Computer Vision – Lecture 5

Segmentation

30.04.2019

Bastian Leibe

Visual Computing Institute
RWTH Aachen University
http://www.vision.rwth-aachen.de/

leibe@vision.rwth-aachen.de

Course Outline

- Image Processing Basics
  - Recap: Structure Extraction
- Segmentation
  - Segmentation as Clustering
  - Graph-theoretic Segmentation
- Recognition
  - Global Representations
  - Subspace representations
- Local Features & Matching
- Object Categorization
- 3D Reconstruction

Recap: Hough Transform

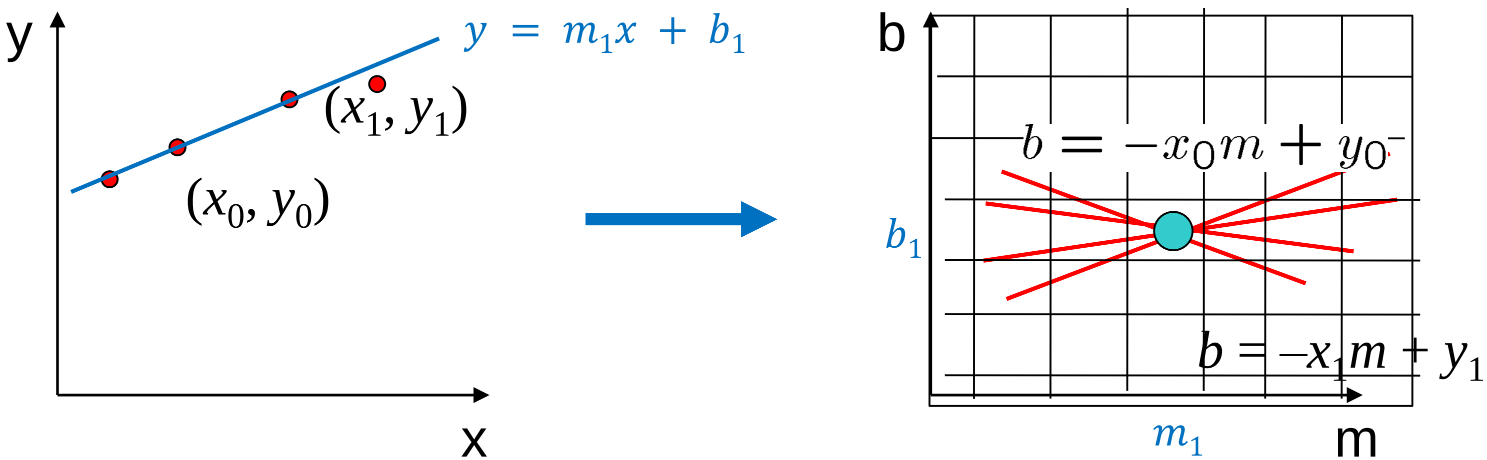


Image space

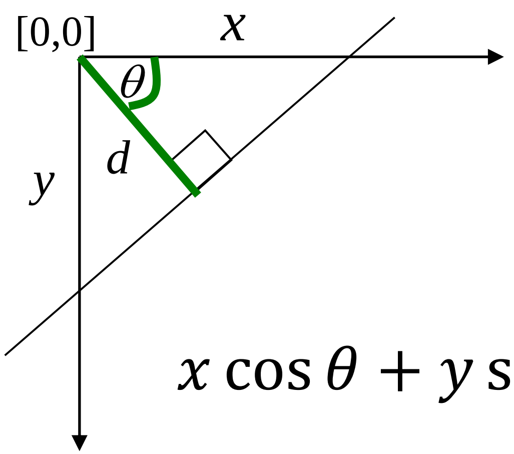
Hough (parameter) space

- How can we use this to find the most likely parameters (m, b) for the most prominent line in the image space?
  - Let each edge point in image space *vote* for a set of possible parameters in Hough space
  - Accumulate votes in discrete set of bins; parameters with the most votes indicate line in image space.

Slide credit: Steve Seitz

Recap: Hough Transf. Polar Parametrization

- Usual (m, b) parameter space problematic:
  - Can take on infinite values, undefined for vertical lines.

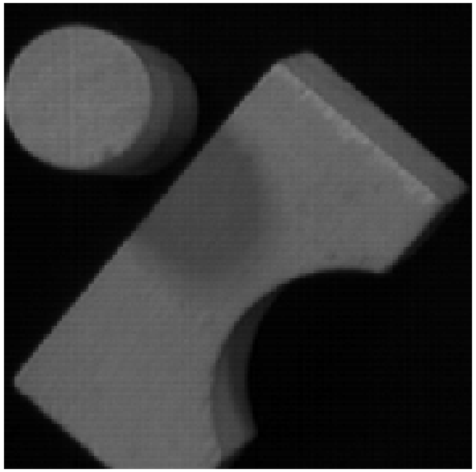


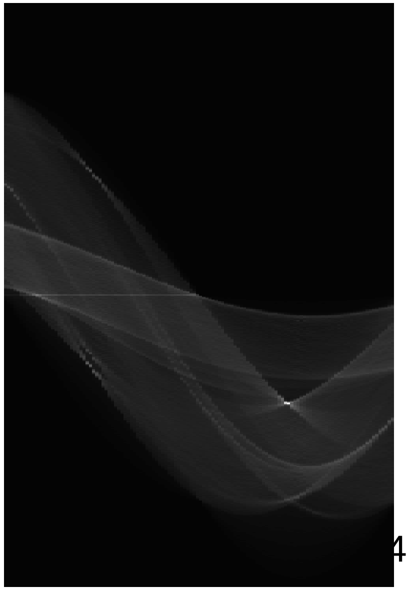
d : perpendicular distance from line to origin

θ : angle the perpendicular makes with the x-axis

$$x \cos \theta + y \sin \theta = d$$

- Point in image space
  $\Rightarrow$ Sinusoid segment in Hough space





Slide adapted from Steve Seitz

Recap: Hough Transform for Circles

- Circle: center (a, b) and radius r

$$(x_i - a)^2 + (y_i - b)^2 = r^2$$

- For an unknown radius r, unknown gradient direction

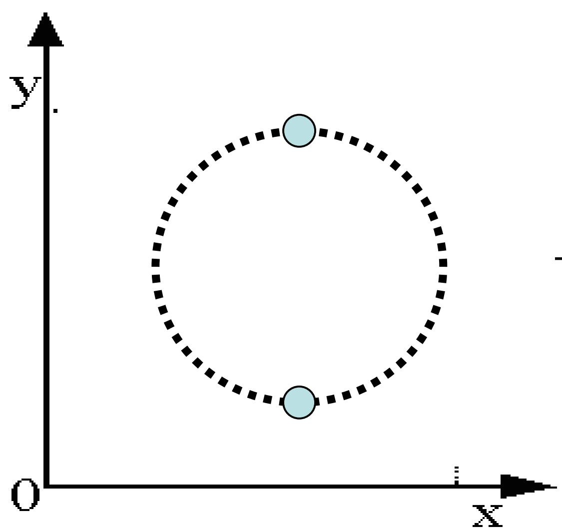
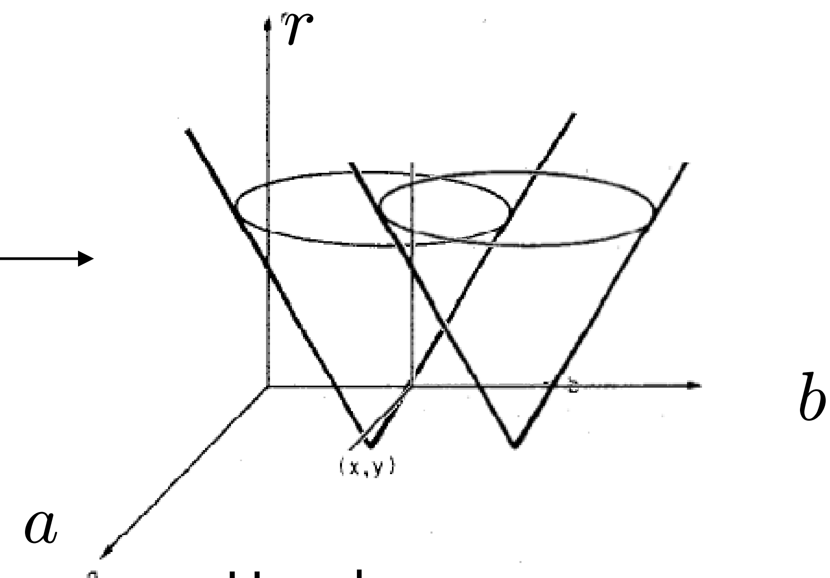


Image space



Hough space

Recap: Generalized Hough Transform

- What if we want to detect arbitrary shapes defined by boundary points and a reference point?

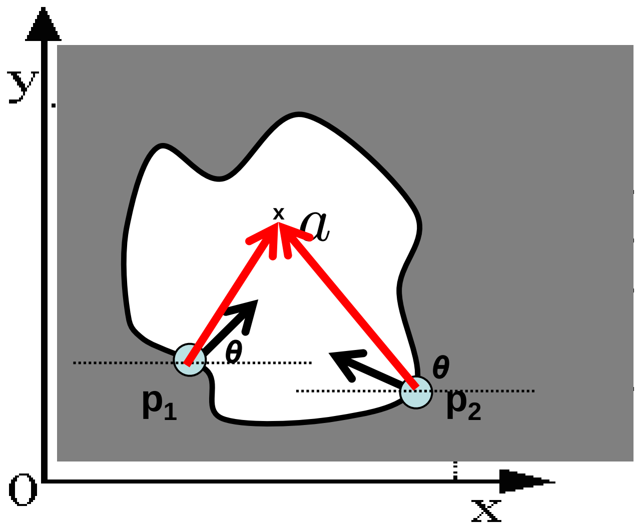


Image space

At each boundary point, compute displacement vector: $r = a - p_i$.

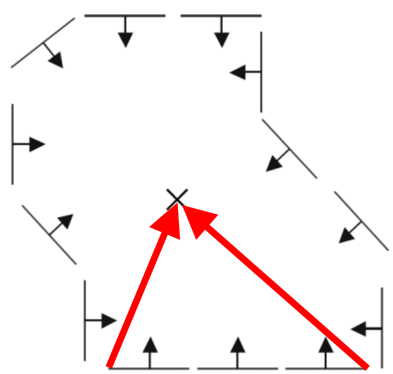
For a given model shape: store these vectors in a table indexed by gradient orientation θ.

[Dana H. Ballard, Generalizing the Hough Transform to Detect Arbitrary Shapes, 1980]

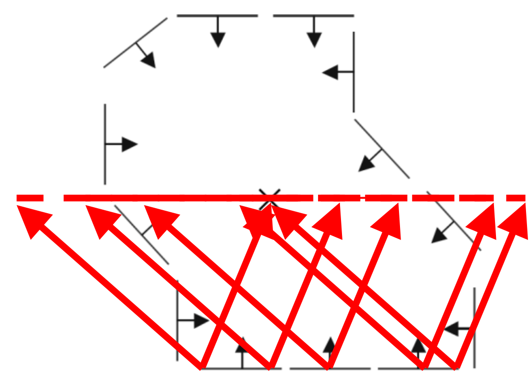
Recap: Generalized Hough Transform

To detect the model shape in a new image:

- For each edge point
  - Index into table with its gradient orientation θ
  - Use retrieved r vectors to vote for position of reference point
- Peak in this Hough space is reference point with most supporting edges



Displacement vectors based on model shape



Voting locations for test points

Slide credit: Kristen Grauman

Topics of This Lecture

- Segmentation and grouping
  - Gestalt principles
  - Image Segmentation
- Segmentation as clustering
  - k-Means
  - Feature spaces
- Probabilistic clustering
  - Mixture of Gaussians, EM
- Model-free clustering
  - Mean-Shift clustering

Examples of Grouping in Vision

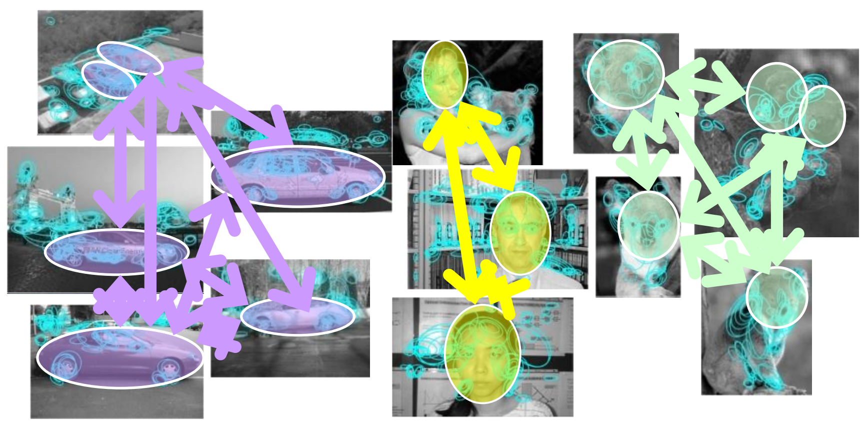
Determining image regions

Grouping video frames into shots

Figure-ground

What things should be grouped?

What cues indicate groups?



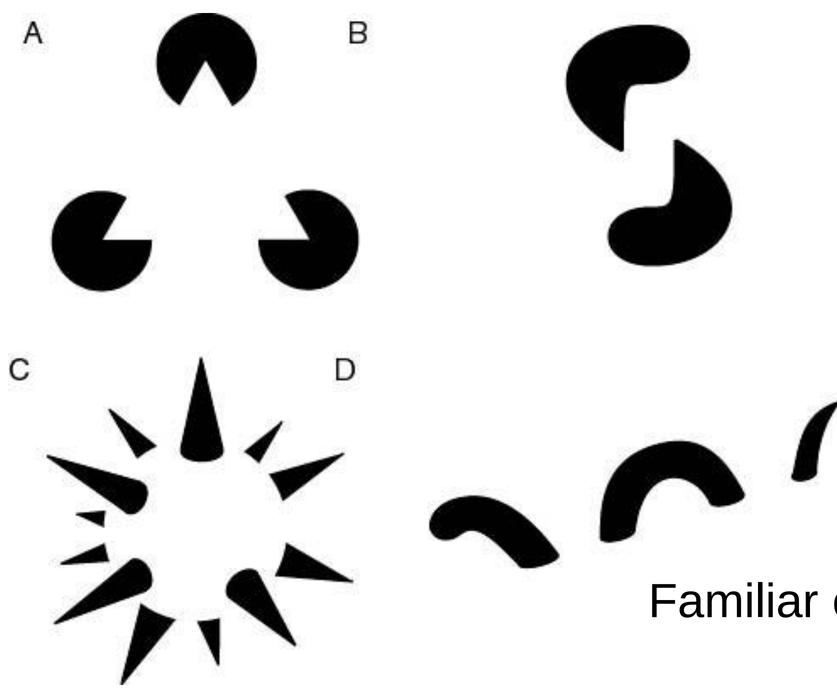
Object-level grouping

The Gestalt School

- Grouping is key to visual perception
- Elements in a collection can have properties that result from relationships
  - “The whole is greater than the sum of its parts”

Illusory/subjective contours

Occlusion



Familiar configuration

http://en.wikipedia.org/wiki/Gestalt_psychology

Slide credit: Svetlana Lazebnik

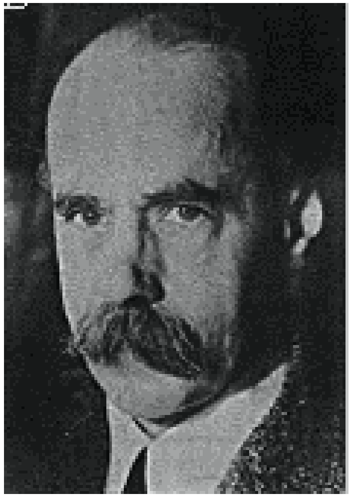
Image source: Steve Lehar

Gestalt Theory

- Gestalt: whole or group
  - Whole is greater than sum of its parts
  - Relationships among parts can yield new properties/features
- Psychologists identified series of factors that predispose set of elements to be grouped (by human visual system)

