

# Statistical Natural Language Processing

## Distributed representations

Çağrı Çöltekin

University of Tübingen  
Seminar für Sprachwissenschaft

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## Representations of linguistic units

- Most ML methods we use depend on how we represent the objects of interest, such as
  - words, morphemes
  - sentences, phrases
  - letters, phonemes
  - documents
  - speakers, authors
  - ...
- The way we represent these objects interacts with the ML methods
- We will mostly talk about word representations
  - They are also applicable any of the above

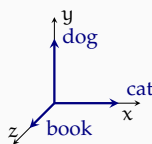
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Summer Semester 2018 1 / 1

## Symbolic (one-hot) representations

A common way to represent words is one-hot vectors

cat = (0, ..., 1, 0, 0, ..., 0)  
dog = (0, ..., 0, 1, 0, ..., 0)  
book = (0, ..., 0, 0, 1, ..., 0)  
...



- No notion of similarity
- Large and sparse vectors

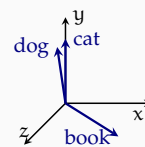
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Summer Semester 2018 2 / 1

## More useful vector representations

- The idea is to represent similar words with similar vectors

cat = (0, 3, 1, ..., 4)  
dog = (0, 3, 0, ..., 3)  
book = (4, 1, 4, ..., 5)  
...



- The similarity between the vectors may represent similarities based on
  - syntactic
  - semantic
  - topical
  - form
  - ... features useful in a particular task

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Summer Semester 2018 3 / 1

## Where do the vector representations come from?

- The vectors are (almost certainly) learned from the data
- Typically using an unsupervised (or self-supervised) method
- The idea goes back to,  
*You shall know a word by the company it keeps.*  
—Firth (1957)
- In practice, we make use of the contexts (company) of the words to determine their representations
- The words that appear in similar contexts are mapped to similar representations

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Summer Semester 2018 4 / 1

## How to calculate word vectors?

count word in context

	$c_1$	$c_2$	$c_3$	...	$c_m$
cat	0	3	1	...	4
dog	0	3	0	...	3
book	4	1	4	...	5

- + Now words that appear in the same contexts will have similar vectors
- The frequencies are often normalized (PMI, TF-IDF)
- The data is highly correlated: lots of redundant information
- Still large and sparse

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Summer Semester 2018 5 / 1

## How to calculate word vectors?

count, factorize, truncate

$$\begin{matrix} w_1 \\ w_2 \\ w_3 \end{matrix} \begin{bmatrix} c_1 & c_2 & c_3 & \dots & c_m \\ 0 & 3 & 1 & \dots & 4 \\ 0 & 3 & 0 & \dots & 3 \\ 4 & 1 & 4 & \dots & 5 \\ \dots & & & & \end{bmatrix} = \begin{matrix} z_1 & z_2 & z_3 & \dots & z_m \\ 1 & 5 & 9 & \dots & 4 \\ 1 & 4 & 1 & \dots & 3 \\ 9 & 1 & 1 & \dots & 5 \\ \dots & & & & \end{matrix} \begin{bmatrix} \sigma_1 & \dots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \dots & \sigma_m \end{bmatrix} \begin{matrix} c_1 & c_2 & c_3 & \dots & c_m \\ 0 & 3 & 1 & \dots & 4 \\ 0 & 3 & 0 & \dots & 3 \\ 9 & 1 & 8 & \dots & 0 \\ \dots & & & & \end{matrix} \begin{matrix} u_1 \\ u_2 \\ u_3 \end{matrix}$$

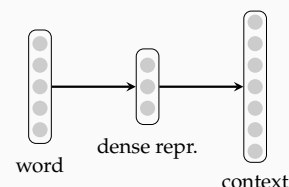
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Summer Semester 2018 6 / 1

## How to calculate word vectors?

predict the context from the word, or word from the context

- The task is predicting
  - the context of the word from the word itself
  - or the word from its context
- Task itself is not interesting
- We are interested in the hidden layer representations learned

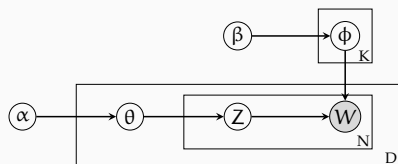


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Summer Semester 2018 7 / 1

## How to calculate word vectors?

latent variable models (e.g., LDA)



- Assume that the each 'document' is generated based on a mixture of latent variables
- Learn the probability distributions
- Typically used for *topic modeling*
- Can model words too (as a mixture of latent variables)

## A toy example

A four-sentence corpus with *bag of words* (BOW) model.

