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Programming Assignment 1: Learning Distributed Word Representations

Version: 1.2

Changes by Version:

- (v1.1)
  1. Part 1 Description: indicated that each word is associated with two embedding vectors and two biases
  2. Part 1: Updated `calculate_log_co_occurence` to include the last pair of consecutive words as well
  3. Part 2: Updated question description for 2.1
  4. Part 4: Updated answer requirement for 4.1
  5. (1.3) Fixed symmetric GLoVE gradient
  6. (1.3) Clarified that W_tilde and b_tilde gradients also need to be implemented
  7. (2) Removed extra space leading up to docstring for `compute_loss_derivative`
- (v1.2)
  1. (1.4) Updated the training function `train_GLoVE` to not use inplace update (e.g. `W = W - learning_rate * grad_W` instead), so the initial weight variables are not overwritten between asymmetric and symmetric GLoVE models.
  2. (2) Noted that `compute_loss_derivative` input argument `target_mask` is 3D tensor with shape `[batch_size x context_len x 1]`

Version Release Date: 2021-01-27

Due Date:Thursday, Feb. 4, at 11:59pm

Based on an assignment by George Dahl

For CSC413/2516 in Winter 2021 with Professor Jimmy Ba and Professor Bo Wang

Submission: You must submit two files through MarkUs:

1. [ ] A PDF file containing your writeup, titled *a1-writeup.pdf*, which will be the PDF export of this notebook (i.e., by printing this notebook webpage as PDF). Your writeup must be typed. There will be sections in the notebook for you to write your responses. Make sure that the relevant outputs (e.g. `print_gradients()` outputs, plots, etc.) are included and clearly visible.
2. [ ] This `a1-code.ipynb` iPython Notebook.

The programming assignments are individual work. See the Course Syllabus for detailed policies.

You should attempt all questions for this assignment. Most of them can be answered at least partially even if you were unable to finish earlier questions. If you think your computational results are incorrect, please say so; that may help you get partial credit.

The teaching assistants for this assignment are Harris Chan and Summer Tao. Send your email with subject "*[CSC413] PA1*" to mailto:csc413-2021-01-tas@cs.toronto.edu or post on Piazza with the tag `pa1`.

Introduction

In this assignment we will learn about word embeddings and make neural networks learn about words. We could try to match statistics about the words, or we could train a network that takes a sequence of words as input and learns to predict the word that comes next.

This assignment will ask you to implement a linear embedding and then the backpropagation computations for a neural language model and then run some experiments to analyze the learned representation. The amount of code you have to write is very short but each line will require you to think very carefully. You will need to derive the updates mathematically, and then implement them using matrix and vector operations in NumPy.

Starter code and data

First, perform the required imports for your code:

In [ ]:
```
import collections
import pickle
import numpy as np
import os
from tqdm import tqdm
import pylab
from six.moves.urllib.request import urlretrieve
import tarfile
import sys

TINY = 1e-30
EPS = 1e-4
nax = np.newaxis
```

If you're using colaboratory, this following script creates a folder - here we used 'CSC413/A1' - in order to download and store the data. If you're not using colaboratory, then set the path to wherever you want the contents to be stored at locally.

You can also manually download and unzip the data from [http://www.cs.toronto.edu/~jba/a1_data.tar.gz] and put them in the same folder as where you store this notebook.

Feel free to use a different way to access the files *data.pk* , *partially_trained.pk*, and *raw_sentences.txt*.

The file *raw_sentences.txt* contains the sentences that we will be using for this assignment. These sentences are fairly simple ones and cover a vocabulary of only 250 words (+ 1 special `[MASK]`

In [ ]:

```
######################################################################
# Setup working directory
######################################################################
# Change this to a local path if running locally
%mkdir -p /content/CSC413/A1/
%cd /content/CSC413/A1

######################################################################
# Helper functions for loading data
######################################################################
# adapted from
# https://github.com/fchollet/keras/blob/master/keras/datasets/cifar10.py

def get_file(fname,
             origin,
             untar=False,
             extract=False,
             archive_format='auto',
             cache_dir='data'):
    datadir = os.path.join(cache_dir)
    if not os.path.exists(datadir):
        os.makedirs(datadir)

    if untar:
        untar_fpath = os.path.join(datadir, fname)
        fpath = untar_fpath + '.tar.gz'
    else:
        fpath = os.path.join(datadir, fname)

    print('File path: %s' % fpath)
    if not os.path.exists(fpath):
        print('Downloading data from', origin)

        error_msg = 'URL fetch failure on {}: {} -- {}'
        try:
            try:
                urlretrieve(origin, fpath)
            except URLError as e:
                raise Exception(error_msg.format(origin, e.errno, e.reason))
            except HTTPError as e:
                raise Exception(error_msg.format(origin, e.code, e.msg))
        except (Exception, KeyboardInterrupt) as e:
            if os.path.exists(fpath):
                os.remove(fpath)
            raise

    if untar:
        if not os.path.exists(untar_fpath):
            print('Extracting file.')
            with tarfile.open(fpath) as archive:
                archive.extractall(datadir)
        return untar_fpath

    if extract:
        _extract_archive(fpath, datadir, archive_format)

    return fpath
```

```
/content/CSC413/A1
```

In [ ]:

```python
# Download the dataset and partially pre-trained model
get_file(fname='a1_data',
                         origin='http://www.cs.toronto.edu/~jba/a1_data.tar.gz',
                         untar=True)
drive_location = 'data'
PARTIALLY_TRAINED_MODEL = drive_location + '/' + 'partially_trained.pk'
data_location = drive_location + '/' + 'data.pk'
```

```
File path: data/a1_data.tar.gz
Downloading data from http://www.cs.toronto.edu/~jba/a1_data.tar.gz
Extracting file.
```

We have already extracted the 4-grams from this dataset and divided them into training, validation, and test sets. To inspect this data, run the following:

In [ ]:

```python
data = pickle.load(open(data_location, 'rb'))
print(data['vocab'][0]) # First word in vocab is [MASK]
print(data['vocab'][1])
print(len(data['vocab'])) # Number of words in vocab
print(data['vocab']) # All the words in vocab
print(data['train_inputs'][:10]) # 10 example training instances
```

```
[MASK]
all
251
['[MASK]', 'all', 'set', 'just', 'show', 'being', 'money', 'over', 'both', 'ye
ars', 'four', 'through', 'during', 'go', 'still', 'children', 'before', 'polic
e', 'office', 'million', 'also', 'less', 'had', ',', 'including', 'should', 't
o', 'only', 'going', 'under', 'has', 'might', 'do', 'them', 'good', 'around',
'get', 'very', 'big', 'dr.', 'game', 'every', 'know', 'they', 'not', 'world',
'now', 'him', 'school', 'several', 'like', 'did', 'university', 'companies', '
these', 'she', 'team', 'found', 'where', 'right', 'says', 'people', 'house', '
national', 'some', 'back', 'see', 'street', 'are', 'year', 'home', 'best', 'ou
t', 'even', 'what', 'said', 'for', 'federal', 'since', 'its', 'may', 'state',
'does', 'john', 'between', 'new', ';', 'three', 'public', '?', 'be', 'we', 'af
ter', 'business', 'never', 'use', 'here', 'york', 'members', 'percent', 'put',
'group', 'come', 'by', '$', 'on', 'about', 'last', 'her', 'of', 'could', 'days
', 'against', 'times', 'women', 'place', 'think', 'first', 'among', 'own', 'fa
mily', 'into', 'each', 'one', 'down', 'because', 'long', 'another', 'such', 'o
ld', 'next', 'your', 'market', 'second', 'city', 'little', 'from', 'would', 'f
ew', 'west', 'there', 'political', 'two', 'been', '.', 'their', 'much', 'music
', 'too', 'way', 'white', ':', 'was', 'war', 'today', 'more', 'ago', 'life', '
that', 'season', 'company', '-', 'but', 'part', 'court', 'former', 'general',
'with', 'than', 'those', 'he', 'me', 'high', 'made', 'this', 'work', 'up', 'us
', 'until', 'will', 'ms.', 'while', 'officials', 'can', 'were', 'country', 'my
', 'called', 'and', 'program', 'have', 'then', 'is', 'it', 'an', 'states', 'ca
se', 'say', 'his', 'at', 'want', 'in', 'any', 'as', 'if', 'united', 'end', 'no
', ')', 'make', 'government', 'when', 'american', 'same', 'how', 'mr.', 'other
', 'take', 'which', 'department', '--', 'you', 'many', 'nt', 'day', 'week', 'p
lay', 'used', "'s", 'though', 'our', 'who', 'yesterday', 'director', 'most', '
president', 'law', 'man', 'a', 'night', 'off', 'center', 'i', 'well', 'or', 'w
ithout', 'so', 'time', 'five', 'the', 'left']
[[ 28  26  90 144]
 [184  44 249 117]
 [183  32  76 122]
 [117 247 201 186]
 [223 190 249   6]
 [ 42  74  26  32]
 [242  32 223  32]
```

```
[223  32 158 144]
[ 74  32 221  32]
```

Now `data` is a Python dict which contains the vocabulary, as well as the inputs and targets for all three splits of the data. `data['vocab']` is a list of the 251 words in the dictionary; `data['vocab'][0]` is the word with index 0, and so on. `data['train_inputs']` is a 372,500 x 4 matrix where each row gives the indices of the 4 consecutive context words for one of the 372,500 training cases. The validation and test sets are handled analogously.

Even though you only have to modify two specific locations in the code, you may want to read through this code before starting the assignment.

Part 1: GLoVE Word Representations (2pts)

In this part of the assignment, you will implement a simplified version of the GLoVE embedding (please see the handout for detailed description of the algorithm) with the loss defined as

$$L(\{\mathbf{w}_i, \tilde{\mathbf{w}}_i, b_i, \tilde{b}_i\}_{i=1}^{V}) = \sum_{i,j=1}^{V} (\mathbf{w}_i^\top \tilde{\mathbf{w}}_j + b_i + \tilde{b}_j - \log X_{ij})^2$$

.

Note that each word is represented by two d-dimensional embedding vectors $\mathbf{w}_i, \tilde{\mathbf{w}}_i$ and two scalar biases $b_i, \tilde{b}_i$.

Answer the following questions:

1.1. GLoVE Parameter Count [0pt]

Given the vocabulary size V and embedding dimensionality d, how many parameters does the GLoVE model have? Note that each word in the vocabulary is associated with 2 embedding vectors and 2 biases.

1.1 **Answer**:

$$V(2d + 2)$$

1.2. Expression for gradient $\frac{\partial L}{\partial \mathbf{w}_i}$ [1pt]

Write the expression for $\frac{\partial L}{\partial \mathbf{w}_i}$, the gradient of the loss function L with respect to one parameter vector $\mathbf{w}_i$. The gradient should be a function of $\mathbf{w}, \tilde{\mathbf{w}}, b, \tilde{b}, X$ with appropriate subscripts (if any).

