
Chapter 4: Unsupervised Learning

Most slides courtesy Bing Liu

Road map

- **Basic concepts**
- **K-means algorithm**
- **Representation of clusters**
- **Hierarchical clustering**
- **Distance functions**
- **Data standardization**
- **Handling mixed attributes**
- **Which clustering algorithm to use?**
- **Cluster evaluation**
- **Discovering holes and data regions**
- **Summary**

Supervised learning vs. unsupervised learning

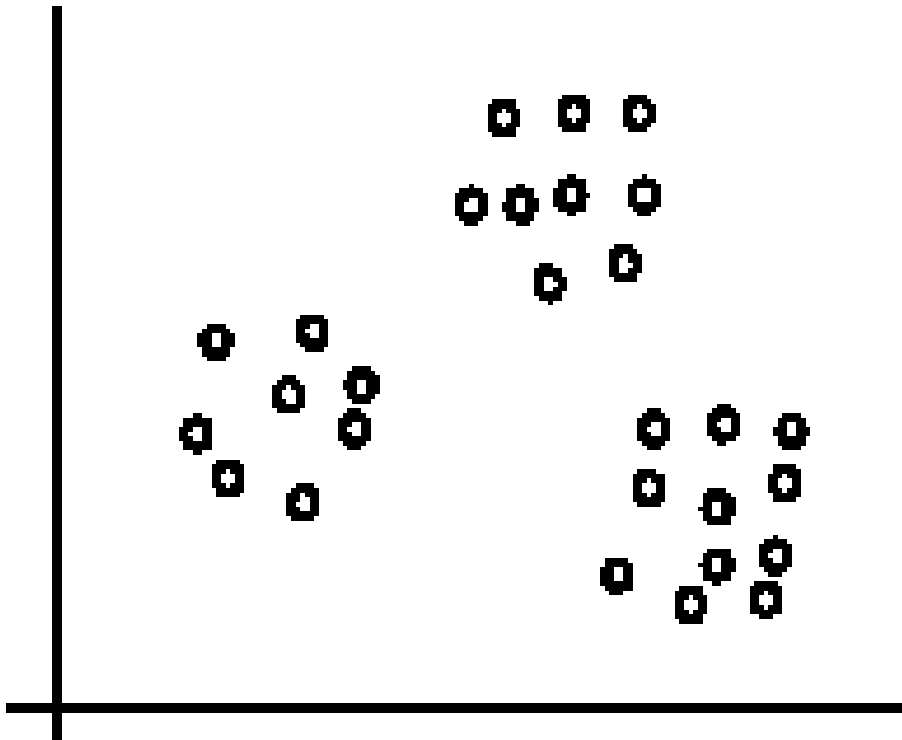
- **Supervised learning:** discover patterns in the data that relate data attributes with a target (class) attribute.
 - These patterns are then utilized to predict the values of the target attribute in future data instances.
- **Unsupervised learning:** The data have no target attribute.
 - We want to explore the data to find some intrinsic structures in them.

Clustering

- Clustering is a technique for finding **similarity groups** in data, called **clusters**. I.e.,
 - it groups data instances that are similar to (near) each other in one cluster and data instances that are very different (far away) from each other into different clusters.
- Clustering is often called an **unsupervised learning** task as no class values denoting an *a priori* grouping of the data instances are given, which is the case in supervised learning.
- Due to historical reasons, clustering is often considered synonymous with unsupervised learning.
 - In fact, association rule mining is also unsupervised
- This chapter focuses on clustering.

An illustration

- The data set has three natural groups of data points, i.e., 3 natural clusters.



What is clustering for?

- Let us see some real-life examples
- **Example 1:** groups people of similar sizes together to make “small”, “medium” and “large” T-Shirts.
 - Tailor-made for each person: too expensive
 - One-size-fits-all: does not fit all.
- **Example 2:** In marketing, segment customers according to their similarities
 - To do targeted marketing.

What is clustering for? (cont...)

- **Example 3:** Given a collection of text documents, we want to organize them according to their content similarities
 - To produce a topic hierarchy
- **In fact, clustering is one of the most utilized data mining techniques.**
 - It has a long history, and used in almost every field, e.g., medicine, psychology, sociology, biology, archeology, marketing, insurance, libraries, etc.
 - In recent years, due to the rapid increase of online documents, text clustering becomes important.

Aspects of clustering

- **A clustering algorithm**
 - Partitional clustering
 - Hierarchical clustering
 - ...
- **A distance (similarity, or dissimilarity) function**
- **Clustering quality**
 - Inter-clusters distance \Rightarrow maximized
 - Intra-clusters distance \Rightarrow minimized
- The **quality** of a clustering result depends on the algorithm, the distance function, and the application.

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K-means clustering

- K-means is a **partitional clustering** algorithm
- Let the set of data points (or instances) D be $\{\mathbf{x}_1, \mathbf{x}_2, \dots, \mathbf{x}_n\}$,
where $\mathbf{x}_i = (x_{i1}, x_{i2}, \dots, x_{ir})$ is a **vector** in a real-valued space $X \subseteq R^r$, and r is the number of attributes (dimensions) in the data.
- The k -means algorithm partitions the given data into k clusters.
 - Each cluster has a cluster **center**, called **centroid**.
 - k is specified by the user

K-means algorithm

- Given k , the *k-means* algorithm works as follows:
 - 1) Randomly choose k data points (**seeds**) to be the initial **centroids**, cluster centers
 - 2) Assign each data point to the closest **centroid**
 - 3) Re-compute the **centroids** using the current cluster memberships.
 - 4) If a convergence criterion is not met, go to 2).

K-means algorithm – (cont ...)

Algorithm k -means(k, D)

- 1 Choose k data points as the initial centroids (cluster centers)
- 2 **repeat**
- 3 **for** each data point $\mathbf{x} \in D$ **do**
- 4 compute the distance from \mathbf{x} to each centroid;
- 5 assign \mathbf{x} to the closest centroid // a centroid represents a cluster
- 6 **endfor**
- 7 re-compute the centroids using the current cluster memberships
- 8 **until** the stopping criterion is met

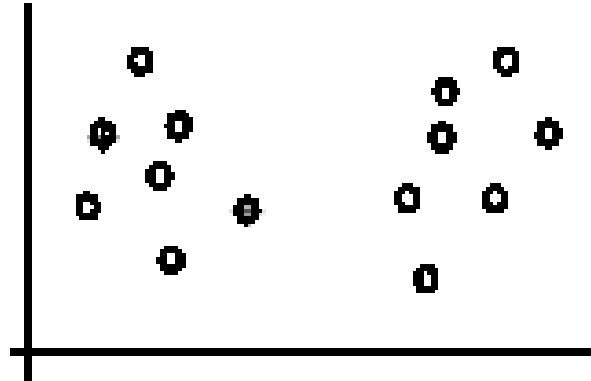
Stopping/convergence criterion

1. no (or minimum) re-assignments of data points to different clusters,
2. no (or minimum) change of centroids, or
3. minimum decrease in the **sum of squared error (SSE)**,

