Fall 2023	**CSC 466:** Knowledge Discovery from Data	Alex Dekhtyar

Lab 4: Clustering

Due date: Friday, November 10, 2:00pm.

Overview

In this assignment you will use unsupervised learning techniques to discover clusters in a number of simple datasets. You will implement three cluster analysis methods, ***k*-means clustering**, **agglomerative hierarchical clustering** and DBSCAN.

Assignment Preparation

This is a pair programming assignment. Each student teams up with a partner. **For this lab, unless you have already changed a partner once in this course, pick a partner different than your Lab 3 partner. If you have changed partners before, you can, but do not have to change partners.** I **strongly recommend** that all students take active part in implementing each of the algorithms.
Note: Open-source versions of clustering algorithms are plentiful. It is considered cheating to re-use code for clustering algorithms that was written by someone else. (You may use code from other *explicitly acknowledged sources* for other purposes in the program, e.g., for parsing input).

Data

We provide multiple **simple datasets** for use in this assignment. Each dataset consists of two files: a CSV (comma-separated values) file containing the actual data and a text `.txt` file containing the *header* of the dataset, specifying the names of the attributes.

Most of the datasets were adopted from

http://people.sc.fsu.edu/~burkardt/datasets/hartigan/hartigan.html

which contains a list of datasets from [1] and [2]. Some of these datasets contain real data, some — are synthesized. One more dataset, Iris, is a classical machine learning dataset. from the University of California, Irvine Machine Learning repository[1] The remaining data file come from the FATAL ACCIDENTS dataset, collected by Peter Oyler[2]. The dataset contains information about automobile accidents in California that resulted in fatalities. All CSV files for all datasets have exactly the same format.

CSV file format. The first line of each CSV file is analogous to the restrictions file in the **Lab 3** assignment. It is a **binary vector** identifying which columns of the CSV file shall be used for clustering. In some CSV files, one of the columns is used as a `rowId`, and should be excluded from the analysis, while in some other files, all columns contain data. In the Iris dataset, the last column (labeled as 0 by the restrictions vector) is actually a class label, which can be used as ground truth to validate the quality of the clustering.
0 in position i of the first row means that column i should be ignored in the cluster analysis.
1 in position 1 of the first row means that column i should be used in the cluster analysis.

The remaining rows of the CSV file contain data points.

[1] http://archive.ics.uci.edu/ml/index.html
[2] Peter took the first version of CSC 466. The FATAL ACCIDENTS dataset was his data analytical project.

Text files. Text files need not be processed by your programs. Text files contain the original headers for each dataset, split from the CSV data to simplify parsing. The headers describe the nature of the dataset, contain references to its origins and specify the names of each column in the dataset. If you want to use attribute headers in your program (e.g., for generating output), you may either add a header file name as a parameter to your program, or deduce the header file name (it will always be `header_` followed by the name of the data file w/o extension, followed by `.txt`).

List of Datasets

The following datasets are *officially* provided to you for this assignment. Each file listed below, as well as a `zip` archive of the entire collection is available at the following URL:

http://www.csc.calpoly.edu/ dekhtyar/466-Fall2021/lab04.html

CSV File	Header File	Dataset	Source
`4clusters.csv`	`header_4clusters.txt`	4 clusters in 2D space (synthetic)	Spaeth[2]
`mammal_milk.csv`	`header_mammal_milk.txt`	constituents of mammal milk	Hartigan[1]
`planets.csv`	`header_planets.txt`	sightings of minor planets	Hartigan[1]
`iris.csv`	`header_iris.txt`	measurements of different Iris flowers	UCI ML repository
`AccidentsSet03.csv`	`header_AccidentsSet03.csv`	fatal automotive accidents	P. Oyler

More datasets can be manufactured and used by each team, but only the datasets listed above will be used as part of your lab deliverables.

Lab Assignment

You will investigate the behavior of three common clustering procedures, ***k*-means clustering** **agglomerative hierarchical clustering** and DBSCAN on the datasets provided to you. Part of your assignment involves implementation of the three clustering procedures. In addition to this, you will study the datasets using your implementations of the clustering algorithms, and will submit the results you have obtained.

For simplicity, the lab refers to Java or Python programs whenever specific pieces of code are mentioned. **However, each team is free to implement clustering algorithms in their programming language of choice** *(provided that the instructions on how to run their programs are submitted as part of the lab deliverables).*

k-means Clustering

You will implement the ***k*-means clustering** algorithm as `kmeans.java` or `kmeans.py` programs[3].

Input. The program shall take as input two parameters:

```
java kmeans <Filename> <k>
```

or

```
python kmeans.py <Filename> <k>
```

`<Filename>` is the name of the CSV file containing the input dataset.
`<k>` is the number of clusters the program has to produce.