1.2 **Answer**:

$$\frac{\partial L}{\partial \mathbf{w}_i} = \sum_{j=1}^{V} \frac{\partial L}{\partial \mathbf{w}_i} \left[(\mathbf{w}_i^\top \tilde{\mathbf{w}}_j + b_i + \tilde{b}_j - \log X_{ij})^2 \right]$$

1.3. Implement the gradient update of GLoVE. [1pt]

See `YOUR CODE HERE` Comment below for where to complete the code

We have provided a few functions for training the embedding:

- `calculate_log_co_occurence` computes the log co-occurrence matrix of a given corpus
- `train_GLoVE` runs momentum gradient descent to optimize the embedding
- `loss_GLoVE` :
  - INPUT - $V \times d$ matrix `W` (collection of V embedding vectors, each d-dimensional); $V \times d$ matrix `W_tilde`; $V \times 1$ vector `b` (collection of V bias terms); $V \times 1$ vector `b_tilde`; $V \times V$ log co-occurrence matrix.
  - OUTPUT - loss of the GLoVE objective
- `grad_GLoVE` : **TO BE IMPLEMENTED.**
  - INPUT:
    - $V \times d$ matrix `W` (collection of V embedding vectors, each d-dimensional), embedding for first word;
    - $V \times d$ matrix `W_tilde`, embedding for second word;
    - $V \times 1$ vector `b` (collection of V bias terms);
    - $V \times 1$ vector `b_tilde`, bias for second word;
    - $V \times V$ log co-occurrence matrix.
  - OUTPUT:
    - $V \times d$ matrix `grad_W` containing the gradient of the loss function w.r.t. `W`;
    - $V \times d$ matrix `grad_W_tilde` containing the gradient of the loss function w.r.t. `W_tilde`;
    - $V \times 1$ vector `grad_b` which is the gradient of the loss function w.r.t. `b`.
    - $V \times 1$ vector `grad_b_tilde` which is the gradient of the loss function w.r.t. `b_tilde`.

Run the code to compute the co-occurence matrix. Make sure to add a 1 to the occurences, so there are no 0's in the matrix when we take the elementwise log of the matrix.

In [ ]:

```
vocab_size = len(data['vocab']) # Number of vocabs

def calculate_log_co_occurence(word_data, symmetric=False):
  "Compute the log-co-occurence matrix for our data."
  log_co_occurence = np.zeros((vocab_size, vocab_size))
  for input in word_data:
    # Note: the co-occurence matrix may not be symmetric
    log_co_occurence[input[0], input[1]] += 1
    log_co_occurence[input[1], input[2]] += 1
    log_co_occurence[input[2], input[3]] += 1
    # If we want symmetric co-occurence can also increment for these.
    if symmetric:
      log_co_occurence[input[1], input[0]] += 1
      log_co_occurence[input[2], input[1]] += 1
      log_co_occurence[input[3], input[2]] += 1
  delta_smoothing = 0.5  # A hyperparameter.  You can play with this if you wa
  log_co_occurence += delta_smoothing  # Add delta so log doesn't break on 0's
  log_co_occurence = np.log(log_co_occurence)
  return log_co_occurence
```

In [ ]:

```
asym_log_co_occurence_train = calculate_log_co_occurence(data['train_inputs'],
asym_log_co_occurence_valid = calculate_log_co_occurence(data['valid_inputs'],
```

- [ ] **TO BE IMPLEMENTED**: Calculate the gradient of the loss function w.r.t. the parameters W, $\tilde{W}$, $\mathbf{b}$, and $\mathbf{b}$. You should vectorize the computation, i.e. not loop over every word.

In [ ]:

```
def loss_GLoVE(W, W_tilde, b, b_tilde, log_co_occurence):
  "Compute the GLoVE loss."
  n,_ = log_co_occurence.shape
  if W_tilde is None and b_tilde is None:
    return np.sum((W @ W.T + b @ np.ones([1,n]) + np.ones([n,1])@b.T - log_co_
  else:
    return np.sum((W @ W_tilde.T + b @ np.ones([1,n]) + np.ones([n,1])@b_tilde

def grad_GLoVE(W, W_tilde, b, b_tilde, log_co_occurence):
  "Return the gradient of GLoVE objective w.r.t W and b."
  "INPUT: W - Vxd; W_tilde - Vxd; b - Vx1; b_tilde - Vx1; log_co_occurence: V
  "OUTPUT: grad_W - Vxd; grad_W_tilde - Vxd, grad_b - Vx1, grad_b_tilde - Vx1"
  n,_ = log_co_occurence.shape

  if not W_tilde is None and not b_tilde is None:
  ###########################   YOUR CODE HERE   #############################
    loss = (W @ W_tilde.T
              + b @ np.ones([1,n]) + np.ones([n,1])@b_tilde.T
              - log_co_occurence)
    grad_W = 2 *(W_tilde.T @ loss).T
    grad_W_tilde = 2 *(W.T @ loss).T
    grad_b = 2 * (loss @ np.ones([n,1])) # 2 * (np.ones([1,n]) @ loss).T
    grad_b_tilde = 2 * (np.ones([1,n]) @ loss).T # 2 * (loss @ np.ones([n,1]))
    # _, d = W.shape
    # assert grad_W.shape == (n, d)
    # assert grad_W_tilde.shape == (n, d)
    # assert grad_b.shape == (n, 1)
    # assert grad_b_tilde.shape == (n, 1)
  ##########################################################################
  else:
    loss = (W @ W.T + b @ np.ones([1,n]) + np.ones([n,1])@b.T - 0.5*(log_co_oc
    grad_W = 4 *(W.T @ loss).T
    grad_W_tilde = None
    grad_b = 4 * (np.ones([1,n]) @ loss).T
    grad_b_tilde = None

  return grad_W, grad_W_tilde, grad_b, grad_b_tilde

def train_GLoVE(W, W_tilde, b, b_tilde, log_co_occurence_train, log_co_occuren
  "Traing W and b according to GLoVE objective."
  n,_ = log_co_occurence_train.shape
  learning_rate = 0.05 / n  # A hyperparameter.  You can play with this if you
  for epoch in range(n_epochs):
    grad_W, grad_W_tilde, grad_b, grad_b_tilde = grad_GLoVE(W, W_tilde, b, b_t
    W = W - learning_rate * grad_W
    b = b - learning_rate * grad_b
    if not grad_W_tilde is None and not grad_b_tilde is None:
      W_tilde = W_tilde - learning_rate * grad_W_tilde
      b_tilde = b_tilde - learning_rate * grad_b_tilde
    train_loss, valid_loss = loss_GLoVE(W, W_tilde, b, b_tilde, log_co_occuren
    if do_print:
      print(f"Train Loss: {train_loss}, valid loss: {valid_loss}, grad_norm:
  return W, W_tilde, b, b_tilde, train_loss, valid_loss
```

1.4. Effect of embedding dimension d [0pt]

Train the both the symmetric and asymmetric GLoVe model with varying dimensionality d by running the cell below. Comment on:

1. Which d leads to optimal validation performance for the asymmetric and symmetric models?
2. Why does / doesn't larger d always lead to better validation error?
3. Which model is performing better, and why?

1.4 Answer: ****TODO: Write Part 1.4 answer here****

Train the GLoVE model for a range of embedding dimensions

In [ ]:

```
np.random.seed(1)
n_epochs = 500  # A hyperparameter.  You can play with this if you want.
embedding_dims = np.array([1, 2, 10, 128, 256])  # Play with this
# Store the final losses for graphing
asymModel_asymCoOc_final_train_losses, asymModel_asymCoOc_final_val_losses =
symModel_asymCoOc_final_train_losses, symModel_asymCoOc_final_val_losses = [],
Asym_W_final_2d, Asym_b_final_2d, Asym_W_tilde_final_2d, Asym_b_tilde_final_2d
W_final_2d, b_final_2d = None, None
do_print = False  # If you want to see diagnostic information during training

for embedding_dim in tqdm(embedding_dims):
  init_variance = 0.1  # A hyperparameter.  You can play with this if you want
  W = init_variance * np.random.normal(size=(vocab_size, embedding_dim))
  W_tilde = init_variance * np.random.normal(size=(vocab_size, embedding_dim))
  b = init_variance * np.random.normal(size=(vocab_size, 1))
  b_tilde = init_variance * np.random.normal(size=(vocab_size, 1))
  if do_print:
    print(f"Training for embedding dimension: {embedding_dim}")

  # Train Asym model on Asym Co-Oc matrix
  Asym_W_final, Asym_W_tilde_final, Asym_b_final, Asym_b_tilde_final, train_lo
  if embedding_dim == 2:
    # Save a parameter copy if we are training 2d embedding for visualization
    Asym_W_final_2d = Asym_W_final
    Asym_W_tilde_final_2d = Asym_W_tilde_final
    Asym_b_final_2d = Asym_b_final
    Asym_b_tilde_final_2d = Asym_b_tilde_final
  asymModel_asymCoOc_final_train_losses += [train_loss]
  asymModel_asymCoOc_final_val_losses += [valid_loss]
  if do_print:
    print(f"Final validation loss: {valid_loss}")

  # Train Sym model on Asym Co-Oc matrix
  W_final, W_tilde_final, b_final, b_tilde_final, train_loss, valid_loss = tra
  if embedding_dim == 2:
    # Save a parameter copy if we are training 2d embedding for visualization
    W_final_2d = W_final
    b_final_2d = b_final
  symModel_asymCoOc_final_train_losses += [train_loss]
  symModel_asymCoOc_final_val_losses += [valid_loss]
  if do_print:
    print(f"Final validation loss: {valid_loss}")
```

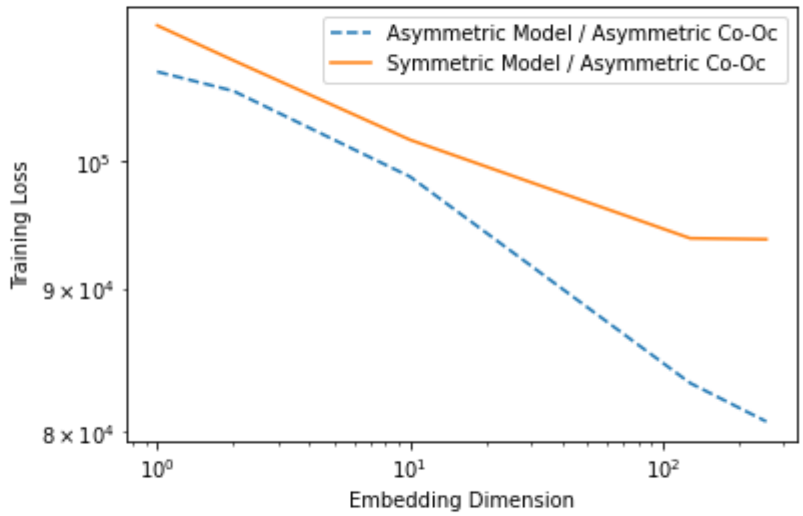
```
100%|██████████| 5/5 [00:30<00:00,  6.10s/it]
```

Plot the training and validation losses against the embedding dimension.

