

CIS 520, Machine Learning, Fall 2020  
Homework 6  
Due: Monday, November 9th, 11:59pm  
Submit to Gradescope

**Instructions.** Please write up your responses to the following problems clearly and concisely. We require you to write up your responses using L<sup>A</sup>T<sub>E</sub>X; we have provided a L<sup>A</sup>T<sub>E</sub>X template, available on Canvas, to make this easier. **Submit your answers in PDF form to Gradescope. We will not accept paper copies of the homework.**

**Collaboration.** You are allowed and encouraged to work together. You may discuss the **written homework** to understand the problem and reach a solution in groups. However, **it is recommended that each student also write down the solution independently and without referring to written notes from the joint session.** You must understand the solution well enough to reconstruct it by yourself. (This is for your own benefit: you have to take the exams alone.)

## Learning Objectives

After completing this assignment, you will be able to:

- Understand how to use the EM algorithm.
- Understand how to choose suitable performance measures for a given task.
- Understand how different data imputation techniques compare to each other.
- Understand the effects of input scaling on K-means.
- Understand different heuristics to choose a good value of K for K-means.

## Deliverables

This homework can be completed **individually or in groups of 2**. You need to make one submission per group. Make sure to add your team member's name on Gradescope when submitting the homework's written and coding parts.

1. **A PDF compilation of `hw6_template.tex` with your solutions**
2. **A Notebook `.ipynb` file with all the functions implemented**

# 1 Programming: Missing Data Imputation [25 points]

For this question, refer to the Jupyter Notebook. You will be implementing different imputation techniques – the notebook will have detailed instructions.

## 1.1 Zero Imputation

[5 points] Look for the code marked #TODO in the notebook and complete the code between the segments according to the instructions.

- Add the accuracy and the Frobenius norm in this report.

Frobenius Norm	—
Accuracy	—

Table 1: Accuracy and Frobenius norm for Zero Imputation

- Add the code of the completed zeroImpute method.

```
1 # TODO
```

Listing 1: zeroImpute method

## 1.2 Mean Imputation

[6 points] Look for the code marked #TODO in the notebook and complete the code between the segments according to the instructions.

- Add the accuracy and the Frobenius norm in this report.

Frobenius Norm	—
Accuracy	—

Table 2: Accuracy and Frobenius norm for Mean Imputation

- Add the code of the completed meanImpute method.

```
1 # TODO
```

Listing 2: meanImpute method

## 1.3 Regression Imputation

[6 points] Look for the code marked #TODO in the notebook and complete the code between the segments according to the instructions.

- Complete the following table.

Epoch	Frobenius Norm	Accuracy
After Base Imputation	—	—
1	—	—
2	—	—
3	—	—
4	—	—
5	—	—

Table 3: Accuracy and Frobenius norm for Zero Imputation

- Plot for Accuracy for Regression based imputation vs. Number of Features imputed
- Plot for Norm for Regression based imputation vs. Number of Features imputed
- Plot for Accuracy for Regression based imputation vs Number of Epochs
- Plot for Norm for Regression based imputation vs. Number of Epochs
- Add the code of the completed regressedImpute method.

```
1 # TODO
```

Listing 3: regressedImpute method

## 1.4 Follow Up Questions

1. **[2 points]** Which is the best of the three imputation methods? Why (briefly)?
2. **[2 points]** Could you potentially do a better job of imputation if you also used y vales as well as x's? How might that help? If using the y's for imputation helps, why do people mostly not use them?  
*Hint: think through the whole process of model estimation and use.*
3. **[2 points]** Describe the trend for the accuracy and the norm as impute more features for regression imputation. Give a plausible explanation behind the trend.
4. **[2 points]** Describe the trend for the accuracy and the norm as re-impute again for several epochs for regression imputation. Give a plausible explanation behind the trend.

## 2 Programming: K-Means Analysis [25 points]

In this assignment, we will implement the K-means algorithm and perform it on a breast cancer data set. Please follow the attached Python notebook to write and plot the functions.

## 2.1 Part 1: K-means iteration function

Write the K-means iteration function as is described in the notebook. Each iteration takes the data and current centroid values for each class as parameters, and returns both updated centroid values along with a list of labels telling which class each datapoint belongs to.

