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Markov Random Fields in Image Segmentation

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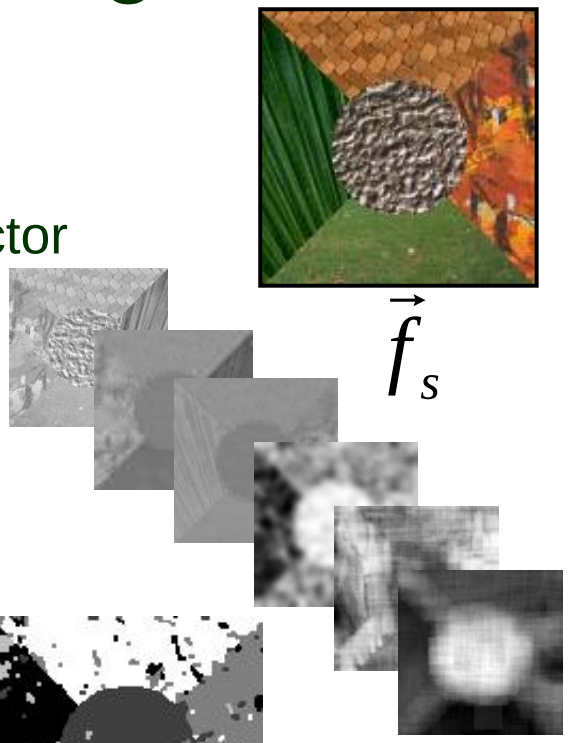
Overview

- Segmentation as pixel labeling
- Probabilistic approach
  - Segmentation as MAP estimation
  - Markov Random Field (MRF)
  - Gibbs distribution & Energy function
- Classical energy minimization
  - Simulated Annealing
  - Markov Chain Monte Carlo (MCMC) sampling
- Example MRF model & Demo
- Parameter estimation (EM)

Segmentation as a Pixel Labelling Task

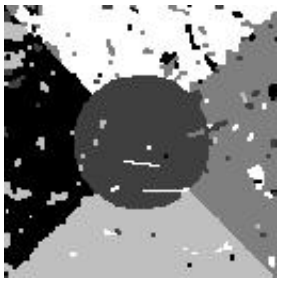


1. Extract features from the input image
   - Each pixel *s* in the image has a feature vector
   - For the whole image, we have

$$f = \{\vec{f}_s : s \in S\}$$

2. Define the set of labels Λ
   - Each pixel *s* is assigned a label $\omega_s \in \Lambda$
   - For the whole image, we have

$$\omega = \{\omega_s, s \in S\}$$



- For an $N \times M$ image, there are $|\Lambda|^{NM}$ possible labelings.
  - **Which one is the right segmentation?**

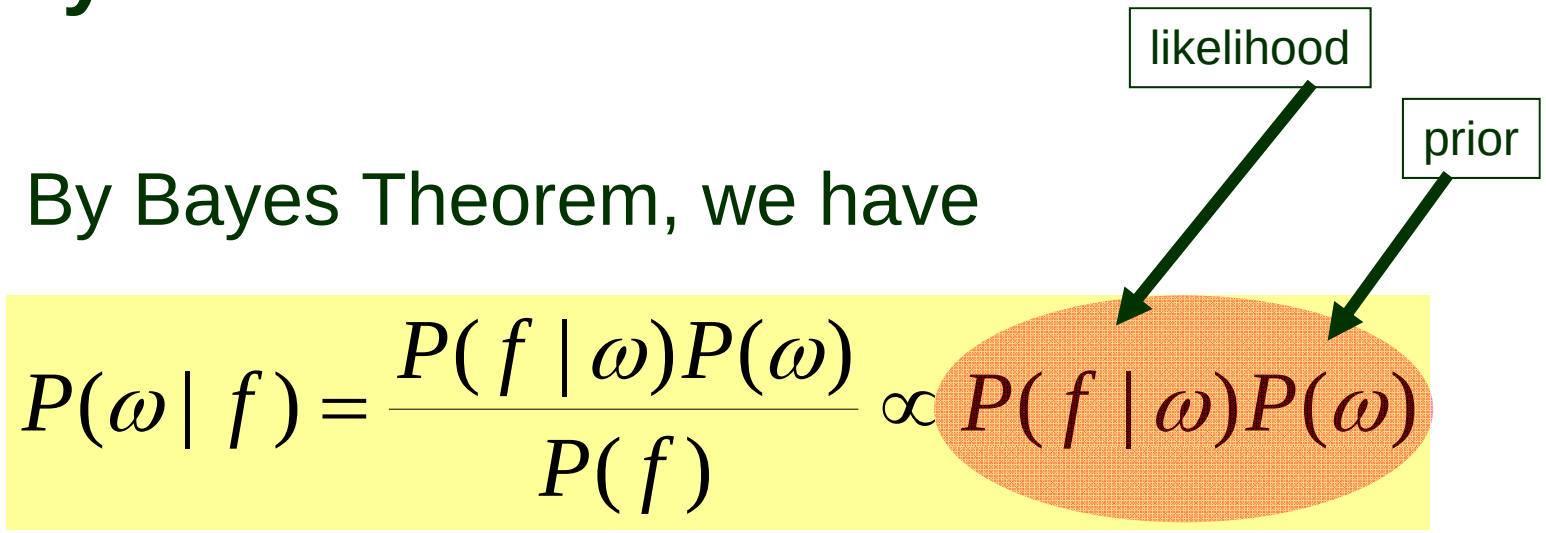
Probabilistic Approach, MAP

- Define a *probability measure* on the set of all possible labelings and select the most likely one.
- $P(\omega \mid f)$ measures the probability of a labelling, given the observed feature f
- Our goal is to find an optimal labeling $\hat{\omega}$ which *maximizes* $P(\omega \mid f)$
- This is called the *Maximum a Posteriori* (MAP) estimate:

$$\hat{\omega}^{MAP} = \arg\max_{\omega \in \Omega} P(\omega \mid f)$$

Bayesian Framework

- By Bayes Theorem, we have



$$P(\omega \mid f) = \frac{P(f \mid \omega)P(\omega)}{P(f)} \propto P(f \mid \omega)P(\omega)$$

- $P(f)$ is constant
- We need to define $P(\omega)$ and $P(f \mid \omega)$ in our model
  - We will use Markov Random Fields

Why MRF Modelization?

