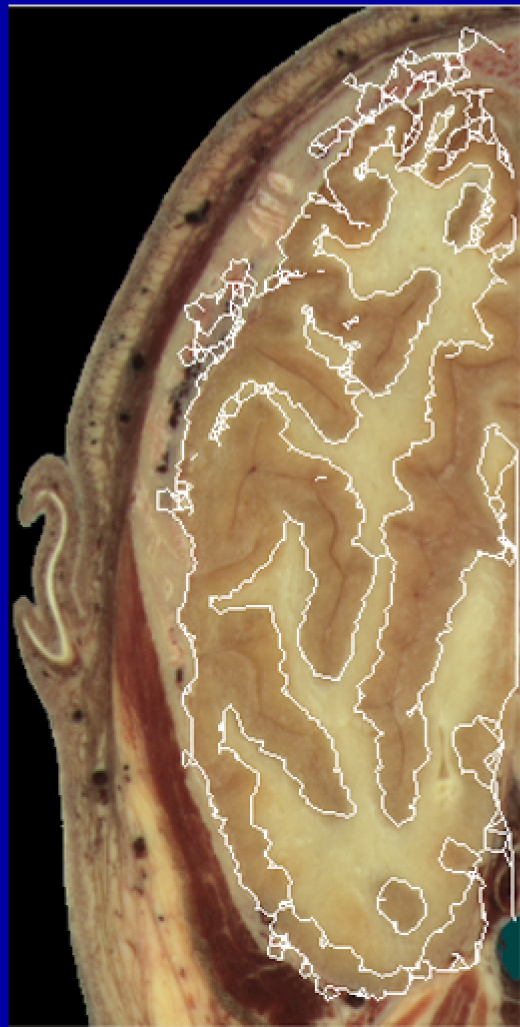




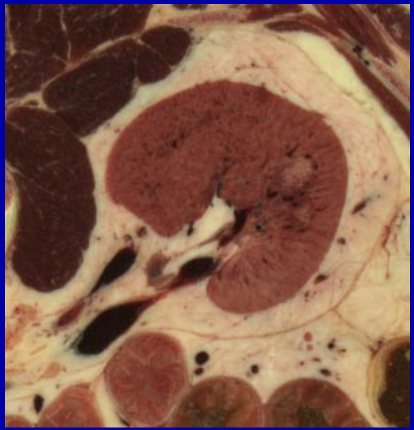
Segmentation of Brain Tissue



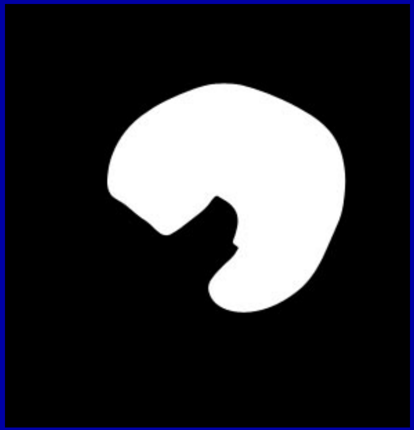




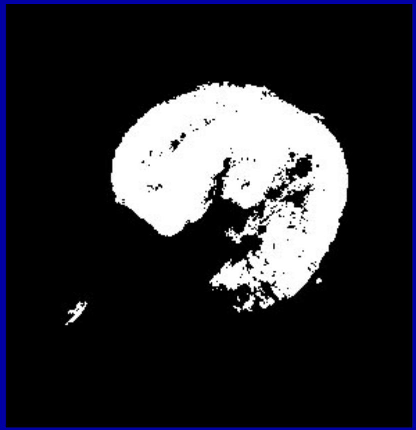
Hybrid Segmentation: Visible Human Male: Kidney



