

Natural Language and Speech Processing

Lecture 7: Neural Language Models and Word
Embeddings

Tanel Alumäe

Contents

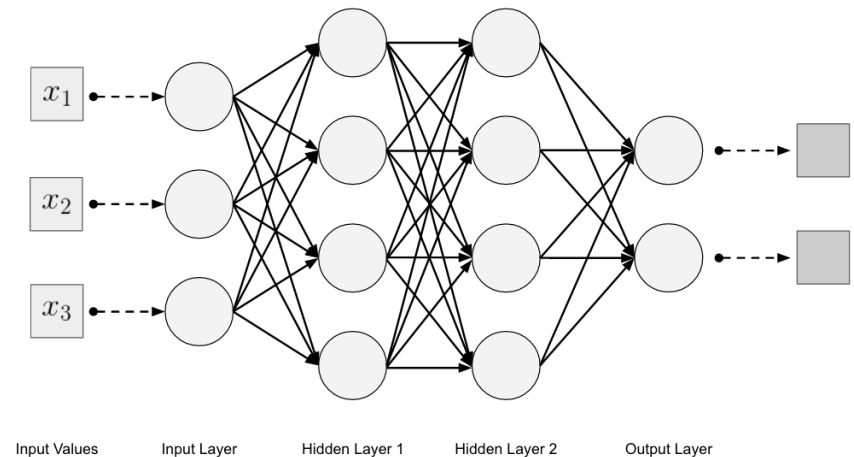
- Using neural networks for language modeling
- Side effect of language modeling: word embeddings
- Properties and applications of word embeddings

Language modeling

- Language modeling with N-gram models was covered in Lecture 4
- Problems with N-gram language models:
 - Cannot share strength among **similar words**:
she **bought** a **car**
she **purchased** a **car**
 - Cannot condition on context with **intervening words**:
Dr. Jane **Smith**
Dr. Gertrud **Smith**
 - Cannot handle **long-distance dependencies**
for **tennis** class he wanted to buy his own **racquet**
for **programming** class he wanted to buy his own **computer**

Neural network language model

- Neural network language model use previous N-1 words (context) as features
- Output layer is softmax over the whole vocabulary (+ sentence end token $\langle /s \rangle$)
- Hidden layer can be viewed as a feature extractor that computes more complex representation of the context
- But how to represent the context words as features?



One-hot-encoding of context words

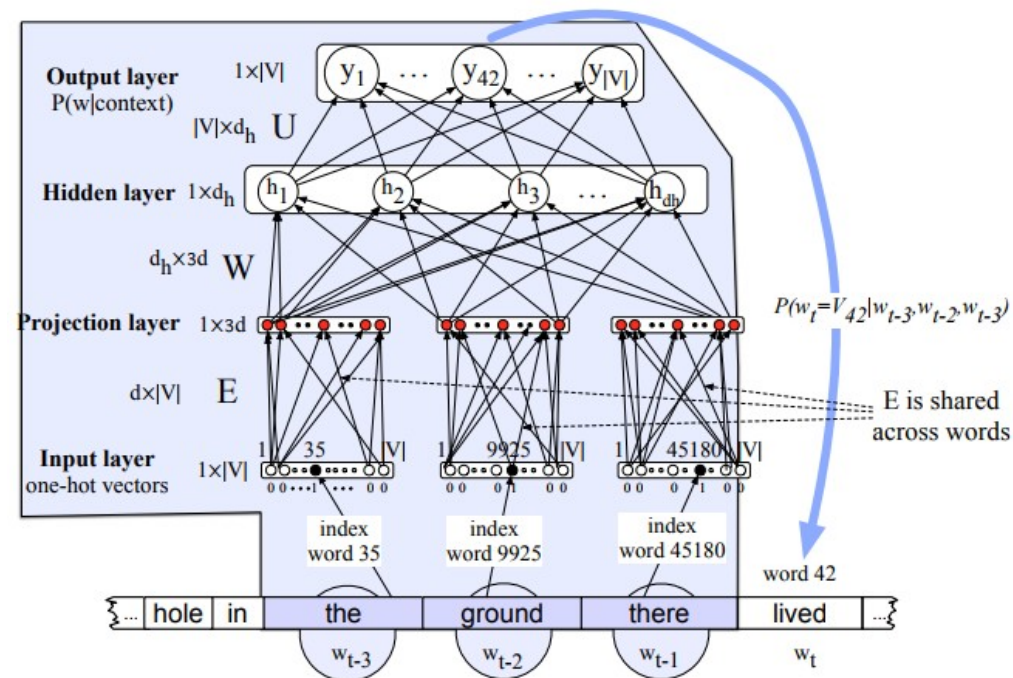
- N-1 previous words are represented using **one-hot encoding**
- Each word index is associated with a **projection vector** e
- The vectors together form a projection matrix E
- The projector vector maps a word index to continuous vector representation (typically dimensionality: 100)
- The projection vectors of N-1 previous words are concatenated

Projection layer output:

