

Advanced NN Architectures

Word Embeddings

Learning goals

- Understand what word embeddings are
- Learn the main methods of creating them

MOTIVATION (1)

- How to represent words in a neural network?
- Possible solution: indicator vectors of length $|V|$ (vocabulary size).

$$\vec{w}^{(\text{the})} = \begin{bmatrix} 1 \\ 0 \\ 0 \\ \vdots \end{bmatrix} \quad \vec{w}^{(\text{cat})} = \begin{bmatrix} 0 \\ 1 \\ 0 \\ \vdots \end{bmatrix} \quad \vec{w}^{(\text{dog})} = \begin{bmatrix} 0 \\ 0 \\ 1 \\ \vdots \end{bmatrix}$$

- **Question:** Why is this a bad idea?
 - Parameter explosion ($|V|$ might be $> 1M$)
 - All word vectors are orthogonal to each other \rightarrow no notion of word similarity

MOTIVATION (2)

- Learn one word vector $\vec{w}^{(i)} \in \mathbb{R}^D$ (“word embedding”) per word i
- Typical dimensionality: $50 \leq D \leq 1000 \ll |V|$
- Embedding matrix: $\mathbf{W} \in \mathbb{R}^{|V| \times D}$
- **Question:** Advantages of using word vectors?
 - We can express similarities between words, e.g., with cosine similarity:

$$\cos(\vec{w}^{(i)}, \vec{w}^{(j)}) = \frac{\mathbf{w}^{(i)T} \mathbf{w}^{(j)}}{\|\mathbf{w}^{(i)}\|_2 \cdot \|\mathbf{w}^{(j)}\|_2}$$

- Since the embedding operation is a *lookup operation*, we only need to update the vectors that occur in a given training batch

MOTIVATION (3)

- Training from scratch: Initialize embedding matrix randomly and learn it during training phase
- \rightarrow words that play similar roles w.r.t. task get similar embeddings
- e.g., from sentiment classification, we might expect
$$\vec{w}^{(\text{great})} \approx \vec{w}^{(\text{awesome})}$$
- **Question:** What could be a problem at test time?
 - If training set is small, many words are unseen during training and therefore have random vectors
- We typically have more unlabelled than labelled data. Can we learn embeddings from the unlabelled data?

MOTIVATION (4)

- Distributional hypothesis: “a word is characterized by the company it keeps” (Firth, 1957)
- Basic idea: learn similar vectors for words that occur in similar contexts
- Word2Vec, FastText, Glove

LANGUAGE MODELS

- **Question:** What is a Language Model?
 - Function to assign probability to a sequence of words.
- **Question:** What is an n-gram language Model?
 - Markov assumption: probability of word only depends on no more than $n - 1$ other (previous) words:

$$P(w_{[1]} \dots w_{[T]}) = \prod_{t=1}^T P(w_{[t]} | w_{[t-1]} \dots w_{[t-n+1]})$$

WORD2VEC AS A BIGRAM LANGUAGE MODEL

- Words in our vocabulary are represented as two sets of vectors:
 - $\vec{w}^{(i)} \in \mathbb{R}^D$ if they are to be predicted
 - $\vec{v}^{(i)} \in \mathbb{R}^D$ if they are conditioned on as context
- Predict word i given previous word j :

$$P(i|j) = f(\vec{w}^{(i)}, \vec{v}^{(j)})$$

- **Question:** What is a possible function $f(\cdot)$?

A SIMPLE NEURAL NETWORK BIGRAM LANGUAGE MODEL

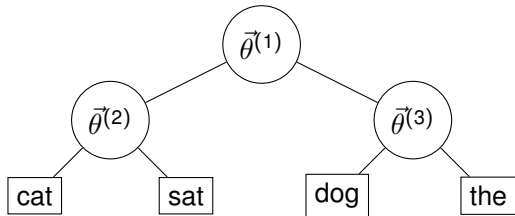
- Softmax!

$$P(i|j) = \frac{\exp(\mathbf{w}^{(i)T} \mathbf{v}^{(j)})}{\sum_{k=1}^{|V|} \exp(\mathbf{w}^{(k)T} \mathbf{v}^{(j)})}$$

- **Question:** Problem with training softmax?
 - \Rightarrow Slow. Needs to compute dot products with the whole vocabulary for every single prediction.