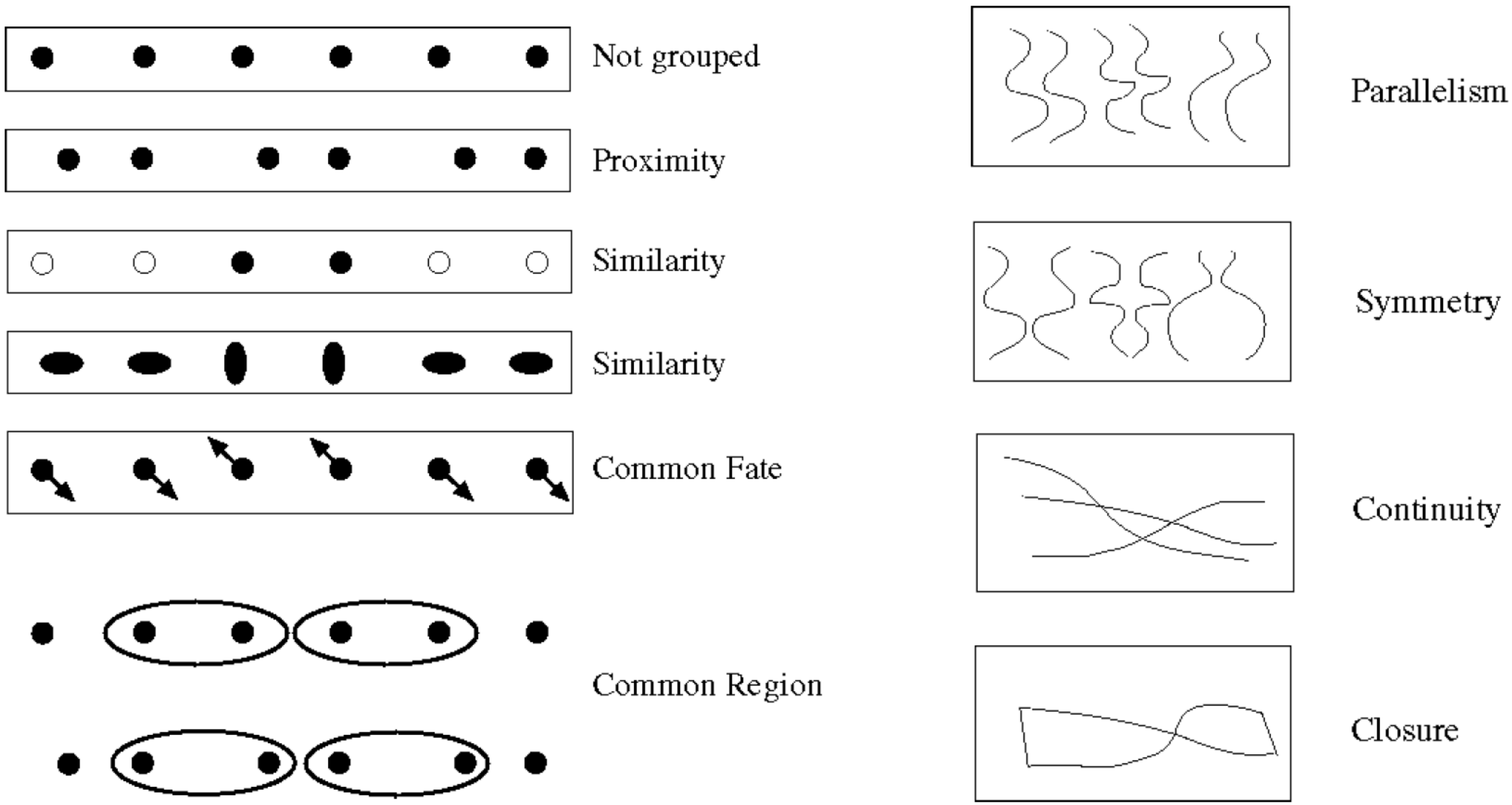
"I stand at the window and see a house, trees, sky. Theoretically I might say there were 327 brightnesses and nuances of colour. Do I have "327"? No. I have sky, house, and trees."

Max Wertheimer
(1880-1943)



Untersuchungen zur Lehre von der Gestalt,
Psychologische Forschung, Vol. 4, pp. 301-350, 1923
http://psy.ed.asu.edu/~classics/Wertheimer/Forms/forms.htm

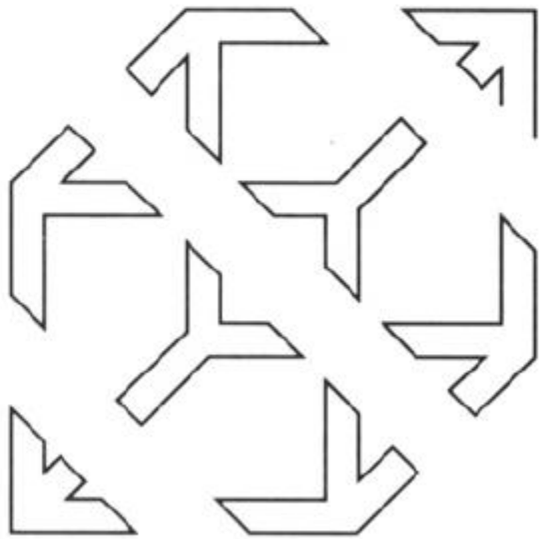
Gestalt Factors



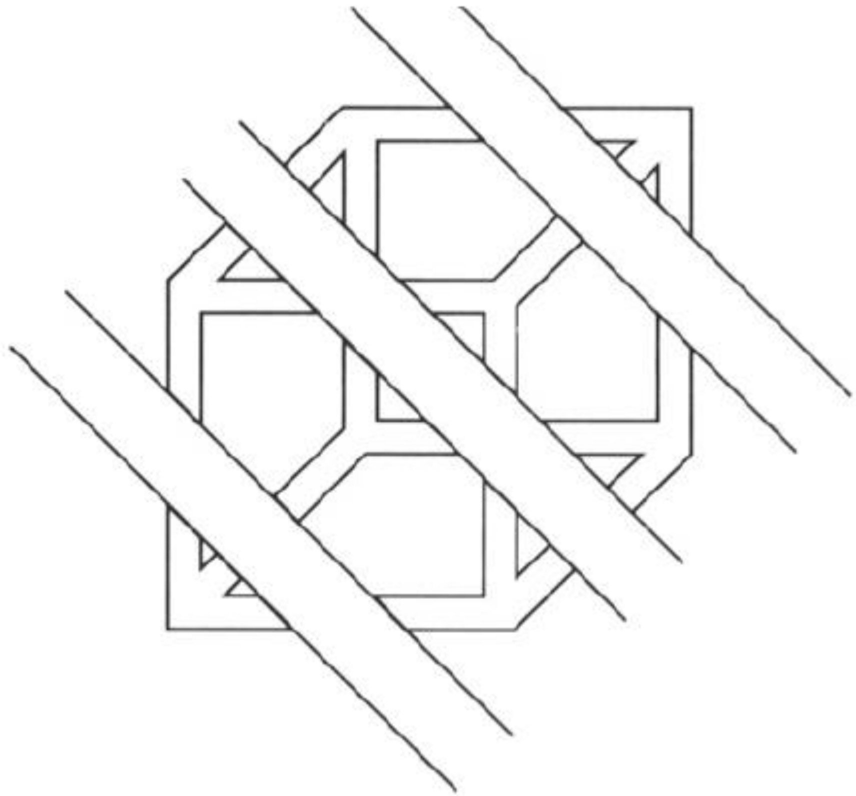
- These factors make intuitive sense, but are very difficult to translate into algorithms.

Image source: Forsyth & Ponce

Continuity through Occlusion Cues



Continuity through Occlusion Cues



Continuity, explanation by occlusion

Continuity through Occlusion Cues

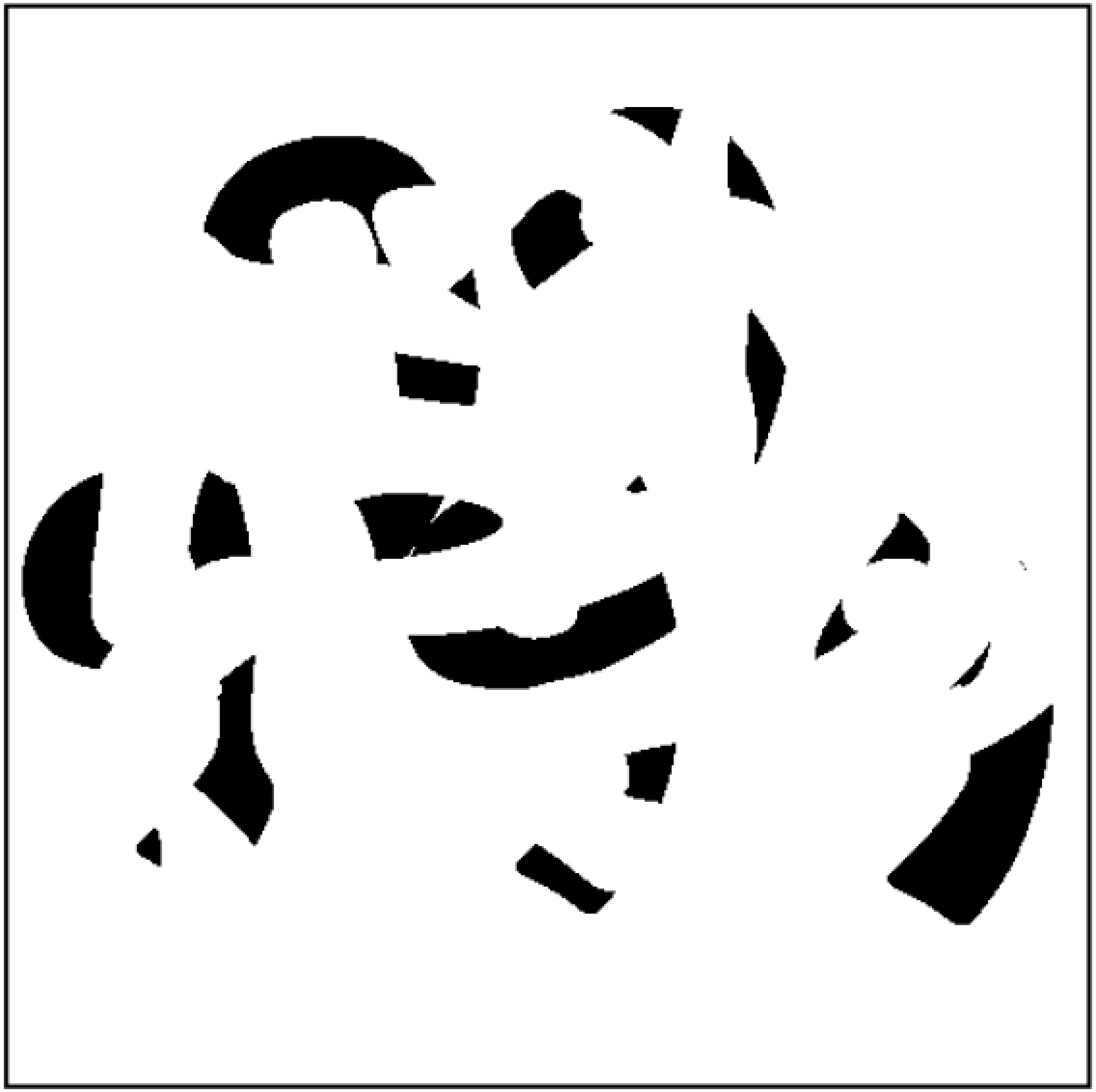


Image source: Forsyth & Ponce

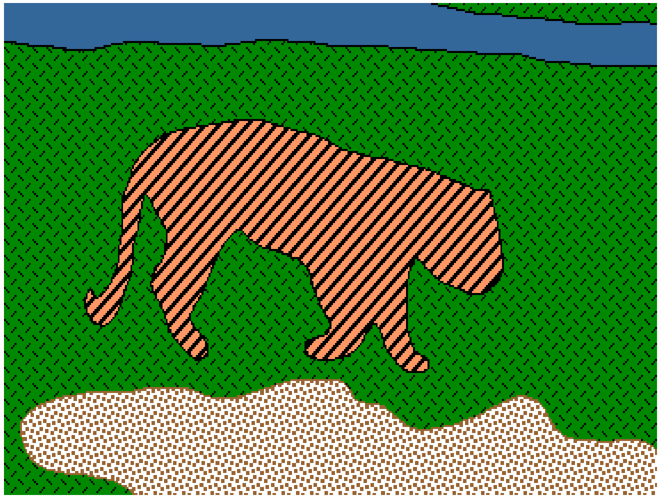
Continuity through Occlusion Cues

Image source: Forsyth & Ponce

The Ultimate Gestalt?

Image Segmentation

- Goal: identify groups of pixels that go together



Slide credit: Steve Seitz, Kristen Grauman

The Goals of Segmentation

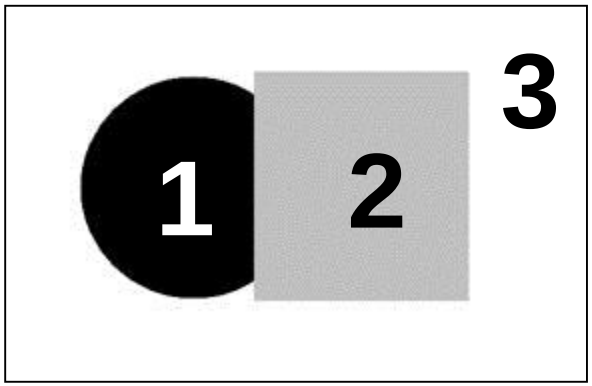
- Separate image into coherent "objects"

Image | Human segmentation

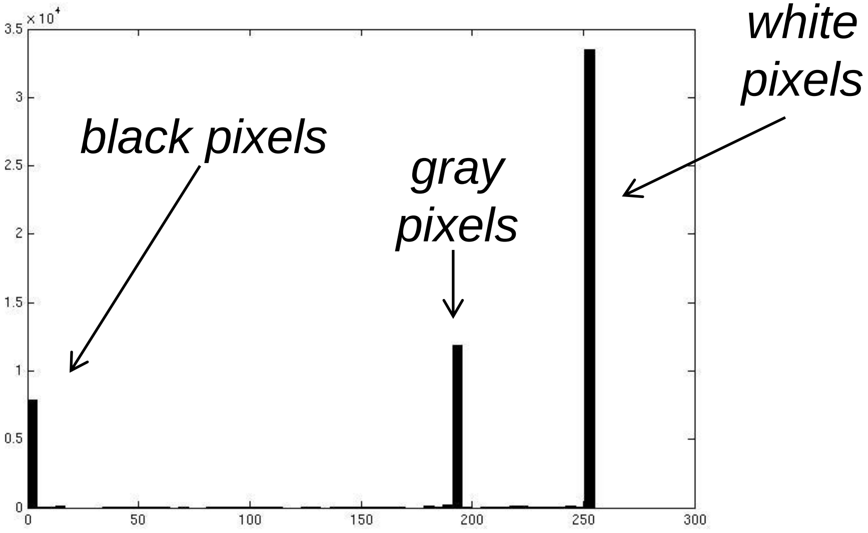
Topics of This Lecture

- Segmentation and grouping
  - Gestalt principles
  - Image Segmentation
- Segmentation as clustering
  - k-Means
  - Feature spaces
- Probabilistic clustering
  - Mixture of Gaussians, EM
- Model-free clustering
  - Mean-Shift clustering

Image Segmentation: Toy Example

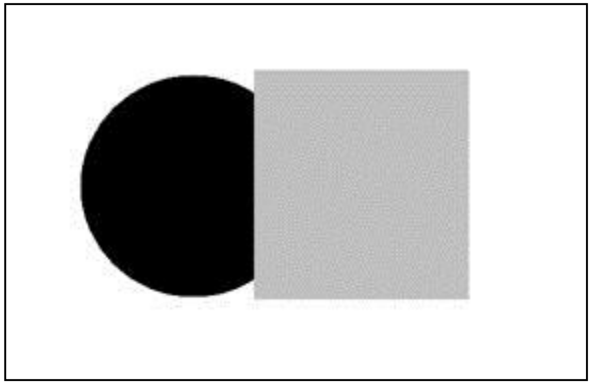


input image

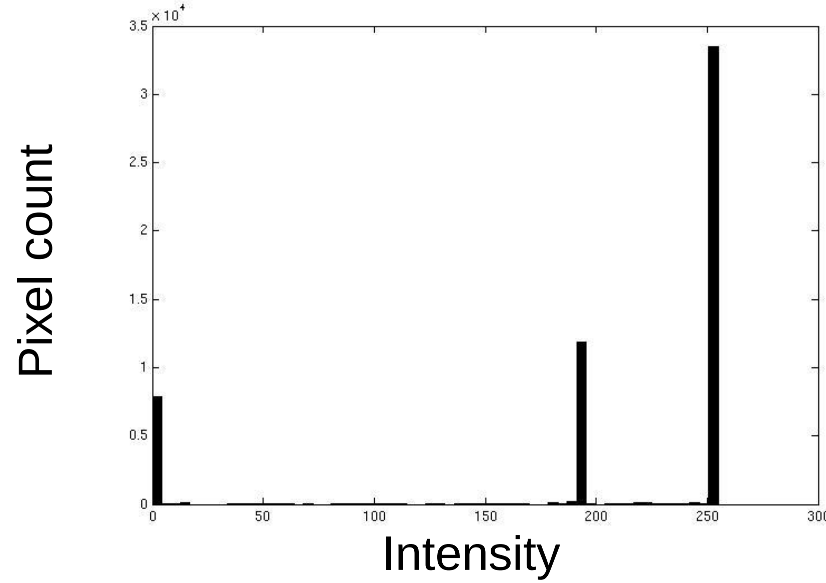


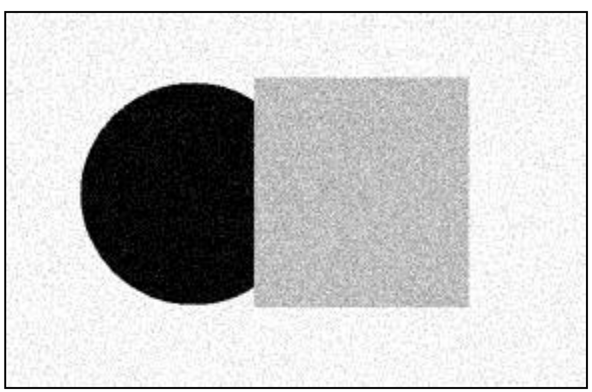
intensity

- These intensities define the three groups.
- We could label every pixel in the image according to which of these primary intensities it is.
  - i.e., segment the image based on the intensity feature.
- What if the image isn't quite so simple?

