

# Project-4 of “introduction to Statistical Learning and Machine Learning”

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## Abstract

(1) This is the fourth project of our course. The project is released on Dec 10, 2017. The deadline is 5:00pm, Dec 30, 2017 (and happy New Year, by the way). Please send the report to 582195191@qq.com, or 17210240267@fudan.edu.cn.

(2) The goal of your write-up is to **document the experiments you’ve done and your main findings. So be sure to explain the results.** The report can be written by Word or Latex. Generate a single pdf file of your mini-projects and turned in along with your code. package your code and a copy of the write-up pdf document into a zip or tar.gz file and named as Project4-\*your-student-id\*\_your\_name.[zip|tar.gz]. Only include functions and scripts that you modified. Also put the names and Student ID in your paper. To submit the report, email the pdf file to 582195191@qq.com, or 17210240267@fudan.edu.cn..

(3) About the deadline and penalty. In general, you should submit the paper according to the deadline of each mini-project. The late submission is also acceptable; however, you will be penalized 10% of scores for each week’s delay.

(4) Note that if you are not satisfied with the initial report, the updated report will also be acceptable, nevertheless given the necessary score penalty of late submission. The good thing is that we will compare and choose the higher score from several submissions as your final score of this project.

(6) OK! That’s all. Please let me know if you have any additional doubts of this project. Enjoy!

## 1 Dimensionality Reduction

This practical session is an opportunity to explore data using the methods. We have provided two data sets:

- freyface.mat – images of Brendan Frey’s face in a variety of expressions: start with this one
- swiss roll – There is also MATLAB code to generate the artificial “swiss roll” data. Feel free to use other data sets if you have them. We have also provided code to help with visualisation, as well as LLE and Isomap.

Matlab code for other dimensionality reduction techniques is available from: <https://lvdmaaten.github.io/drtoolbox/>

### 1.1 freyface.mat

X contains 1965 images of Brendan Frey’s face. It is stored in integer format, although MATLAB does not support this very well. It is best to convert to double:

```
>> load freyface.mat
>> X = double(X);
```

The function *showfreyface* renders the image(s) in its argument. Try *showfreyface(X(:,1:100))*.

## 1.2 PCA

Find the eigenvectors of  $X * X^T / N$ , both with and without first removing the mean:

```
>> N = size(X, 2);
>> [Vun, Dun] = eig(X*X'/N);
>> [lambda_un, order] = sort(diag(Dun));
>> Vun = Vun(:, order);
>> Xctr = X - repmat(mean(X, 2), 1, N);
>> [Vctr, Dctr] = eig(Xctr*Xctr'/N);
>> [lambda_ctr, order] = sort(diag(Dctr));
>> Vctr = Vctr(:, order);
```

Which of these corresponds to PCA?

1. Look at the *eigspectra* (i.e. plot the  $\lambda$ ). What might be a good choice for  $k$ ? Is it easy to tell?
2. Look at the top 16 eigenvectors in each case (the sorted output of *eig* above placed eigenvalues in increasing order, so this would be *showfreyface(V(:,end-15:end))*; or you can use *eigs* to obtain just the top 16). Can you interpret them? How do they differ?
3. Project the data onto the top two eigenvectors, and plot the resulting 2D points. You can use the function *explorefreymanifold* to explore this space. Does what you see make sense?

```
>> Y = V(:,end-1:end)' * X;
>> plot(Y(1,:), Y(2,:), '.');
>> explorefreymanifold(Y, X);
```

(note:  $V$  here could be either  $Vun$  or  $Vctr$ : how do the manifolds differ?)

4. Try reconstructing a face from an arbitrary point in this space. That is, choose a point  $y$  within the space and compose the corresponding projected vector  $\hat{x}$ . Remember to add back in the mean when working with eigenvectors in the centered data. Does it look reasonable?
5. Try adding noise to a face (help *randn* if you don't know how), projecting to the manifold (i.e. find the corresponding  $y$ ) and then reconstructing (i.e. find  $\hat{x}$ ).

## 1.3 swissroll.m

This is code provided by Roweis and Saul to generate “swiss roll” data and run LLE. You may want to extract the data generation part of it and try running other algorithms on the same data set. Please show the images you visualized in the report.

## 2 Gaussian Mixture Model

In this assignment, you will experiment with the mixture of Gaussians model. Some code that implements mixture of Gaussians model will be provided for you (both MATLAB and Python).

You will be working with the following dataset:

**Digits:** The file `digits.mat` contains 6 sets of 1616 greyscale images in vector format (the pixel intensities are between 0 and 1 and were read into the vectors in a raster-scan manner). The images contain centered, handwritten 2's and 3's, scanned from postal envelopes. `train2` and `train3` contain examples of 2's and 3's respectively to be used for training. There are 300 examples of each digit, stored as 256x300 matrices. Note that each data vector is a column of the matrix. `valid2` and `valid3` contain data to be used for validation (100 examples of each digit) and `test2` and `test3` contain test data to be used for final evaluation only (200 examples of each digit).