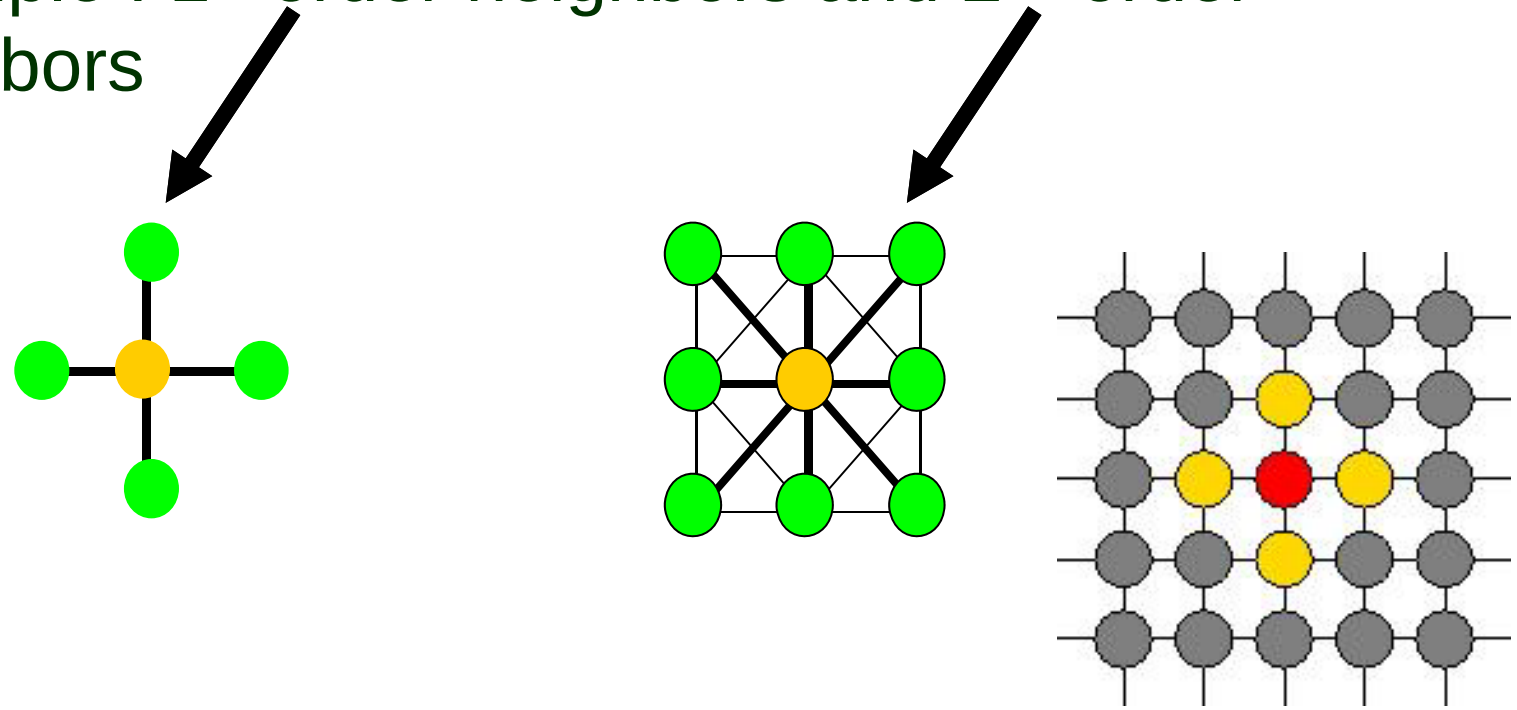
- In real images, regions are often homogenous; neighboring pixels usually have similar properties (intensity, color, texture, …)
- Markov Random Field (MRF) is a probabilistic model which captures such contextual constraints
- Well studied, strong theoretical background
- Allows MCMC sampling of the (hidden) underlying structure ➔ Simulated Annealing
- Fast and exact solution for certain type of models ➔ Graph cut [Kolmogorov]

What is MRF?

- To give a formal definition for Markov Random Fields, we need some basic building blocks
  - Observation Field and (hidden) Labeling Field
  - Pixels and their Neighbors
  - Cliques and Clique Potentials
  - Energy function
  - Gibbs Distribution

Definition – Neighbors

- For each pixel, we can define some surrounding pixels as its neighbors.
- Example : 1st order neighbors and 2nd order neighbors

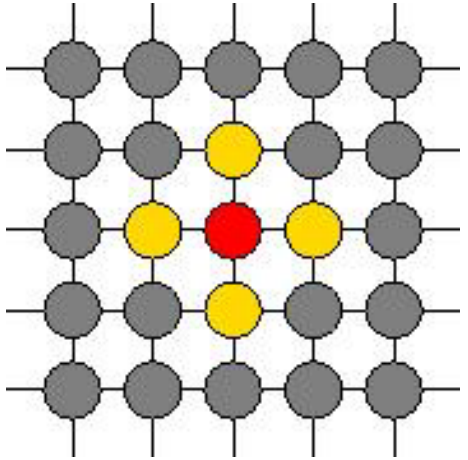


Definition – MRF

- The labeling field X can be modeled as a Markov Random Field (MRF) if
  1. For all $\omega \in \Omega : P(X = \omega) > 0$
  2. For every $s \in S$ and $\omega \in \Omega$:

$$P(\omega_s \mid \omega_r, r \neq s) = P(\omega_s \mid \omega_r, r \in N_s)$$

N_s denotes the neighbors of pixel s

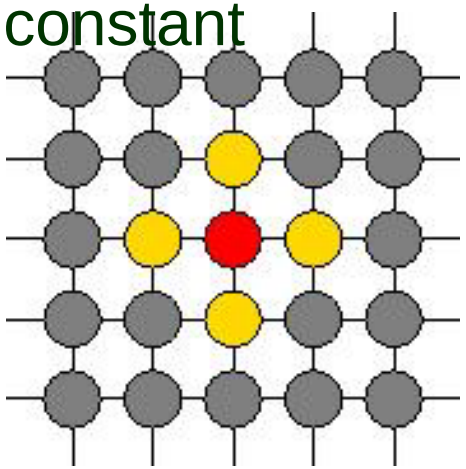


Hammersley-Clifford Theorem

- The Hammersley-Clifford Theorem states that a random field is a MRF if and only if $P(\omega)$ follows a Gibbs distribution.

$$P(\omega) = \frac{1}{Z}\exp(-U(\omega)) = \frac{1}{Z}\exp(-\sum_{c\in C} V_c(\omega))$$

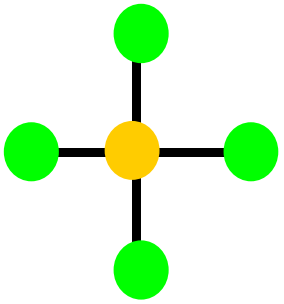
- where $Z = \sum_{\omega\in\Omega}\exp(-U(\omega))$ is a normalization constant
- This theorem provides us an easy way of defining MRF models via *clique potentials*.

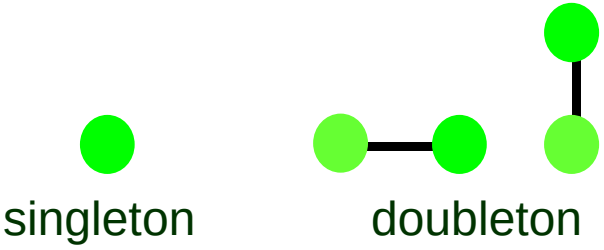


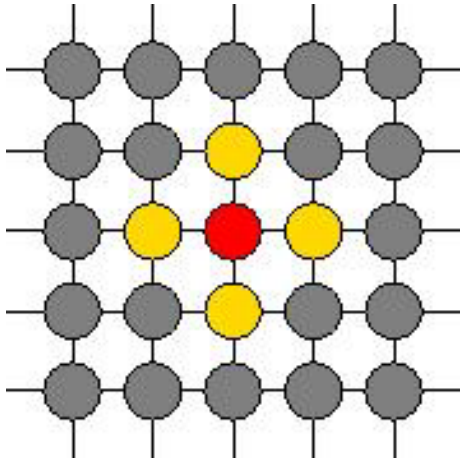
Definition – Clique

- A subset $C \subseteq S$ is called a *clique* if every pair of pixels in this subset are neighbors.
- A clique containing *n* pixels is called *n^{th} order clique*, *denoted by* C_n .
- The set of cliques in an image is denoted by

