Segmentation of Medical Images

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Image Segmentation in SSIP'04 Projects

- 24 projects suggested
- 1 pure mathematical with visualization (nD cube)
- 2 could use segmented data (avatar, traffic)
- 1 depends on segmented data (central path)
- 20 have image segmentation as their main or secondary task (…)

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Application Context

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X-ray

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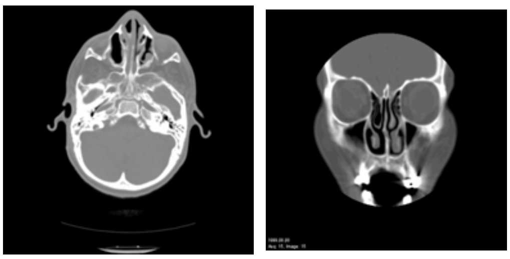
Computed Tomography (CT)



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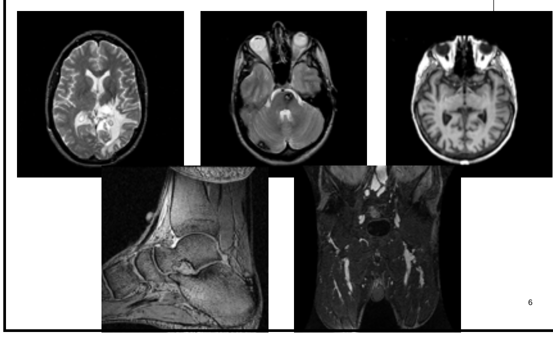
Magnetic Resonance (MR)



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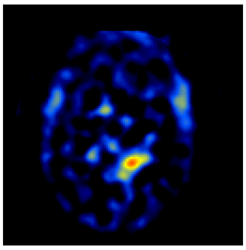
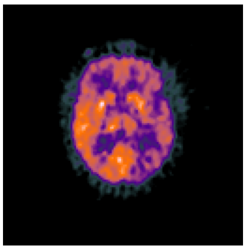
SPECT and PET





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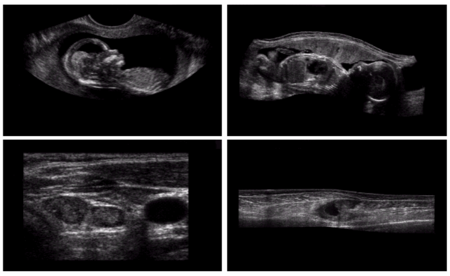
Ultrasound



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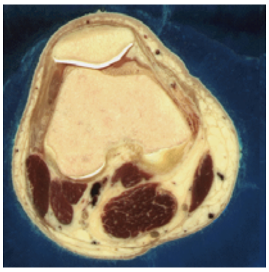
Cryosection Photographs



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Thermographic Images

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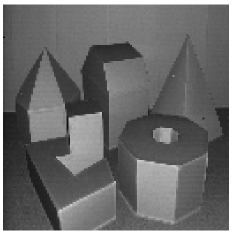
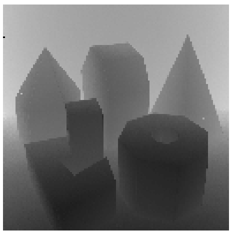
Range Images



Reflection image



Range image

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Specialties about Medical Images and Processing

- Subject of imaging
  - Human beings
- Side effects/health hazards of the acquisition
  - Contrast agents
  - Radiation
  - Invasive techniques
- Data handling
  - Privacy
- Evaluation
  - No ground truth!

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Challenges of Medical Imaging

- Grey-level appearance of tissues
- Characteristics of imaging modality
- Geometry of anatomy

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Limitations of Acquisition Techniques

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

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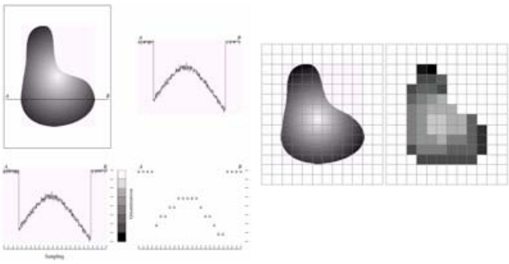
Noise and Sampling Errors



