Lecture 10: Clustering

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https://shuaili8.github.io

https://shuaili8.github.io/Teaching/VE445/index.html

Outline

- Unsupervised learning
- Clustering
- K-means
    - Algorithm
    - How to choose K
    - Initialization
    - Properties
- Agglomerative clustering

Unsupervised Learning

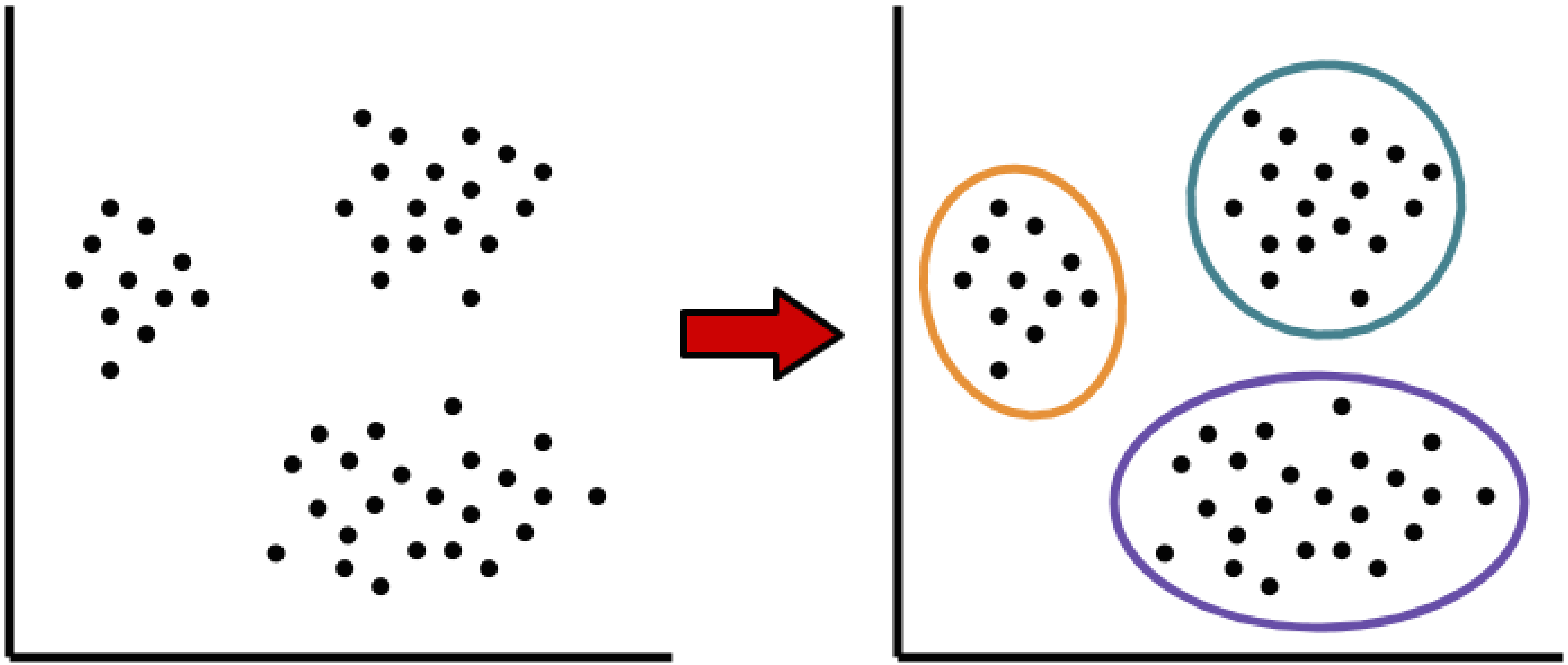
Machine Learning Categories

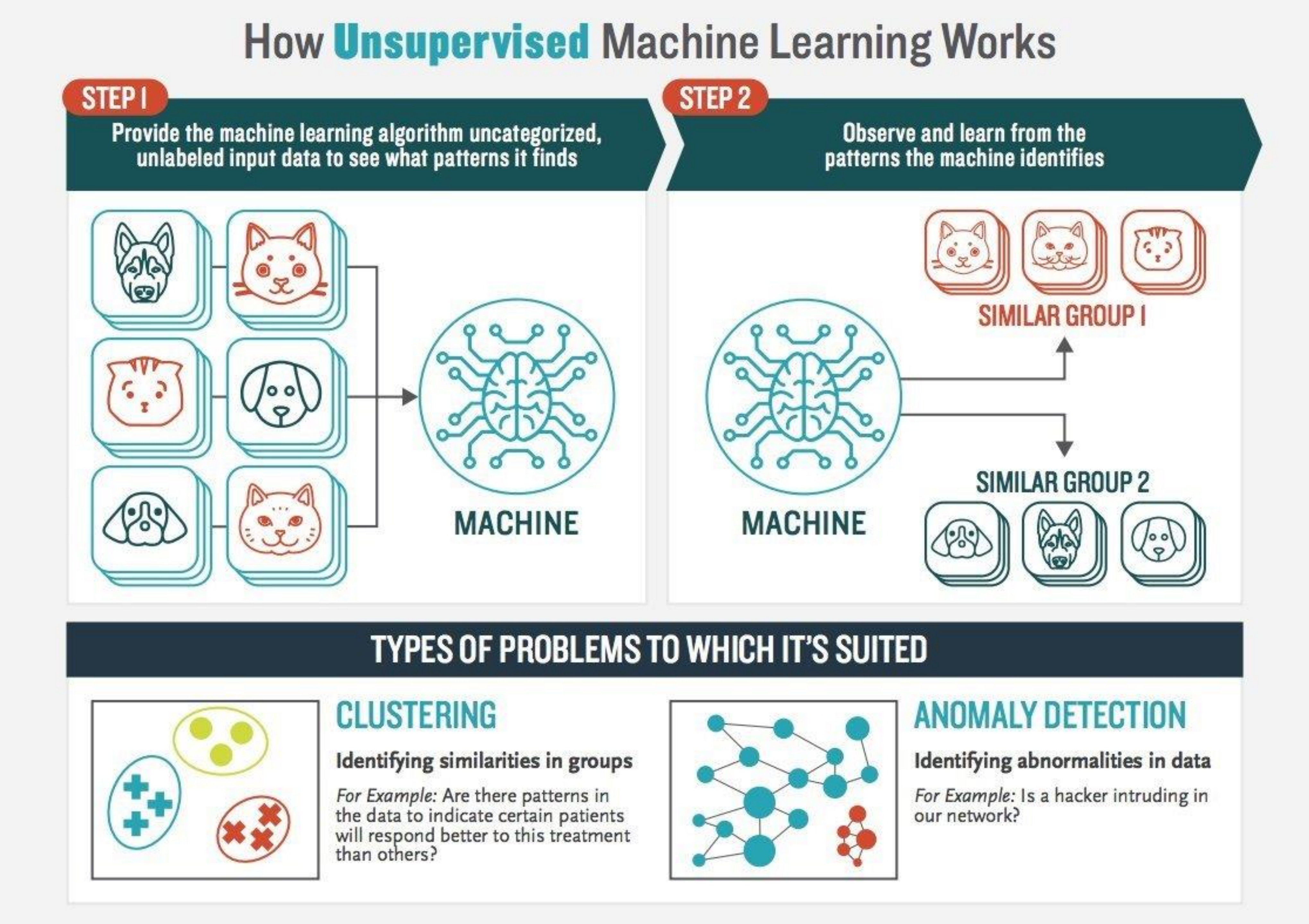
- Unsupervised learning
  - No labeled data
- Supervised learning
  - Use labeled data to predict on unseen points
- Semi-supervised learning
  - Use labeled data and unlabeled data to predict on unlabeled/unseen points
- Reinforcement learning
  - Sequential prediction and receiving feedbacks

Course outline

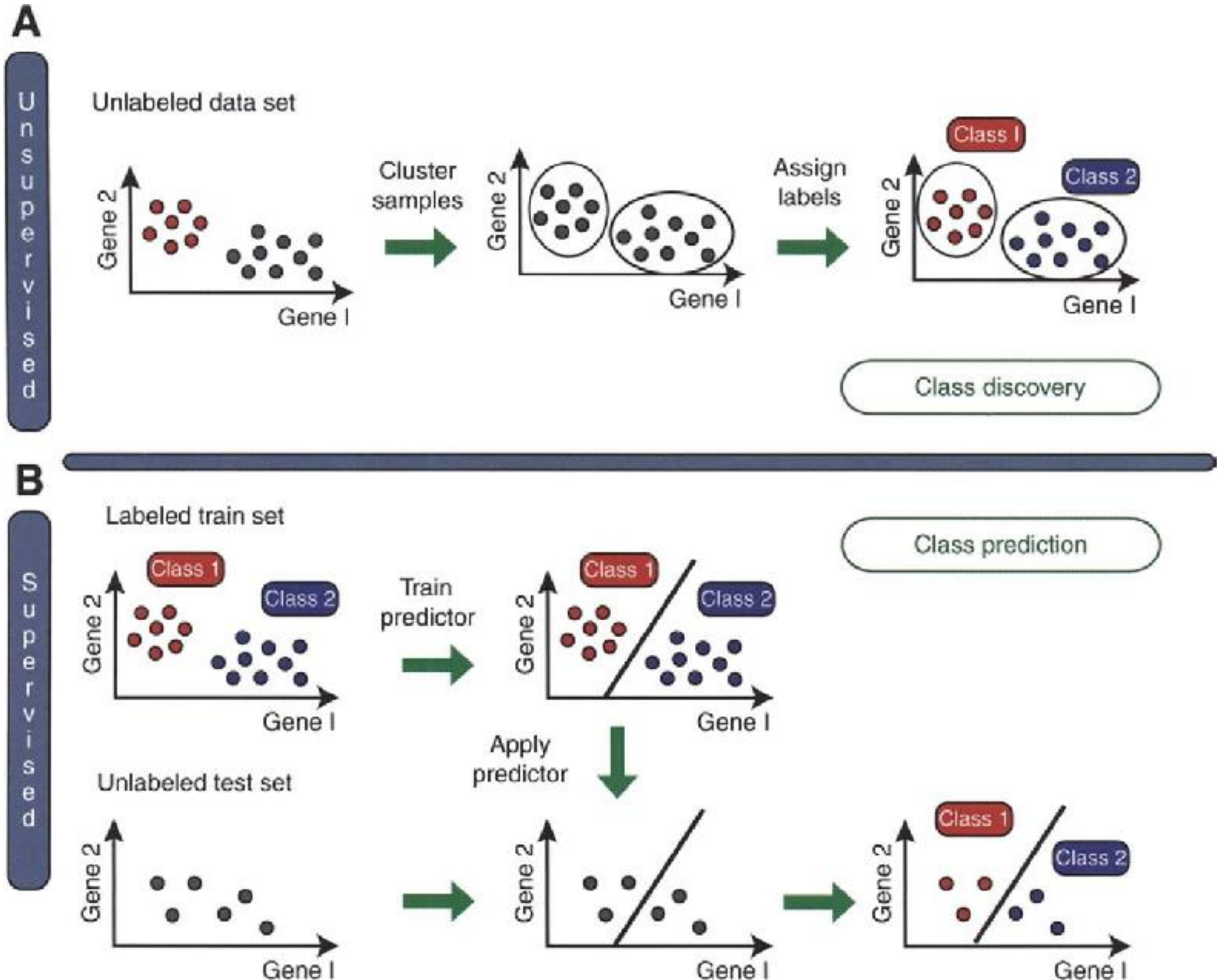
- Basics
- Supervised learning
  - Linear Regression
  - Logistic regression
  - SVM and Kernel methods
  - Decision Tree
- Deep learning
  - Neural Networks
  - Backpropagation
  - Convolutional Neural Network
  - Recurrent Neural Network
- Unsupervised learning
  - K-means, PCA, EM, GMM
- Reinforcement learning
  - Multi-armed bandits
  - MDP
  - Bellman equations
  - Q-learning
- Learning theory
  - PAC, VC-dimension, bias-variance decomposition

Unsupervised learning example




How Unsupervised Machine Learning Works
STEP 1
Provide the machine learning algorithm uncategorized, unlabeled input data to see what patterns it finds
MACHINE
STEP 2
Observe and learn from the patterns the machine identifies
MACHINE
SIMILAR GROUP 1
SIMILAR GROUP 2
TYPES OF PROBLEMS TO WHICH IT'S SUITED
CLUSTERING
Identifying similarities in groups
For Example: Are there patterns in the data to indicate certain patients will respond better to this treatment than others?
ANOMALY DETECTION
Identifying abnormalities in data
For Example: Is a hacker intruding in our network?

