Knowledge Discovery and Data Mining Based on Hierarchical Segmentation of Image Data

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Talk Outline

I. **Hierarchical Image Segmentation by Recursive Hierarchical Step-Wise Optimization and Constrained Spectral Clustering.**

II. Project Status Report: Knowledge Discovery and Data Mining Based on Hierarchical Segmentation of Image Data

III. HSEGViewer Demonstration.

Hierarchical Image Segmentation by Recursive Hierarchical Step-Wise Optimization and Constrained Spectral Clustering

What is Image Segmentation?

A partitioning of an image into related sections or regions.

- A earth remote sensing example: water, snow, types of natural vegetation, types of rock formation, types of agricultural crops, and types of other man created development.

- Generic case: region 1, region 2, …, region N.

What is a Hierarchical Image Segmentation?

A set of image segmentations that

i. consist of segmentations at different levels of detail, in which

ii. the coarser segmentations can be produced from merges of regions from the finer segmentations, and

iii. the region boundaries are maintained at the full image spatial resolution.

Original Image

Ninety-Six Regions

Prepared for Presentation in the JHU Visionary Lecture Series, April 19, 2004. 7

Fifty-Five Regions

Prepared for Presentation in the JHU Visionary Lecture Series, April 19, 2004. 8

Forty-Five Regions

Prepared for Presentation in the JHU Visionary Lecture Series, April 19, 2004. 9

Twenty-Three Regions

Prepared for Presentation in the JHU Visionary Lecture Series, April 19, 2004. 10

Twenty Regions

Prepared for Presentation in the JHU Visionary Lecture Series, April 19, 2004. 11

Fifteen Regions

Prepared for Presentation in the JHU Visionary Lecture Series, April 19, 2004. 12

Twelve Regions

Prepared for Presentation in the JHU Visionary Lecture Series, April 19, 2004. 13

Eleven Regions

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Ten Regions

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Eight Regions

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Six Regions

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Five Regions

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Four Regions

Prepared for Presentation in the JHU Visionary Lecture Series, April 19, 2004. 19

Two Regions

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Hierarchical Boundary Map

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Original Image

Prepared for Presentation in the JHU Visionary Lecture Series, April 19, 2004. 22

How can a Hierarchical Image Segmentation be Useful?

For a Segmentation Hierarchy of sufficient quality and resolution, an object of interest will:

- be represented by multiple image segments at finer levels
- be merged into the background at coarser levels
- be represented as a single segment at some intermediate level

How can a Hierarchical Image Segmentation be Generated?

The approaches for generating a Segmentation Hierarchy fall into two main categories:

i. multiresolution analysis

ii. region growing

Overview of Previous Region Growing Approaches

A. Logical Predicate Region Growing
B. Region Growing Based on Region Dissimilarity
C. Split-and-Merge Segmentation
D. Hierarchical Step-Wise Optimization (HSWO)

Logical Predicate Region Growing

A segmentation of the image X can be defined as a partition of X into N disjoint subsets X_1, X_2, …, X_N, such that

1) $\bigcup_{i=1}^{N} X_i = X$,

2) X_i, $i = 1, 2, \ldots, N$ are connected,

Logical Predicate Region Growing (cont'd)

3) $P(X_i) = TRUE$ for $i = 1, 2, \ldots, N$.

4) $P(X_i \bigcup X_j) = FALSE$ for $i \neq j$, where X_i and X_j are adjacent.

$P(X_i)$ is a logical predicate that assigns the value TRUE or FALSE to X_i, depending on the image data values in X_i.

Logical Predicate Region Growing (cont'd)

An example of a logical predicate is:

$$P_{\infty\text{-Norm}}(X_i) = (\|x_p - u_i\|_\infty \leq T \;\forall\; x_p \in X_i)$$

where

$$\|x_p - u_i\|_\infty = \max\{|\chi_{pb} - \mu_{ib}| : b = 1, 2, \ldots, B\}$$

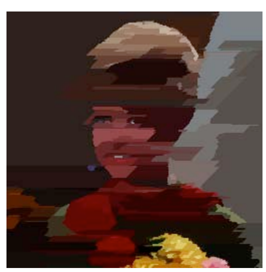
Logical Predicate Region Growing (cont'd)

The Logical Predicate definition of Region Growing does not lead to a unique algorithm for calculating the segmentation.