Input data

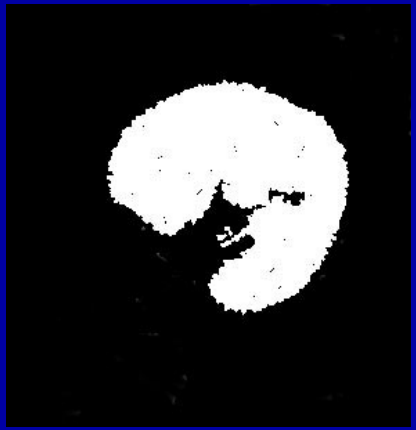


Hand Segmentation

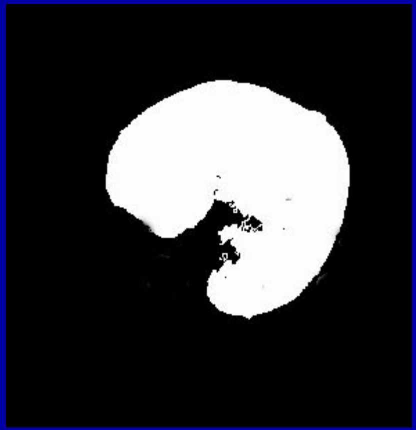


Result: FC

Result: FC/VD



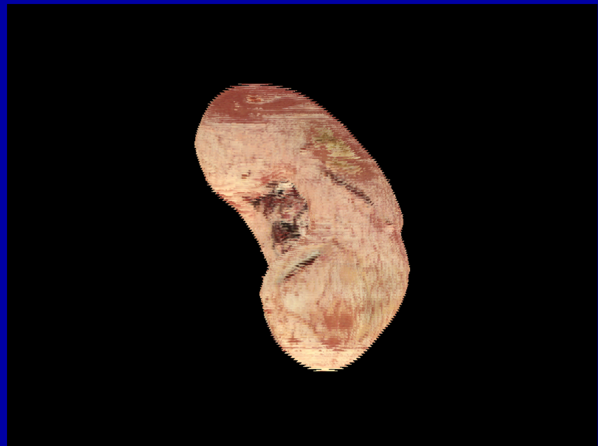
Result: FC/VD/CC