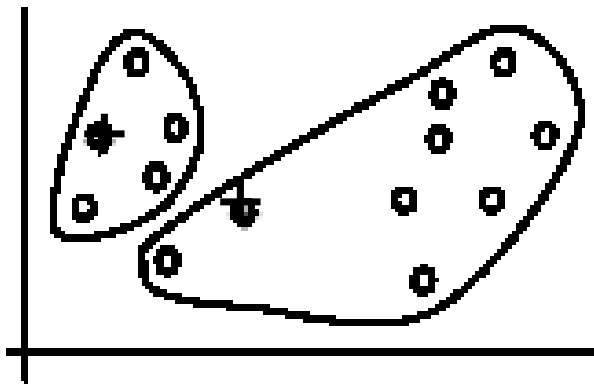
$$SSE = \sum_{j=1}^k \sum_{\mathbf{x} \in C_j} \text{dist}(\mathbf{x}, \mathbf{m}_j)^2 \quad (1)$$

- C_j is the j th cluster, \mathbf{m}_j is the centroid of cluster C_j (the mean vector of all the data points in C_j), and $\text{dist}(\mathbf{x}, \mathbf{m}_j)$ is the distance between data point \mathbf{x} and centroid \mathbf{m}_j .

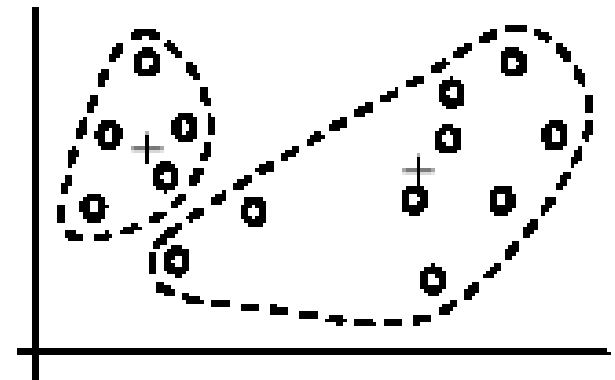
An example



(A). Random selection of k centers

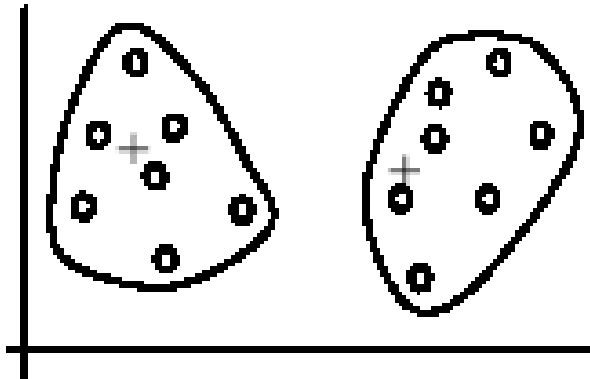


Iteration 1: (B). Cluster assignment

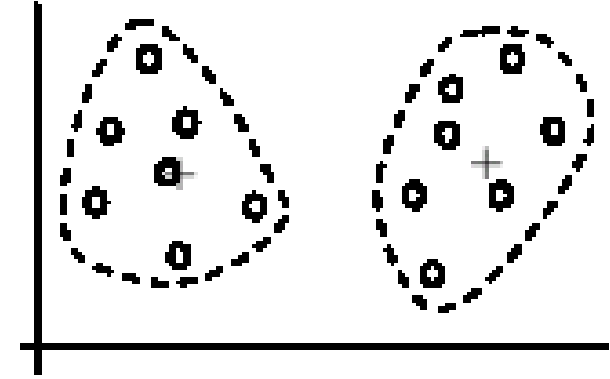


(C). Re-compute centroids

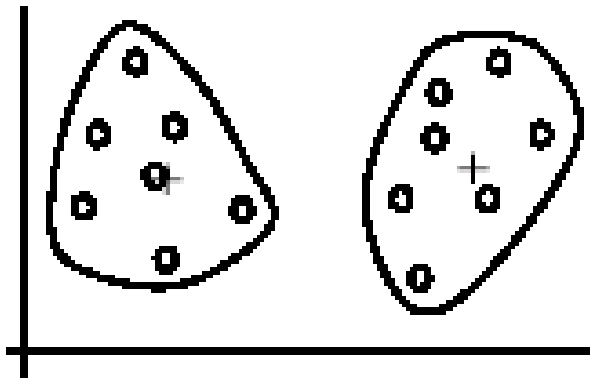
An example (cont ...)



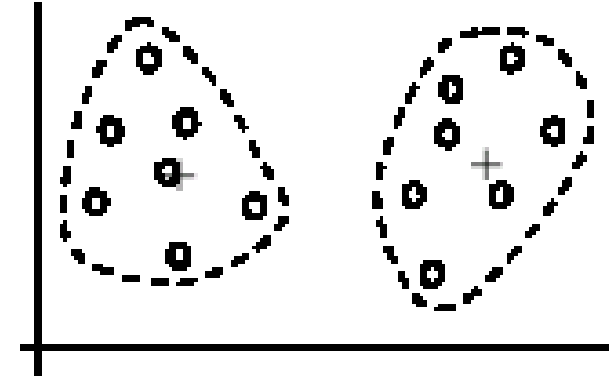
Iteration 2: (D). Cluster assignment



(E). Re-compute centroids



Iteration 3: (F). Cluster assignment



(G). Re-compute centroids

An example distance function

The k -means algorithm can be used for any application data set where the **mean** can be defined and computed. In the **Euclidean space**, the mean of a cluster is computed with:

$$\mathbf{m}_j = \frac{1}{|C_j|} \sum_{\mathbf{x}_i \in C_j} \mathbf{x}_i \quad (2)$$

where $|C_j|$ is the number of data points in cluster C_j . The distance from one data point \mathbf{x}_i to a mean (centroid) \mathbf{m}_j is computed with

$$\begin{aligned} \text{dist}(\mathbf{x}_i, \mathbf{m}_j) &= \|\mathbf{x}_i - \mathbf{m}_j\| \\ &= \sqrt{(x_{i1} - m_{j1})^2 + (x_{i2} - m_{j2})^2 + \dots + (x_{ir} - m_{jr})^2} \end{aligned} \quad (3)$$

A disk version of k -means

- K-means can be implemented with data on disk
 - In each iteration, it scans the data once.
 - as the centroids can be computed incrementally
- It can be used to cluster large datasets that do not fit in main memory
- We need to control the number of iterations
 - In practice, a limited is set (< 50).
- Not the best method. There are other scale-up algorithms, e.g., BIRCH.

A disk version of k-means (cont.)