Note: Your program *may take additional parameters* based on the needs of your implementation (see below). All additional parameters must be supplied after the first two and must be properly documented in your `README` file.

[3]Feel free to have as many support .java or .py files as you need.

Internals. There is a variety of versions of the k-**means clustering algorithm**. Each team is encouraged to (a) select the specific version and, possibly (b) experiment with different versions [4] to discover the one that produces better clusters (or works faster).

Among the different decisions that each team can make are:

- Choice of **initial cluster centroids**. Random, SelectCentroids/KMeans++ procedure, pre-selected, other variations....
- Choice of **centroid recomputation method**. Typically, the **mean** point of the cluster (hence the "k-**means**" in the name of the method), but you can use **medians** or **modes** if so desired.
- **Stopping criterion.** Minimum point reassignment, minimum centroid change, threshold on sum of squared error (SSE) (for the latter — you need to find a good threshold).
- **Distance measure.** While Eucledean distance makes sense for some of the datasets (the 2D synthetic ones, e.g.), you may choose to try other distance measures to see if your cluster organization changes/becomes more pronounced.
- **Data normalization/standardization.** While this is not part of the k-means clustering algorithm per se, you may choose to include an optional data normalization or data standardization procedure to deal with input data where different attributes have values from drastically different scales.
- **Dealing with outliers.** Attempt to detect outliers vs. no outlier detection.

Output. The output of your program shall consist of two things:

1. Description of the detected clusters.
2. Evaluation of the computed clustering of the data.

Since our datasets are small, describe detected clusters **by listing all points belonging to them** (this also simplifies grading/comparison). If data points come with `rowIds`, you are allowed to output just them. You can also threshold direct output of all data points in a cluster, and, if your code runs on larger datasets, output a selection of data points in each cluster, or use some output approach.

Since except for the Iris dataset we lack well-established (and available to your program) **ground truth** on clusters, only **internal evaluation measures** for clusters need to be computed and reported. For the Iris dataset, you can compute the accuracy/cluster purity measures for each cluster.

For each cluster, compute and report:

1. Number of points in the cluster.
2. Coordinates of its centroid.
3. Maximum, minimum, and the average distance from a point to cluster centroid.
4. Sum of Squared Errors (SSE) for the points in the cluster.

You may *additionally* choose to report any other internal measures, e.g., **inter-cluster distances**.

Here is an example of an output for a single cluster (w/o the SSE):

```
Cluster 0:
Center: 26.25,28.0,
Max Dist. to Center: 10.077822185373186
Min Dist. to Center: 3.010398644698074
Avg Dist. to Center: 6.569312544990502
```

[4] This is where two people can work in parallel on the same program.

```
4 Points:
25.0,38.0,
32.0,27.0,
26.0,25.0,
22.0,22.0,
```

(Your output does not have to match this, but should report the information in an easy-to-read way).

Hierarchical Clustering

You will implement the **agglomerative hierarchical clustering** method as an `hclustering.java` or an `hlcustering.py` program.

Input. Your program shall take two parameters as input:

```
java hclustering <Filename> [<threshold>]
```

or

```
python hclustering <Filename> [<threshold>]
```

`<Filename>` is the name of the CSV file containing the input dataset.
`<threshold>` is the *optional* threshold at which your program will "cut" the cluster hierarchy to report the clusters.

If `<threshold>` parameter is **specified** in the input, your program shall produce both the cluster hierarchy, and the appropriate list of clusters cut at the specified threshold.

If `<threshold>` parameter is **not specified** in the input, your program shall produce the cluster hierarchy **alone**.

Note. Your program may include other optional parameters (e.g., selection of the linkage method) after the first two parameters are entered. If you are including additional parameters, please document them properly in the `README` file.

Internals. Commonly, **hierarchical clustering algorithms** take as input the distance matrix for the points in the input dataset. Your algorithm will work with the same data as the ***k*-means clustering algorithm**, i.e., the actual dataset. Your implementation of the hierarchical clustering method will be responsible for computing the distances between all points in the dataset.

I strongly recommend that you separate the computation of the distance matrix from the actual clustering procedure and make your implementation of the hierarchical clustering take a distance matrix computed from the input data as input. This will allow for some code reuse between the implementation of the hierarchical clustering algorithm and DBSCAN.

Additionally, as with ***k*-means clustering**, in your implementation of the **agglomerative hierarchical clustering** algorithm, you can select the specific details of implementation that you prefer, or experiment with multiple options.

Among the features you have to select are:

- **Distance measure for points.** See ***k*-means clustering algorithm** discussion.
- **Distance measure for clusters.** Select between **single-link**, **complete-link** and **average-link** methods (you can also try **centroid** or **Ward's** methods).