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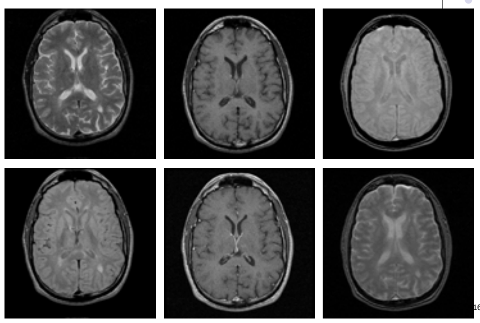
Different Tissue Contrast



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Applications of Image Segmentation

- Virtually everywhere

- Visualization
- Qualitative and quantitative studies

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

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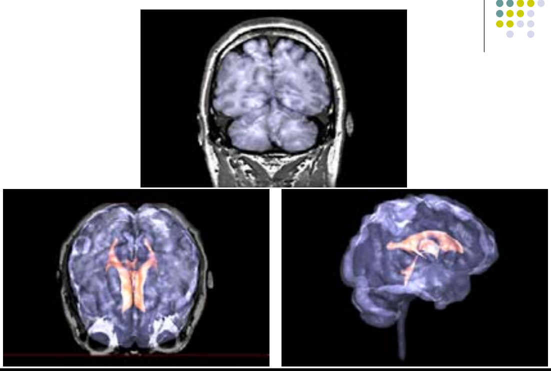
Brain and the Ventricles



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

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Computer Aided Diagnosis (CAD)

- The computer can store, process, compare, present (visualize) data
- The computer may even make suggestions
- The physician has to make the final judgment

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Segmentation Approaches

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Purpose of 3D Imaging

- IN: multiple multimodality images (CT, MR, PET, SPECT, US, …)
- OUT: information about an object/object system (qualitative, quantitative)

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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 a 3D image 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)

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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

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Object Characteristics in Images

- Graded composition
  - heterogeneity of intensity in the object region due to heterogeneity of object material and blurring caused by the imaging device
- Hanging-togetherness
  - natural grouping of voxels constituting an object a human viewer readily sees in a display of the scene in spite of intensity heterogeneity

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Preprocessing

- IN: a set of scenes of a body region
- OUT: a set of scenes of the body region or a structure/structure system

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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

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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

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Segmentation

- Purpose
  - to extract object information from scenes and represent it as a structure/ structure system
- Consists of
  - RECOGNITION: determining roughly the objects' whereabouts in the scene
  - DELINEATION: determining the objects' precise spatial extent and graded composition
- Needed for most 3D imaging operations

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Segmentation

- Recognition: humans >> computer algorithms
- Delineation: computer algorithms >> humans
- Manual delineation specifying graded composition is impossible
- Object knowledge facilitates segmentation ⇨ segmentation is needed for segmentation
- Most critical operation and most challenging

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Segmentation

- 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
- Premise: provide user control on the segmentation process just as much as is needed

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Approaches to Recognition

- Automatic
  - Knowledge- and atlas-based artificial intelligence techniques used to represent object knowledge
  - Preliminary delineation needed to form object hypotheses
  - Atlas representing objects' geometry and relationship used. Map geometric information from scene to atlas

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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

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Approaches to Delineation

- Boundary-based
  - output boundary description of objects
- Region-based
  - output regions occupied by objects

- Hard (crisp)
- Fuzzy

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Boundary-based Segmentation Methods

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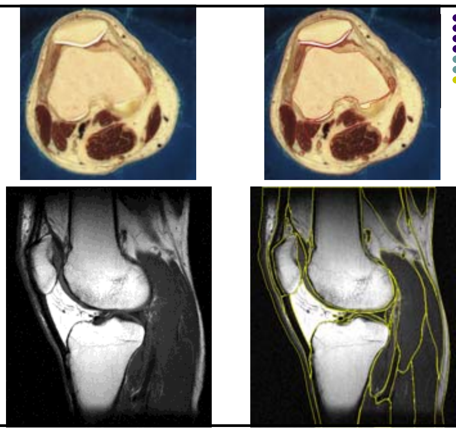

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Pre-processing

- Feature detection
  - Point
  - Line
  - Edge

-1	-1	-1
-1	8	-1
-1	-1	-1

Horizontal			+45°			Vertical			-45°		
-1	-1	-1	-1	-1	2	-1	2	-1	2	-1	-1
2	2	2	-1	2	-1	-1	2	-1	-1	2	-1
-1	-1	-1	2	-1	-1	-1	2	-1	-1	-1	2

