

# Feedforward Neural Networks and Word Embeddings

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# Outline

- 1 Linear models
- 2 Limitations of linear models
- 3 Neural networks
- 4 A neural language model
- 5 Word embeddings

# LINEAR MODELS

# Binary Classification with Linear Models

**Example:** the seminar at < time > 4 pm will

**Classification task:** Do we have an < time > tag in the current position?

Word	Lemma	LexCat	Case	SemCat	Tag
the	the	Art	low		
seminar	seminar	Noun	low		
at	at	Prep	low		stime
4	4	Digit	low		
pm	pm	Other	low	timeid	
will	will	Verb	low		

# Feature Vector

Encode context into **feature vector**:

1	bias term		<b>1</b>
2	-3_lemma_the		<b>1</b>
3	-3_lemma_giraffe		<b>0</b>
...	...	...	
102	-2_lemma_seminar		<b>1</b>
103	-2_lemma_giraffe		<b>0</b>
...	...	...	
202	-1_lemma_at		<b>1</b>
203	-1_lemma_giraffe		<b>0</b>
...	...	...	
302	+1_lemma_4		<b>1</b>
303	+1_lemma_giraffe		<b>0</b>
...	...	...	

## Dot product with (initial) weight vector

$$h(X) = X \cdot \Theta^T$$

$$X = \begin{bmatrix} x_0 = 1 \\ x_1 = 1 \\ x_2 = 0 \\ \dots \\ x_{101} = 1 \\ x_{102} = 0 \\ \dots \\ x_{201} = 1 \\ x_{202} = 0 \\ \dots \\ x_{301} = 1 \\ x_{302} = 0 \\ \dots \end{bmatrix}$$

$$\Theta = \begin{bmatrix} w_0 = 1.00 \\ w_1 = 0.01 \\ w_2 = 0.01 \\ \dots \\ x_{101} = 0.01 \\ x_{102} = 0.01 \\ \dots \\ x_{201} = 0.01 \\ x_{202} = 0.01 \\ \dots \\ x_{301} = 0.01 \\ x_{302} = 0.01 \\ \dots \end{bmatrix}$$

## Prediction with dot product

$$\begin{aligned}h(X) &= X \cdot \Theta^T \\&= x_0 w_0 + x_1 w_1 + \dots + x_n w_n \\&= 1 * 1 + 1 * 0.01 + 0 * 0.01 + \dots + 0 * 0.01 + 1 * 0.01\end{aligned}$$

# Predictions with linear models

**Example:** the seminar at **< time >** 4 pm will

**Classification task:** Do we have an **< time >** tag in the current position?

**Linear Model:**  $h(X) = X \cdot \Theta^T$

**Prediction:** If  $h(X) \geq 0$ , yes. Otherwise, no.



## Getting the right weights

**Training:** Find weight vector  $\Theta$  such that  $h(X)$  is the **correct answer** as many times as possible.

- Given a set  $T$  of training examples  $t_1, \dots, t_n$  with **correct labels**  $y_i$ , find  $\Theta$  such that  $h(X(t_i)) = y_i$  for as many  $t_i$  as possible.
- $X(t_i)$  is the feature vector for the  $i$ -th training example  $t_i$

## Dot product with **trained** weight vector

$$h(X) = X \cdot \Theta^T$$

$$X = \begin{bmatrix} x_0 = 1 \\ x_1 = 1 \\ x_2 = 0 \\ \dots \\ x_{101} = 1 \\ x_{102} = 0 \\ \dots \\ x_{201} = 1 \\ x_{202} = 0 \\ \dots \\ x_{301} = 1 \\ x_{302} = 0 \\ \dots \end{bmatrix}$$

$$\Theta = \begin{bmatrix} w_0 = 1.00 \\ w_1 = 0.001 \\ w_2 = 0.02 \\ \dots \\ x_{101} = 0.012 \\ x_{102} = 0.0015 \\ \dots \\ x_{201} = 0.4 \\ x_{202} = 0.005 \\ \dots \\ x_{301} = 0.1 \\ x_{302} = 0.04 \\ \dots \end{bmatrix}$$

## Working with real-valued features

E.g. measure semantic similarity:

Word	sim(time)
the	0.0014
seminar	0.0014
at	0.1
4	2.01
pm	3.02
will	0.5

## Working with real-valued features

$$h(X) = X \cdot \Theta^T$$

$$X = \begin{bmatrix} x_0 = 1.0 \\ x_1 = 50.5 \\ x_2 = 52.2 \\ \dots \\ x_{101} = 45.6 \\ x_{102} = 60.9 \\ \dots \\ x_{201} = 40.4 \\ x_{202} = 51.9 \\ \dots \\ x_{301} = 40.5 \\ x_{302} = 35.8 \\ \dots \end{bmatrix}$$

$$\Theta = \begin{bmatrix} w_0 = 1.00 \\ w_1 = 0.001 \\ w_2 = 0.02 \\ \dots \\ x_{101} = 0.012 \\ x_{102} = 0.0015 \\ \dots \\ x_{201} = 0.4 \\ x_{202} = 0.005 \\ \dots \\ x_{301} = 0.1 \\ x_{302} = 0.04 \\ \dots \end{bmatrix}$$

