MRFs and Segmentation with Graph Cuts

Computer Vision
CS 543 / ECE 549
University of Illinois

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Logistics

• HW 3 grades released

• HW 4 due next Monday

• Final project proposals due Friday (by email)
Today’s class

• Review/Finish EM

• MRFs

• Segmentation with Graph Cuts
Missing Data Problems: Segmentation

Challenge: Segment the image into figure and ground without knowing what the foreground looks like in advance.

Three subproblems:
1. If we had labels, how could we model the appearance of foreground and background? **MLE: maximum likelihood estimation**
2. Once we have modeled the fg/bg appearance, how do we compute the likelihood that a pixel is foreground? **Probabilistic inference**
3. How can we get both labels and appearance models at once? **Hidden data problem: Expectation Maximization**
EM: Mixture of Gaussians

1. Initialize parameters

2. Compute likelihood of hidden variables for current parameters

\[ \alpha_{nm} = p(z_n = m \mid x_n, \mu^{(t)}, \sigma^{2(t)}, \pi^{(t)}) = \frac{p(x_n \mid z_n = m, \theta_m)p(z_n = m \mid \theta_m)}{\sum_k p(x_n \mid z_n = k, \theta_k)p(z_n = k \mid \theta_k)} \]

Given by normal distribution

3. Estimate new parameters for each component, weighted by likelihood

\[ \hat{\mu}_{m}^{(t+1)} = \frac{1}{\sum_n \alpha_{nm}} \sum_n \alpha_{nm} x_n \]
\[ \hat{\sigma}_{m}^{2(t+1)} = \frac{1}{\sum_n \alpha_{nm}} \sum_n \alpha_{nm} (x_n - \hat{\mu}_m)^2 \]
\[ \hat{\pi}_m^{(t+1)} = \frac{\sum_n \alpha_{nm}}{N} \]
Gaussian Mixture Models: Practical Tips

• Design decisions
  – Number of components
    • Select by hand based on knowledge of problem
    • Select using cross-validation or sample data
    • Usually, not too sensitive and safer to use more components
  – Variance
    • “Spherical covariance”: dimensions within each component are independent with equal variance (1 parameter but usually too restrictive)
    • “Diagonal covariance”: dimensions within each component are not independent with difference variances (N parameters for N-D data)
    • “Full covariance”: no assumptions (N*(N+1)/2 parameters); for high N might be expensive to do EM, to evaluate, and may overfit
    • Typically use “Full” if lots of data, few dimensions; Use “Diagonal” otherwise

• Can get stuck in local minima
  – Use multiple restarts
  – Choose solution with greatest data likelihood
“Hard EM”

• Same as EM except compute $z^*$ as most likely values for hidden variables

• K-means is an example

• Advantages
  – Simpler: can be applied when cannot derive EM
  – Sometimes works better if you want to make hard predictions at the end

• But
  – Generally, pdf parameters are not as accurate as EM
EM Demo

• GMM with images demos
What’s wrong with this prediction?

$P(\text{foreground} \mid \text{image})$
Solution: encode dependencies between pixels

\[ P(\text{foreground | image}) \]

Normalizing constant called “partition function”

\[ P(y; \theta, data) = \frac{1}{Z} \prod_{i=1..N} f_1(y_i; \theta, data) \prod_{i,j \in \text{edges}} f_2(y_i, y_j; \theta, data) \]

- Labels to be predicted
- Individual predictions
- Pairwise predictions
Writing Likelihood as an “Energy”

\[
P(y; \theta, \text{data}) = \frac{1}{Z} \prod_{i=1..N} p_1(y_i; \theta, \text{data}) \prod_{i,j \in \text{edges}} p_2(y_i, y_j; \theta, \text{data})
\]

\[
\text{Energy}(y; \theta, \text{data}) = \sum_i \psi_1(y_i; \theta, \text{data}) + \sum_{i,j \in \text{edges}} \psi_2(y_i, y_j; \theta, \text{data})
\]

Cost of assignment \(y_i\)

Cost of pairwise assignment \(y_i, y_j\)
Notes on energy-based formulation

\[
Energy(y; \theta, data) = \sum_{i} \psi_1(y_i; \theta, data) + \sum_{i,j \in \text{edges}} \psi_2(y_i, y_j; \theta, data)
\]

• Primarily used when you only care about the most likely solution (not the confidences)

• Can think of it as a general cost function

• Can have larger “cliques” than 2
  – Clique is the set of variables that go into a potential function
Markov Random Fields

\[
\text{Energy}(y; \theta, data) = \sum_i \psi_1(y_i; \theta, data) + \sum_{i,j \in \text{edges}} \psi_2(y_i, y_j; \theta, data)
\]

Node \( y_i \): pixel label

Cost to assign a label to each pixel

Edge: constrained pairs

Cost to assign a pair of labels to connected pixels
Markov Random Fields

- Example: “label smoothing” grid

\[ \text{Unary potential} \]
\[ 0: -\log P(y_i = 0 \mid \text{data}) \]
\[ 1: -\log P(y_i = 1 \mid \text{data}) \]

\[ \sum_{i} \psi_1 (y_i; \theta, \text{data}) + \sum_{i,j \in \text{edges}} \psi_2 (y_i,y_j; \theta, \text{data}) \]
Solving MRFs with graph cuts

\[ \text{Energy}(y; \theta, \text{data}) = \sum_{i} \psi_1(y_i; \theta, \text{data}) + \sum_{i, j \in \text{edges}} \psi_2(y_i, y_j; \theta, \text{data}) \]
Solving MRFs with graph cuts

\[ \text{Energy}(y; \theta, \text{data}) = \sum_i \psi_1(y_i; \theta, \text{data}) + \sum_{i,j \in \text{edges}} \psi_2(y_i, y_j; \theta, \text{data}) \]
GrabCut segmentation

User provides rough indication of foreground region.