In [ ]:

```
pylab.loglog(embedding_dims, asymModel_asymCoOc_final_train_losses, label="Asy
pylab.loglog(embedding_dims, symModel_asymCoOc_final_train_losses , label="Syr
pylab.xlabel("Embedding Dimension")
pylab.ylabel("Training Loss")
pylab.legend()
```

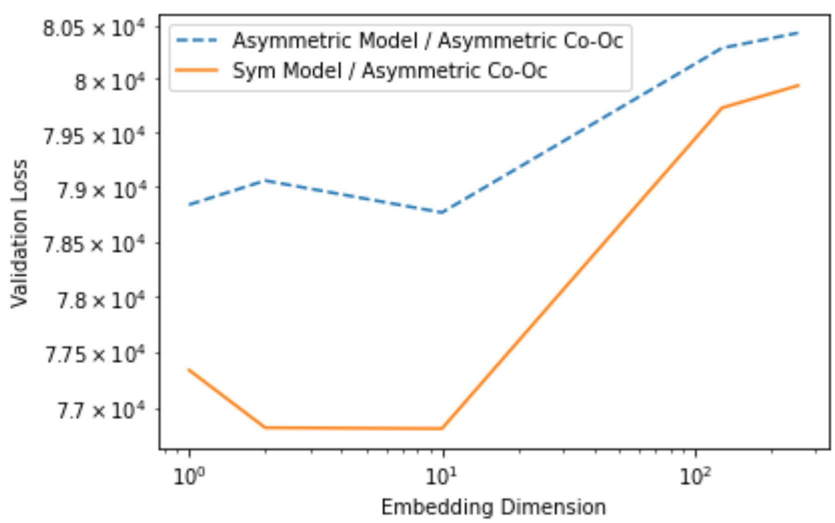
Out[ ]: <matplotlib.legend.Legend at 0x7fee2e54c0f0>



In [ ]:

```
pylab.loglog(embedding_dims, asymModel_asymCoOc_final_val_losses, label="Asymr
pylab.loglog(embedding_dims, symModel_asymCoOc_final_val_losses , label="Sym M
pylab.xlabel("Embedding Dimension")
pylab.ylabel("Validation Loss")
pylab.legend(loc="upper left")
```

Out[ ]: <matplotlib.legend.Legend at 0x7fee2deba7b8>



> 1. Which d leads to optimal validation performance for the asymmetric and symmetric models?

From the plot above, it appears that $d = 10$ is optimal.

> 1. Why does / doesn’t larger d always lead to better validation error?

Larger d may have overfitted on the training data.

> 1. Which model is performing better, and why?

Part 2: Network Architecture (2pts)

See the handout for the written questions in this part.

Answer the following questions

2.1. Number of parameters in neural network model [1pt]

Assume in general that we have V words in the dictionary and use the previous N words as inputs. Suppose we use a D-dimensional word embedding and a hidden layer with H hidden units. The trainable parameters of the model consist of 3 weight matrices and 2 sets of biases. What is the total number of trainable parameters in the model, as a function of V, N, D, H?

In the diagram given, which part of the model (i.e., `word_embbeding_weights`, `embed_to_hid_weights`, `hid_to_output_weights`, `hid_bias`, or `output_bias`) has the largest number of trainable parameters if we have the constraint that $V \gg H > D > N$? Note: The symbol $\gg$ means much greater than" Explain your reasoning.

2.1 Answer:

The number of parameters is:

$$N \times D + ND \times H + H \times V + 2$$

Given $V \gg H > D > N$, then the last layer of `hid_to_output_weights` would have the largest number of trainable parameters ($H \times V$) since V is much greater than all other hyper-parameters.

2.2 Number of parameters in n-gram model [1pt]

Another method for predicting the next words is an n-gram model, which was mentioned in Lecture 3. If we wanted to use an n-gram model with the same context length N as our network, we'd need to store the counts of all possible $(N+1)$-grams. If we stored all the counts explicitly, how many entries would this table have?

2.2 Answer:

$$V^{N+1}$$

2.3. Comparing neural network and n-gram model scaling [0pt]

How do the parameters in the neural network model scale with the number of context words N versus how the number of entries in the n-gram model scale with N? [0pt]

2.3 Answer:

In the neural network model, assuming $V \gg N$, the number of parameter is mostly determined by $H \times V$ which is not dependent upon N. In the $(N+1)$-gram model, increasing N by one would increase the number of parameters by V times, which grows exponentially.

Part 3: Training the model (3pts)

We will modify the architecture slightly from the previous section, inspired by BERT \citep{devlin2018bert}. Instead of having only one output, the architecture will now take in $N = 4$ context words, and also output predictions for $N = 4$ words. See Figure 2 diagram in the handout for the diagram of this architecture.

During training, we randomly sample one of the N context words to replace with a `[MASK]` token. The goal is for the network to predict the word that was masked, at the corresponding output word position. In practice, this `[MASK]` token is assigned the index 0 in our dictionary. The weights $W^{(2)}$ = `hid_to_output_weights` now has the shape $NV \times H$, as the output layer has NV neurons, where the first V output units are for predicting the first word, then the next V are for predicting the second word, and so on. We call this as *concatenating* output uniits across all word positions, i.e. the $(j + nV)$-th column is for the word j in vocabulary for the n-th output word position. Note here that the softmax is applied in chunks of V as well, to give a valid probability distribution over the V words. Only the output word positions that were masked in the input are included in the cross entropy loss calculation:

There are three classes defined in this part: `Params`, `Activations`, `Model`. You will make changes to `Model`, but it may help to read through `Params` and `Activations` first.

$$C = -\sum_i^B \sum_n^N \sum_j^V m_n^{(i)} (t_{n,j}^{(i)} \log y_{n,j}^{(i)}),$$

Where $y_{n,j}^{(i)}$ denotes the output probability prediction from the neural network for the i-th training example for the word j in the n-th output word, and $t_{n,j}^{(i)}$ is 1 if for the i-th training example, the word j is the n-th word in context. Finally, $m_n^{(i)} \in \{0, 1\}$ is a mask that is set to 1 if we are predicting the n-th word position for the i-th example (because we had masked that word in the input), and 0 otherwise.

There are three classes defined in this part: `Params`, `Activations`, `Model`. You will make

In [ ]:

```
class Params(object):
    """A class representing the trainable parameters of the model. This class

          word_embedding_weights, a matrix of size V x D, where V is the numb
                  and D is the embedding dimension.
          embed_to_hid_weights, a matrix of size H x ND, where H is the numbe
                  columns represent connections from the embedding of the fi
                  for the second context word, and so on. There are N context
          hid_bias, a vector of length H
          hid_to_output_weights, a matrix of size NV x H
          output_bias, a vector of length NV"""

    def __init__(self, word_embedding_weights, embed_to_hid_weights, hid_to_ou
                 hid_bias, output_bias):
        self.word_embedding_weights = word_embedding_weights
        self.embed_to_hid_weights = embed_to_hid_weights
        self.hid_to_output_weights = hid_to_output_weights
        self.hid_bias = hid_bias
        self.output_bias = output_bias

    def copy(self):
        return self.__class__(self.word_embedding_weights.copy(), self.embed_t
                              self.hid_to_output_weights.copy(), self.hid_bias

    @classmethod
    def zeros(cls, vocab_size, context_len, embedding_dim, num_hid):
        """A constructor which initializes all weights and biases to 0."""
        word_embedding_weights = np.zeros((vocab_size, embedding_dim))
        embed_to_hid_weights = np.zeros((num_hid, context_len * embedding_dim)
        hid_to_output_weights = np.zeros((vocab_size * context_len, num_hid))
        hid_bias = np.zeros(num_hid)
        output_bias = np.zeros(vocab_size * context_len)
        return cls(word_embedding_weights, embed_to_hid_weights, hid_to_output
                   hid_bias, output_bias)

    @classmethod
    def random_init(cls, init_wt, vocab_size, context_len, embedding_dim, num_
        """A constructor which initializes weights to small random values and
        word_embedding_weights = np.random.normal(0., init_wt, size=(vocab_si
        embed_to_hid_weights = np.random.normal(0., init_wt, size=(num_hid, co
        hid_to_output_weights = np.random.normal(0., init_wt, size=(vocab_size
        hid_bias = np.zeros(num_hid)
        output_bias = np.zeros(vocab_size * context_len)
        return cls(word_embedding_weights, embed_to_hid_weights, hid_to_output
                   hid_bias, output_bias)

    ###### The functions below are Python's somewhat oddball way of overloadi
    ###### we can do arithmetic on Params instances. You don't need to unders

    def __mul__(self, a):
        return self.__class__(a * self.word_embedding_weights,
                              a * self.embed_to_hid_weights,
                              a * self.hid_to_output_weights,
                              a * self.hid_bias,
                              a * self.output_bias)

    def __rmul__(self, a):
        return self * a
```

```
    def __sub__(self, other):
        return self + -1. * other
```

In [ ]:

```
class Activations(object):
    """A class representing the activations of the units in the network. This

        embedding_layer, a matrix of B x ND matrix (where B is the batch size,
                and N is the number of input context words), representing the
                layer on all the cases in a batch. The first D columns represe
                first context word, and so on.
        hidden_layer, a B x H matrix representing the hidden layer activations
        output_layer, a B x V matrix representing the output layer activations

    def __init__(self, embedding_layer, hidden_layer, output_layer):
        self.embedding_layer = embedding_layer
        self.hidden_layer = hidden_layer
        self.output_layer = output_layer

def get_batches(inputs, batch_size, shuffle=True):
    """Divide a dataset (usually the training set) into mini-batches of a give
    'generator', i.e. something you can use in a for loop. You don't need to u
    works to do the assignment."""

    if inputs.shape[0] % batch_size != 0:
        raise RuntimeError('The number of data points must be a multiple of th
    num_batches = inputs.shape[0] // batch_size

    if shuffle:
        idxs = np.random.permutation(inputs.shape[0])
        inputs = inputs[idxs, :]

    for m in range(num_batches):
        yield inputs[m * batch_size:(m + 1) * batch_size, :]
```

In this part of the assignment, you implement a method which computes the gradient using backpropagation. To start you out, the *Model* class contains several important methods used in training:

- `compute_activations` computes the activations of all units on a given input batch
- `compute_loss` computes the total cross-entropy loss on a mini-batch
- `evaluate` computes the average cross-entropy loss for a given set of inputs and targets

You will need to complete the implementation of two additional methods which are needed for training, and print the outputs of the gradients.

3.1 Implement gradient with respect to output layer inputs [1pt]

`compute_loss_derivative` computes the derivative of the loss function with respect to the output layer inputs.

In other words, if C is the cost function, and the softmax computation for the j-th word in vocabulary for the n-th output word position is:

$$y_{n,j} = \frac{e^{z_{n,j}}}{\sum_l e^{z_{n,l}}}$$

This function should compute a $B \times NV$ matrix where the entries correspond to the partial derivatives $\partial C / \partial z_j^n$. Recall that the output units are concatenated across all positions, i.e. the $(j + nV)$-th column is for the word j in vocabulary for the n-th output word position.

3.2 Implement gradient with respect to parameters [1pt]

`back_propagate` is the function which computes the gradient of the loss with respect to model parameters using backpropagation. It uses the derivatives computed by *compute_loss_derivative*. Some parts are already filled in for you, but you need to compute the matrices of derivatives for `embed_to_hid_weights`, `hid_bias`, `hid_to_output_weights`, and `output_bias`. These matrices have the same sizes as the parameter matrices (see previous section).

In order to implement backpropagation efficiently, you need to express the computations in terms of matrix operations, rather than *for* loops. You should first work through the derivatives on pencil and paper. First, apply the chain rule to compute the derivatives with respect to individual units, weights, and biases. Next, take the formulas you've derived, and express them in matrix form. You should be able to express all of the required computations using only matrix multiplication, matrix transpose, and elementwise operations --- no *for* loops! If you want inspiration, read through the code for *Model.compute_activations* and try to understand how the matrix operations correspond to the computations performed by all the units in the network.

To make your life easier, we have provided the routine `checking.check_gradients`, which checks your gradients using finite differences. You should make sure this check passes before continuing with the assignment.