The corpus:

S1: She likes cats and dogs  
S2: He likes dogs and cats  
S3: She likes books  
S4: He reads books

Term-document (sentence) matrix

	S1	S2	S3	S4
she	1	0	1	0
he	0	1	0	1
likes	1	1	1	0
reads	0	0	0	1
cats	1	1	0	0
dogs	1	1	0	0
books	0	0	1	1
and	1	1	0	0

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A four-sentence corpus with *bag of words* (BOW) model.

The corpus:

S1: She likes cats and dogs  
S2: He likes dogs and cats  
S3: She likes books  
S4: He reads books

Term-term (left-context) matrix

	#	she	he	likes	reads	cats	dogs	books	and
she	2	0	0	0	0	0	0	0	0
he	2	0	0	0	0	0	0	0	0
likes	0	2	1	0	0	0	0	0	0
reads	0	0	1	0	0	0	0	0	0
cats	0	0	0	1	0	0	0	0	1
dogs	0	0	0	1	0	0	0	0	1
books	0	0	0	1	1	0	0	0	0
and	0	0	0	0	0	1	1	0	0

## Term-document matrices

- The rows are about the terms: similar terms appear in similar contexts
- The columns are about the context: similar contexts contain similar words
- The term-context matrices are typically sparse and large

Term-document (sentence) matrix

	S1	S2	S3	S4
she	1	0	1	0
he	0	1	0	1
likes	1	1	1	0
reads	0	0	0	1
cats	1	1	0	0
dogs	1	1	0	0
books	0	0	1	1
and	1	1	0	0

## SVD (again)

- Singular value decomposition is a well-known method in linear algebra
- An  $n \times m$  ( $n$  terms  $m$  documents) term-document matrix  $X$  can be decomposed as

$$X = U \Sigma V^T$$

$U$  is a  $n \times r$  unitary matrix, where  $r$  is the rank of  $X$  ( $r \leq \min(n, m)$ ). Columns of  $U$  are the eigenvectors of  $XX^T$   
 $\Sigma$  is a  $r \times r$  diagonal matrix of singular values (square root of eigenvalues of  $XX^T$  and  $X^T X$ )  
 $V^T$  is a  $r \times m$  unitary matrix. Columns of  $V$  are the eigenvectors of  $X^T X$

- One can consider  $U$  and  $V$  as PCA performed for reducing dimensionality of rows (terms) and columns (documents)

## Truncated SVD

$$X = U \Sigma V^T$$

- Using eigenvectors (from  $U$  and  $V$ ) that correspond to  $k$  largest singular values ( $k < r$ ), allows reducing dimensionality of the data with minimum loss
- The approximation,

$$\hat{X} = U_k \Sigma_k V_k$$

results in the best approximation of  $X$ , such that  $\|\hat{X} - X\|_F$  is minimum

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- Note that  $r$  and  $n$  may easily be millions (of words or contexts), while we choose  $k$  much smaller (a few hundreds)