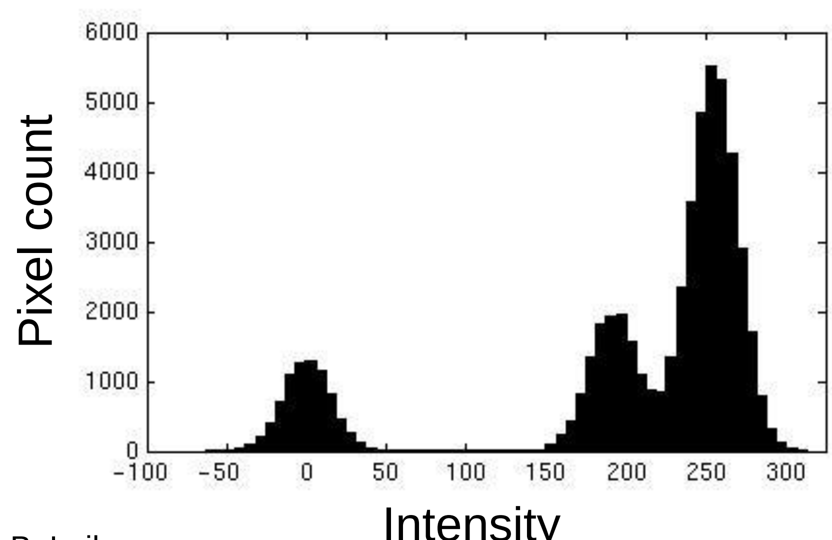


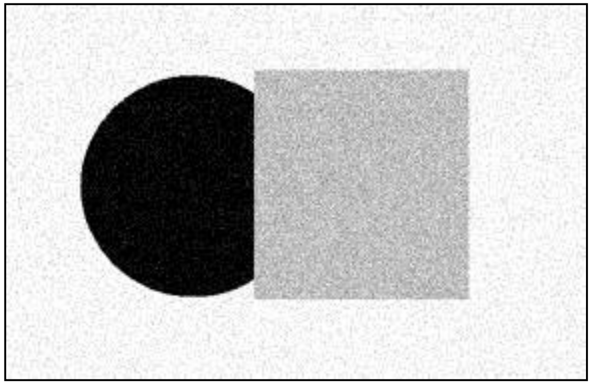
Input image



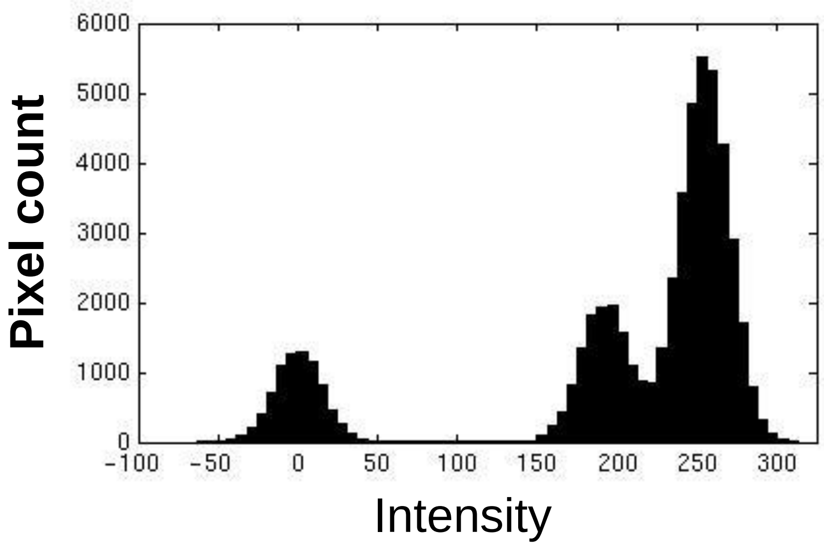


Input image

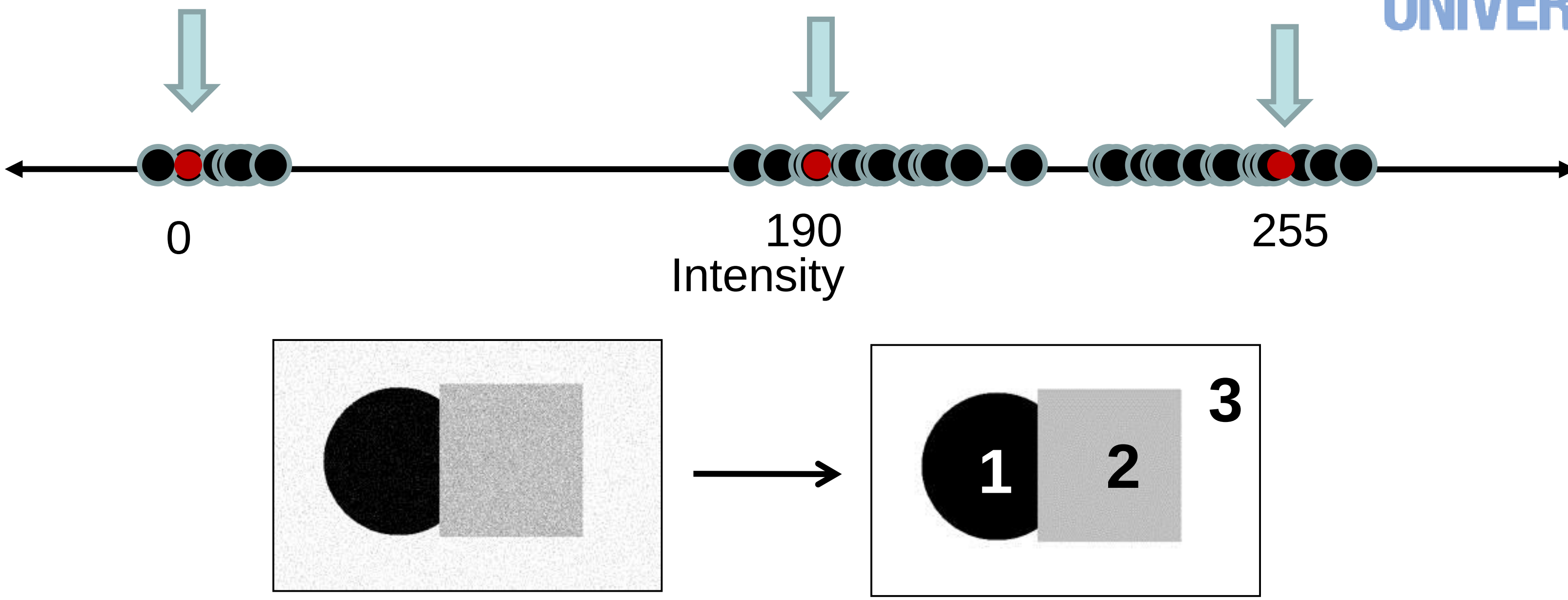




Input image



- Now how to determine the three main intensities that define our groups?
- We need to cluster.

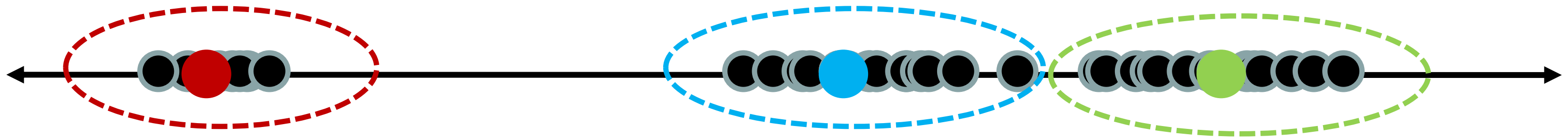


- Goal: choose three "centers" as the representative intensities, and label every pixel according to which of these centers it is nearest to.
- Best cluster centers are those that minimize SSD between all points and their nearest cluster center c_i:

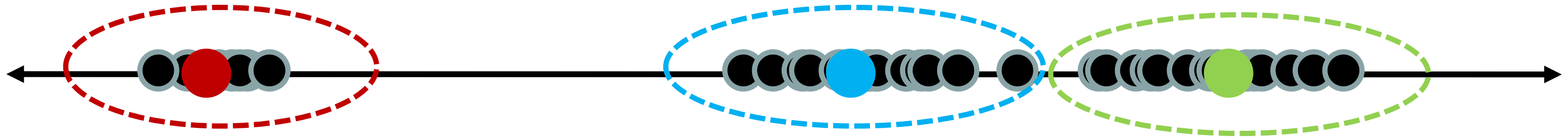
$$\sum_{\text{clusters } i} \sum_{\text{points p in cluster } i} \|p - c_i\|^2$$

Clustering

- With this objective, it is a “chicken and egg” problem:
  - If we knew the *cluster centers*, we could allocate points to groups by assigning each to its closest center.



  - If we knew the *group memberships*, we could get the centers by computing the mean per group.



K-Means Clustering

- Basic idea: randomly initialize the *k* cluster centers, and iterate between the two steps we just saw.
    1. Randomly initialize the cluster centers, $c_1, \ldots, c_K$
    2. Given cluster centers, determine points in each cluster
        - For each point p, find the closest c_i. Put p into cluster i
    3. Given points in each cluster, solve for c_i
        - Set c_i to be the mean of points in cluster i
    4. If c_i have changed, repeat Step 2

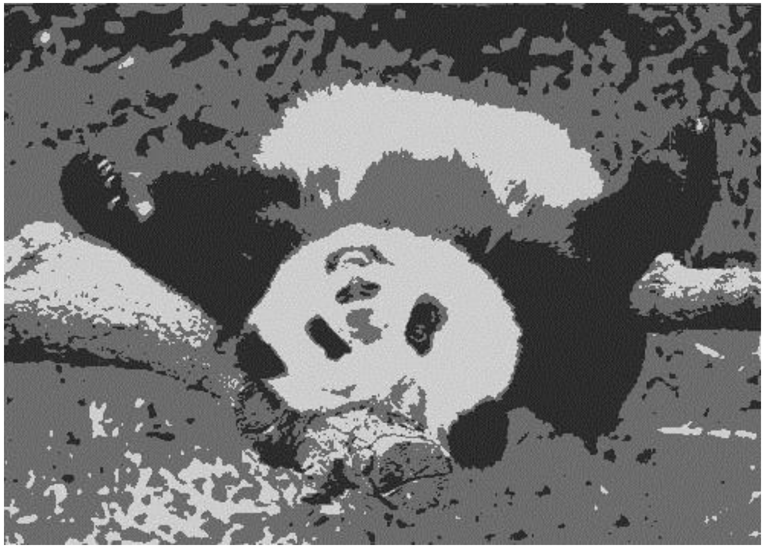
- Properties
    - Will always converge to *some* solution
    - Can be a "local minimum"
        - Does not always find the global minimum of objective function:

$$\sum_{\text{clusters } i} \sum_{\text{points p in cluster } i} ||p - c_i||^2$$

Segmentation as Clustering

K=2

K=3



```
img_as_col = double(im(:));
cluster_membs = kmeans(img_as_col, K);

labelim = zeros(size(im));
for i=1:k
   inds = find(cluster_membs==i);
   meanval = mean(img_as_column(inds));
   labelim(inds) = meanval;
end
```


Slide credit: Kristen Grauman

K-Means++

- Can we prevent arbitrarily bad local minima?

1. Randomly choose first center.
2. Pick new center with prob. proportional to $||p - c_i||^2$
   - (Contribution of *p* to total error)
3. Repeat until *k* centers.

- Expected error = *O*(log *k*) * optimal

[Arthur & Vassilvitskii 2007]

Feature Space

- Depending on what we choose as the *feature space*, we can group pixels in different ways.

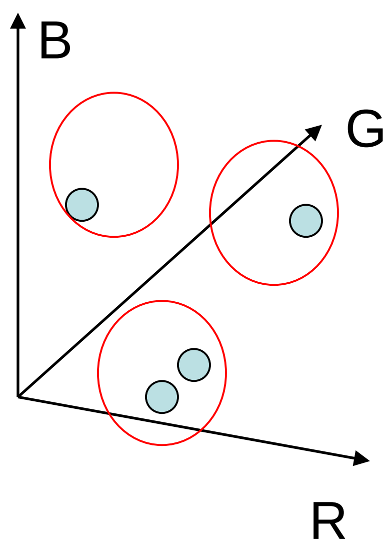
- Grouping pixels based on intensity similarity

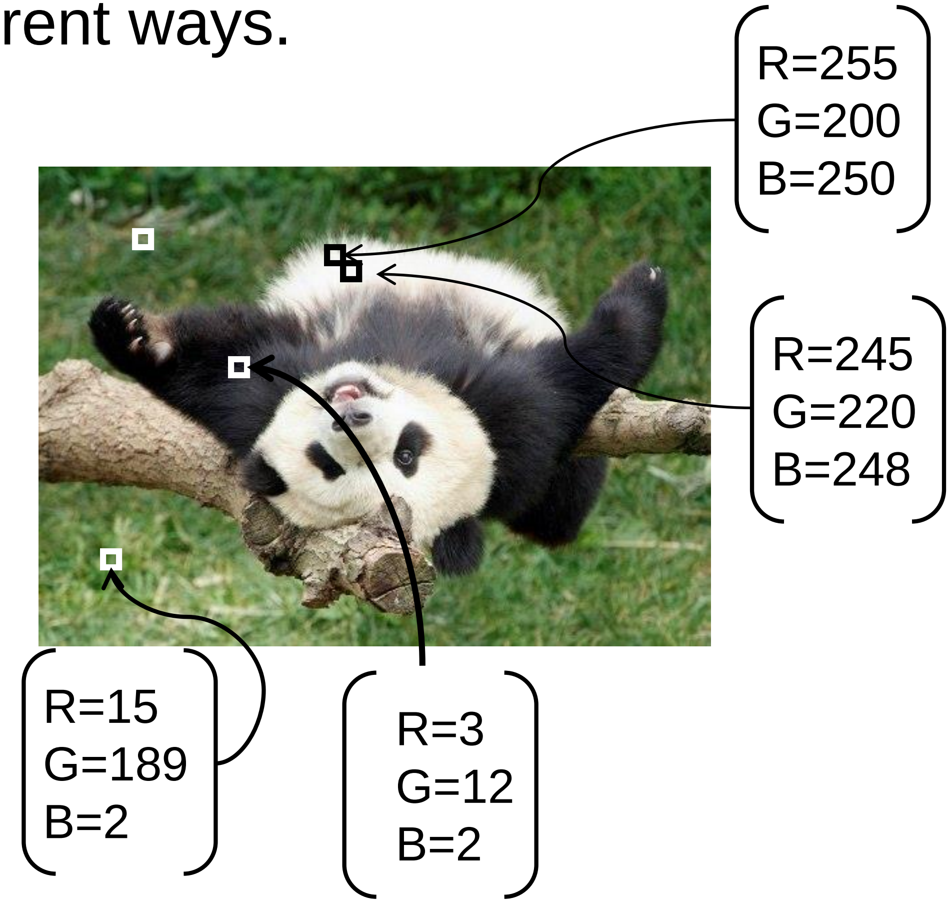
- Feature space: intensity value (1D)

Feature Space

- Depending on what we choose as the *feature space*, we can group pixels in different ways.

- Grouping pixels based on color similarity



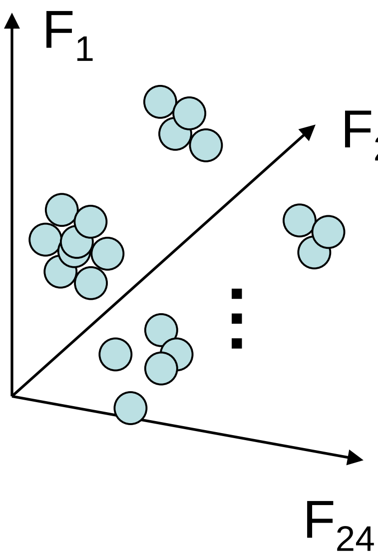


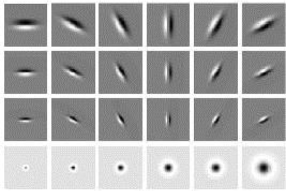
- Feature space: color value (3D)

Segmentation as Clustering

- Depending on what we choose as the *feature space*, we can group pixels in different ways.

