

Prof. Ryan Cotterell

## Course Assignment Episode 1

23/10/2020 - 15:24h

## Question 1: Backpropagation (15 pts)

(a) In the following question, we consider the function  $f(v, x, y, z) = z \cdot \log((x - y)^2 + \exp(v)) - \exp(v) \cdot x^{-z}$  where  $\log$  is the natural logarithm.

- (i) Draw the computation graph for  $f$ .
- (ii) Evaluate your computation graph from (i) at the point (1,2,3,4), filling in the value of all intermediate nodes in your drawing.
- (iii) Now apply backpropagation to your computation graph from (i) at the point (1,2,3,4), making use of the values you found in (ii) after applying forward propagation. Again, fill in all intermediate values in your drawing. (To make the graders' lives easier, it may make sense to give two drawings of the graphs to keep it from getting too crowded.) Show that your computation is correct by computing  $[\frac{\partial f}{\partial v}, \frac{\partial f}{\partial x}, \frac{\partial f}{\partial y}, \frac{\partial f}{\partial z}]$  with symbolic differentiation<sup>1</sup> and comparing it to the output of backpropagation.

(b) Backpropagation on a computation graph can be used to efficiently obtain the derivatives of a function with respect to the input. In this problem, we consider a differentiable map  $f : \mathbb{R}^n \rightarrow \mathbb{R}$ . This question makes heavy use of the operator  $\nabla$  (pronounced nabla). We write  $\nabla f(\mathbf{x})$  to denote the **Jacobian** of  $f$  evaluated at point  $\mathbf{x}$ . Importantly, in the special case that the codomain of  $f$  is simply  $\mathbb{R}$ , we refer to the Jacobian of  $f$  as the **gradient** of  $f$ . Furthermore, we write  $\nabla \nabla f(\mathbf{x})$  or  $\nabla^2 f(\mathbf{x})$  to indicate the **Hessian** of  $f$ . Recall from Lecture 2 that  $f(\mathbf{x})$ 's Hessian is the matrix of second derivatives at point  $\mathbf{x}$ . This notation is intuitive because the Hessian of  $f$  is simply the Jacobian of the gradient of  $f$ .

We now discuss an extension to backpropagation to compute the Hessian  $\nabla^2 f(\mathbf{x})$  using one additional backward pass.

(i) First, show the following identity:

$$\nabla^2 f(\mathbf{x}) = \begin{bmatrix} \nabla(\mathbf{e}_1^\top \nabla f(\mathbf{x})) \\ \vdots \\ \nabla(\mathbf{e}_n^\top \nabla f(\mathbf{x})) \end{bmatrix} \quad (1)$$

where  $h > 0$  is taken to be small. We make use of  $\{\mathbf{e}_1, \dots, \mathbf{e}_n\}$  as the standard basis vectors.

<sup>1</sup>By symbolic differentiation, we mean use partial differentiation as you learned it in calculus class.

- (ii) Use the identity in (i), to give an efficient algorithm for computing  $\nabla^2 f(\mathbf{x})$ . Analyze the runtime of your algorithm. Take  $m$  to be the number of edges in the function's computation graph. Recall from class that this implies that the computation of  $f$  runs in  $\mathcal{O}(m)$  time.
- (iii) Now, suppose we wish to compute the tensor of  $k^{\text{th}}$ -order derivatives. Give an algorithm  $m$  to produce this tensor and analyze its runtime in terms of  $m$ . To make this question not dependent on tedious tensor notation, rigorously give an algorithm to produce the 3-tensor of third-order derivatives and analyze its runtime. Then, give a non-rigorous generalization to the  $k^{\text{th}}$ -order derivatives.
- (iv) **Bonus:** Give an  $\mathcal{O}(m)$  algorithm for computing the *diagonal* of  $\nabla^2 f(\mathbf{x})$ .
- (c) Now, we will analyze the finite-difference procedure (also known as numerical differentiation) to calculate the derivative of the loss with respect to each parameter in the model. Recall from Lecture 2 that the finite-difference approximation can give us an estimate of the derivative of a function with respect to a single variable:

$$\frac{\partial f(\mathbf{x})}{\partial x_i} \approx \frac{f(\mathbf{x} + h \cdot \mathbf{e}_i) - f(\mathbf{x})}{h} \quad (2)$$

where we again take  $\{\mathbf{e}_1, \dots, \mathbf{e}_n\}$  to be the standard basis. The approximation becomes exact as  $h \rightarrow 0$ ; eq. 2 is simply the definition of the derivative after all!