1. **[8 points]** Fill in the table below by reporting the resulting cluster labels and resulting centroids from running the iteration function on the given parameters.

X	Initial Centroids	Resulting Cluster Labels	Resulting Centroids
[[1], [2], [10], [12]]	[1, 2]		
[[1], [2], [10], [12]]	[1, 8]		
[[1], [2], [10], [12]]	[2, 2]		
[[0,5,0],[0,5,0],[0,4,3],[0,3,4]]	[[2.5,0,0],[-2.5,0,0]]		

2. **[2 points]** If an iteration of the k-means algorithm returns less than K classes, what might that indicate about the data?

## 2.2 Part 2: Putting the algorithm together

Now write the whole K-means function using your iteration function, as is described in the notebook. The function takes in the data set with the number of classes and returns the final centroid values, the final list of labels telling which class each data point belongs to, and the number of K-means iterations.

1. **[5 points]** Put your 3 sanity-check graphs here.
2. **[2 points]** Write down how many iterations it took for your k-means to converge for each of the sanity-check graphs. How does this number compare with what you expected it to be? How does the number of iterations seem to vary proportional to k?

## 2.3 Part 3: Choosing the value of K

Write the test\_cluster\_size function using your k-means function, as is described in the notebook. The function takes in the data set with the number of classes and returns a list of scores where each score is the distortion for that value of k.

1. **[5 points]** Using the breast cancer data set, record your labeled plots for distortion, min-max scaled distortion, and log scaled distortion here
2. **[3 points]** Why can't we hold out some of the data in a validation set, and choose the value of k which minimizes a cross-validation error like we have in the past for algorithms like linear regression?

### 3 Performance Measures for Face Detection in Images [20 points]

Consider a face detection problem, where the goal is to build a system that can automatically detect faces in images. Two research groups develop systems for this problem using slightly different approaches. In both cases, the central component of the system is a binary classifier which, when applied to a  $24 \times 24$  image, decides whether or not it is a face. The two groups train their classifiers using different learning algorithms. Moreover, when given a new image, they also apply their classifiers in slightly different ways: group A tests  $24 \times 24$  regions of the image taking strides of size 2 (so, for example, for a  $100 \times 100$  image,  $(39)^2$  regions would be tested); group B tests  $24 \times 24$  regions of the image taking strides of size 5 (so here, for a  $100 \times 100$  image, only  $(16)^2$  regions would be tested).<sup>1</sup> On a standard benchmark suite of test images that contains 300 faces altogether, the two groups have the following performances (assume the regions tested by both systems include all the 300 true face regions):

Research group	Number of regions tested	Number of faces detected correctly	Number of non-face regions detected as faces
A	20,000	280	100
B	12,500	270	60

1. [10 points] Based on the above numbers, calculate the TPR (recall), TNR, and precision of each group's system as tested. Also calculate the resulting geometric mean (GM) and  $F_1$  measures for each system. If you were to select a system based on the GM measure, which system would you choose? Would your choice change if you were to select a system based on the  $F_1$  measure? (Note, the geometric mean (GM) is defined as  $\sqrt{TPR \times TNR}$ .)
2. [4 points] Which performance measure would be more suitable for this problem – the GM measure or the  $F_1$  measure? Why?
3. [2 points] Another way to determine which method to choose would be to look at the ROC curve. Because you are given instances of different algorithms, not the algorithm itself, each method corresponds to a *point* on the TPR vs. FPR graph, not a curve.

What is the Euclidean distance from each instance to the 0-error (perfect classification) point  $(0, 1)$ ? Based on this metric, which method would you choose?

4. [4 points] Now assume that there is a third group C which trains their classifier using a newly discovered learning algorithm. Some of the resulting statistical measures are described below:

Research group	TPR	TNR	FPR	FNR
C	0.95	0.990	0.01	0.05

- (a) Suppose you worked for a social media platform, where you want to identify as many faces as possible for your photo tagging systems (prioritize recall). Would you prefer the algorithm created by group C over the algorithms created by groups A and B?
- (b) Now suppose you worked for law enforcement, where every face detected will be checked against a criminal database, which is an expensive operation. You'd like maximize specificity  $(1 - \text{FPR})$  in this case to avoid unnecessary costs. Would you prefer the algorithm created by group C over the algorithms created by groups A and B?