- Grouping pixels based on texture similarity



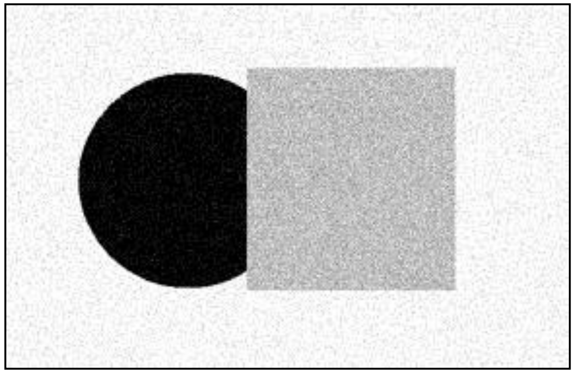


Filter bank of 24 filters

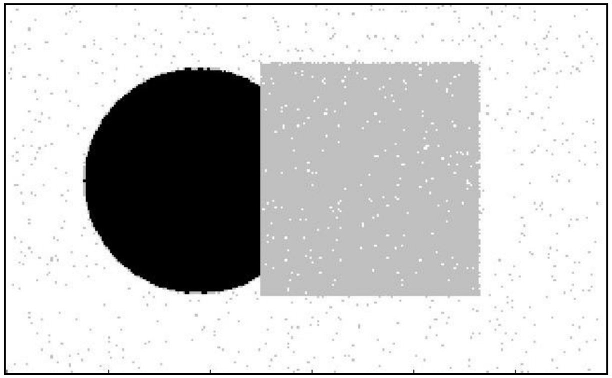
- Feature space: filter bank responses (e.g., 24D)

Smoothing Out Cluster Assignments

- Assigning a cluster label per pixel may yield outliers:

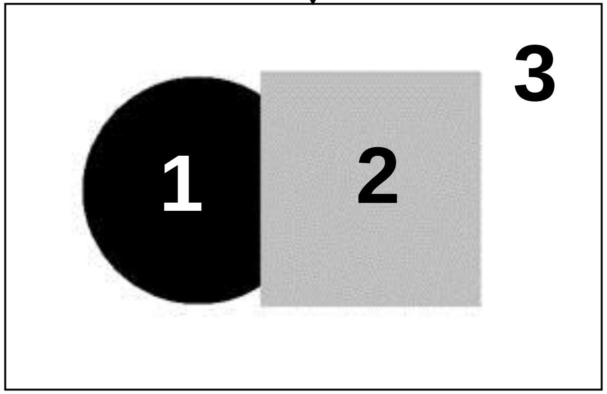


Original



Labeled by cluster center's intensity

?

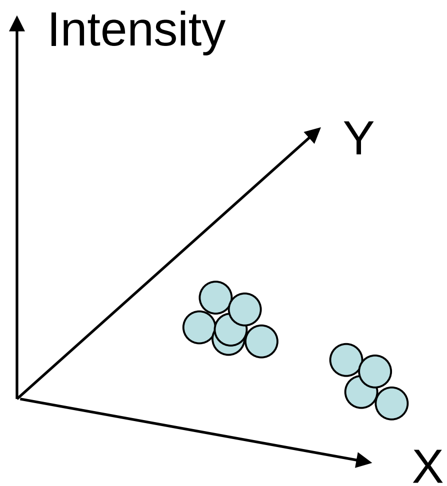


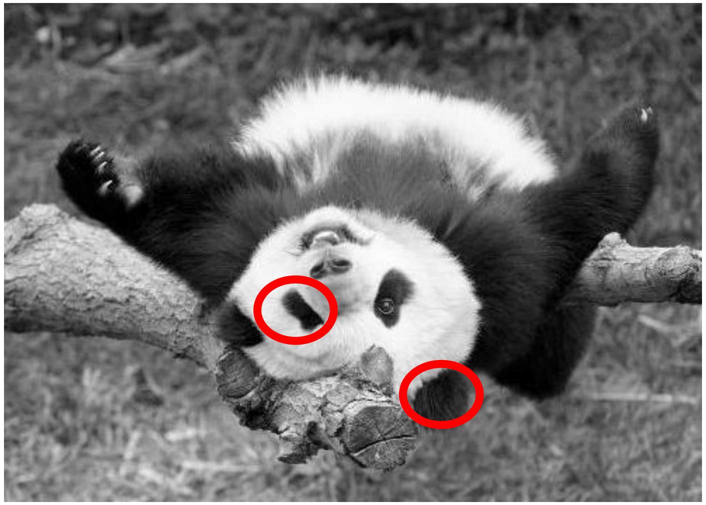
- How can we ensure they are spatially smooth?

Segmentation as Clustering

- Depending on what we choose as the *feature space*, we can group pixels in different ways.

- Grouping pixels based on *intensity+position* similarity



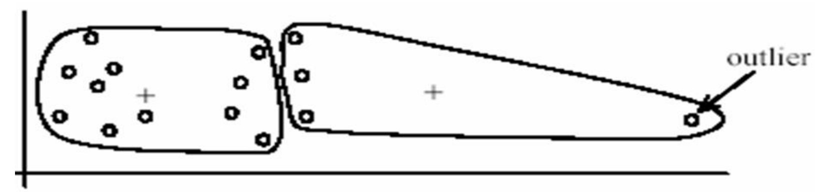


$\Rightarrow$ Simple way to encode both *similarity* and *proximity.*

$\Rightarrow$ *What could be a problem with this solution?*

Summary K-Means

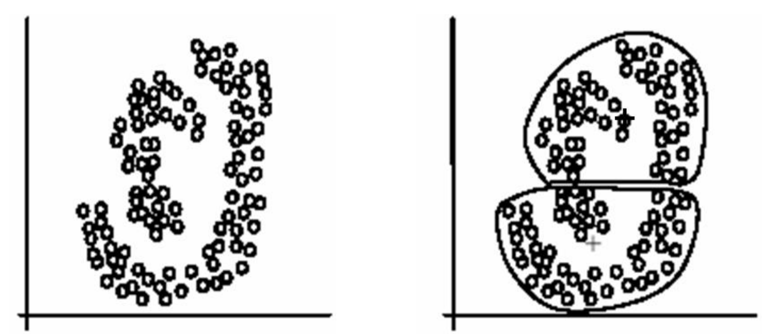
- Pros
  - Simple, fast to compute
  - Converges to local minimum of within-cluster squared error



(A): Undesirable clusters

(B): Ideal clusters

- Cons/issues
  - Setting k?
  - Sensitive to initial centers
  - Sensitive to outliers
  - Detects spherical clusters only
  - Assuming means can be computed



(A): Two natural clusters

(B): *k*-means clusters

Topics of This Lecture

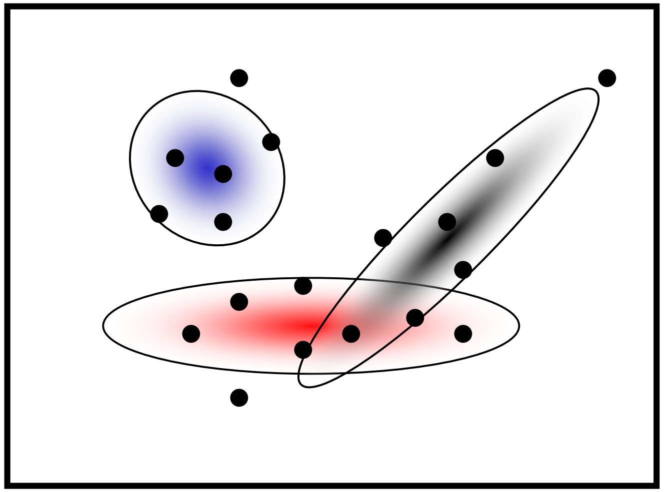
- Segmentation and grouping
  - Gestalt principles
  - Image Segmentation
- Segmentation as clustering
  - k-Means
  - Feature spaces
- Probabilistic clustering
  - Mixture of Gaussians, EM
- Model-free clustering
  - Mean-Shift clustering

Probabilistic Clustering

- Basic questions
  - What's the probability that a point x is in cluster m?
  - What's the shape of each cluster?
- K-means doesn't answer these questions.

- Basic idea
  - Instead of treating the data as a bunch of points, assume that they are all generated by sampling a continuous function.
  - This function is called a generative model.
  - Defined by a vector of parameters θ

Mixture of Gaussians



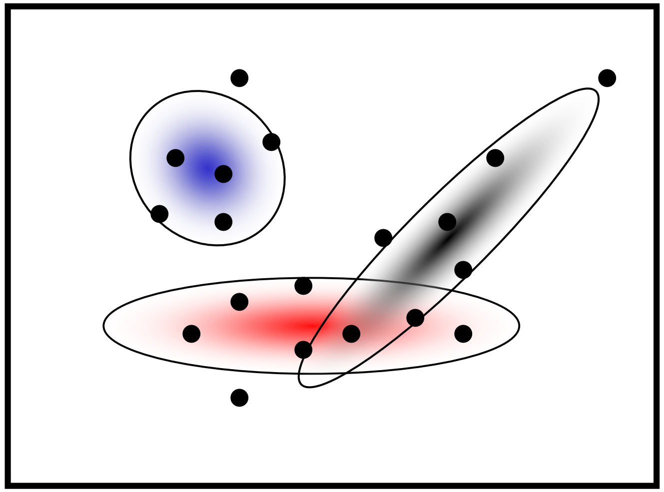
- One generative model is a mixture of Gaussians (MoG)
  - K Gaussian blobs with means μ_j, cov. matrices $\mathbf{\Sigma}_j$, dim. D

$$p(\mathbf{x}|\theta_j) = \frac{1}{(2\pi)^{D/2}|\mathbf{\Sigma}_j|^{1/2}} \exp\left\{-\frac{1}{2}(\mathbf{x}-\boldsymbol{\mu}_j)^{\mathrm{T}}\mathbf{\Sigma}_j^{-1}(\mathbf{x}-\boldsymbol{\mu}_j)\right\}$$

  - Blob j is selected with probability π_j
  - The likelihood of observing $\mathbf{x}$ is a weighted mixture of Gaussians

$$p(\mathbf{x}|\theta) = \sum_{j=1}^{K} \pi_j p(\mathbf{x}|\theta_j) \qquad \theta = (\pi_1, \boldsymbol{\mu}_1, \mathbf{\Sigma}_1, \ldots, \pi_M, \boldsymbol{\mu}_M, \mathbf{\Sigma}_M)$$

Expectation Maximization (EM)



- Goal
  - Find blob parameters θ that maximize the likelihood function:

$$p(data|\theta) = \prod_{n=1}^{N} p(\mathbf{x}_n|\theta)$$

- Approach:
  1. E-step: given current guess of blobs, compute ownership of each point
  2. M-step: given ownership probabilities, update blobs to maximize likelihood function
  3. Repeat until convergence

see lecture Machine Learning!

EM Algorithm

- Expectation-Maximization (EM) Algorithm
  - E-Step: softly assign samples to mixture components

$$\gamma_j(\mathbf{x}_n) \leftarrow \frac{\pi_j \mathcal{N}(\mathbf{x}_n|\boldsymbol{\mu}_j, \boldsymbol{\Sigma}_j)}{\sum_{k=1}^{K} \pi_k \mathcal{N}(\mathbf{x}_n|\boldsymbol{\mu}_k, \boldsymbol{\Sigma}_k)} \qquad \forall j = 1, \ldots, K, \quad n = 1, \ldots, N$$

  - M-Step: re-estimate the parameters (separately for each mixture component) based on the soft assignments

$$\hat{N}_j \leftarrow \sum_{n=1}^{N} \gamma_j(\mathbf{x}_n)$$ = soft number of samples labeled j

$$\hat{\pi}_j^{\text{new}} \leftarrow \frac{\hat{N}_j}{N}$$

$$\hat{\boldsymbol{\mu}}_j^{\text{new}} \leftarrow \frac{1}{\hat{N}_j} \sum_{n=1}^{N} \gamma_j(\mathbf{x}_n)\mathbf{x}_n$$

$$\hat{\boldsymbol{\Sigma}}_j^{\text{new}} \leftarrow \frac{1}{\hat{N}_j} \sum_{n=1}^{N} \gamma_j(\mathbf{x}_n)(\mathbf{x}_n - \hat{\boldsymbol{\mu}}_j^{\text{new}})(\mathbf{x}_n - \hat{\boldsymbol{\mu}}_j^{\text{new}})^{\mathrm{T}}$$

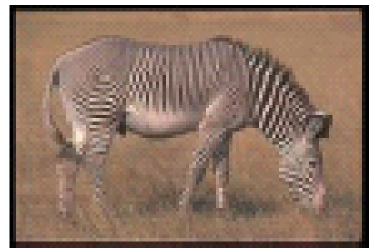
Slide adapted from Bernt Schiele

Applications of EM

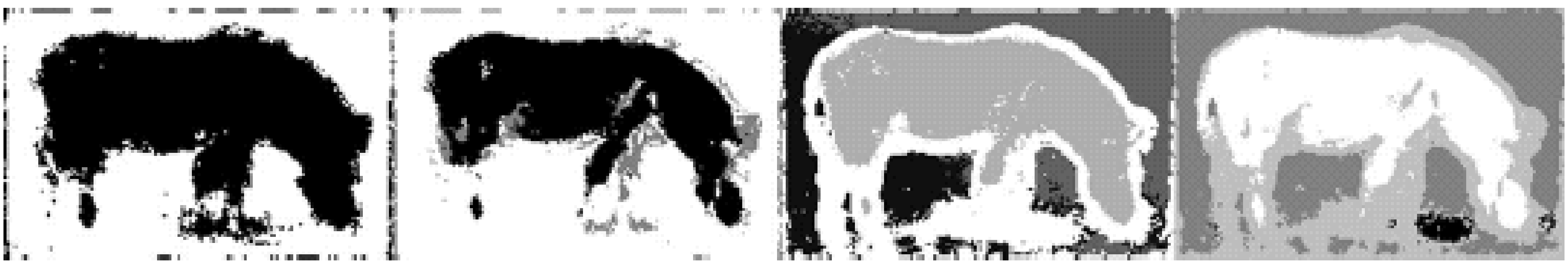
- Turns out this is useful for all sorts of problems
  - Any clustering problem
  - Any model estimation problem
  - Missing data problems
  - Finding outliers
  - Segmentation problems
    - Segmentation based on color
    - Segmentation based on motion
    - Foreground/background separation
  - ...

Segmentation with EM

Original image



EM segmentation results



k=2 k=3 k=4 k=5

Image source: Serge Belongie

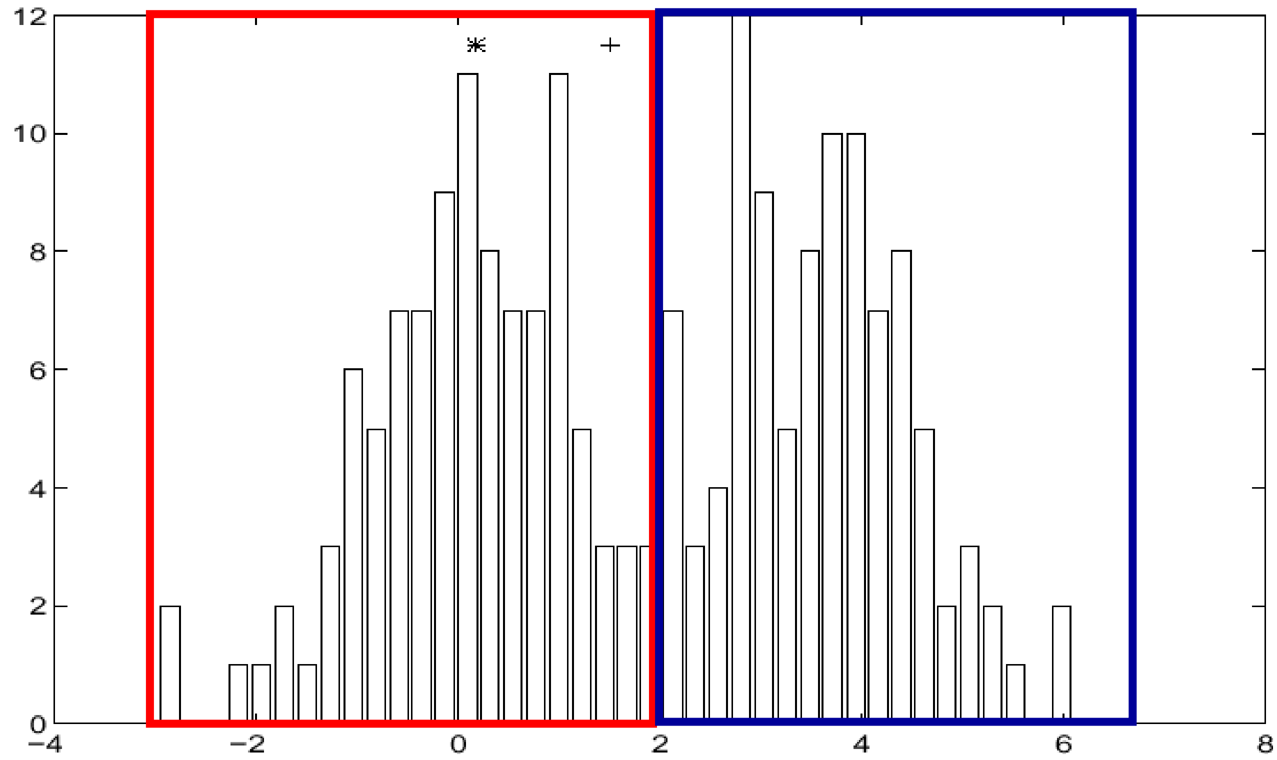
Summary: Mixtures of Gaussians, EM

- Pros
  - Probabilistic interpretation
  - Soft assignments between data points and clusters
  - Generative model, can predict novel data points
  - Relatively compact storage
- Cons
  - Local minima
    - k-means is NP-hard even with k=2
  - Initialization
    - Often a good idea to start with some k-means iterations.
  - Need to know number of components
    - Solutions: model selection (AIC, BIC), Dirichlet process mixture
  - Need to choose generative model
  - Numerical problems are often a nuisance