- Contour following
- Edge linking
- Canny edge-detector

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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

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Gradient-based

Roberts

-1	0	0	-1
0	1	1	0

Prewitt

-1	-1	-1	-1	0	1
0	0	0	-1	0	1
1	1	1	-1	0	1

Sobel

-1	-2	-1	-1	0	1
0	0	0	-2	0	2
1	2	1	-1	0	1

Prewitt

0	1	1	-1	-1	0
-1	0	1	-1	0	1
-1	-1	0	0	1	1

Sobel

0	1	2	-2	-1	0
-1	0	1	-1	0	1
-2	-1	0	0	1	2

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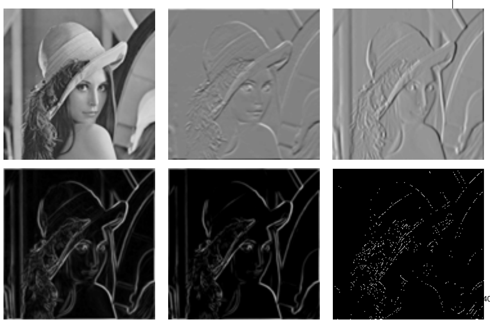
Creating Edges From Image Gradient



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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

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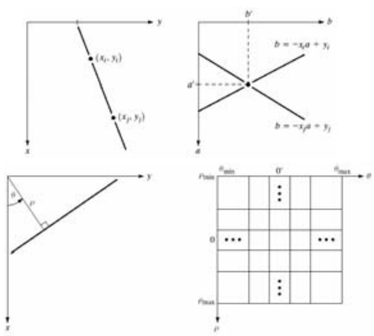
Parameterization of a Line



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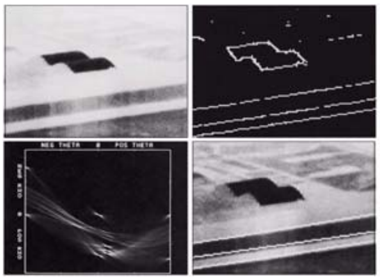
Detecting Lines via Hough Transform



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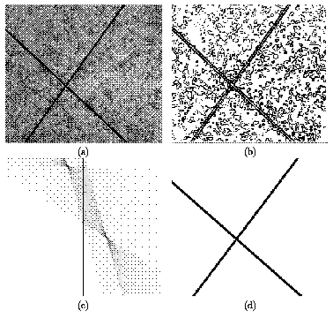
Detecting Lines via Hough Transform



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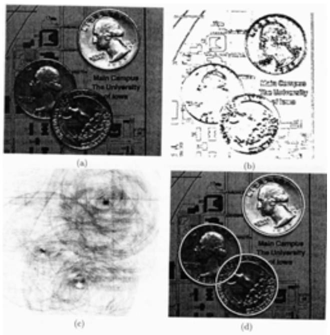
Detecting Circles via Hough Transform



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Graph Search

- Live wire
- Live lane
- Live wire 3D

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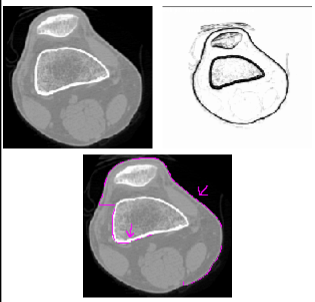
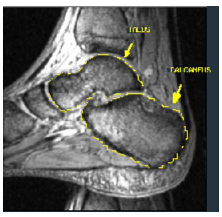
Live Wire Segmentation of the Knee and the Ankle





Deformable Boundaries

- Active/dynamic contour, snake
- Active surface, balloon
- Active shape
- Active appearance

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

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

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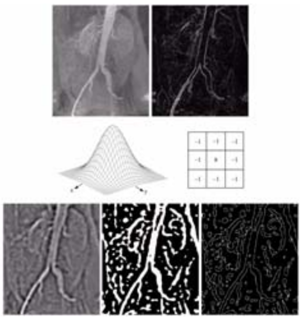
Laplace of a Gaussian (LoG)