### 2.1 EM for Mixture of Gaussians

Let us consider a Gaussian mixture model:

$$p(x) = \sum_{k=1}^K \pi_k \mathcal{N}(x | \mu_k, \Sigma_k)$$

Consider a special case of a Gaussian mixture model in which the covariance matrices  $\Sigma_k$  of the components are all constrained to have a common value  $\Sigma$ . In other words  $\Sigma_k = \Sigma$ , for all  $k$ . Derive the EM equations for maximizing the likelihood function under such a model.

### 2.2 Mixtures of Gaussians

The Matlab file `mogEM.m` implements the EM algorithm for the MoG model. The file `mogLogProb.m` computes the log-probability of data under a MoG model. The file `kmeans.m` contains the k-means algorithm. The file `distmat.m` contains a function that efficiently computes pairwise distances between sets of vectors. It is used in the implementation of k-means.

Similarly, `mogEM.py` implements methods related to training MoG models. The file `kmeans.py` implements k-means.

As always, read and understand code before using it.

### 2.3 Training

The Matlab variables `train2` and `train3` each contain 300 training examples of handwritten 2's and 3's, respectively. Take a look at some of them to make sure you have transferred the data properly. In Matlab, plot the digits as images using `imagesc(reshape(vector,16,16))`, which converts a 256-vector to an 16x16 image. You may also need to use `colormap(gray)` to obtain grayscale image. Look at `kmeans.py` to see an example of how to do this in Python.

For each training set separately, train a mixture-of-Gaussians using the code in `mogEM.m`. Let the number of clusters in the Gaussian mixture be 2, and the minimum variance be 0.01. You will also need to experiment with the parameter settings, e.g. `randConst`, in that program to get sensible clustering results. And you'll need to execute `mogEM` a few times for each digit, and see the local optima the EM algorithm finds. Choose a good model for each digit from your results.

For each model, show both the mean vector(s) and variance vector(s) as images, and show the mixing proportions for the clusters within each model. Finally, provide  $\log P(\text{TrainingData})$  for each model.

## 2.4 Initializing a mixture of Gaussians with k-means

Training a MoG model with many components tends to be slow. People have found that initializing the means of the mixture components by running a few iterations of k-means tends to speed up convergence. You will experiment with this method of initialization. You should do the following.

- Read and understand *kmeans.m* and *distmat.m* (Alternatively, *kmeans.py*).
- Change the initialization of the means in *mogEM.m* (or *mogEm.py*) to use the k-means algorithm. As a result of the change the model should run k-means on the training data and use the returned means as the starting values for  $\mu$ . Use 5 iterations of k-means.
- Train a MoG model with 20 components on all 600 training vectors (both 2's and 3's) using both the original initialization and the one based on k-means. Comment on the speed of convergence as well as the final *log-prob* resulting from the two initialization methods.

## 2.5 Classification using MoGs

Now we will investigate using the trained mixture models for classification. The goal is to decide which digit class  $d$  a new input image  $x$  belongs to. We'll assign  $d = 1$  to the 2's and  $d = 2$  to the 3's.

For each mixture model, after training, the likelihoods  $P(x | d)$  for each class can be computed for an image  $x$  by consulting the model trained on examples from that class; probabilistic inference can be used to compute  $P(d | x)$ , and the most probable digit class can be chosen to classify the image.

Write a program that computes  $P(d = 1 | x)$  and  $P(d = 2 | x)$  based on the outputs of the two trained models. You can use *mogLogProb.m* (or the method *mogLogProb* in *mogEm.py*) to compute the log probability of examples under any model.

You will compare models trained with the same number of mixture components. You have trained 2's and 3's models with 2 components. Also train models with more components: 5, 15 and 25. For each number, use your program to classify the validation and test examples.

For each of the validation and test examples, compute  $P(d | x)$  and classify the example. Plot the results. The plot should have 3 curves of classification error rates versus number of mixture components (averages are taken over the two classes):

- The average classification error rate, on the training set;
- The average classification error rate, on the validation set;
- The average classification error rate, on the test set.

Provide answers to these questions:

1. You should find that the error rates on the training sets generally decrease as the number of clusters increases. Explain why.
2. Examine the error rate curve for the test set and discuss its properties. Explain the trends that you observe.
3. If you wanted to choose a particular model from your experiments as the best, how would you choose it? If your aim is to achieve the lowest error rate possible on the new images your system will receive, which model (number of clusters) would you select? Why?