

# Clustering algorithms

Konstantinos Koutroumbas

## Unit 12

- Cluster validity
- Clustering tendency

# Cluster validity

- Consider a data set  $X$ . Then
  - (a) application of an **inappropriate algorithm** **or**
  - (b) application of an appropriate algorithm with **inappropriate values** of its (hyper)parametersmay lead **to poor results**. Hence the need for **further evaluation** of clustering results is apparent.
- **Cluster validity**: a task that **evaluates** **quantitatively** the **results** of a clustering algorithm.
- A **clustering structure**  $C$ , resulting from an algorithm may be either
  - A **hierarchy of clusterings** or
  - A **single clustering**.

# Cluster validity

Cluster validity may be approached through three possible directions:

- $C$  is evaluated in terms of an independently drawn structure, imposed on  $X$  *a priori*. The criteria used in this case are called external criteria.
- $C$  is evaluated in terms of quantities that involve the vectors of  $X$  themselves (e.g., proximity matrix). The criteria used in this case are called internal criteria.
- $C$  is evaluated by comparing it with other clustering structures, resulting from the application of the same clustering algorithm but with different parameter values, or other clustering algorithms, on  $X$ . Criteria of this kind are called relative criteria.

# Cluster validity

## ➤ Cluster validity for the cases of external and internal criteria

- Hypothesis testing is employed.
- The null hypothesis  $H_0$ , which is a statement of randomness concerning the structure of  $X$ , is defined.
- The generation of a reference data population of size  $r$  under the random hypothesis takes place.
- An appropriate statistic,  $q$ , whose values are indicative of the structure of a data set, is defined. The value of  $q$  that results for our data set  $X$ ,  $q^*$ , is compared against the  $r$  values of  $q$ ,  $q_1, \dots, q_r$ , associated with the  $r$  members of the reference (random) population.
- If  $q^*$  is (a) greater than  $(1 - \rho) \cdot r$ , (b) less than  $\rho \cdot r$ , (c) less than  $\frac{\rho}{2} \cdot r$  OR greater than  $\left(1 - \frac{\rho}{2}\right) \cdot r$ , the null hypothesis is rejected(\*).

Ways for generating reference populations under the null hypothesis (each one used in different situations) (\*\*):

- Random position hypothesis.
- Random graph hypothesis.
- Random label hypothesis.

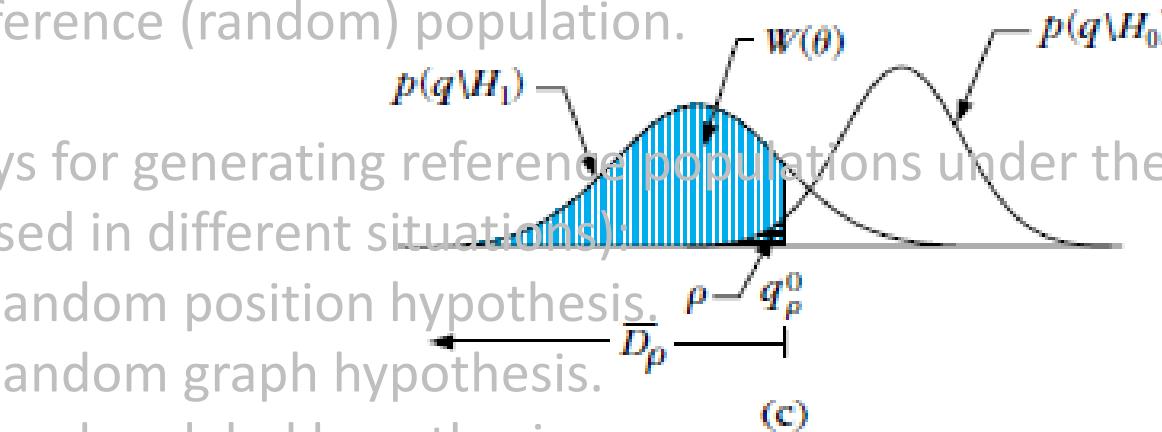
(\*)Actually, we approximate the  $p(q|H_0)$ , via Monte Carlo simulations.

(\*\*)The three cases are related to the kind of the adopted statistic  $q$  (see next slide).

# Cluster validity

## ➤ Cluster validity for the cases of external and internal criteria

- Hypothesis testing is employed.
- The null hypothesis  $H_0$ , which is a statement of randomness concerning the structure of  $X$ , is defined.
- The generation of a reference data population of size  $r$  under the random hypothesis takes place.
- An appropriate statistic,  $q$ , whose values are indicative of the structure of a data set, is defined. The value of  $q$  that results from our data set  $X$  is compared against the  $r$  values of  $q$  associated with the members of the reference (random) population.



Ways for generating reference populations under the null hypothesis (each one used in different situations):

- Random position hypothesis.
- Random graph hypothesis.
- Random label hypothesis.

# Cluster validity

➤ Cluster validity for the cases of external and internal criteria

• Random position hypothesis.

It **requires** that “all the arrangements of the  $N$  vectors in a specific region of the  $l$ -dimensional data space are equally likely to occur”.

It can be used with respect to both external and internal criteria.

# Cluster validity

## ➤ Cluster validity for the cases of external and internal criteria

### Statistics suitable for external criteria

- For the comparison of  $C$  with an independently drawn partition  $P$  of  $X$ 
  - Rand statistic
  - Jaccard statistic
  - Fowlkes-Mallows index
  - Hubert's  $\Gamma$  statistic
  - Normalized  $\Gamma$  statistic
- For assessing the agreement between  $P$  and the proximity matrix  $P$ .
  - $\Gamma$  statistic.

