dm22s1

Topic 11 : Clustering

Part 01 : Overview

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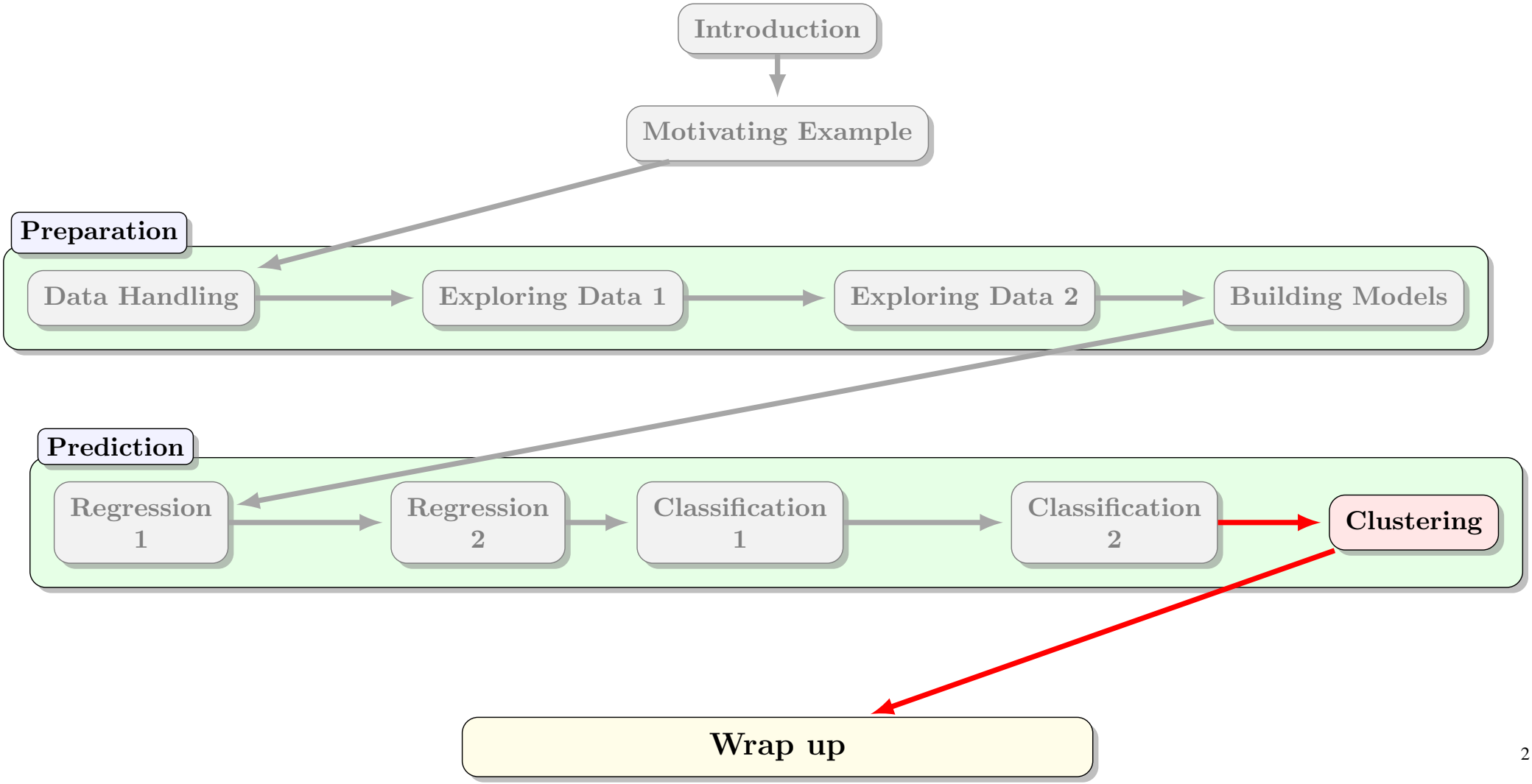
Outline

- How to compute distances between instances
- Algorithms that partition the data

Data Mining (Week 11)



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This Week's Aim

This week's aim is to introduce the main concepts and representative algorithms used in cluster analysis.

- Introduction to unsupervised learning
- Clustering as a means of understanding data
- Choice of distance function and metaparameters
- Clusters that partition the data
  - Iris data: predicting which of three species

Clustering is a long-established form of analysis, having much in common with exploratory data analysis. We look at the main concepts and algorithms today.

Background: Unsupervised Learning

Definition 1 (Unsupervised Learnng)

With unsupervised learning, the system receives input instances $x_1, x_2, \ldots$ but obtains neither target outputs, nor rewards from its environment. Its goal is to build representations of the input that can be used for decision making, predicting future inputs, efficiently communicating the inputs to another machine, etc. It does this by finding patterns in the data beyond what would be considered pure unstructured noise (**Ghahramani2004**).

Regression and classification are examples of supervised learning because they require labeled *training* data.

We saw *dimensionality reduction* in Topic 8 (Regression 2). Other unsupervised learning techniques include *anomaly detection* and the very "hot" *Generative Adversarial Networks* of deep learning. We look at *clustering* today.

Introduction to Clustering

Definition 2 (Clustering)

Clustering is the operation of grouping objects into a smaller number of clusters (or segments), which have two properties. Firstly, they are not defined in advance by an analyst, but are discovered during the operation, unlike the classes used in classification. Secondly, the clusters combine objects having similar characteristics, which are separated from objects having different characteristics (resulting in *internal homogeneity* and *external heterogeneity* (**Tuffery2011**).

Clustering is usually called *segmentation* in marketing studies.
Usually clustering is not an end in itself: it generates insights that are used to motivate and inform other analyses.
The "quality" of a cluster analysis is difficult to determine objectively - there is no equivalent of *recall*, say.