$e_{i-1} e_{i-2} e_{i-3}$

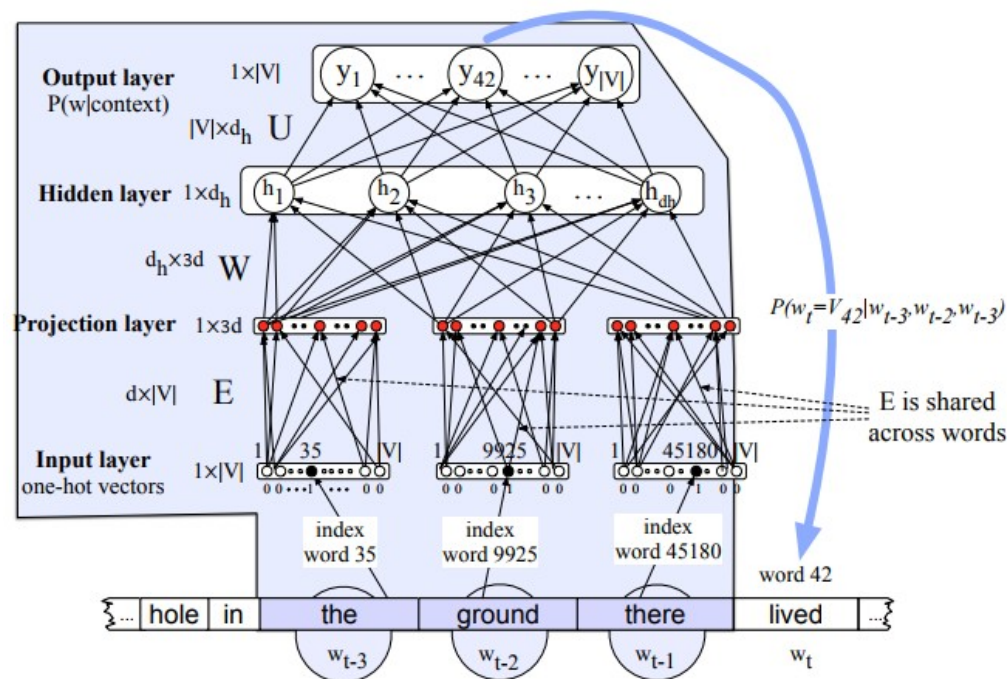
- The output of the projection layer is sent to the next hidden layer
- Projection vectors are **shared** between positions

i.e., we use the same e for the word “dog”, regardless whether it is w_{i-1} or w_{i-2}



Neural network language model walkthrough

- Calculate probability of “*lived*”, given previous words “*the ground there*”:
- Look up the indices of context words:
the → 35, *ground* → 9925, *there* → 45180
- Look up the projection vectors, i.e. rows 35, 9925, 45180 from projection matrix E
- Concatenate projection vectors:
 $e = e_{35} \ e_{9925} \ e_{45180}$
- Apply the hidden layer:
 $h = \text{sigmoid}(W * e + b)$
- Apply the softmax layer:
 $y = \text{softmax}(U * h)$
- Look up probability of the current word: *lived* → 42
- **The probability of “*lived*”, given the context, is y_{42}**



Training the neural network language model

- Neural network language model can be trained using batch stochastic gradient descent, using cross entropy loss (although it's expensive)
- Training examples are simply n-grams from the training corpus, with the first $n-1$ words used as features and the last word of the n-gram as the target label
- It is important to shuffle n-grams before training (and at each epoch)

Training tricks

- Language models typically have a vocabulary of thousands of words (e.g. 200 000 is quite typical)
- This makes computing the output of the softmax layer very slow
- Solutions:

Use *shortlist*: use only most frequent 1000 words in the output layer, and use a regular N-gram model for the rest

- But this kind ruins the point of NNLM, as it is supposed to better model rare context/word combinations

Use a hierarchical softmax

- Allows to compute the probability of a single word in $O(\log(|V|))$, rather than $O(|V|)$

Self-normalizing approaches

- E.g. noise-contrastive estimation: model the target word against a small set of randomly drawn words
- Modify the training algorithm so that the outputs of the last layer are encouraged to sum to approximately 1, so that normalizing (which is very expensive) can be left out

Using Dropout for regularization

- To prevent overfitting to training data, a technique called **dropout** is often used during training
- Applicable to all kinds of neural nets, not only to NNLMs
- Method: at each training stage (e.g. minibatch), ignore randomly selected neurons

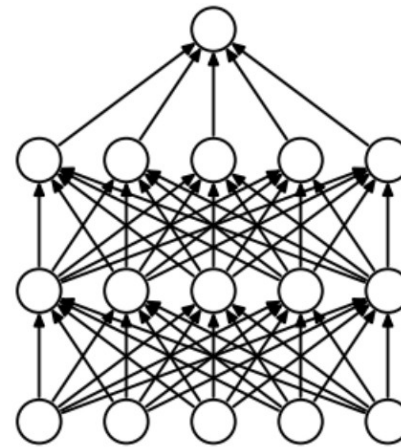
This means that their contribution to the activation of downstream neurons is temporally removed on the forward pass and any weight updates are not applied to the neuron on the backward pass