### Statistics suitable for internal criteria

- Validation of hierarchy of clusterings
  - Cophenetic correlation coefficient (CPCC)
  - $\gamma$  statistic
  - Kudall's  $\tau$  statistic.
- Validation of individual clusterings
  - $\Gamma$  statistic
  - Normalized  $\Gamma$  statistic

# Cluster validity

## ➤ Cluster validity for the cases of external and internal criteria

### Statistics suitable for external criteria

- For the comparison of  $C$  with an independently drawn partition  $P$  of  $X$ 
  - Rand statistic

Let  $P$  be an **external partition** of  $X$  into **groups** and  $C$  a **clustering**

A pair  $(x_i, x_j)$  is denoted as

SS if  $x_i, x_j$  belong to the **same cluster** in  $C$  and to the **same group** in  $P$ .

SD if  $x_i, x_j$  belong to the **same cluster** in  $C$  and to **different groups** in  $P$ .

DS if  $x_i, x_j$  belong to **different clusters** in  $C$  and to the **same group** in  $P$ .

DD if  $x_i, x_j$  belong to **different clusters** in  $C$  and to **different groups** in  $P$ .

Let  $a$ = number of SS,  $b$ = number of SD,  $c$ =number of DS,  $d$ = number of DD  
 $M$ =total number of pairs of points ( $= a + b + c + d$ )

Rand statistic  $R = (a + d)/M$

The **greater** the value of  $R$  the **greater** the **degree of agreement** between  $P$  and  $C$ .

# Cluster validity

## ➤ Cluster validity for the cases of external and internal criteria

### Statistics suitable for external criteria

**Example:** Consider a data set  $X = \{x_i \in H_l \equiv [0,1]^l, i = 1, \dots, 100\}$  so that the first 25 ( $x_1 - x_{25}$ ) stem from  $N(\mu_1, 0.2 \cdot I)$ , the next 25 ( $x_{26} - x_{50}$ ) from  $N(\mu_2, 0.2 \cdot I)$ , the next 25 ( $x_{51} - x_{75}$ ) from  $N(\mu_3, 0.2 \cdot I)$  and the final 25 ( $x_{76} - x_{100}$ ) from  $N(\mu_4, 0.2 \cdot I)$ , where

$\mu_1 = [0.2, 0.2, 0.2]^T$ ,  $\mu_2 = [0.5, 0.2, 0.8]^T$ ,  $\mu_3 = [0.5, 0.8, 0.2]^T$ ,  $\mu_4 = [0.8, 0.8, 0.8]^T$  and  $I$  is the  $3 \times 3$  identity matrix.

**External information:** The points form the following four different groups  $P_1 = \{x_1, \dots, x_{25}\}$ ,  $P_2 = \{x_{26}, \dots, x_{50}\}$ ,  $P_3 = \{x_{51}, \dots, x_{75}\}$ ,  $P_4 = \{x_{76}, \dots, x_{100}\}$ . Thus, we have the partition  $P = \{P_1, P_2, P_3, P_4\}$ .

We run the  $k$ -means algorithm for  $m = 4$  and let  $C = \{C_1, C_2, C_3, C_4\}$  be the resulting clustering.

**Question:** Are  $C$  and  $P$  in good agreement with each other?

# Cluster validity

## ➤ Cluster validity for the cases of external and internal criteria

Statistics suitable for external criteria

Example (cont.):

- Compute the  $\text{Rand}(\mathbf{C}, \mathbf{P})$  ( $= 0.91$ ).
- For  $i = 1$  to  $r$  ( $= 100$ )
  - Generate a data set  $X^i$  of 100 vectors in  $H_3$ , so the vectors are uniformly distributed in it.
  - Assign each vector  $\mathbf{y}_j^i \in X^i$  to the group where the respective  $\mathbf{x}_j \in X$  belongs according to  $\mathbf{P}$ .
  - Run the  $k$ -means algorithm for  $X^i$  and let  $\mathbf{C}^i$  be the resulting clustering
  - Compute  $\text{Rand}(\mathbf{C}^i, \mathbf{P})$
- End for
- Set the significance level  $\rho$  to 0.05.

It turns out that  $\text{Rand}(\mathbf{C}, \mathbf{P})$  is greater than  $(1 - \rho) \cdot r = 95$  values

$\text{Rand}(\mathbf{C}^i, \mathbf{P}), i = 1, \dots, r$  (actually, it is greater than all 100 values).

Thus, the null hypothesis that  $\mathbf{C}$  is in agreement with  $\mathbf{P}$  by chance is rejected at significance level 0.05.

Exercise: What would be the case if the clusters variances were  $0.8 \cdot I$ ?

