Natural Language Processing with Deep Learning

Word Window Classification, Neural Networks, and Matrix Calculus
Classification setup and notation

- Generally we have a training dataset consisting of samples

\[ \{x_i, y_i\}_{i=1}^{N} \]

- \( x_i \) are inputs, e.g. words (indices or vectors!), sentences, documents, etc.
  - Dimension \( d \)

- \( y_i \) are labels (one of \( C \) classes) we try to predict, for example:
  - classes: sentiment, named entities, buy/sell decision
  - other words
  - later: multi-word sequences
Classification intuition

- **Training data:** \( \{x_i, y_i\}_{i=1}^{N} \)

- **Simple illustration case:**
  - Fixed 2D word vectors to classify
  - Using softmax/logistic regression
  - Linear decision boundary

- **Traditional ML/Stats approach:** assume \( x_i \) are fixed, train (i.e., set) softmax/logistic regression weights \( W \in \mathbb{R}^{C \times d} \) to determine a decision boundary (hyperplane) as in the picture

- **Method:** For each \( x \), predict:
  \[
  p(y|x) = \frac{\exp(W_{y,x})}{\sum_{c=1}^{C} \exp(W_{c,x})}
  \]
Details of the softmax classifier

\[ p(y|x) = \frac{\exp(W_y.x)}{\sum_{c=1}^{C} \exp(W_c.x)} \]

We can tease apart the prediction function into two steps:

1. Take the \( y^{th} \) row of \( W \) and multiply that row with \( x \):

   \[ W_y.x = \sum_{i=1}^{d} W_{yi}x_i = f_y \]

   Compute all \( f_c \) for \( c = 1, ..., C \)

2. Apply softmax function to get normalized probability:

   \[ p(y|x) = \frac{\exp(f_y)}{\sum_{c=1}^{C} \exp(f_c)} = \text{softmax}(f_y) \]
Training with softmax and cross-entropy loss

• For each training example \((x, y)\), our objective is to maximize the probability of the correct class \(y\)

• Or we can minimize the negative log probability of that class:

\[
- \log p(y|x) = - \log \left( \frac{\exp(f_y)}{\sum_{c=1}^{C} \exp(f_c)} \right)
\]
Background: What is “cross entropy” loss/error?

- Concept of “cross entropy” is from information theory
- Let the true probability distribution be $p$
- Let our computed model probability be $q$
- The cross entropy is:

$$H(p, q) = - \sum_{c=1}^{C} p(c) \log q(c)$$

- Assuming a ground truth (or true or gold or target) probability distribution that is 1 at the right class and 0 everywhere else: $p = [0, ..., 0, 1, 0, ..., 0]$ then:
- **Because of one-hot $p$, the only term left is the negative log probability of the true class**
Classification over a full dataset

- Cross entropy loss function over full dataset \( \{x_i, y_i\}_{i=1}^{N} \)

\[
J(\theta) = \frac{1}{N} \sum_{i=1}^{N} - \log \left( \frac{e^{f_{y_i}}}{\sum_{c=1}^{C} e^{f_c}} \right)
\]

- Instead of

\[
f_y = f_y(x) = W_y \cdot x = \sum_{j=1}^{d} W_{yj} x_j
\]

We will write \( f \) in matrix notation:

\[
f = W x
\]
Traditional ML optimization

• For general machine learning $\theta$ usually only consists of columns of $W$:

$$\theta = \begin{bmatrix} W_{1} \\ \vdots \\ W_{d} \end{bmatrix} = W(:) \in \mathbb{R}^{Cd}$$

• So we only update the decision boundary via

$$\nabla_{\theta} J(\theta) = \begin{bmatrix} \nabla W_{1} \\ \vdots \\ \nabla W_{d} \end{bmatrix} \in \mathbb{R}^{Cd}$$
Neural Network Classifiers

- Softmax (≈ logistic regression) alone not very powerful
- Softmax gives only linear decision boundaries

This can be quite limiting

→ Unhelpful when a problem is complex

Wouldn’t it be cool to get these correct?
Neural Nets for the Win!

