

CMPS242 Homework #3 – Logistic Regression

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1 Homework Objective

Develop a logistic regression-based learner that can identify SMS text messages as either spam or ham (i.e., not spam). Additional requirements include:

- Learner should implement a batch gradient descent
- Create a Jupyter (i.e., IPython) notebook to document all work

Four extra credit tasks are implemented for this homework, specifically:

1. Support a bias term in the weight vector (\mathbf{w}) that is not regularized
2. Experiment with different regularizers, such as $\lambda \|\mathbf{w}\|_1$.
3. Implement the stochastic gradient descent algorithm
4. Implement the exponentiated gradient (EG) \pm algorithm.

2 Gradient Descent Update Rule

Logistic regression is a subcategory of binary classification. Define the logistic (sigmoid) function as shown in Eq. (1).

$$\sigma(a) = \frac{e^a}{1 + e^a} \quad (1)$$

As shown in Figure 1, this function is bounded between 0 and 1 making it ideal for binary classification since it can be used to represent probabilities without additional normalization. The following notes show the derivation of the logistic update rule.¹

Define Z as a random variable that maps one classification value (e.g., ham) to 0 and the other classification result (e.g., SPAM) to 1. We could then define the probability of a 0 or a 1 as shown in Eq. (2) and (3) respectively. This can be written compactly as shown in Eq. (4).

$$\Pr\{Z = 0|a\} = 1 - \sigma(a) \quad (2)$$

$$\Pr\{Z = 1|a\} = \sigma(a) \quad (3)$$

$$\Pr\{Z = z|a\} = \sigma(a)^z (1 - \sigma(a))^{1-z} \quad (4)$$

Given a target classification vector \mathbf{y} and the relation $a = \mathbf{w}^T \mathbf{x}_i$, the likelihood (L) is in turn defined as shown in Eq. (5). Since each element is independent, this probability can be transformed into a product as shown in Eq. (6), where $n = |\mathbf{y}|$.

$$L(\mathbf{w}) = \Pr\{\mathbf{y}|\mathbf{w}, \mathbf{X}\} \quad (5)$$

$$= \prod_{i=1}^n \Pr\{y_i|\mathbf{w}, \mathbf{x}_i\} \quad (6)$$

As with homework #1, the value that maximizes the likelihood of a strictly positive function also maximizes the log likelihood. Hence, Eq. (6) can be transformed to Eq. (11).

¹This proof is based on the lecture notes of Andrew Ng.

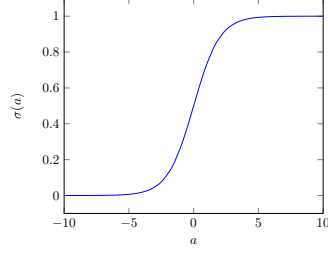


Figure 1: Plot of the Logistic Function

$$\ln L(\mathbf{w}) = \ln \left(\prod_{i=1}^n \Pr\{y_i | \mathbf{w}, \mathbf{x}_i\} \right) \quad (7)$$

$$= \sum_{i=1}^n \ln \Pr\{y_i | \mathbf{w}, \mathbf{x}_i\} \quad (8)$$

$$= \sum_{i=1}^n \ln \left(\sigma(\mathbf{w}^T \mathbf{x}_i)^{y_i} (1 - \sigma(\mathbf{w}^T \mathbf{x}_i))^{1-y_i} \right) \quad (9)$$

$$= \sum_{i=1}^n \ln \left(\sigma(\mathbf{w}^T \mathbf{x}_i)^{y_i} \right) + \ln \left((1 - \sigma(\mathbf{w}^T \mathbf{x}_i))^{1-y_i} \right) \quad (10)$$

$$= \sum_{i=1}^n y_i \ln \sigma(\mathbf{w}^T \mathbf{x}_i) + (1 - y_i) \ln(1 - \sigma(\mathbf{w}^T \mathbf{x}_i)) \quad (11)$$