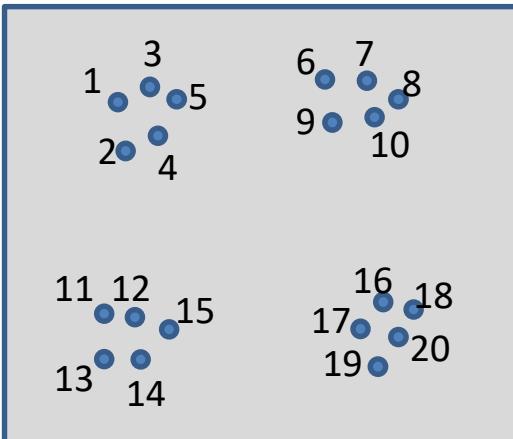
# Cluster validity

➤ Cluster validity for the cases of external and internal criteria

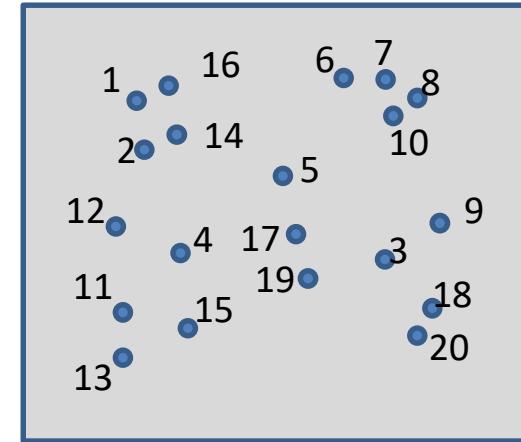
Statistics suitable for external criteria

**Example (cont.):** External information:  $P = \{P_1, P_2, P_3, P_4\} = \{\{x_1, \dots, x_5\}, \{x_6, \dots, x_{10}\}, \{x_{11}, \dots, x_{15}\}, \{x_{16}, \dots, x_{20}\}\}$

Data set under study



Randomly generated data set



**Clustering result**

$$\begin{aligned}C &= \{C_1, C_2, C_3, C_4\} \\&= \left\{ \{x_1, \dots, x_5\}, \{x_6, \dots, x_{10}\}, \right. \\&\quad \left. \{x_{11}, \dots, x_{15}\}, \{x_{16}, \dots, x_{20}\} \right\}\end{aligned}$$

**Clustering result**

$$\begin{aligned}C &= \{C_1, C_2, C_3, C_4\} \\&= \left\{ \begin{array}{l} \{x_1, x_2, x_{14}, x_{16}\}, \\ \{x_{12}, x_4, x_{11}, x_{13}, x_{15}, x_{17}, x_{19}\}, \\ \{x_6, x_7, x_8, x_{10}, x_5\}, \{x_3, x_9, x_{18}, x_{20}\} \end{array} \right\}\end{aligned}$$

# Cluster validity

## ➤ Cluster validity for the cases of external and internal criteria

Statistics suitable for internal criteria

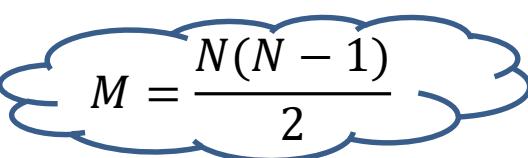
- Validation of individual clusterings
  - $\Gamma$  statistic

Consider two  $N \times N$  matrices  $X = [x_{ij}]$  and  $Y = [y_{ij}]$ , drawn **independently** from **each other**. Then

$$\Gamma(X, Y) = \frac{1}{N^2} \sum_{i=1}^N \sum_{j=1}^N x_{ij} y_{ij}$$

or, for **symmetric matrices**,

$$\Gamma(X, Y) = \frac{1}{M} \sum_{i=1}^N \sum_{j=i+1}^N x_{ij} y_{ij}$$


$$M = \frac{N(N - 1)}{2}$$

# Cluster validity

## ➤ Cluster validity for the cases of external and internal criteria

Statistics suitable for internal criteria

- Validation of individual clusterings

**Example:** Consider a data set  $X = \{x_i \in H_l \equiv [0,1]^l, i = 1, \dots, 100\}$  so that the first 25 ( $x_1 - x_{25}$ ) stem from  $N(\mu_1, 0.1 \cdot I)$ , the next 25 ( $x_{26} - x_{50}$ ) from  $N(\mu_2, 0.1 \cdot I)$ , the next 25 ( $x_{51} - x_{75}$ ) from  $N(\mu_3, 0.1 \cdot I)$  and the final 25 ( $x_{76} - x_{100}$ ) from  $N(\mu_4, 0.1 \cdot I)$ , where

$\mu_1 = [0.2, 0.2]^T$ ,  $\mu_2 = [0.8, 0.2]^T$ ,  $\mu_3 = [0.2, 0.8]^T$ ,  $\mu_4 = [0.8, 0.8]^T$  and  $I$  is the  $2 \times 2$  identity matrix.

Run the k-means algorithm and let  $C = \{C_1, C_2, C_3, C_4\}$  be the resulting clustering.

**Question:** Does the clustering agrees with the “internal structure” of the data by chance ( $H_0$  hypothesis) or not (alternative hypothesis)?

Let the internal structure of  $X$  be reflected in the dissimilarity matrix  $P_{N \times N}$ , based on the squared Euclidean distance.

# Cluster validity

- Cluster validity for the cases of external and internal criteria

Statistics suitable for internal criteria

- Validation of individual clusterings

**Example (cont.):**

Define the matrix  $Y_{N \times N} = [y_{ij}]$  as follows

$$y_{ij} = \begin{cases} 1, & \text{if } x_i \text{ and } x_j \text{ belong to different clusters} \\ 0, & \text{otherwise} \end{cases}$$

Compute  $\Gamma(Y, P)$  ( $= 0.57$ ).

- **For**  $i = 1$  to  $r$  ( $= 100$ )

- **Generate** a data set  $X^i$  of 100 vectors **uniformly distributed** in  $H_2$ .
- **Compute** the associated  $P^i$  dissimilarity matrix.
- **Run** the  $k$ -means algorithm for  $X^i$  and let  $C^i$  be the resulting clustering
- **Form** the  $N \times N$  matrix  $Y^i$  as above and **compute**  $\Gamma(Y^i, P^i)$

- **End for**

- Set the significance level  $\rho$  to **0.05**.