Example Applications

Identify possible applications for clustering

Hierarchical versus Partitional techniques

Hierarchical

- Intermediate steps are interpretable
- More than one clustering generated - see *dendrogram*
- Given choice of linkage, algorithm proceeds *deterministically*
  - no concept of starting values
  - no concept of local versus global optimum
- relatively few parameters to specify
- more complex interpretation

Partitional

- Interpret the final clustering only
- Single clustering returned; repeat with different conditions to improve it
- Optimisation by gradient descent, so
  - result depends on starting values
  - might find local rather than global optimum
- more parameters to specify
- interpretation is relatively easy

Distance Measures and their role in clustering

Definition 3 (Distance Measure)

A *distance measure* (c.f., its complement, a *similarity measure*) is a scalar number $d(x_1, x_2)$ that quantifies the degree of agreement between two (usually vector-valued) observations x_1 and x_2. When $x_1 = x_2$, $d(x_1, x_2) = 0$ and $d(x_1, x_2) > 0$ otherwise. It increases as the difference in the observations increases.

By definition, clustering is based on within-cluster homogeneity (measured by small d) versus large d between clusters. Thus choice of distance measure plays a critical part in generating useful clusters.

Distance Measures for numeric data

Definition 4 (Minkowski $p-$norm)

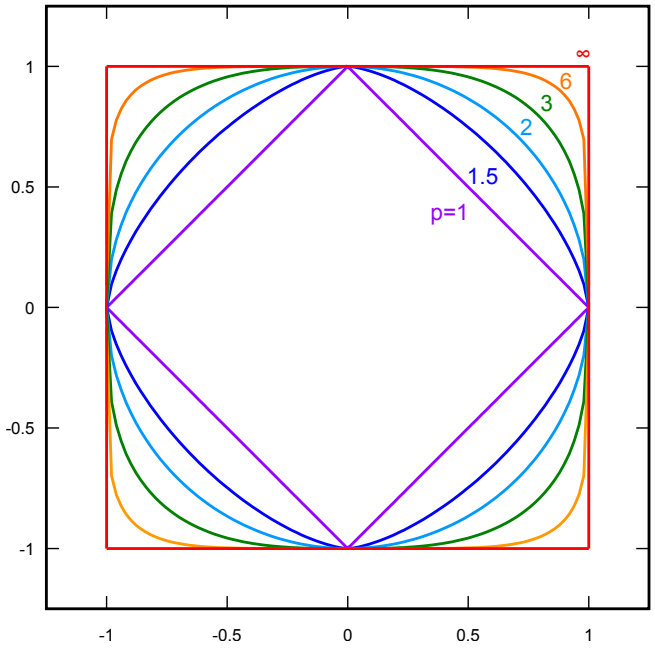
For a real number $1 \leq p < \infty$, the p-norm of $\boldsymbol{x}$ is defined by

$$\|\boldsymbol{x}\|_p \equiv \left(|x_1|^p + |x_2|^p + \ldots + |x_n|^p\right)^{\frac{1}{p}} .$$

The limiting case of $p = \infty$ is defined as

$$\|\boldsymbol{x}\|_\infty \equiv \max\{|x_1|, |x_2|, \ldots, |x_n|\}.$$

See the visualisation of the "unit balls" alongside, for $p = 1, 1.5, 2, 3, 6, \infty$.



Source: wikipedia

The most common norms are when $p = 1, 2, \text{or}, \infty$. Choice of p depends on the application scenario. Can you think of when you would use each?

(Selected) Distance Measures for categorical data

Let $\boldsymbol{x}_1 = [e_{1,1}, e_{1,2}, \ldots e_{1,k}]^T$ and $\boldsymbol{x}_2 = [e_{2,1}, e_{2,2}, \ldots e_{2,k}]^T$. Furthermore let $e_{1,j}e_{2,j} = 1$ if $e_{1,j} = e_{2,j}$ and $e_{1,j}e_{2,j} = 0$ otherwise. To compute s, the number of matching attributes between $\boldsymbol{x}_1$ and $\boldsymbol{x}_2$, we can just compute the dot product:

$$s = \boldsymbol{x}_1^T \boldsymbol{x}_2$$

and the number of mismatches is $d = k - s$, where k is the number of attributes in $\boldsymbol{x}$.

Definition 5 (Euclidean distance for categorical observations)

$\|\boldsymbol{x}_1 - \boldsymbol{x}_2\| = \sqrt{\boldsymbol{x}_1^T\boldsymbol{x}_1 - 2\boldsymbol{x}_1^T\boldsymbol{x}_2 + \boldsymbol{x}_2^T\boldsymbol{x}_2} = \sqrt{2(k-s)}$. So the maximum distance occurs when $s = 0$ ($\boldsymbol{x}_1$ and $\boldsymbol{x}_2$ share no attribute values in common, as expected).

Definition 6 (Hamming Distance)

This is the number of mismatched values $k - s$.

(Selected) Distance Measures for categorical data - ratios

Definition 7 (Cosine similarity)

$\cos\theta_{1,2} = \frac{\boldsymbol{x}_1^T\boldsymbol{x}_2}{\|\boldsymbol{x}_1\|\|\boldsymbol{x}_2\|} = \frac{s}{\sqrt{k}\sqrt{k}} = \frac{s}{k}$.

because $\|\boldsymbol{x}\| \equiv \sqrt{\boldsymbol{x}^T\boldsymbol{x}} = \sqrt{k}$.

Definition 8 (Jaccard Coefficient)

This is the ratio of the number of matching values s to the number of distinct values that appear in $\boldsymbol{x}_1$ and $\boldsymbol{x}_2$, across the d *distinct* attributes of both. It is $J(\boldsymbol{x}_1,\boldsymbol{x}_2) = \frac{s}{2(k-s)+s} = \frac{s}{2k-s}$.