Result: FC/VD/CC/DM

Hybrid Segmentation: Visible Human Male: Kidney

Result: FC/VD/CC



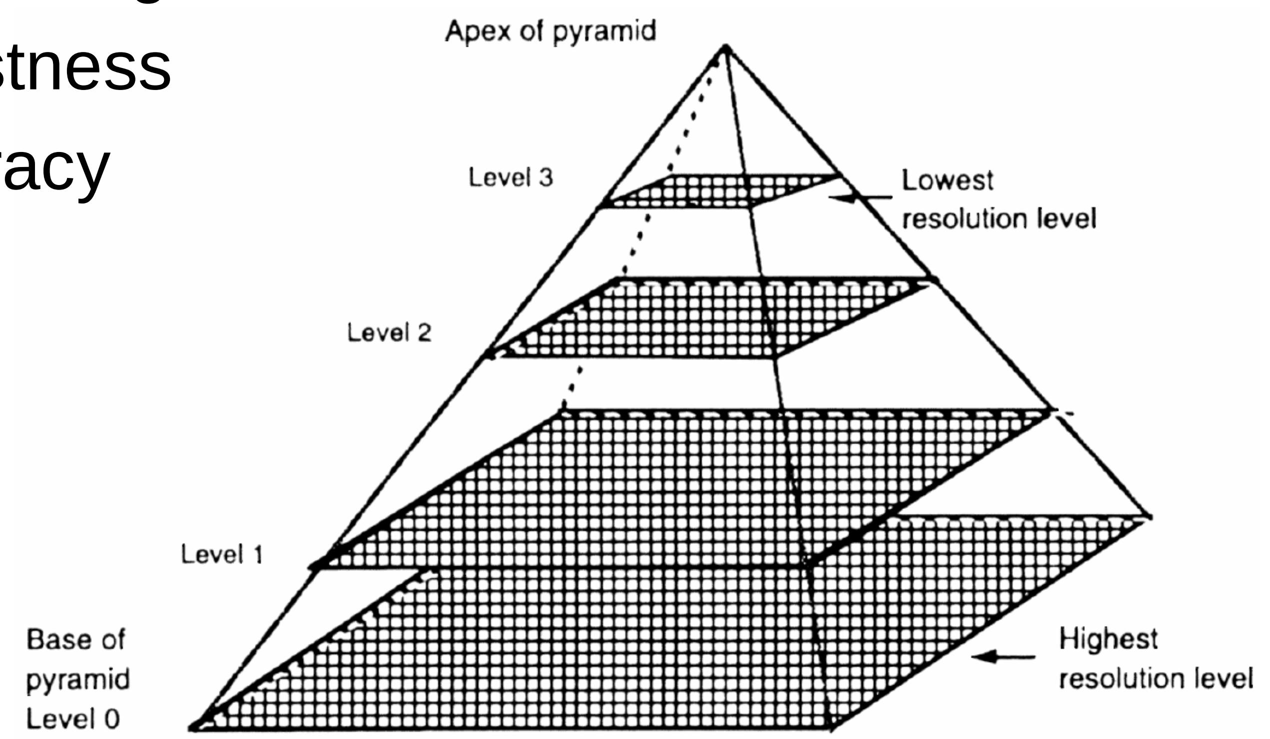
Result: FC/VD/CC/DM

Hand Segmentation

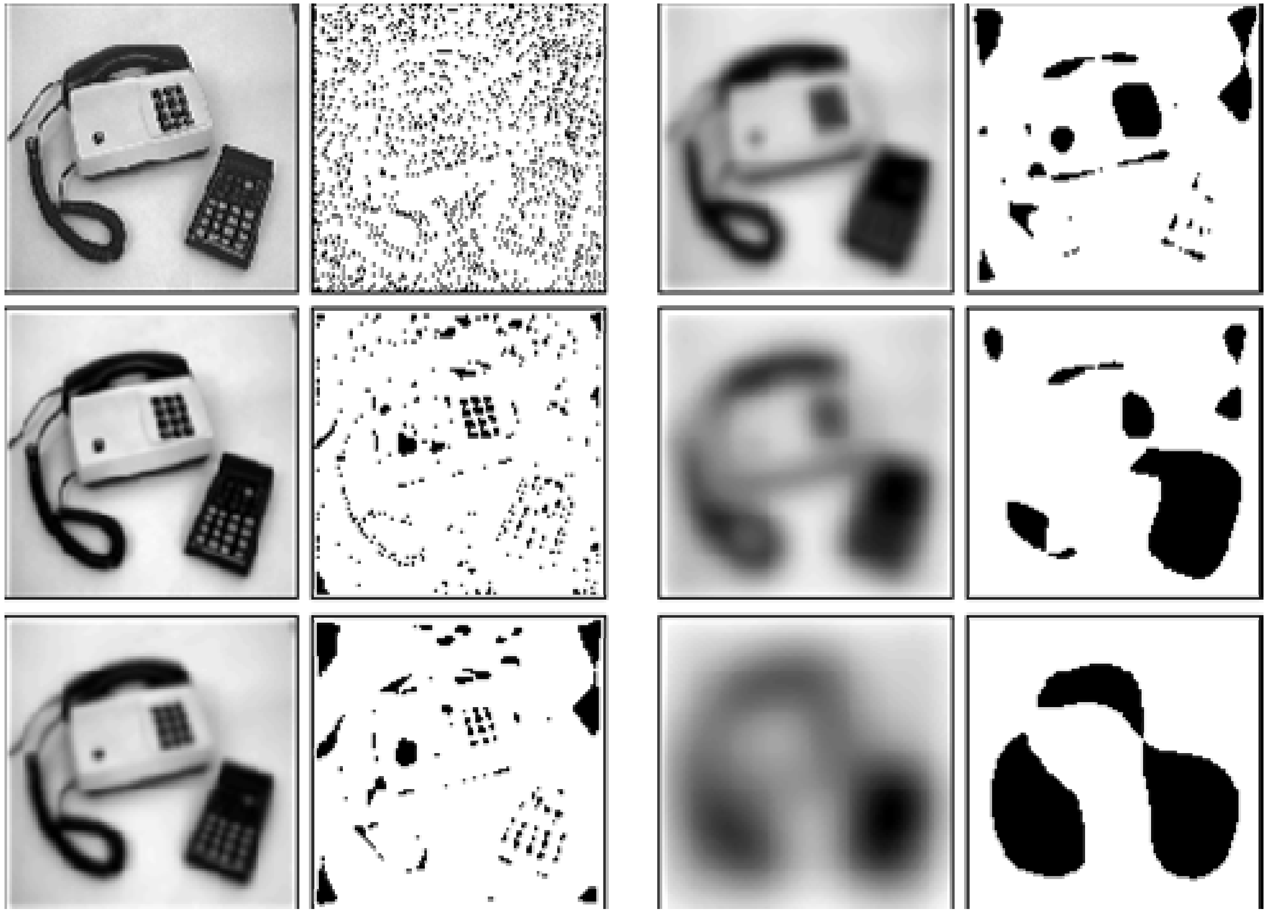