Algorithm disk- k -means(k, D)

```
1  Choose  $k$  data points as the initial centroids  $\mathbf{m}_j, j = 1, \dots, k$ ;  
2  repeat  
3      initialize  $\mathbf{s}_j = \mathbf{0}, j = 1, \dots, k$ ;           //  $\mathbf{0}$  is a vector with all 0's  
4      initialize  $n_j = 0, j = 1, \dots, k$ ;           //  $n_j$  is the number points in cluster  $j$   
5      for each data point  $\mathbf{x} \in D$  do  
6           $j = \arg \min_j \text{dist}(\mathbf{x}, \mathbf{m}_j)$ ;  
7          assign  $\mathbf{x}$  to the cluster  $j$ ;  
8           $\mathbf{s}_j = \mathbf{s}_j + \mathbf{x}$ ;  
9           $n_j = n_j + 1$ ;  
10     endfor  
11      $\mathbf{m}_i = \mathbf{s}_j / n_j, i = 1, \dots, k$ ;  
12 until the stopping criterion is met
```

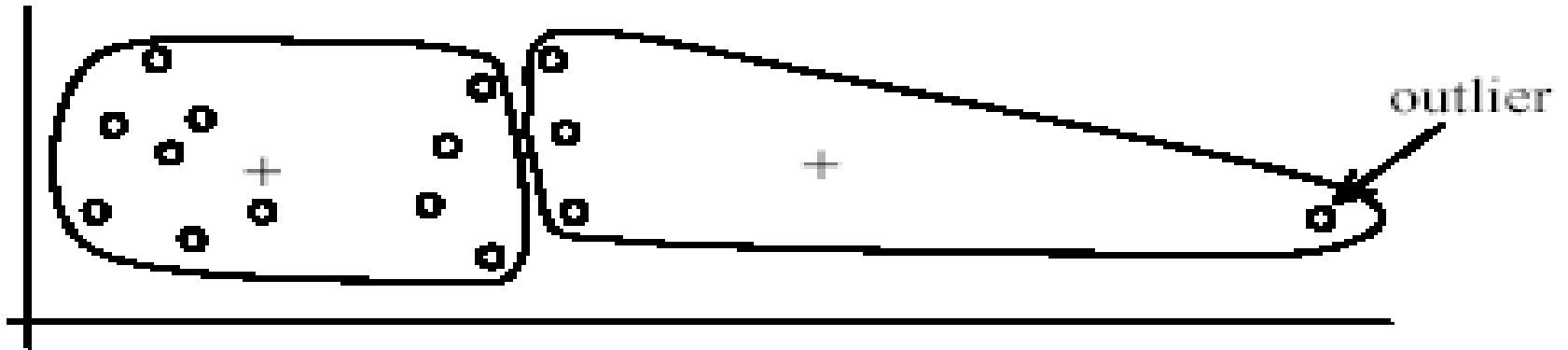
Strengths of k-means

- Strengths:
 - Simple: easy to understand and to implement
 - Efficient: Time complexity: $O(tkn)$, where n is the number of data points, k is the number of clusters, and t is the number of iterations.
 - Since both k and t are small, k -means is considered a linear algorithm.
- K-means is the most popular clustering algorithm.
- Note: it terminates at a **local optimum** if SSE is used. The **global optimum** is hard to find due to complexity.

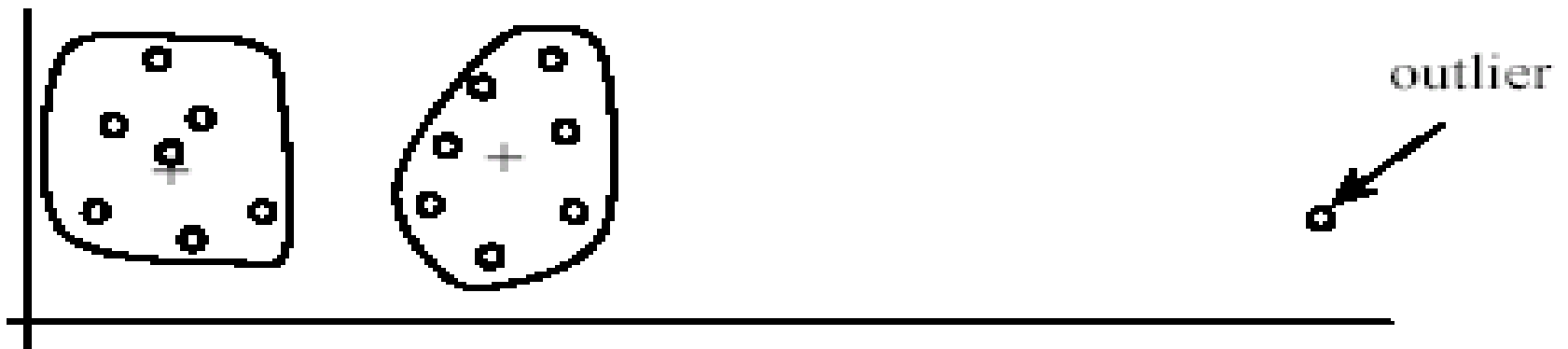
Weaknesses of k-means

- The algorithm is only applicable if the **mean** is defined.
 - For categorical data, *k*-mode - the centroid is represented by most frequent values.
- The user needs to specify *k*.
- The algorithm is sensitive to **outliers**
 - Outliers are data points that are very far away from other data points.
 - Outliers could be errors in the data recording or some special data points with very different values.

Weaknesses of k-means: Problems with outliers



(A): Undesirable clusters



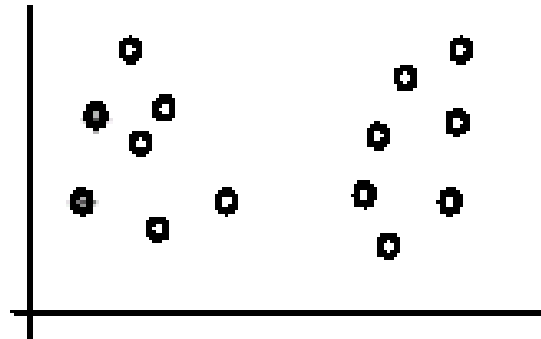
(B): Ideal clusters

Weaknesses of k-means: To deal with outliers

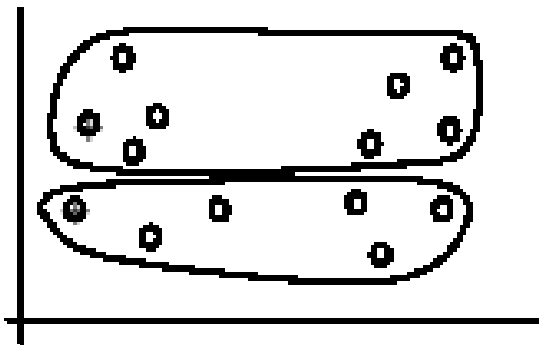
- One method is to remove some data points in the clustering process that are much further away from the centroids than other data points.
 - To be safe, we may want to monitor these possible outliers over a few iterations and then decide to remove them.
- Another method is to perform random sampling. Since in sampling we only choose a small subset of the data points, the chance of selecting an outlier is very small.
 - Assign the rest of the data points to the clusters by distance or similarity comparison, or classification

Weaknesses of k-means (cont.)