- (i) What would the runtime of this approach be for a single update of all parameters in the model? Make sure to specify in which units you are giving runtime.
- (ii) Assume the machine we are using gives us precision on the order of  $\mathcal{O}(10^{-16})$  for additive and multiplicative operations and  $\mathcal{O}(10^{-12})$  for the sigmoid operation. What is the expected precision in the calculation of eq. 2 (that is, for a single  $x_i$ ) for a multi-layer perceptron with 3 layers where our input  $\mathbf{x} \in \mathbb{R}^n$  and each layer has  $m$  hidden units.

## Question 2: Parameter Estimation for Log-Linear Models (15 pts)

In this problem, we consider multi-label classification, which is an extension of binary classification that is distinct from multi-class classification. The problem set-up is as follows: We have an input pre-encoded as  $\mathbf{x} \in \mathbb{R}^n$  and a series of  $K$  classes. Define  $\mathbb{B} = \{0, 1\}$ . An element  $\mathbf{y} \in \mathbb{B}^K$  is a binary vector of length  $K$ , i.e.  $\mathbf{y} = [y_1, \dots, y_K]$  where each  $y_k \in \mathbb{B} = \{0, 1\}$ . Our goal is to build a probabilistic model  $p(\mathbf{y} \mid \mathbf{x})$  where  $\mathbf{y} \in \mathbb{B}^K$ . We consider a simple model for multi-label classification that consists of  $K$  independent binary classification models. Specifically, let each of the classifiers for label  $y_k$  be a logistic model:

$$p(Y_k = 1 \mid \mathbf{x}; \boldsymbol{\theta}_k) = \sigma(\boldsymbol{\theta}_k^\top \mathbf{x}) = \frac{1}{1 + e^{-\boldsymbol{\theta}_k^\top \mathbf{x}}} \quad (3)$$

where  $\Theta \in \mathbb{R}^{K \times n}$  is a matrix of parameters and the row vector  $\boldsymbol{\theta}_k \in \mathbb{R}^n$  are the parameters corresponding to the  $k^{\text{th}}$  class.

- (a) Let  $\mathcal{D} = \{(\mathbf{y}^{(j)}, \mathbf{x}^{(j)})\}_{j=1}^J$  be a training set of  $J$  items. Compute the maximum-likelihood estimate  $\Theta_{\text{MLE}}$ . (**Hint:** Compute the log-likelihood of the training data  $\mathcal{D}$  then use calculus to find the maximizer.)

- (b) Argue that the log-likelihood is continuous, concave, and differentiable at all points in  $\mathbb{R}^{K \times n}$ .
- (c) Now suppose we would like to regularize our parameters  $\Theta$  to prevent overfitting. We apply both the  $L_1$  and  $L_2$  regularization, i.e., we add  $\lambda_1 \sum_{k=1}^K \|\theta_k\|_1$  and  $\lambda_2 \sum_{k=1}^K \|\theta_k\|_2$  to the log-likelihood you found in (a) to create an augmented log-likelihood. Compute a new estimate  $\Theta_{\text{MLE}++}$  by finding a maximizer of the augmented log-likelihood.
- (d) Assume  $\lambda_1, \lambda_2 \neq 0$ . Is the augmented log-likelihood from (c) still continuous, concave and differentiable for all  $\Theta \in \mathbb{R}^{K \times n}$ ?
- (e) Show that maximizing the augmented log-likelihood is a form of **maximum-a-posteriori** estimation. Specifically, express the problem as maximization of the log of the likelihood multiplied by a prior.
- (f) Prove the prior found in (e) is a member of the exponential family.