To find the maximizing likelihood, the derivative is taken and set equal to 0. We use the identity $\frac{\partial \sigma(a)}{\partial a} = \sigma(a)(1 - \sigma(a))$ without proof, but the proof is trivial. Hence the maximizing value is shown in Eq. (15); note that the *chain rule* was used for this derivative.

$$0 = \sum_{i=1}^n \left(y_i \frac{1}{\sigma(\mathbf{w}^T \mathbf{x}_i)} \frac{\partial \sigma(\mathbf{w}^T \mathbf{x}_i)}{\partial \mathbf{w}} - (1 - y_i) \frac{1}{1 - \sigma(\mathbf{w}^T \mathbf{x}_i)} \frac{\partial \sigma(\mathbf{w}^T \mathbf{x}_i)}{\partial \mathbf{w}} \right) \quad (12)$$

$$= \sum_{i=1}^n \left(y_i \frac{1}{\sigma(\mathbf{w}^T \mathbf{x}_i)} \sigma(\mathbf{w}^T \mathbf{x}_i)(1 - \sigma(\mathbf{w}^T \mathbf{x}_i)) \mathbf{x}_i - (1 - y_i) \frac{1}{1 - \sigma(\mathbf{w}^T \mathbf{x}_i)} \sigma(\mathbf{w}^T \mathbf{x}_i)(1 - \sigma(\mathbf{w}^T \mathbf{x}_i)) \mathbf{x}_i \right) \quad (13)$$

$$= \sum_{i=1}^n \left(y_i(1 - \sigma(\mathbf{w}^T \mathbf{x}_i)) - (1 - y_i)\sigma(\mathbf{w}^T \mathbf{x}_i) \right) \mathbf{x}_i \quad (14)$$

$$= \sum_{i=1}^n (y_i - \sigma(\mathbf{w}^T \mathbf{x}_i)) \mathbf{x}_i \quad (15)$$

Eq. (15) represents the maximizing gradient for the log likelihood. This can then be substituted into the update rule for gradient descent, where η is the hyperparameter, learning rate.

$$\mathbf{w}_{t+1} := \mathbf{w}_t + \eta \nabla \ln L(\mathbf{w}) \quad (16)$$

Eq. (16) rewritten using tensor notation forms the batch update rule.

$$\mathbf{w}_{t+1} := \mathbf{w}_t + \eta \mathbf{X}^T (\mathbf{y} - \hat{\mathbf{y}})^T \quad (17)$$

Note that that \mathbf{w}_t was used in the gradient since it is not known how to maximize on \mathbf{w}_{t+1} . In addition, the learning rate, η uses a constant configured by the user an aging term as shown in Eq. (18).

$$\eta = \frac{\eta_0}{t^{0.9}} \quad (18)$$

Our implementation uses the update rule and learning rate in Eq. (17) and (18) respectively for all batch gradient descent experiments in this paper.

3 Text Preprocessor

Before learning can be attempted, the natural language text in the form of SMS messages much be turned into feature vectors. We accomplish this through a multistep process described (in order) below.

- *Import CSV File* – Pandas’ native CSV support as part of the `DataFrame` object was used.
- *Invalid Character Removal* – The original text files (before my team cleaned them for the class) had invalid, unsupported characters. We removed the characters that could not be properly encoded.
- *Punctuation Removal* – The punctuation set is defined by Python’s `string` package (i.e., “`string.punctuation`”). Punctuation removal entailed replacing all punctuation symbols with the empty string (e.g., “couldn’t” becomes “couldnt”).
- *Capitalization Correction* – Standardizes case so that words with different capitalization are not treated differently.
- *Stop Words Removal* – There is not standard set of English “stop words.” For our experiments, we used the English “corpus” dictionary bundled with the Natural Language Toolkit (NLTK).

Next, tokenization is performed on the training set. The words in training set will be the vocabulary for the test set. This step is required since new words in the testing set would otherwise not have associated weights.