## Working with real-valued features

$$\begin{aligned}h(X) &= X \cdot \Theta^T \\&= x_0 w_0 + x_1 w_1 + \dots + x_n w_n \\&= 1.0 * 1 + 50.5 * 0.001 + \dots + 40.5 * 0.1 + 35.8 * 0.04 \\&= 540.5\end{aligned}$$

# Working with real-valued features

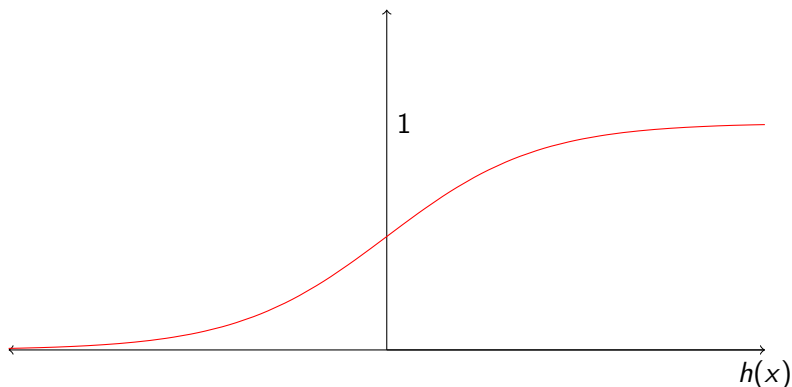
**Classification task:** Do we have an `< time >` tag in the current position?

Prediction:  $h(X) = 540.5$

- Can we transform this into a probability?

## Sigmoid function

We can push  $h(X)$  between 0 and 1 using a **non-linear activation** function  
The **sigmoid function**  $\sigma(Z)$  is often used



# Logistic Regression

**Classification task:** Do we have an `< time >` tag in the current position?

**Linear Model:**  $Z = X \cdot \Theta^T$

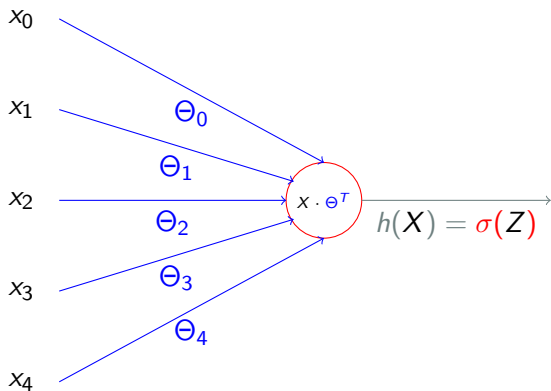
**Prediction:** If  $\sigma(Z) > 0.5$ , yes. Otherwise, no.

**Logistic regression:**

- Use a **linear model** and squash values between 0 and 1.
  - ▶ Convert real values to probabilities
- Put threshold to 0.5.
- Positive class above threshold, negative class below.



# Logistic Regression

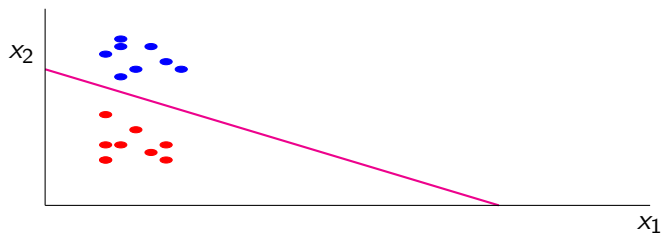


# LINEAR MODELS: LIMITATIONS

# Decision Boundary

What do **linear** models do?

- $\sigma(Z) > 0.5$  when  $Z(= X \cdot \Theta^T) \geq 0$
- Model defines a **decision boundary** given by  $X \cdot \Theta^T = 0$ 
  - positive examples (have time tag)
  - negative examples (no time tag)

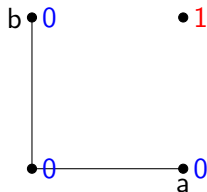


## Exercise

When we model a task with linear models, what assumption do we make about positive/negative examples?