### Question 3: Sentiment Classification\* (15 pts)

- (a) Download the Pang and Lee movie review data.<sup>2</sup> Hold out a randomly-selected 400 reviews as a test set. Download a sentiment lexicon, such as the one currently available from Bing Liu.<sup>3</sup>
  - (i) Tokenize the data using a library of your choosing<sup>4</sup> and classify each document as positive if it has more positive sentiment words than negative sentiment words. Compute the accuracy and F-measure<sup>5</sup> on detecting positive reviews on the test set, using this lexicon-based classifier.
  - (ii) Then train a discriminative classifier (averaged perceptron or logistic regression) on the training set, and compute its accuracy and F-measure on the test set.
  - (iii) Qualitatively compare the difference in accuracy between the two methods. Does the discriminative classifier do overwhelmingly better than guessing the mode? Describe a method for quantifying the significance of the difference between the two methods.
- (b) The next problem will require you to build a classifier and test its properties. Pick a multi-class text classification dataset that is not already tokenized. One example is a dataset of New York Times headlines and topics (Boydston, 2013).<sup>6</sup> Divide your data into training (60%), development (20%), and test sets (20%), if no such division already exists. If your dataset is very large, you may want to focus on a few thousand instances at first.
  - (i) Compare various vocabulary sizes of  $10^2, 10^3, 10^4, 10^5$ , using the most frequent words in each case. Train log-linear models, using feature extraction methods discussed in Lecture 3, for each vocabulary size. Plot the accuracy and macro F-measure on the test set with the increasing vocabulary size.

<sup>2</sup><http://www.cs.cornell.edu/people/pabo/movie-review-data/>

<sup>3</sup><https://www.cs.uic.edu/~liub/FBS/sentiment-analysis.html>

<sup>4</sup>e.g., NLTK, Stanford CoreNLP, moesetokenizer

<sup>5</sup>We take F-measure ( $F_1$ ) to be the harmonic mean of precision  $p$  and recall  $r$ , i.e.,  $F_1 = \frac{2}{\frac{1}{p} + \frac{1}{r}}$

<sup>6</sup>available as a CSV file at <http://www.amber-boydstun.com/supplementary-information-for-making-the-news.html>; Use the field TOPIC\_2DIGIT for this problem.

- (ii) Train the same set of log-linear models for each vocabulary size but this time, with an  $L_2$  penalty on the models' weights. Tune the regularizer's coefficient to maximize accuracy on the development set. Again plot the accuracy and macro F-measure on the test set against the increasing vocabulary size.
- (iii) Provide an analysis of the results from above. At what point do we see diminishing returns in evaluation metrics when increasing the vocabulary size? Does regularization appear to help some of the classifiers? If so, is there a clear relationship between vocabulary size and the difference in evaluation metrics for regularized vs. unregularized models?

#### Question 4: Unigram Language Models\* (10 pts)

In this problem, we consider the estimation of unigram language distributions. If  $V$  is a vocabulary, a unigram language is a distribution over words in  $V$  out of context. A unigram has no context!

- (a) Consider a unigram language model over a vocabulary of size  $|V|$ . Suppose that a word appears  $m$  times in a corpus with  $M$  tokens in total. Apply add- $\lambda$  smoothing to the corpus. For what values of  $m$  is the smoothed probability greater than the unsmoothed probability?
- (b) Consider a simple language in which each token is drawn from the vocabulary  $V$  with probability  $\frac{1}{|V|}$ , independent of all tokens.
  - (i) Given a corpus of size  $M$ , what is the expected value of the fraction of all possible bigrams with zero count? (You may assume BOS is in  $V$  so that the corpus has  $M$  bigrams.)
  - (ii) Determine the value of  $M$  such that the fraction of bigrams with zero count is at most  $\varepsilon \in (0, 1)$ .

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\* Problems adapted from Jacob Eisenstein's Introduction to Natural Language Processing textbook.