- Use all neurons during the prediction phase

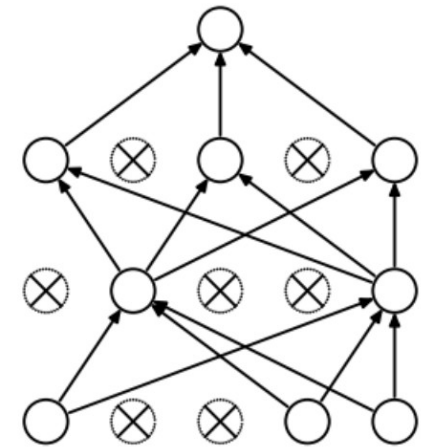
End effect: prediction is much like the average of the predictions across all these smaller nets

- Result: the network becomes less sensitive to the specific weights of neurons

This in turn results in a network that is capable of better generalization and is less likely to overfit the training data



(a) Standard Neural Net



(b) After applying dropout.

Benefits of Neural Network Language Model

- Improvements over the simple N-gram model

Can share strength among **similar words**:

she **bought** a **car**

she **purchased** a **car**

Can condition on context with **intervening words**:

Dr. Jane **Smith**

Dr. Gertrud **Smith**

- Does not solve the following problem

Cannot handle **long-distance dependencies**

for **tennis** class he wanted to buy his own **racquet**

for **programming** class he wanted to buy his own **computer**

This is handled by the recurrent neural network language model and transformers (we will study both of them in future lectures)

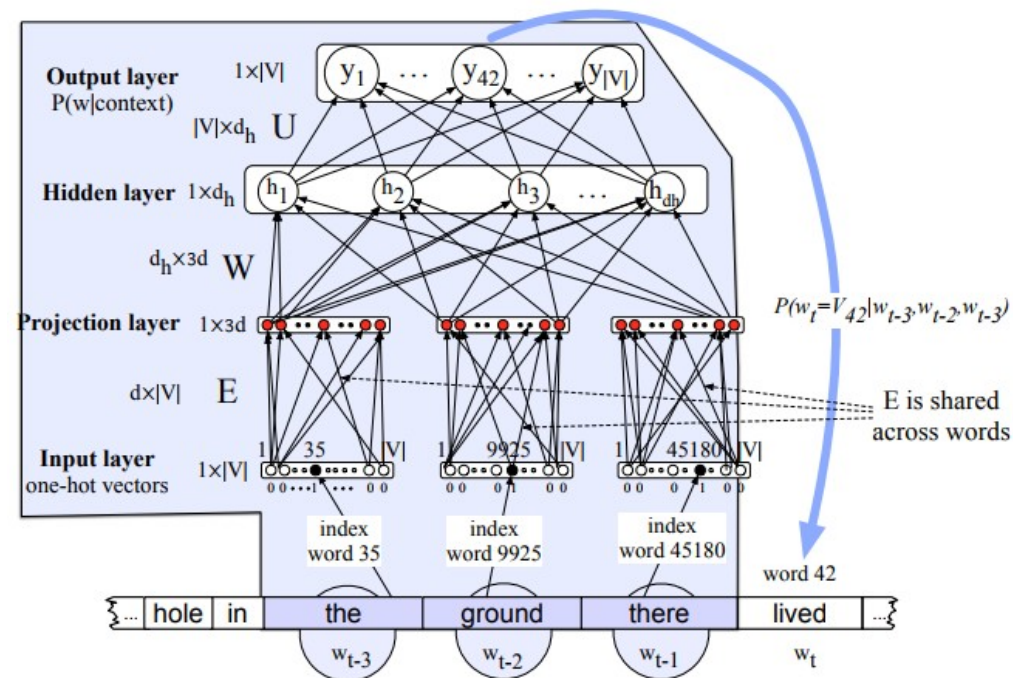
- In reality, NNLMs are better than N-grams with Kneser-Ney smoothing, but not a lot

Why not a lot? Probably because generalization sometimes hurts

- Typically used together with N-grams (probabilities are interpolated)

Useful side effect of NNLMs: word embeddings

- When training a NNLM, we train a projection vector for each word
- The projection vectors are optimized using gradient descent, like all other model parameters
- The projection vectors map discrete words to continuous (typically 100 dimensional) space
- Training finds projections that are useful for language modeling
- Actual result: words that are **similar** (syntactically and semantically) have **similar** vectors!
- The projection vectors are also known as **word embeddings**



One-hot vs embedding vectors

- One-hot vectors:
 - “dog” → [0 0 0 0 0 1 0 0 0 0]
 - “cat” → [0 0 0 0 0 0 1 0 0 0]
 - “and” → [0 0 0 0 0 0 0 0 0 1]
- Embeddings, e.g.
 - “dog” → [0.7 0.1 -0.5 1.7]
 - “cat” → [0.4 0.1 -0.4 1.8]
 - “and” → [-0.1 0.2 -0.9 0.2]
- Which representation knows that “dog” and “cat” more similar than “dog” and “and”?
- Which representation scales badly with vocabulary size?
- Which one loses some information?