In [ ]:

```
class Model(object):
    """A class representing the language model itself. This class contains va
    the model and visualizing the learned representations. It has two fields:

        params, a Params instance which contains the model parameters
        vocab, a list containing all the words in the dictionary; vocab[0] is
               0, and so on."""

    def __init__(self, params, vocab):
        self.params = params
        self.vocab = vocab

        self.vocab_size = len(vocab)
        self.embedding_dim = self.params.word_embedding_weights.shape[1]
        self.embedding_layer_dim = self.params.embed_to_hid_weights.shape[1]
        self.context_len = self.embedding_layer_dim // self.embedding_dim
        self.num_hid = self.params.embed_to_hid_weights.shape[0]

    def copy(self):
        return self.__class__(self.params.copy(), self.vocab[:])

    @classmethod
    def random_init(cls, init_wt, vocab, context_len, embedding_dim, num_hid)
        """Constructor which randomly initializes the weights to Gaussians wi
        and initializes the biases to all zeros."""
        params = Params.random_init(init_wt, len(vocab), context_len, embeddi
        return Model(params, vocab)

    def indicator_matrix(self, targets, mask_zero_index=True):
        """Construct a matrix where the (k + j*V)th entry of row i is 1 if the
         for example i is k, and all other entries are 0.

         Note: if the j-th target word index is 0, this corresponds to the [M
               and we set the entry to be 0.
        """
        batch_size, context_len = targets.shape
        expanded_targets = np.zeros((batch_size, context_len * len(self.vocab
        targets_offset = np.repeat((np.arange(context_len) * len(self.vocab))
        targets += targets_offset

        for c in range(context_len):
          expanded_targets[np.arange(batch_size), targets[:,c]] = 1.
          if mask_zero_index:
            # Note: Set the targets with index 0, V, 2V to be zero since it c
            expanded_targets[np.arange(batch_size), targets_offset[:,c]] = 0.
        return expanded_targets

    def compute_loss_derivative(self, output_activations, expanded_target_bat
        """Compute the derivative of the multiple target position cross-entro

            For example:

         [y_{0} ....  y_{V-1}] [y_{V}, ..., y_{2*V-1}] [y_{2*V} ... y_{i,3*V-

         Where for colum j + n*V,

            y_{j + n*V} = e^{z_{j + n*V}} / \sum_{m=0}^{V-1} e^{z_{m + n*V}},
```

```
        C = -\sum_{i,j,n} mask_{i,n} (t_{i, j + n*V} log y_{i, j + n*V}),

    where mask_{i,n} = 1 if the i-th training example has n-th context wo
    otherwise mask_{i,n} = 0.

    The arguments are as follows:

        output_activations - A [batch_size x (context_len * vocab_size)] t
            for the activations of the output layer, i.e. the y_j's.
        expanded_target_batch - A [batch_size (context_len * vocab_size)]
            where expanded_target_batch[i,n*V:(n+1)*V] is the indicator ve
            the n-th context target word position, i.e. the (i, j + n*V) e
            i'th example, the context word at position n is j, and 0 other
        target_mask - A [batch_size x context_len x 1] tensor, where targe
            if for the i'th example the n-th context word is a target pos

    Outputs:
        loss_derivative - A [batch_size x (context_len * vocab_size)] matr
            where loss_derivative[i,0:vocab_size] contains the gradient
            dC / dz_0 for the i-th training example gradient for 1st outpu
            context word, and loss_derivative[i,vocab_size:2*vocab_size] i
            the 2nd output context word of the i-th training example, etc
    """

    ###########################   YOUR CODE HERE  #######################
    batch_size, VN = output_activations.shape
    batch_size, N, _ = target_mask.shape
    V = VN / N
    mask = np.repeat(target_mask, V, axis=-1).reshape(batch_size, VN)
    loss_derivative = -(expanded_target_batch - output_activations) * mas
    return loss_derivative
    ####################################################################

def compute_loss(self, output_activations, expanded_target_batch):
    """Compute the total loss over a mini-batch. expanded_target_batch is
    by calling indicator_matrix on the targets for the batch."""
    return -np.sum(expanded_target_batch * np.log(output_activations + TI

def compute_activations(self, inputs):
    """Compute the activations on a batch given the inputs. Returns an Ac
    You should try to read and understand this function, since this will
    how to implement back_propagate."""

    batch_size = inputs.shape[0]
    if inputs.shape[1] != self.context_len:
        raise RuntimeError('Dimension of the input vectors should be {}, 
            self.context_len, inputs.shape[1]))

    # Embedding layer
    # Look up the input word indies in the word_embedding_weights matrix
    embedding_layer_state = np.zeros((batch_size, self.embedding_layer_di
    for i in range(self.context_len):
```

```
        # softmax unit does not affect the outputs. So subtract the maximum to
        # make all inputs <= 0. This prevents overflows when computing their e
        inputs_to_softmax -= inputs_to_softmax.max(1).reshape((-1, 1))

        # Take softmax along each V chunks in the output layer
        output_layer_state = np.exp(inputs_to_softmax)
        output_layer_state_shape = output_layer_state.shape
        output_layer_state = output_layer_state.reshape((-1, self.context_len,
        output_layer_state /= output_layer_state.sum(axis=-1, keepdims=True)
        output_layer_state = output_layer_state.reshape(output_layer_state_sha

        return Activations(embedding_layer_state, hidden_layer_state, output_l

    def back_propagate(self, input_batch, activations, loss_derivative):
        """Compute the gradient of the loss function with respect to the trai
        of the model. The arguments are as follows:

             input_batch - the indices of the context words
             activations - an Activations class representing the output of Mod
             loss_derivative - the matrix of derivatives computed by compute_l

        Part of this function is already completed, but you need to fill in th
        computations for hid_to_output_weights_grad, output_bias_grad, embed_t
        and hid_bias_grad. See the documentation for the Params class for a de
        these matrices represent."""

        # The matrix with values dC / dz_j, where dz_j is the input to the jth
        # i.e. h_j = 1 / (1 + e^{-z_j})
        hid_deriv = np.dot(loss_derivative, self.params.hid_to_output_weights)
                    * activations.hidden_layer * (1. - activations.hidden_laye

        ###########################   YOUR CODE HERE  ########################
        batch_size, _ = loss_derivative.shape
        hid_to_output_weights_grad = (activations.hidden_layer.T @ loss_deriva
        output_bias_grad = (np.ones([1, batch_size]) @ loss_derivative).ravel

        loss_derivative_hidden = loss_derivative @ self.params.hid_to_output_w
        embed_to_hid_weights_grad = (activations.embedding_layer.T @ loss_deri
        hid_bias_grad = (np.ones([1, batch_size]) @ loss_derivative_hidden).ra
        ######################################################################

        # The matrix of derivatives for the embedding layer
        embed_deriv = np.dot(hid_deriv, self.params.embed_to_hid_weights)

        # Embedding layer
```

```
        ndata = inputs.shape[0]

        total = 0.
        for input_batch in get_batches(inputs, batch_size):
            mask = self.sample_input_mask(batch_size)
            input_batch_masked = input_batch * (1 - mask)
            activations = self.compute_activations(input_batch_masked)
            target_batch_masked = input_batch * mask
            expanded_target_batch = self.indicator_matrix(target_batch_masked)
            cross_entropy = -np.sum(expanded_target_batch * np.log(activations
            total += cross_entropy

        return total / float(ndata)

    def display_nearest_words(self, word, k=10):
        """List the k words nearest to a given word, along with their distance

        if word not in self.vocab:
            print('Word "{}" not in vocabulary.'.format(word))
            return

        # Compute distance to every other word.
        idx = self.vocab.index(word)
        word_rep = self.params.word_embedding_weights[idx, :]
        diff = self.params.word_embedding_weights - word_rep.reshape((1, -1))
        distance = np.sqrt(np.sum(diff ** 2, axis=1))

        # Sort by distance.
        order = np.argsort(distance)
        order = order[1:1 + k]  # The nearest word is the query word itself, 
        for i in order:
            print('{}: {}'.format(self.vocab[i], distance[i]))

    def word_distance(self, word1, word2):
        """Compute the distance between the vector representations of two word

        if word1 not in self.vocab:
```

3.3 Print the gradients [1pt]

To make your life easier, we have provided the routine `check_gradients`, which checks your gradients using finite differences. You should make sure this check passes before continuing with the assignment. Once `check_gradients()` passes, call `print_gradients()` and include its output in your write-up.