Note that all these distance measures are functions of s and k, where k is a constant and s is a count of the number of matching attribute values across the two observations in question.

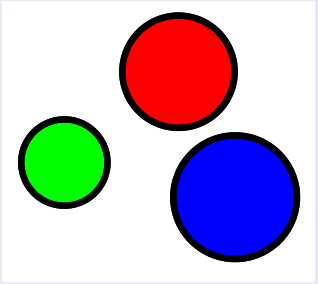
Clustering as a partitioning problem

- Often the purpose of clustering is to assign one or more labels to each observation, so that "similar" observations are given the same cluster membership label.
- In the standard case, each observation is assigned a single label, and clustering defines a (hard) *partitioning* of the data. Lloyd's *k-means* algorithm does this.
- If each observation is assigned a membership probability for each cluster, this is a *soft partitioning* of the data. A hard partition can be derived by choosing, for each observation, the cluster for which it has the highest probability of membership. *Gaussian Mixture* models can be used for this purpose.
- Some clustering algorithms, notably *density-based clustering*, do not always assign a label to each observation. However, if an observation is assigned a label, it will be just one such label.

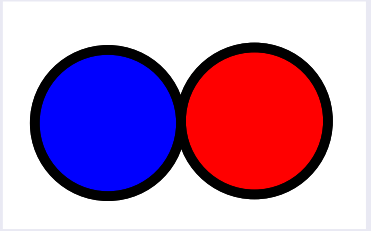
Representative-based clustering finds a region around a *cluster centre* so that observations can be assigned to the cluster if they are found in that region.
Density-based clustering looks for regions, possibly non-convex, where the data density is higher, and assigns observations in those regions to the relevant cluster. Any other observations are assumed to be either "noise" or "border" observations.

Types of partitional clustering

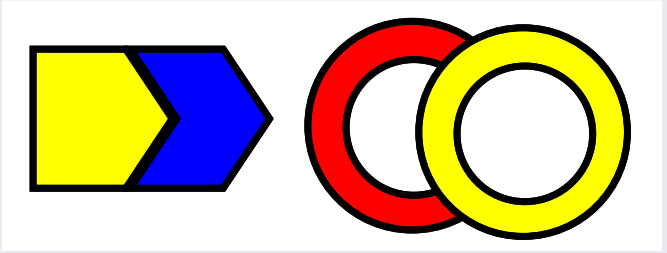
Well-separated clusters



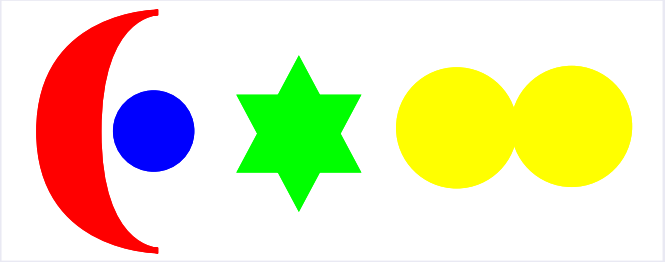
Centre-based clusters



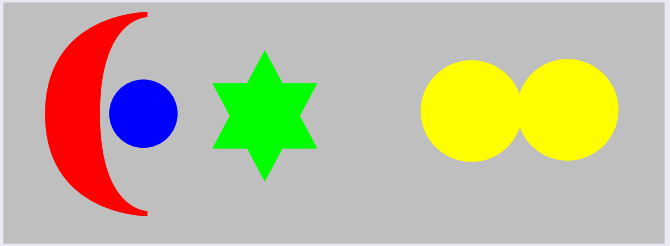
Conceptual clusters



Contiguity-based clusters



Density-based clusters



K-means algorithm: Overview

- The $k-$means algorithm assigns each observation to one of k clusters, by finding the nearest cluster centre for that observation (E-step).
- Each cluster centre is calculated as the centroid of the observations assigned to that cluster (M-step).
- The algorithms proceeds in two steps (E-M). At each iteration, the algorithm finds the nearest centre for each observation, then assigns it to that centre and recomputes the centres.
- Lloyd's algorithm is an example EM-algorithm: Expectation-Maximisation (general algorithm, used in many scenarios, especially clustering).
- Variants include

  Mini-batch k-means : work with a random sample of the data at each iteration: scales better, small loss of accuracy

  kmeans++ : Choose initial centres that are well-separated from each other; "normal" k-means afterwards.

  k-medoids : Manhattan (ℓ_1) distance is used instead of Euclidean (ℓ_2), and centres are constrained to be data points); PAM and CLARA algorithms.
- Generally Lloyd's algorithm is robust, although it is affected by the choice of initial centres, and care must be taken to avoid empty clusters

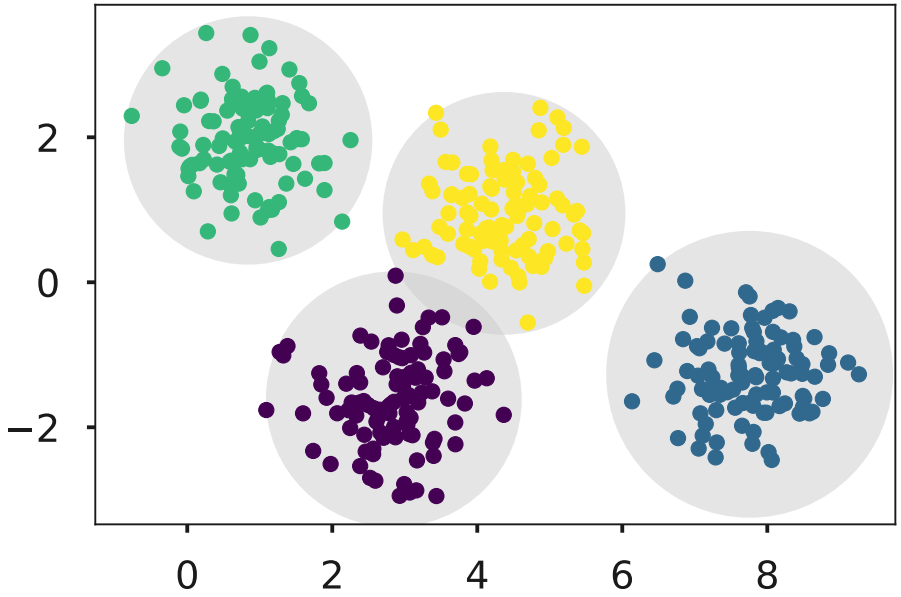
K-means algorithm: Detail

Method (k-means algorithm)