Intuition behind word embeddings

- Dimension 1 might be **more positive for nouns**
- Dimension 3 might be **more positive for plural nouns**
- Dimension N might be **more positive for domestic pets**
- Dimension 2 might have **no meaning whatsoever**

- *“dogs”*



2.5

-0.2

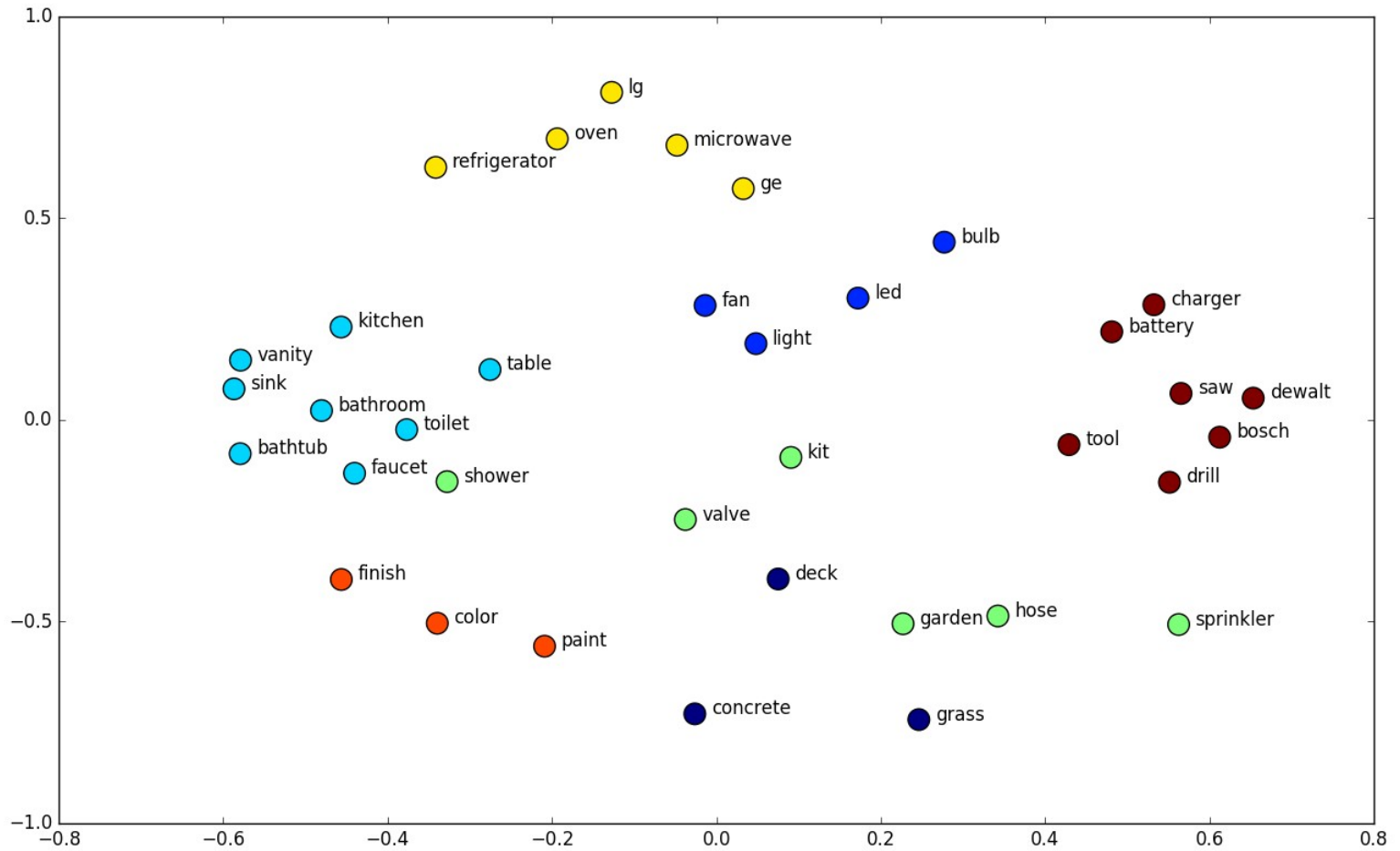
3.7

-0.6

...