The implementation used in this study based on scanning the image data pixel-by-pixel, line-by-line, and then again region-by-region.

Logical Predicate Region Growing (cont'd)

Kodak Girl



Region Mean

Boundary Map

235 Region Segmentation with ∞-Norm Logical Predicate.

Logical Predicate Region Growing (cont'd)

Poor results with marked scan order dependence.

Very inefficient: must visit each pixel in each Region each time logical predicate is calculated.

The 256-by-256 pixel Kodak Girl picture took 2.5 minutes to segment.

Region Growing Based on Region Dissimilarity

A much improved region growing segmentation result may be obtained more efficiently through the use of a region dissimilarity function based on aggregated region features. The 256-by-256 pixel Kodak Girl picture takes one second to segment.

Pixel, x_p, is placed in neighboring region, X_j, if $d(x_p,X_j) < d(x_p,X_k)$ $\forall$ regions adjacent to pixel x_p with $j \neq k$ and $d(x_p,X_j) \leq T$.

Region Growing Based on Region Dissimilarity (cont'd)

Region, X_i, is merged with neighboring region, X_j, if $d(X_i, X_j) < d(X_i, X_k)$ $\forall$ regions adjacent to pixel X_j with $j \neq k$ and $d(X_i, X_j) \leq T$.

An example of a region dissimilarity function is:

$$d_{\infty\text{-Norm}}(X_i, X_j) = \| u_i - u_j \|_\infty ,$$

where

$$\| u_i - u_j \|_\infty = \max\{| \mu_{ib} - \mu_{jb}| : b = 1, 2, \ldots, B\}$$

Region Growing Based on Region Dissimilarity (cont'd)

Kodak Girl

Region Mean

Boundary Map

230 Region Segmentation with ∞-Norm Dissimilarity Function.

Region Growing Based on Region Dissimilarity (cont'd)

More commonly, the region dissimilarity function is based on the selection of merges that minimize the increase in the mean squared error between the region mean image and the original image data.

The sample estimate of mean squared error of spectral band b is:

$$MSE_b(X) = \frac{1}{M-1}\sum_{i=1}^{N} MSE_b(X_i),$$

where

$$MSE_b(X_i) = \sum_{x_p \in X_i} \left(\chi_{pb} - \mu_{ib}\right)^2$$

Region Growing Based on Region Dissimilarity (cont'd)

A dissimilarity function is given by:

$$\mathrm{d}_{BSMSE}\left(X_i, X_j\right) = \sum_{b=1}^{B} \Delta MSE_b\left(X_i, X_j\right)$$

where

$$\Delta MSE_b(X_i,X_j) = MSE_b(X_i \cup X_j) - MSE_b(X_i) - MSE_b(X_j)$$

$$= \sum_{x_p \in X_{ij}} \left[\chi_{pb} - \mu_{ijb}\right] - \sum_{x_p \in X_i} \left[\chi_{pb} - \mu_{ib}\right] - \sum_{x_p \in X_j} \left[\chi_{pb} - \mu_{jb}\right]$$

$$= n_i\left(\mu_{ib} - \mu_{ijb}\right)^2 + n_j\left(\mu_{jb} - \mu_{ijb}\right)^2 .$$

Region Growing Based on Region Dissimilarity (cont'd)

Since

$$\mu_{ijb} = \frac{n_i \mu_{ib} + n_j \mu_{jb}}{n_i + n_j},$$

$$\Delta MSE_b\left(X_i, X_j\right) = \frac{n_i n_j}{\left(n_i + n_j\right)}\left(\mu_{ib} - \mu_{jb}\right)^2.$$