Supervised Learning	Unsupervised Learning
Input data is labelled	Input data is unlabeled
Uses training dataset	Uses just input dataset
Used for prediction	Used for analysis
Classification and regression	Clustering, density estimation and dimensionality reduction


A
Unsupervised
Unlabeled data set
Gene 2
Gene I
Cluster samples
Assign labels
Class I
Class 2
Class discovery
B
Supervised
Labeled train set
Class 1
Class 2
Train predictor
Class prediction
Apply predictor
Unlabeled test set

Clustering

Clustering

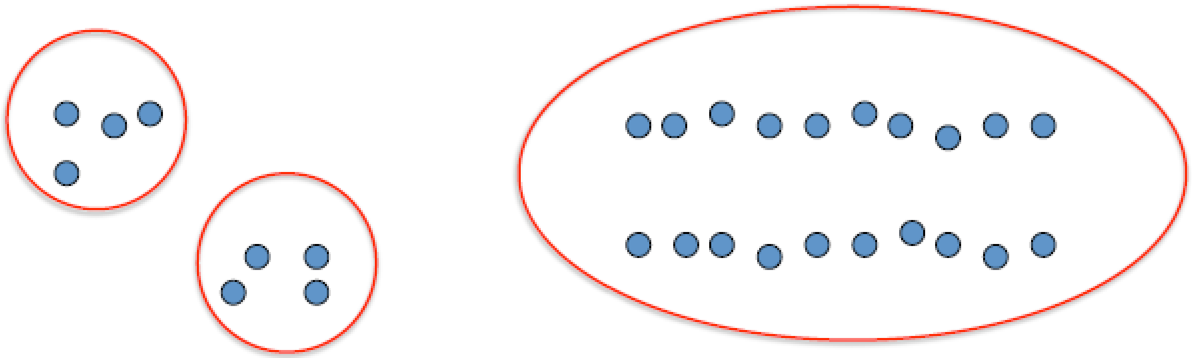
- Unsupervised learning
- Requires data, but no labels
- Detect patterns e.g. in
  - Group emails or search results
  - Customer shopping patterns
  - Regions of images
- Useful when don’t know what you’re looking for
- But: can get gibberish

Clustering (cont.)

- Goal: Automatically segment data into groups of similar points
- Question: When and why would we want to do this?
- Useful for:
  - Automatically organizing data
  - Understanding hidden structure in some data
  - Representing high-dimensional data in a low-dimensional space
- Examples:
  - Cluster customers according to purchase histories
  - Cluster genes according to expression profile
  - Cluster search results according to topic
  - Cluster Facebook users according to interests
  - Cluster a museum catalog according to image similarity

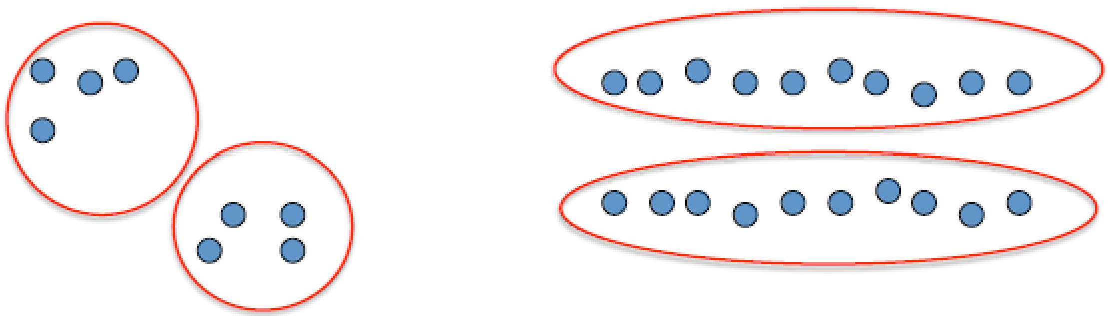
Intuition

- Basic idea: group together similar instances
- Example: 2D point patterns



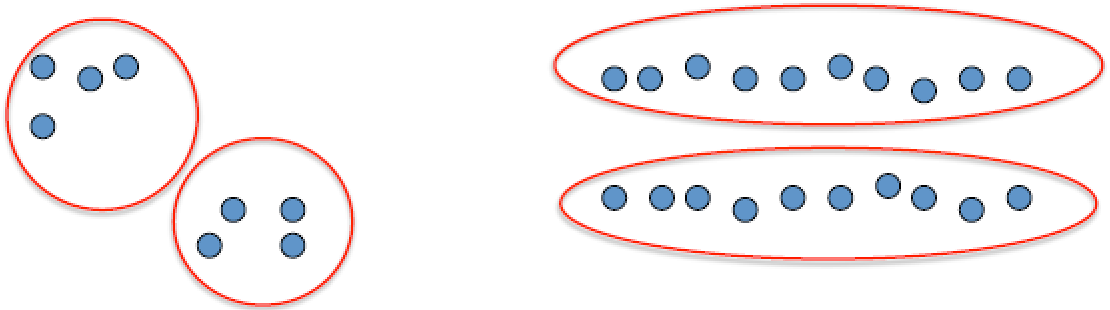
Intuition (cont.)

- Basic idea: group together similar instances
- Example: 2D point patterns



Intuition (cont.)

- Basic idea: group together similar instances
- Example: 2D point patterns



- What could “similar” mean?
- – One option: small Euclidean distance (squared)
- – Clustering results are crucially dependent on the measure of similarity (or distance) between “points” to be clustered

Set-up

- Given the data: $\mathcal{D} = \{\mathbf{x}_1, \ldots, \mathbf{x}_N\}$

- Each data point x is p-dimensional:

$$\mathbf{x}_n = \langle x_{n,1}, \ldots, x_{n,p} \rangle.$$

- Define a distance function between data:

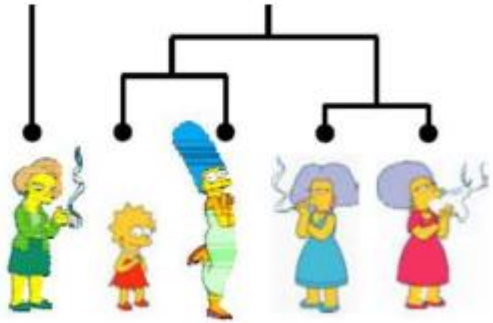
$$d(\mathbf{x}_n, \mathbf{x}_m).$$

- Goal: segment the data into K groups

Clustering algorithms

- Partition algorithms (flat clustering)
  - K-means
  - Mixture of Gaussian
  - Spectral Clustering

- Hierarchical algorithms
  - Bottom up-agglomerative
  - Top down-divisive

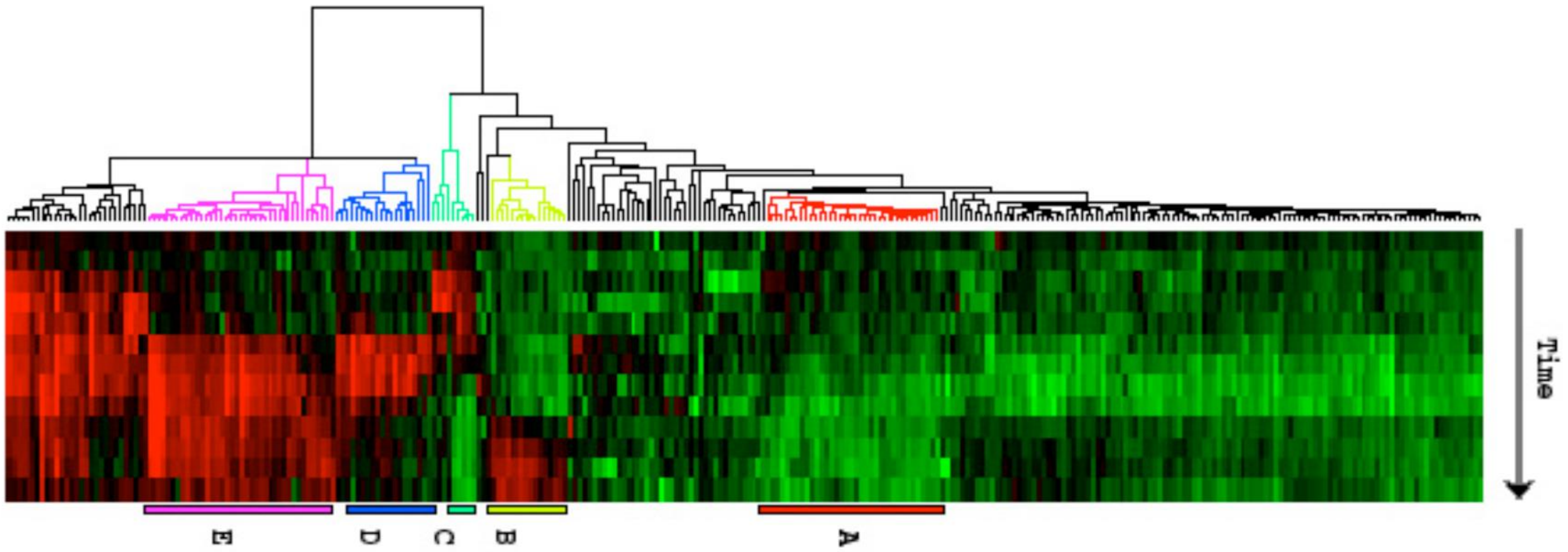


Example

- Image segmentation
- Goal: Break up the image into meaningful or perceptually similar regions

Example 2

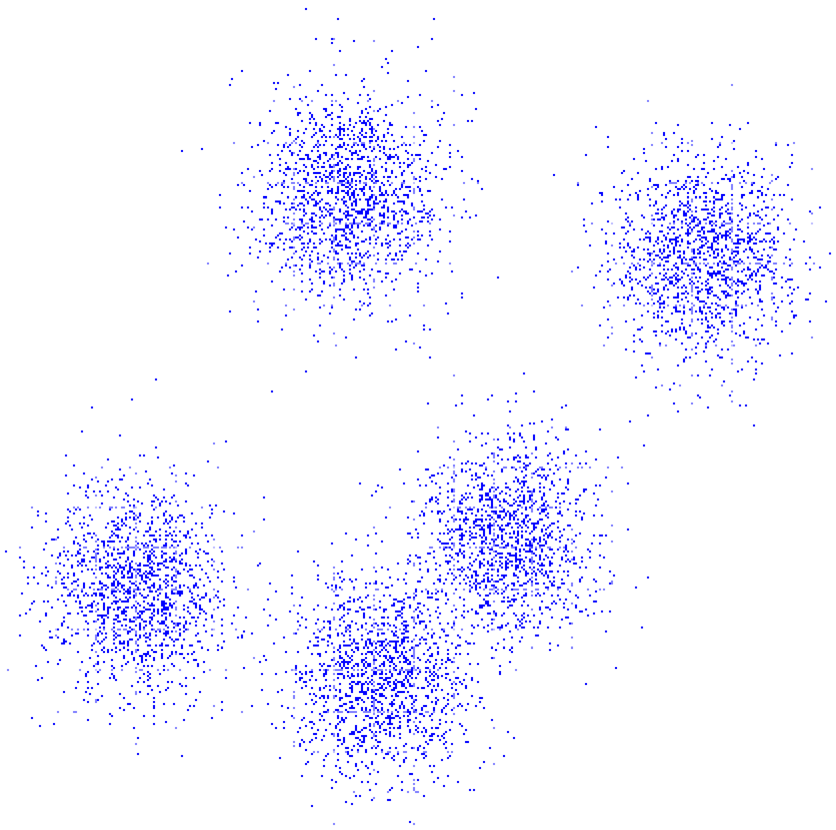
- Gene expression data clustering
  - Activity level of genes across time



K-Means

K-Means

- An iterative clustering algorithm
- Initialize: Pick K random points as cluster centers
- Alternate:
  - Assign data points to closest cluster center
  - Change the cluster center to the average of its assigned points
- Stop: when no points' assignments change



K-Means (cont.)