$$C = C_1 \cup C_2 \cup ... \cup C_k$$



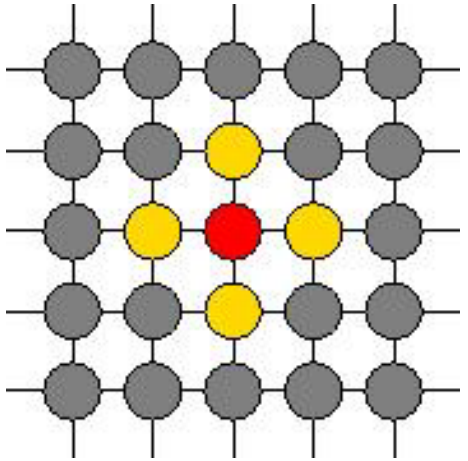




Definition – Clique Potential

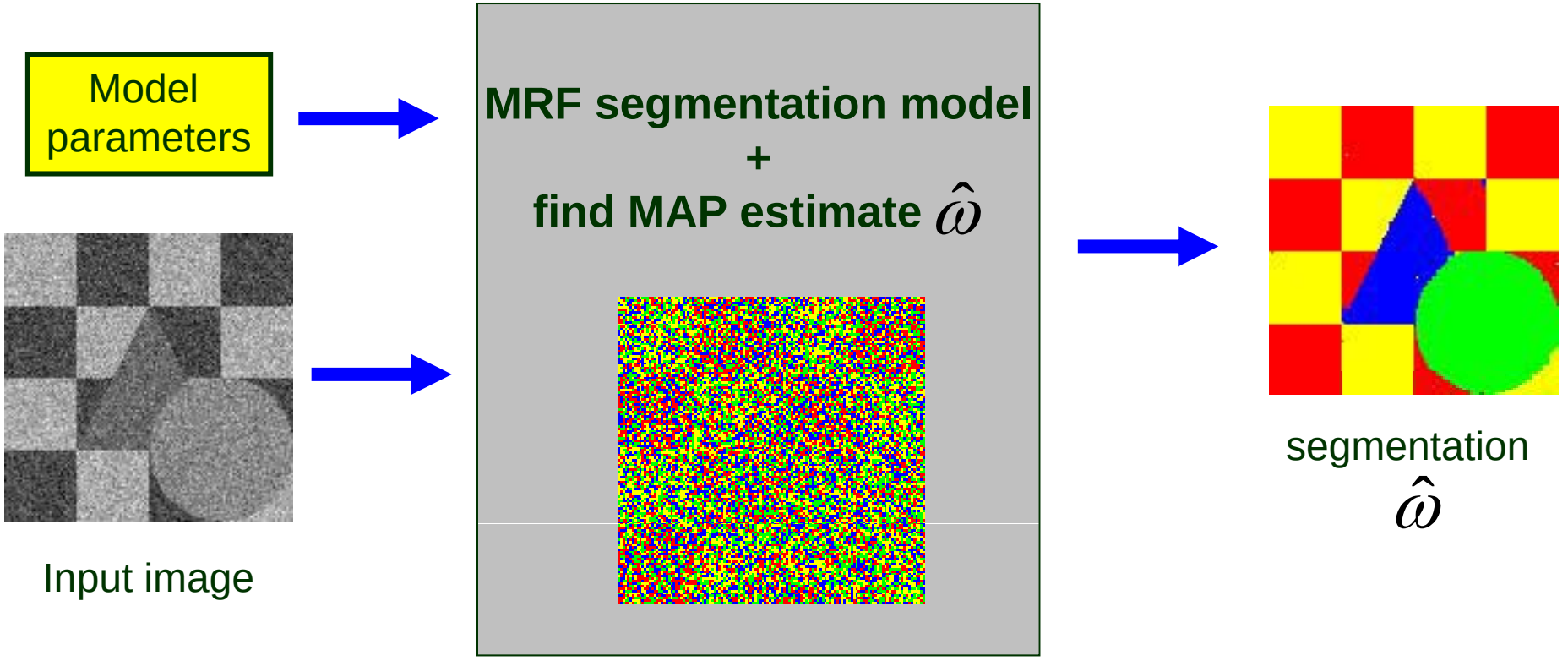
- For each clique *c* in the image, we can assign a value $V_c(\omega)$ which is called *clique potential* of *c*, where ω is the configuration of the labeling field
- The sum of potentials of all cliques gives us the energy $U(\omega)$ of the configuration ω

$$U(\omega) = \sum_{c \in C} V_c(\omega) = \sum_{i \in C_1} V_{C_1}(\omega_i) + \sum_{(i,j) \in C_2} V_{C_2}(\omega_i, \omega_j) + \ldots$$



Segmentation of grayscale images: A simple MRF model

- Construct a segmentation model where regions are formed by spatial clusters of pixels with similar intensity:



MRF segmentation model

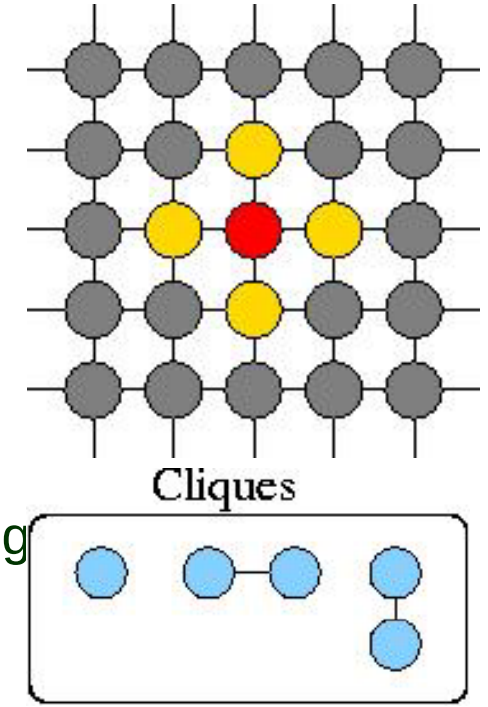
- Pixel labels (or classes) are represented by Gaussian distributions:

$$P(f_s \mid \omega_s) = \frac{1}{\sqrt{2\pi}\sigma_{\omega_s}} \exp\left(-\frac{(f_s - \mu_{\omega_s})^2}{2\sigma_{\omega_s}^2}\right)$$