Useful Techniques

Scale-space and Multi-level/ Multi-scale Techniques

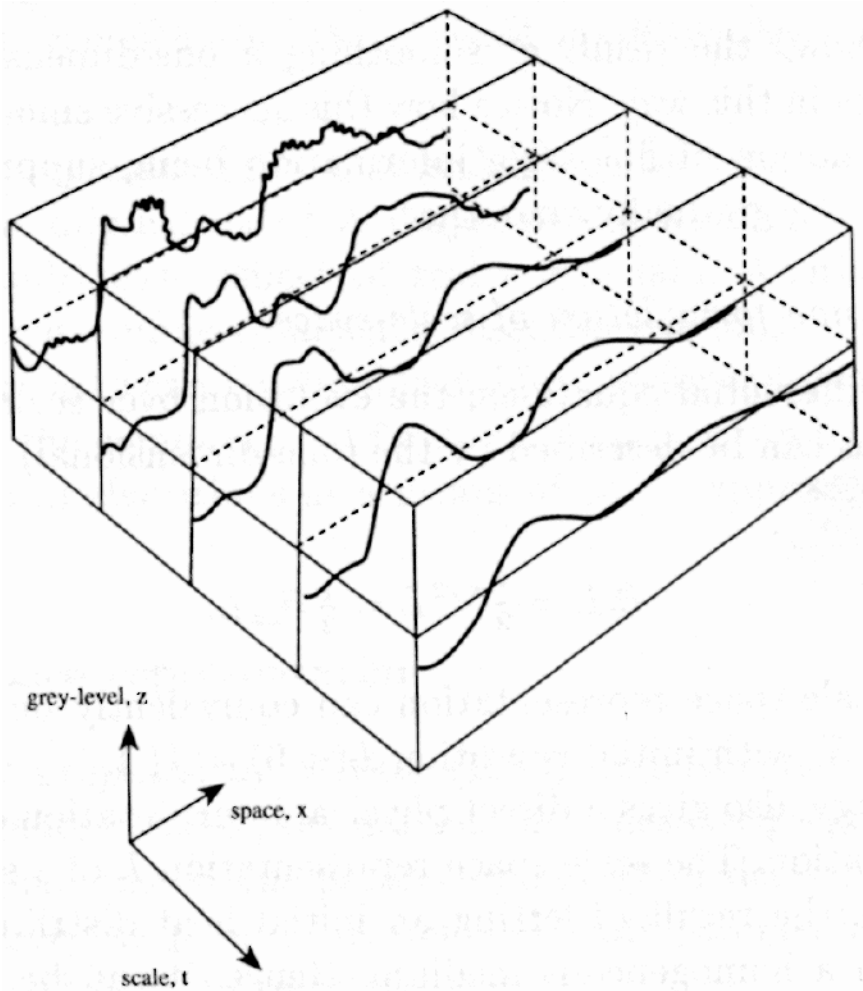
- Gaussian Pyramid
- Reduction of data
- Gain in processing time
- Gain in robustness
- Gain in accuracy