It turns out that  $\Gamma(Y, P)$  is greater than  $(1 - \rho) \cdot r = 95$  values  $\Gamma(Y^i, P^i)$ ,  $i = 1, \dots, r$  (actually, it is greater than 99 values).

Thus, the **null hypothesis** that  $C$  is in **agreement** with  $P$  by chance is **rejected**

# Cluster validity

➤ Cluster validity for the cases of external and internal criteria

Statistics suitable for internal criteria

- Validation of individual clusterings

**Exercise 1:** What would be the case if the clusters variances were  $0.2 \cdot I$ ?

**Exercise 2:** What would change in the above procedure if  $y_{ij}$ 's were defined as

$$y_{ij} = \begin{cases} 1, & \text{if } x_i \text{ and } x_j \text{ belong to the same cluster} \\ 0, & \text{otherwise} \end{cases}$$

# Cluster validity

## ➤ Cluster validity for the cases of relative criteria

Let  $A$  denote the set of parameters of a clustering algorithm.

### Statement of the problem

- “Among the clusterings produced by a specific clustering algorithm, for different values of the parameters in  $A$ , choose the one that best fits the data set  $X$ ”.

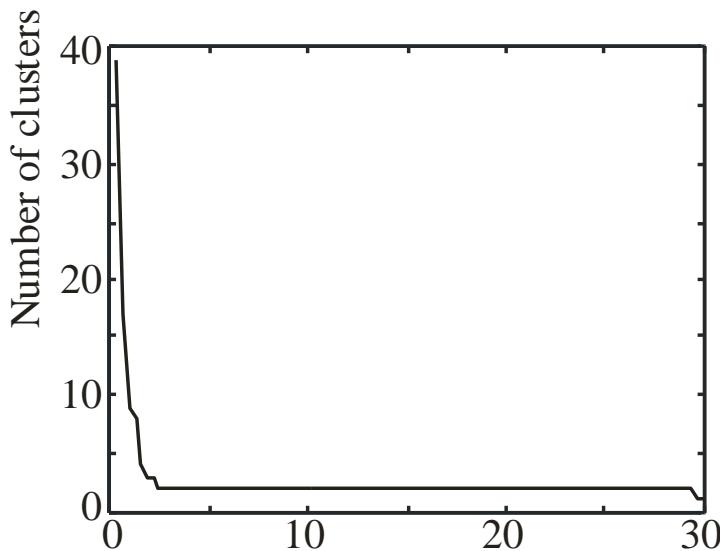
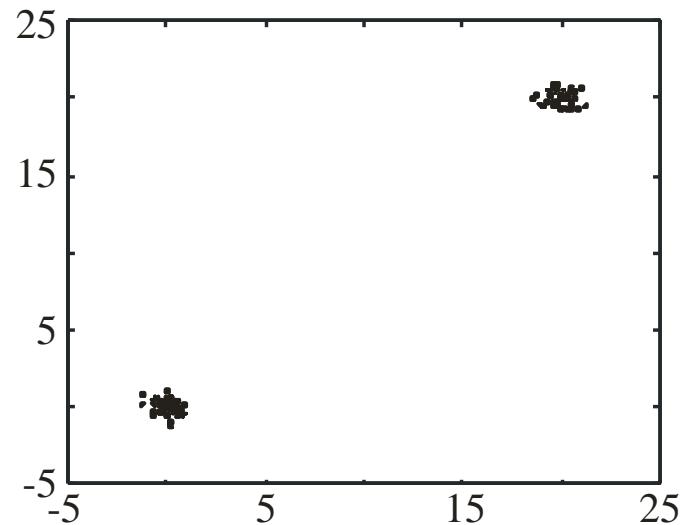
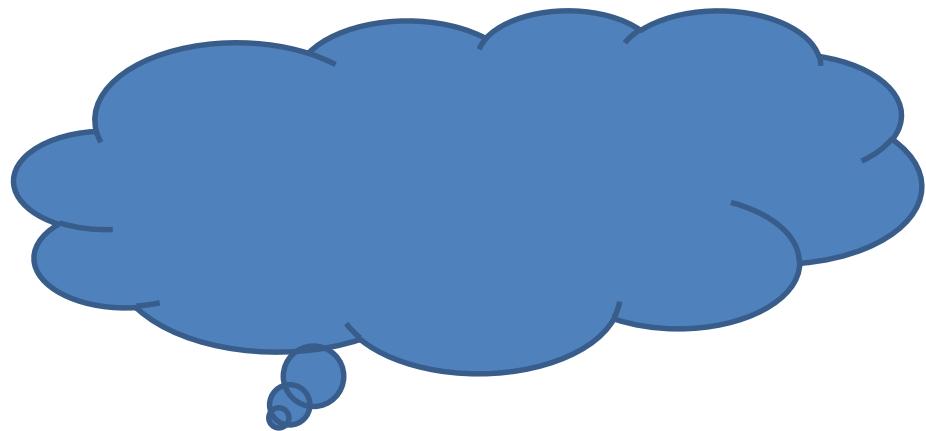
We consider two cases

(a)  $A$  **does not** contain the number of clusters  $m$ .