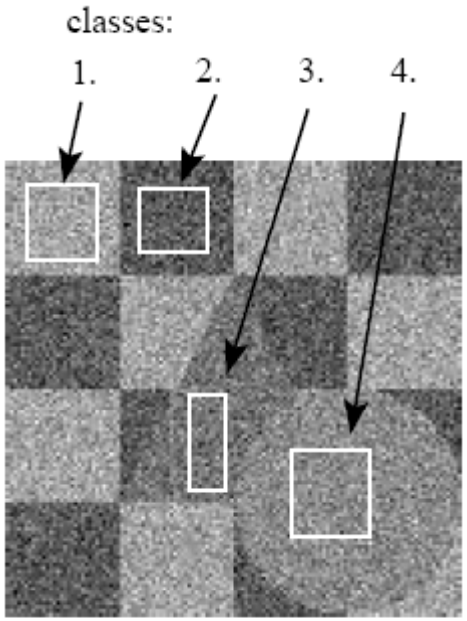
- Clique potentials:
  - ***Singleton***: proportional to the likelihood of features given ω: *log(P(f | ω)).*
  - ***Doubleton***: favours similar labels at neighbouring pixels – ***smoothness prior***

$$V_{c_2}(i,j) = \beta\delta(\omega_i,\omega_j) = \begin{cases} -\beta & if \quad \omega_i = \omega_j \\ +\beta & if \quad \omega_i \neq \omega_j \end{cases}$$

As β increases, regions become more homogenous

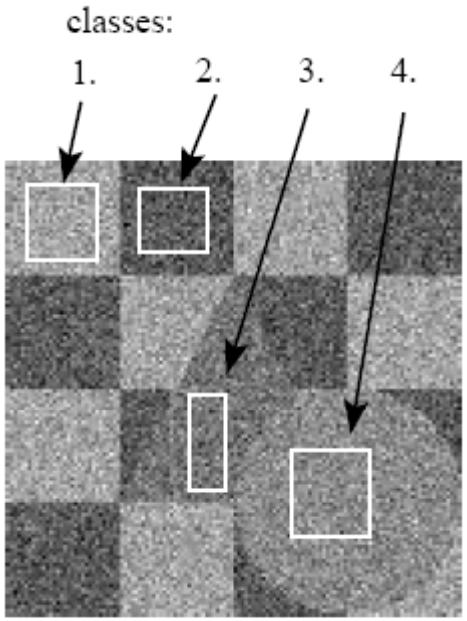


Model parameters



- Doubleton potential β
  - less dependent on the input ➔
    - can be fixed a priori
- Number of labels ($|\Lambda|$)
  - Problem dependent➔
    - usually given by the user or
    - inferred from some higher level knowledge
- Each label $\lambda \in \Lambda$ is represented by a Gaussian distribution $N(\mu_\lambda, \sigma_\lambda)$:
  - estimated from the input image

Model parameters



- The class statistics (mean and variance) can be estimated via the *empirical mean and variance*:

$$\forall \lambda \in \Lambda : \qquad \mu_\lambda = \frac{1}{|S_\lambda|} \sum_{s \in S_\lambda} f_s,$$

$$\sigma_\lambda^2 = \frac{1}{|S_\lambda|} \sum_{s \in S_\lambda} (f_s - \mu_\lambda)^2$$

  - where S_λ denotes the set of pixels in the training set of class λ
  - a training set consists in a representative region selected by the user

Energy function

- Now we can define the energy function of our MRF model:

$$U(\omega) = \sum_s \left(\log(\sqrt{2\pi}\sigma_{\omega_s}) + \frac{(f_s - \mu_{\omega_s})^2}{2\sigma_{\omega_s}^2} \right) + \sum_{s,r} \beta\delta(\omega_s, \omega_r)$$

- Recall:

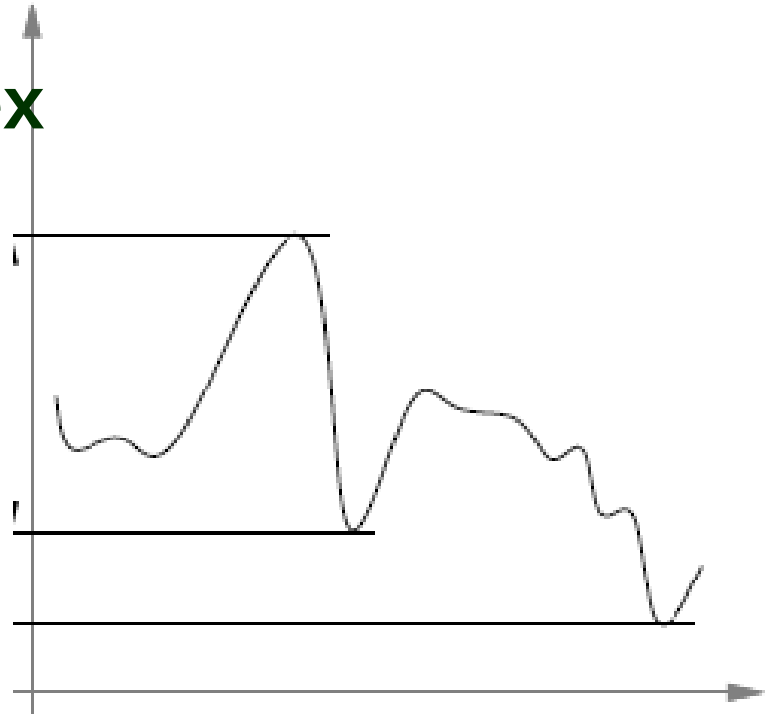
$$P(\omega \mid f) = \frac{1}{Z}\exp(-U(\omega)) = \frac{1}{Z}\exp(-\sum_{c\in C} V_c(\omega))$$

- Hence

$$\hat{\omega}^{MAP} = \arg\max_{\omega\in\Omega} P(\omega \mid f) = \arg\min_{\omega\in\Omega} U(\omega)$$

Optimization

- Problem reduced to the minimization of a **non-convex** energy function
  - Many local minima
- Gradient descent?
  - Works only if we have a *good* initial segmentation
- Simulated Annealing
  - Always works (at least in theory)



ICM (~Gradient descent) [Besag86]

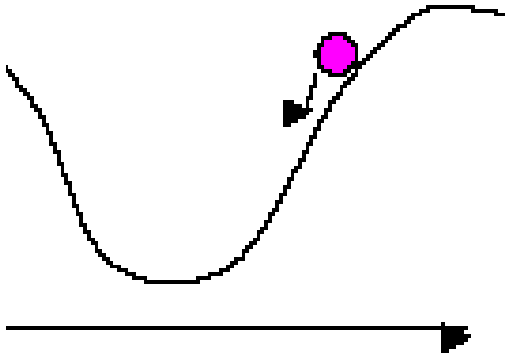
① *Start at a "good" initial configuration* ω^0 *and set* $k = 0$.

② *For each configuration which differs at most in one element from the current configuration* ω^k *(they are denoted by* $\mathcal{N}_{\omega^k}$*), compute the energy* $U(\eta)$ $(\eta \in \mathcal{N}_{\omega^k})$.