Output. Your implementation shall produce as output the following information:

- The **dendrogram of the cluster hierarchy** constructed by the algorithm. This dendrogram is independent of the threshold and shall be produced each time the program is run. It is useful to output the dendrogram into a separate file.
- The **actual clusters** obtained by applying the input threshold to the computed **cluster hierarchy**.
- The **evaluation** measures specifying the quality of the obtained clusters.

The latter two types of output should be produced **only if** the threshold value is specified in the input. If it is not specified, only the tree is produced and returned.

Dendrogram. Create an XML or a JSON version of the cluster hierarchy dendrogram and output it. You need to output the dendrogram XML to `stdout`, but you may, if you want, also create an XML or JSON file to store it (in fact, it is recommended that you do so).

XML. The XML representing the dendrogram is simple and straightforward. The dendrogram is a binary labeled tree. You will use three XML elements:

- `<tree>` to indicate the root node of the dendrogram.
- `<node>` for all inner nodes.
- `<leaf>` for all leaf nodes containing individual data points. Leaf elements are `EMPTY`.

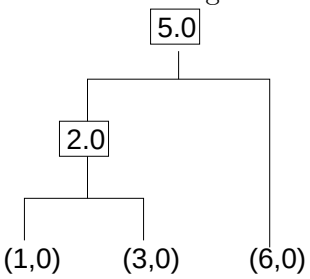
The `<tree>` and `<node>` elements will contain an attribute `height` representing the height label of the node (the distance between the two clusters that are merged).

The `<leaf>` elements will contain an attribute `data` whose contents shall be the data point from the dataset represented by the leaf node (or its `rowId`). For the sake of completeness, feel free to add a `height` attribute with the value of 0 to the `<leaf>` elements.

The `<tree>` and all `<node>` elements shall have exactly two children: either `<node>` or `<leaf>` elements.

Here is an example of a small XML output and the dendrogram it represents.

```
<tree height = "5.0" >
   <node height = "2.0">
      <leaf height= "0" data ="1, 0"/>
      <leaf height= "0" data ="3, 0"/>
   </node>
   <leaf height = "0" data = "6,0"/>
</tree>
```



JSON. The JSON version of the dendrogram represents the same information as the XML version. Use for following JSON format.

- The root node, and any internal node JSON object shall contian three attributes:

`type`	`"root"` for root node, `"node"` for internal nodes
`height`	the height of the node in the tree
`nodes`	a JSON array consisting of two JSON objects representing the subtrees

- A JSON object for a leaf node shall contain the following three attributes:

`type`	`"leaf"`
`height`	the height of the node in the tree (typically value is 0.0)
`data`	data point represented by the leaf

Here is the same tree in JSON format.

```
{"type": "root"
 "height": 5.0,
 "nodes": [{"type": "node",
            "height": 2.0,
            "nodes": [{ "type":"leaf"
                        "height":0,
                        "data": "1,0"},
                      { "type": "leaf":
                        "height": 0,
                        "data" :"3,0"
                      }]
           },
          {"type": "leaf",
           "height": 0,
           "data": "6,0"
           }
          ]
}
```

Note: You may use a JSON array for storing the value of the `data` attribute in the leaf node:

```
{"type": "leaf",
 "height": 0,
 "data": [6,0] }
```

Clusters and measures. Whenever a threshold is specified, your program shall, in addition to producing the full dendrogram, also report the clusters that are formed when the dendrogram is cut at the specified threshold. The clusters and their parameters shall be reported in the same way as your ***k*-means clustering algorithm** implementation does it.

DBSCAN

You will implement the **agglomerative hierarchical clustering** method as a `dbscan.java` or `dbscan.py` program.

Input. Your program shall take three parameters as input:

```
java dbscan <Filename> <epsilon> <NumPoints>
```

or

```
python dbscan <Filename> <epsilon> <NumPoints>
```

`<Filename>` is the name of the CSV file containing the input dataset.
`<epsilon>` is the *Epsilon (ε)* parameter of the DBSCAN algorithm: the radius within which DBSCAN shall search for points.
`<NumPoint>` is the minimal number of points within the `<epsilon>` distance from a given point to continue building the cluster.

Internals. Efficient implementation of DBSCAN requires knowledge of spatial data structures (such as R-trees, or k-d trees) to store data points and allow the algorithm to prune computations of distances between the points. Given the sizes of the input datasets, it is ok for you to implement DBSCAN *naïvely* as follows:

- compute the matrix of pairwise distances between the points
- for each point, construct a list of points within the `<epsilon>`-vicinity
- using the data structure you constructed on the previous step, perform DBSCAN search until you run out of points.

With proper data structures used, this algorithm will be rather efficient for small datasets.

Output. The output of your `dbscan.java` or `dbscan.py` program shall look similar to the output of your `kmeans` program, with one additional caveat.