SPEEDING UP TRAINING: HIERARCHICAL SOFTMAX

- Context vectors \vec{v} are defined like before.
- Word vectors \vec{w} are replaced by a binary tree:

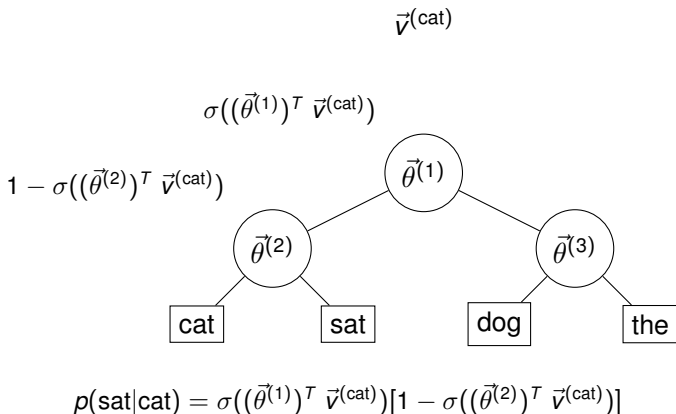


HIERARCHICAL SOFTMAX

- Each tree node l has parameter vector $\vec{\theta}^{(l)}$
- Probability of going left at node l given context word j :
 $p(\text{left}|l, j) = \sigma((\vec{\theta}^{(l)})^T \vec{v}^{(j)})$
- Probability of going right: $p(\text{right}|l, j) = 1 - p(\text{left}|l, j)$
- Probability of word i given j : product of probabilities on the path from root to i

EXAMPLE

Calculate $p(\text{sat}|\text{cat})$.



QUESTIONS

- **Question:** How many dot products do we need to calculate to get to $p(i|j)$? How does this compare to the naive softmax?
 - $\log_2 |V| \ll |V|$
- **Question:** Show that $\sum_{i'} p(i'|j)$ sums to 1.

SPEEDING UP TRAINING: NEGATIVE SAMPLING

- Another trick: **negative sampling** (aka *noise contrastive estimation*)
- This changes the objective function, and the resulting model is not a language model anymore!
- Idea: Instead of predicting probability distribution over whole vocabulary, make binary decisions for a small number of words.
- Positive training set: Bigrams seen in the corpus.
- Negative training set: Random bigrams (not seen in the corpus).

NEGATIVE SAMPLING: LIKELIHOOD

- Given:
 - Positive training set: $\text{pos}(\mathcal{O})$
 - Negative training set: $\text{neg}(\mathcal{O})$

$$L = \prod_{(i,j) \in \text{pos}(\mathcal{O})} P(\text{pos} | \vec{w}^{(i)}, \vec{v}^{(j)}) \prod_{(i',j') \in \text{neg}(\mathcal{O})} P(\text{neg} | \vec{w}^{(i')}, \vec{v}^{(j')})$$

- $P(\text{pos} | \vec{w}, \vec{v}) = \sigma(\vec{w}^T \vec{v})$
- $P(\text{neg} | \vec{w}, \vec{v}) = 1 - P(\text{pos} | \vec{w}, \vec{v})$
- **Question:** Why not just maximize $\prod_{(i,j) \in \text{pos}(\mathcal{O})} P(\text{pos} | \vec{w}^{(i)}, \vec{v}^{(j)})$?
 - Trivial solution: make all \vec{w}, \vec{v} identical

WORD2VEC WITH NEGATIVE SAMPLING AS CLASSIFICATION

- Maximize likelihood of training data:

$$\mathcal{L}(\theta) = \prod_i P(y^{(i)} | x^{(i)}; \theta)$$

- \Leftrightarrow minimize negative log likelihood:

$$NLL(\theta) = -\log \mathcal{L}(\theta) = -\sum_i \log P(y^{(i)} | x^{(i)}; \theta)$$

- **Question:** What do these components stand for in Word2Vec with negative sampling?
 - $x^{(i)}$ Word pair, from corpus OR randomly created
 - $y^{(i)}$ Label: 1 = word pair is from positive training set, 0 = word pair is from negative training set
 - θ Parameters \vec{v} , \vec{w}
 - $P(\dots)$ Logistic sigmoid: $P(1|\cdot) = \sigma(\vec{w}^T \vec{v})$, resp. $P(0|\cdot) = 1 - \sigma(\vec{w}^T \vec{v})$.

SPEEDING UP TRAINING: NEGATIVE SAMPLING

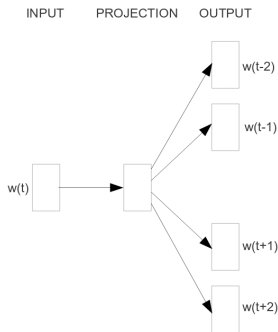
- Constructing a good negative training set can be difficult
- Often it is some random perturbation of the training data (e.g. replacing the second word of each bigram by a random word).
- The number of negative samples is often a multiple (1x to 20x) of the number of positive samples
- Negative sets are often constructed per batch

QUESTIONS

- **Question:** How many dot products do we need to calculate for a given word pair? How does this compare to the naive and hierarchical softmax?
 - $M + 1 \approx \log_2 |V| \ll |V|$
 - (for $M = 20, |V| = 1,000,000$)

SKIP-GRAM (WORD2VEC)

- Idea: Learn many bigram language models at the same time.
- Given word $w_{[t]}$, predict words inside a window around $w_{[t]}$:
 - One position before the target word: $p(w_{[t-1]}|w_{[t]})$
 - One position after the target word: $p(w_{[t+1]}|w_{[t]})$
 - Two positions before the target word: $p(w_{[t-2]}|w_{[t]})$
 - ... up to a specified window size c .
- Models share all \vec{w} , \vec{v} parameters!