The estimation of the best set of parameter values is carried out as follows:

- **Run** the algorithm for a **wide range** of **values of its parameters**.
- **Plot** the number of clusters,  $m$ , **versus** the **parameters** of  $A$ .
- **Choose** the **widest range** for which  $m$  remains **constant**.
- **Adopt** the **clustering** that **corresponds** to the **values** of the parameters in  $A$  that **lie** in the **middle** of this **range**.

## Example:



# Cluster validity

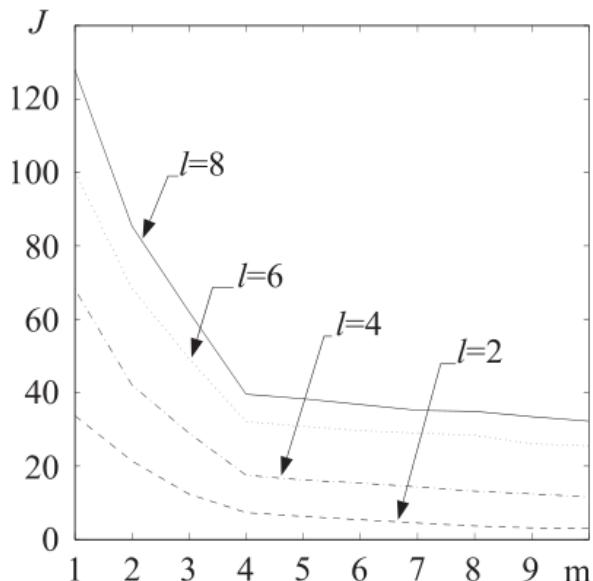
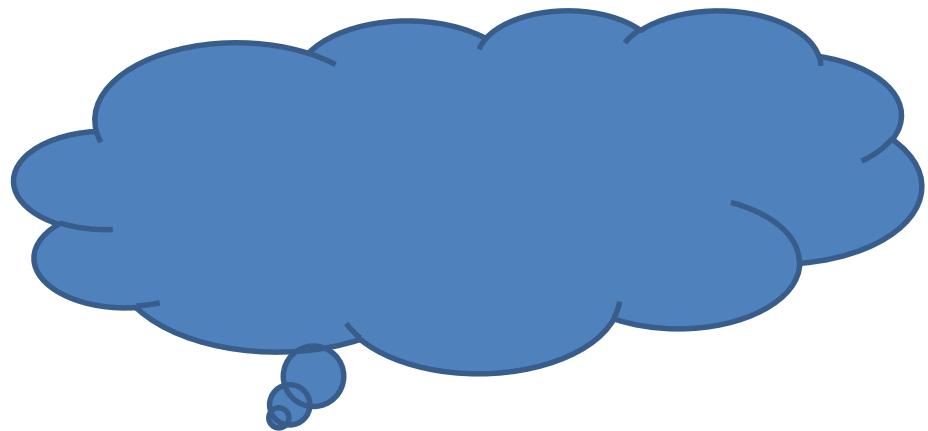
## ➤ Cluster validity for the cases of relative criteria

### (b) $A$ **does** contain the number of clusters $m$ .

The estimation of the best set of parameter values is carried out as follows:

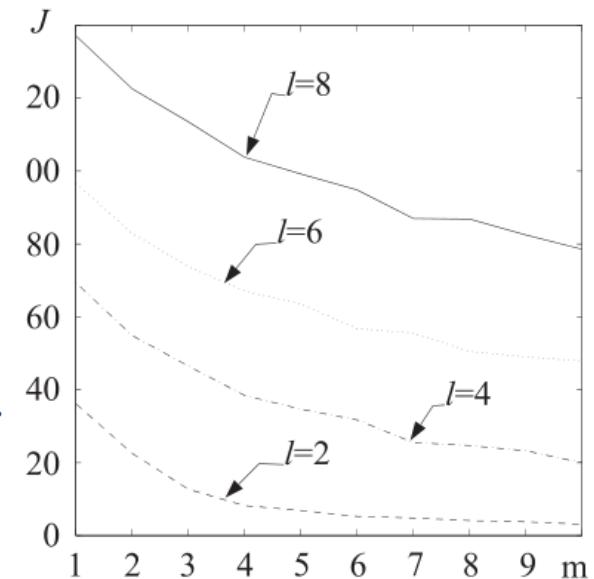
- **Select** a suitable **performance index  $q$**  (the best clustering is identified in terms of  $q$ ).
- **For**  $m = m_{min}$  to  $m_{max}$ 
  - **Run** the **algorithm  $r$  times** using different sets of values for the other parameters of  $A$  and **each time** compute  $q$ .
  - **Choose** the clustering that corresponds to the best  $q$ .
- **End for**
- **Plot** the **best values of  $q$**  for each  $m$  versus  $m$ .
- The **presence** of a **significant knee indicates** the number of clusters underlying  $X$ . **Adopt the clustering that corresponds to that knee.**
- The **absence** of such a **knee indicates** that  $X$  possesses **no** clear clustering structure.

## Example:



Clustered data

Non-clustered  
data



# Cluster validity

➤ Cluster validity for the cases of relative criteria

➤ *Statistics suitable for relative criteria*

- Hard clustering

- Modified Hubert  $\Gamma$  statistic
  - **Dunn** and Dunn-like indices

$$D_m = \min_{i=1, \dots, m} \left\{ \min_{j=i+1, \dots, m} \left( \frac{d(C_i, C_j)}{\max_{k=1, \dots, m} \text{diam}(C_k)} \right) \right\}$$
$$d(C_i, C_j) = \min_{x \in C_i, y \in C_j} d(x, y)$$
$$\text{diam}(C) = \max_{x, y \in C} d(x, y)$$

- Davies-Bouldin (DB) and DB-like indices
  - The **silhouette index**

- Fuzzy clustering

- Indices for clusters with point representatives
    - o Partition coefficient (PC)
    - o Partition entropy coefficient (PE)
    - o Xie-Beni (XB) index
    - o Fukuyama-Sugeno index
    - o Total fuzzy hypervolume
    - o Average partition density
    - o Partition density

# Cluster validity

➤ *Cluster validity for the cases of relative criteria*

➤ *Statistics suitable for relative criteria*

- Fuzzy clustering (cont.)