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Active Contour

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Gradient Vector Field

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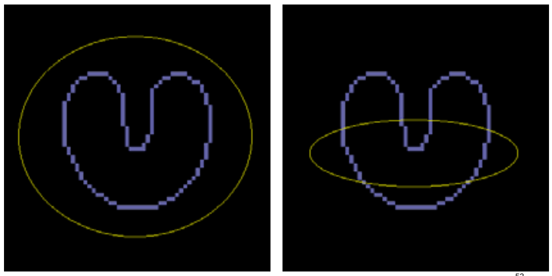
Active Contour with GVF



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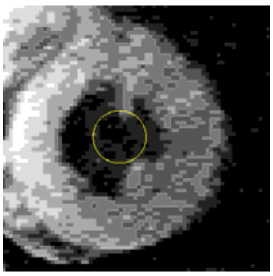
AC for the Left Ventricle



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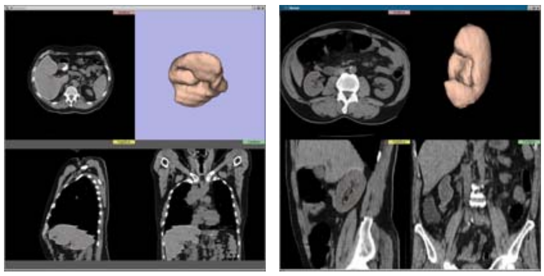
Segmentation of the Liver and the Right Kidney with Active Surface



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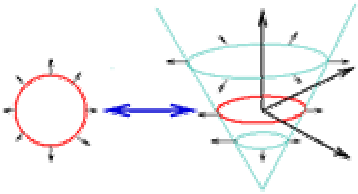
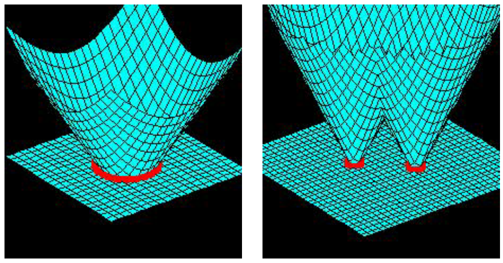
Level-set Methods

- Osher and Sethian



Evolving Level Set Functions

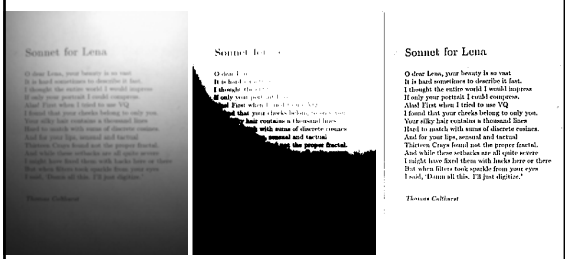


Region-based Segmentation Methods

Thresholding

- General form: $T = T\{\, \mathbf{x}, A(\mathbf{x}), f(\mathbf{x}) \,\}$
  - Global: $T = T\{\, f(\mathbf{x}) \,\}$
  - Local: $T = T\{\, A(\mathbf{x}), f(\mathbf{x}) \,\}$
  - Adaptive / dynamic: $T = T\{\, \mathbf{x}, A(\mathbf{x}), f(\mathbf{x}) \,\}$
  - Single threshold
  - Band thresholding
  - Hysteresis thresholding
- Dozens of strategies for determining thresholds

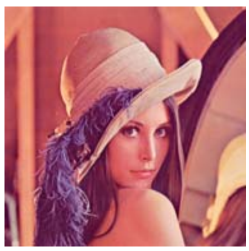
Thresholding



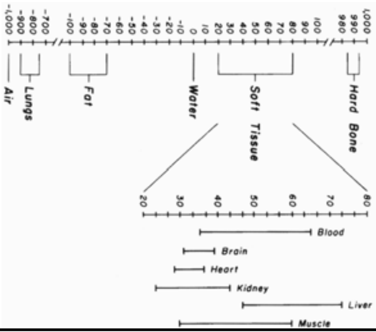
Original image | Global thresholding | Local thresholding

Sonnet for Lena *(by Thomas W. Colthurst)*

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."