In [ ]:

```python
def relative_error(a, b):
    return np.abs(a - b) / (np.abs(a) + np.abs(b))


def check_output_derivatives(model, input_batch, target_batch):
    def softmax(z):
        z = z.copy()
        z -= z.max(-1, keepdims=True)
        y = np.exp(z)
        y /= y.sum(-1, keepdims=True)
        return y

    batch_size = input_batch.shape[0]
    z = np.random.normal(size=(batch_size, model.context_len, model.vocab_size
    y = softmax(z).reshape((batch_size, model.context_len * model.vocab_size))
    z = z.reshape((batch_size, model.context_len * model.vocab_size))

    expanded_target_batch = model.indicator_matrix(target_batch)
    target_mask = expanded_target_batch.reshape(-1, model.context_len, len(moc
    loss_derivative = model.compute_loss_derivative(y, expanded_target_batch,

    if loss_derivative is None:
        print('Loss derivative not implemented yet.')
        return False

    if loss_derivative.shape != (batch_size, model.vocab_size * model.context_
        print('Loss derivative should be size {} but is actually {}.'.format(
            (batch_size, model.vocab_size), loss_derivative.shape))
        return False

    def obj(z):
        z = z.reshape((-1, model.context_len, model.vocab_size))
        y = softmax(z).reshape((batch_size, model.context_len * model.vocab_s
        return model.compute_loss(y, expanded_target_batch)

    for count in range(1000):
        i, j = np.random.randint(0, loss_derivative.shape[0]), np.random.rand

        z_plus = z.copy()
        z_plus[i, j] += EPS
        obj_plus = obj(z_plus)

        z_minus = z.copy()
        z_minus[i, j] -= EPS
        obj_minus = obj(z_minus)

        empirical = (obj_plus - obj_minus) / (2. * EPS)
        rel = relative_error(empirical, loss_derivative[i, j])
        if rel > 1e-4:
            print('The loss derivative has a relative error of {}, which is to
            return False

    print('The loss derivative looks OK.')
    return True


def check_param_gradient(model, param_name, input_batch, target_batch):
    activations = model.compute_activations(input_batch)
```

```
        return model.compute_loss(activations.output_layer, expanded_target_ba

    dims = getattr(model.params, param_name).shape
    is_matrix = (len(dims) == 2)

    if getattr(param_gradient, param_name).shape != dims:
        print('The gradient for {} should be size {} but is actually {}.'.form
            param_name, dims, getattr(param_gradient, param_name).shape))
        return

    for count in range(1000):
        if is_matrix:
            slc = np.random.randint(0, dims[0]), np.random.randint(0, dims[1])
        else:
            slc = np.random.randint(dims[0])

        model_plus = model.copy()
        getattr(model_plus.params, param_name)[slc] += EPS
        obj_plus = obj(model_plus)

        model_minus = model.copy()
        getattr(model_minus.params, param_name)[slc] -= EPS
        obj_minus = obj(model_minus)

        empirical = (obj_plus - obj_minus) / (2. * EPS)
        exact = getattr(param_gradient, param_name)[slc]
        rel = relative_error(empirical, exact)
        if rel > 3e-4:
            import pdb; pdb.set_trace()
            print('The loss derivative has a relative error of {}, which is to
            return False

    print('The gradient for {} looks OK.'.format(param_name))


def load_partially_trained_model():
    obj = pickle.load(open(PARTIALLY_TRAINED_MODEL, 'rb'))
    params = Params(obj['word_embedding_weights'], obj['embed_to_hid_weights']
                                  obj['hid_to_output_weights'], obj['hid_bias
                                  obj['output_bias'])
    vocab = obj['vocab']
    return Model(params, vocab)


def check_gradients():
    """Check the computed gradients using finite differences."""
    np.random.seed(0)

    np.seterr(all='ignore')   # suppress a warning which is harmless

    model = load_partially_trained_model()
    data_obj = pickle.load(open(data_location, 'rb'))
```

```python
def print_gradients():
    """Print out certain derivatives for grading."""
    np.random.seed(0)

    model = load_partially_trained_model()
    data_obj = pickle.load(open(data_location, 'rb'))
    train_inputs = data_obj['train_inputs']
    input_batch = train_inputs[:100, :]

    mask = model.sample_input_mask(input_batch.shape[0])
    input_batch_masked = input_batch * (1 - mask)
    activations = model.compute_activations(input_batch_masked)
    target_batch_masked = input_batch * mask
    expanded_target_batch = model.indicator_matrix(target_batch_masked)
    target_mask = expanded_target_batch.reshape(-1, model.context_len, len(moc
    loss_derivative = model.compute_loss_derivative(activations.output_layer,
    param_gradient = model.back_propagate(input_batch, activations, loss_deriv

    print('loss_derivative[2, 5]', loss_derivative[2, 5])
    print('loss_derivative[2, 121]', loss_derivative[2, 121])
    print('loss_derivative[5, 33]', loss_derivative[5, 33])
    print('loss_derivative[5, 31]', loss_derivative[5, 31])
    print()
    print('param_gradient.word_embedding_weights[27, 2]', param_gradient.word_
    print('param_gradient.word_embedding_weights[43, 3]', param_gradient.word_
    print('param_gradient.word_embedding_weights[22, 4]', param_gradient.word_
    print('param_gradient.word_embedding_weights[2, 5]', param_gradient.word_e
    print()
    print('param_gradient.embed_to_hid_weights[10, 2]', param_gradient.embed_t
    print('param_gradient.embed_to_hid_weights[15, 3]', param_gradient.embed_t
    print('param_gradient.embed_to_hid_weights[30, 9]', param_gradient.embed_t
    print('param_gradient.embed_to_hid_weights[35, 21]', param_gradient.embed_
    print()
    print('param_gradient.hid_bias[10]', param_gradient.hid_bias[10])
    print('param_gradient.hid_bias[20]', param_gradient.hid_bias[20])
    print()
    print('param_gradient.output_bias[0]', param_gradient.output_bias[0])
    print('param_gradient.output_bias[1]', param_gradient.output_bias[1])
    print('param_gradient.output_bias[2]', param_gradient.output_bias[2])
    print('param_gradient.output_bias[3]', param_gradient.output_bias[3])
```

In [ ]:

```python
# Run this to check if your implement gradients matches the finite difference
```

```
The loss derivative looks OK.
The gradient for word_embedding_weights looks OK.
The gradient for embed_to_hid_weights looks OK.
The gradient for hid_to_output_weights looks OK.
The gradient for hid_bias looks OK.
The gradient for output_bias looks OK.
```

In [ ]:

```python
# Run this to print out the gradients
print_gradients()
```

```
loss_derivative[2, 5] 0.0
loss_derivative[2, 121] 0.0
loss_derivative[5, 33] 0.0
loss_derivative[5, 31] 0.0

param_gradient.word_embedding_weights[27, 2] 0.0
param_gradient.word_embedding_weights[43, 3] 0.011596892511489444
param_gradient.word_embedding_weights[22, 4] -0.022267062381729714
param_gradient.word_embedding_weights[2, 5] 0.0

param_gradient.embed_to_hid_weights[10, 2] 0.37932570919301645
param_gradient.embed_to_hid_weights[15, 3] 0.01604516132110917
param_gradient.embed_to_hid_weights[30, 9] -0.4312854367997418
param_gradient.embed_to_hid_weights[35, 21] 0.06679896665436336

param_gradient.hid_bias[10] 0.02342880312334518
param_gradient.hid_bias[20] -0.024370452378874256

param_gradient.output_bias[0] 0.0009701061469027941
param_gradient.output_bias[1] 0.1686894627476322
param_gradient.output_bias[2] 0.0051664774143909235
param_gradient.output_bias[3] 0.1509622647181436
```

3.4 Run model trainin [0pt]

Once you've implemented the gradient computation, you'll need to train the model. The function *train* implements the main training procedure. It takes two arguments:

- `embedding_dim` : The number of dimensions in the distributed representation.
- `num_hid` : The number of hidden units

As the model trains, the script prints out some numbers that tell you how well the training is going. It shows:

- The cross entropy on the last 100 mini-batches of the training set. This is shown after every 100 mini-batches.
- The cross entropy on the entire validation set every 1000 mini-batches of training.

At the end of training, this function shows the cross entropies on the training, validation and test sets. It will return a *Model* instance.

In [ ]:

```
_train_inputs = None
_train_targets = None
_vocab = None

DEFAULT_TRAINING_CONFIG = {'batch_size': 100,  # the size of a mini-batch
                           'learning_rate': 0.1,  # the learning rate
                           'momentum': 0.9,  # the decay parameter for the mom
                           'epochs': 50,  # the maximum number of epochs to ru
                           'init_wt': 0.01,  # the standard deviation of the i
                           'context_len': 4,  # the number of context words us
                           'show_training_CE_after': 100,  # measure training
                           'show_validation_CE_after': 1000,  # measure valida
                           }


def find_occurrences(word1, word2, word3):
    """Lists all the words that followed a given tri-gram in the training set
    times each one followed it."""

    # cache the data so we don't keep reloading
    global _train_inputs, _train_targets, _vocab
    if _train_inputs is None:
        data_obj = pickle.load(open(data_location, 'rb'))
        _vocab = data_obj['vocab']
        _train_inputs, _train_targets = data_obj['train_inputs'], data_obj['tr

    if word1 not in _vocab:
        raise RuntimeError('Word "{}" not in vocabulary.'.format(word1))
    if word2 not in _vocab:
        raise RuntimeError('Word "{}" not in vocabulary.'.format(word2))
    if word3 not in _vocab:
        raise RuntimeError('Word "{}" not in vocabulary.'.format(word3))

    idx1, idx2, idx3 = _vocab.index(word1), _vocab.index(word2), _vocab.index
    idxs = np.array([idx1, idx2, idx3])

    matches = np.all(_train_inputs == idxs.reshape((1, -1)), 1)

    if np.any(matches):
        counts = collections.defaultdict(int)
        for m in np.where(matches)[0]:
            counts[_vocab[_train_targets[m]]] += 1

        word_counts = sorted(list(counts.items()), key=lambda t: t[1], reverse
        print('The tri-gram "{} {} {}" was followed by the following words in
            word1, word2, word3))
        for word, count in word_counts:
            if count > 1:
                print('    {} ({} times)'.format(word, count))
            else:
                print('    {} (1 time)'.format(word))
    else:
        print('The tri-gram "{} {} {}" did not occur in the training set.'.fo


def train(embedding_dim, num_hid, config=DEFAULT_TRAINING_CONFIG):
    """This is the main training routine for the language model. It takes two
```

```
    vocab = data_obj['vocab']
    train_inputs = data_obj['train_inputs']
    valid_inputs = data_obj['valid_inputs']
    test_inputs = data_obj['test_inputs']

    # Randomly initialize the trainable parameters
    model = Model.random_init(config['init_wt'], vocab, config['context_len'],

    # Variables used for early stopping
    best_valid_CE = np.infty
    end_training = False

    # Initialize the momentum vector to all zeros
    delta = Params.zeros(len(vocab), config['context_len'], embedding_dim, nur

    this_chunk_CE = 0.
    batch_count = 0
    for epoch in range(1, config['epochs'] + 1):
        if end_training:
            break

        print()
        print('Epoch', epoch)

        for m, (input_batch) in enumerate(get_batches(train_inputs, config['ba
            batch_count += 1

            # For each example (row in input_batch), select one word to mask c
            mask = model.sample_input_mask(config['batch_size'])
            input_batch_masked = input_batch * (1 - mask) # We only zero out c
            target_batch_masked = input_batch * mask # We want to predict the

            # Forward propagate
            activations = model.compute_activations(input_batch_masked)

            # Compute loss derivative
            expanded_target_batch = model.indicator_matrix(target_batch_maskec
            loss_derivative = model.compute_loss_derivative(activations.output
            loss_derivative /= config['batch_size']

            # Measure loss function
            cross_entropy = model.compute_loss(activations.output_layer, expar
            this_chunk_CE += cross_entropy
            if batch_count % config['show_training_CE_after'] == 0:
                print('Batch {} Train CE {:1.3f}'.format(
                    batch_count, this_chunk_CE / config['show_training_CE_afte
                this_chunk_CE = 0.

            # Backpropagate
            loss_gradient = model.back_propagate(input_batch, activations, los

            # Update the momentum vector and model parameters
```

```
    print()
    train_CE = model.evaluate(train_inputs)
    print('Final training cross-entropy: {:1.3f}'.format(train_CE))
    valid_CE = model.evaluate(valid_inputs)
    print('Final validation cross-entropy: {:1.3f}'.format(valid_CE))
    test_CE = model.evaluate(test_inputs)
    print('Final test cross-entropy: {:1.3f}'.format(test_CE))

    return model
```

Run the training.