Thus

$$\mathrm{d}_{BSMSE}\left(X_i, X_j\right) = \frac{n_i n_j}{\left(n_i + n_j\right)} \sum_{b=1}^{B} \left(\mu_{ib} - \mu_{jb}\right)^2.$$

Region Growing Based on Region Dissimilarity (cont'd)

Kodak Girl

Region Mean

Boundary Map

226 Region Segmentation with *BSMSE* Dissimilarity Function.

Region Growing Based on Region Dissimilarity (cont’d)

Kodak Girl

Region Mean

Boundary Map

230 Region Segmentation with ∞-Norm Dissimilarity Function.

Region Growing Based on Region Dissimilarity (cont’d)

Kodak Girl

Region Mean

Boundary Map

226 Region Segmentation with *BSMSE* Dissimilarity Function.

Split-and-Merge Segmentation

Kodak Girl

Region Mean

Boundary Map

242 Region Segmentation with *BSMSE* Dissimilarity Function.

Hierarchical Step-Wise Optimization (HSWO)

1. Initalize the segmentation by assigning each image pixel a region label. If a pre-segmentation is provided, label each image pixel according to the pre-segmentation. Otherwise, label each image pixel as a separate region.
2. Calculate the dissimilarity criterion value between all pairs of spatially adjacent regions, find the pair of spatially adjacent regions with the smallest dissimilarity criterion value, and merge that pair of regions.
3. Stop if no more merges are required. Otherwise, return to step 2.

Hierarchical Step-Wise Optimization

Kodak Girl 34 Region Mean Hier. Boundary
Map

Segmentation with *BSMSE* Dissimilarity Function took 35 minutes.

Split-and-Merge Segmentation

Kodak Girl Region Mean Boundary Map

242 Region Segmentation with *BSMSE* Dissimilarity Function.

Improvements in HSWO for Hierarchical Segmentation

A. Selection of Hierarchical Levels
B. Recursive HSWO (RHSWO)
C. Processing Window Artifact Elimination

Selection of Hierarchical Levels

Could Monitor the global dissimilarity function. For example:

$$D_{BSMSE}(X) = \sum_{b=1}^{B} MSE_b(X)$$

$$= \frac{1}{(M-1)} \sum_{i=1}^{N} \sum_{x_p \in X_i} \sum_{b=1}^{B} (\chi_{pb} - \mu_{ib})^2.$$

Selection of Hierarchical Levels (cont'd)

A more sensitive global dissimilarity function is one based on a vector 2-Norm:

$$D_{2\text{-}Norm}(X) = \frac{1}{M}\sum_{i=1}^{N}\sum_{x_p \in X_i}\left\| x_p - u_i \right\|_2$$

$$= \frac{1}{M}\sum_{i=1}^{N}\sum_{x_p \in X_i}\left[\sum_{b=1}^{B}\left(\chi_{pb} - \mu_{ib}\right)^2\right]^{1/2}.$$

Selection of Hierarchical Levels (cont'd)

HSWO with Selection of Segmentation Hierarchy:

1. Give each image pixel a region label and set the global criterion value, *dval*, equal to zero. If a pre-segmentation is provided, label each image pixel according to the pre-segmentation. Otherwise, label each image pixel as a separate region.
2. Calculate the dissimilarity criterion value, *dissim_val*, between all pairs of spatially adjacent regions.
3. Find the smallest *dissim_val* and set *thresh_val* equal to it. Then merge all pairs of spatially adjacent regions with *dissim_val* ≤ *threshval*.
4. If the number of regions remaining is less than the preset value *chk_nregions*, go to step 5. Otherwise, go to step 2.

Selection of Hierarchical Levels (cont'd)

HSWO with Selection of Segmentation Hierarchy (cont'd):

5. If the number of regions remaining is less than or equal to *conv_nregions*, save the current region label map to disk along with associated region information and STOP. Otherwise, let *prev_dval* = *dval*, calculate the current global criterion value, and set *dval* equal to this value. If *prev_dval* = zero, save the current region label map to disk along with associated region information, and go to step 2. Otherwise, calculate *dratio* = *dval*/ *prev_dval*. If *dratio* is greater than the preset threshold *convfact*, save the region label map from the previous iteration to disk along with associated region information, and go to step 2. Otherwise, just go to step 2.