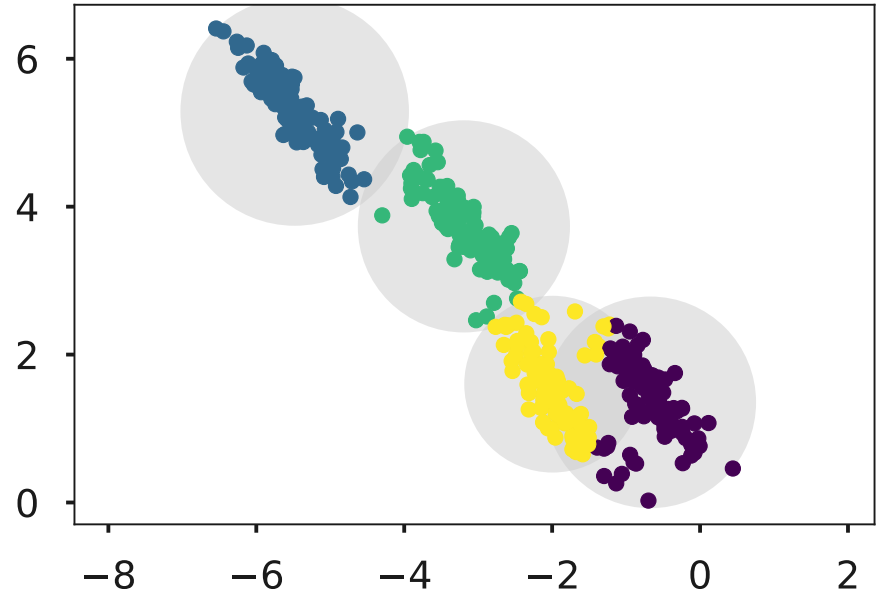
$t \leftarrow 0$;
Initialise centres $\{\boldsymbol{\mu}_j^t, j = 1, \ldots, k\}$: choose k points randomly, without replacement;
repeat
  $t \leftarrow t + 1$;
  $C_j \leftarrow \emptyset, \forall j = 1, \ldots, k$; ▷ Cluster Assignment Step **E**
  for all $\boldsymbol{x}$ **do** ▷ Assign $\boldsymbol{x}_j$ to the nearest centroid from the previous iteration
    $j^* \leftarrow \arg\min_i \left\{ \|\boldsymbol{x}_j - \boldsymbol{\mu}_i^{t-1}\|^2 \right\}$;
    $C_{j^*} \leftarrow C_{j^*} \cup \{\boldsymbol{x}_j\}$;
  end for ▷ Centroid Update Step **M**
  for all $i = 1$ to k **do**
    $\boldsymbol{\mu}_i^t \leftarrow \frac{1}{|C_i|} \sum_{\boldsymbol{x}_j \in C_i} \boldsymbol{x}_j$;
  end for
until $\sum_{i=1}^{k} \|\boldsymbol{\mu}_i^t - \boldsymbol{\mu}_i^{t-1}\|^2 \leq \epsilon$

The termination condition is that the difference in centre positions should not exceed a small tolerance ϵ.
Happens when points stay in their cluster from iteration p to $p + 1$, so cluster centre stays same.

K-means algorithm: In practice



With the original globular clusters, *k*-means was able to find the centres and clusters easily.



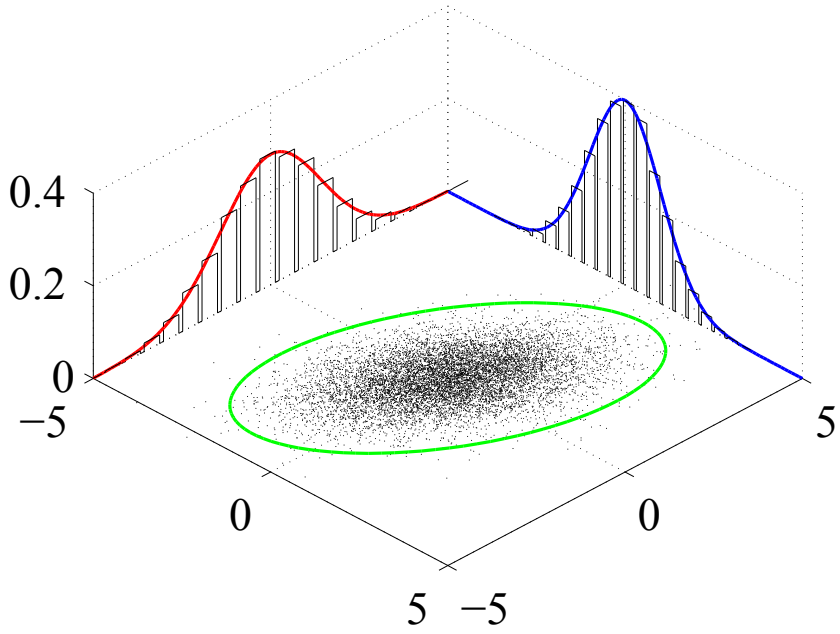
With the stretched clusters, *k*-means had more difficulty, e.g., with the yellow and purple clusters.

k-means minimises the within-cluster sum of squared distances (also known as *inertia*) so the choice of distance function is critical.