Skip-gram

SKIP-GRAM: OBJECTIVE

- Optimize the joint likelihood of the $2c$ language models:

$$p(w_{[t-c]} \dots w_{[t-1]} w_{[t+1]} \dots w_{[t+c]} | w_{[t]}) = \prod_{\substack{i \in \{-c \dots c\} \\ i \neq 0}} p(w_{[t+i]} | w_{[t]})$$

- Negative Log-likelihood for whole corpus (of size N):

$$NLL = - \sum_{t=1}^N \sum_{\substack{i \in \{-c \dots c\} \\ i \neq 0}} \log p(w_{[t+i]} | w_{[t]})$$

- Using negative sampling as approximation:

$$\approx - \sum_{t=1}^N \sum_{\substack{i \in \{-c \dots c\} \\ i \neq 0}} \left[\log \sigma(\vec{w}_{[t+i]}^T \vec{v}_{[t]}) + \sum_{m=1}^M \log[1 - \sigma(\vec{w}^{(*)T} \vec{v}_{[t]})] \right]$$

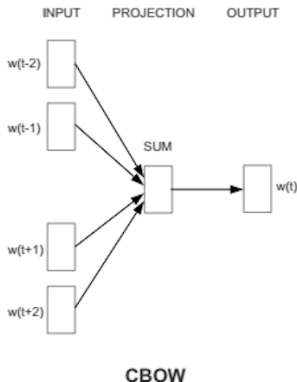
- $\vec{w}^{(*)}$ is the word vector of a random word, M is the number of negatives per positive sample

C(ONTINUOUS) B(AG) O(F) W(ORDS)

- Like Skipgram, but...
- Predict word $w_{[t]}$, given the words inside the window around $w_{[t]}$:

$$p(w_{[t]} | w_{[t-c]} \dots w_{[t-1]} w_{[t+1]} \dots w_{[t+c]})$$

$$\propto \vec{w}_{[t]}^T \sum_{\substack{i \in -c \dots c \\ i \neq 0}} \vec{v}_{[t+i]}$$



CBOW COMMAND EXAMPLE

```
$ word2vec -train data.txt -output vec.txt -window 5  
-negative 20 -hs 0 -cbow 1
```

FASTTEXT (1)

- Even if we train Word2Vec on a very large corpus, we will still encounter unknown words at test time
- Orthography can often help us:
- $\vec{w}^{(\text{remuneration})}$ should be similar to
 - $\vec{w}^{(\text{remunerate})}$ (same stem)
 - $\vec{w}^{(\text{iteration})}$, $\vec{w}^{(\text{consideration})}$. . . (same suffix \approx same POS)

FASTTEXT (2)

$$\text{known word: } \vec{w}^{(i)} = \frac{1}{|\text{ngrams}(i)| + 1} \left[\vec{u}^{(i)} + \sum_{n \in \text{ngrams}(i)} \vec{u}^{(n)} \right]$$

$$\text{unknown word: } \vec{w}^{(i)} = \frac{1}{|\text{ngrams}(i)|} \sum_{n \in \text{ngrams}(i)} \vec{u}^{(n)}$$

$$\text{ngrams}(\text{remuneration}) = \{\$re, rem, \$rem, \dots, ration, ation\$ \}$$

FASTTEXT TRAINING

- ngrams typically contains 3- to 6-grams
- Replace \vec{w} in Skipgram objective with its new definition
- During backpropagation, loss gradient vector $\frac{\partial J}{\partial \vec{w}^{(i)}}$ is distributed to word vector $\vec{u}^{(i)}$ and associated n-gram vectors $\vec{u}^{(n)}$

SUMMARY

- Word2Vec as a bigram Language Model
- Hierarchical Softmax
- Negative Sampling
- Skipgram: Predict words in window given word in the middle
- CBOW: Predict word in the middle given words in window
- fastText: N-gram embeddings generalize to unseen words
- Any questions?