Topics of This Lecture

- Segmentation and grouping
  - Gestalt principles
  - Image segmentation
- Segmentation as clustering
  - k-Means
  - Feature spaces
- Probabilistic clustering
  - Mixture of Gaussians, EM
- Model-free clustering
  - Mean-Shift clustering

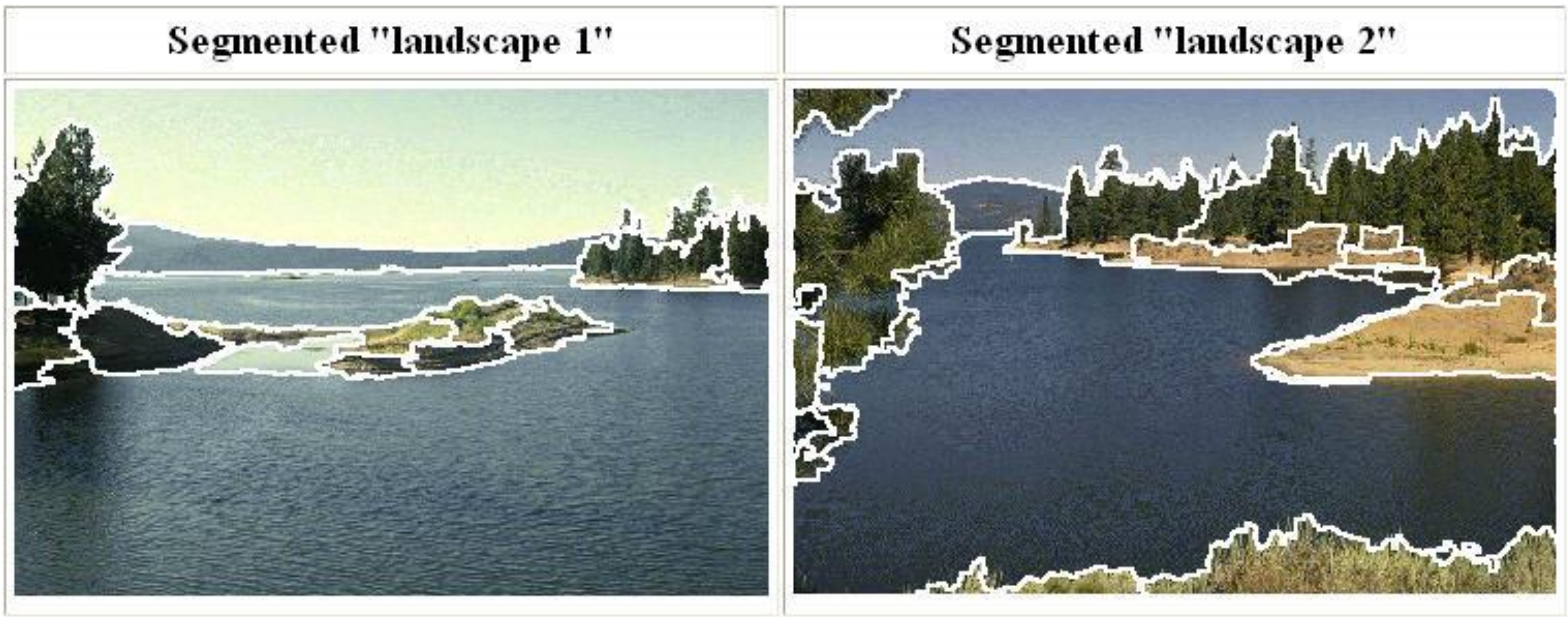
Finding Modes in a Histogram



- How many modes are there?
  - *Mode* = local maximum of the density of a given distribution
  - Easy to see, hard to compute

Mean-Shift Segmentation

- An advanced and versatile technique for clustering-based segmentation

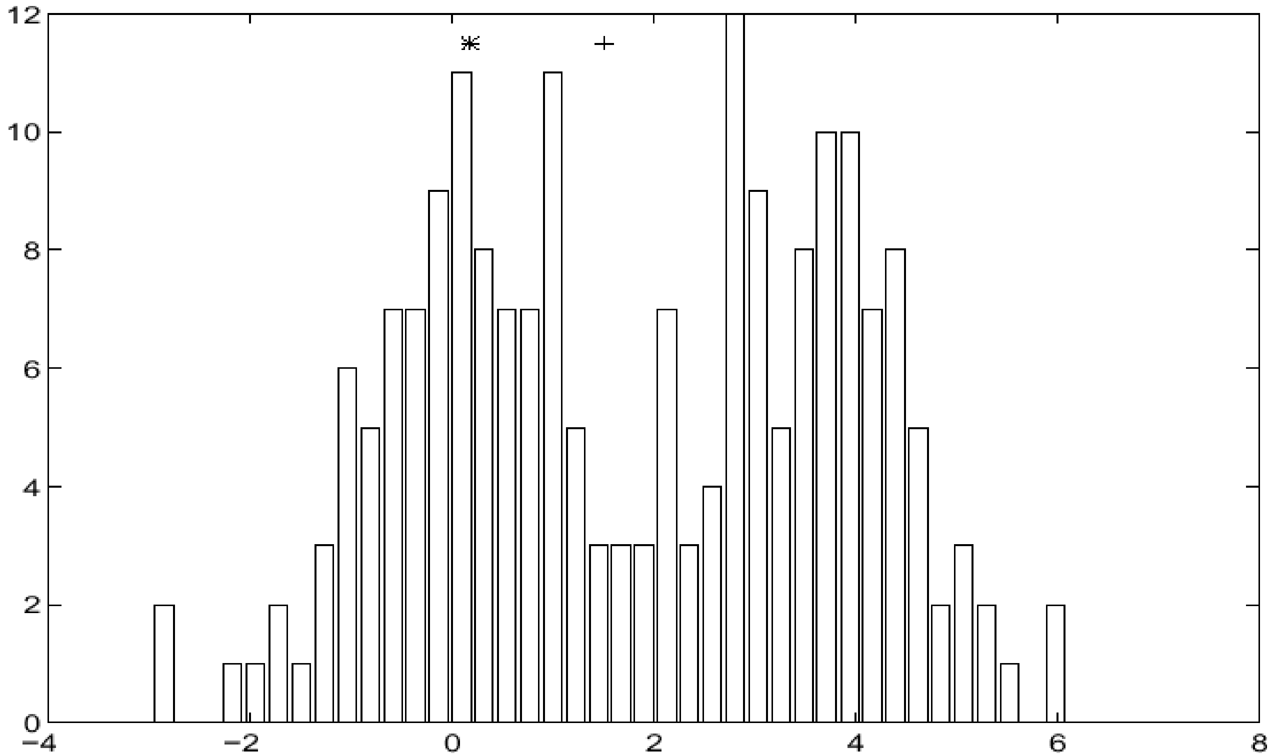


http://www.caip.rutgers.edu/~comanici/MSPAMI/msPamiResults.html

D. Comaniciu and P. Meer, Mean Shift: A Robust Approach toward Feature Space Analysis, PAMI 2002.

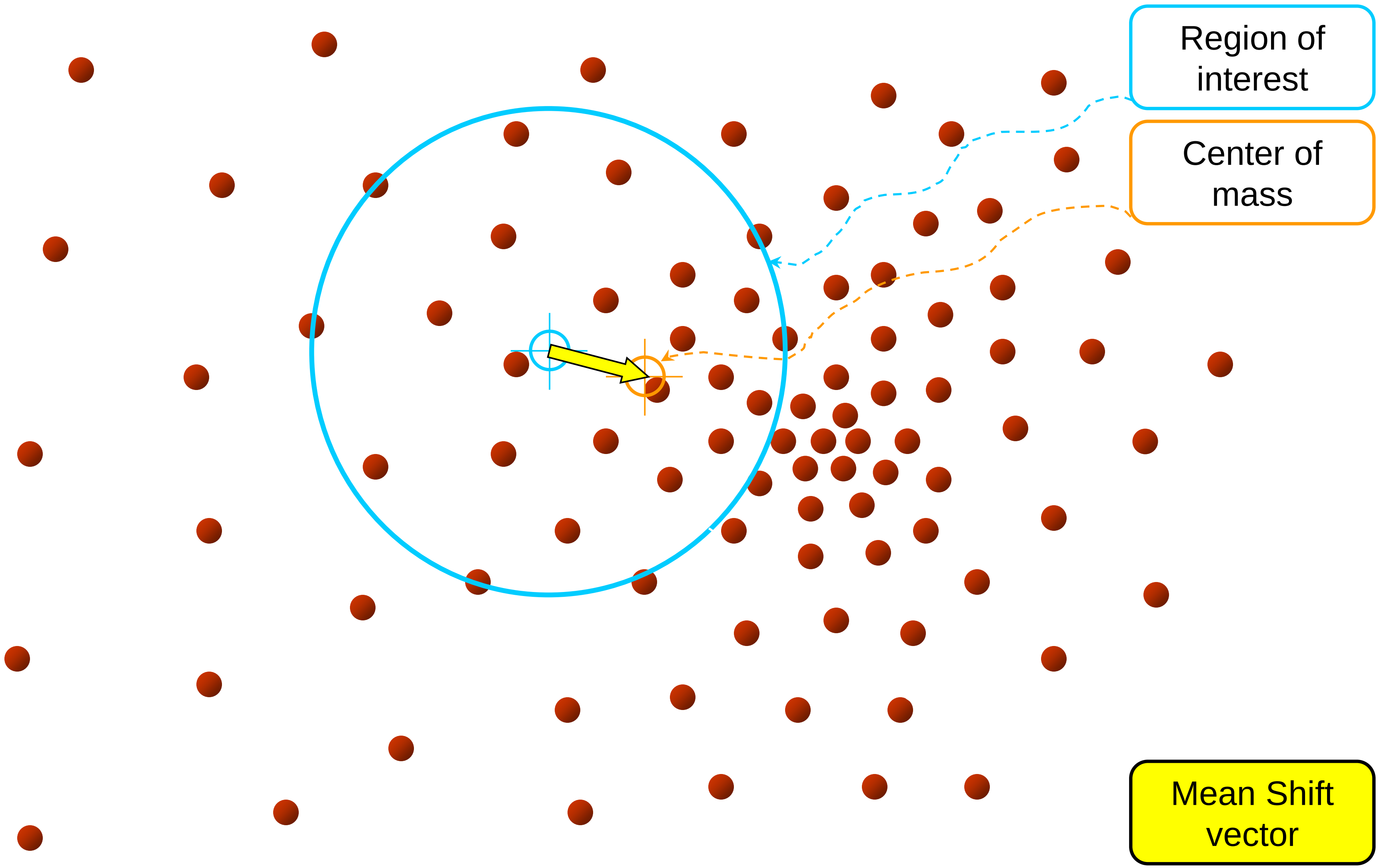
Slide credit: Svetlana Lazebnik

Mean-Shift Algorithm



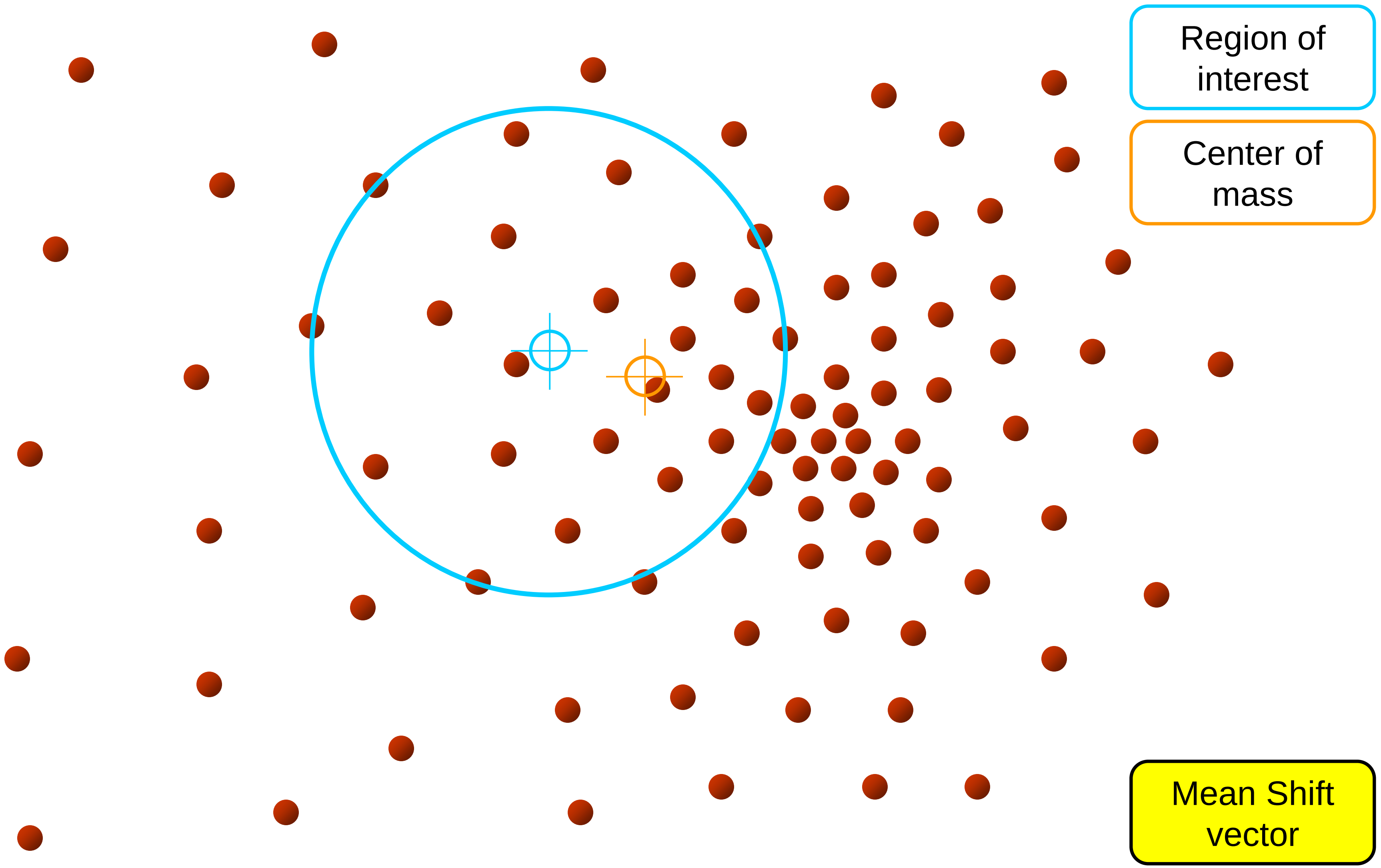
- Iterative Mode Search
  1. Initialize random seed, and window W
  2. Calculate center of gravity (the "mean") of W: $\sum_{x \in W} x H(x)$
  3. Shift the search window to the mean
  4. Repeat Step 2 until convergence