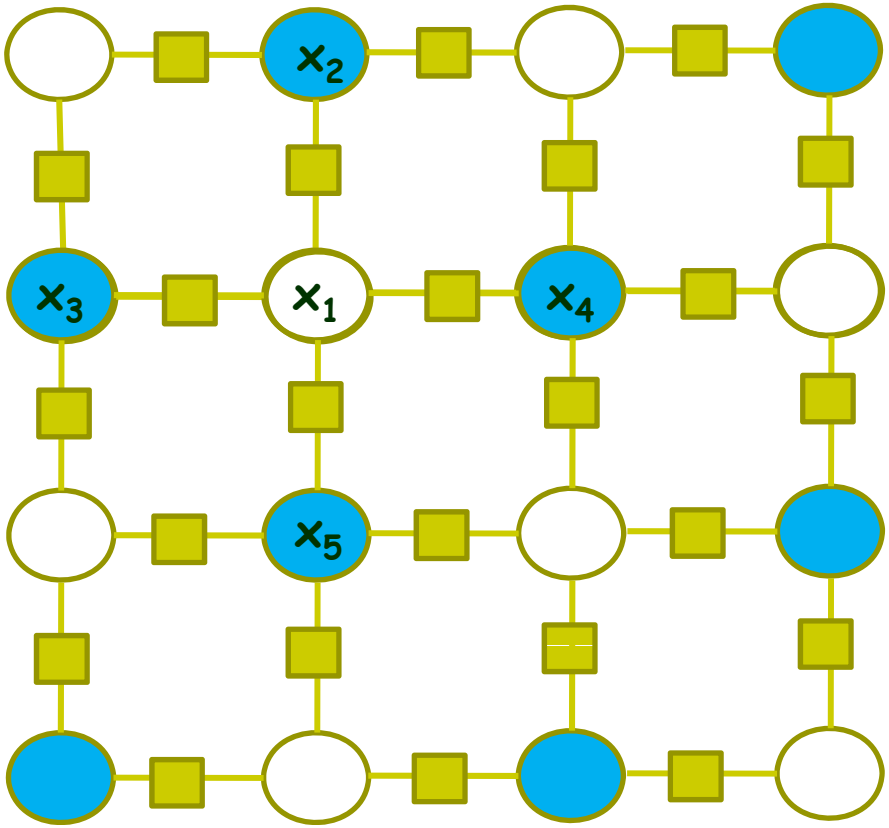
③ *From the configurations in* $\mathcal{N}_{\omega^k}$*, select the one which has a minimal energy:*

$$\omega^{k+1} = \arg \min_{\eta \in \mathcal{N}_{\omega^k}} U(\eta). \qquad (6)$$

④ *Goto Step ② with* $k = k + 1$ *until convergence is obtained (for example, the energy change is less than a certain threshold).*



ICM (iterated conditional mode)



means observed

ICM

Global min

Simulated Annealing: accept a move even if energy increases (with certain probability)

Can get stuck in local minima!

Slide adopted from C. Rother ICCV'09 tutorial:
http://research.microsoft.com/en-us/um/cambridge/projects/tutorial/

Simulated Annealing (Metropolis)

① *Set $k = 0$ and initialize ω randomly. Choose a sufficiently high initial temperature $T = T_0$.*

② *Construct a trial perturbation η from the current configuration ω such that η differs only in one element from ω.*

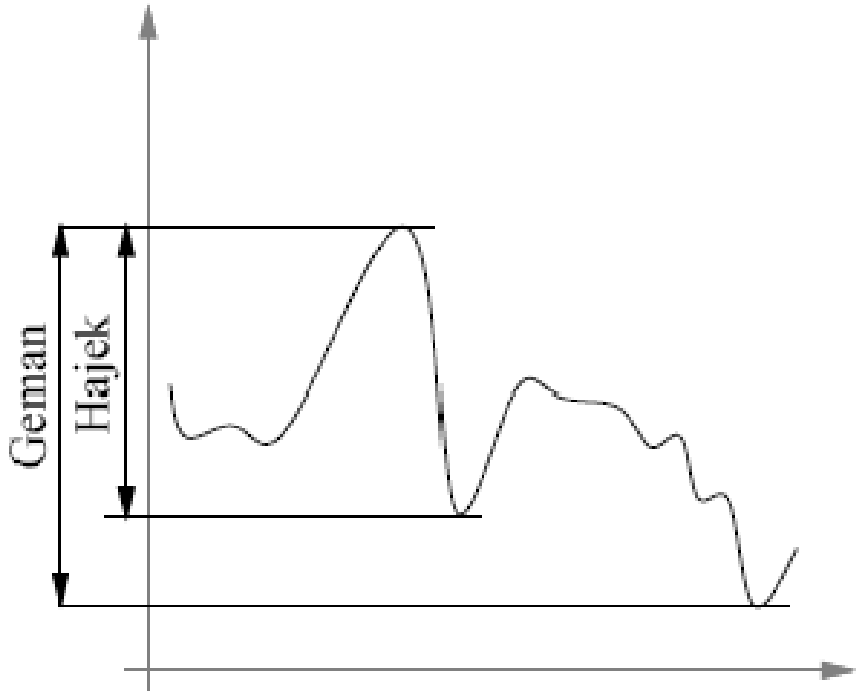
③ **(Metropolis criteria)** *Compute $\Delta U = U(\eta) - U(\omega)$ and accept η if $\Delta U < 0$ else accept with probability $\exp(-\Delta U/T)$ (analogy with thermodynamics):*

$$\omega = \begin{cases} \eta & \text{if } \Delta U \leq 0, \\ \eta & \text{if } \Delta U > 0 \text{ and } \xi < \exp(-\Delta U/T), \\ \omega & \text{otherwise} \end{cases} \quad (4)$$

where ξ is a uniform random number in $[0, 1)$.

④ *Decrease the temperature: $T = T_{k+1}$ and goto Step ② with $k = k + 1$ until the system is frozen.*

Temperature Schedule

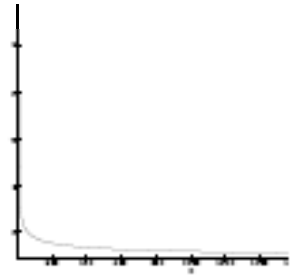


$$T_k \geq \frac{\Gamma}{\ln(k)} \qquad (8)$$

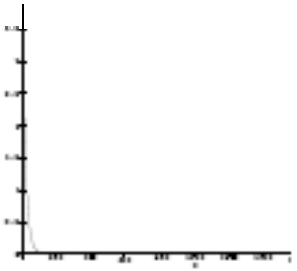
with

$$\Gamma > \max_{\omega \in \Omega} U(\omega) - \min_{\omega \in \Omega} U(\omega) \qquad (9)$$

Temperature Schedule



Logarithmic schedule $(4/\ln(k))$.