Goal: Automatically provide a pixel-level segmentation.
Colour Model

Gaussian Mixture Model (typically 5-8 components)

Source: Rother
**Graph cuts**

**Boykov and Jolly (2001)**

**Image**

**Cut**: separating source and sink; Energy: collection of edges

**Min Cut**: Global minimal energy in polynomial time

Source: Rother
Colour Model

Gaussian Mixture Model (typically 5-8 components)

Source: Rother
GrabCut segmentation

1. Define graph
   - usually 4-connected or 8-connected
     • Divide diagonal potentials by $\sqrt{2}$

2. Define unary potentials
   - Color histogram or mixture of Gaussians for background and foreground
   \[
   \text{unary}_\text{- potential}(x) = -\log \frac{P(c(x); \theta_{\text{foreground}})}{P(c(x); \theta_{\text{background}})}
   \]

3. Define pairwise potentials
   \[
   \text{edge}_\text{- potential}(x, y) = k_1 + k_2 \exp \left\{ -\frac{\|c(x) - c(y)\|^2}{2\sigma^2} \right\}
   \]

4. Apply graph cuts

5. Return to 2, using current labels to compute foreground, background models
What is easy or hard about these cases for graphcut-based segmentation?
Easier examples

GrabCut – Interactive Foreground Extraction
More difficult Examples

Camouflage & Low Contrast

Fine structure

Harder Case

Initial Rectangle

Initial Result
3 Graph-cuts (30 pts)

Let us apply Graph-cuts for foreground/background segmentation. In the “cat” image, you are given a rough polygon of a foreground cat. Apply Graph-cuts to get a better segmentation.

First, you need an energy function. Your energy function should include a unary term, a data-independent smoothing term, and a contrast-sensitive smoothing term. Your unary terms should be $-\log \left[ \frac{P(\text{pixel} | \text{foreground})}{P(\text{pixel} | \text{background})} \right]$. Your pairwise term should include uniform smoothing and the contrast-sensitive term. To construct the unary term, use the provided polygon to obtain an estimate of foreground and background color likelihood. You may choose the likelihood distribution (e.g., color histograms or color mixture of Gaussians. Yes, you can use MATLAB GMM functions this time). Apply graph cut code for segmentation. You must define the graph structure and unary and pairwise terms and use the provided graph cut code or another package of your choice. Include in your writeup:

- Explain your foreground and background likelihood function. (5 pt)
- Write unary and pairwise term as well as the whole energy function, in math expressions. (5 pt)
- Your foreground and background likelihood map. Display $P(\text{foreground}|\text{pixel})$ as an intensity map (bright = confident foreground). (10 pt)
- Final segmentation. Create an image for which the background pixels are blue, and the foreground pixels have the color of the input image. (10 pt)

Notes
- look at GraphCut.m in provided code (skip README) – if you have trouble using package get help from TA
- Use poly2mask to convert the polygon to a foreground mask
Lazy Snapping (Li et al. SG 2004)
Graph cuts with multiple labels

• Alpha expansion
  Repeat until no change
  For $\alpha = 1..M$
    Assign each pixel to current label or $\alpha$ (2-class graphcut)
  – Achieves “strong” local minimum

• Alpha-beta swap
  Repeat until no change
  For $\alpha = 1..M$, $\beta = 1..M$ (except $\alpha$)
    Re-assign all pixels currently labeled as $\alpha$ or $\beta$ to one of those two labels while keeping all other pixels fixed
Using graph cuts for recognition

TextonBoost (Shotton et al. 2009 IJCV)
Using graph cuts for recognition

Unary Potentials from classifier

Alpha Expansion Graph Cuts

TextonBoost (Shotton et al. 2009 IJCV)
Limitations of graph cuts

- Associative: edge potentials penalize different labels
  
  Must satisfy
  \[ E^{i,j}(0,0) + E^{i,j}(1,1) \leq E^{i,j}(0,1) + E^{i,j}(1,0) \]

- If not associative, can sometimes clip potentials

- Graph cut algorithm applies to only 2-label problems
  - Multi-label extensions are not globally optimal (but still usually provide very good solutions)
Graph cuts: Pros and Cons

• Pros
  – Very fast inference
  – Can incorporate data likelihoods and priors
  – Applies to a wide range of problems (stereo, image labeling, recognition)

• Cons
  – Not always applicable (associative only)
  – Need unary terms (not used for bottom-up segmentation, for example)

• Use whenever applicable
More about MRFs/CRFs

• Other common uses
  – Graph structure on regions
  – Encoding relations between multiple scene elements

• Inference methods
  – Loopy BP or BP-TRW
    • Exact for tree-shaped structures
    • Approximate solutions for general graphs
    • More widely applicable and can produce marginals but often slower
Further reading and resources

• Graph cuts
  – Classic paper: What Energy Functions can be Minimized via Graph Cuts? (Kolmogorov and Zabih, ECCV '02/PAMI '04)

• Belief propagation
Next section: Object Recognition

- Face recognition
- Image categorization and general classification methods
- Object category detection
- Tracking objects