Hounsfield Unit Ranges for CT



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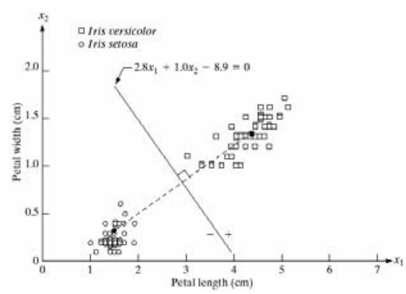
Clustering Techniques



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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

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k-means algorithm

1. Choose and fix number of classes *k*
2. For each pixel in the image, assign that pixel to a class such that the distance from this pixel to the center of that class is minimized
3. For each class, recalculate the means of the class based on the pixels that belong to that class
4. Iterate steps 2 and 3 until there is no change of the means

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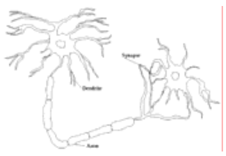
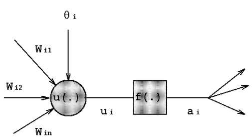
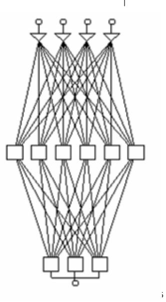
Artificial Neural Networks (ANN)

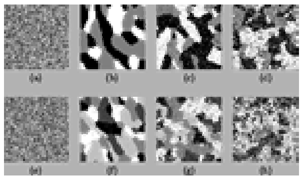






Markov Random Fields (MRF)

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



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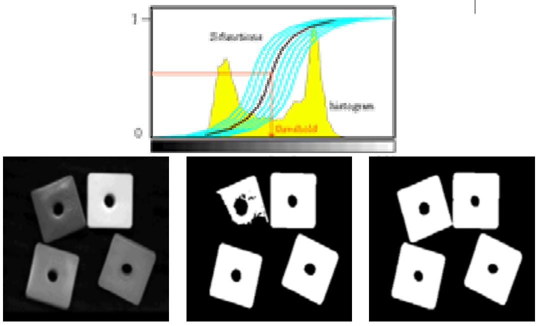
Thresholding Using Fuzziness



Fuzzy c-means

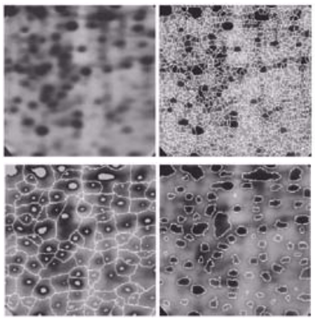
1. Choose and fix number of classes *c*
2. Determine the set *X* of points to which given scene maps in feature space
3. Partition *X* into *c* clusters such that the sum (over all clusters) of squared distance between points in cluster and its center is minimum

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

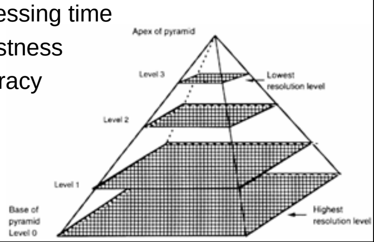
Over-segmentation with the Watershed Method



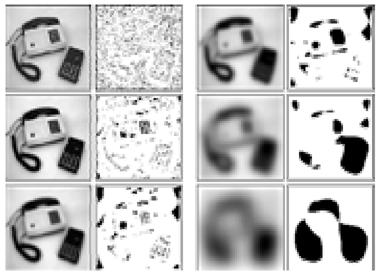
Useful Techniques

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



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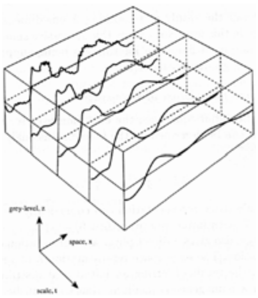
Details at Different Scales



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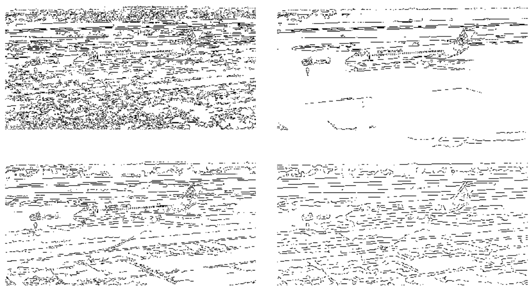
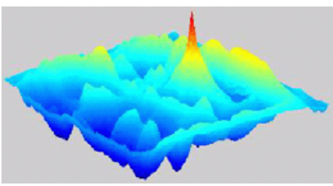
Edge Maps at Different Scales with Different Thresholds