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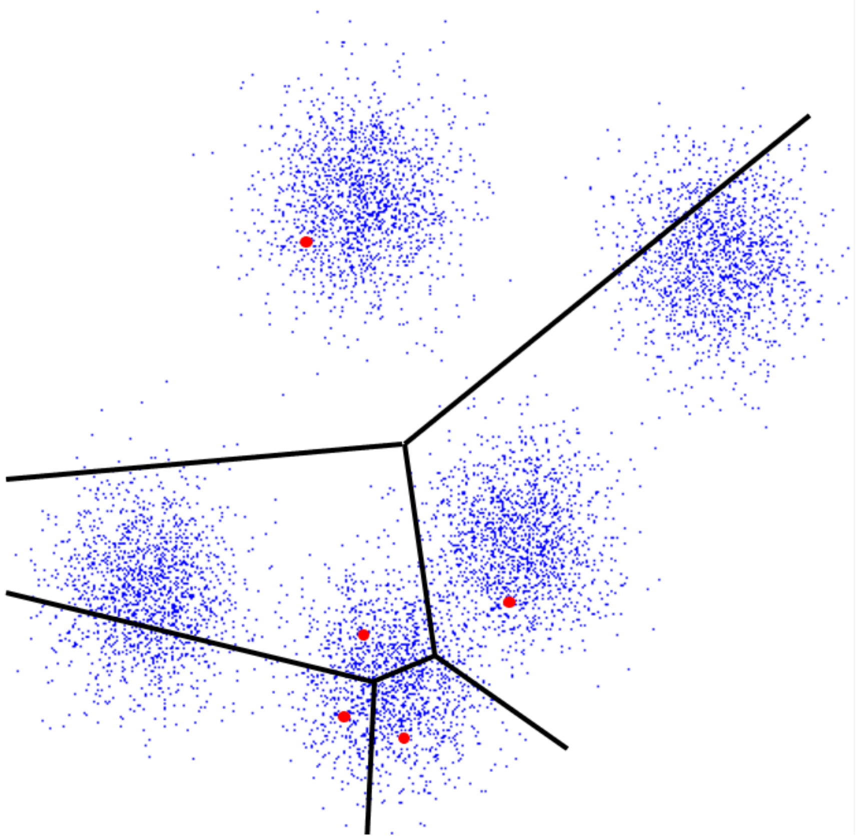

K-Means (cont.)

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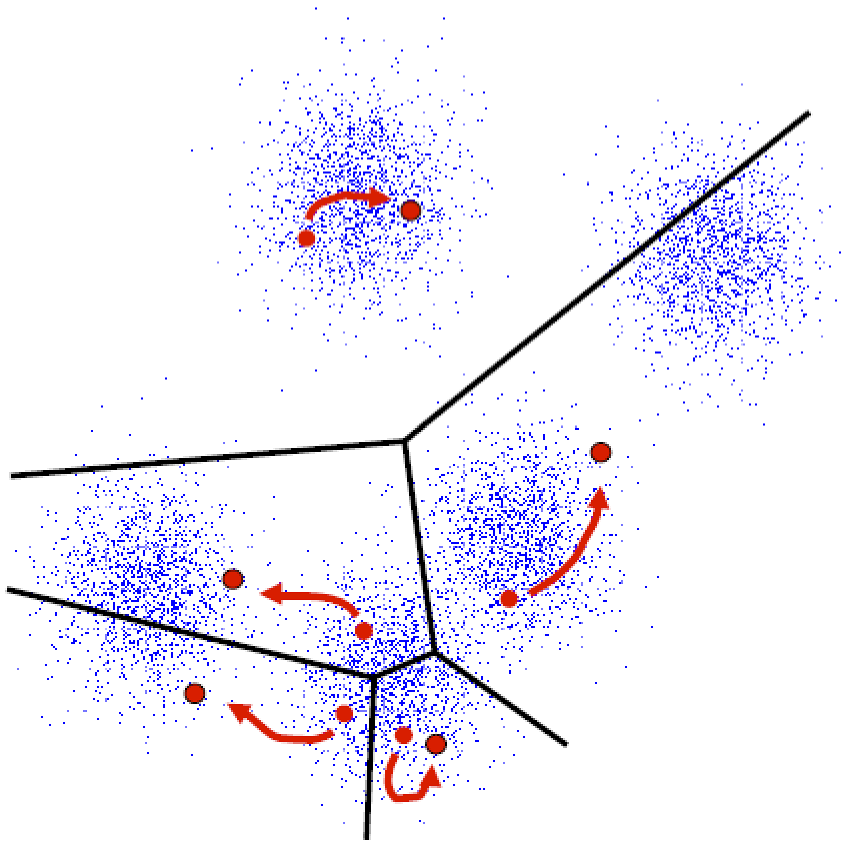
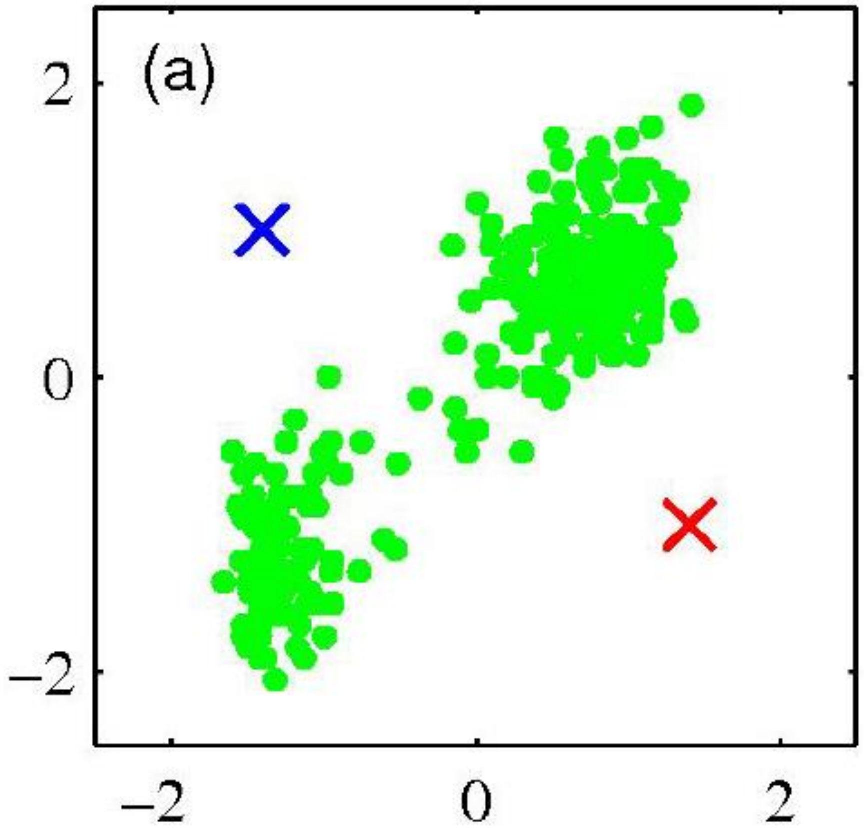


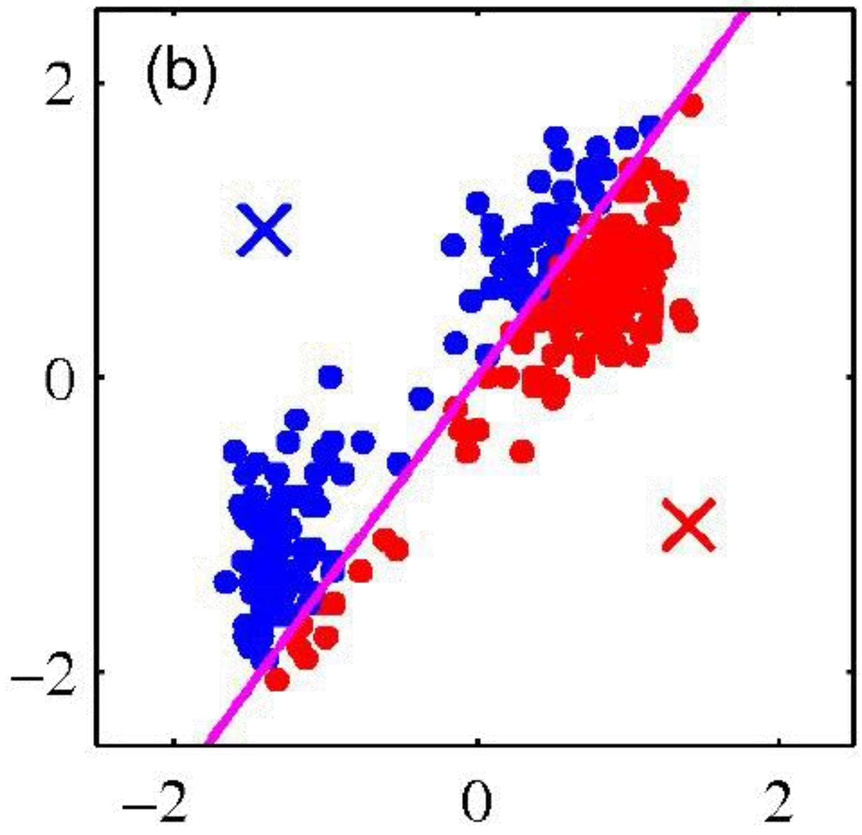
Example

- Pick K random points as cluster centers (means)
- Shown here for $K = 2$



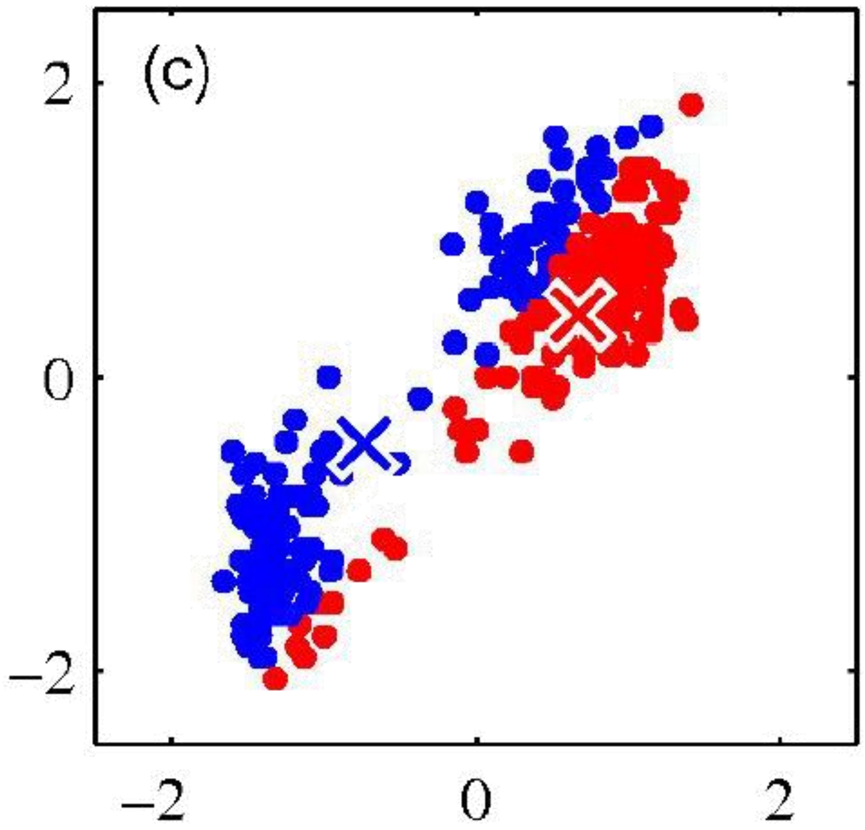
Example (cont.)