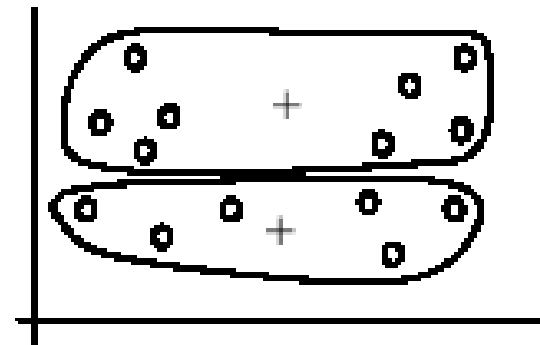
- The algorithm is sensitive to **initial seeds**.



(A). Random selection of seeds (centroids)



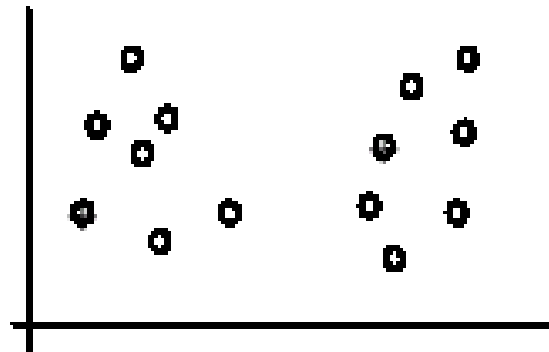
(B). Iteration 1



(C). Iteration 2

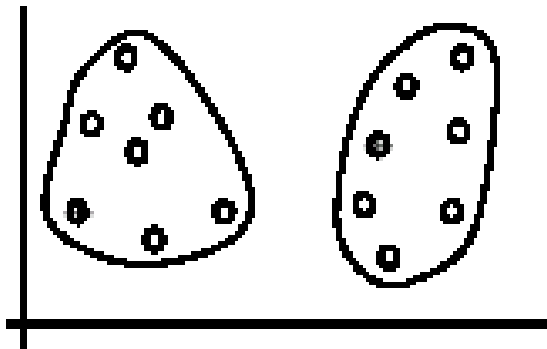
Weaknesses of k-means (cont.)

- If we use **different seeds**: good results

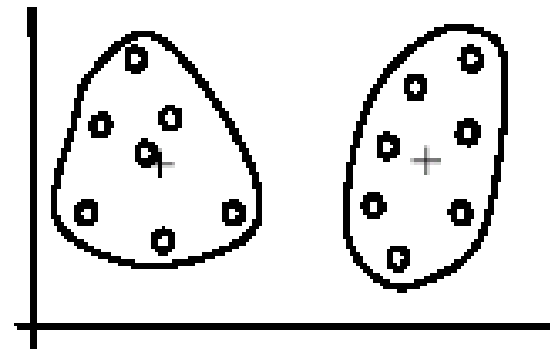


- There are some methods to help choose good seeds

(A). Random selection of k seeds (centroids)



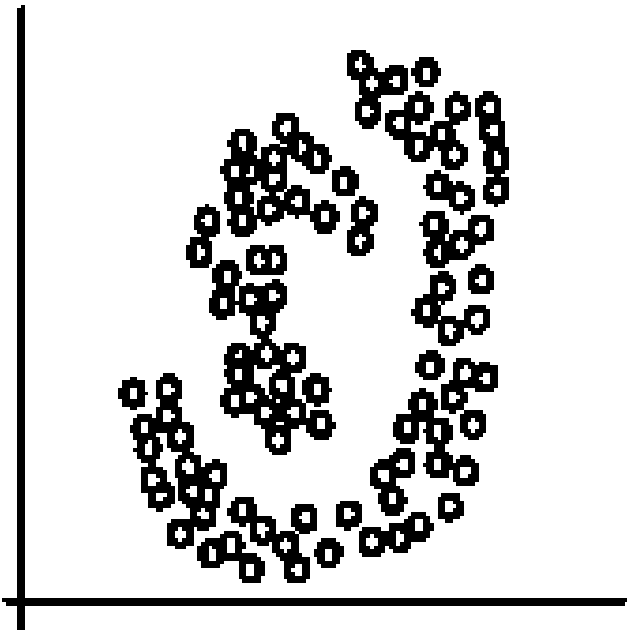
(B). Iteration 1



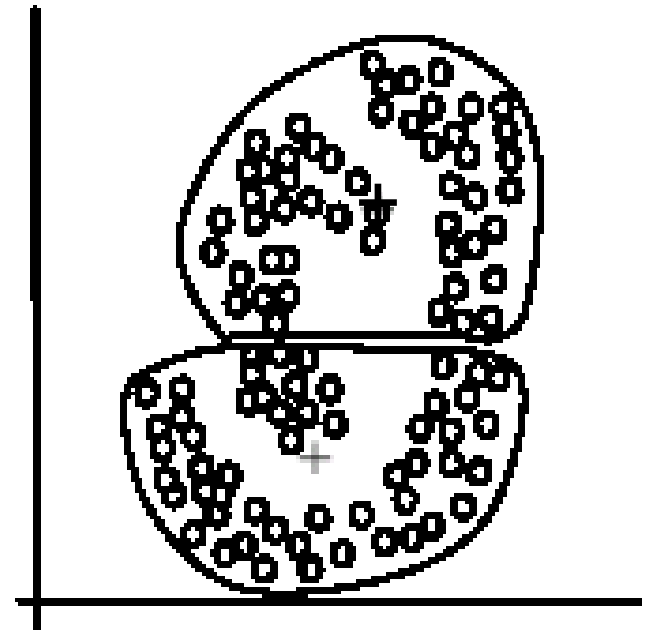
(C). Iteration 2

Weaknesses of k -means (cont.)

- The k -means algorithm is not suitable for discovering clusters that are not hyper-ellipsoids (or hyper-spheres).



(A): Two natural clusters



(B): k -means clusters

K-means summary

- Despite weaknesses, *k*-means is still the most popular algorithm due to its simplicity, efficiency and
 - other clustering algorithms have their own lists of weaknesses.
- No clear evidence that any other clustering algorithm performs better in general
 - although they may be more suitable for some specific types of data or applications.
- Comparing different clustering algorithms is a difficult task. No one knows the correct clusters!