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<sup>1</sup>In practice, the  $24 \times 24$  classifier would also be applied to multiple scaled versions of the input image; we ignore this issue here for simplicity.

## 4 EM Algorithm with Red and Blue Coins [30 points]

Your friend has two coins: a red coin and a blue coin, with biases  $p_r$  and  $p_b$ , respectively (i.e. the red coin comes up heads with probability  $p_r$ , and the blue coin does so with probability  $p_b$ ). She also has an inherent preference  $\pi$  for the red coin. She conducts a sequence of  $m$  coin tosses: for each toss, she first picks either the red coin with probability  $\pi$  or the blue coin with probability  $1 - \pi$ , and then tosses the corresponding coin; the process for each toss is carried out independently of all other tosses. You don't know which coin was used on each toss; all you are told are the outcomes of the  $m$  tosses (heads or tails). In particular, for each toss  $i$ , define a random variable  $X_i$  as

$$X_i = \begin{cases} 1 & \text{if the } i\text{-th toss results in heads} \\ 0 & \text{otherwise.} \end{cases}$$

Then the data you see are the values  $x_1, \dots, x_m$  taken by these  $m$  random variables. Based on this data, you want to estimate the parameters  $\theta = (\pi, p_r, p_b)$ . To help with this, for each toss  $i$ , define a latent (unobserved) random variable  $Z_i$  as follows:

$$Z_i = \begin{cases} 1 & \text{if the } i\text{-th toss used the red coin} \\ 0 & \text{otherwise.} \end{cases}$$

1. **[6 points]** Let  $X$  be a random variable denoting the outcome of a coin toss according to the process described above, and let  $Z$  be the corresponding latent random variable indicating which coin was used, also as described above (both  $X$  and  $Z$  take values in  $\{0, 1\}$  as above). Write an expression for the joint distribution of  $X$  and  $Z$ . Give your answer in the form

$$p(x, z; \theta) = \underline{\hspace{2cm}}.$$

2. **[6 points]** Write an expression for the complete-data log-likelihood,  $\ln \mathcal{L}_c(\theta) = \sum_{i=1}^m \ln p(x_i, z_i; \theta)$ .
3. **[6 points]** Suppose you knew the values  $z_i$  taken by the latent variables  $Z_i$ . What would be the maximum-likelihood parameter estimates  $\hat{\theta}$ ? Give expressions for  $\hat{\pi}$ ,  $\hat{p}_r$ , and  $\hat{p}_b$  (in terms of  $x_i$  and  $z_i$ ).
4. **[6 points]** In the absence of knowledge of  $z_i$ , one possibility for estimating  $\theta$  is to use the EM algorithm. Recall that the algorithm starts with some initial parameter estimates  $\theta^0$ , and then on each iteration  $t$ , performs an E-step followed by an M-step. Let  $\theta^t$  denote the parameter estimates at the start of iteration  $t$ . In the E-step, for each toss  $i$ , the algorithm requires computing the posterior distribution of the latent variable  $Z_i$  under the current parameters  $\theta^t$ . Calculate the posterior probability  $\mathbf{P}(Z_i = 1 | X_i = x_i; \theta^t)$ . (*Hint: Use Bayes' rule.*)
5. **[6 points]** For each toss  $i$ , denote the posterior probability computed in part (d) above by  $\gamma_i^t$  (so that  $\gamma_i^t = \mathbf{P}(Z_i = 1 | X_i = x_i; \theta^t)$ ). Then the expected complete-data log-likelihood with respect to these posterior distributions is

$$\sum_{i=1}^m \left( \gamma_i^t \cdot \ln p(x_i, 1; \theta) + (1 - \gamma_i^t) \cdot \ln p(x_i, 0; \theta) \right).$$

The M-step of the EM algorithm requires finding parameters  $\theta^{t+1}$  that maximize this expected complete-data log-likelihood. Determine the updated parameters  $\theta^{t+1}$ . Give expressions for  $\pi^{t+1}$ ,  $p_r^{t+1}$ , and  $p_b^{t+1}$  (in terms of  $x_i$  and  $\gamma_i^t$ ).