Selection of Hierarchical Levels (cont'd)

Kodak Girl

34 Region Mean

Hier. Boundary Map

26 Hierarchical Levels with *chk_nregions* = 256 & *convfact* = 1.01.

Recursive HSWO (RHSWO)

Recursive HSWO:

1. Given an input image X, specify the number levels of recursion required (rnb_levels) and pad the input image, if necessary, so that the width and height of the image can be evenly divided by 2nblevels-1. (A good value for rnb_levels results in an image section at level = rnb_levels consisting of roughly 1000 to 4000 pixels.) Set level = 1.
2. Call rhswo(level,X).
3. Execute the HSWO algorithm (per part A this section) on the image X using as a pre-segmentation the segmentation output by the call to rhswo( ) in step 2.

RHSWO (cont'd)

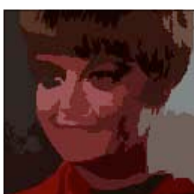
where rhswo(*level*,*X*) is:

1. If *level* = *rnb_levels*, go to step 3. Otherwise, divide the image data into quarters (i.e., half the width and height dimensions) and call rhswo*(level+1,X*/4*)* for each image quarter (represented as *X*/4).
2. After all four calls to rhswo() from step 1 complete processing, reassemble the image segmentation results.
3. If *level* < *rnb_levels*, initialize the segmentation with the reassembled segmentation results from step 2. Otherwise, initialize the segmentation with one pixel per region. Execute the HSWO algorithm on the image *X* with the following modification: Terminate the algorithm when the number of regions reaches the preset value *min_nregions*. Exit.

RHSWO (cont'd)

Kodak Girl Region Mean Hier. Boundary
Map

33 region segmentation with *rnb_levels* = 5 took 12 seconds.



Processing Window Artifact Elimination

Squared off region corner under the girl's left eye is a processing window artifact. Such artifacts are eliminated through a process that

i. Identifies regions that may contain pixels whose region assignment should be switched to that of another region, and, for each such region, keeps a list of regions that pixel could be potentially switched to.
ii. Computes the dissimilarity of the pixels contained in the identified regions to their own region and to the regions listed as regions the pixel could be switched to.
iii. If the pixel is more similar to one of the listed regions, its region assignment is switched to that region.

Processing Window Artifact Elimination

Kodak Girl

Region Mean

Hier. Boundary Map

36 region segmentation has no artifacts. Processing time 16 seconds.

Hierarchical Image Segmentation

A. Addition of Spectral Clustering to HSWO
B. Recursive HSEG (RHSEG)
C. Varying Importance of Spectral Clustering

Addition of Spectral Clustering

HSEG Basic Algorithm:

1. Give each image pixel a region label and set the global criterion value, *dval*, equal to zero. If a pre-segmentation is provided, label each image pixel according to the pre-segmentation. Otherwise, label each image pixel as a separate region.
2. Calculate the dissimilarity criterion value, *dissim_val*, between all pairs of spatially adjacent regions.
3. Find the smallest *dissim_val* and set *thresh_val* equal to it. Then merge all pairs of spatially adjacent regions with *dissim_val* ≤ *threshval*.

Addition of Spectral Clustering (cont'd)

HSEG Basic Algorithm (cont'd):

4. If *spclust_wght* equals zero, go to step 6. Otherwise, calculate the *dissim_val* between all pairs of non-spatially adjacent regions.
5. Merge all pairs of non-spatially adjacent regions with *dissim_val* ≤ *spclust_wght***thresh_val*.
6. If the number of regions remaining is less than the preset value *chk_nregions*, go to step 5. Otherwise, go to step 2.