Template Matching with Cross-correlation



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Other Useful Techniques

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

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Fuzzy Connectedness

Object Characteristics in Images

- Graded composition
  - heterogeneity of intensity in the object region due to heterogeneity of object material and blurring caused by the imaging device
- Hanging-togetherness
  - natural grouping of voxels constituting an object a human viewer readily sees in a display of the scene in spite of intensity heterogeneity

Fuzzy Sets and Relations

- Fuzzy subset: $\mathrm{A} = \{(x, \mu_{\mathrm{A}}(x)) \mid x \in X\}$
- Membership function: $\mu_{\mathrm{A}} : X \rightarrow [0,1]$
- Fuzzy relation: $\rho = \{((x,y), \mu_\rho(x,y)) \mid (x,y) \in X \times X\}$
  $\mu_\rho : X \times X \rightarrow [0,1]$
- 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:

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

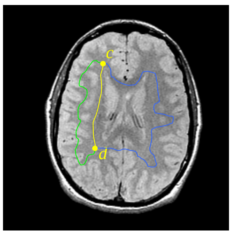
- Fuzzy digital space: (Z^n, α)
- Scene (over a fuzzy digital scene): $\mathrm{C} = (C, f)$

Fuzzy Connectedness

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

$$\mu_\kappa(c,d) = h(\mu_\alpha(c,d), f(c), f(d), c, d)$$

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



Fuzzy Connected Objects

- Binary relation K_θ

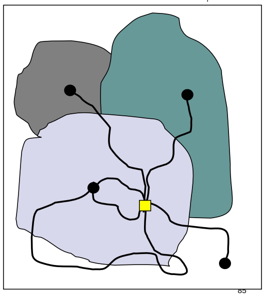
$$\mu_{K_\theta}(c,d) = \begin{cases} 1, & \text{if } \mu_\kappa(c,d) \in \theta \\ 0, & \text{otherwise} \end{cases}$$

- Fuzzy κ-component of strength θ_x
- Fuzzy $\kappa_{\theta x}$ object containing o

- Very important property: robustness

Fuzzy Connectedness Variants

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



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Scale-based Affinity

- Aspects
  - spatial adjacency
  - homogeneity
  - object feature
  - object scale
  - global hanging-togetherness

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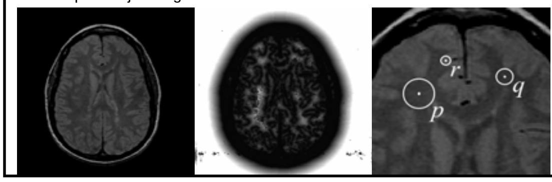
Scale As Used in Fuzzy Connectedness

- "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.



Algorithm for Computing Fuzzy Connectedness (Dijkstra's-like)

Begin
  Set all elements of C_o to 0 except o which is set to 1 ;
  Push o to Q ;
  While Q is not empty do
    Remove a spel c from Q for which $f_o(c)$ is maximal ;
    For each spel e such that $\mu_\kappa(c,e) > 0$ do
      Set $f_{min} = \min(f_o(c), \mu_\kappa(c,e))$;
      If $f_{min} > f_o(e)$ then
        Set $f_o(e) = f_{min}$;
        If e is already in Q then
          Update e in Q ;
        Else
          Push e to Q ;
        Endif
      Endif
    Endfor
  Endwhile
End

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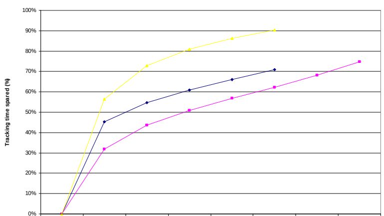
Effect of Using Small Thresholds on Affinity



	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7
WM	0.00%	45.35%	54.60%	60.99%	66.04%	71.04%		
GM	0.00%	31.86%	43.52%	50.93%	56.73%	62.26%	68.06%	74.75%
CSF	0.00%	56.36%	72.93%	80.89%	86.41%	90.37%		

Threshold

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Image Segmentation Using the Fuzzy Connectedness Framework