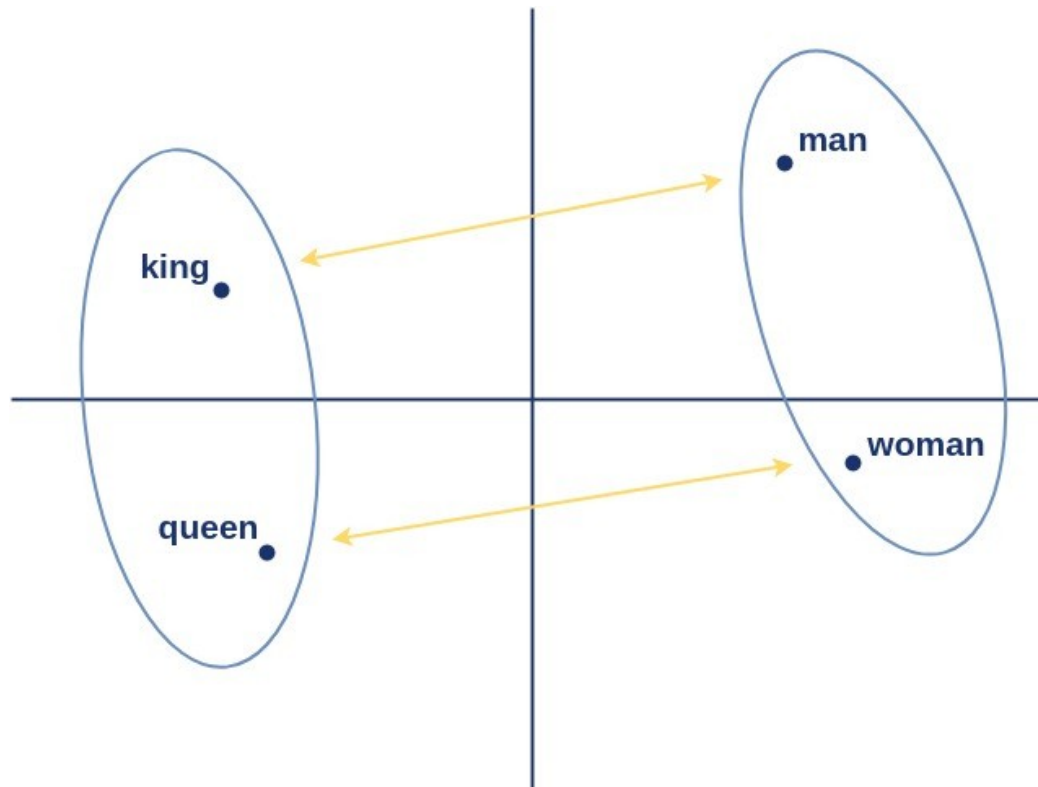
5.2

Example of word embeddings

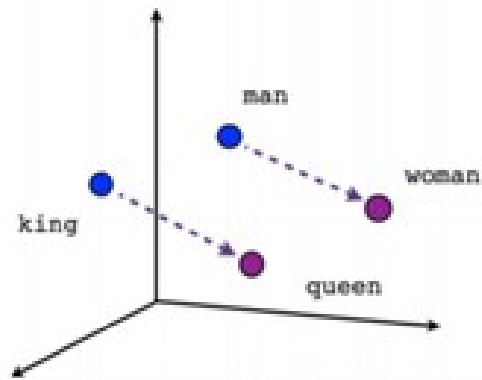


Word embeddings encode relationships between words

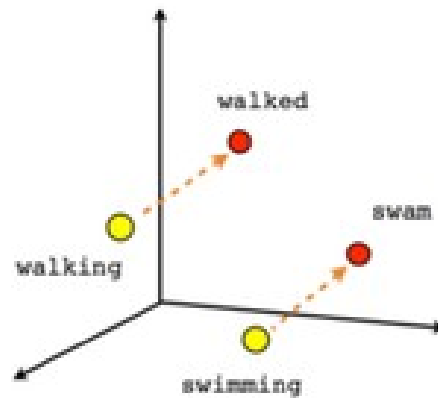
- Since words are now vectors, we can add them
- Result: *king - man + woman = queen*