- Iterative step 1
- Assign data points to closest cluster center



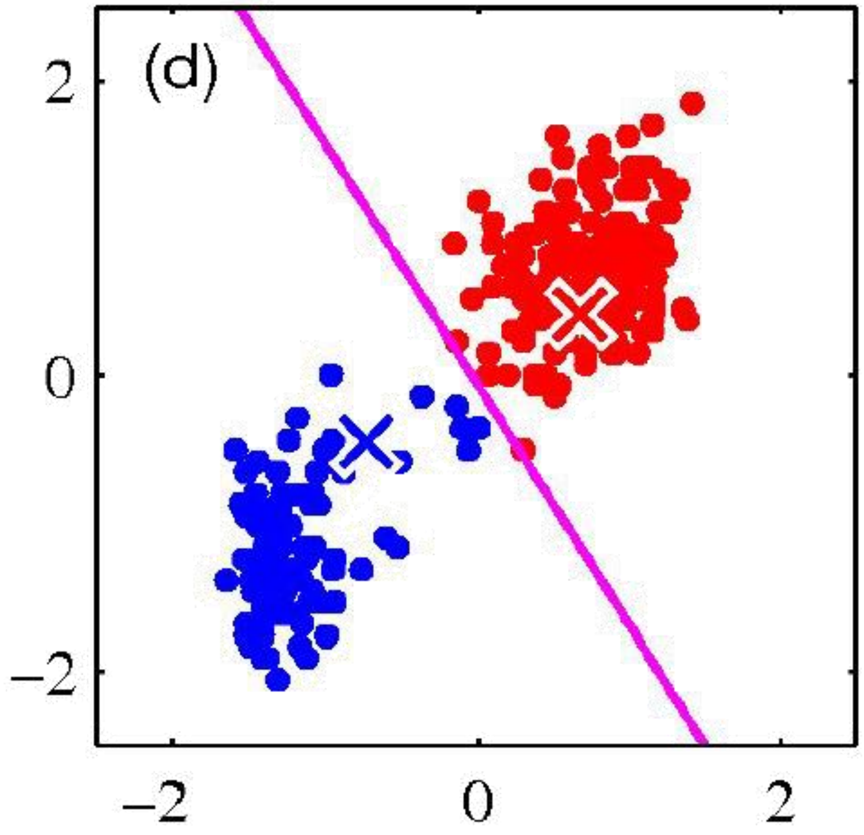
Example (cont.)

- Iterative step 2
- Change the cluster center to the average of the assigned points



Example (cont.)

- Repeat until convergence
- Convergence means that the differences of the center positions in two continuous loops is smaller than a threshold



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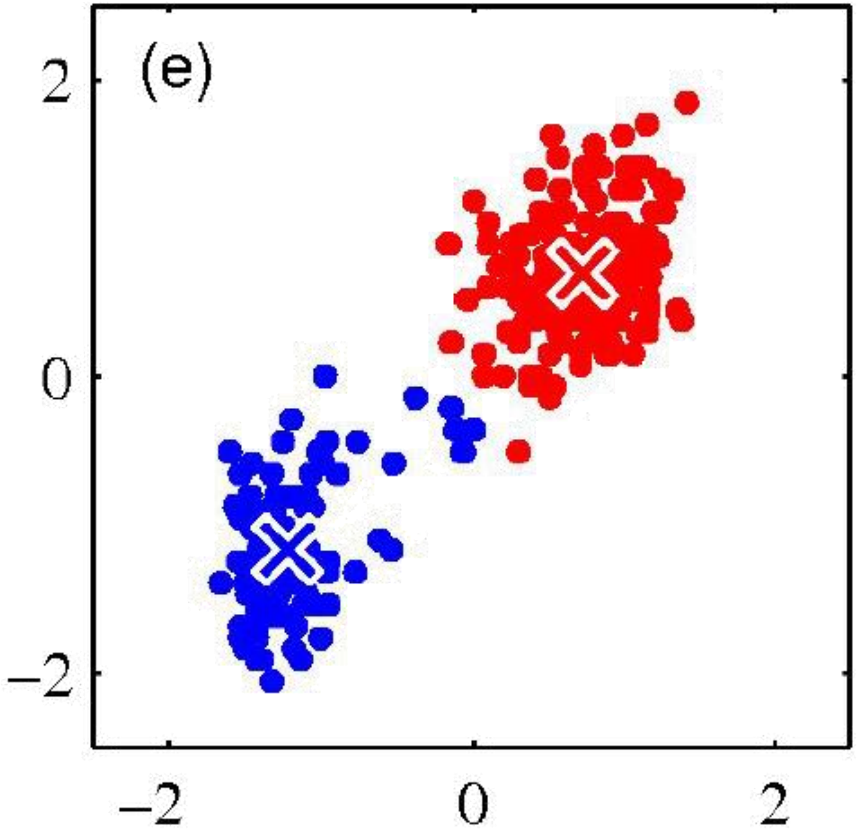

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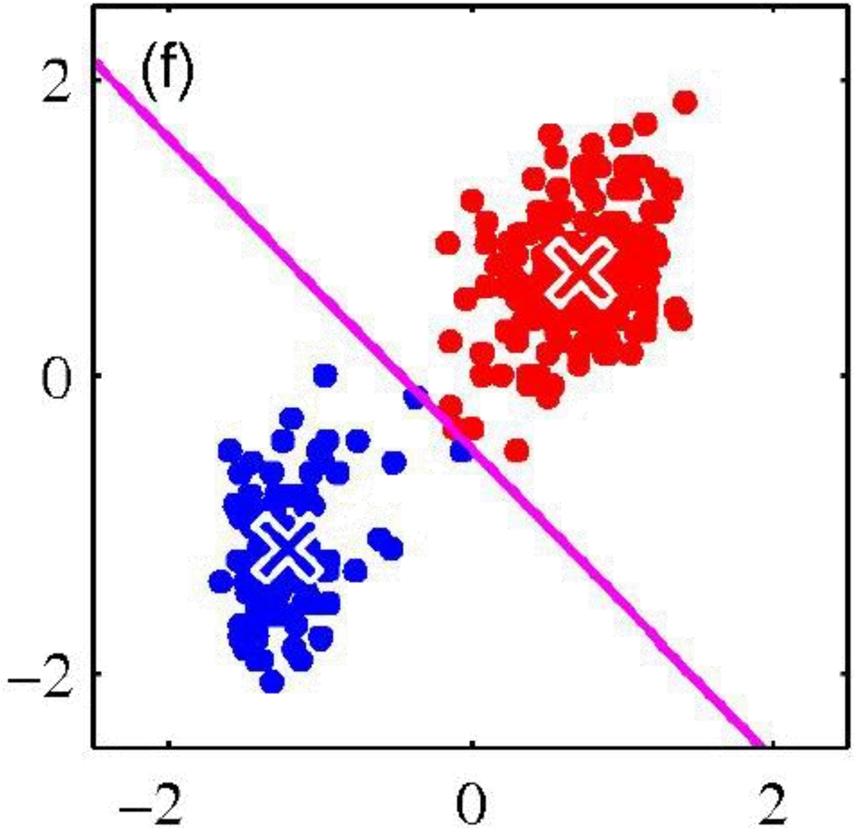
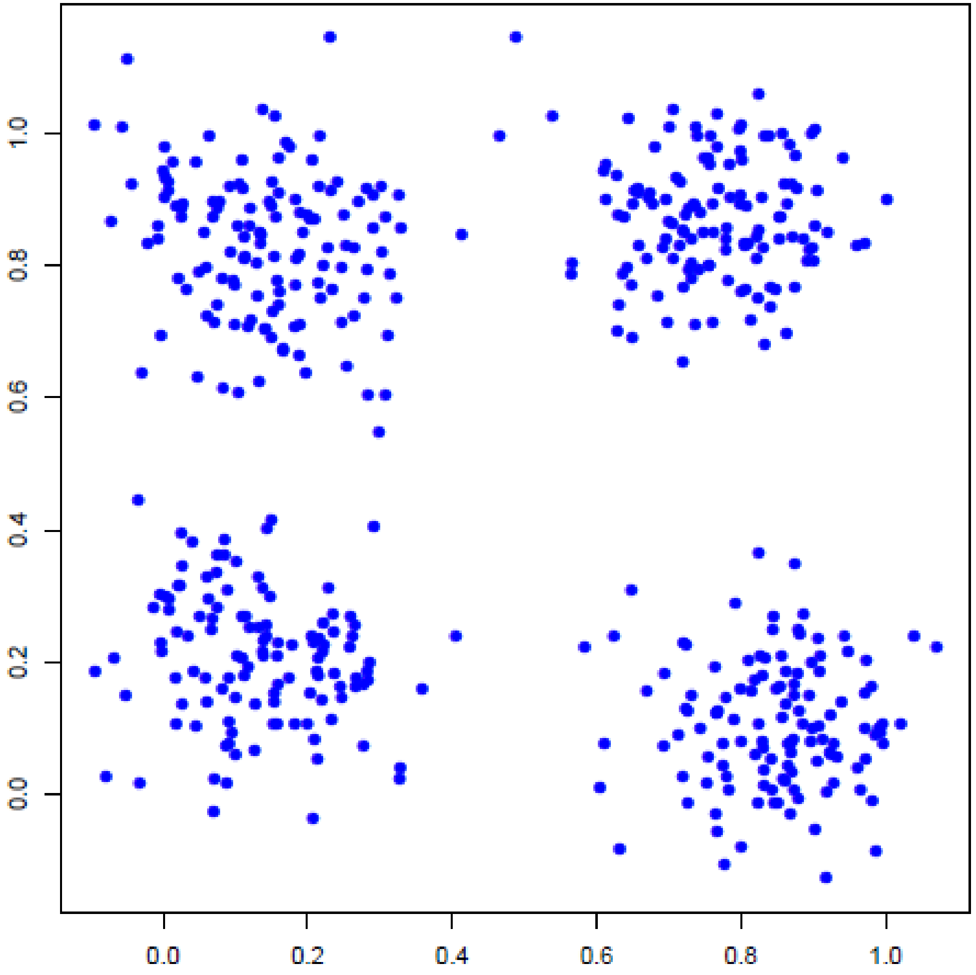


Example 2

- $K = 4$



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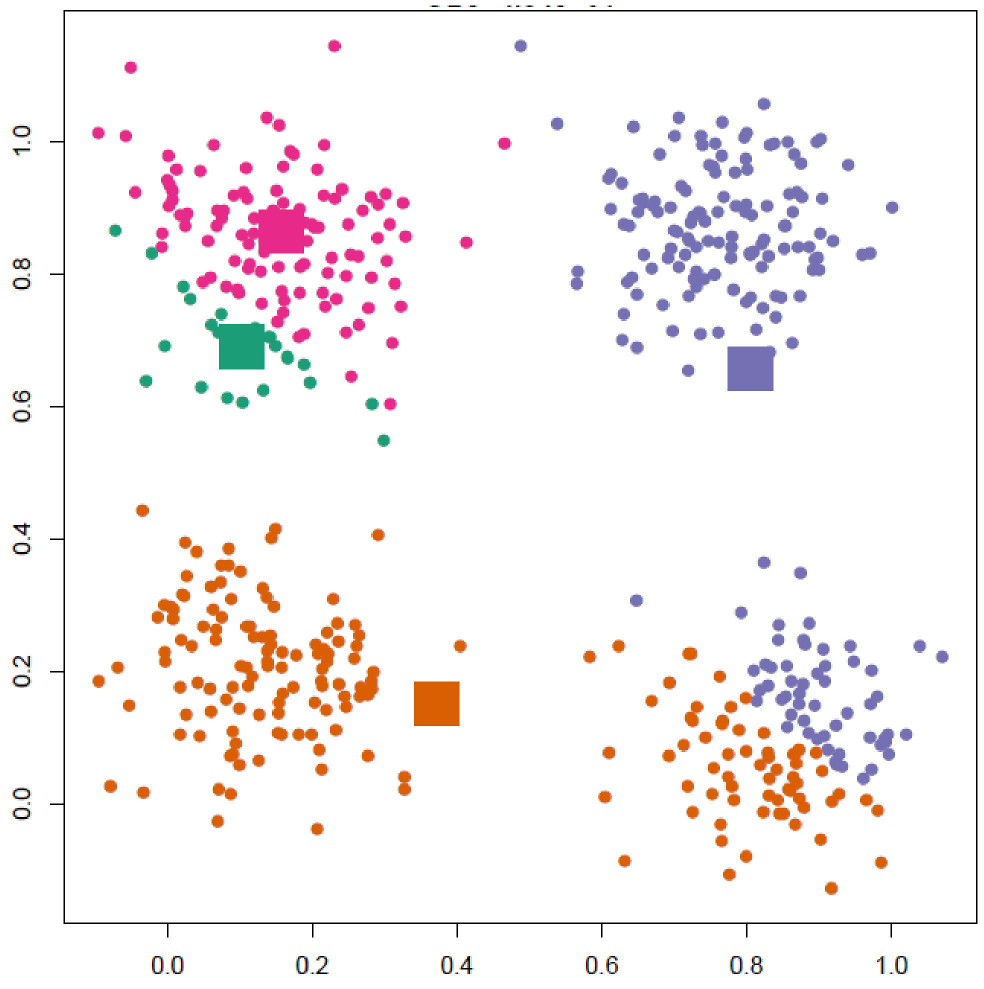