After tokenization, term frequency-inverse document frequency (TF-IDF) is performed. TF-IDF is defined as:

$$\text{TF-IDF}(d, t) = Tf(d, t) \cdot IDF(t) \quad (19)$$

Term frequency (Tf) is the number of times a specified term, t , appears in a document d . Similarly, given a corpus of n documents, the document frequency (df) is the number of documents that contain term t . It is formally defined as:

$$IDF(t) = \ln \left(\frac{n + 1}{df(t) + 1} \right) + 1 \quad (20)$$

Note that the addition of 1 in the numerator and denominator is a smoothing factor. Since we are restricting the test set to the training set’s vocabulary, its benefit is limited. However, we included it nonetheless to more closely follow standard techniques.

We observed that not normalizing the term frequency yielded better results so we do not normalize it in our implementation.

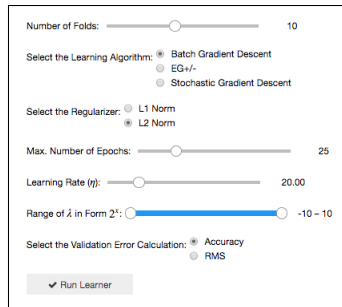


Figure 2: Jupyter notebook experiment configuration widgets

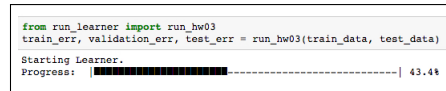


Figure 3: Jupyter notebook learner progress indicator

4 Jupyter Notebook Implementation

Jupyter notebooks serve as a intermediary layer that insulates users from the underlying code implementation. We included multiple features into our Jupyter notebook to improve the user experience and provide external learner configurability and data visualization.

4.1 Specifying Hyperparameters

Since Jupyter notebook masks the code from the user, some may find it difficult to experiment with different configurations. To address this limitation, we added a series of widgets to our notebook. They leverage Python's `ipywidgets` library. The specific hyperparameters that are controllable by widgets are:

- Cross-validation fold count (k)
- Learning algorithm (e.g., standard gradient descent and stochastic gradient descent)
- Regularizer selection (e.g., L_2 or L_1 norm)
- Error calculation formula (e.g., $1 - \text{Accuracy}$ or root-mean-square, RMS)
- Maximum number of training epochs/rounds
- Learning rate (α)
- λ range – These are the powers of 2 to test.

Figure 2 shows a screenshot from our Jupyter notebook with the widgets included.

4.2 Learner Progress Indicator

As with most iterative learning algorithms, our learner does provide instantaneous results. Depending on the user specified configuration described in the previous section, it may take several minutes before a run of the algorithm completes. Our implementation provides visual feedback on the learner's progress via a text-based progress bar, which is shown in Figure 3.²

²The underlying implementation used for this feature was from an online resource and not developed natively by our team.

λ	0	2^{-10}	2^{-9}	2^{-8}	2^{-7}	2^{-6}	2^{-5}	2^{-4}	2^{-3}	2^{-2}	2^{-1}	2^0
Training	0.0053	0.0052	0.0051	0.0055	0.0077	0.0113	0.0199	0.0433	0.0495	0.0906	0.1390	0.1390
Validation	0.0300	0.0300	0.0297	0.0297	0.0313	0.0410	0.0590	0.0700	0.0727	0.1067	0.1390	0.1390
Test	0.0233	0.0229	0.0241	0.0257	0.0276	0.0385	0.0525	0.0614	0.0634	0.0956	0.1283	0.1283

Figure 4: Example Jupyter notebook table of experimental results

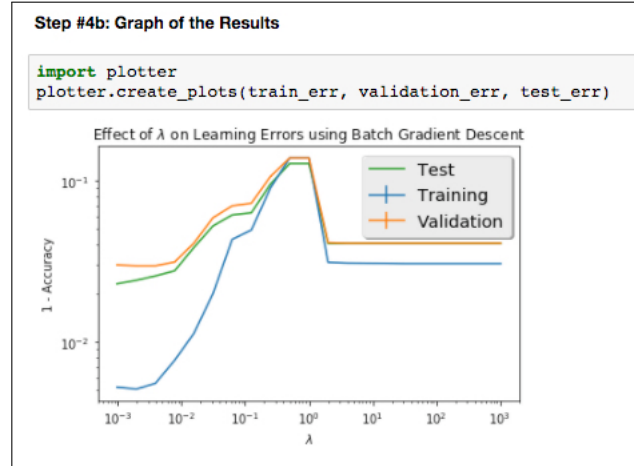


Figure 5: Example Jupyter notebook graph of experimental results

4.3 Embedded Results Table

To improve the Jupyter notebook experience, we included support for a table that displays the latest execution's results. The minimum training, validation and test error values are bolded and highlighted in yellow as shown in Figure 4.