Mean-Shift



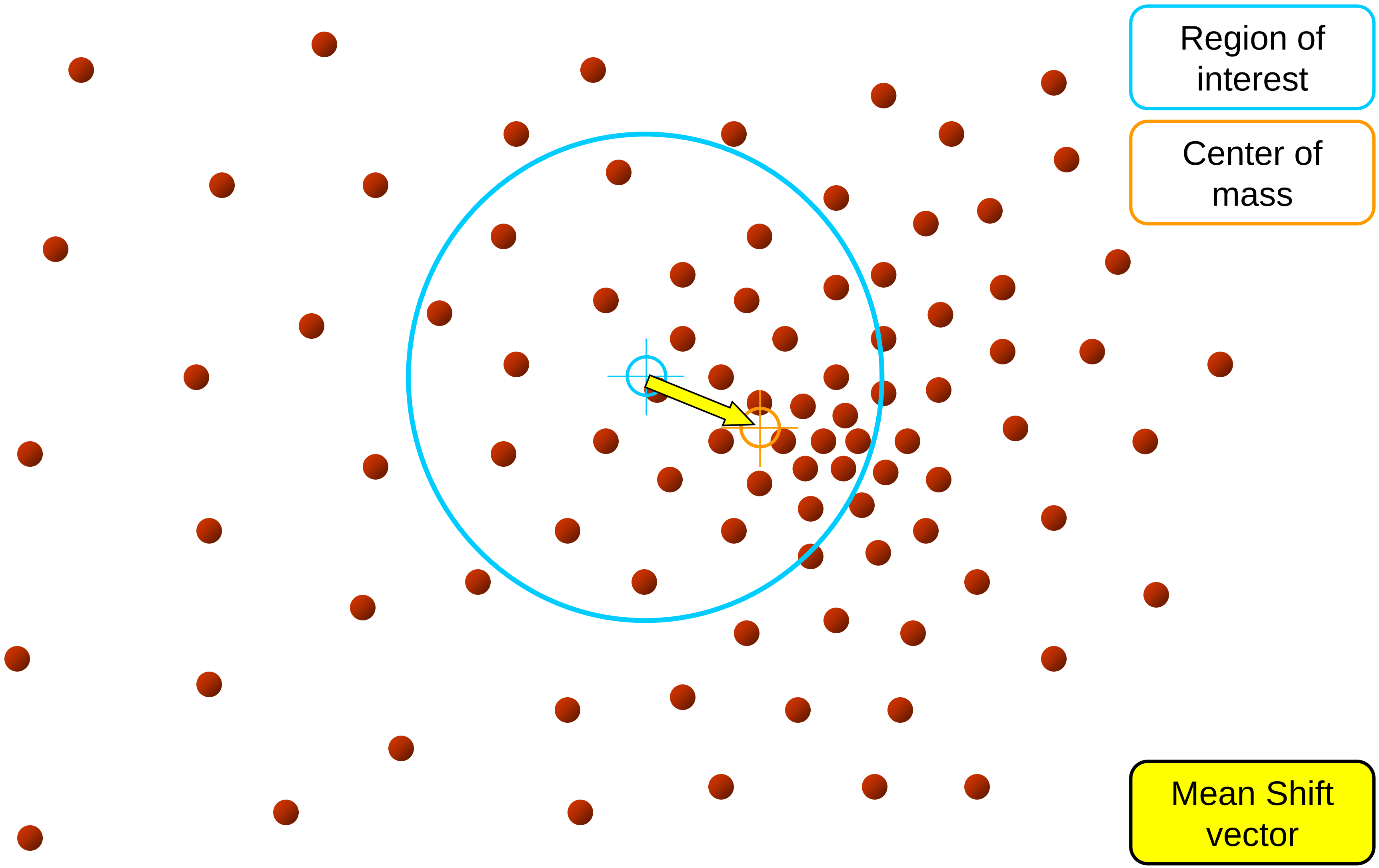
Slide by Y. Ukrainitz & B. Sarel

Mean-Shift

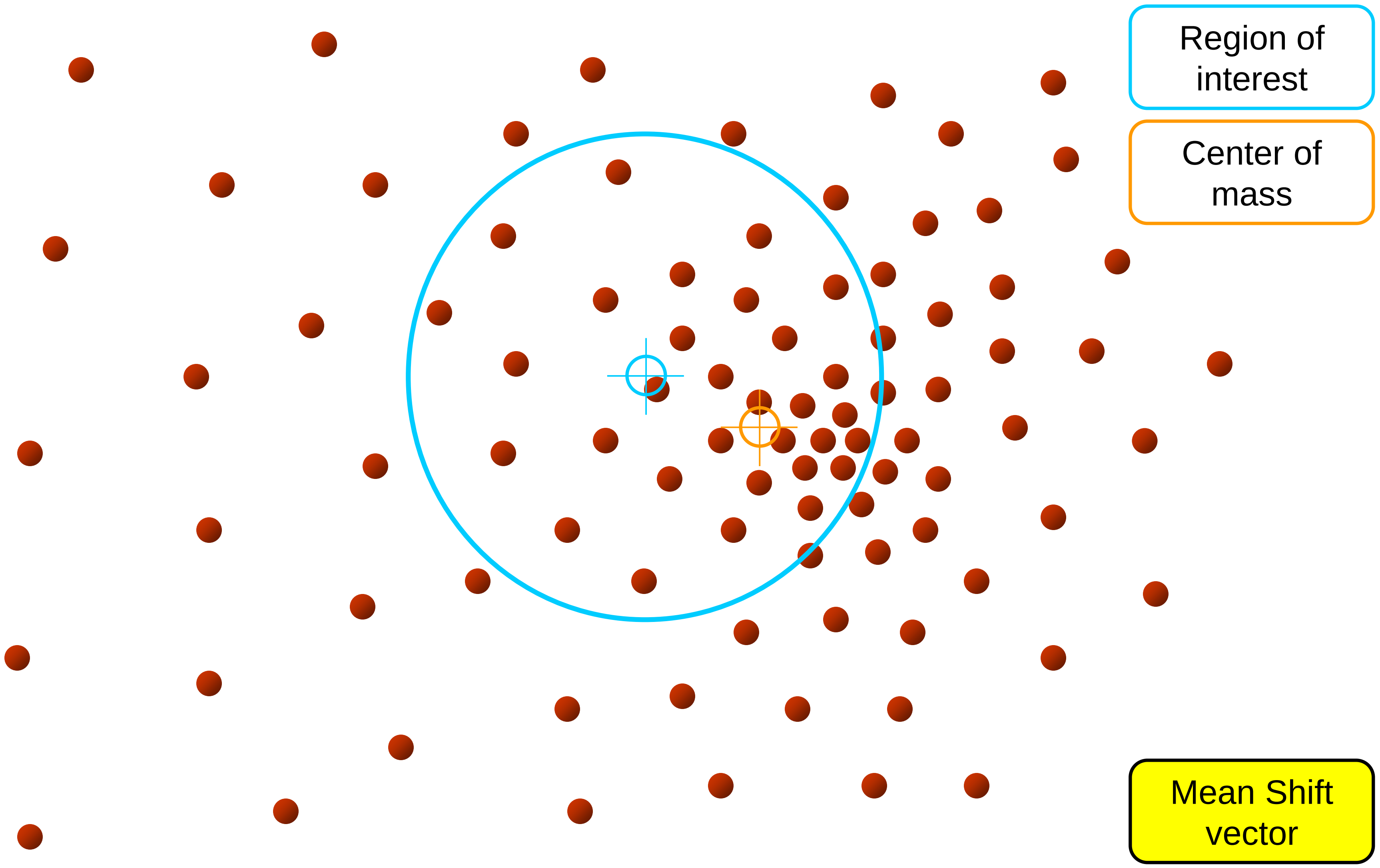


Slide by Y. Ukrainitz & B. Sarel

Mean-Shift

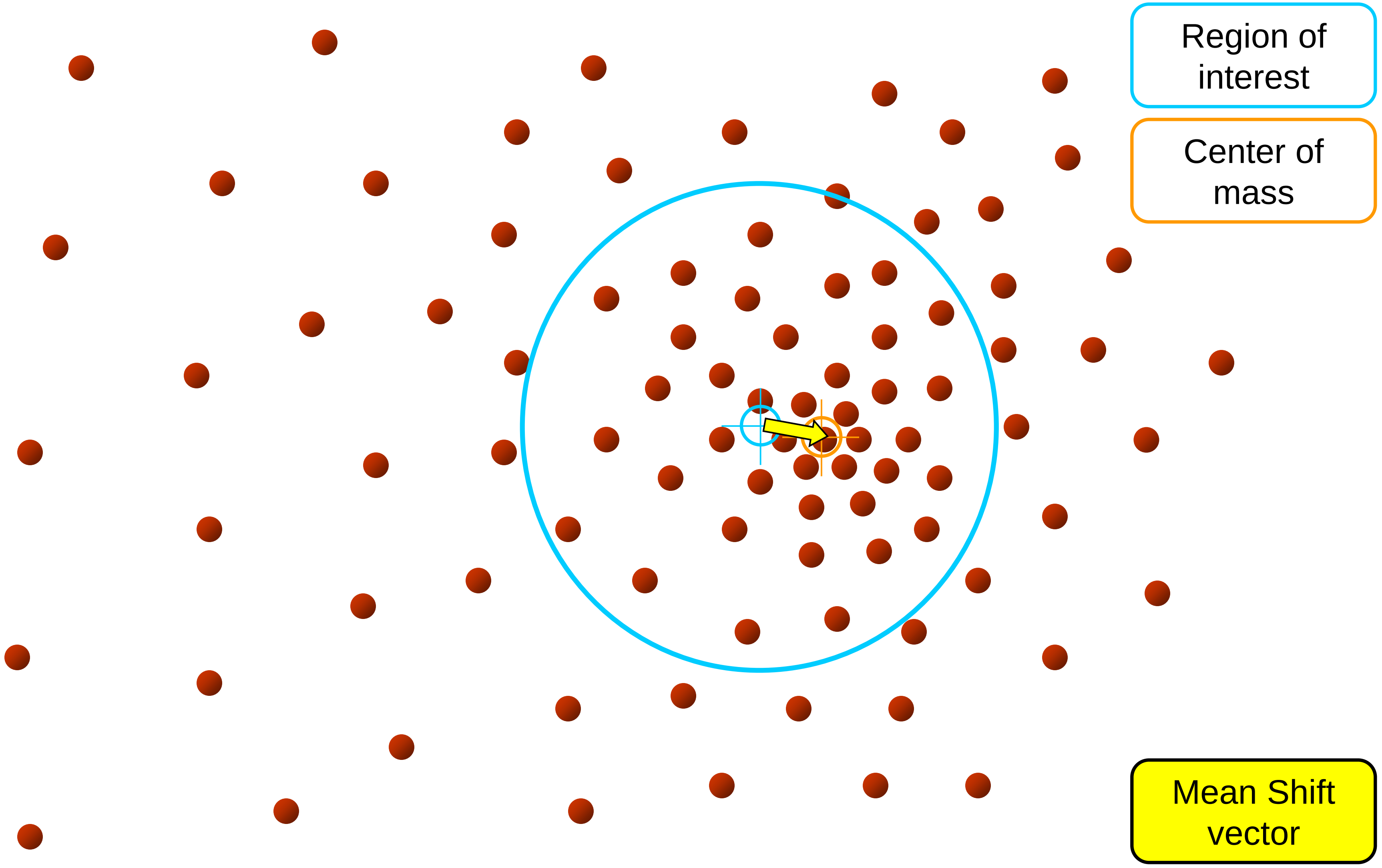


Mean-Shift



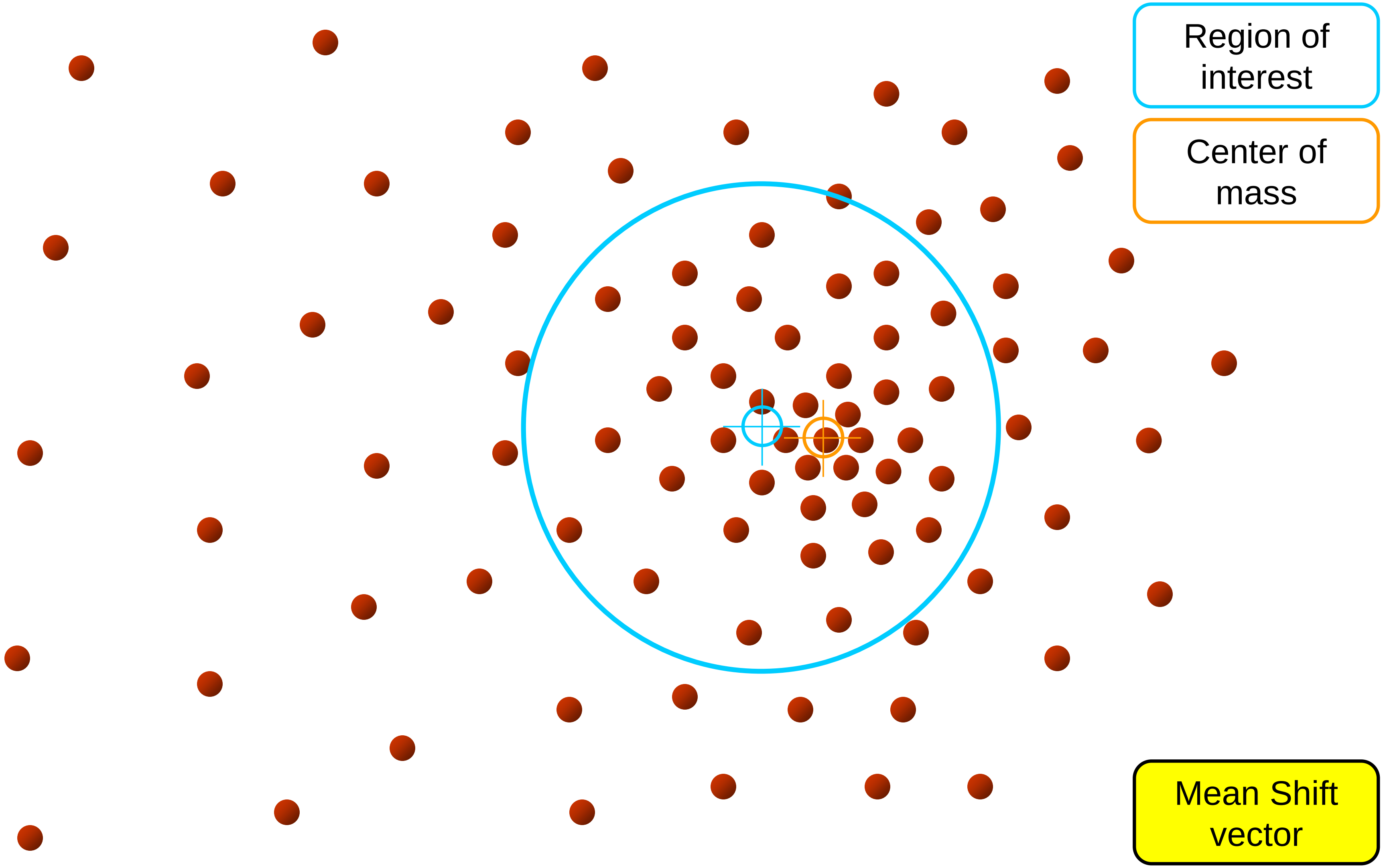
Slide by Y. Ukrainitz & B. Sarel

Mean-Shift



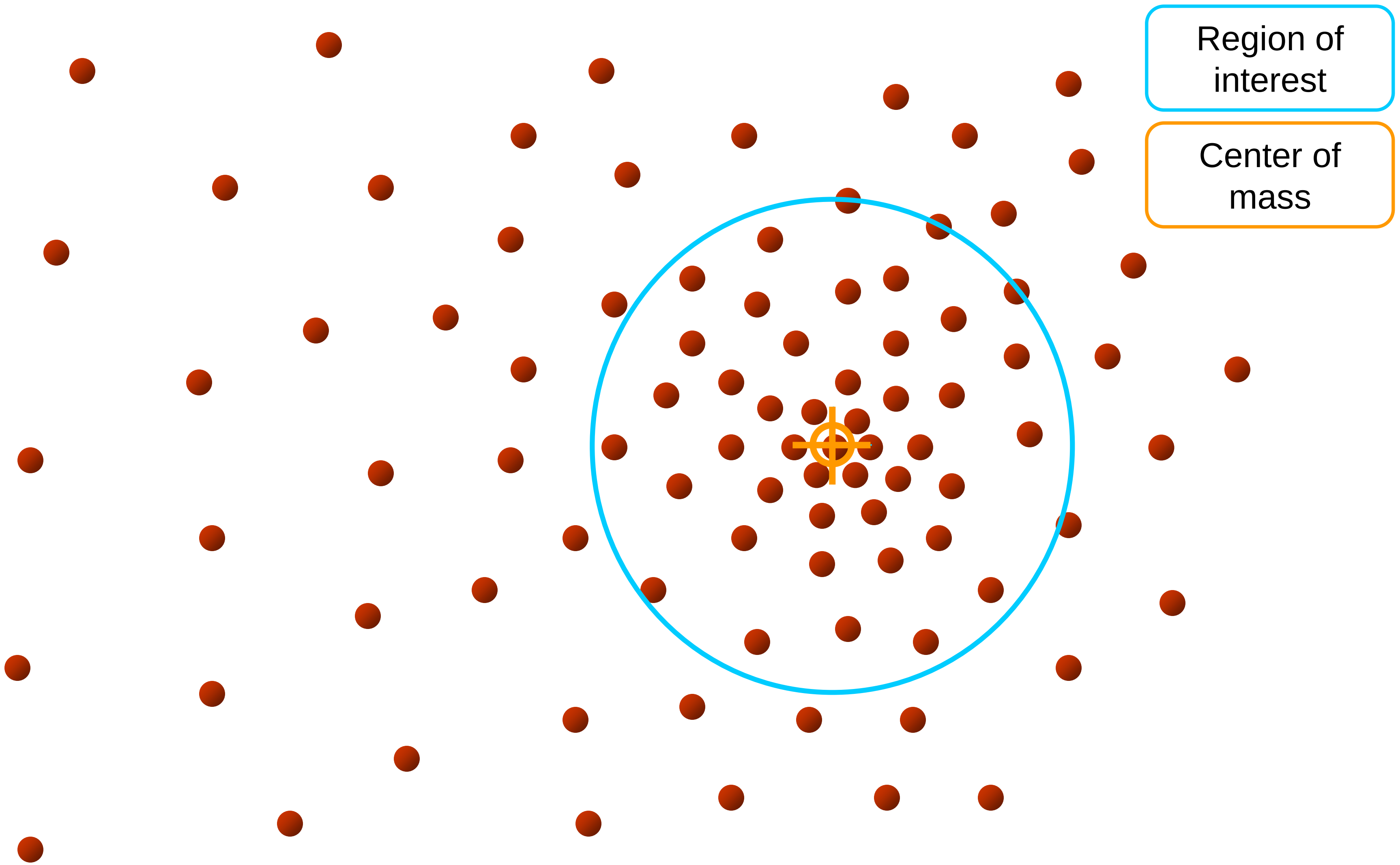
Slide by Y. Ukrainitz & B. Sarel

Mean-Shift



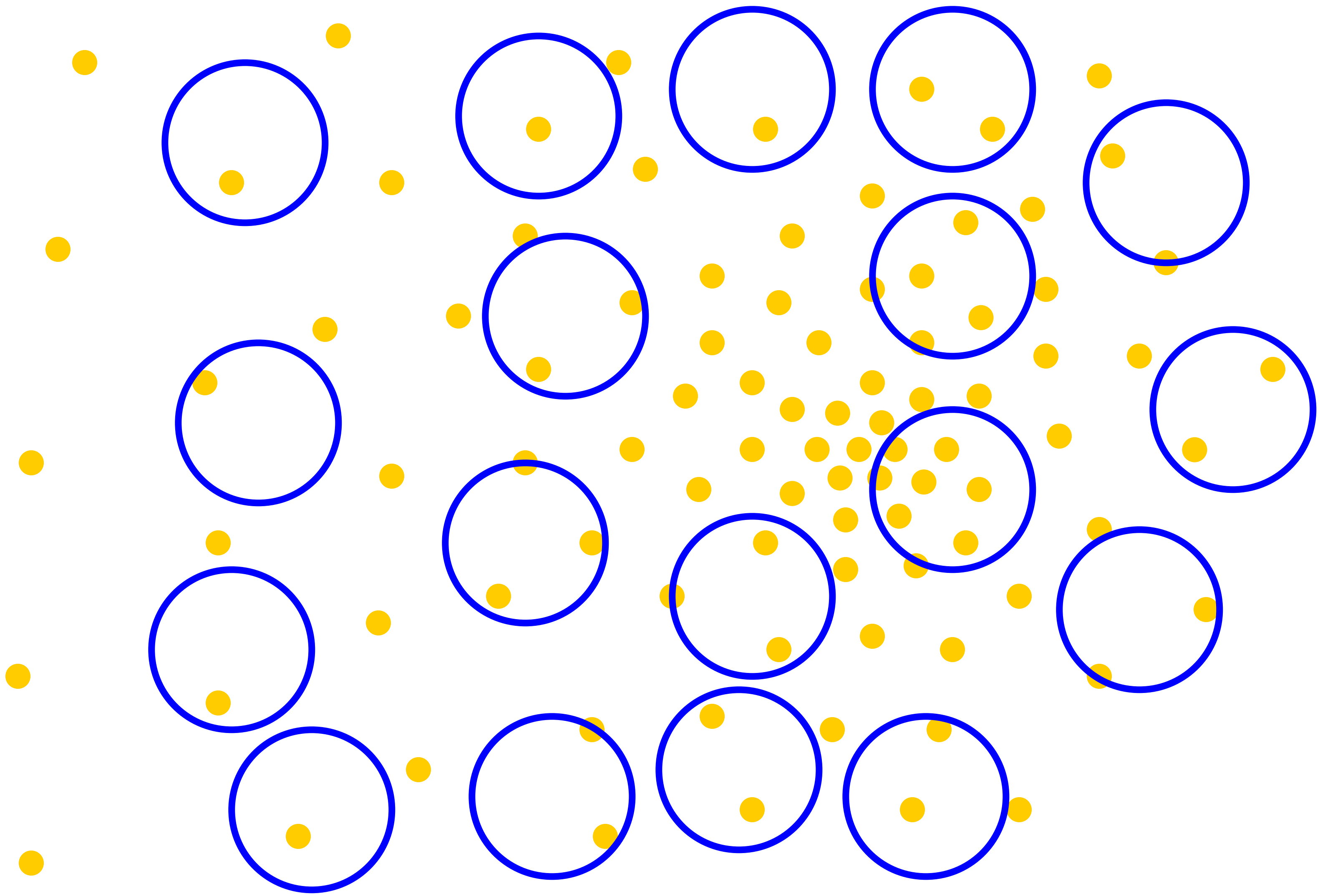
Slide by Y. Ukrainitz & B. Sarel

Mean-Shift



Slide by Y. Ukrainitz & B. Sarel

Real Modality Analysis

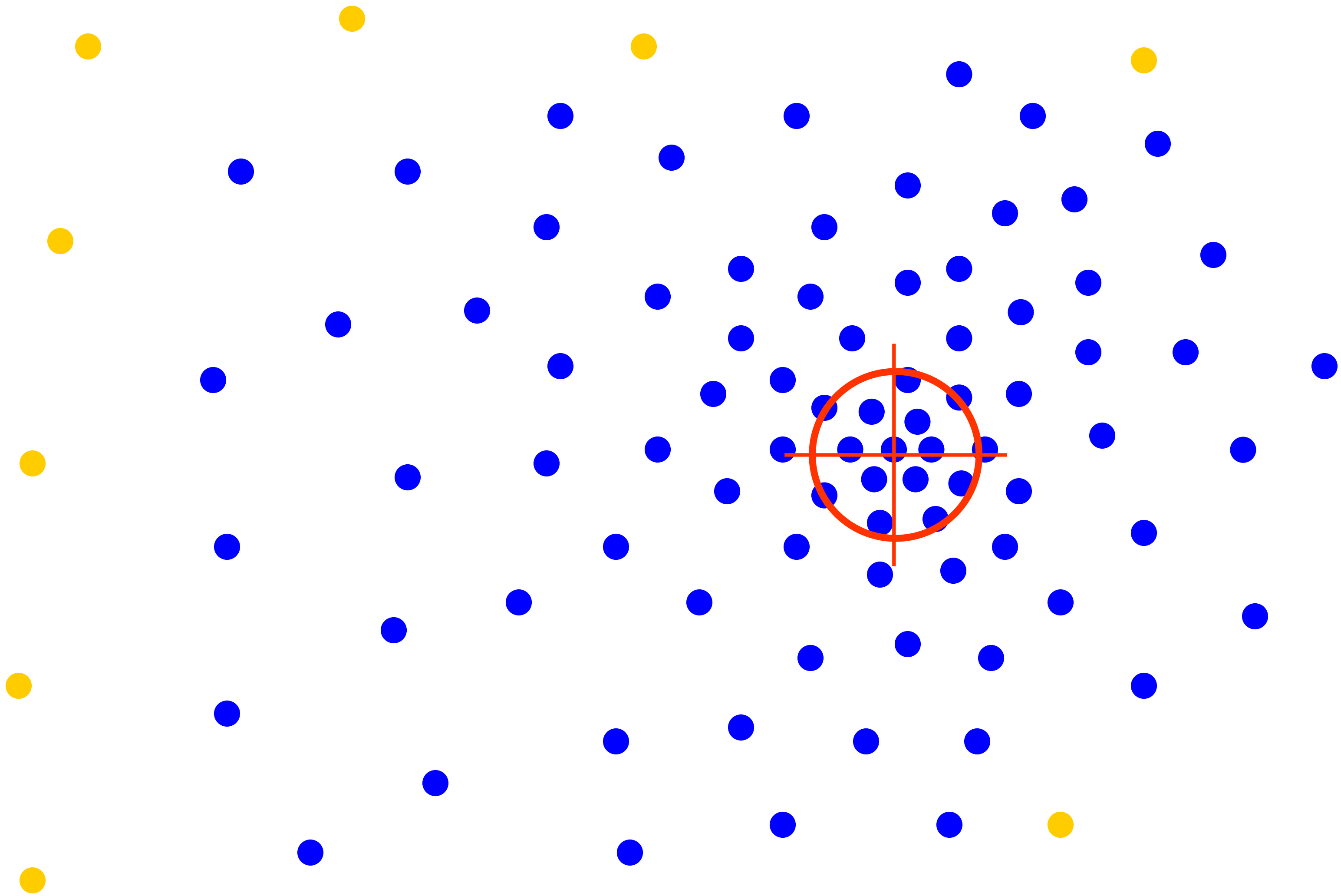


Tessellate the space with windows

Run the procedure in parallel