Road map

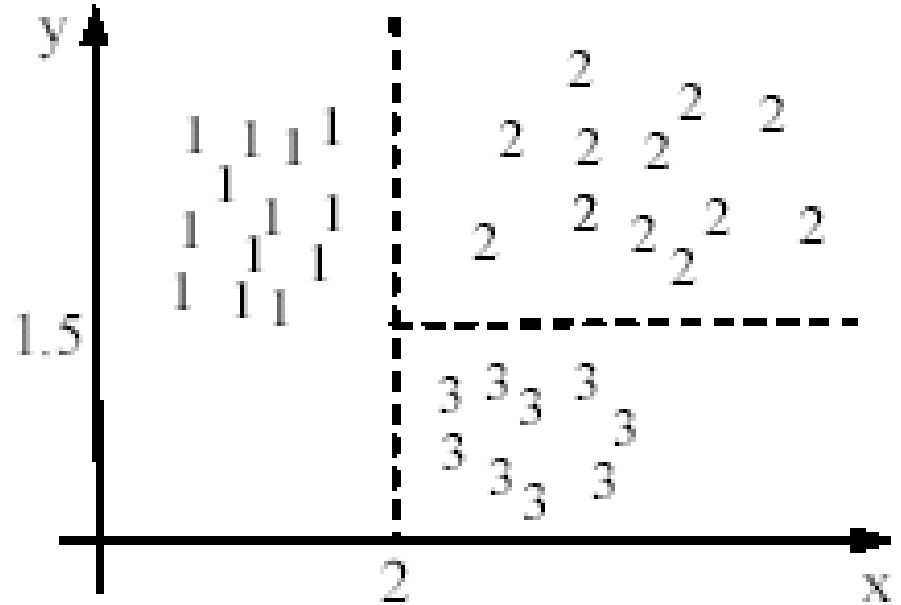
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Common ways to represent clusters

- Use the centroid of each cluster to represent the cluster.
 - compute the radius and
 - standard deviation of the cluster to determine its spread in each dimension
- The centroid representation alone works well if the clusters are of the hyper-spherical shape.
- If clusters are elongated or are of other shapes, centroids are not sufficient

Using classification model

- All the data points in a cluster are regarded to have the same class label, e.g., the cluster ID.
 - run a supervised learning algorithm on the data to find a classification model.



$x \leq 2 \rightarrow$ cluster 1

$x > 2, y > 1.5 \rightarrow$ cluster 2

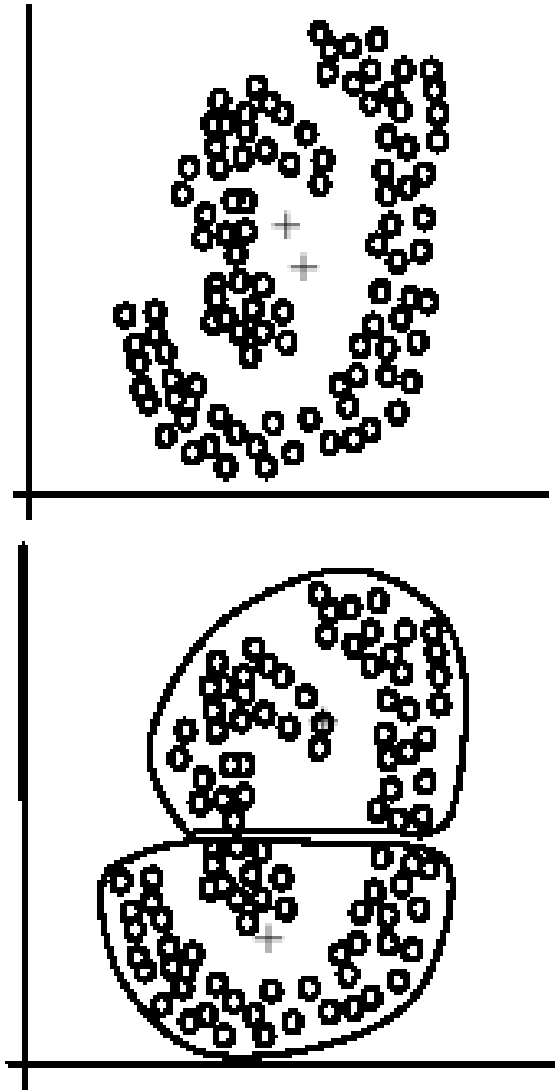
$x > 2, y \leq 1.5 \rightarrow$ cluster 3

Use frequent values to represent cluster

- This method is mainly for clustering of categorical data (e.g., *k*-modes clustering).
- Main method used in text clustering, where a small set of frequent words in each cluster is selected to represent the cluster.

Clusters of arbitrary shapes

- Hyper-elliptical and hyper-spherical clusters are usually easy to represent, using their centroid together with spreads.
- **Irregular shape clusters are hard to represent.** They may not be useful in some applications.
 - Using centroids are not suitable (upper figure) in general
 - K-means clusters may be more useful (lower figure), e.g., for making 2 size T-shirts.

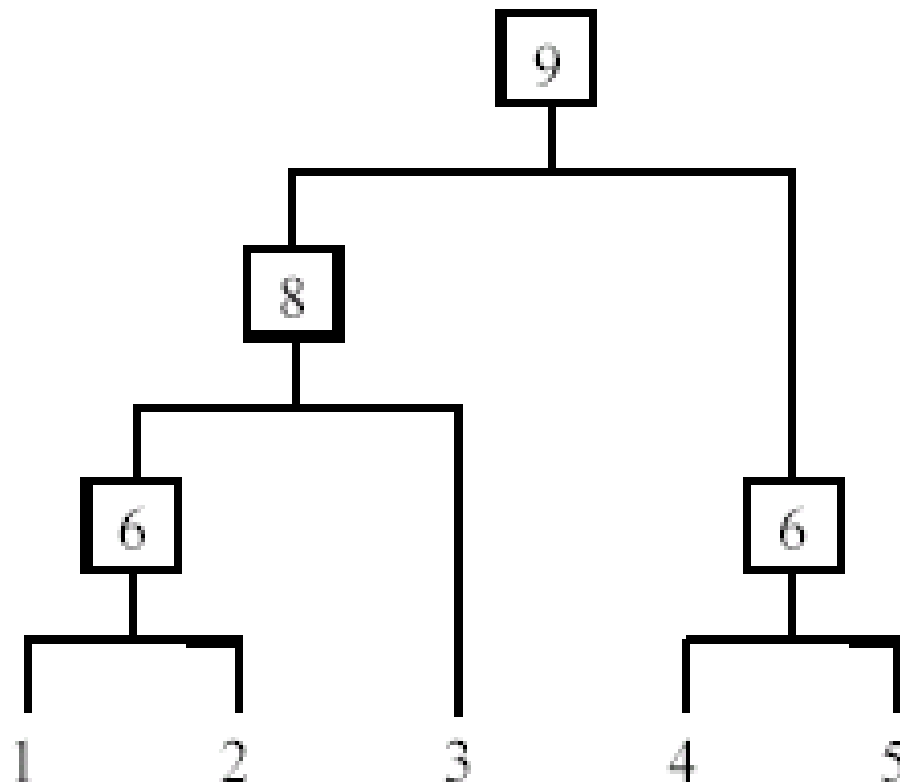


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Hierarchical Clustering

- Produce a nested sequence of clusters, a **tree**, also called **Dendrogram**.