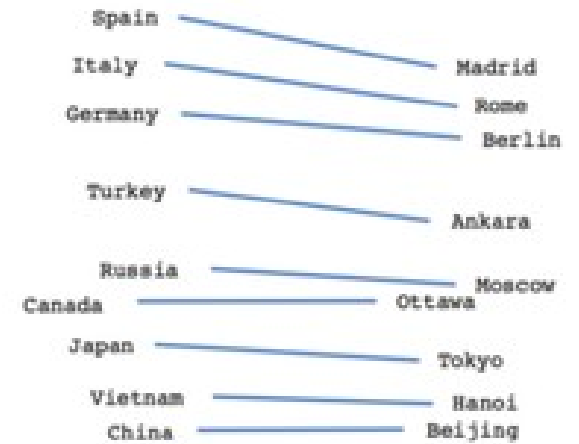
Relationships in word embeddings



Male-Female



Verb tense



Country-Capital

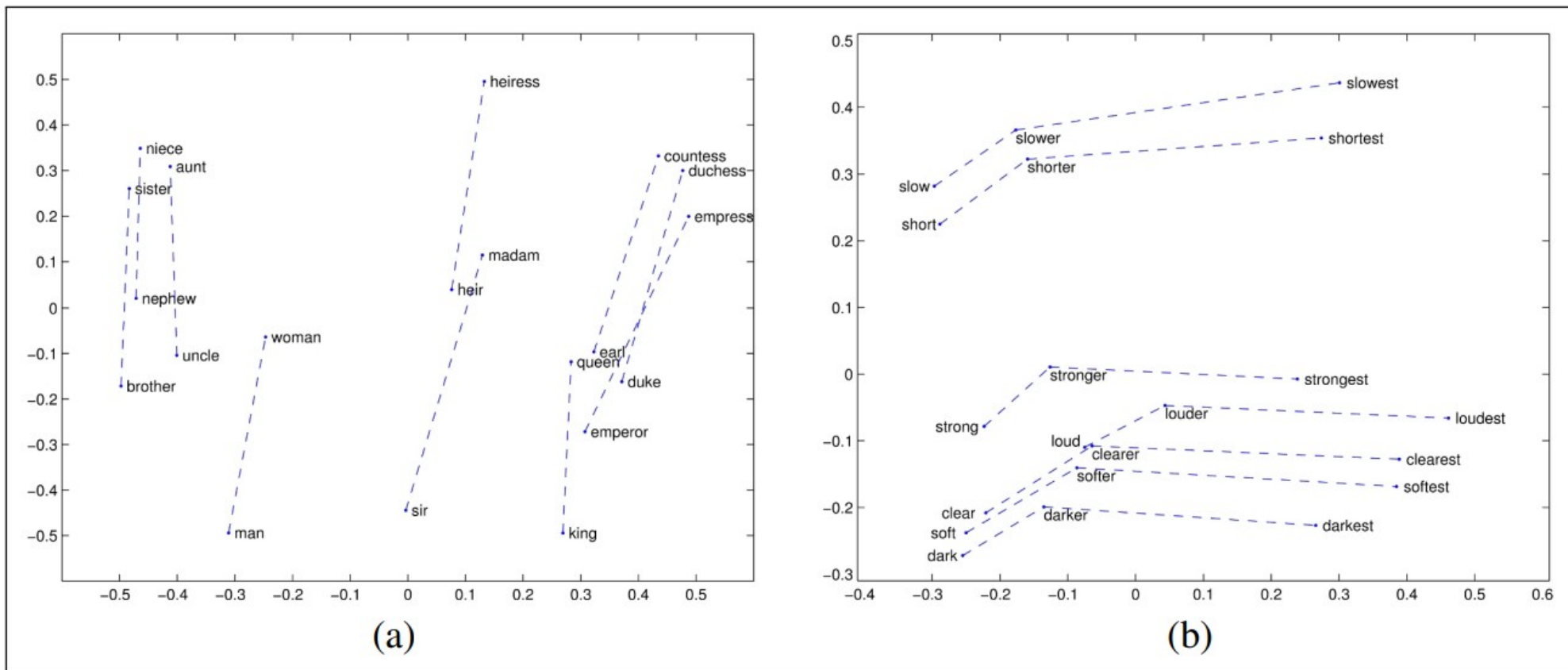
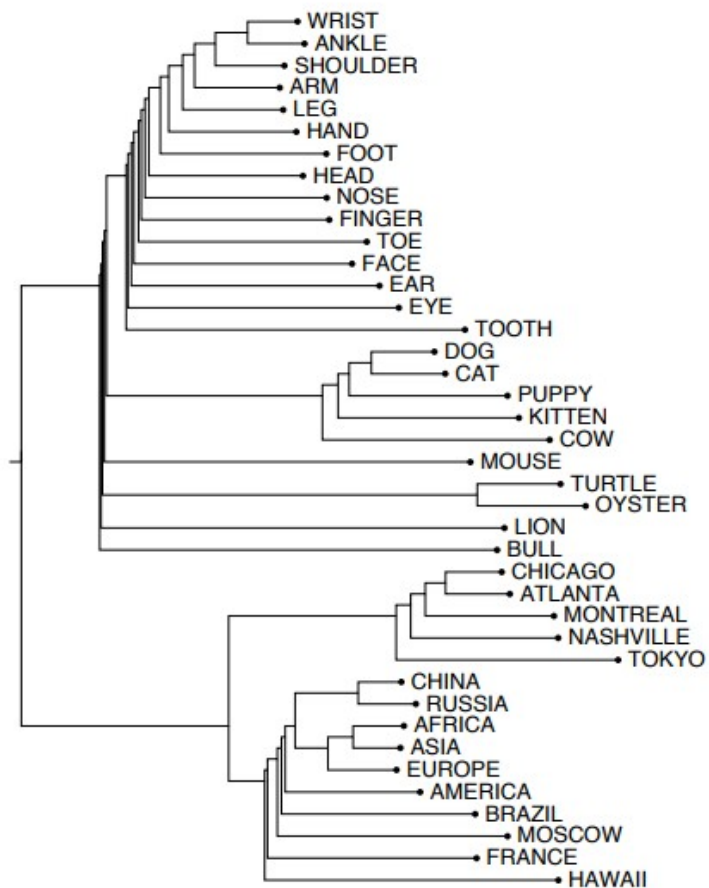



Figure 6.16 Relational properties of the GloVe vector space, shown by projecting vectors onto two dimensions. (a) $\vec{\text{king}} - \vec{\text{man}} + \vec{\text{woman}}$ is close to $\vec{\text{queen}}$. (b) offsets seem to capture comparative and superlative morphology (Pennington et al., 2014).