4.4 Embedded Result Graphing

We also implemented graphing into our Jupyter notebook. This uses Python's `matplotlib` package. An example graph is shown in Figure 5.

5 Experiment Setup

Our solver is implemented in Python 2.7.13. It requires a set of external packages, including:

- Pandas
- Scikit-Learn
- NumPy
- IPython
- matplotlib
- ipywidgets.

The default experiment configuration was:

- *Performance Metric*: Accuracy which rounds \hat{y} to the closest integer.
- *Learning Algorithm*: Batch gradient descent

```
def l2_norm_regularizer(lambda_val, w):
    reg_err = np.multiply(lambda_val, w)
    reg_err[0, 0] = 0 # Exclude the bias
    return reg_err
```

Figure 6: Implementation of Bias Regularizer Error Removal

Table 1: Effect of the L_2 Regularizer on Batch Gradient Descent Performance

λ	0	2^{-10}	2^{-9}	2^{-8}	2^{-7}	2^{-6}	2^{-5}	2^{-4}	2^{-3}	2^{-2}
Training	0.008	0.007	0.007	0.006	0.008	0.013	0.023	0.043	0.058	0.099
Validation	0.027	0.028	0.029	0.029	0.032	0.039	0.057	0.072	0.081	0.113
Test	0.024	0.024	0.024	0.026	0.028	0.034	0.051	0.060	0.061	0.098

- *Regularizer: L_2 norm*
- *Cross-validation Fold Count (k): 10*
- *Number of Training Epochs/Rounds: 15*
- *λ Range: $0, 2^{-10}, 2^{-9}, \dots, 2^9, 2^{10}$*
- *Learning Rate (η_0): 20*
- *Graph Error Bars: These are included in all graphs. However, the variance between folds is low meaning they are often not visible.*

This configuration applies in the following sections unless otherwise specified.

6 Extra Credit #1: Bias Term Support

A bias term in the learning algorithm can only improve the learner's performance by accounting for shifts in the data. As such, our implementation only supports training with a bias; we deliberately chose that this feature could not be disabled.

The bias term is added to the input tensor, X , as a column of value 1. This is done using NumPy. When calculating the regularization error, we ignore the error caused by the bias term by setting its error to 0 as shown in Figure 6.

7 Batch Gradient Descent Learning Performance

Our batch gradient descent implementation followed the experiment setup described in Section 5. The best error was observed when there was no regularizer as shown in Table 1 and Figure 7. It is also important to note that as the regularizer increased, the error drops precipitously and remains largely unchanged. This occurs because the regularizer begins to saturate the sigmoid function causing it to return a \hat{y} of 0 for all but the most obvious cases of spam. Since most of the dataset is ham, the graph false makes it appear that the learner is performing well, but this is misleading.

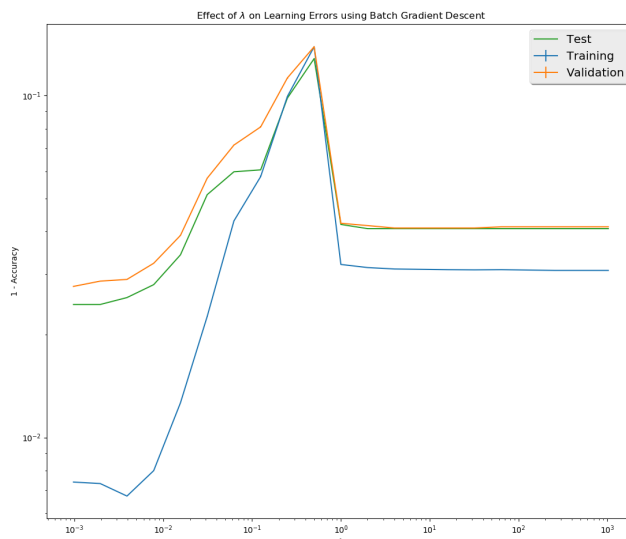


Figure 7: Effect of regularizer λ on batch gradient descent performance using L_2 norm