USING PRETRAINED EMBEDDINGS

- Knowledge *transfer* from unlabelled corpus
- Design choice: Fine-tune embeddings on task or freeze them?
 - Pro: Can learn/strengthen features that are important for task
 - Contra: Training vocabulary is small subset of entire vocabulary → we might overfit and mess up topology w.r.t. unseen words

INITIALIZING NN WITH PRETRAINED EMBEDDINGS

Model	MR	SST-1	SST-2	Subj	TREC	CR	MPQA
CNN-rand (randomly initialized)	76.1	45.0	82.7	89.6	91.2	79.8	83.4
CNN-static (pretrained+frozen)	81.0	45.5	86.8	93.0	92.8	84.7	89.6
CNN-non-static (pretrained+fine-tuned)	81.5	48.0	87.2	93.4	93.6	84.3	89.5
CNN-multichannel (combination)	81.1	47.4	88.1	93.2	92.2	85.0	89.4

Table from Kim 2014: Convolutional Neural Networks for Sentence Classification.

RESOURCES

- <https://fasttext.cc/docs/en/crawl-vectors.html>
 - Embeddings for 157 languages, trained on big web crawls, up to 2M words per language
- <https://nlp.stanford.edu/projects/glove/>
 - GloVe word vectors: Cooccurrence-count objective, not n-gram based

ANALOGY MINING (1)

country-capital

$$\vec{w}(\text{Tokio}) - \vec{w}(\text{Japan}) + \vec{w}(\text{Poland}) \approx \vec{w}(\text{Warsaw})$$

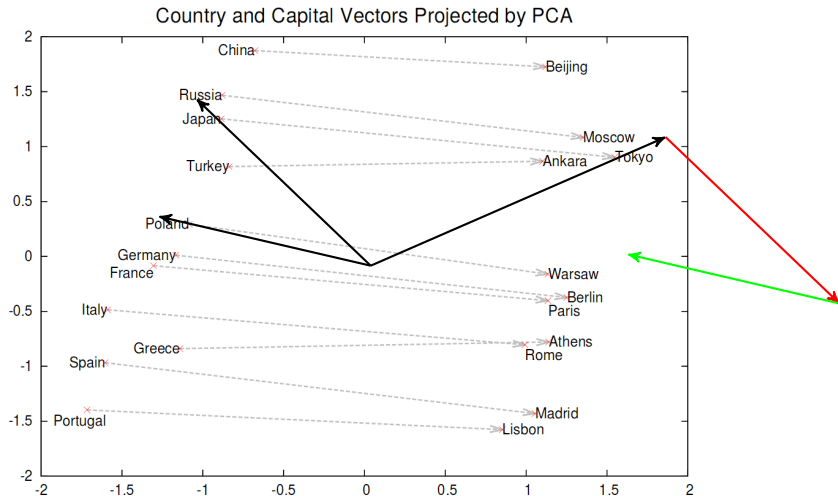
opposite

$$\vec{w}(\text{unacceptable}) - \vec{w}(\text{acceptable}) + \vec{w}(\text{logical}) \approx \vec{w}(\text{illogical})$$

Nationality-adjective

$$\vec{w}(\text{Australian}) - \vec{w}(\text{Australia}) + \vec{w}(\text{Switzerland}) \approx \vec{w}(\text{Swiss})$$

ANALOGY MINING (2)



ANALOGY MINING (3)

$$\vec{w}^{(a)} - \vec{w}^{(b)} + \vec{w}^{(c)} = \vec{w}^{(?)}$$

$$\vec{w}^{(d)} = \operatorname{argmax}_{\vec{w}^{(d')} \in \mathbf{W}} \cos(\vec{w}^{(?)}, \vec{w}^{(d')})$$

Table 8: *Examples of the word pair relationships, using the best word vectors from Table 4 (Skip-gram model trained on 783M words with 300 dimensionality).*

Relationship	Example 1	Example 2	Example 3
France - Paris	Italy: Rome	Japan: Tokyo	Florida: Tallahassee
big - bigger	small: larger	cold: colder	quick: quicker
Miami - Florida	Baltimore: Maryland	Dallas: Texas	Kona: Hawaii
Einstein - scientist	Messi: midfielder	Mozart: violinist	Picasso: painter
Sarkozy - France	Berlusconi: Italy	Merkel: Germany	Koizumi: Japan
copper - Cu	zinc: Zn	gold: Au	uranium: plutonium
Berlusconi - Silvio	Sarkozy: Nicolas	Putin: Medvedev	Obama: Barack
Microsoft - Windows	Google: Android	IBM: Linux	Apple: iPhone
Microsoft - Ballmer	Google: Yahoo	IBM: McNealy	Apple: Jobs
Japan - sushi	Germany: bratwurst	France: tapas	USA: pizza

SUMMARY

- Applications of Word Embeddings
 - Word vector initialization in neural networks for NLP tasks
 - E.g., sentiment classification of reviews, topical classification of news
 - Analogy mining
 - Information retrieval: semantic search, query expansion
 - Simple and fast aggregations of sentence representations
 - ...
- Any questions...?