## Truncated SVD (2)

$$\begin{bmatrix} x_{1,1} & x_{1,2} & x_{1,3} & \dots & x_{1,m} \\ x_{2,1} & x_{2,2} & x_{2,3} & \dots & x_{2,m} \\ x_{3,1} & x_{3,2} & x_{3,3} & \dots & x_{3,m} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ x_{n,1} & x_{n,2} & x_{n,3} & \dots & x_{n,m} \end{bmatrix} = \begin{bmatrix} u_{1,1} & \dots & u_{1,k} \\ u_{2,1} & \dots & u_{2,k} \\ u_{3,1} & \dots & u_{3,k} \\ \vdots & \ddots & \vdots \\ u_{n,1} & \dots & u_{n,k} \end{bmatrix} \times \begin{bmatrix} \sigma_1 & \dots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \dots & \sigma_k \end{bmatrix} \times \begin{bmatrix} v_{1,1} & v_{1,2} & \dots & v_{1,m} \\ \vdots & \vdots & \ddots & \vdots \\ v_{k,1} & v_{k,2} & \dots & v_{k,m} \end{bmatrix}$$

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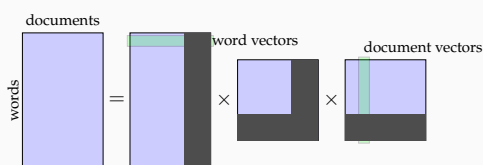
The term<sub>1</sub> can be represented using the first row of  $\mathbf{U}_k$

## Truncated SVD (2)

$$\begin{bmatrix} x_{1,1} & x_{1,2} & x_{1,3} & \dots & x_{1,m} \\ x_{1,1} & x_{1,2} & x_{1,3} & \dots & x_{1,m} \\ x_{2,1} & x_{2,2} & x_{2,3} & \dots & x_{2,m} \\ x_{3,1} & x_{3,2} & x_{3,3} & \dots & x_{3,m} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ x_{n,1} & x_{n,2} & x_{n,3} & \dots & x_{n,m} \end{bmatrix} = \begin{bmatrix} u_{1,1} & \dots & u_{1,k} \\ u_{2,1} & \dots & u_{2,k} \\ u_{3,1} & \dots & u_{3,k} \\ \vdots & \ddots & \vdots \\ u_{n,1} & \dots & u_{n,k} \end{bmatrix} \times \begin{bmatrix} \sigma_1 & \dots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \dots & \sigma_k \end{bmatrix} \times \begin{bmatrix} v_{1,1} & v_{1,2} & \dots & v_{1,m} \\ \vdots & \vdots & \ddots & \vdots \\ v_{k,1} & v_{k,2} & \dots & v_{k,m} \end{bmatrix}$$

The document<sub>1</sub> can be represented using the first column of  $\mathbf{V}_k^T$

## Truncated SVD: with a picture



Step 1 Get word-context associations

Step 2 Decompose

Step 3 Truncate

## Truncated SVD example

The corpus:

(S1) She likes cats and dogs  
(S2) He likes dogs and cats  
(S3) She likes books  
(S4) He reads books

	S1	S2	S3	S4
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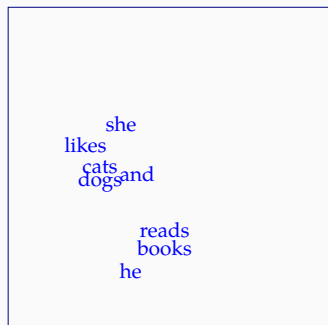
Truncated SVD ( $k = 2$ )

$$\mathbf{U} = \begin{bmatrix} -0.30 & 0.28 \\ -0.24 & -0.63 \\ -0.52 & 0.15 \\ -0.03 & -0.49 \\ -0.43 & 0.01 \\ -0.43 & 0.01 \\ -0.03 & -0.49 \\ -0.43 & 0.01 \end{bmatrix} \begin{matrix} \text{she} \\ \text{he} \\ \text{likes} \\ \text{reads} \\ \text{cats} \\ \text{dogs} \\ \text{books} \\ \text{and} \end{matrix}$$

$$\Sigma = \begin{bmatrix} 3.11 & 0 \\ 0 & 1.81 \end{bmatrix}$$

$$\mathbf{V}^T = \begin{bmatrix} -0.68 & 0.26 & -0.11 & -0.66 \\ -0.66 & -0.23 & 0.48 & 0.50 \end{bmatrix} \begin{matrix} S1 & S2 & S3 & S4 \end{matrix}$$