Types of hierarchical clustering

- **Agglomerative (bottom up) clustering:** It builds the dendrogram (tree) from the bottom level, and
 - merges the most similar (or nearest) pair of clusters
 - stops when all the data points are merged into a single cluster (i.e., the root cluster).
- **Divisive (top down) clustering:** It starts with all data points in one cluster, the root.
 - Splits the root into a set of child clusters. Each child cluster is recursively divided further
 - stops when only singleton clusters of individual data points remain, i.e., each cluster with only a single point

Agglomerative clustering

It is more popular than divisive methods.

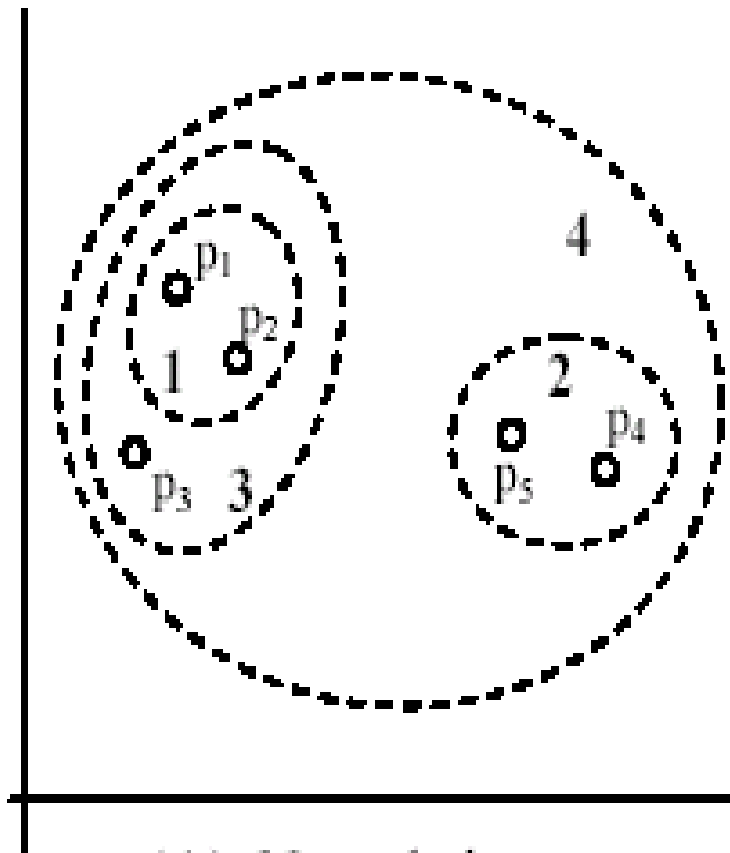
- At the beginning, each data point forms a cluster (also called a node).
- Merge nodes/clusters that have the least distance.
- Go on merging
- Eventually all nodes belong to one cluster

Agglomerative clustering algorithm

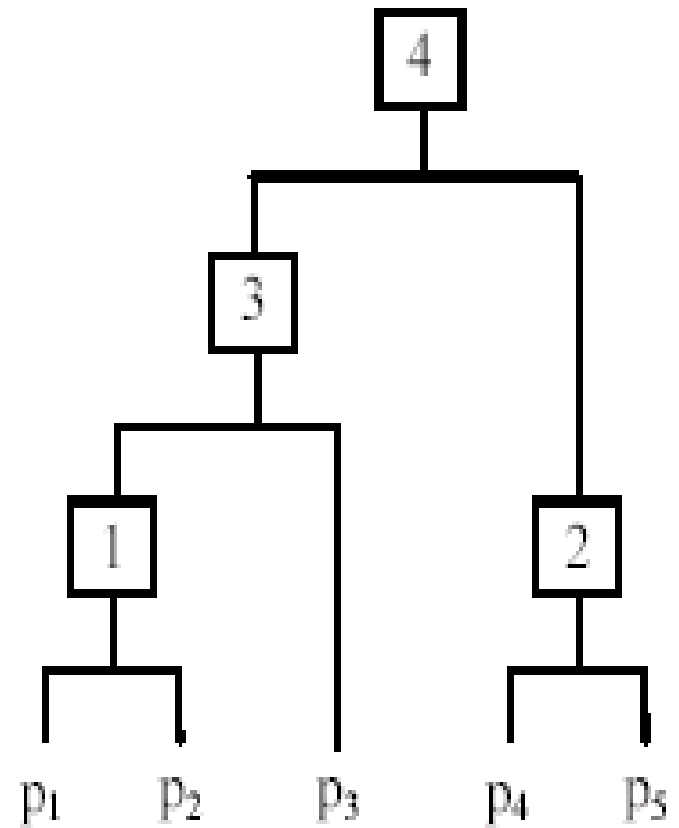
Algorithm Agglomerative(D)

- 1 Make each data point in the data set D a cluster,
- 2 Compute all pair-wise distances of $\mathbf{x}_1, \mathbf{x}_2, \dots, \mathbf{x}_n \in D$;
- 2 repeat
- 3 find two clusters that are nearest to each other;
- 4 merge the two clusters form a new cluster c ;
- 5 compute the distance from c to all other clusters;
- 12 until there is only one cluster left

Agglomerative example



(A). Nested clusters



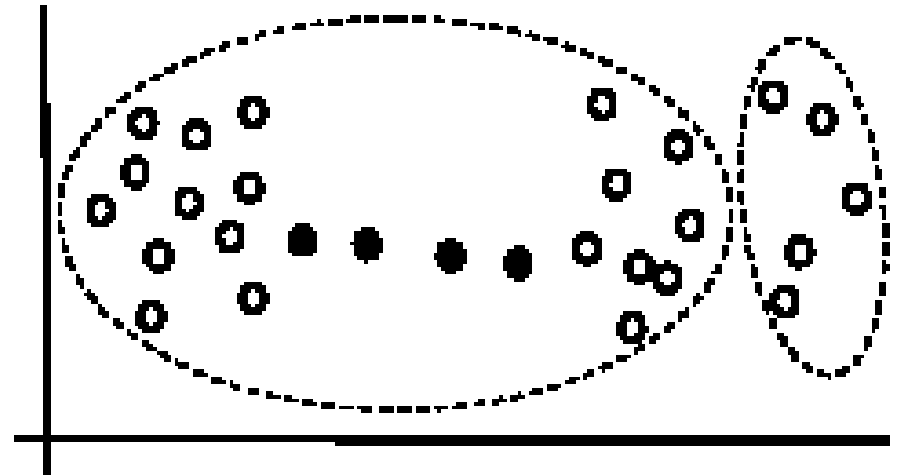
(B) Dendrogram

Measuring the distance of two clusters

- There are multiple ways to measure distances of two clusters.
- Results in different variations of the algorithm.
 - Single link
 - Complete link
 - Average link
 - Centroids
 - ...