Addition of Spectral Clustering (cont'd)

HSEG Basic Algorithm (cont'd):

7. If the number of regions remaining is less than or equal to *conv_nregions*, save the current region label map to disk along with associated region information and STOP. Otherwise, let *prev_dval* = *dval*, calculate the current global criterion value, and set *dval* equal to this value. If *prev_dval* = zero, save the current region label map to disk along with associated region information, and go to step 2. Otherwise, calculate *dratio* = *dval*/ *prev_dval*. If *dratio* is greater than the preset threshold *convfact*, save the region label map from the previous iteration to disk along with associated region information, and go to step 2. Otherwise, just go to step 2.

Recursive HSEG (RHSEG)

Kodak Girl

Region Mean

Hier. Boundary Map

11 region segmentation with *spclust_wght* = 1.0 took 37 seconds.

Varying Importance of Spectral Clustering (RHSEG)

Kodak Girl Region Mean Hier. Boundary
Map

11 region segmentation with *spclust_wght* = 0.1.

HSEG/RHSEG Variations

A. RHSEG/RHSWO hybrid
B. Variations in Neighborhood Size
C. Variations in Dissimilarity Criterion
   i. Normalization
   ii. Vector Norms
   iii. Other Dissimilarity Criteria

RHSEG/RHSWO Hybrid

RHSEG to 32 regions
connected labeling gives 3621 regions
RHSWO to completion

Kodak Girl

Region Mean

Hier. Boundary

Map

34 region segmentation result with *spclust_wght* = 0.1.

Variations in Neighborhood Size

12	17	11	15	23
13	5	3	7	19
9	1	0	2	10
20	8	4	6	14
24	16	12	18	22

RHSEG/RHSWO Hybrid

RHSEG to 32 regions
connected labeling gives 3621 regions
RHSWO to completion

Kodak Girl

Region Mean

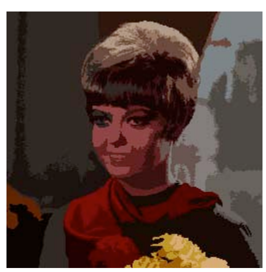
Hier. Boundary
Map

34 region segmentation result with *spclust_wght* = 0.1.

RHSEG/HSWO Hybrid

RHSEG to 32 regions
connected labeling gives 3621 regions
HSWO to completion

Kodak Girl



Region Mean

Hier. Boundary
Map

28 region segmentation result with *spclust_wght* = 0.1 and with twenty-four nearest neighbors neighborhood.

Normalization

$$\mu_b = \frac{1}{M}\sum_{m=1}^{M}\chi_{mb} \quad \text{and} \quad \acute{o}_b^2 = \frac{1}{M-1}\sum_{m=1}^{M}(\chi_{mb} - \mu_b)^2$$

To normalize the data to have mean = M and variance = Σ^2, set

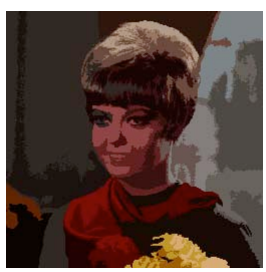
$$\zeta_{mb} = \left[\frac{\Sigma}{\sigma_b}(\chi_{mb} - \mu_b)\right] + \mathrm{M} = \Sigma_b^{'}\chi_{mb} + \mathrm{M}_b^{'}$$

where $\Sigma'_b = \Sigma/\sigma_b$ and $\mathrm{M}'_b = \mathrm{M} - \Sigma(\mu_b/\sigma_b)$.

RHSEG/HSWO Hybrid

RHSEG to 32 regions
connected labeling gives 3621 regions
HSWO to completion

Kodak Girl Map



Region Mean

Hier. Boundary

28 region segmentation result with *spclust_wght* = 0.1 and with twenty-four nearest neighbors neighborhood.

Normalization

RHSEG to 32 regions
connected labeling gives 4122 regions
HSWO to completion

Kodak Girl
Map

Region Mean

Hier. Boundary

29 region segmentation result 24nn neighborhood and each band normalized separately to M = 1.0 and Σ = 1.0.

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