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Segmentation in Two Phases

- Training for parameters and set up
  - Performed only once for each task (protocol, body region, organ)
- Segmenting each dataset into the desired objects (i.e., BP, WM, GM, and CSF)
  - Parameters found and fixed in Training
  - Some input obtained from user for each given data set

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Phase 1: Training

- For each protocol, a few datasets are selected and used to extract the values for the parameters
  - Also used for testing the flow of operations and the control scripts step-by-step
- Mostly requires continuous user control, since the fine tuning of parameters is a modify-and-verify iteration

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Phase 2: Segmentation

- Most steps are automatic
  - Parameters are determined and fixed in the training/setup phase
- Interactive steps require:
  - Simple mouse clicks from the user to specify points
  - "cut" and "add" operations when correcting the brain mask

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Steps of the Method

- Correct for RF field inhomogeneity
- Standardize MR image intensities
- Compute fuzzy affinity
- Specify seeds and VOI
- Compute fuzzy connectedness
- Determine fuzzy connected objects
- Create brain mask
- Correct brain mask
- Create masks for objects

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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
  - Cancer, cyst, polyp detection and quantification
  - Stenosis and aneurism detection and quantification
- Digitized mammography
  - Detecting of microcalcifications
- Craniofacial 3D imaging
  - Visualization and surgical planning

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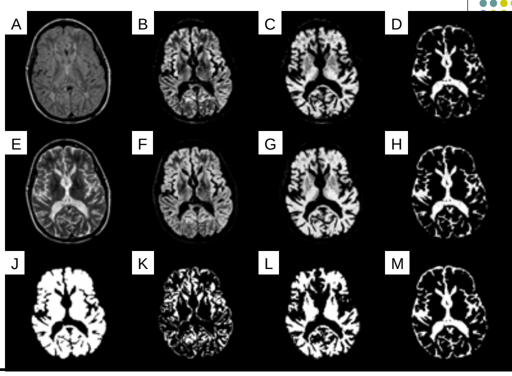
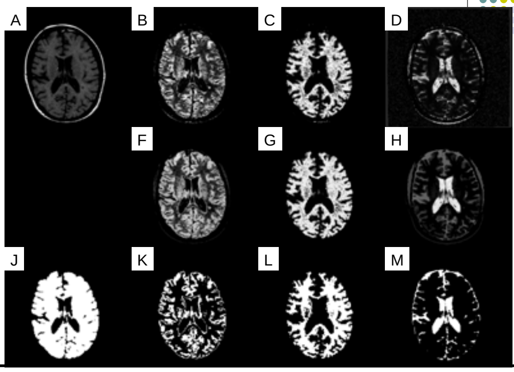
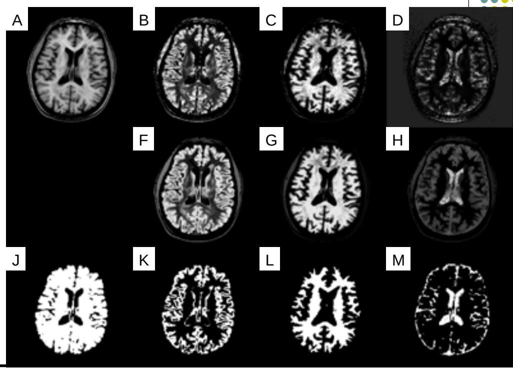
Brain Tissue Segmentation (FSE)



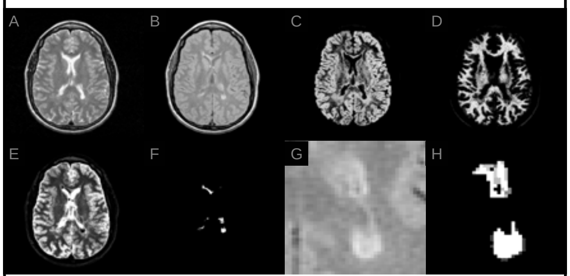
Brain Tissue Segmentation (T1)



Brain Tissue Segmentation (SPGR)



MS Lesion Quantification (FSE)