Single link method

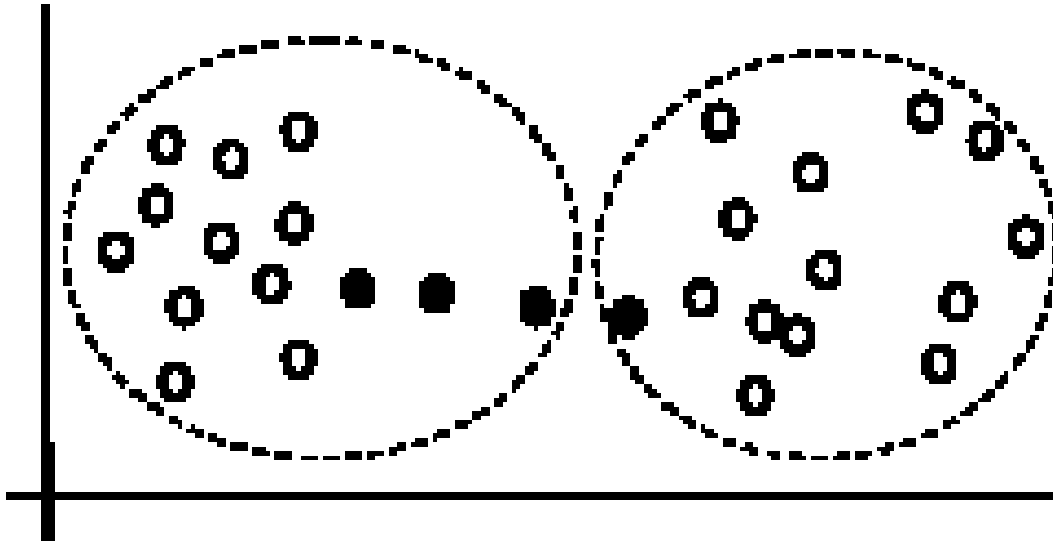
- The distance between two clusters is the distance between two **closest data points** in the two clusters, one data point from each cluster.
- It can find arbitrarily shaped clusters, but
 - It may cause the undesirable “**chain effect**” by noisy points



Two natural clusters are split into two

Complete link method

- The distance between two clusters is the distance of two **furthest** data points in the two clusters.
- It is sensitive to outliers because they are far away



Average link and centroid methods

■ Average link:

- A compromise between
 - the sensitivity of complete-link clustering to outliers and
 - the tendency of single-link clustering to form long chains that do not correspond to the intuitive notion of clusters as compact, spherical objects.
- The distance between two clusters is the average distance of all pair-wise distances between the data points in two clusters.

■ Centroid method:

- The distance between two clusters is the distance between their centroids

The complexity

- All the algorithms are at least $O(n^2)$. n is the number of data points.
- Single link can be done in $O(n^2)$.
- Complete and average links can be done in $O(n^2 \log n)$.
- Due the complexity, hard to use for large data sets.
 - Sampling
 - Scale-up methods (e.g., BIRCH).

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Distance functions

- Key to clustering. “similarity” and “dissimilarity” can also commonly used terms.
- There are numerous distance functions for
 - Different types of data
 - Numeric data
 - Nominal data
 - Different specific applications

Distance functions for numeric attributes

- Most commonly used functions are
 - Euclidean (L_2 , 2-norm) distance and
 - Manhattan (city block, L_1 , 1-norm) distance
- We denote distance with: $dist(\mathbf{x}_i, \mathbf{x}_j)$, where \mathbf{x}_i and \mathbf{x}_j are data points (vectors)
- They are special cases of **Minkowski distance**. h is ≥ 1 .

$$dist(\mathbf{x}_i, \mathbf{x}_j) = \left((x_{i1} - x_{j1})^h + (x_{i2} - x_{j2})^h + \dots + (x_{ir} - x_{jr})^h \right)^{\frac{1}{h}}$$

Euclidean distance / Manhattan distance

- If $h = 2$, it is the **Euclidean distance**

$$\text{dist}(\mathbf{x}_i, \mathbf{x}_j) = \sqrt{(x_{i1} - x_{j1})^2 + (x_{i2} - x_{j2})^2 + \dots + (x_{ir} - x_{jr})^2}$$

- If $h = 1$, it is the **Manhattan distance**

$$\text{dist}(\mathbf{x}_i, \mathbf{x}_j) = |x_{i1} - x_{j1}| + |x_{i2} - x_{j2}| + \dots + |x_{ir} - x_{jr}|$$

- **Weighted Euclidean distance**

$$\text{dist}(\mathbf{x}_i, \mathbf{x}_j) = \sqrt{w_1(x_{i1} - x_{j1})^2 + w_2(x_{i2} - x_{j2})^2 + \dots + w_r(x_{ir} - x_{jr})^2}$$

Squared distance and Chebychev distance

- **Squared Euclidean distance:** to place progressively greater weight on data points that are further apart.

$$\text{dist}(\mathbf{x}_i, \mathbf{x}_j) = (x_{i1} - x_{j1})^2 + (x_{i2} - x_{j2})^2 + \dots + (x_{ir} - x_{jr})^2$$

- **Chebychev distance:** one wants to define two data points as "different" if they are different on any one of the attributes.

$$\text{dist}(\mathbf{x}_i, \mathbf{x}_j) = \max(|x_{i1} - x_{j1}|, |x_{i2} - x_{j2}|, \dots, |x_{ir} - x_{jr}|)$$

Distance functions for binary and nominal attributes

- **Binary attribute**: has two values or states but no ordering relationships, e.g.,
 - Gender: male and female.
- We use a confusion matrix to introduce the distance functions/measures.
- Let the i th and j th data points be \mathbf{x}_i and \mathbf{x}_j (vectors)

Confusion matrix

$$\begin{array}{c} \text{Data point } i \\ \begin{array}{c} 1 \\ 0 \end{array} \end{array} \begin{array}{c} \text{Data point } j \\ \begin{array}{cc} 1 & 0 \end{array} \end{array} \begin{array}{c} a+b \\ c+d \\ a+c \quad b+d \quad a+b+c+d \end{array} \quad (10)$$

	1	0	
1	a	b	$a+b$
0	c	d	$c+d$
	$a+c$	$b+d$	$a+b+c+d$

- a : the number of attributes with the value of 1 for both data points.
- b : the number of attributes for which $x_{if} = 1$ and $x_{jf} = 0$, where x_{if} (x_{jf}) is the value of the f th attribute of the data point \mathbf{x}_i (\mathbf{x}_j).
- c : the number of attributes for which $x_{if} = 0$ and $x_{jf} = 1$.
- d : the number of attributes with the value of 0 for both data points.