In [ ]:

```
embedding_dim = 16
num_hid = 128
trained_model = train(embedding_dim, num_hid)
```

```
Epoch 1
Batch 100 Train CE 4.793
Batch 200 Train CE 4.645
Batch 300 Train CE 4.649
Batch 400 Train CE 4.629
Batch 500 Train CE 4.633
Batch 600 Train CE 4.648
Batch 700 Train CE 4.617
Batch 800 Train CE 4.607
Batch 900 Train CE 4.606
Batch 1000 Train CE 4.615
Running validation...
Validation cross-entropy: 4.615
Batch 1100 Train CE 4.615
Batch 1200 Train CE 4.624
Batch 1300 Train CE 4.608
Batch 1400 Train CE 4.595
Batch 1500 Train CE 4.611
Batch 1600 Train CE 4.598
Batch 1700 Train CE 4.577
Batch 1800 Train CE 4.578
Batch 1900 Train CE 4.568
Batch 2000 Train CE 4.589
Running validation...
Validation cross-entropy: 4.589
Batch 2100 Train CE 4.573
Batch 2200 Train CE 4.611
Batch 2300 Train CE 4.562
```

```
Batch 2400 Train CE 4.587
Batch 2500 Train CE 4.589
Batch 2600 Train CE 4.587
Batch 2700 Train CE 4.561
Batch 2800 Train CE 4.544
Batch 2900 Train CE 4.521
Batch 3000 Train CE 4.524
Running validation...
Validation cross-entropy: 4.496
Batch 3100 Train CE 4.504
Batch 3200 Train CE 4.449
Batch 3300 Train CE 4.384
Batch 3400 Train CE 4.352
Batch 3500 Train CE 4.324
Batch 3600 Train CE 4.261
Batch 3700 Train CE 4.267

Epoch 2
Batch 3800 Train CE 4.208
Batch 3900 Train CE 4.168
Batch 4000 Train CE 4.117
Running validation...
Validation cross-entropy: 4.112
Batch 4100 Train CE 4.105
Batch 4200 Train CE 4.049
Batch 4300 Train CE 4.008
Batch 4400 Train CE 3.986
Batch 4500 Train CE 3.924
Batch 4600 Train CE 3.897
Batch 4700 Train CE 3.857
Batch 4800 Train CE 3.790
Batch 4900 Train CE 3.796
Batch 5000 Train CE 3.773
Running validation...
Validation cross-entropy: 3.776
Batch 5100 Train CE 3.766
Batch 5200 Train CE 3.714
Batch 5300 Train CE 3.720
Batch 5400 Train CE 3.668
Batch 5500 Train CE 3.668
Batch 5600 Train CE 3.639
Batch 5700 Train CE 3.571
Batch 5800 Train CE 3.546
Batch 5900 Train CE 3.537
Batch 6000 Train CE 3.511
Running validation...
Validation cross-entropy: 3.531
Batch 6100 Train CE 3.494
Batch 6200 Train CE 3.495
Batch 6300 Train CE 3.477
Batch 6400 Train CE 3.455
Batch 6500 Train CE 3.435
Batch 6600 Train CE 3.446
Batch 6700 Train CE 3.411
Batch 6800 Train CE 3.376
Batch 6900 Train CE 3.419
Batch 7000 Train CE 3.375
Running validation...
Validation cross-entropy: 3.386
Batch 7100 Train CE 3.398
Batch 7200 Train CE 3.383
Batch 7300 Train CE 3.371
Batch 7400 Train CE 3.355

Epoch 3
```

```
Batch 7500 Train CE 3.320
Batch 7600 Train CE 3.315
Batch 7700 Train CE 3.342
Batch 7800 Train CE 3.293
Batch 7900 Train CE 3.285
Batch 8000 Train CE 3.296
Running validation...
Validation cross-entropy: 3.294
Batch 8100 Train CE 3.271
Batch 8200 Train CE 3.291
Batch 8300 Train CE 3.287
Batch 8400 Train CE 3.274
Batch 8500 Train CE 3.228
Batch 8600 Train CE 3.256
Batch 8700 Train CE 3.250
Batch 8800 Train CE 3.256
Batch 8900 Train CE 3.266
Batch 9000 Train CE 3.221
Running validation...
Validation cross-entropy: 3.233
Batch 9100 Train CE 3.247
Batch 9200 Train CE 3.229
Batch 9300 Train CE 3.223
Batch 9400 Train CE 3.216
Batch 9500 Train CE 3.209
Batch 9600 Train CE 3.196
Batch 9700 Train CE 3.197
Batch 9800 Train CE 3.229
Batch 9900 Train CE 3.184
Batch 10000 Train CE 3.180
Running validation...
Validation cross-entropy: 3.179
Batch 10100 Train CE 3.170
Batch 10200 Train CE 3.168
Batch 10300 Train CE 3.166
Batch 10400 Train CE 3.200
Batch 10500 Train CE 3.171
Batch 10600 Train CE 3.177
Batch 10700 Train CE 3.145
Batch 10800 Train CE 3.176
Batch 10900 Train CE 3.187
Batch 11000 Train CE 3.102
Running validation...
Validation cross-entropy: 3.148
Batch 11100 Train CE 3.166

Epoch 4
Batch 11200 Train CE 3.153
Batch 11300 Train CE 3.139
Batch 11400 Train CE 3.137
Batch 11500 Train CE 3.156
Batch 11600 Train CE 3.123
Batch 11700 Train CE 3.121
Batch 11800 Train CE 3.161
Batch 11900 Train CE 3.109
Batch 12000 Train CE 3.133
Running validation...
Validation cross-entropy: 3.126
Batch 12100 Train CE 3.141
Batch 12200 Train CE 3.133
Batch 12300 Train CE 3.120
Batch 12400 Train CE 3.100
Batch 12500 Train CE 3.070
Batch 12600 Train CE 3.130
Batch 12700 Train CE 3.117
```

```
Batch 12800 Train CE 3.124
Batch 12900 Train CE 3.085
Batch 13000 Train CE 3.109
Running validation...
Validation cross-entropy: 3.099
Batch 13100 Train CE 3.114
Batch 13200 Train CE 3.093
Batch 13300 Train CE 3.092
Batch 13400 Train CE 3.088
Batch 13500 Train CE 3.078
Batch 13600 Train CE 3.078
Batch 13700 Train CE 3.092
Batch 13800 Train CE 3.081
Batch 13900 Train CE 3.089
Batch 14000 Train CE 3.086
Running validation...
Validation cross-entropy: 3.090
Batch 14100 Train CE 3.092
Batch 14200 Train CE 3.112
Batch 14300 Train CE 3.130
Batch 14400 Train CE 3.077
Batch 14500 Train CE 3.079
Batch 14600 Train CE 3.128
Batch 14700 Train CE 3.092
Batch 14800 Train CE 3.077
Batch 14900 Train CE 3.076

Epoch 5
Batch 15000 Train CE 3.045
Running validation...
Validation cross-entropy: 3.057
Batch 15100 Train CE 3.095
Batch 15200 Train CE 3.074
Batch 15300 Train CE 3.094
Batch 15400 Train CE 3.089
Batch 15500 Train CE 3.048
Batch 15600 Train CE 3.088
Batch 15700 Train CE 3.081
Batch 15800 Train CE 3.082
Batch 15900 Train CE 3.078
Batch 16000 Train CE 3.084
Running validation...
Validation cross-entropy: 3.076
Validation error increasing!  Training stopped.

Final training cross-entropy: 3.058
Final validation cross-entropy: 3.073
```

To convince us that you have correctly implemented the gradient computations, please include the following with your assignment submission:

- [ ] You will submit `a1-code.ipynb` through MarkUs. You do not need to modify any of the code except the parts we asked you to implement.
- [ ] In your writeup, include the output of the function `print_gradients`. This prints out part of the gradients for a partially trained network which we have provided, and we will check them against the correct outputs. **Important:** make sure to give the output of `print_gradients`, **not** `check_gradients`.

This is worth 4 points:

- 1 for the loss derivatives,

- 1 for the bias gradients, and
- 2 for the weight gradients.

Since we gave you a gradient checker, you have no excuse for not getting full points on this part.

Part 4: Arithmetics and Analysis (2pts)

In this part, you will perform arithmetic calculations on the word embeddings learned from previous models and analyze the representation learned by the networks with t-SNE plots.

4.1 t-SNE

You will first train the models discussed in the previous sections; you'll use the trained models for the remainder of this section.

Important: if you've made any fixes to your gradient code, you must reload the a1-code module and then re-run the training procedure. Python does not reload modules automatically, and you don't want to accidentally analyze an old version of your model.

These methods of the Model class can be used for analyzing the model after the training is done:

- `tsne_plot_representation` creates a 2-dimensional embedding of the distributed representation space using an algorithm called t-SNE. (You don't need to know what this is for the assignment, but we may cover it later in the course.) Nearby points in this 2-D space are meant to correspond to nearby points in the 16-D space.
- `display_nearest_words` lists the words whose embedding vectors are nearest to the given word
- `word_distance` computes the distance between the embeddings of two words

Plot the 2-dimensional visualization for the trained model from part 3 using the method `tsne_plot_representation`. Look at the plot and find a few clusters of related words. What do the words in each cluster have in common? Plot the 2-dimensional visualization for the GloVe model from part 1 using the method `tsne_plot_GLoVe_representation`. How do the t-SNE embeddings for both models compare? Plot the 2-dimensional visualization using the method `plot_2d_GLoVe_representation`. How does this compare to the t-SNE embeddings? Please answer in 2 sentences for each question and show the plots in your submission.

4.1 **Answer**:

In `tsne_plot_representation(trained_model)`, the different parts of speech are grouped together in different parts of the 2D plot, e.g. on the left we have cluster of verbs like "says", "does", in the middle we have have cluster of nouns like "members", "companies", and on the top we have have cluster of interrogatives like "what", "how".

In `tsne_plot_GLoVE_representation(W_final, b_final)`, there is a cluster of political nouns in the center ("president", "political", "federal", "government"), while the other words in the periphery were spread out in the plot without obvious clustering.

In `plot_2d_GLoVE_representation(W_final_2d, b_final_2d)`, there is a similar trend where political nouns are clustered at the bottom whereas the other words are spread out.

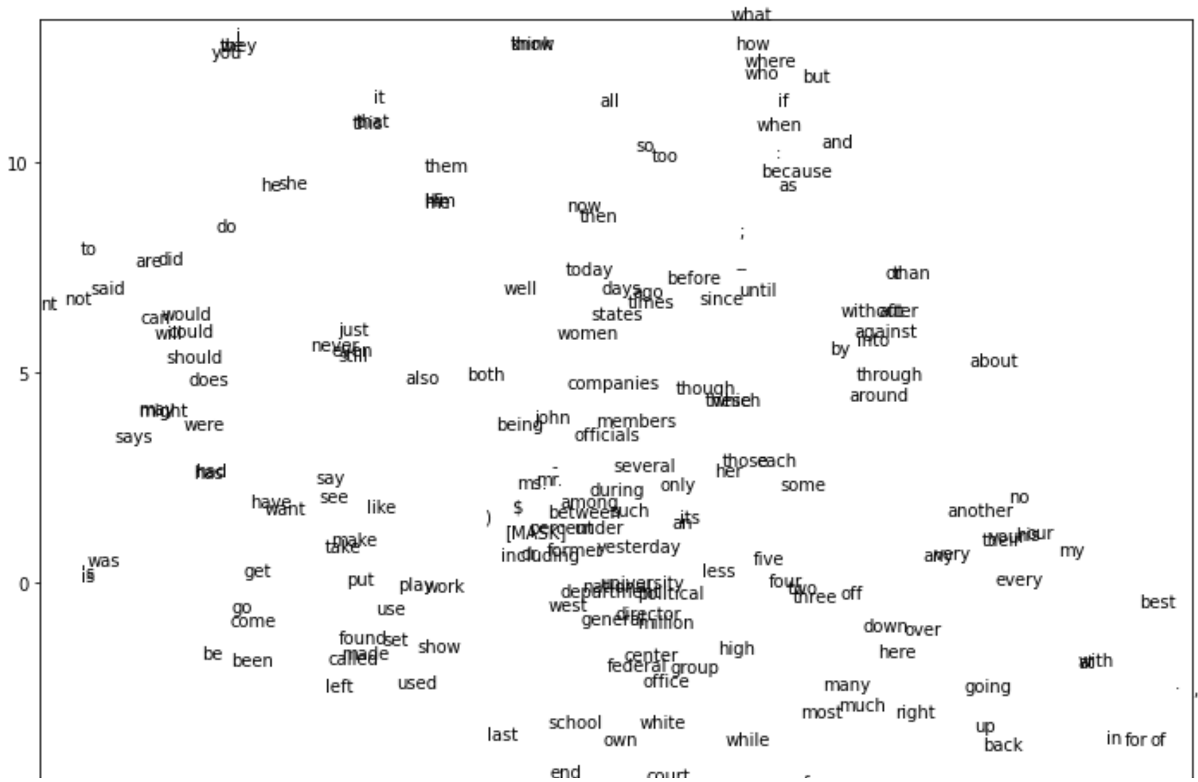
In [42]:

```
from sklearn.manifold import TSNE

def tsne_plot_representation(model):
    """Plot a 2-D visualization of the learned representations using t-SNE."""
    print(model.params.word_embedding_weights.shape)
    mapped_X = TSNE(n_components=2).fit_transform(model.params.word_embedding_
    pylab.figure(figsize=(12,12))
    for i, w in enumerate(model.vocab):
        pylab.text(mapped_X[i, 0], mapped_X[i, 1], w)
    pylab.xlim(mapped_X[:, 0].min(), mapped_X[:, 0].max())
    pylab.ylim(mapped_X[:, 1].min(), mapped_X[:, 1].max())
    pylab.show()

def tsne_plot_GLoVE_representation(W_final, b_final):
    """Plot a 2-D visualization of the learned representations using t-SNE."""
    mapped_X = TSNE(n_components=2).fit_transform(W_final)
    pylab.figure(figsize=(12,12))
    data_obj = pickle.load(open(data_location, 'rb'))
    for i, w in enumerate(data_obj['vocab']):
        pylab.text(mapped_X[i, 0], mapped_X[i, 1], w)
    pylab.xlim(mapped_X[:, 0].min(), mapped_X[:, 0].max())
    pylab.ylim(mapped_X[:, 1].min(), mapped_X[:, 1].max())
    pylab.show()

def plot_2d_GLoVE_representation(W_final, b_final):
    """Plot a 2-D visualization of the learned representations."""
    mapped_X = W_final
    pylab.figure(figsize=(12,12))
    data_obj = pickle.load(open(data_location, 'rb'))
    for i, w in enumerate(data_obj['vocab']):
        pylab.text(mapped_X[i, 0], mapped_X[i, 1], w)
    pylab.xlim(mapped_X[:, 0].min(), mapped_X[:, 0].max())
    pylab.ylim(mapped_X[:, 1].min(), mapped_X[:, 1].max())
    pylab.show()
```