Semantic structures in word embeddings



- Word vectors can be structured into a tree, using clustering
- Interesting semantic structures appear

How to train word embeddings

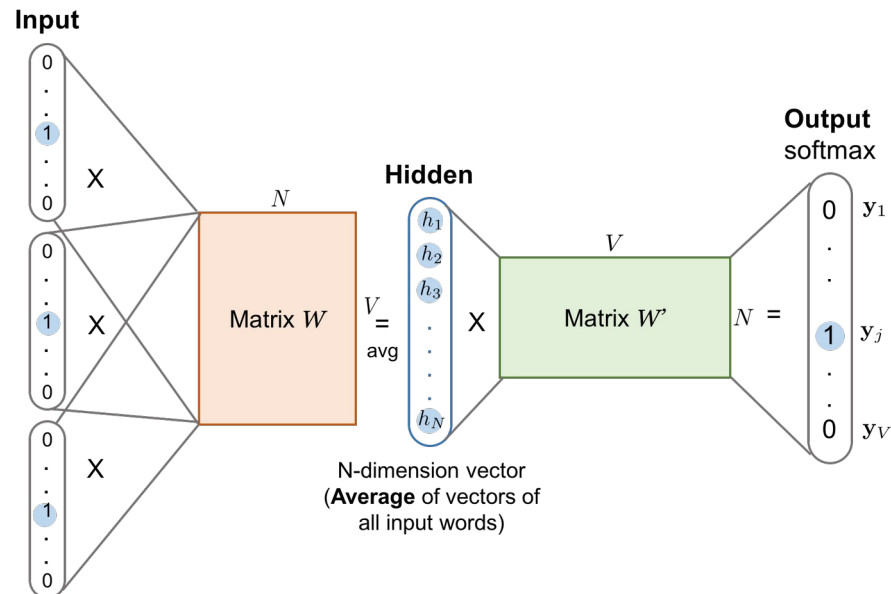
- Train on the task:
 - e.g., if your model does named entity recognition, train word embeddings from scratch, together with the rest of the model
 - Good: embeddings will be optimized
 - Bad: needs large amounts of annotated (with names labeled) data
 - Pre-train on large amounts of (unsupervised) text data
 - Use distributional similarity techniques to obtain “universal” word vectors
 - Good: can take advantage of large amounts of unlabeled text data
 - Bad: not necessarily optimal for the task
- Best of both: use pre-trained embeddings, and retrain them a little on the task
- 

Unsupervised training of word embeddings

- Neural network language model gives us unsupervised word embeddings
 - Why unsupervised – we don't need words annotated with POS tags or NER labels
- However, NNLM is slow to train
- But we don't actually need a properly normalized language model, we just want embeddings!
- Then it's possible to use some tricks to make training of word embeddings much faster

CBOW

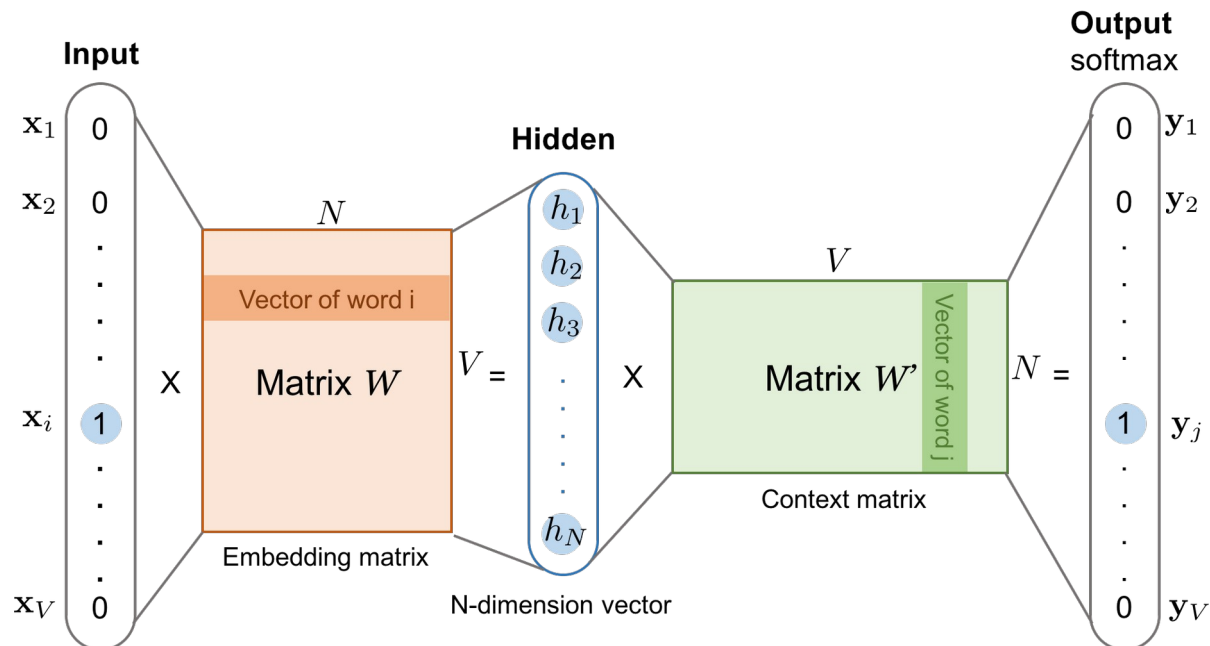
- CBOW: Continuous Bag of Words
- Predict **center word** from **(a bag of) context words**
- The embeddings of context words are averaged
- The average embedding is a feature vector to predict the center word
- At the end, the embeddings corresponding to context words are our word embeddings