Slide by Y. Ukrainitz & B. Sarel

Real Modality Analysis

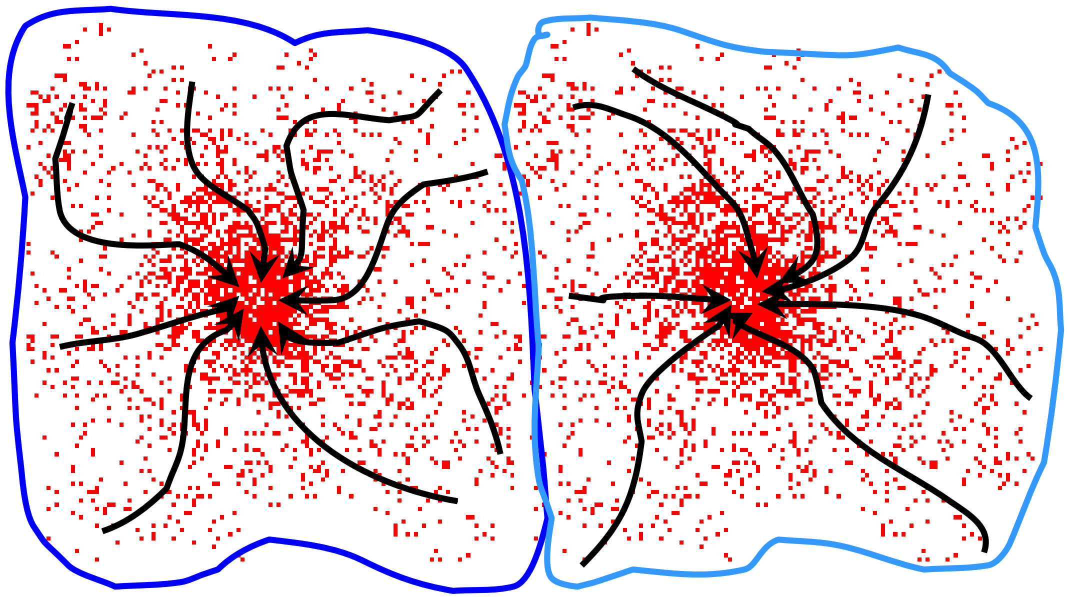


The blue data points were traversed by the windows towards the mode.

Slide by Y. Ukrainitz & B. Sarel

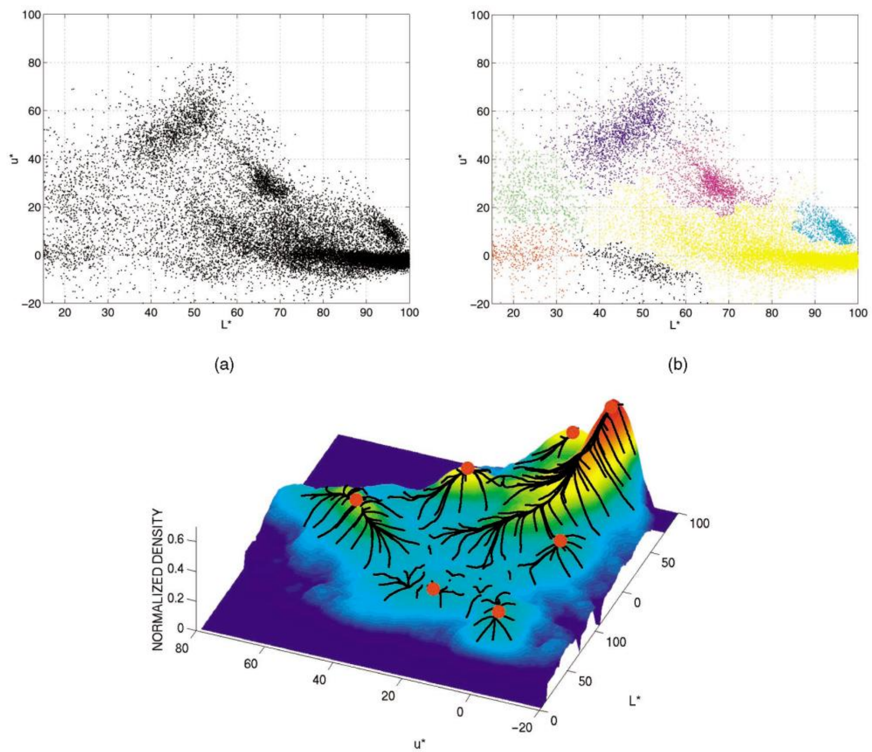
Mean-Shift Clustering

- Cluster: all data points in the attraction basin of a mode
- Attraction basin: the region for which all trajectories lead to the same mode

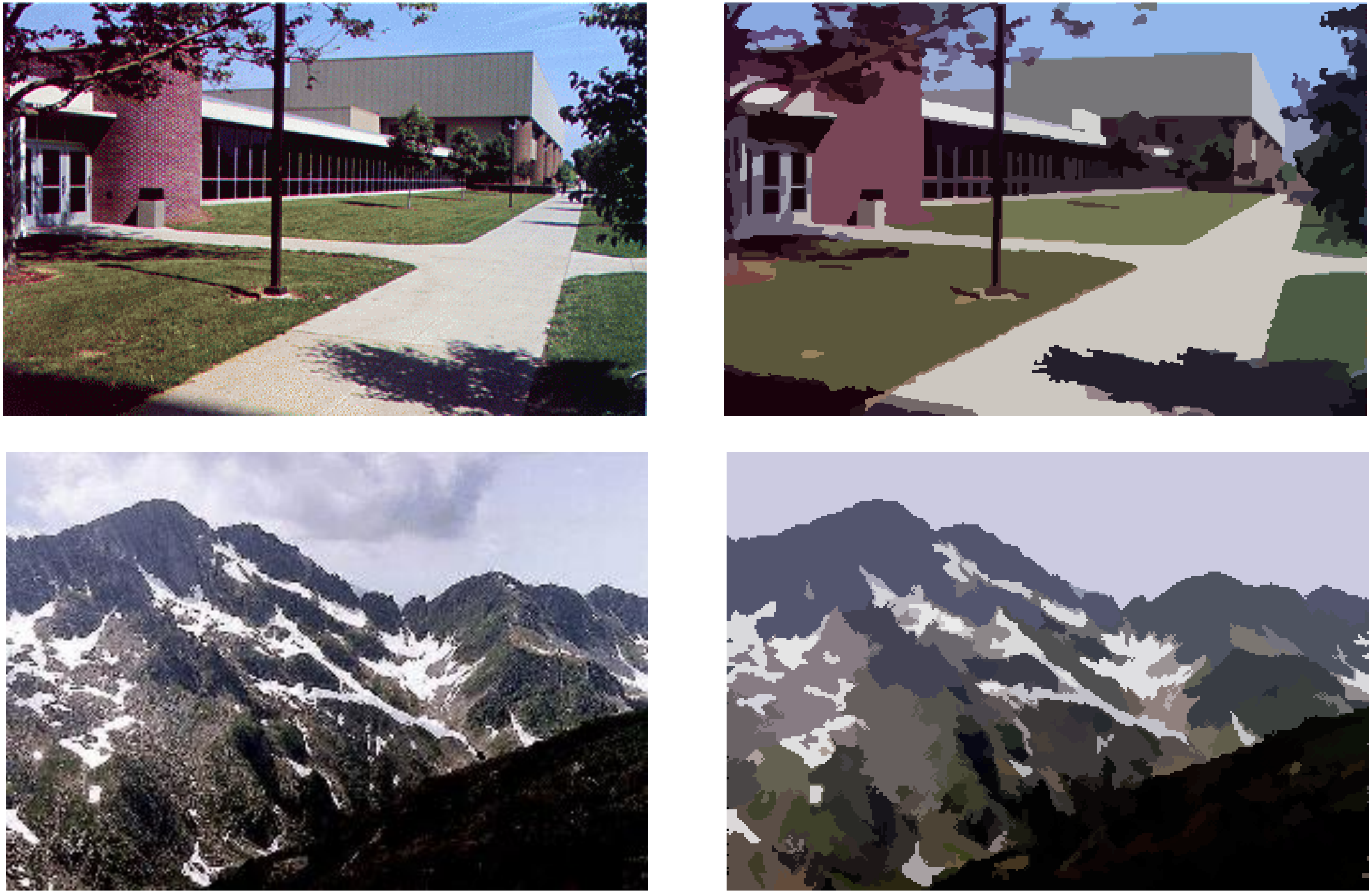


Mean-Shift Clustering/Segmentation

- Find features (color, gradients, texture, etc)
- Initialize windows at individual pixel locations
- Perform mean shift for each window until convergence
- Merge windows that end up near the same "peak" or mode