Probabilistic models for clustering

- k-means is an example of *hard* clustering, where each data point is mapped to a single cluster
- As such it is best suited to well-separated clusters - but what if they are close or even overlap?
- *fuzzy* clustering: points are assigned to multiple clusters, and are given a membership score in [0,1] for each cluster
- fuzzy c-means algorithm is a straightforward extension of k-means, just using probability $P(x_i, \mu_j)$ to weight each point x_i when calculating the centroid of each cluster μ_j (M-step)
- P is a function of the relative Euclidean distances to the cluster centres $\{\mu_j\}$
- This probability function can be generalised, notably to take account of the *shape* of the clusters and not just their centres, leading to *Gaussian Mixture Model* (GMM) probabilistic clustering

Review: Multivariate (2D) Gaussian/Normal distribution



Source: Wikipedia

- The distribution can have different dimensions that do not need to align with the coordinate axes; captured as a 2x2 covariance matrix C
- The distribution stretches to infinity in the plane, but points far from the centre of the distribution have very low probability.
- A collection of clusters can be modelled by overlaying a *mixture* of such Gaussian distributions on the plane.

Review of Bayes Theorem

Use of Bayes Theorem in Classification

Likelihood is the probability of the data given the label. Prior measures our belief about how likely each label is *before* we have seen any data. The Posterior includes influences of both the Prior and the Likelihood.

$$P(y = c|x) = \frac{P(x|y = c)P(y = c)}{P(x)}$$

The Posterior here is $P(y = c|x)$, the Likelihood is $P(x|y = c)$ and the Prior is $P(y = c)$. $P(x)$ is a normalizing constant that measures how likely the observed data x is.

When used for Gaussian Mixture Models, there is not just a *single* cluster label c, but a linear combination of many.

Overview of EM algorithm for GMM clustering

E-step For each x_i, calculate the probability that x_i belongs to the j^{th} distribution

$$P(\Theta_j|x_i,\Theta) = \frac{P(x_i|\Theta_j)}{\sum_{l=1}^{k} P(x_i|\Theta_l)},$$

where Θ_j is the set of parameters defining Gaussian distribution j, namely its centre $\boldsymbol{\mu}_j$ and covariance matrix C_j.

M-step Maximise the expected likelihood $P(\{x_i\}|\Theta)$ by updating the Gaussian mixture. That is, for each $\boldsymbol{\mu}_j$ and C_j, use all x_i and the $P(\Theta_j|x_i,\Theta)$ computed in the E-step) to derive the new Gaussian distribution parameters.

Note that the E-step computes a membership probability for each point based on all the Gaussian models and their parameters. By contrast, the M-step computes the new Gaussian models based on all the points and their membership probabilities.
Lloyd's k-means algorithm is equivalent: the membership probability is either 1 (allocated to this cluster) or 0 (not allocated to this cluster) for each point. The M-step re-computes the cluster centres based on all the points and their cluster assignment.

GMM compared with k-means

	k-means	GMM
E-step	Compute membership probability which is either 1 (allocated to this cluster) or 0 (not allocated to this cluster) for each point	Compute membership probability for each point based on all the Gaussian models and their parameters.
M-step	Recompute the new cluster centres based on all the points and their cluster assignment	Recompute the new Gaussian models based on all the points and their membership probabilities
Use for	Well-separated	Centre-based or well-separated
Shape	nondirectional (“spherical”)	directional (“ellipsoidal”) or nondirectional

Relaxing the constraints: density-based clustering

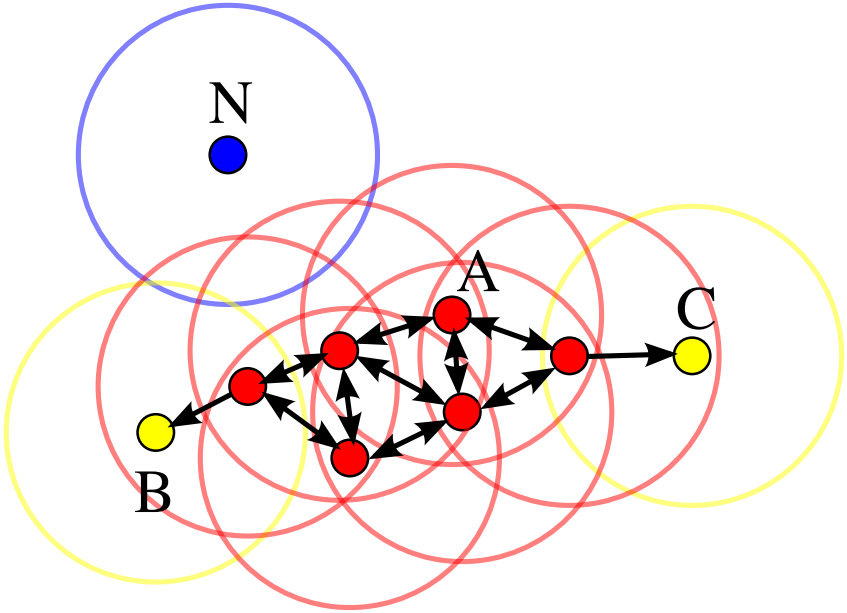
k-means and GMM are both characterised by the following properties:

- the number of clusters k must be specified beforehand
- clusters have a convex shape
- they work best when the clusters are linearly separable
- all points are assigned to clusters, so can be sensitive to outliers

Density-based clustering relaxes these conditions

It uses the heuristic that clusters are (arbitrarily-shaped) contiguous regions with high datapoint density.
Datapoints outside these regions represent *noise* and are ignored.
Rather than specifying k, the user specifies density thresholds.