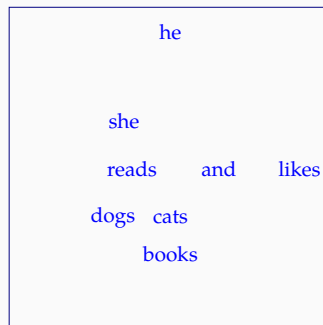
## Truncated SVD (with BOW sentence context)



The corpus:

(S1) She likes cats and dogs  
(S2) He likes dogs and cats  
(S3) She likes books  
(S4) He reads books

## Truncated SVD (with single word context)



The corpus:

(S1) She likes cats and dogs  
(S2) He likes dogs and cats  
(S3) She likes books  
(S4) He reads books

## SVD: LSI/LSA

SVD applied to term-document matrices are called

- *Latent semantic analysis (LSA)* if the aim is constructing *term* vectors
  - Semantically similar words are closer to each other in the vector space
- *Latent semantic indexing (LSI)* if the aim is constructing *document* vectors
  - Topically related documents are closer to each other in the vector space

## Context matters

In SVD (and other) vector representations, the choice of context matters

- Larger contexts tend to find semantic/topical relationships
- Smaller (also order-sensitive) contexts tend to find syntactic generalizations

## SVD based vectors: practical concerns

- In practice, instead of raw counts of terms within contexts, the term-document matrices typically contain
  - pointwise mutual information
  - tf-idf
- If the aim is finding latent (semantic) topics, frequent/syntactic words (*stopwords*) are often removed
- Depending on the measure used, it may also be important to normalize for the document length

## SVD-based vectors: applications

- The SVD-based methods is commonly used in information retrieval
  - The system builds document vectors using SVD
  - The search terms are also considered as a 'document'
  - System retrieves the documents whose vectors are similar to the search term
- The well known Google *PageRank* algorithm is a variation of the SVD

In this context, the results is popularly called "the \$25 000 000 000 eigenvector".

## SVD-based vectors: applications

- The SVD-based methods for semantic similarity is also common
- It was shown that the vector space models outperform humans in
  - TOEFL synonym questions  
Receptors for the sense of smell are located at the top of the nasal cavity.  
**A.** upper end **B.** inner edge **C.** mouth **D.** division
  - SAT analogy questions  
Paltry is to significance as \_\_\_\_\_ is to \_\_\_\_\_.  
**A.** redundant : discussion  
**B.** austere : landscape  
**C.** opulent : wealth  
**D.** oblique : familiarity  
**E.** banal : originality
- In general the SVD is a very important method in many fields

## Predictive models

- Instead of dimensionality reduction through SVD, we try to predict
  - either the target word from the context
  - or the context given the target word
- We assign each word to a fixed-size random vector
- We use a standard ML model and try to reduce the prediction error with a method like gradient descent
- During learning, the algorithm optimizes the vectors as well as the model parameters
- In this context, the word-vectors are called **embeddings**
- This types of models has been very popular during last few years

## Predictive models

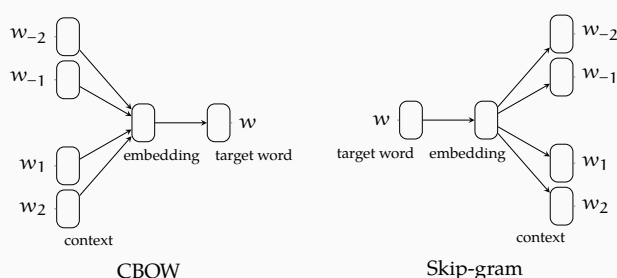
- The idea is the 'locally' predict the context a particular word occurs
- Both the context and the words are represented as low dimensional dense vectors
- Typically, neural networks are used for the prediction
- The hidden layer representations are the vectors we are interested

## word2vec

- **word2vec** is a popular algorithm and open source application for training word vectors (**mikolov2013**)
- It has two modes of operation
  - CBOW** or continuous bag of words predict the word using a window around the word
  - Skip-gram** does the reverse, it predicts the words in the context of the target word using the target word as the predictor