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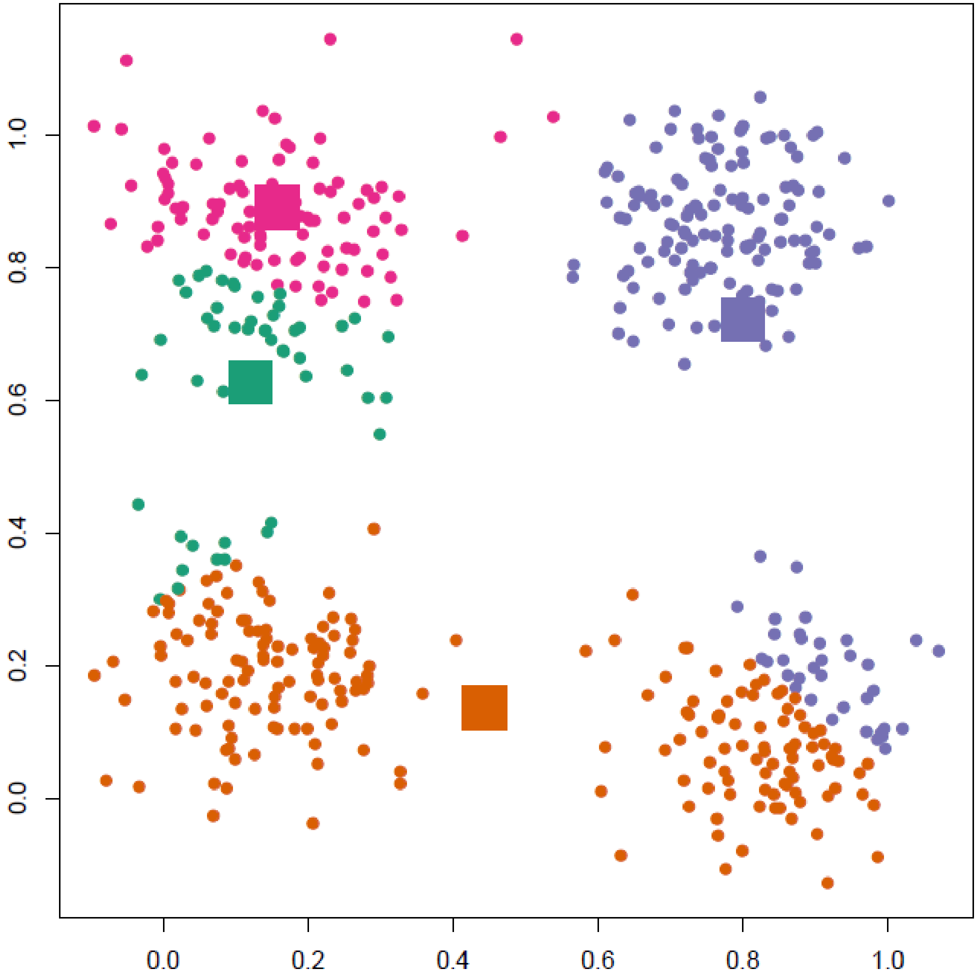

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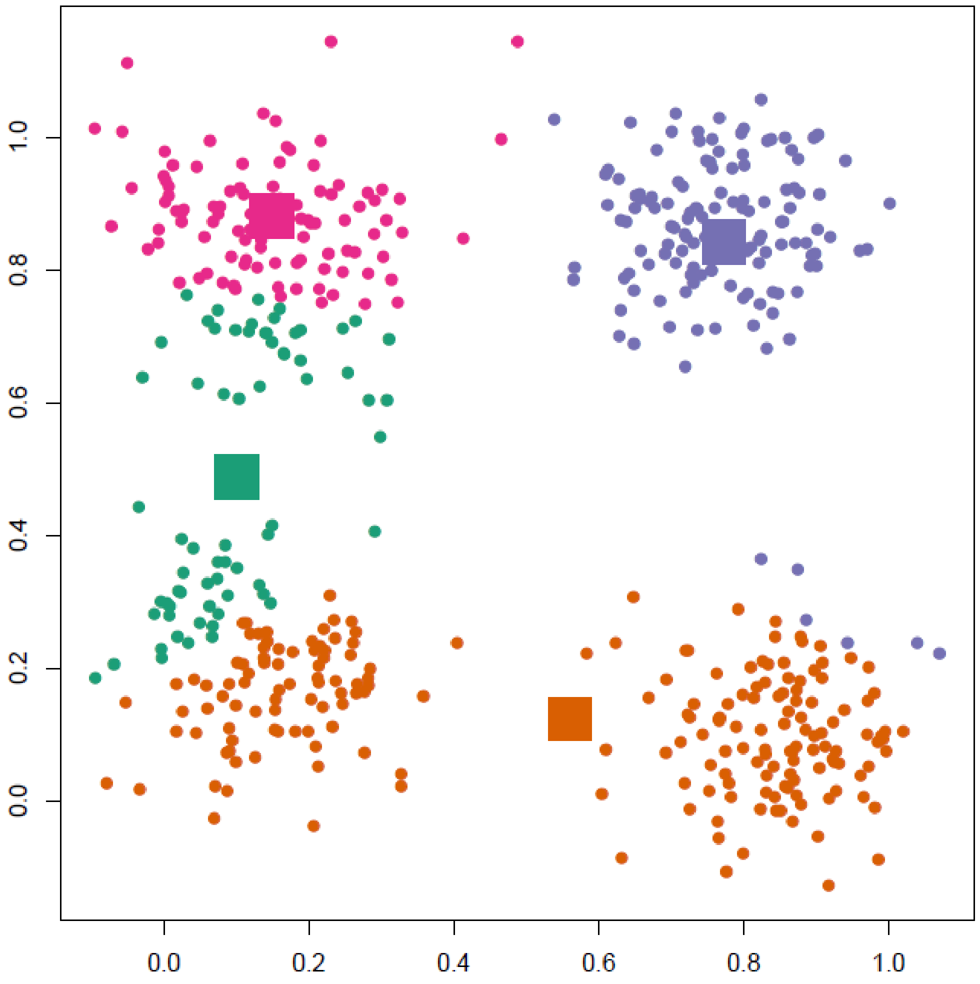

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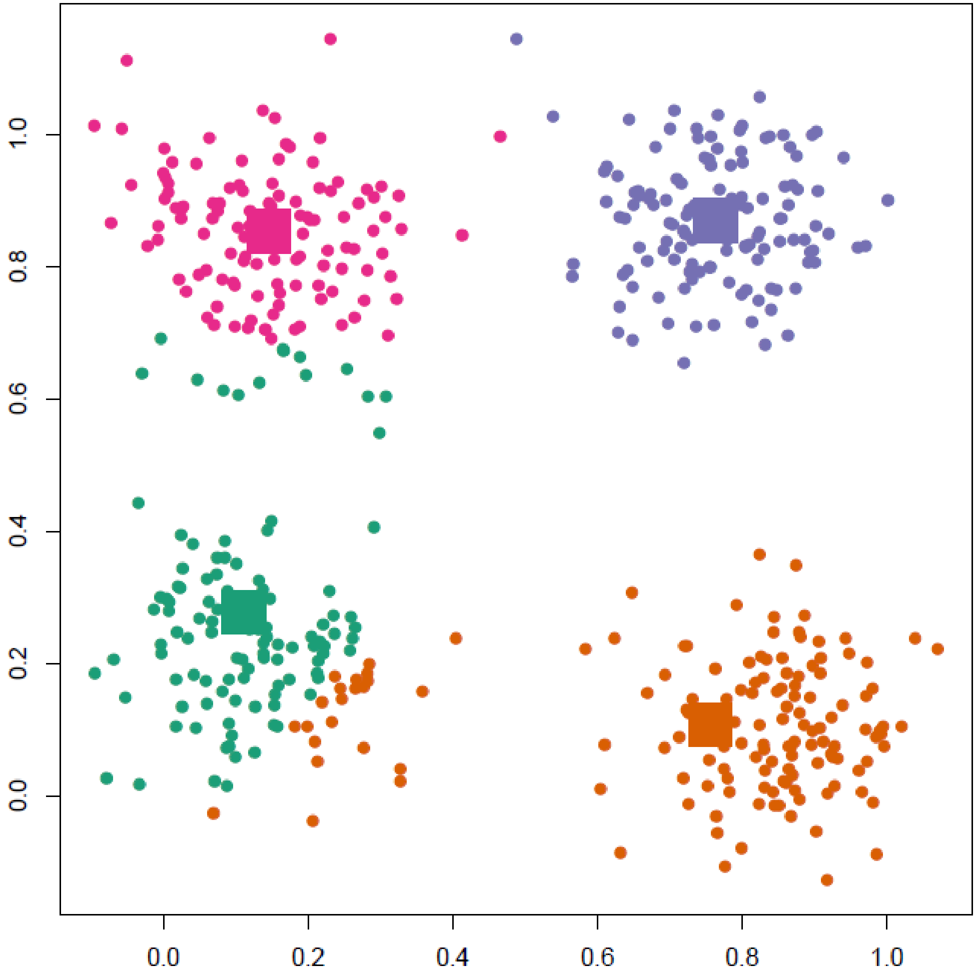

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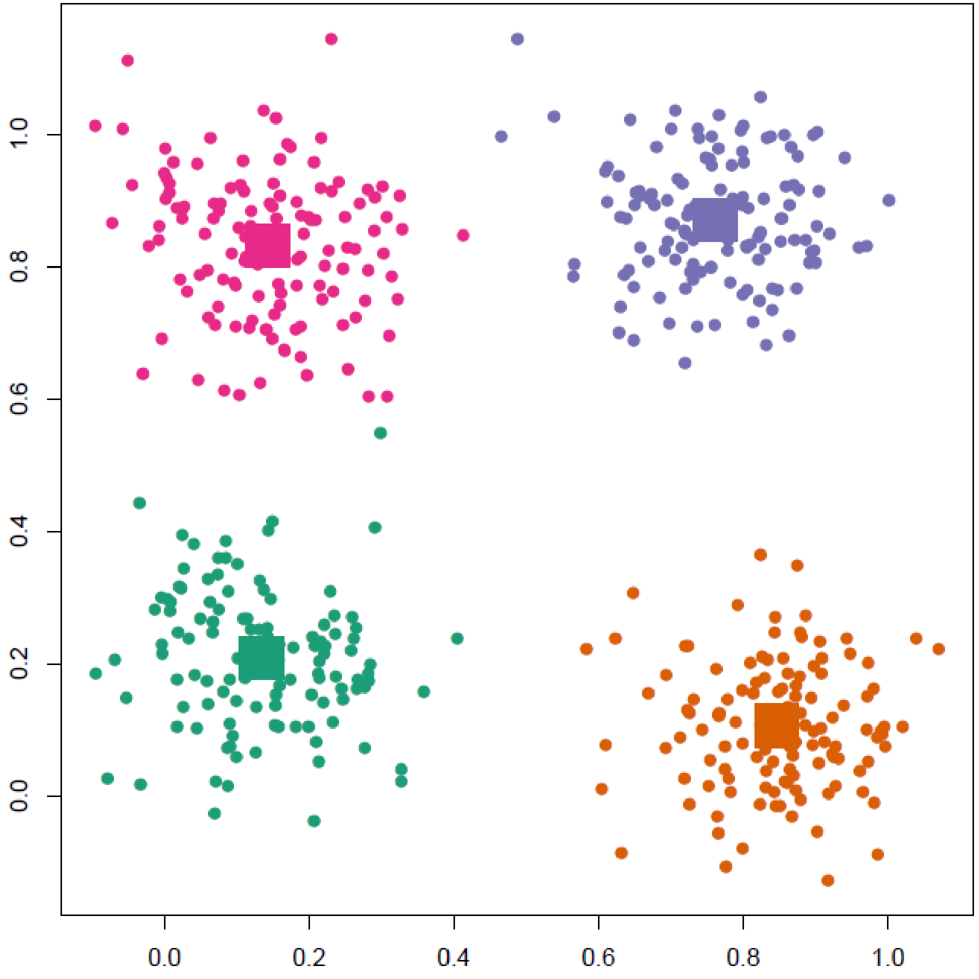