• Neural networks can learn much more complex functions and nonlinear decision boundaries!
  • In original space
Classification difference with word vectors

- Commonly in NLP deep learning:
  - We learn **both** \( W \) and word vectors \( x \)
  - We learn **both** conventional parameters and **re**presentations
  - The word vectors re-represent one-hot vectors—move them around in an intermediate layer vector space—for easy classification with a (linear) softmax classifier via layer \( x = Le \)

\[
\nabla_{\theta} J(\theta) = \begin{bmatrix}
\nabla W_1 \\
\vdots \\
\nabla W_d \\
\n\nabla x_{\text{aardvark}} \\
\vdots \\
\n\nabla x_{\text{zebra}}
\end{bmatrix} \in \mathbb{R}^{C \cdot d+V \cdot d}
\]

Very large number of parameters!
Neural computation
An artificial neuron

- Neural networks come with their own terminological baggage
- But if you understand how softmax models work, then you can easily understand the operation of a neuron!

\[
\sum_i w_i x_i + b \rightarrow f
\]
A neuron can be a binary logistic regression unit

\[ f = \text{nonlinear activation fct. (e.g. sigmoid)}, \ w = \text{weights}, \ b = \text{bias}, \ h = \text{hidden}, \ x = \text{inputs} \]

\[ h_{w,b}(x) = f(w^T x + b) \]

\[ f(z) = \frac{1}{1 + e^{-z}} \]

\( b \): We can have an “always on” feature, which gives a class prior, or separate it out, as a bias term

\( w, b \) are the parameters of this neuron i.e., this logistic regression model
A neural network = running several logistic regressions at the same time

If we feed a vector of inputs through a bunch of logistic regression functions, then we get a vector of outputs ...

But we don’t have to decide ahead of time what variables these logistic regressions are trying to predict!
A neural network = running several logistic regressions at the same time

... which we can feed into another logistic regression function

It is the loss function that will direct what the intermediate hidden variables should be, so as to do a good job at predicting the targets for the next layer, etc.
A neural network
= running several logistic regressions at the same time

Before we know it, we have a multilayer neural network....
Matrix notation for a layer

We have

\[ a_1 = f(W_{11}x_1 + W_{12}x_2 + W_{13}x_3 + b_1) \]
\[ a_2 = f(W_{21}x_1 + W_{22}x_2 + W_{23}x_3 + b_2) \]

etc.

In matrix notation

\[ z = Wx + b \]

\[ a = f(z) \]

Activation \( f \) is applied element-wise:

\[ f([z_1, z_2, z_3]) = [f(z_1), f(z_2), f(z_3)] \]
Non-linearities (aka “f”): Why they’re needed

- Example: function approximation, e.g., regression or classification
  - Without non-linearities, deep neural networks can’t do anything more than a linear transform
  - Extra layers could just be compiled down into a single linear transform: $W_1 W_2 x = Wx$
  - With more layers, they can approximate more complex functions!
The European Commission [ORG] said on Thursday it disagreed with German [MISC] advice.

Only France [LOC] and Britain [LOC] backed Fischler [PER]'s proposal.

“What we have to be extremely careful of is how other countries are going to take Germany 's lead”, Welsh National Farmers ' Union [ORG] ( NFU [ORG] ) chairman John Lloyd Jones [PER] said on BBC [ORG] radio.

Possible purposes:
- Tracking mentions of particular entities in documents
- For question answering, answers are usually named entities
- A lot of wanted information is really associations between named entities
- The same techniques can be extended to other slot-filling classifications
- Often followed by Named Entity Linking/Canonicalization into Knowledge Base
Named Entity Recognition on word sequences

We predict entities by classifying words in context and then extracting entities as word subsequences

- Foreign ORG B-ORG
- Ministry ORG I-ORG
- spokesman O O
- Shen PER B-PER
- Guofang PER I-PER
- told O O
- Reuters ORG B-ORG
- that O O

👍 BIO encoding
Why might NER be hard?

• Hard to work out boundaries of entity

  **First National Bank Donates 2 Vans To Future School Of Fort Smith**

  Is the first entity “First National Bank” or “National Bank”

• Hard to know if something is an entity

  Is there a school called “Future School” or is it a future school?

• Hard to know class of unknown/novel entity:

  To find out more about Zig Ziglar and read features by other Creators Syndicate writers and

  What class is “Zig Ziglar”? (A person.)

• Entity class is ambiguous and depends on context

  “Charles Schwab” is PER not ORG here! ✅ where Larry Ellison and Charles Schwab can live discreetly amongst wooded estates. And
Binary word window classification

• In general, classifying single words is rarely done

• Interesting problems like ambiguity arise in context!

• Example: auto-antonyms:
  • "To sanction" can mean "to permit" or "to punish"
  • "To seed" can mean "to place seeds" or "to remove seeds"

• Example: resolving linking of ambiguous named entities:
  • Paris ➔ Paris, France vs. Paris Hilton vs. Paris, Texas
  • Hathaway ➔ Berkshire Hathaway vs. Anne Hathaway
Window classification

- **Idea**: classify a word in its context window of neighboring words.