Skip-ngrams

- Predict context words (position independent) given the center word
e.g., using a 5-word window
- Each pair of (center word, context word) is treated as a new observation when training the model
- E.g., given the sentence “the dog **eats** a bone”, the target word “*eats*” produces independent training examples:

(“eats”, “dog”), (“eats”, “a”), (“eats”, “the”), (“eats”, “bone”)



Negative sampling

- Negative sampling allows very fast training of word embeddings, when we don't really care about the NNLM probabilities
- Softmax over words is replaced with a single sigmoid that is treated as a probability
- Training maximizes the probability of correct (seen) (word, context) pairs
- And minimizes the probability of randomly sampled (word, context) pairs
- In other words, the model tries to differentiate “real” word pairs from “fake” (unobserved) ones, using logistic regression
- The negative words are sampled from distribution Q that is something like a unigram distribution

Effect of context size

- Context size in CBOW and skip-ngram is a tunable parameter that has a large effect on the nature of the embeddings
- Small context window: more syntax-based embeddings
- Large context window: more semantics-based topical embeddings

For example [Levy and Goldberg \(2014a\)](#) showed that using skip-gram with a window of ± 2 , the most similar words to the word *Hogwarts* (from the *Harry Potter* series) were names of other fictional schools: *Sunnydale* (from *Buffy the Vampire Slayer*) or *Evernight* (from a vampire series). With a window of ± 5 , the most similar words to *Hogwarts* were other words topically related to the *Harry Potter* series: *Dumbledore*, *Malfoy*, and *half-blood*.

More interactive visualizations

- <https://projector.tensorflow.org/>
- http://bionlp-www.utu.fi/wv_demo/

Limitation of word embeddings

- Sensitive to **superficial differences** (*dog* vs *dogs*)
- **Insensitive to context** (financial *bank*, *bank* of a river)
- **Not necessarily coordinated** with knowledge or across languages
- **Not interpretable**
- Can **encode bias** (encode stereotypical gender roles, racial biases)

Sub-word embeddings

- The internal character structure is ignored by regular word embedding models
- In inflected languages (e.g., Estonian), many words (e.g., “*koertelegi*”) occur rarely, making it difficult to learn good word embeddings for them
- But in inflected languages (and in most other languages), word formation follows some rules
- Is it possible to use character-level information for improving word embeddings?

Sub-word embeddings

- In the sub-word based model, each word is represented as a bag of character n-grams, and a special token corresponding to itself

where \rightarrow [`_wh`, `whe`, `her`, `ere`, `re_`, `<where>`]

Use all n-grams with $n=3\dots6$

- A word embedding is obtained by summing the embeddings of its components
- There are **a lot of** character n-grams of length 3...6
- Hashing trick is used to map all n-grams to integers from 1 to K (e.g. $K=1000000$)
- This technique is used in the *fastText* toolkit by Facebook

De-biasing embeddings

- Word embeddings tend to **amplify** biases in training data
- E.g. man-woman ~ architect-receptionist
- Occupations that are related to
 - Females: homemaker, nurse, receptionist, librarian, hairdresser, nanny, bookkeeper
 - Males: skipper, philosopher, captain, architect, warrior, broadcaster, boss
- Why is it bad? It reflects the bias in society, doesn't it?
 - Consider a web search "*TalTech computer science Master student*" (e.g., by a potential employer)
 - If the search engine ranks web pages based on word embeddings, then a homepage of a female (e.g. *Mary*) might be ranked lower than that of a male (e.g. *John*), because *John* and "*computer science*" have closer embeddings
 - Therefore, gender bias in society could be **amplified** by systems using word embeddings
- Bias can be reduced by removing the gender-associations of gender-neutral words
 - But it's very difficult, no method works very well