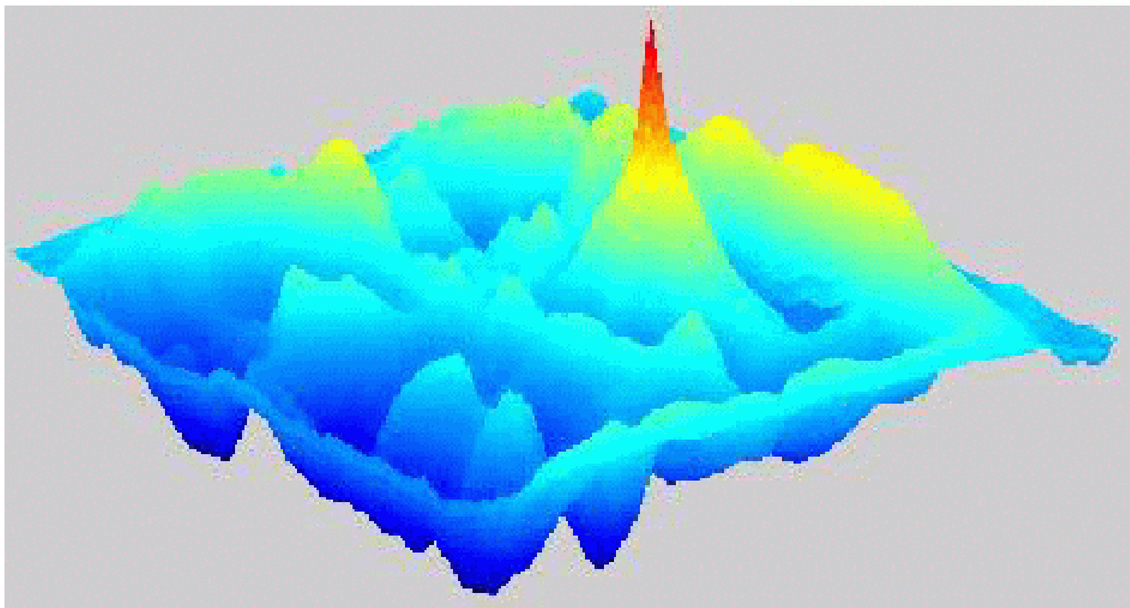
Details at Different Scales



Details at Different Scales



Template Matching with Cross-correlation



Other Useful Techniques

- Morphological operators
  - Dilation, erosion, opening, closing
  - Cavity filling
- Connected component labeling
- Distance transform
  - Euclidean
  - City block / Manhattan
  - 3-4-5 chamfer

Evaluation of Image Segmentation Methods

Measures and Figures of Merit

- The method's effectiveness can be assessed by several sets of measures
  - Precision (reliability)
  - Accuracy (validity)
  - Efficiency (practical viability in terms of the time required)

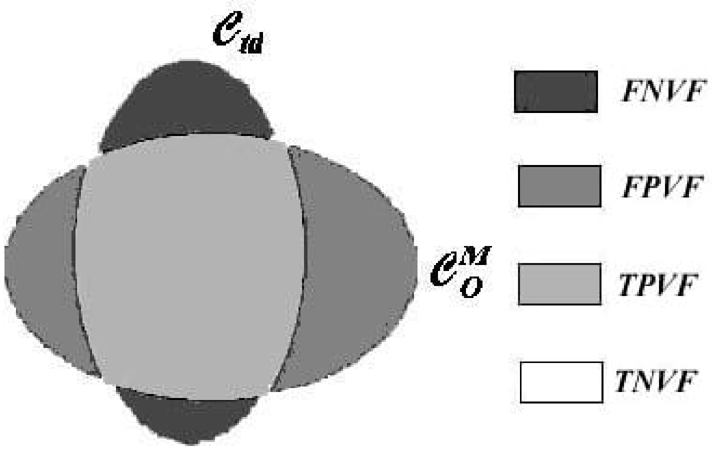
- In fact, effectiveness should be assessed by all measures, since one measure by itself is not always meaningful

Precision

- Three types of precision is usually measured
  - Intra-operator precision
  - Inter-operator precision
  - Repeat-scan precision
- For each test, volume difference and overlap agreement may be measured
- For repeat-scan overlap measurement, registration of the two scenes is necessary

Accuracy

- Segmentation results of a method are usually compared to some surrogate truth since real truth is rarely available
- Measures for comparison
  - Absolute values (number of voxels, volumes)
    - True positives (TP)
    - False positives (FP)
    - False negatives (FN)
  - Relative values (comparable among different studies)
    - TP volume fraction (TPVF)
    - FP volume fraction (FPVF)
    - FN volume fraction (FNVF)



Efficiency

- Unfortunately, this sort of evaluation is often neglected
- Possible measures
  - Running time (wall clock time)
    - highly dependent on what type of hardware the program is running on
  - Amount of necessary human interaction
    - number and length of interactive sessions
  - How convenient it is for the operator
    - the way the human input is required

Motto:
“There is no silver bullet”

- Whatever technique you choose you have to tailor it to the particular application context

- This usually means not only setting parameters but also designing new algorithms built from existing ones, combining different pre- and post-processing techniques with robust algorithms, sometimes even combining several segmentation algorithms to achieve the goal, designing workflows, user interfaces, and validation methods