In [43]:

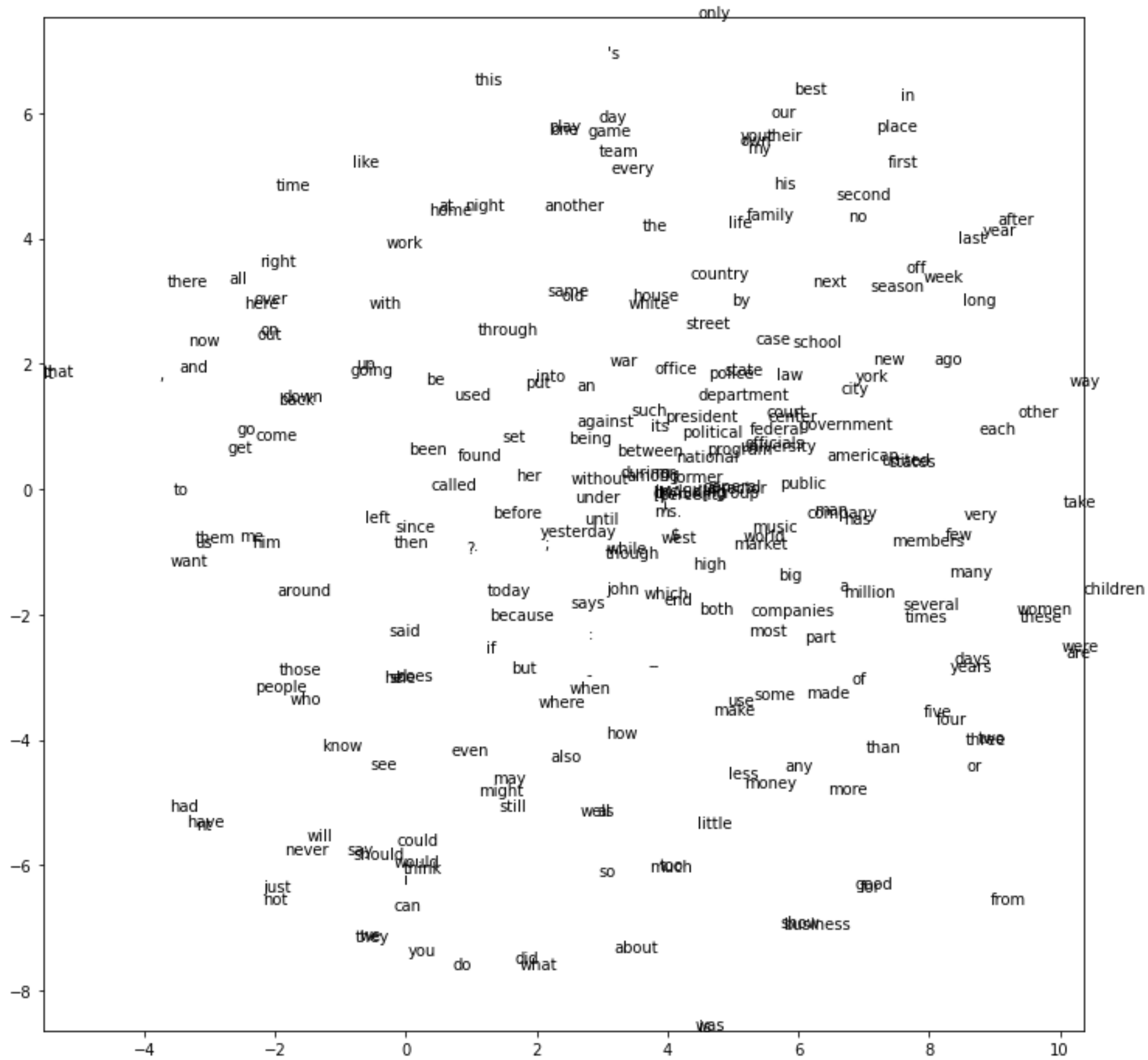
```
tsne_plot_representation(trained_model)
```

```
(251, 16)
```



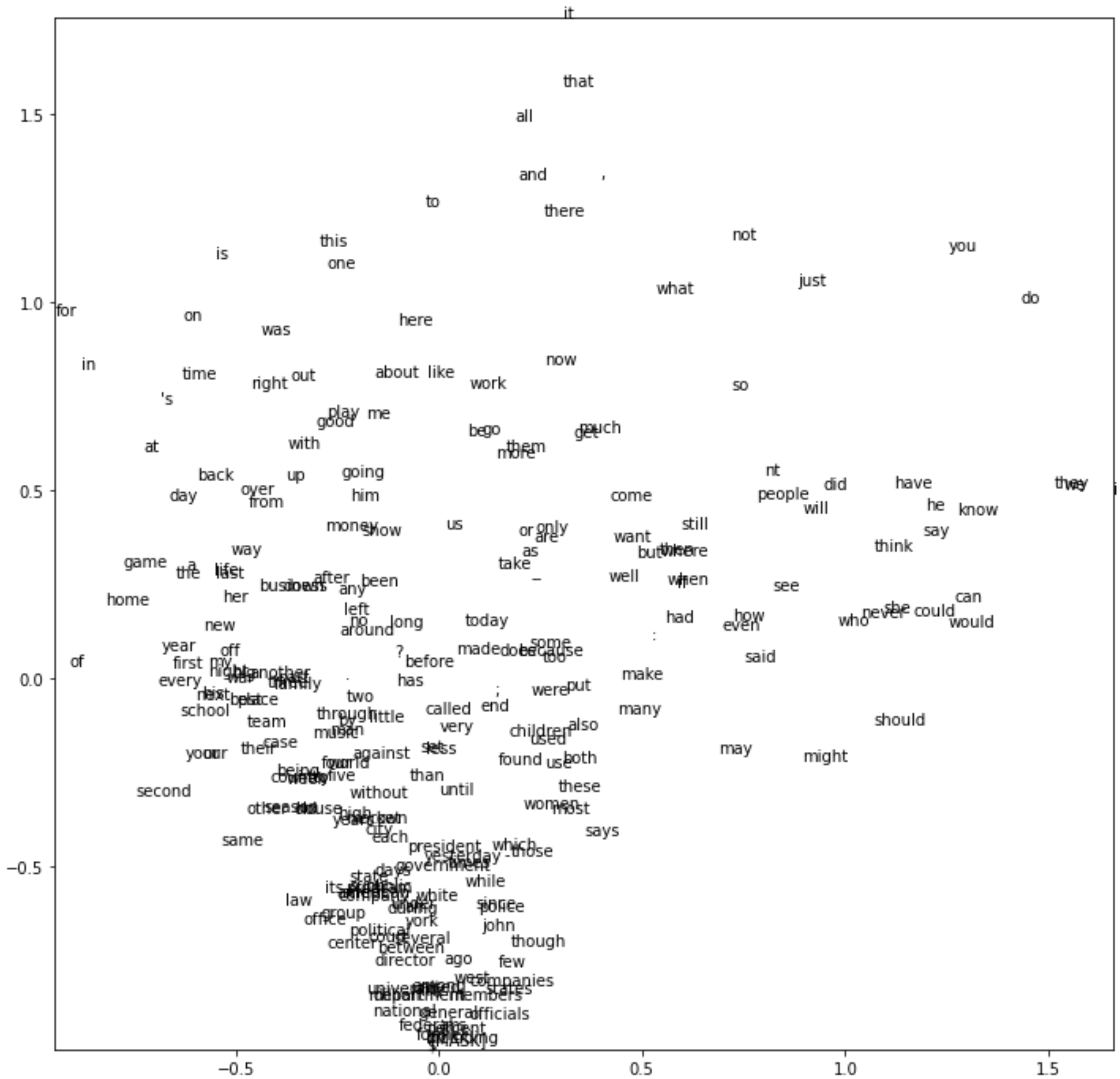
In [44]:

```
tsne_plot_GLoVE_representation(W_final, b_final)
```