Table 2: Effect of the L_1 Regularizer on Batch Gradient Descent Performance

λ	0	2^{-10}	2^{-9}	2^{-8}	2^{-7}	2^{-6}	2^{-5}	2^{-4}	2^{-3}	2^{-2}
Training	0.007	0.007	0.007	0.008	0.008	0.008	0.008	0.008	0.008	0.008
Validation	0.030	0.030	0.030	0.030	0.030	0.030	0.030	0.031	0.031	0.031
Test	0.024	0.024	0.024	0.024	0.024	0.024	0.024	0.024	0.024	0.026

8 Extra Credit #2: Multiple Regularizer Experimentation

An extra credit portion of the assignment was to investigate the performance of the learner with another regularizer. As the homework proposed, we use the L_1 . Unlike the L_2 norm from Section 7, the derivative of the L_1 norm is a vector of ones multiplied by λ . As such, the value of \mathbf{w} does not affect this regularization. As expected, the effect of this norm on the learner's performance is far more muted as shown in Table 2 and Figure 8. The clamping of the logistic function was not observed, and there was not significant change in the learner's performance for small values of λ (i.e., less than 1). This behavior is fully expected.

9 Extra Credit #3: Stochastic Gradient Descent

In each training round/epoch, batch gradient descent performs a single update of the weight vector based off *all* the training samples. In contrast, given a dataset of size m , stochastic gradient descent (SGD) performs m updates of the weight vector in each epoch. This generally should cause the trainer to require less epochs and train faster on average.

Since a single element at a time is used to update the weight vector, the learning rate, η_0 should be smaller to prevent over-correction based on a single outlier. As such, we reduced the learning rate to 0.1 for this experiment. Figure 9 and Table 3 show that SGD had better performance than batch gradient descent with either regularizer. Although the selected regularizer (2^{-10}) did not have the minimum test error, the difference is quite small. Likewise, despite also using the L_2 norm, SGD did not have the same clamped

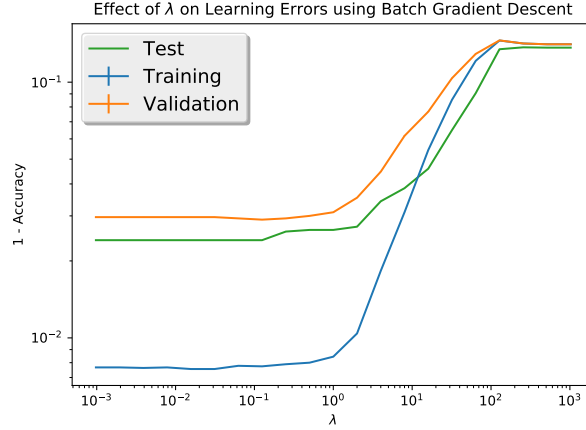


Figure 8: Effect of regularizer λ on batch gradient descent performance using L_1 norm

Table 3: Effect of the L_1 Regularizer on Batch Gradient Descent Performance

λ	0	2^{-10}	2^{-9}	2^{-8}	2^{-7}	2^{-6}	2^{-5}	2^{-4}	2^{-3}	2^{-2}
Training	0	0	0	0	0.001	0.002	0.005	0.013	0.024	0.046
Validation	0.026	0.025	0.029	0.030	0.030	0.032	0.032	0.034	0.040	0.061
Test	0.018	0.019	0.019	0.021	0.021	0.022	0.020	0.026	0.037	0.056

error for larger values of λ .