Remained Questions in K-Means

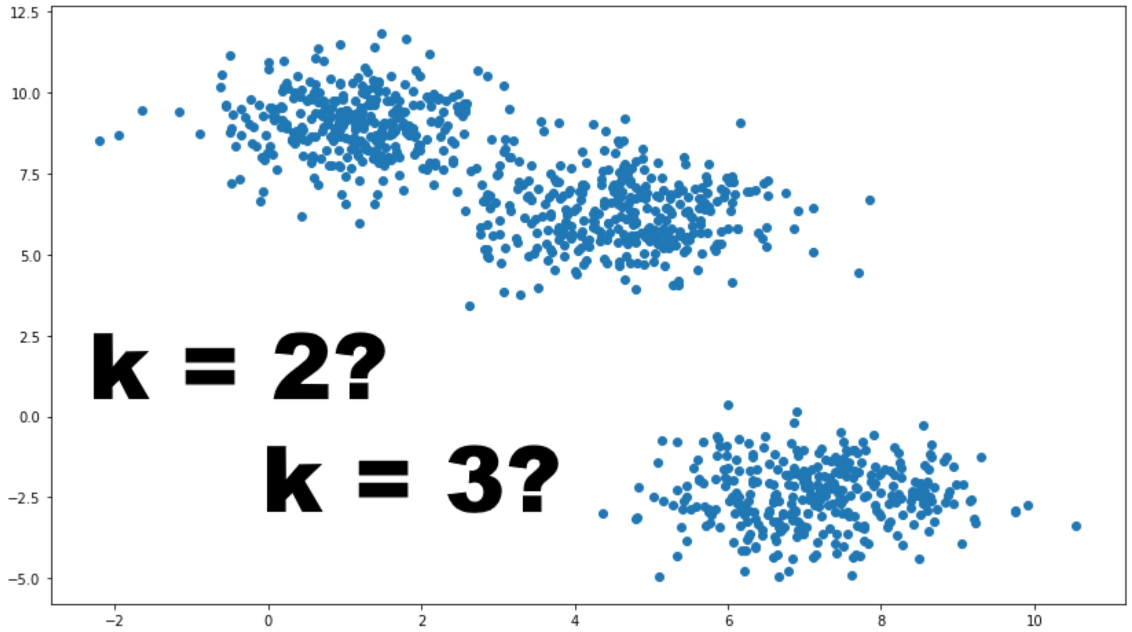
Remained questions in K-means

- Although the workflow of K-means is straight forward, there are some important questions that need to be discussed

- How to choose the hyper-parameter K?
- How to initialize?

How to choose K?

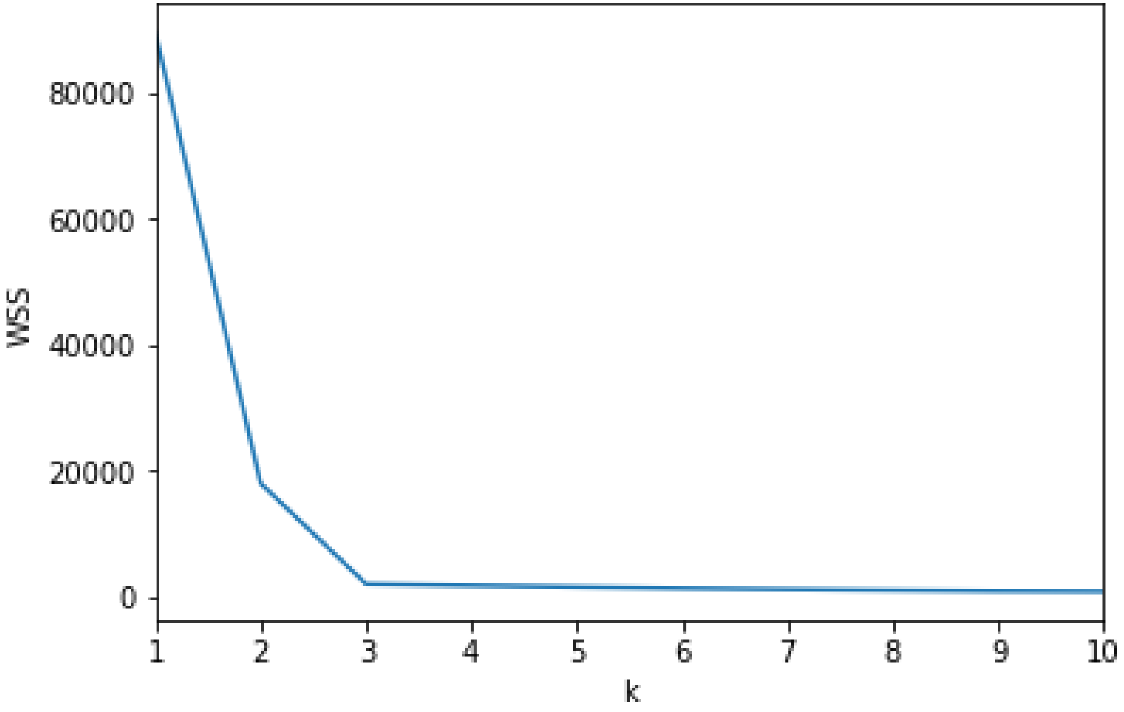
- K is the most important hyper-parameter in K-means which strongly affects its performance. In some situation, it's not an easy task to find the proper K
- The solution includes:
  - The elbow method
  - The silhouette method



The elbow method

- Calculate the Within-Cluster-Sum of Squared Errors (WSS) for different values of K, and choose the K ***for which WSS stops dropping significantly***. In the plot of WSS-versus-k, this is visible as an elbow

- Example: $K = 3$



The silhouette method

- The problem of the elbow method is that in many situations the most suitable K cannot be unambiguously identified. So we need the silhouette method

- The silhouette value measures how similar a point is to its own cluster (cohesion) compared to other clusters (separation). The range of the silhouette value is between +1 and -1. A high value is desirable and indicates that the point is placed in the correct cluster

The silhouette method (cont.)

- For each data point $i \in C_k$, let $a(i)$ be its mean distance to all other points in the same cluster

$$a(i) = \frac{1}{|C_k| - 1} \sum_{j \in C_k, i \neq j} d(i, j)$$

- And let $b(i)$ be the smallest mean distance to other clusters

$$b(i) = \min_{l \neq k} \frac{1}{|C_l|} \sum_{j \in C_l} d(i, j)$$

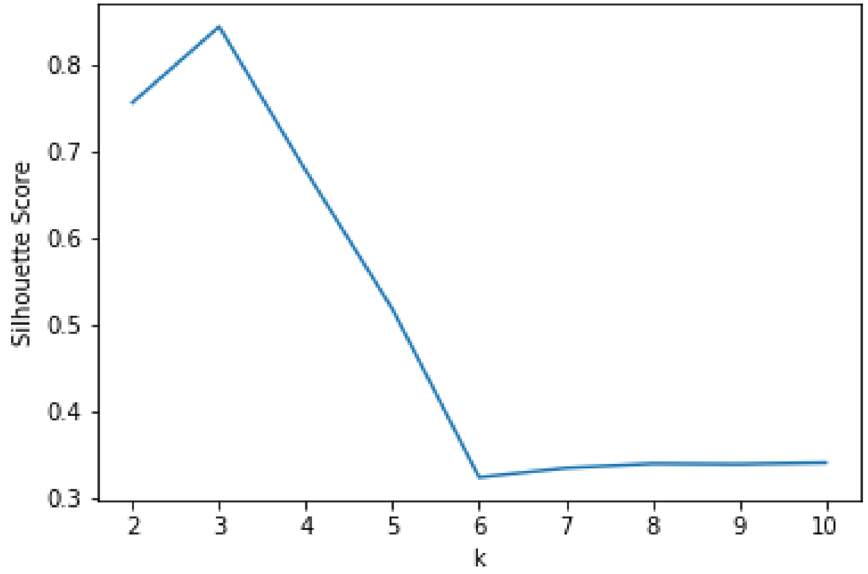
The silhouette method (cont.)

- The silhouette value is defined as:

$$s(i) = \frac{b(i) - a(i)}{\max\{a(i), b(i)\}}, \text{ if } |C_i| > 1$$

- And $s(i) = 0$, if $|C_i| = 1$

- Choose the k where the silhouette value is maximized



How to initialize center positions?

- The positions of the centers in the stage of initialization are also very important in K-means algorithms. In some situations it can produce totally different clustering results
- Example:

How to initialize center positions? (cont.)

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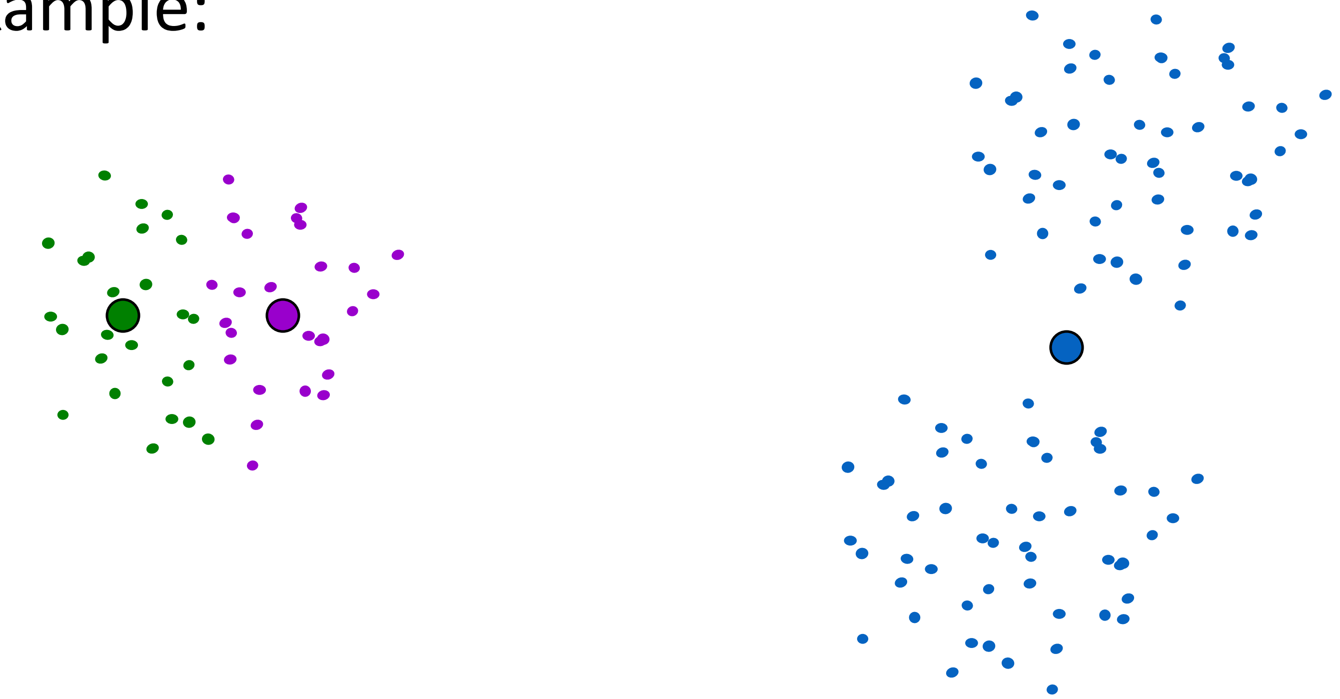
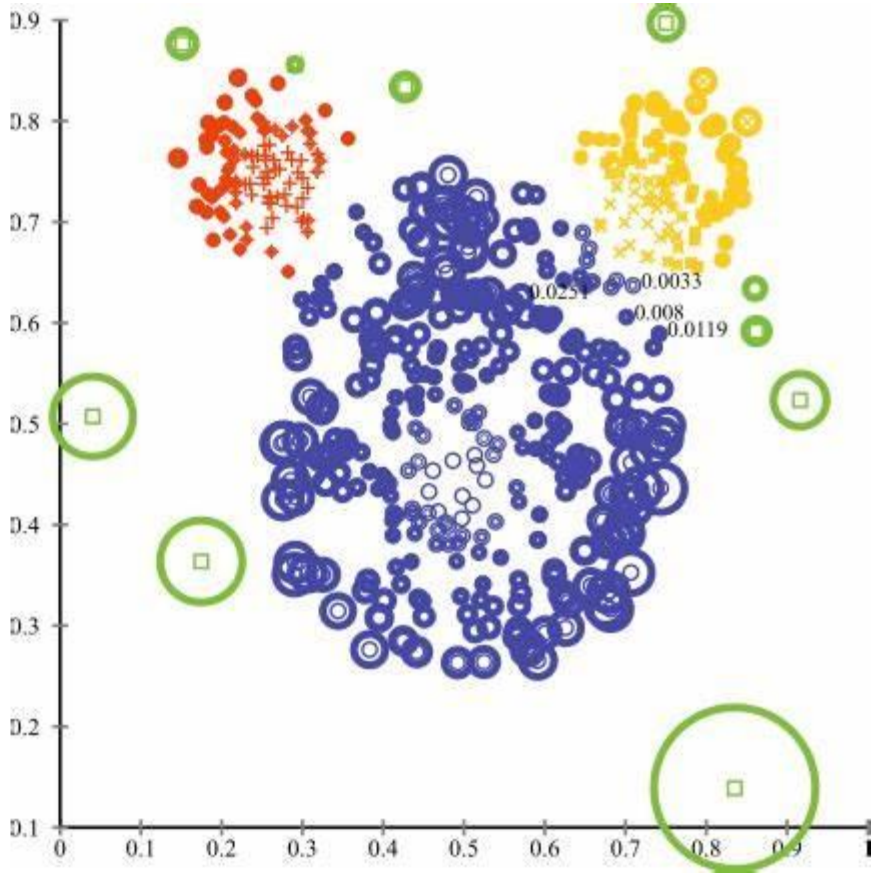
- Example:



A possible solution

- Pick one point at random, then $K - 1$ other points, each as far away as possible from the previous points
  - OK, as long as there are no *outliers* (points that are far from any reasonable cluster)



K-means++

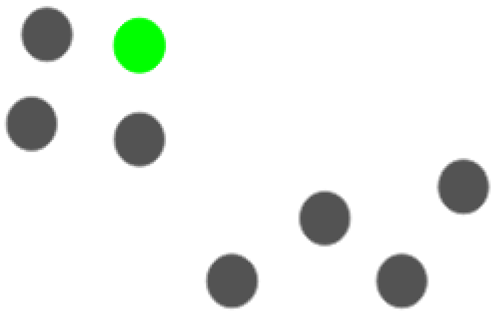
1. The first centroid is chosen uniformly at random from the data points that we want to cluster. This is similar to what we do in K-Means, but instead of randomly picking all the centroids, we just pick one centroid here
2. Next, we compute the distance d_x is the nearest distance from data point x to the centroids that have already been chosen
3. Then, choose the new cluster center from the data points with the probability of x being proportional to d_x^2
4. We then repeat steps 2 and 3 until K clusters have been chosen

Example

- Suppose we have the following points and we want to make 3 clusters here:

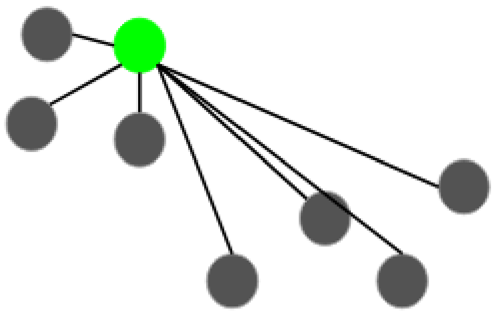
Example (cont.)

- First step is to randomly pick a data point as a cluster centroid:



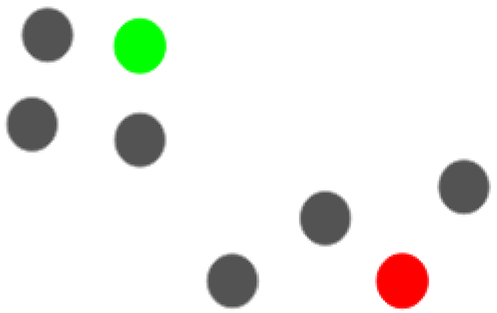
Example (cont.)

- Calculate the distance d_x of each data point with this centroid:



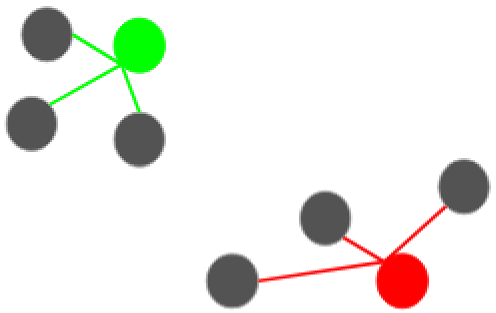
Example (cont.)

- The next centroid will be sampled with the probability proportional to d_x^2
- Say the sampled is the red one



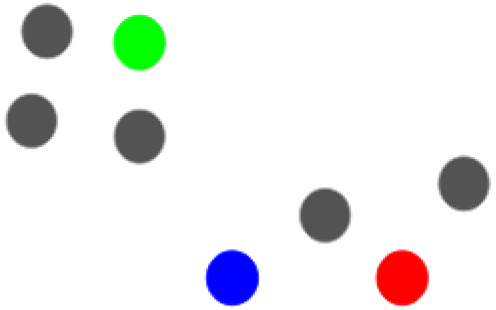
Example (cont.)

- To select the last centroid, compute d_x, which is the distance to its closest centroid



Example (cont.)

- Sample the one with the probability proportional to d_x^2
- Say, the blue one



Properties of K-Means

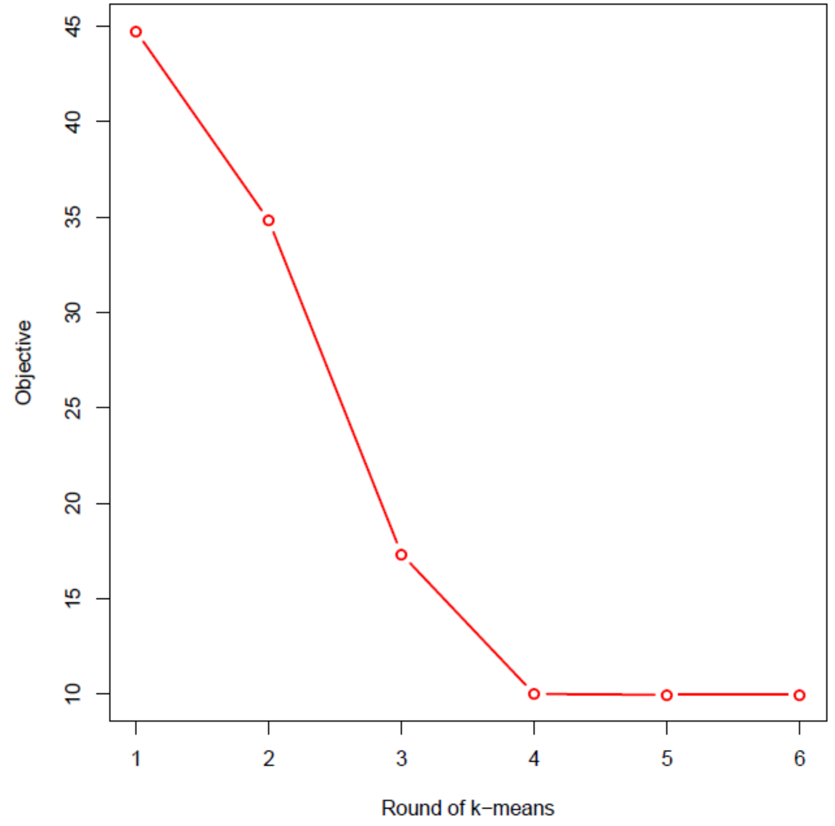
How to measure the performance

- K-means can be evaluated by the sum of distance from points to corresponding centers

number of clusters   number of cases   centroid for cluster *j*

case *i*

objective function $\leftarrow$ $$J = \sum_{j=1}^{k}\sum_{i=1}^{n}\underbrace{\left\| x_i^{(j)} - c_j \right\|^2}_{\text{Distance function}}$$



- The loss will become zero when increase K

Properties of the K-means algorithm

- Guaranteed to converge in a finite number of iterations

- Running time per iteration:
    1. Assign data points to closest cluster center
       O(KN) time
    2. Change the cluster center to the average of its assigned points
       O(N)

Distance

- Distance is of crucial importance in K-means. So what kind of properties should the distance measure have?

- Symmetric
  - $D(A,B) = D(B,A)$

- Positivity, and self-similarity
  - $D(A,B) \geq 0$, and $D(A,B) = 0$ iff $A = B$

- Triangle inequality
  - $D(A,B) + D(B,C) \geq D(A,C)$

Convergence of K-means

Objective

$$\min_{\mu}\min_{C}\sum_{i=1}^{k}\sum_{x\in C_i}|x-\mu_i|^2$$

1. Fix μ, optimize C:

Step 1 of kmeans

$$\min_{C}\sum_{i=1}^{k}\sum_{x\in C_i}|x-\mu_i|^2=\min_{c}\sum_{i}^{n}\left|x_i-\mu_{x_i}\right|^2$$

2. Fix C, optimize μ:

$$\min_{\mu}\sum_{i=1}^{k}\sum_{x\in C_i}|x-\mu_i|^2$$

   – Take partial derivative of μ_i and set to zero, we have

$$\mu_i=\frac{1}{|C_i|}\sum_{x\in C_i}x$$

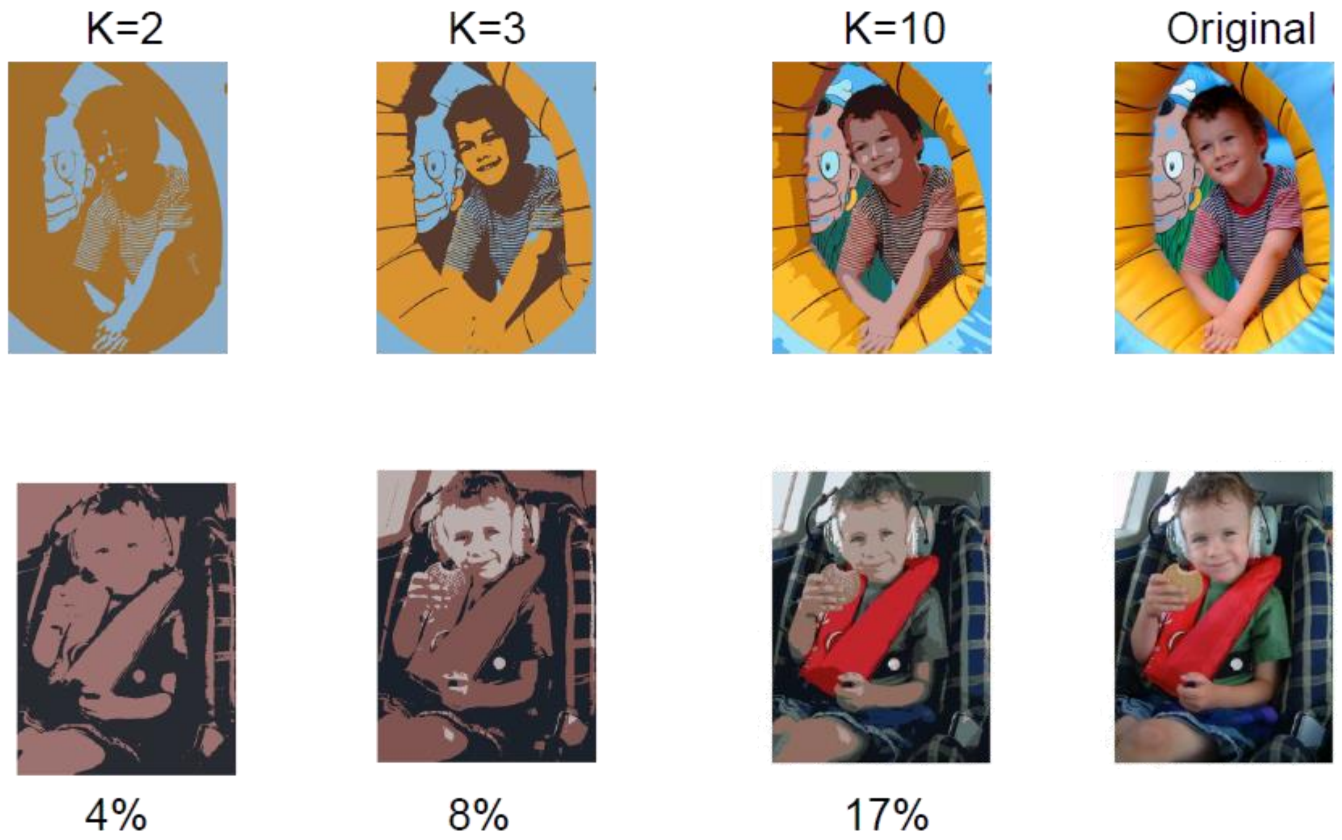
Step 2 of kmeans

Not guaranteed to converge to optimal

Kmeans takes an alternating optimization approach, each step is guaranteed to decrease the objective – thus guaranteed to converge