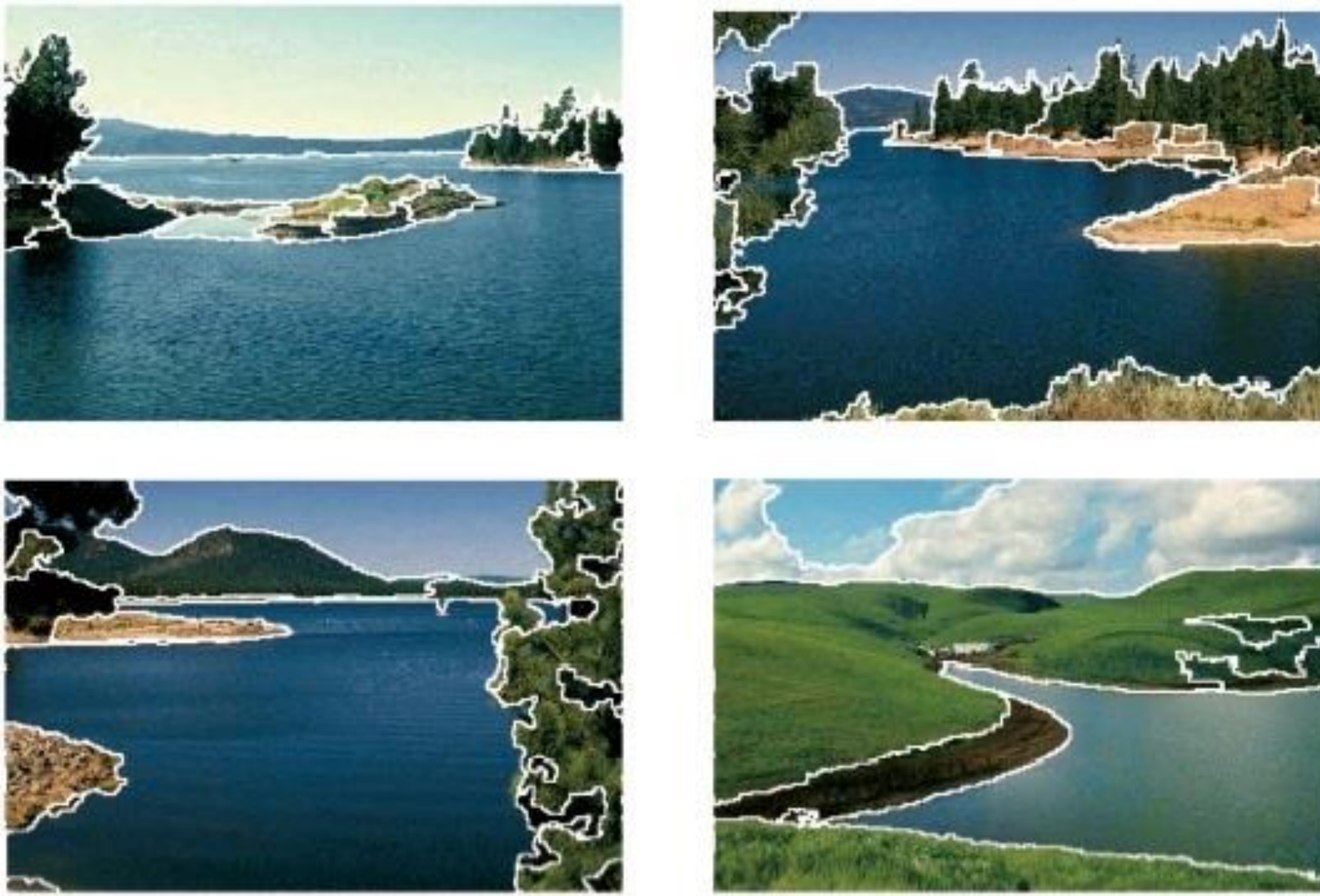


Mean-Shift Segmentation Results



http://www.caip.rutgers.edu/~comanici/MSPAMI/msPamiResults.html

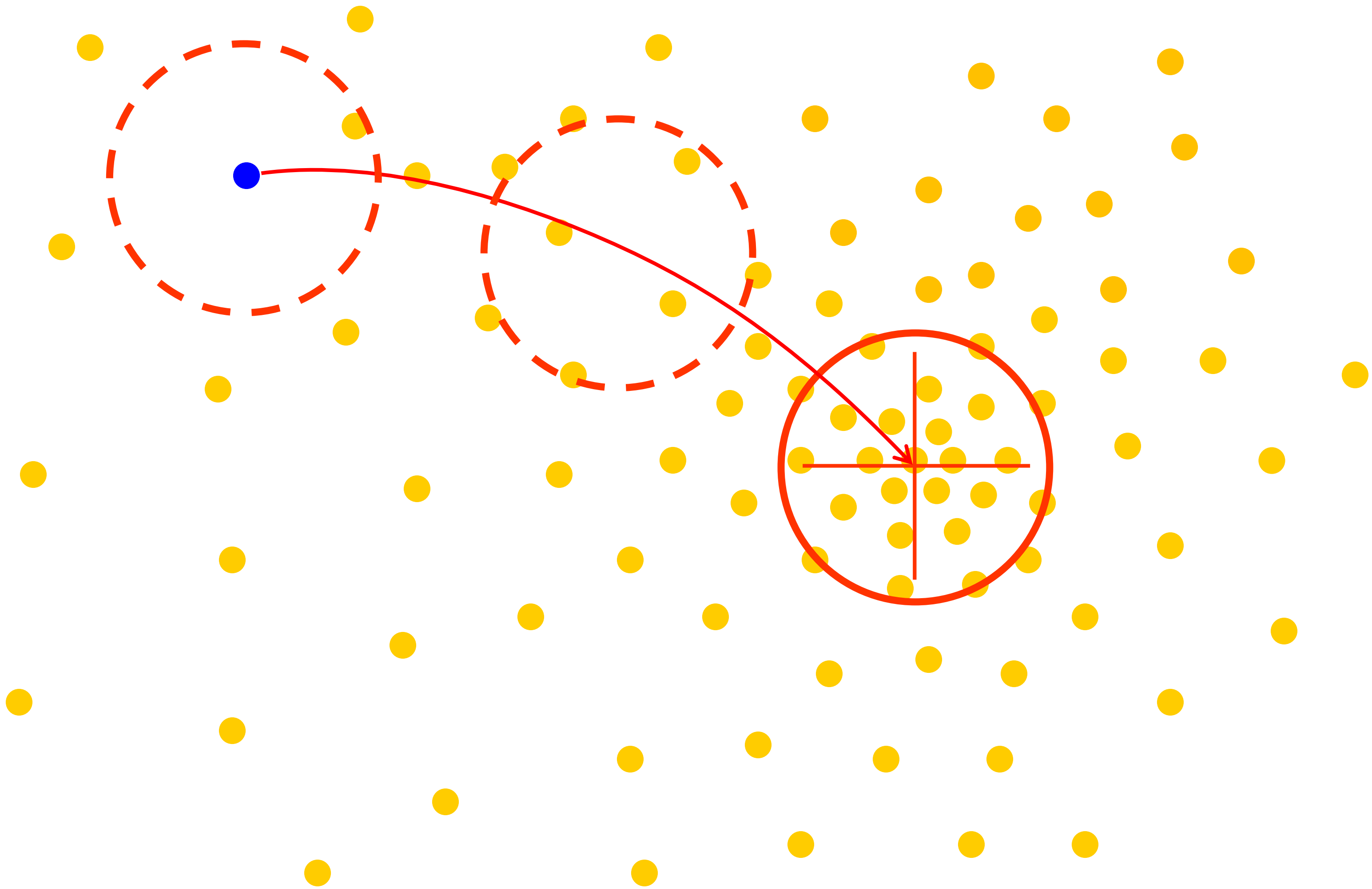
More Results



Slide credit: Svetlana Lazebnik

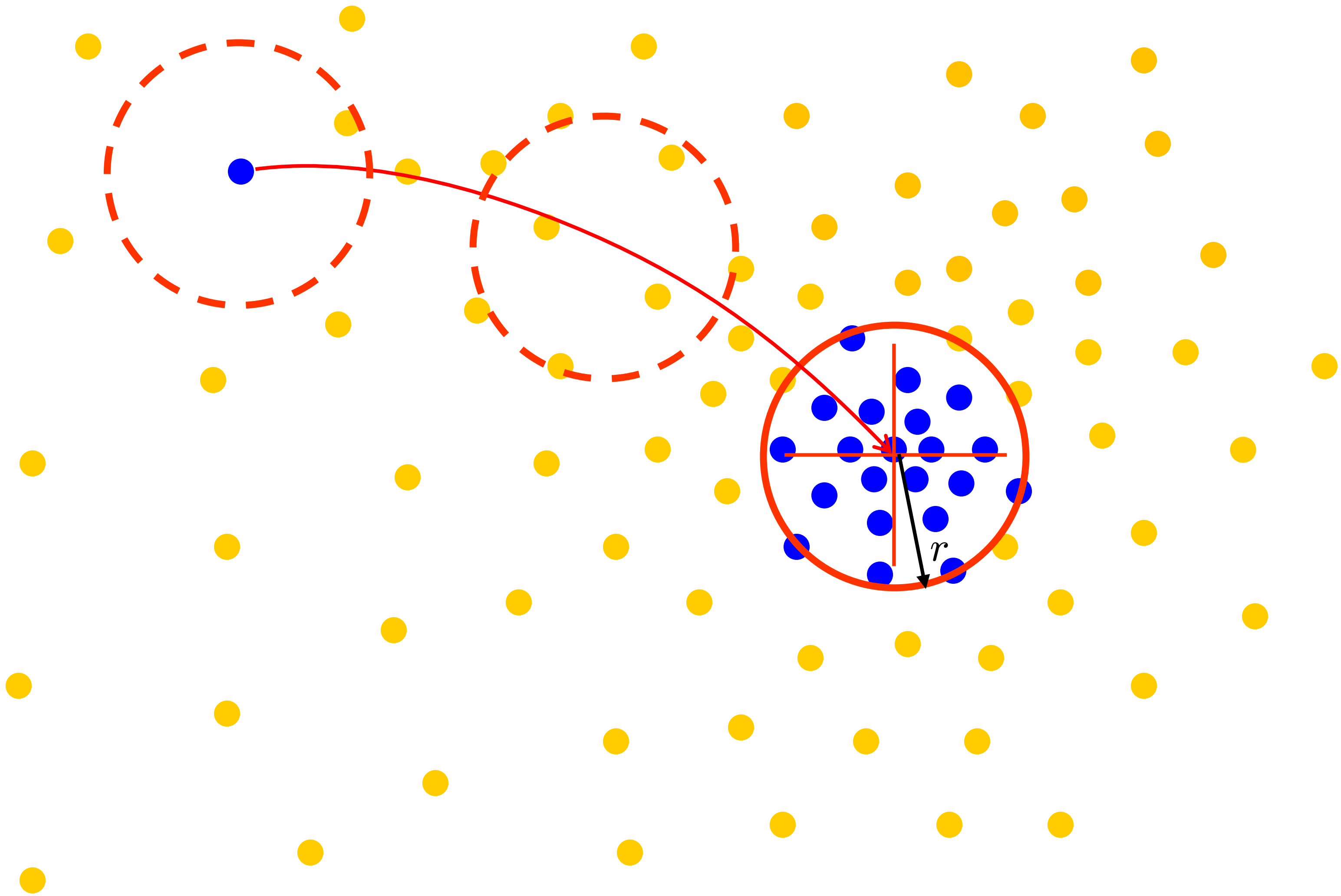
More Results

Problem: Computational Complexity



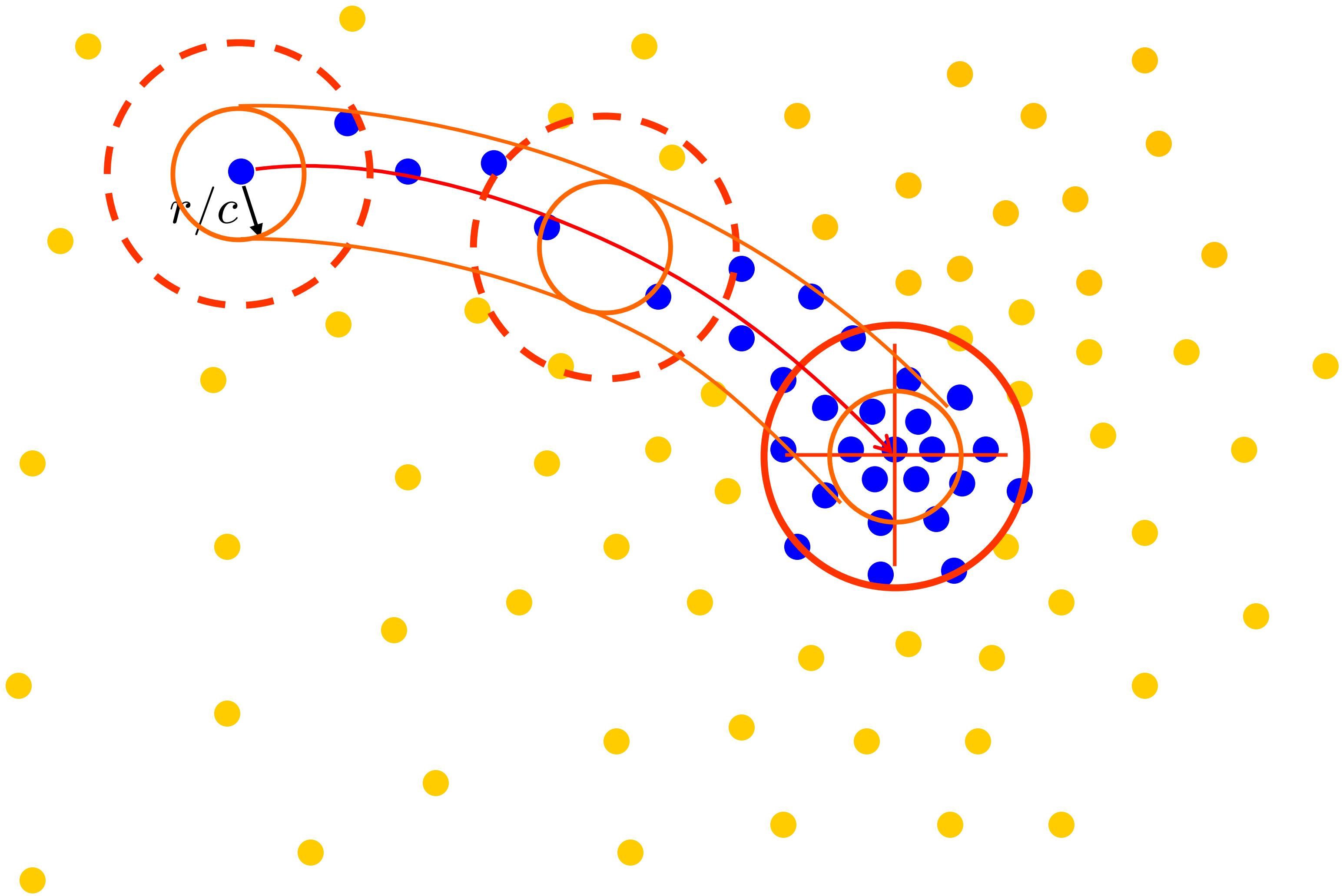
- Need to shift many windows…
- Many computations will be redundant.

Speedups: Basin of Attraction



1. Assign all points within radius r of end point to the mode.

Speedups



2. Assign all points within radius r/c of the search path to the mode.

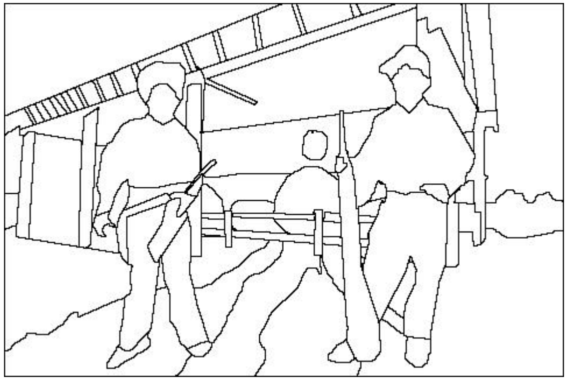
Summary Mean-Shift

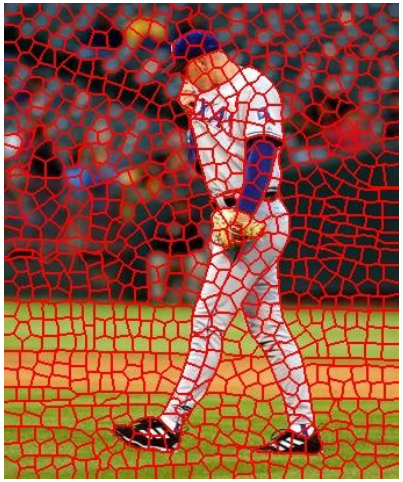
- Pros
  - General, application-independent tool
  - Model-free, does not assume any prior shape (spherical, elliptical, etc.) on data clusters
  - Just a single parameter (window size h)
    - h has a physical meaning (unlike k-means)
  - Finds variable number of modes
  - Robust to outliers

- Cons
  - Output depends on window size
  - Window size (bandwidth) selection is not trivial
  - Computationally (relatively) expensive
  - Does not scale well with dimension of feature space

Segmentation: Caveats

- We've looked at *bottom-up* ways to segment an image into regions, yet finding meaningful segments is intertwined with the recognition problem.
- Often want to avoid making hard decisions too soon
- Difficult to evaluate; when is a segmentation successful?



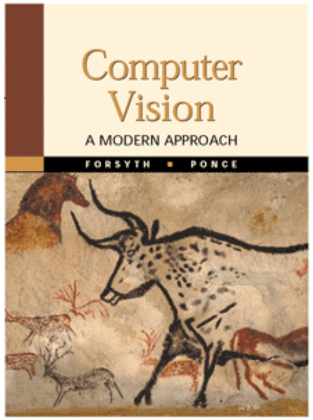


Generic Clustering

- We have focused on ways to group pixels into image segments based on their appearance
  - Find groups; "quantize" feature space
- In general, we can use clustering techniques to find groups of similar "tokens", provided we know how to compare the tokens.
  - *E.g.*, segment an image into the types of motions present
  - *E.g.*, segment a video into the types of scenes (shots) present

References and Further Reading

- Background information on segmentation by clustering can be found in Chapter 14 of
  - D. Forsyth, J. Ponce,
    Computer Vision – A Modern Approach.
    Prentice Hall, 2003



- More on the EM algorithm can be found in Chapter 16.1.2.