Symmetric binary attributes

- A binary attribute is **symmetric** if both of its states (0 and 1) have equal importance, and carry the same weights, e.g., male and female of the attribute Gender
- Distance function: **Simple Matching Coefficient**, proportion of mismatches of their values

$$\text{dist}(\mathbf{x}_i, \mathbf{x}_j) = \frac{b + c}{a + b + c + d}$$

Symmetric binary attributes: example

\mathbf{x}_1	1	1	1	0	1	0	0
\mathbf{x}_2	0	1	1	0	0	1	0

$$\text{dist}(\mathbf{x}_1, \mathbf{x}_2) = \frac{2+1}{2+2+1+2} = \frac{3}{7} = 0.429$$

Asymmetric binary attributes

- **Asymmetric**: if one of the states is more important or more valuable than the other.
 - By convention, state 1 represents the more important state, which is typically the rare or infrequent state.
 - **Jaccard coefficient** is a popular measure

$$\text{dist}(\mathbf{x}_i, \mathbf{x}_j) = \frac{b + c}{a + b + c}$$

- We can have some variations, adding weights

Nominal attributes

- **Nominal attributes**: with more than two states or values.
 - the commonly used distance measure is also based on the **simple matching method**.
 - Given two data points \mathbf{x}_i and \mathbf{x}_j , let the number of attributes be r , and the number of values that match in \mathbf{x}_i and \mathbf{x}_j be q .

$$\text{dist}(\mathbf{x}_i, \mathbf{x}_j) = \frac{r - q}{r}$$

Distance function for text documents

- A text document consists of a sequence of sentences and each sentence consists of a sequence of words.
- To simplify: a document is usually considered a “bag” of words in document clustering.
 - Sequence and position of words are ignored.
- A document is represented with a vector just like a normal data point.
- It is common to use similarity to compare two documents rather than distance.
 - The most commonly used similarity function is the **cosine similarity**. We will study this later.

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Choosing a clustering algorithm

- Clustering research has a long history. A vast collection of algorithms are available.
 - We only introduced several main algorithms.
- **Choosing the “best” algorithm is a challenge.**
 - Every algorithm has limitations and works well with certain data distributions.
 - It is very hard, if not impossible, to know what distribution the application data follow. The data may not fully follow any “ideal” structure or distribution required by the algorithms.
 - One also needs to decide how to standardize the data, to choose a suitable distance function and to select other parameter values.

Choosing a clustering alg. (cont.)

- Due to these complexities, the common practice is to
 - run several algorithms using different distance functions and parameter settings, and
 - then carefully analyze and compare the results.
- The interpretation of the results must be based on insight into the meaning of the original data together with knowledge of the algorithms used.
- Clustering is highly **application dependent** and to a certain extent **subjective** (personal preferences).

Road map

- Basic concepts
- K-means algorithm
- Representation of clusters
- Hierarchical clustering
- Distance functions
- Data standardization
- Handling mixed attributes
- Which clustering algorithm to use?
- **Cluster evaluation**
- Discovering holes and data regions
- Summary

Cluster evaluation: hard problem

- The quality of a clustering is very hard to evaluate because
 - We do not know the correct clusters
- Some methods are used:
 - User inspection
 - Study centroids, and spreads
 - Rules from a decision tree.
 - For text documents, one can read some documents in clusters.

Cluster evaluation: ground truth

- We use some labeled data (for classification)
- **Assumption:** Each class is a cluster.
- After clustering, a confusion matrix is constructed. From the matrix, we compute various measurements, entropy, purity, precision, recall and F-score.
 - Let the classes in the data D be $C = (c_1, c_2, \dots, c_k)$. The clustering method produces k clusters, which divides D into k disjoint subsets, D_1, D_2, \dots, D_k .

Evaluation measures: Entropy

Entropy: For each cluster, we can measure its entropy as follows:

$$\text{entropy}(D_i) = - \sum_{j=1}^k \text{Pr}_i(c_j) \log_2 \text{Pr}_i(c_j), \quad (29)$$

where $\text{Pr}_i(c_j)$ is the proportion of class c_j data points in cluster i or D_i . The total entropy of the whole clustering (which considers all clusters) is

$$\text{entropy}_{total}(D) = \sum_{i=1}^k \frac{|D_i|}{|D|} \times \text{entropy}(D_i) \quad (30)$$

Evaluation measures: purity

Purity: This again measures the extent that a cluster contains only one class of data. The purity of each cluster is computed with

$$purity(D_i) = \max_j (\Pr_i(c_j)) \quad (31)$$

The total purity of the whole clustering (considering all clusters) is

$$purity_{total}(D) = \sum_{i=1}^k \frac{|D_i|}{|D|} \times purity(D_i) \quad (32)$$

An example

Example 14: Assume we have a text collection D of 900 documents from three topics (or three classes), Science, Sports, and Politics. Each class has 300 documents. Each document in D is labeled with one of the topics (classes). We use this collection to perform clustering to find three clusters. Note that class/topic labels are not used in clustering. After clustering, we want to measure the effectiveness of the clustering algorithm.

Cluster	Science	Sports	Politics		Entropy	Purity
1	250	20	10		0.589	0.893
2	20	180	80		1.198	0.643
3	30	100	210		1.257	0.617
Total	300	300	300		1.031	0.711

A remark about ground truth evaluation

- Commonly used to compare different clustering algorithms.
- A real-life data set for clustering has no class labels.
 - Thus although an algorithm may perform very well on some labeled data sets, no guarantee that it will perform well on the actual application data at hand.
- The fact that it performs well on some label data sets does give us some confidence of the quality of the algorithm.
- This evaluation method is said to be based on **external data** or information.

Evaluation based on internal information

- **Intra-cluster cohesion** (compactness):
 - Cohesion measures how near the data points in a cluster are to the cluster centroid.
 - Sum of squared error (SSE) is a commonly used measure.
- **Inter-cluster separation** (isolation):
 - Separation means that different cluster centroids should be far away from one another.
- In most applications, expert judgments are still the key.

Indirect evaluation

- In some applications, clustering is **not the primary task**, but used to help perform another task.
- We can use the performance on the primary task to compare clustering methods.
- For instance, in an application, the primary task is to provide recommendations on book purchasing to online shoppers.
 - If we can cluster books according to their features, we might be able to provide better recommendations.
 - We can evaluate different clustering algorithms based on how well they help with the recommendation task.
 - Here, we assume that the recommendation can be reliably evaluated.

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- **Basic concepts**
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Summary

- Clustering is has along history and still active
 - There are a huge number of clustering algorithms
 - More are still coming every year.
- We only introduced several main algorithms. There are many others, e.g.,
 - density based algorithm, sub-space clustering, scale-up methods, neural networks based methods, fuzzy clustering, co-clustering, etc.
- Clustering is hard to evaluate, but very useful in practice. This partially explains why there are still a large number of clustering algorithms being devised every year.
- Clustering is highly application dependent and to some extent subjective.