Relaxing the constraints: density-based clustering



Source: wikipedia

- A, B and C are directly connected points.
- A is a core point
- B and C are border points.
- N is a noise point and so is not assigned to a cluster.
- The connected component of the 8 points (6 red, 2 yellow; including A,B,C) forms a cluster.

DBSCAN algorithm and its concepts

Definition 9 (DBSCAN)

Density-Based Spatial Clustering of Applications with Noise (DBSCAN): an algorithm for deriving clusters in areas of high data density.

Definition 10 (eps-neighbourhood)

Epsilon ϵ parameter defines a region of points $\boldsymbol{t}$ around a point $\boldsymbol{x}$ where $\|\boldsymbol{t} - \boldsymbol{x}\| < \epsilon$.

Definition 11 (core point)

Point with at least `MinPts`-1 other points in its eps-neighbourhood.

Definition 12 (border point)

Point with less than `MinPts`-1 other points in its eps-neighbourhood, but at least one is a core point.

Definition 13 (noise point)

Point with less than `MinPts`-1 other non-core points in its eps-neighbourhood.

Development of the algorithm

Definition 14 (Direct density reachable)

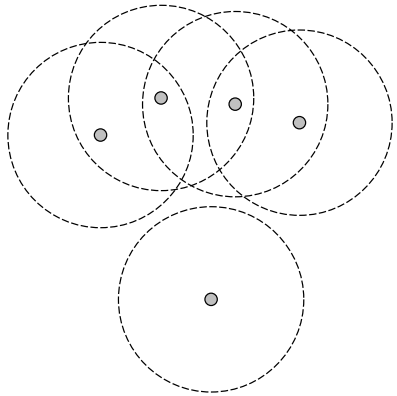
Point $\boldsymbol{x}_A$ is directly density reachable from $\boldsymbol{x}_B$ iff $\boldsymbol{x}_A$ is in the eps-neighborhood of $\boldsymbol{x}_B$ and $\boldsymbol{x}_B$ is a *core point*.

Definition 15 (Density reachable)

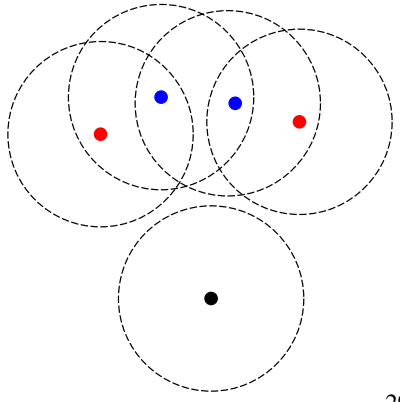
Point $\boldsymbol{x}_A$ is density reachable from $\boldsymbol{x}_B$ if there is a set of core points in each other's eps-neighbourhood between $\boldsymbol{x}_A$ and $\boldsymbol{x}_B$.

Definition 16 (Density connected)

Points $\boldsymbol{x}_A$ and $\boldsymbol{x}_B$ are density connected if there exists a core point $\boldsymbol{x}_C$ so that both $\boldsymbol{x}_A$ and $\boldsymbol{x}_B$ are density reachable from $\boldsymbol{x}_C$.



Core, border and noise points are coloured blue, red and black below.



Steps of the DBSCAN algorithm

Method (DBSCAN)

1. Find the ϵ neighbors of every point.
2. Identify the core points with more than minPts neighbors.
3. Derive the *connected component* graphs of core points, assigning edges between core points that are less than ϵ apart.
4. Identify the border points and assign them to their nearest cluster.
5. Label any remaining points as *noise*.

- A variant (HDBCSAN) excludes border points from the cluster, treating them as noise points (can be more robust).
- Another vatiant (OPTICS) places the points in a priority queue, ordered by reachability distance (updating is slower, but handles varying density better).

Choosing k, the number of clusters

How can we decide on k for k-means and GMM?

- We can do this *graphically* (plot clusters for each k) or by using *scores*.
- Plot within-cluster sum of squared distances (inertia) against k and look for k at the "elbow".
- Use `kmeans.inertia_` as the score for a given instance of the kmeans classifier.
- Can also compute inertia for other partitional clustering techniques, but this is more work and interpretation is more difficult.

Silhouette scores - derivation

How much is any point in a cluster nearer its peers than it is to points in the nearest of the other clusters?

Method (Silhouette score)

Require: Clustering where the i point is assigned to cluster $C(i)$ and there are k such clusters
for all point i in cluster $C(i)$ **do**
Calculate $a(i)$, the mean distance between i and all the other points in $C(i)$. $\triangleright$ $a(i) \equiv 0$ is there is no other point in $C(i)$.
Calculate $b(i)$, minimum of the mean distances between i and all the other points in each of $C(j)$ where $j \neq i$.
Silhouette $s(i) = 1 - a(i)/b(i)$ if $a(i) < b(i)$, $s(i) = 0$ if $a(i) = b(i)$ and $s(i) = b(i)/s(i) - 1$ if $a(i) > b(i)$.
end for
The mean of $s(i)$ over all points ($\bar{s}_k$) is a measure of the clustering efficiency for that value of k.
The k associated with the *maximum* of these $\bar{s}_k$ silhouette scores is the best choice of k.