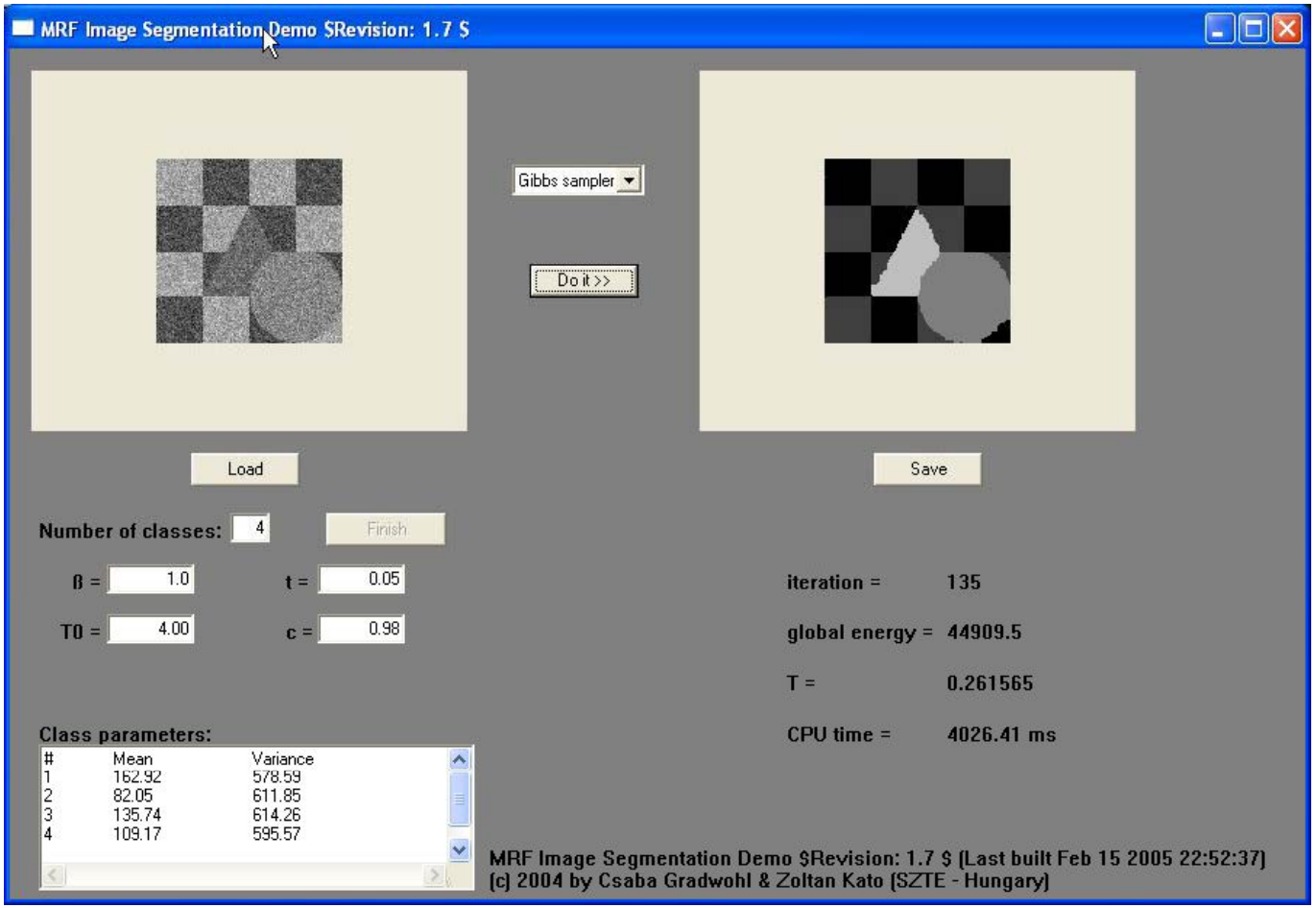
Exponential schedule $(0.95^k \cdot 4)$.

- **Initial temperature:** set it to a relatively low value (~4)➔ faster execution
  - must be high enough to allow random jumps at the beginning!
- **Schedule:** $T_{k+1} = c \cdot T_k, \quad k = 0, 1, 2, \ldots$
- **Stopping criteria:**
  - Fixed number of iterations
  - Energy change is less than a threshols

Demo

- Download from:

  http://www.inf.u-szeged.hu/~kato/software/



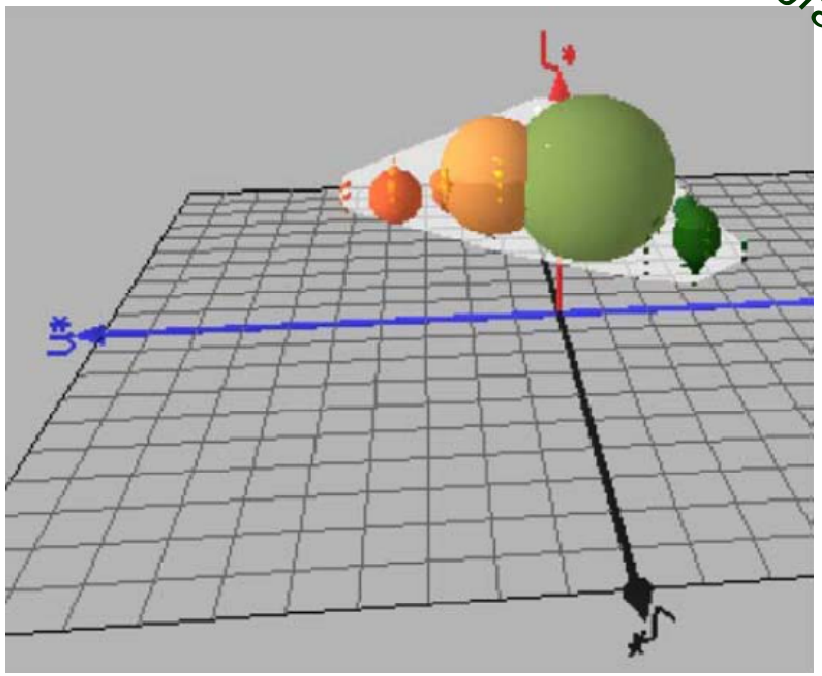
Summary

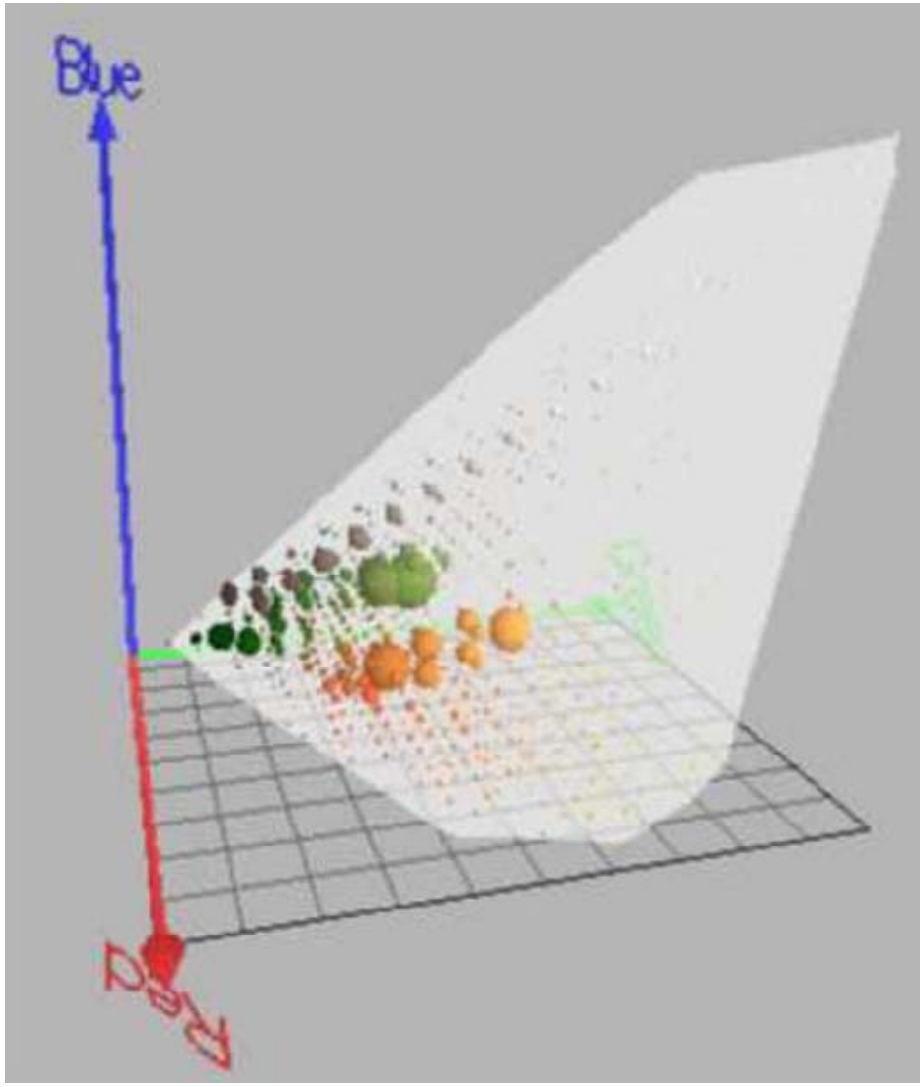
- Design your model carefully
  - Optimization is just a tool, do not expect a good segmentation from a wrong model
- What about other than graylevel features?
  - Extension to color is relatively straightforward

What color features?