DBSCAN allows for easy outlier detection (outliers are all data points that do not get placed into clusters). Because of this, in addition to reporting the information about each cluster, as you would in the output of your `kmeans` program, your DBSCAN output shall also include information about the outliers detected. On small inputs, you can list all outliers, and provide some basic statistics (total number of outliers, percentage of the dataset outliers constitute). For large inputs, you may trim the output of the outliers, but shall still provide the basic statistics.

Study of the datasets

You will use your implementations of the **k-means clustering**, **agglomerative hierarchical clustering** and DBSCAN methods to study the datasets provided to you and to find the *best* (in your opinion) clusters in the data.

The results of your study will be compiled in the report that each team will prepare and submit.

Use all methods. For each dataset provided to you, you need to use all three methods (programs) to discover the best clusters. Your report will indicate the best results you achieved using each of the three programs.

Best clustering. Each implementation has hyperparameters (k, number of clusters, for k-means clustering; threshold for hierarchical clustering, ε and $NumPoints$ for DBSCAN), that affect the output of the respective program. In addition, each team may choose to implement multiple choices for various parts of each algorithm (e.g., you may implement all three *linking* techniques for the hierarchical clustering, or a number of different ways to select the initial centroids for the k-means clustering).

You will run your programs on each dataset with different settings of the input parameters (and any choices that you have implemented) to determine which runs produce the best clustering result. A systematic approach to doing so is called *tuning hyperparameters*. In case of clustering, such tuning may have to be performed manually – as it will fall on you to determine which cluster evaluation metrics computed by your programs constitute a better clustering of your data (in case of hypertuning parameters for classification you often can do it automatically).

Additionally, you may choose to determine the **ground truth** for some (or all) of the datasets and compare the outputs to the results you obtain. Ground truth for the Iris dataset is given in the dataset itself. For some other datasets it can be determined by investigating/visualizing the dataset using any tools available to you. 2D and some 3D datasets, for example, can be plotted as scatterplots using Excel or matplotlib, and visual observation may help you determine the clusters that should be detected by your program. (For some datasets, like the `economy` dataset, which has 10 variables, simple visualization may be infeasible).

Report. Each team will prepare a report of discoveries. The report will consist of the following information:

1. Study Design. Provide brief description of your implementations of the two clustering methods. Specify which features (such as distance measures, centroid chocies, etc.) you have implemented and used in the study.
2. Results. For each dataset, and for each algorithm provide the description of the best result achieved. Specify the input parameters (and features) of the program that lead to the best result, and provide a snapshot of the obtained output. **Do not paste the output verbatim** (you will be putting it in the appendix).
3. Visualization. Where possible (some of your datasets have only 2-3 dimensions), provide a visualization of the clustered data.
4. Discussion. May be embedded into reporting of results. Mention any interesting observations about specific datasets/methods that you have made during the study.
5. Analysis. Present an overall conclusion of your results. Which method(s) performed better? Did some method worked better on some specific type of data and another – on different data? When did each of the algorithms perform well? What features (if any) of each algorithm lead to better performance in what cases?
6. Appendix. Clustering output. Provide the full descriptions of the clusters you obtained on all runs your report covers. Make sure your appendix is carefully organized. Your Results, Visualization and Discussion sections can reference any content in the Appendix, so make sure results of each run are properly annotated with the dataset used, method/algorithm used, and any applicable parameter settings.

PLEASE, keep the length of your report reasonable. In the past, some submitted reports were hundreds of pages long (while others submitted perfectly acceptable reports that were only 10-15 pages long). Make sure your cluster representation outputs are sufficiently compacts. Only include in your reports and the appendix the results that are needed (do not include your entire history of hyperparameter tuning). Your report should present **curated** results to the instructor - curated by you!

Deliverables and submission instructions

This lab has both electronic and harcopy deliverables.

Electronic deliverables.

- `kmeans.java`/`kmeans.py` and all supporting files.
- `hclustering.java`/`hclustering.py` and all supporting files.
- `dbscan.java`/`dbscan.py` and all supporting files.
- `README` file specifying what has been implemented, and providing any instructions for compiling and running the code. (must contain the names of all students on the team).
- **The report.** The electronic version of the report should be submitted in PDF format.

Please place all your deliverables **EXCEPT** the PDF version of the report and the `README` file into a sinlge zip file `lab04.zip`. **Please submit your PDF report the `README` file separately.**

Use the following command

```
$ handin dekhtyar 466-lab04 <Files>
```

References

[1] John Hartigan, *Clustering Algorithms*, Wiley, 1975. ISBN 0-471-35645-X.

[2] Helmut Spaeth, *Cluster Dissection and Analysis, Theory, FORTRAN Programs, Examples*, Ellis Horwood, 1985.