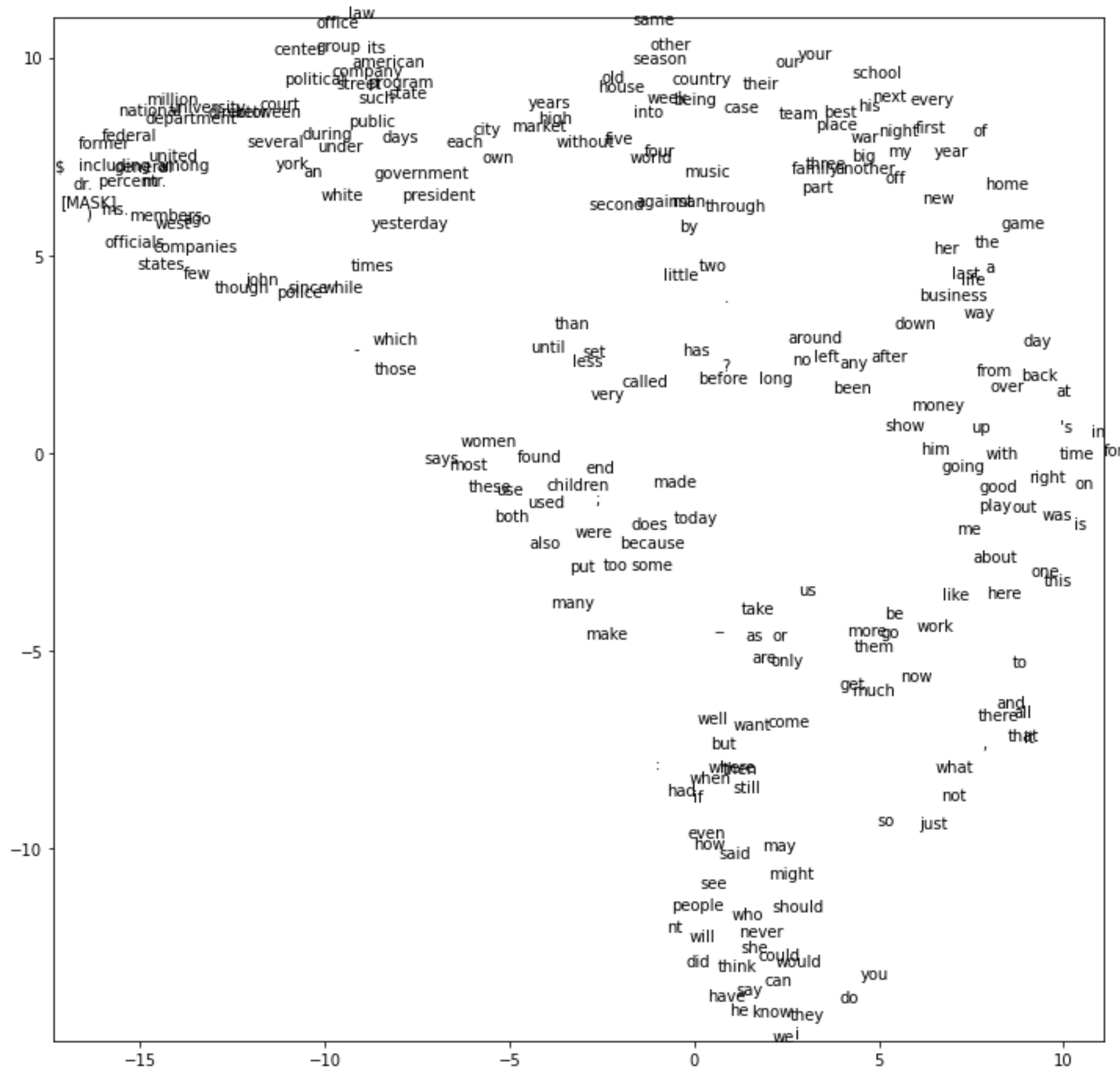
In [45]:

```
plot_2d_GLoVE_representation(W_final_2d, b_final_2d)
```



In [46]:

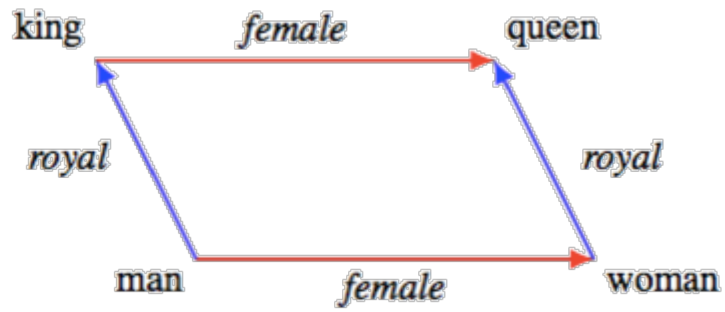
```
tsne_plot_GLoVE_representation(W_final_2d, b_final_2d)
```



4.2 Word Embedding Arithmetic

A word analogy f is an invertible transformation that holds over a set of ordered pairs S iff $\forall(x,y) \in s, f(x) = y \wedge f^{-1}(y) = x$. When f is of the form $\vec{\mathrm{x}} \to \vec{\mathrm{x}} + \vec{\mathrm{r}}$, it is a linear word analogy.

Arithmetic operators can be applied to vectors generated by language models. There is a famous example: $\overrightarrow{\mathrm{king}} - \overrightarrow{\mathrm{man}} + \overrightarrow{\mathrm{women}} \approx \overrightarrow{\mathrm{queen}}$. These linear word analogies form a parallelogram structure in the vector space (Ethayarajh, Duvenaud, \& Hirst, 2019).



In this section, we will explore a property of *linear word analogies*. A linear word analogy holds exactly over a set of ordered word pairs S iff $\| \vec{x} - \vec{y} \|^2$ is the same for every word pair, $\| \vec{a} - \vec{x} \|^2 = \| \vec{b} - \vec{y} \|^2$ for any two word pairs, and the vectors of all words in S are coplanar.

We will use the embeddings from the symmetric, asymmetrical GloVe model, and the neural network model from part 3 to perform arithmetics. The method to perform the arithmetic and retrieve the closest word embeddings is provided in the notebook using the method `find_word_analogy`:

- `find_word_analogy` returns the closest word to the word embedding calculated from the 3 given words.

In [47]:

```
np.random.seed(1)
n_epochs = 500  # A hyperparameter.  You can play with this if you want.
embedding_dims = 16

W_final_sym, W_tilde_final_asym, W_final_asym = None, None, None
init_variance = 0.1  # A hyperparameter.  You can play with this if you want.
W = init_variance * np.random.normal(size=(vocab_size, embedding_dim))
W_tilde = init_variance * np.random.normal(size=(vocab_size, embedding_dim))
b = init_variance * np.random.normal(size=(vocab_size, 1))
b_tilde = init_variance * np.random.normal(size=(vocab_size, 1))

# Symmetric model
W_final_sym, _, b_final_sym, _ , _, _ = train_GLoVE(W, None, b, None, asym_log
# Asymmetric model
W_final_asym, W_tilde_final_asym, b_final_asym, b_tilde_final_asym, _, _ = tra
```

You will need to use different embeddings to evaluate the word analogy

In [48]:

```
def get_word_embedding(word, embedding_weights):
    assert word in data['vocab'], 'Word not in vocab'
    return embedding_weights[data['vocab'].index(word)]
```

In [49]:

```
# word4 = word1 - word2 + word3
def find_word_analogy(word1, word2, word3, embedding_weights):
    embedding1 = get_word_embedding(word1, embedding_weights)
    embedding2 = get_word_embedding(word2, embedding_weights)
    embedding3 = get_word_embedding(word3, embedding_weights)
    target_embedding = embedding1 - embedding2 + embedding3

    # Compute distance to every other word.
    diff = embedding_weights - target_embedding.reshape((1, -1))
    distance = np.sqrt(np.sum(diff ** 2, axis=1))

    # Sort by distance.
    order = np.argsort(distance)[:10]
    print("The top 10 closest words to emb({}) - emb({}) + emb({}) are:".forma
    for i in order:
        print('{}: {}'.format(data['vocab'][i], distance[i]))
```

In this part of the assignment, you will use the find_word_analogy function to analyze quadruplets from the vocabulary.

4.2.1 Specific example

Perform arithmetic on words *her*, *him*, *her*, using: (1) symmetric, (2) averaging asymmetrical GloVe embedding, (3) concatenating asymmetrical GloVe embedding, and (4) neural network word embedding from part 3. That is, we are trying to find the closet word embedding vector to the vector

$$emb(he) - emb(him) + emb(her)$$

For each sets of embeddings, you should list out: (1) what the closest word that is not one of those three words, and (2) the distance to that closest word. Is the closest word *she*? Compare the results with the tSNE plots.

4.2.1 **Answer**:

The closest word, excluding the three input wrds, is "she". In the tSNE plot above, "he" and "she" are indeed very close.

In [50]:

```
## GloVe embeddings
embedding_weights = W_final_sym # Symmetric GloVe
find_word_analogy('he', 'him', 'her', embedding_weights)
```

```
The top 10 closest words to emb(he) - emb(him) + emb(her) are:
he: 1.4213098857979796
she: 1.4816743343259404
said: 2.102596010639777
then: 2.272042598776141
does: 2.3019648677199025
says: 2.3180472932860456
who: 2.328984314854128
where: 2.334702431567161
did: 2.353623598835888
should: 2.412642820598987
```

In [51]:

```
# Concatenation of W_final_asym, W_tilde_final_asym
embedding_weights = np.concatenate((W_tilde_final_asym, W_final_asym), axis=1)
find_word_analogy('he', 'him', 'her', embedding_weights)
```

```
The top 10 closest words to emb(he) - emb(him) + emb(her) are:
he: 1.8408997110954544
she: 3.525381876604418
.: 3.814058213350506
it: 3.834602594000694
not: 3.8502577902101205
,: 3.966789595146414
for: 4.13126564756227
a: 4.306200023685499
this: 4.438955672861169
and: 4.596584831219429
```

In [52]:

```
# Averaging asymmetric GLoVE vectors
embedding_weights = (W_final_asym + W_tilde_final_asym)/2
find_word_analogy('he', 'him', 'her', embedding_weights)
```

```
The top 10 closest words to emb(he) - emb(him) + emb(her) are:
he: 0.9292778645847064
it: 1.7083306595954044
not: 1.7699614409146165
she: 1.791229887150652
.: 1.8365536678089058
,: 1.8464533807206152
for: 2.0494558704389743
and: 2.080481773496633
a: 2.1872093360035865
this: 2.1955159325592937
```

In [53]:

```
## Neural Netework Word Embeddings
embedding_weights = trained_model.params.word_embedding_weights # Neural netw
find_word_analogy('he', 'him', 'her', embedding_weights)
```

```
The top 10 closest words to emb(he) - emb(him) + emb(her) are:
he: 2.5227971235330675
she: 18.307108223760427
have: 26.140341676027298
i: 26.820827267518247
they: 27.05281184243827
want: 27.48337900161015
we: 27.89367936450576
do: 27.983451389041083
but: 29.149544615036554
about: 29.21727858781936
```

4.2.2 Finding another Quadruplet

Pick another quadruplet from the vocabulary which displays the parallelogram property (and also makes sense sementically) and repeat the above procedues. Compare and comment on the results from arithmetic and tSNE plots.

4.2.2 **Answer**:

Due to the limited vocabulary size it was difficult to find good analogies. In the example below, `emb(mr.) - emb(man) + emb(women)` yields `ms.` among the top 10, all of which have

In [71]:

```
# Repeat above with a different set of words
## GloVe embeddings
embedding_weights = W_final_sym # Symmetric GloVe
find_word_analogy('mr.', 'man', 'women', embedding_weights)
```

```
The top 10 closest words to emb(mr.) - emb(man) + emb(women) are:
companies: 1.1149046347686506
women: 1.1449409869354565
several: 1.2034068616552234
these: 1.2575120319348885
members: 1.2613301592755686
few: 1.271957339989323
): 1.3153106203411127
ms.: 1.3527649188424336
$: 1.3531208524706915
[MASK]: 1.3651827423019633
```

What you have to submit

For reference, here is everything you need to hand in. See the top of this handout for submission directions.

- A PDF file titled *a1-writeup.pdf* containing the following:
  - [ ] **Part 1**: Questions 1.1, 1.2, 1.3, 1.4. Completed code for `grad_GLoVE` function.
  - [ ] **Part 2**: Questions 2.1, 2.2, 2.3.
  - [ ] **Part 3**: Completed code for `compute_loss_derivative()` (3.1), `back_propagate()` (3.2) functions, and the output of `print_gradients()` (3.3)
  - [ ] **Part 4**: Questions 4.1, 4.2.1, 4.2.2
- Your code file `a1-code.ipynb`

In [ ]:

```

```