RGB histogram

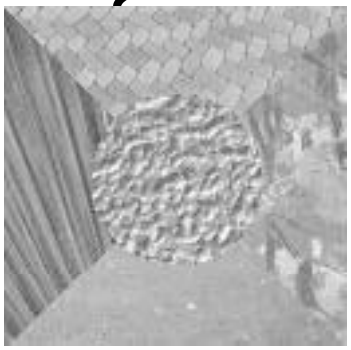
CIE-L*u*v* histogram



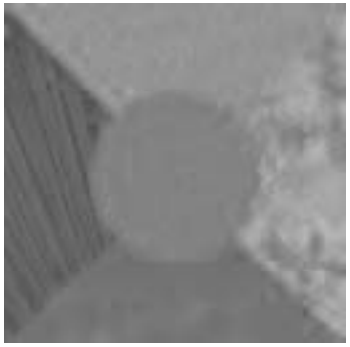


Extract Color Feature

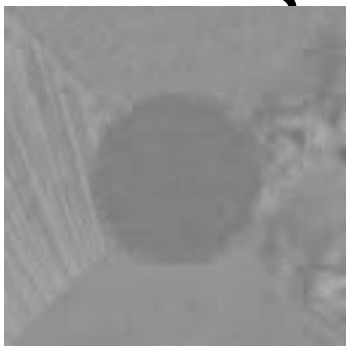
- We adopt the CIE-L*u*v* color space because it is ***perceptually uniform***.
  - Color difference can be measured by Euclidean distance of two color vectors.
- We convert each pixel from RGB space to CIE-L*u*v* space ➔
  - We have 3 color feature images



L*



u*



v*

Color MRF segmentation model

- Pixel labels (or classes) are represented by three-variate Gaussian distributions:

$$P(f_s \mid \omega_s) = \frac{1}{\sqrt{(2\pi)^n \mid \Sigma_{\omega_s} \mid}} \exp\left(-\frac{1}{2}(\vec{f}_s - \vec{u}_{\omega_s})\Sigma_{\omega_s}^{-1}(\vec{f}_s - \vec{u}_{\omega_s})^T\right)$$

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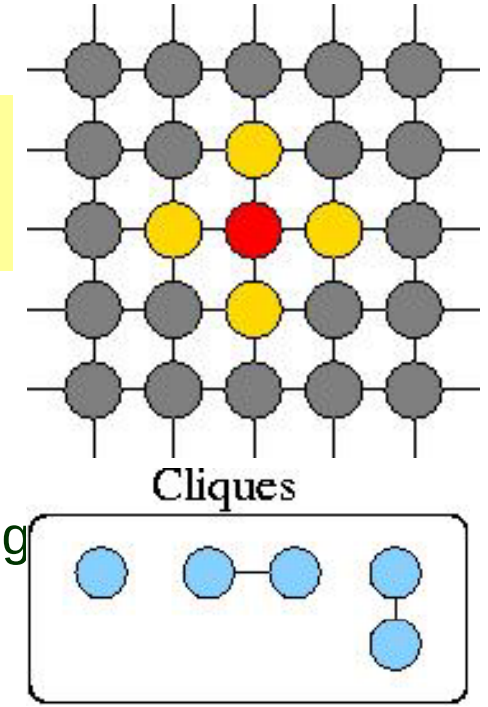

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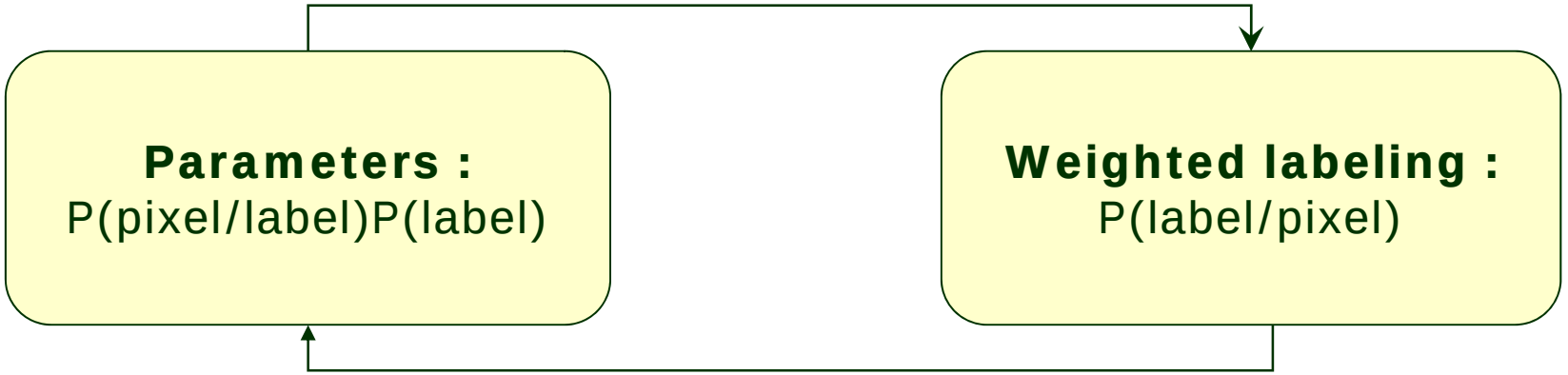
- Can we segment images without user interaction?
  - Yes, but you need to estimate model parameters automatically (EM algorithm)

Incomplete data problem

- Supervised parameter estimation
  - we are given a labelled data set to learn from
    - e.g. somebody manually assigned labels to pixels
- How to proceed without labelled data?
  - Learning from incomplete data
  - Standard solution is an iterative procedure called ***E**xpectation-**M**aximization*
    - Assigns labels and estimates parameters simultaneously
    - Chicken-Egg problem

EM principles : The two steps

E Step : For each pixel,
use parameters to compute probability distribution



M Step : Update the estimates of parameters
based on weighted (or ”soft”) labeling

The basic idea of EM

- Each of the **E** and **M** steps is straightforward assuming the other is solved
  - Knowing the label of each pixel, we can estimate the parameters
    - Similar to supervised learning (hard vs. soft labeling)
  - Knowing the parameters of the distributions, we can assign a label to each pixel
    - by Maximum Likelihood – i.e. using the singleton energies only without pairwise interactions