While stochastic gradient descent takes far fewer epochs to converge (5 versus more than 15 for batch gradient descent), the running time is actually longer for SGD by about a factor of 3 times. This is due primarily to the inefficiencies of Python and how it interacts with NumPy. When all the matrix multiplications are performed at once, the just-in-time (JIT) compiler is able to optimize them. However, it is not able to do the same level of optimization when multiplications are made one at a time in SGD.

10 Extra Credit #4: Exponentiated Gradient

The exponentiated gradient \pm is another approach to perform logistic regression weight updating. The update rule presented in class was

$$w_{t+1,i} = \frac{r_{t,i} w_{t,i}}{\sum_{i=1}^N r_{t,j} w_{t,j}} \quad (21)$$

where $r_{t,j} = \exp(-2\eta(\hat{y}_{t,j} - y_{t,j})x_{t,j})$. We implemented the exponentiated gradient with \pm -correction. However, the results were generally poor compared to both batch and stochastic gradient descent as shown in Figure 10 and Table 4. After discussing with Manfred, we theorize that the performance would be improved if we used the slightly modified exponentiated gradient update rule

$$w_{t+1,i} = U \cdot \frac{r_{t,i} w_{t,i}}{\sum_{i=1}^N r_{t,j} w_{t,j}} \quad (22)$$

where $r_{t,j} = \exp(-2\eta(\hat{y}_{t,j} - y_{t,j})Ux_{t,j})$. This correction using the scalar U was not discussed in class, and we implemented the algorithm as it was explained in class. Similarly, the class discussion did not review how to perform entropy-based regularization as needed by exponentiated gradient (per Ehsan) so our results are devoid of a regularizer.

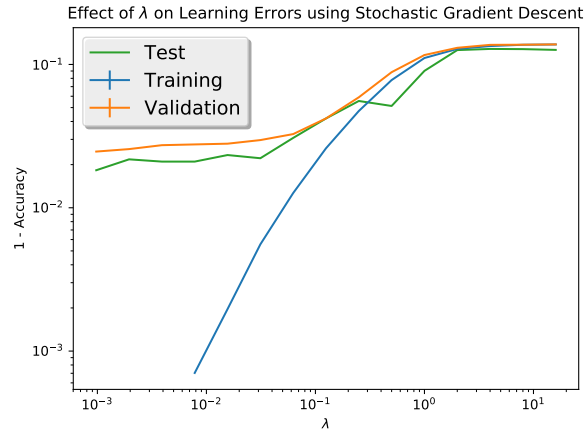


Figure 9: Stochastic Gradient Descent Performance using the L_2 norm and a learning rate of 0.1

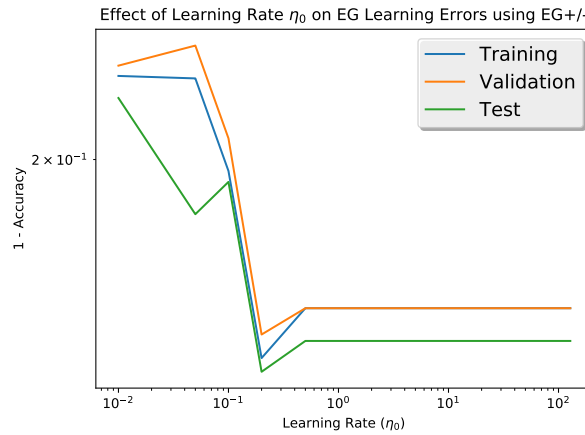


Figure 10: Effect of Learning Rate on Exponentiated Gradient \pm Learning Error

Table 4: Effect of Learning Rate on EG \pm 's Performance

Learning Rate (η_0)	0.01	0.05	0.1	0.2	0.5	1	2	4	8	16
Training	0.245	0.244	0.194	0.123	0.139	0.139	0.139	0.139	0.139	0.139
Validation	0.252	0.264	0.211	0.130	0.139	0.139	0.139	0.139	0.139	0.139
Test	0.233	0.175	0.189	0.119	0.128	0.128	0.128	0.128	0.128	0.128