- Indices for shell-shaped clusters

- Fuzzy shell density

- Average partition shell density

- Shell partition density

- Total fuzzy average shell thickness

# Cluster validity

➤ Cluster validity for the cases of relative criteria

➤ *Statistics suitable for relative criteria*

- Hard clustering - The silhouette index

$C_{c_i}$ : The cluster where  $x_i$  belongs.

$a_i$ : The **average distance** of  $x_i$  from all  $x_j \in C_{c_i}$ .

$b_i$ : The **average distance** of  $x_i$  from its closest cluster  $C_q$ .

$s_i = \frac{b_i - a_i}{\max(b_i, a_i)}$ : **Silhouette width** of  $x_i$  ( $s_i \in [-1, 1]$ ).

Values of  $s_i$  close to

**+1** indicate that  $x_i$  is **well clustered**,

**0** indicate that  $x_i$  is at the **border** of two clusters

**-1** indicate that  $x_i$  is **poorly clustered**.

**Silhouette index of a cluster:**  $S_j = \frac{1}{n_j} \sum_{i: x_i \in C_j} s_i, j = 1, \dots, m$  ( $S_j \in [-1, 1]$ )

**Global silhouette index:**  $S_m = \frac{1}{m} \sum_{j=1}^m S_j$  ( $S_m \in [-1, 1]$ )

**Note:** The higher the value of  $S_m$  the better the clustering.

**Usage:** Plot  $S_m$  versus  $m$ . The **position** of the **maximum** indicates the **true number** of clusters.

# Clustering tendency

## Facts

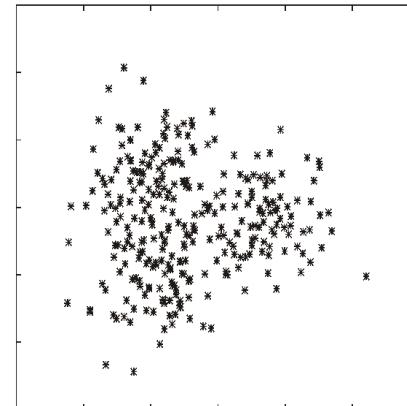
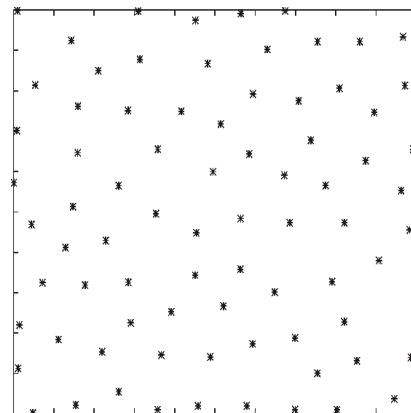
- Most clustering algorithms **impose** a clustering structure to the data set  $X$  at hand.
- However,  $X$  may not possess a clustering structure.
- Before we apply any clustering algorithm on  $X$ , **it must first be verified that  $X$  possesses a clustering structure**. This is known as the **clustering tendency** procedure.
- Clustering tendency is heavily based on **hypothesis testing**. Specifically, it is based on testing the randomness (null) hypothesis ( $H_0$ ) against the regularity ( $H_1$ ) hypothesis and the clustering ( $H_2$ ) hypothesis .
  - **Randomness hypothesis ( $H_0$ )**: “The vectors of  $X$  are randomly distributed, according to the uniform distribution in the sampling window (**the compact convex support set for the underlying distribution of the vectors of the data set  $X$** ) of  $X$ ”.
  - **Regularity hypothesis ( $H_1$ )**: “The vectors of  $X$  are regularly spaced (that is they are not too close to each other) in the sampling window”.
  - **Clustering hypothesis ( $H_2$ )**: “The vectors of  $X$  form clusters”.

# Clustering tendency

- $p(q|H_0)$ ,  $p(q|H_1)$ ,  $p(q|H_2)$  are estimated via Monte Carlo simulations

Some tests for spatial randomness, when the input space dimensionality greater than or equal to 2 are:

- Tests based on **structural graphs**
  - *Test that utilizes the idea of the minimum spanning tree (MST)*
- Tests based on **nearest neighbor distances**
  - *The Hopkins test*
  - *The Cox-Lewis test*
- A method based on **sparse decomposition**.