- For example, **Named Entity Classification** of a word in context:
  - Person, Location, Organization, None

- A simple way to classify a word in context might be to average the word vectors in a window and to classify the average vector
  - Problem: that would lose position information
Window classification: Softmax

• Train softmax classifier to classify a center word by taking concatenation of word vectors surrounding it in a window.

• Example: Classify “Paris” in the context of this sentence with window length 2:

  … museums in Paris are amazing … .

  \[ X_{\text{window}} = \begin{bmatrix} x_{\text{museums}} & x_{\text{in}} & x_{\text{Paris}} & x_{\text{are}} & x_{\text{amazing}} \end{bmatrix}^T \]

• Resulting vector \( x_{\text{window}} \in \mathbb{R}^{5d} \), a column vector!
Simplest window classifier: Softmax

- With $x = x_{\text{window}}$ we can use the same softmax classifier as before

\[
\hat{y}_y = p(y|x) = \frac{\exp(W_{y,x})}{\sum_{c=1}^{C} \exp(W_{c,x})}
\]

- With cross entropy error as before:

\[
J(\theta) = \frac{1}{N} \sum_{i=1}^{N} - \log \left( \frac{e^{f_{y_i}}}{\sum_{c=1}^{C} e^{f_{c}} } \right)
\]

- How do you update the word vectors?
- Short answer: Just take derivatives like last week and optimize
Binary classification with unnormalized scores

Method used by Collobert & Weston (2008, 2011)

- Just recently won ICML 2018 Test of time award

- For our previous example:
  \[ X_{\text{window}} = [ x_{\text{museums}} \ x_{\text{in}} \ x_{\text{Paris}} \ x_{\text{are}} \ x_{\text{amazing}} ] \]

- Assume we want to classify whether the center word is a Location

- Similar to word2vec, we will go over all positions in a corpus. But this time, it will be supervised and only some positions should get a high score.

- E.g., the positions that have an actual NER Location in their center are “true” positions and get a high score
Binary classification for NER Location

• Example: Not all museums in Paris are amazing.

• Here: one true window, the one with Paris in its center and all other windows are “corrupt” in terms of not having a named entity location in their center.

  museums in Paris are amazing

• “Corrupt” windows are easy to find and there are many: Any window whose center word isn’t specifically labeled as NER location in our corpus

  Not all museums in Paris
Neural Network Feed-forward Computation

Use neural activation \( a \) simply to give an unnormalized score

\[
\text{score}(x) = U^T a \in \mathbb{R}
\]

We compute a window’s score with a 3-layer neural net:

- \( s = \text{score}("\text{museums in Paris are amazing}\)"

\[
s = U^T f(Wx + b)
\]

\( x \in \mathbb{R}^{20 \times 1}, W \in \mathbb{R}^{8 \times 20}, U \in \mathbb{R}^{8 \times 1} \)

\[
x_{\text{window}} = [ x_{\text{museums}} \ x_{\text{in}} \ x_{\text{Paris}} \ x_{\text{are}} \ x_{\text{amazing}} ]
\]
Main intuition for extra layer

The middle layer learns non-linear interactions between the input word vectors.

Example: only if “museums” is first vector should it matter that “in” is in the second position.
The max-margin loss

- **Idea for training objective**: Make true window’s score larger and corrupt window’s score lower (until they’re good enough)
- $s = \text{score}(\text{museums in Paris are amazing})$
- $s_c = \text{score}(\text{Not all museums in Paris})$
- Minimize

\[
J = \max(0, 1 - s + s_c)
\]

- This is not differentiable but it is continuous $\rightarrow$ we can use SGD.
Max-margin loss

• Objective for a single window:

\[ J = \max(0, 1 - s + s_c) \]

• Each window with an NER location at its center should have a score +1 higher than any window without a location at its center

• xxx \( \longleftarrow 1 \longrightarrow \) ooo

• For full objective function: Sample several corrupt windows per true one. Sum over all training windows.

• Similar to negative sampling in word2vec
Simple net for score

\[ s = u^T h \]

\[ h = f(Wx + b) \]

\[ x \quad (\text{input}) \]

\[ x = [x_{\text{museums}} \quad x_{\text{in}} \quad x_{\text{paris}} \quad x_{\text{are}} \quad x_{\text{amazing}}] \]
Remember: Stochastic Gradient Descent

- Update equation:
  \[
  \theta_{\text{new}} = \theta_{\text{old}} - \alpha \nabla_{\theta} J(\theta)
  \]
  \(\alpha = \text{step size or learning rate}\)

- How do we compute \(\nabla_{\theta} J(\theta)\)?
  - By hand
  - Algorithmically: the backpropagation algorithm