## word2vec

CBOW and skip-gram modes – conceptually



## word2vec

a bit more in detail

- For each word  $w$  algorithm learns two sets of embeddings
  - $v_w$  for words
  - $c_w$  for contexts
- Objective of the learning is to maximize (skip-gram)

$$P(c | w) = \frac{e^{v_w \cdot c_c}}{\sum_{c' \in c} e^{c_c' \cdot v_w}}$$

Note that the above is simply *softmax* – the learning method is equivalent to logistic regression

- Now, we can use gradient-based approaches to find word and context vectors that maximize this objective

## Issues with softmax

$$P(c | w) = \frac{e^{v_w \cdot c_c}}{\sum_{c' \in \mathcal{C}} e^{c_c \cdot v_w}}$$

- A particular problem with models with a softmax output is high computational cost:
  - For each instance in the training data denominator need to be calculated over the whole vocabulary (can easily be millions)
- Two workarounds exist:
  - *Negative sampling*: a limited number of negative examples (sampled from the corpus) are used to calculate the denominator
  - *Hierarchical softmax*: turn output layer to a binary tree, where probability of a word equals to the probability of the path followed to find the word
- Both methods are applicable to training, during prediction, we still need to compute the full softmax

## word2vec: some notes

- Note that word2vec is not 'deep'
- word2vec performs well, and it is much faster than earlier (more complex) ANN architectures developed for this task
- The resulting vectors used by many (deep) ANN models, but they can also be used by other 'traditional' methods
- word2vec treats the context as a BoW, hence vectors capture semantic relationships
- There are many alternative formulations

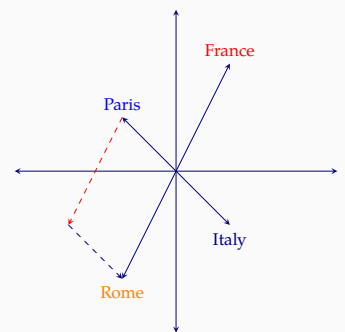
## GloVe

- GloVe is another popular method for obtaining word vectors (**pennington2014**)
- It tries to combine intuitions from both SVD-like 'counting' methods, and prediction-based methods
- It is reported performs better on smaller data sets

## Word vectors and syntactic/semantic relations

Word vectors map some syntactic/semantic relations to vector operations

- **Paris - France + Italy = Rome**
- king - man + woman = queen
- duck - ducks + mouse = mice



## Using vector representations

- Dense vector representations are useful for many ML methods
- They are particularly suitable for neural network models
- 'General purpose' vectors can be trained on unlabeled data
- They can also be trained for a particular purpose, resulting in 'task specific' vectors
- Dense vector representations are not specific to words, they can be obtained and used for any (linguistic) object of interest

## Evaluating vector representations

- Like other unsupervised methods, there are no 'correct' labels
- Evaluation can be based on
  - Intrinsic evaluation based on success on finding analogy/synonymy
  - Extrinsic evaluation, based on whether they improve a particular task (e.g., parsing, sentiment analysis) or not
  - Correlation with human judgments

## Differences of the methods

...or the lack thereof

- It is often claimed, after excitement created by word2vec, that prediction-based models work better
- Careful analyses suggest, however, that word2vec can be seen as an approximation to a special case of SVD
- Performance differences seem to boil down to how well the hyperparameters are optimized
- In practice, the computational requirements is probably a bigger factor in choice

## Summary

- Dense vector representations of linguistic units (as opposed to symbolic representations) allow calculating similarity/difference between the units
- They can be either based on counting (SVD), or predicting (word2vec, GloVe)
- They are particularly suitable for ANNs, deep learning architectures

Next:

Mon Text classification

Fri Q&A, other NLP applications (?)

## Additional reading, references, credits

- Upcoming edition of the textbook (**jurafsky2009**) has two chapters covering the related material.
- See **levy2015** for a comparison of different ways of obtaining embeddings.