Parameter estimation via EM

- Basically, we will fit a mixture of Gaussian to the image histogram
  - We know the number of labels $|\Lambda| \equiv$ number of mixture components
- At each pixel, the complete data includes
  - The observed feature $\mathbf{f}_s$
  - Hidden pixel labels $\mathbf{l}_s$ (a vector of size $|\Lambda|$)
    - specifies the contribution of the pixel feature to each of the labels – i.e. a soft labeling

Parameter estimation via EM

- **E** step: recompute $\mathbf{l}_s^i$ at each pixel s:

$$\mathbf{l}_\mathbf{s}^\mathbf{i} = P(\lambda \mid \mathbf{f}_\mathbf{s}) = \frac{P(\mathbf{f}_\mathbf{s} \mid \lambda) P(\lambda)}{\sum_{\lambda \in \Lambda} P(\mathbf{f}_\mathbf{s} \mid \lambda) P(\lambda)}$$

- **M** step: update Gaussian parameters for each label λ:

$$P(\lambda) = \frac{\sum_{s \in S} P(\lambda \mid \mathbf{f}_\mathbf{s})}{|S|}, \quad \mu_\lambda = \frac{\sum_{s \in S} P(\lambda \mid \mathbf{f}_\mathbf{s}) \mathbf{f}_\mathbf{s}}{\sum_{s \in S} P(\lambda \mid \mathbf{f}_\mathbf{s})}, \ldots$$

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- Design your model carefully
  - Optimization is just a tool, do not expect a good segmentation from a wrong model
- What about other than graylevel features
  - Extension to color is relatively
- Can we segment images without user interaction?
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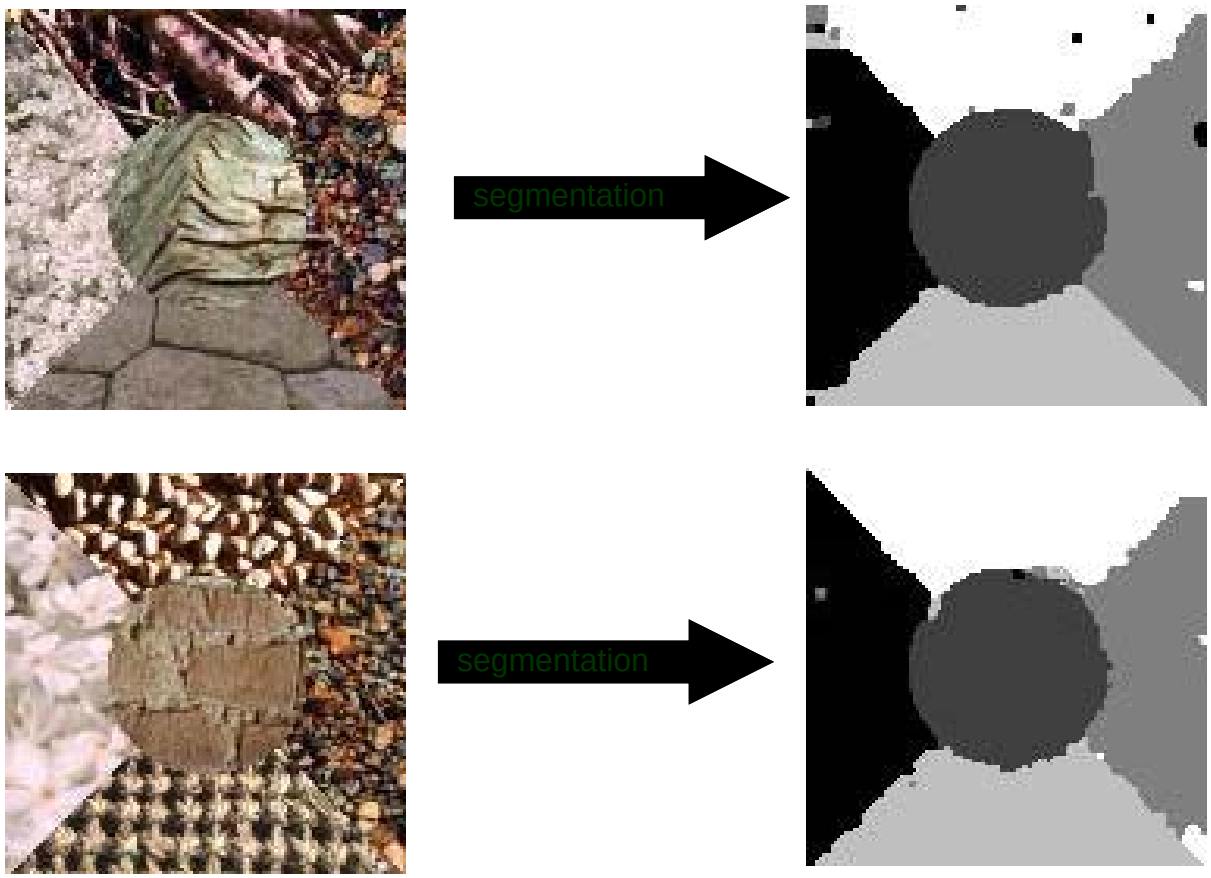
- Can we segment more complex images?
  - Yes, but then you need a more complex MRF model

Color Textured Segmentation



Color & Motion Segmentation

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- Can we segment images without user interaction?
  - Yes, but you need to estimate model parameters automatically (EM algorithm)
- Can we segment more complex images?
  - Yes, but then you need a more complex MRF model
- What if we do not know $|\Lambda|$?
  - Fully automatic segmentation requires
    - Modeling of the parameters AND
    - a more sophisticated sampling algorithm (Reversible jump MCMC)

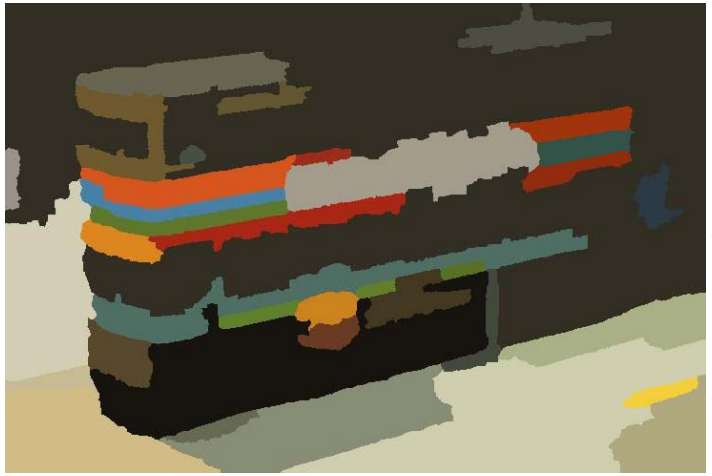
MRF+RJMCMC vs. JSEG

730 X 500

RJMCMC (17 min)

JSEG (Y. Deng, B.S.Manjunath: PAMI'01):

1. **color quantization**: colors are quantized to several representing classes that can be used to differentiate regions in the image.
2. **spatial segmentation**: A region growing method is then used to segment the image.



JSEG (1.5 min)

Benchmark results using the Berkeley Segmentation Dataset

JSEG

RJMCMC

References

- Visit http://www.inf.u-szeged.hu/~kato/
- Forthcoming book:

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Markov random fields in image segmentation

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