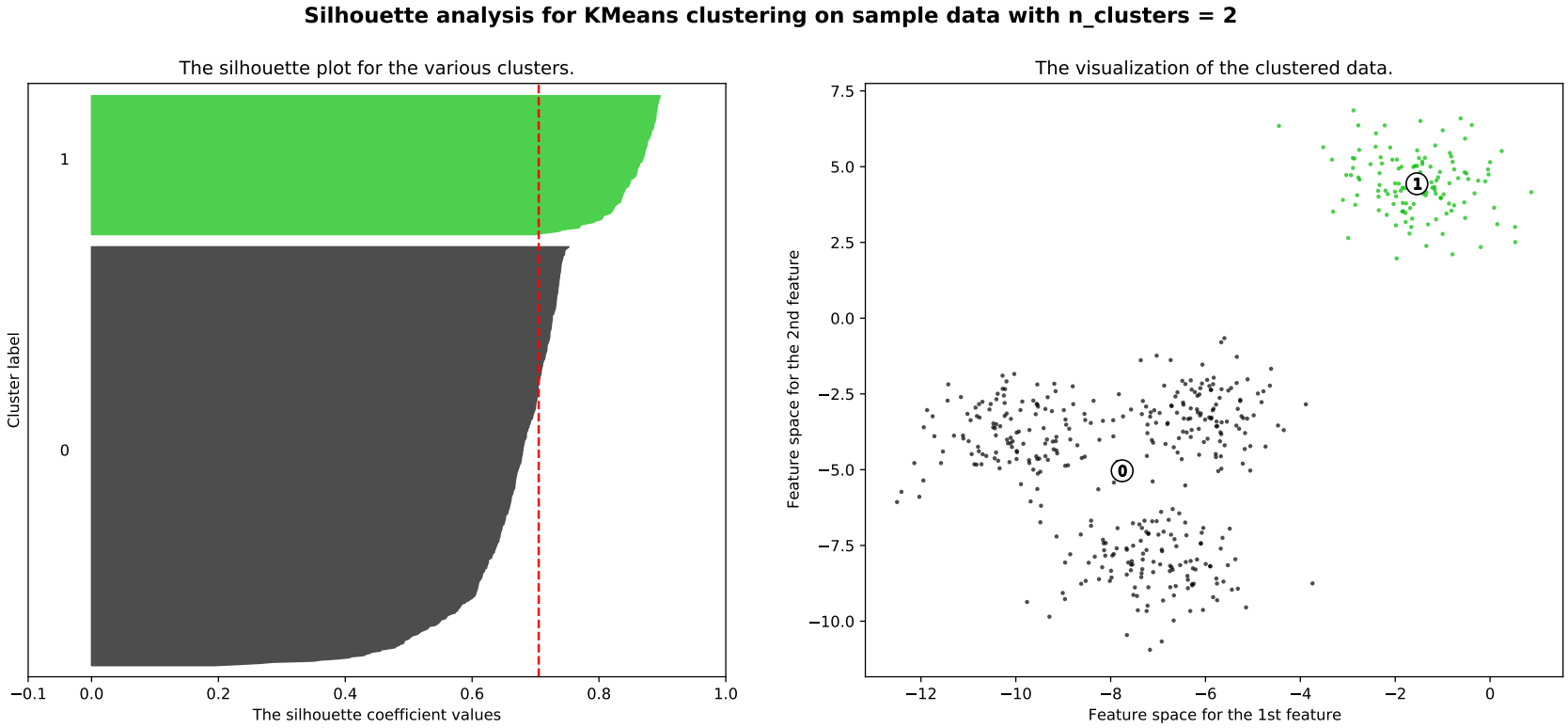
There are many other scores but they require more advanced mathematics and are out of scope for this module.

Silhouette scores - examples

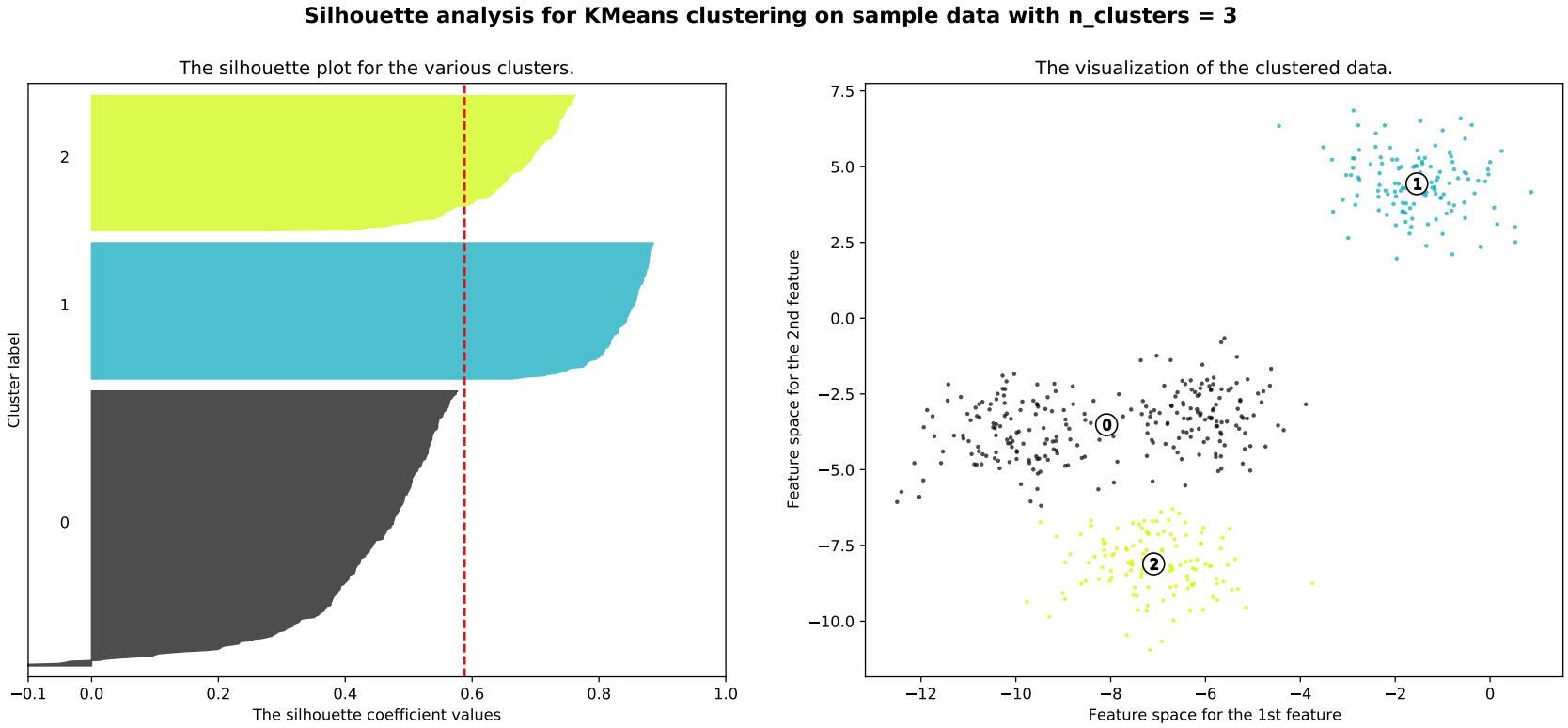
Code to create silhouette plots

```
from sklearn.metrics import silhouette_samples, silhouette_score

clusterer = KMeans(n_clusters=n_clusters, random_state=10)
cluster_labels = clusterer.fit_predict(X)

# The silhouette_score gives the average value for all the samples.
silhouette_avg = silhouette_score(X, cluster_labels)
```