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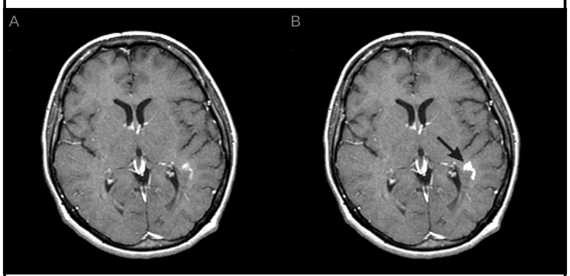
MS Lesion Quantification (T1E)



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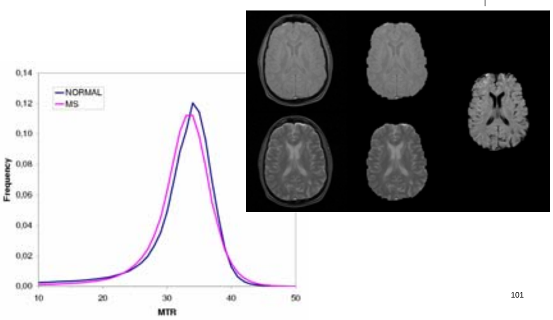
MTR Analysis



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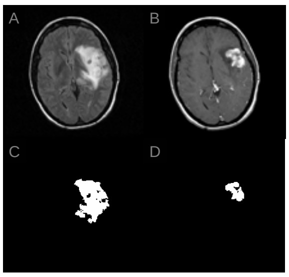
Brain Tumor Quantification



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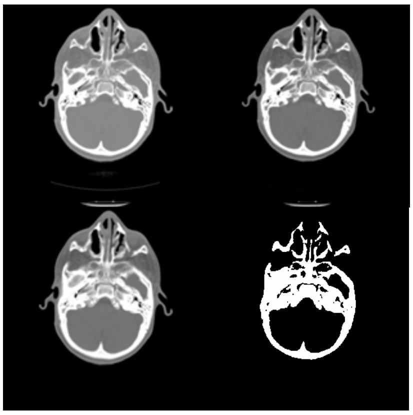
Orig.

Aff.



Conn.

Segm.

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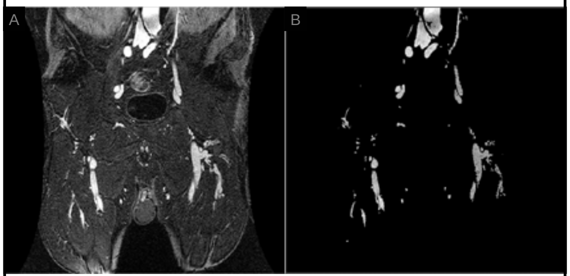
MRA Vessel Segmentation



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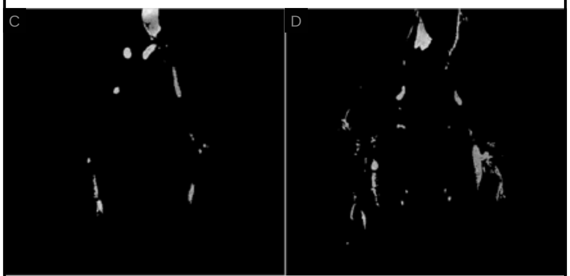
Artery/Vein Separation



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MRA Vessel Segmentation

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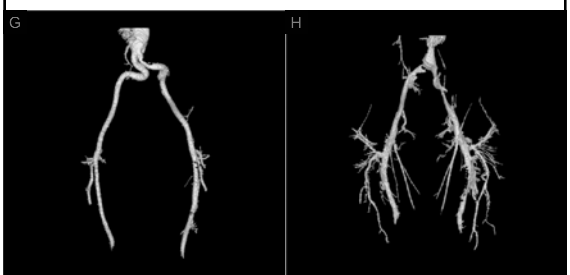
Artery/Vein Separation



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Evaluation of Image Segmentation Methods

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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

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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

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Accuracy

- Segmentation results of a method are usually compared to some surrogate truth since real truth is rarely available
- Comparison may be made by using three accuracy measures
  - true positive volume fraction (TPVF)
  - false positive volume fraction (FPVF)
  - false negative volume fraction (FNVF)

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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

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Challenges in Segmentation

- To develop general methods that can be quickly adapted to applications
- To keep human assistance per scene to a minimum
- To develop fuzzy methods that can realistically handle uncertainties in data
- To asses the efficacy of segmentation methods

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Motto: "There is no magic 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, validation methods

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