# Clustering tendency

## ➤ Important notes:

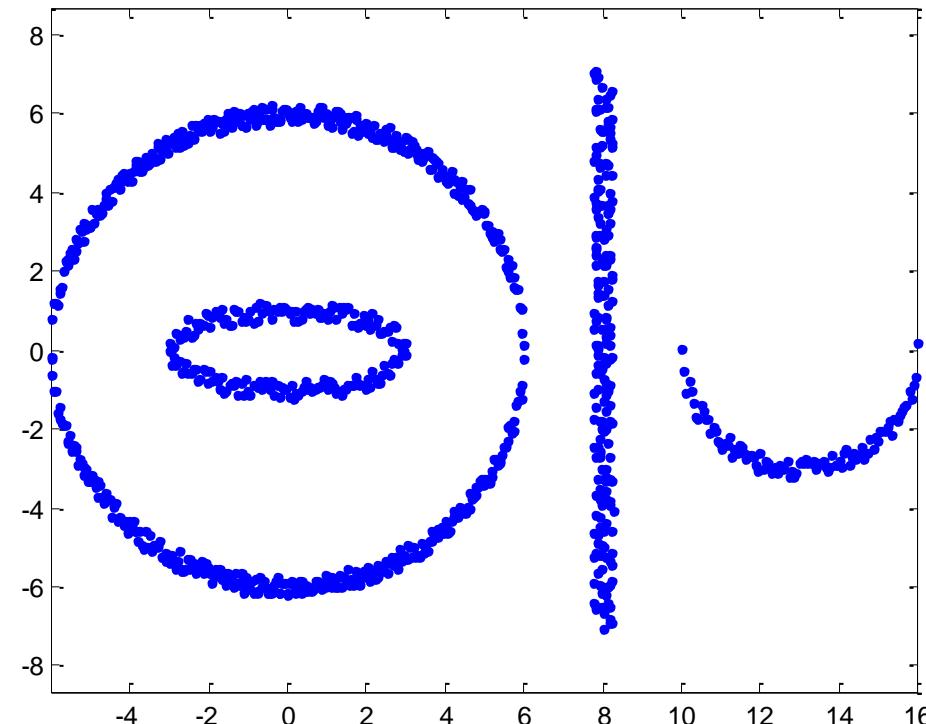
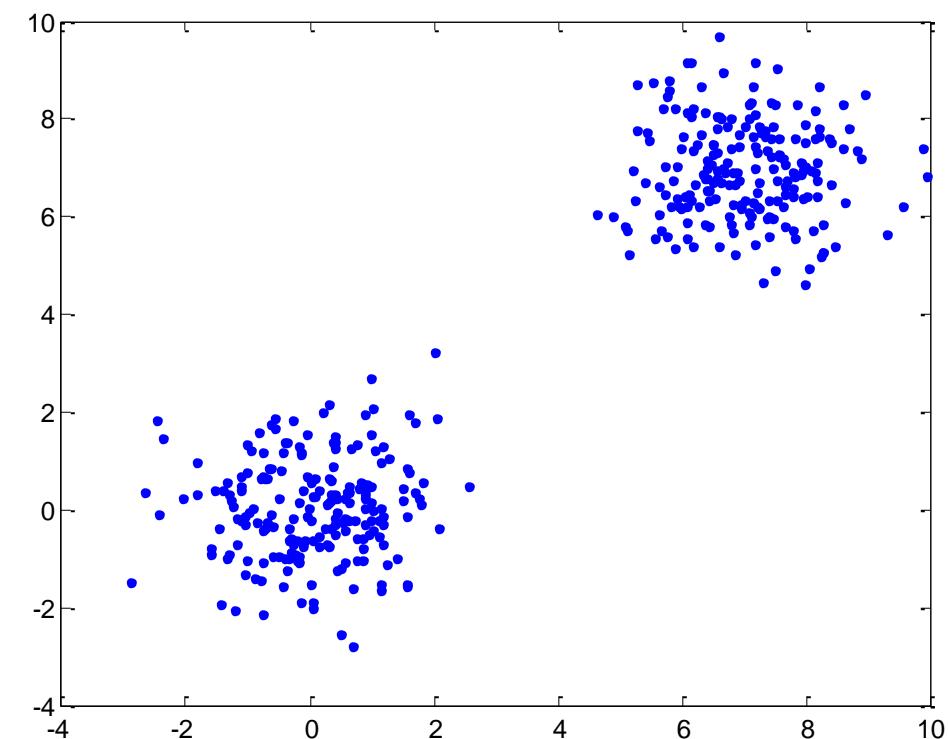
- Clustering algorithms should be applied on  $X$ , only if the randomness and the regularity hypotheses are rejected. Otherwise, methods different than clustering must be used to describe the structure of  $X$ .
- Most studies in clustering tendency focus on the detection of compact clusters.

## ➤ The **basic steps** of the clustering tendency philosophy are:

- Definition of a test statistic  $q$  suitable for the detection of clustering tendency.
- Estimation of the pdf of  $q$  under the null ( $H_0$ ) hypothesis,  $p(q|H_0)$ .
- Estimation of  $p(q|H_1)$  and  $p(q|H_2)$  (they are necessary for measuring the power of  $q$  (the probability of making a correct decision when  $H_0$  is rejected) against the regularity and the clustering tendency hypotheses).
- Evaluation of  $q$  for the data set at hand,  $X$ , and examination whether it lies in the critical interval of  $p(q|H_0)$ , which corresponds to a predetermined significance level  $\rho$ .