Silhouette score with $k = 2$ - looking good

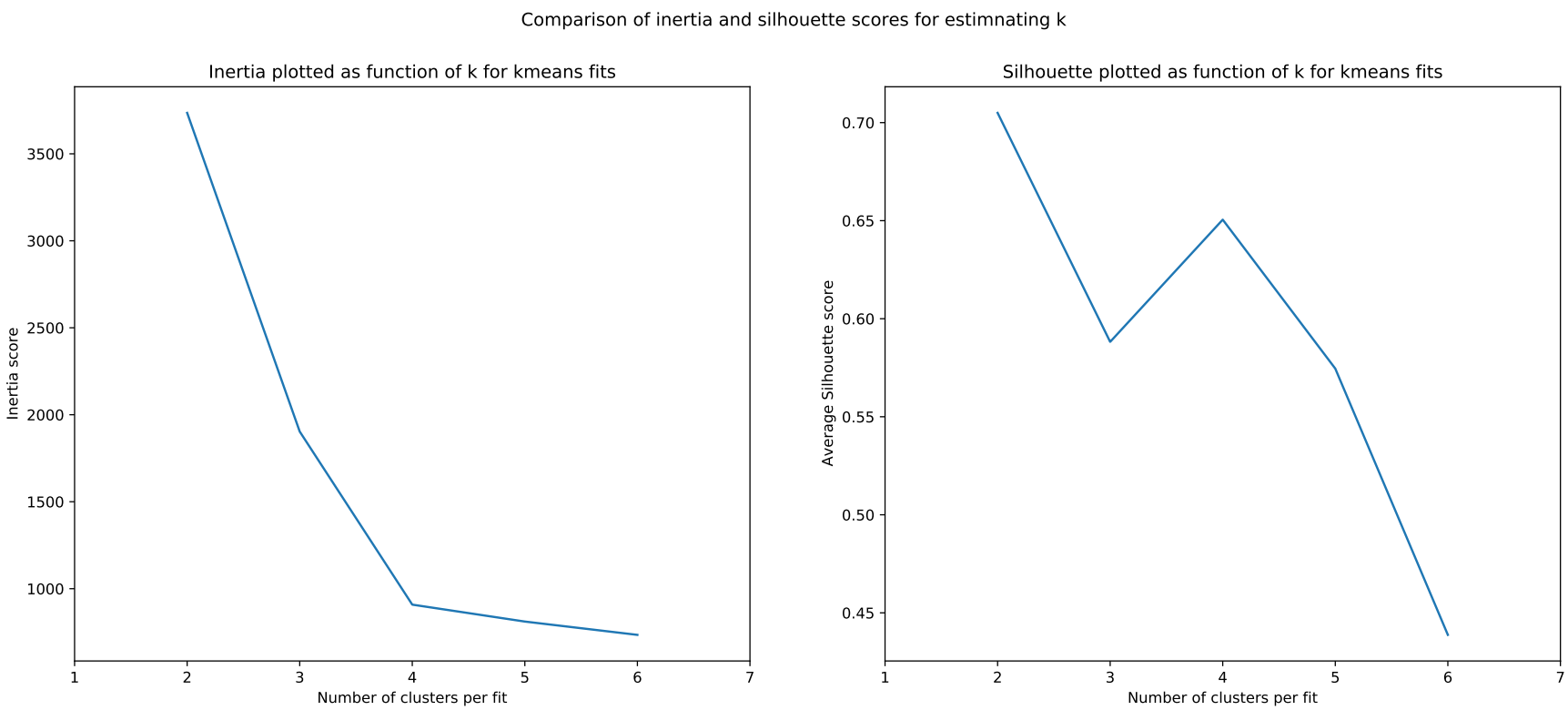


Silhouette score with $k = 3$ - not looking good



Comparing both scoring systems

Inertia/elbow plot and silhouette plot on the same data



Choice of hyperparaneters

k-means : choose distance function, starting condition (cf kmeans++), aggregation (cf k-medoids), k

GMM : choose distance function, k

DBSCAN : choose distance function, `minpts`, `eps`

Tips

- Good idea to scale so that clusters are approximately (hyper)spherical.
- Can be good idea to transform data before clustering.

Summary

- Clustering is perhaps the best known form of unsupervised learning
- Hierarchical clustering can provide insights into the structure of a data set - very useful when exploring data for other techniques
- Partitional clustering can be used to label points according to which cluster they belong to
- Partitional classification has many approaches: centre-based and density based are most common
- Clustering can be used to help create training data for classification purposes (c.f., the digits notebook used in the practical)

References