Application: Segmentation

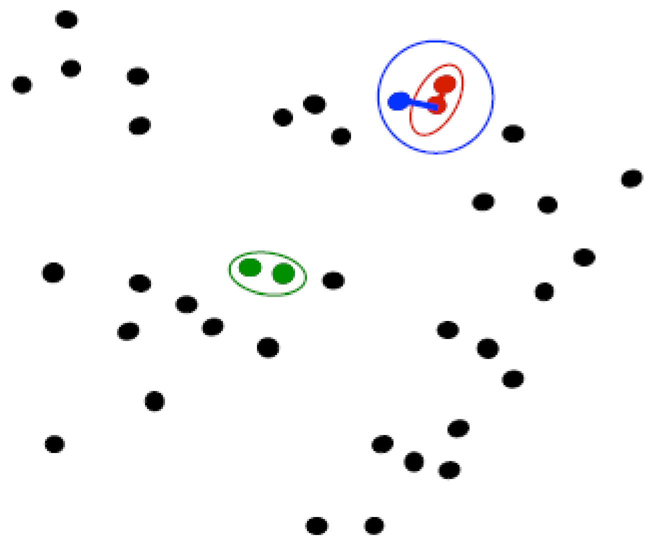
- Goal of segmentation is to partition an image into regions each of which has reasonably homogenous visual appearance
- Cluster the colors



Agglomerative Clustering

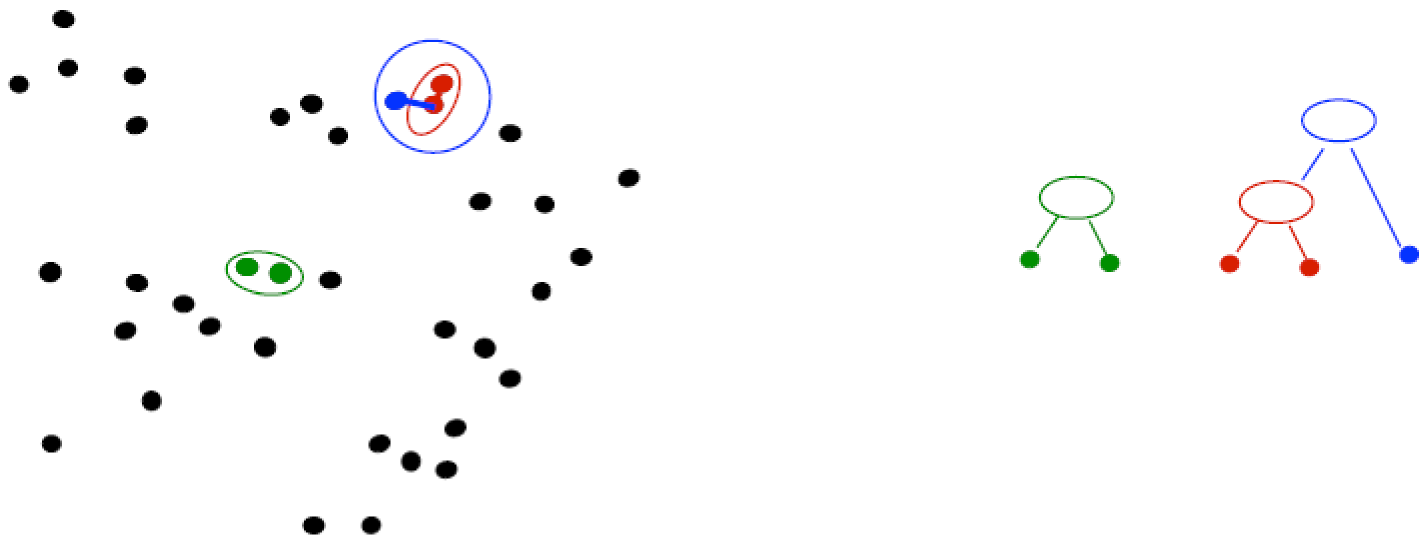
Agglomerative clustering

- Agglomerative clustering:
  - First merge very similar instances
  - Incrementally build larger clusters out of smaller clusters
- Algorithm:
  - Maintain a set of clusters
  - Initially, each instance in its own cluster
  - Repeat:
    - Pick the two closest clusters
    - Merge them into a new cluster
    - Stop when there's only one cluster left



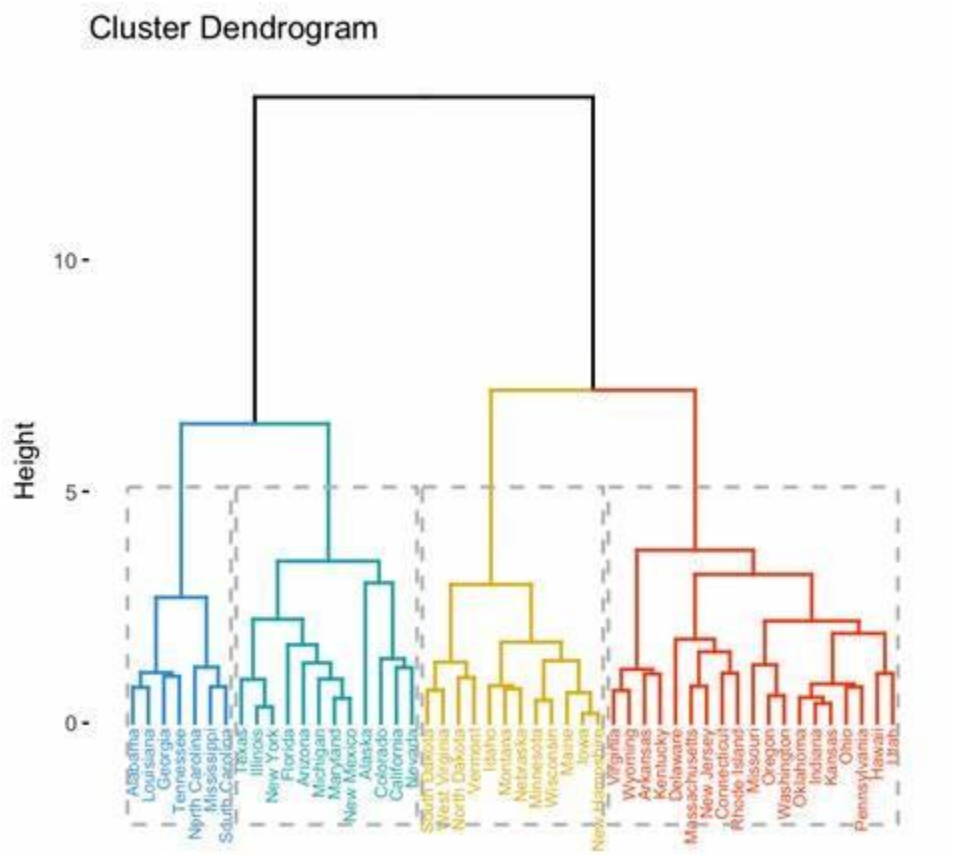
Agglomerative Clustering

- Produces not one clustering, but a family of clusterings represented by a dendrogram



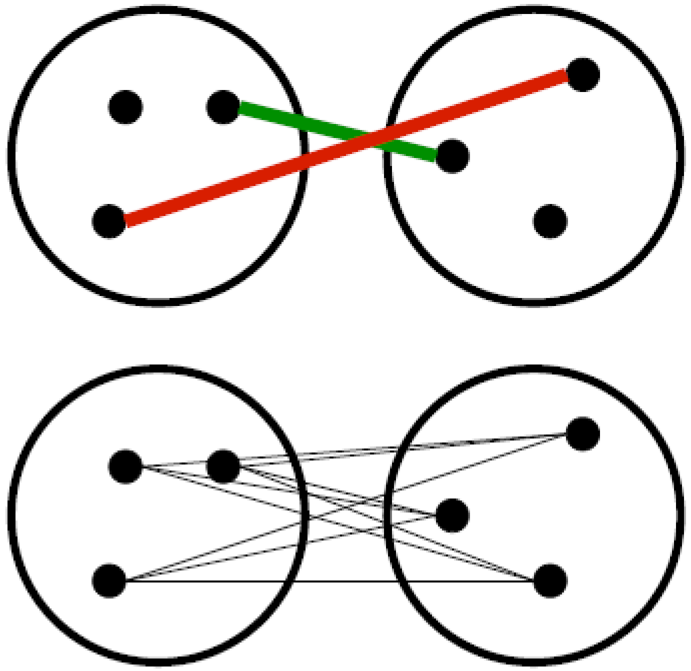
Example

- Different heights give different clustering



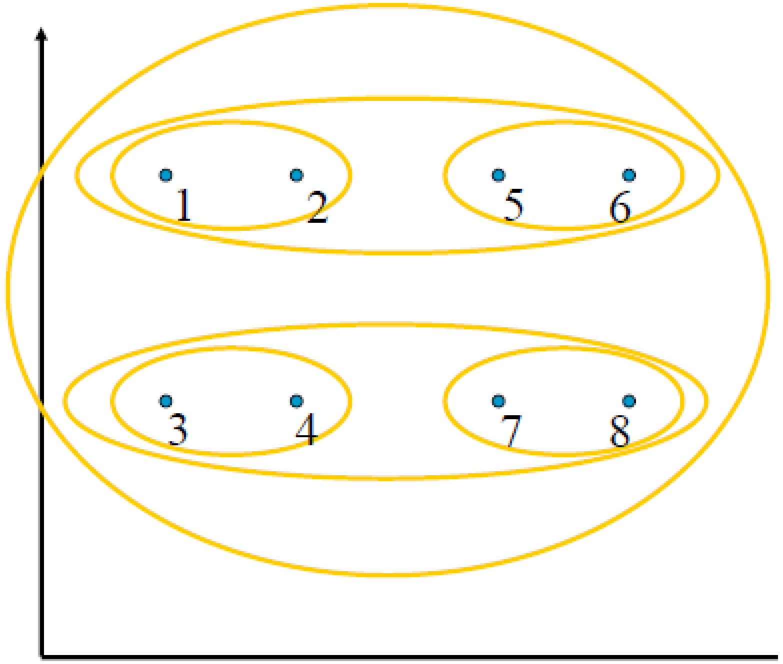
Closeness

- How should we define “closest” for clusters with multiple elements?
- Many options:
  - Closest pair (single-link clustering)
  - Farthest pair (complete-link clustering)
  - Average of all pairs
- Different choices create different clustering behaviors

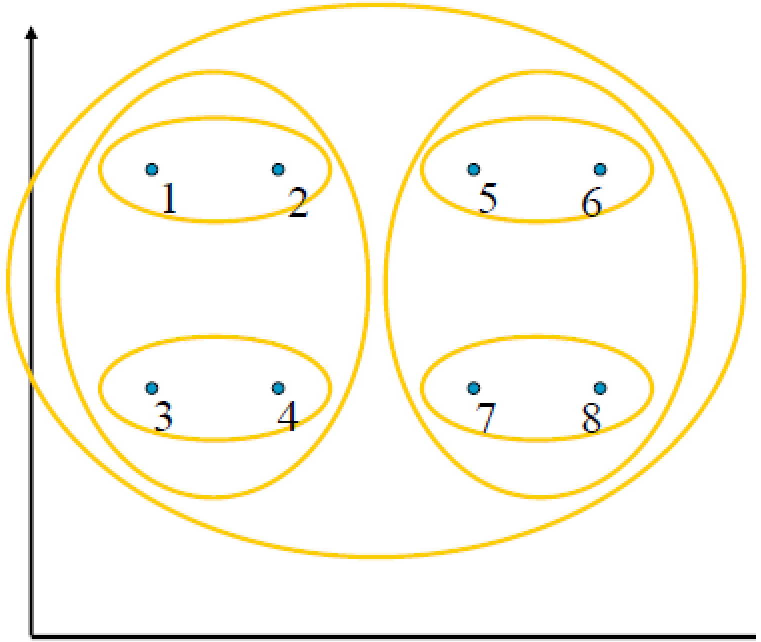


Closeness example

Closest pair
(single-link clustering)



Farthest pair
(complete-link clustering)



Closeness example 2