# Clustering Algorithms: case study 1

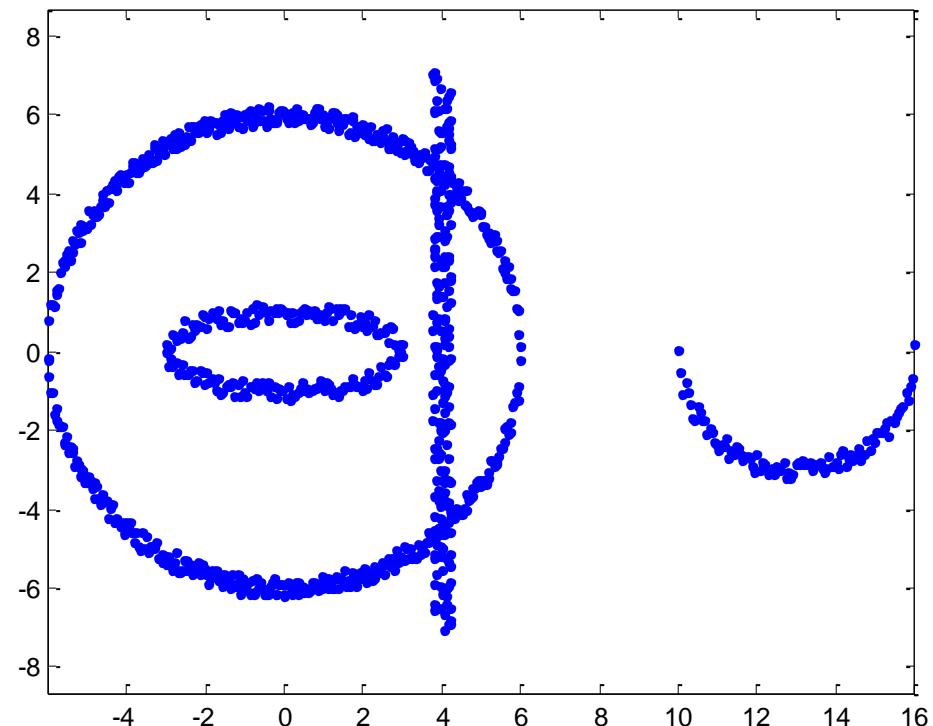
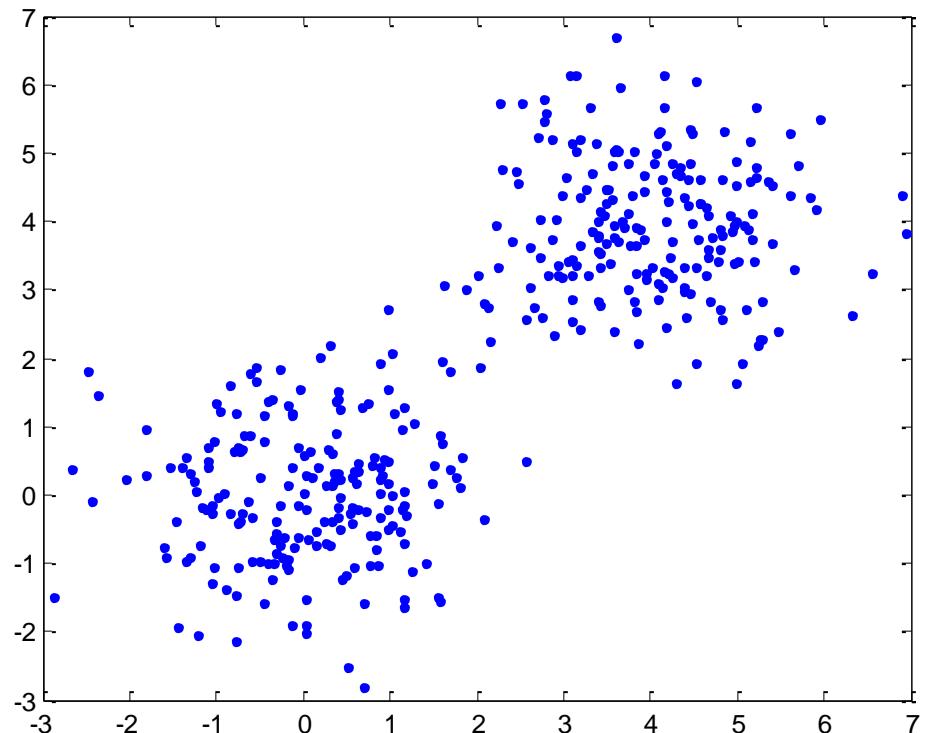
**The problem:** Propose a method/methodology in order to have an indication of whether the data set under study possesses a clustering structure or not.



# Clustering Algorithms: case study 1

rpca-ssa\_CR\_smooth\_image.mat

**The problem:** Propose a method/methodology in order to have an indication of whether the data set under study possesses a clustering structure or not.



# Clustering Algorithms: case studies

**The problem:** Propose a method/methodology in order to have an indication of whether the data set under study possesses a clustering structure or not.

**A possible solution (applied to all but the compact and overlapping clusters case):**

- Consider the associated **graph** where the edges are weighted by the distance of the corresponding data points.
- **Determine** the **Minimum Spanning Tree** (MST) of the graph.
- Check whether its **largest edge** is “**several standard deviations**” away from the **mean** of the **weights** of the edges of the MST.
- Alternatively, one can use the **statistical hypothesis testing** path. That is, to generate a set of  $N$  uniformly randomly distributed data in the space where the data live and to check the distance of the largest MST edge weight from the mean of the MST edge weights.

**Limitations:**

- **Overlapping clusters. A possible solution:** If we know the “shape” of the clusters that are expected to be formed by the data, we can run e.g., k-means (for compact clusters) or algorithms like Fuzzy C Ellipsoidal Shells (**FCES**) for the case of ellipsoidally-shaped clusters, or Gustafson-Kessel for linearly-shaped clusters, we can run the algorithm for a range of the number of clusters  **$m$**  and to search for a significant “knee” in the graph of the cost function vs  **$m$** .

# Clustering Algorithms

THE END