## Modeling 1: Learning a predictor for $\wedge$

a	b	$a \wedge b$
0	0	0
0	1	0
1	0	0
1	1	1

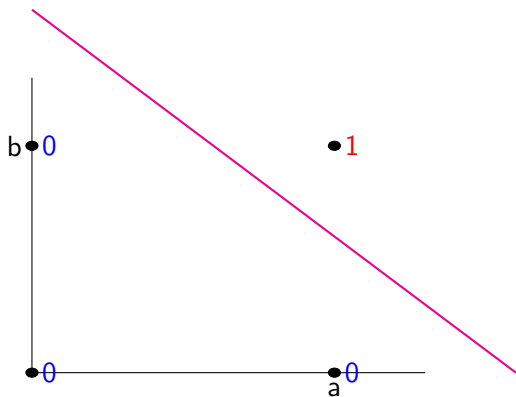


Features : a, b

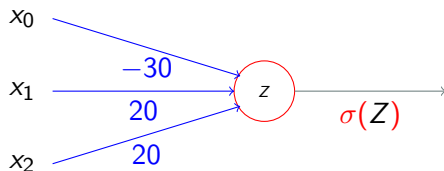
Feature values : binary

Can we learn a linear model to solve this problem?

## Modeling 1: Learning a predictor for $\wedge$



# Modeling 1: Logistic Regression



$x_0$	$x_1$	$x_2$	$x_1 \wedge x_2$
1	0	0	$\sigma(1 * -30 + 0 * 20 + 0 * 20) = \sigma(-30) \approx 0$
1	0	1	$\sigma(1 * -30 + 0 * 20 + 1 * 20) = \sigma(-10) \approx 0$
1	1	0	$\sigma(1 * -30 + 1 * 20 + 1 * 20) = \sigma(-10) \approx 0$
1	1	1	$\sigma(1 * -30 + 1 * 20 + 1 * 20) = \sigma(10) \approx 1$

## Modeling 2: Learning a predictor for $XNOR$

a	b	a $XNOR$ b
0	0	1
0	1	0
1	0	0
1	1	1

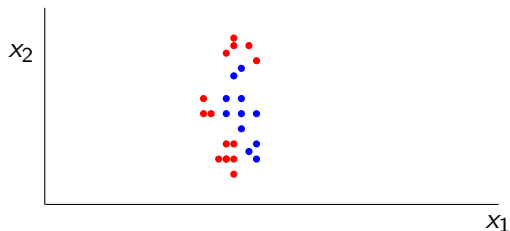
Features : a, b

Feature values : binary

Can we learn a linear model to solve this problem?

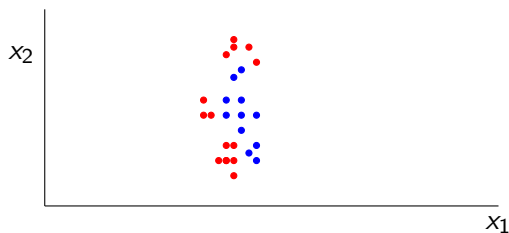


# Non-linear decision boundaries



Can we learn a linear model to solve this problem?

# Non-linear decision boundaries



Can we learn a linear model to solve this problem?

No! Decision boundary is **non-linear**.

# Learning a predictor for *XNOR*

Linear models not suited to learn non-linear decision boundaries.

Neural networks can do that.

# NEURAL NETWORKS

# Learning a predictor for $XNOR$

a	b	a $XNOR$ b
0	0	1
0	1	0
1	0	0
1	1	1

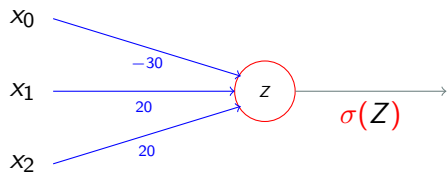
Features : a, b

Feature values : binary

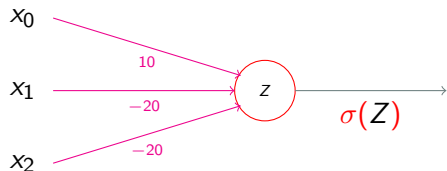
Can we learn a **non-linear model** to solve this problem?

Yes! E.g. through **function composition**.

# Function Composition

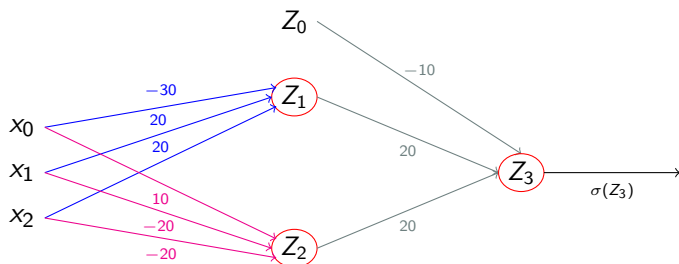


$x_0$	$x_1$	$x_2$	$x_1 \wedge x_2$
1	0	0	$\approx 0$
1	0	1	$\approx 0$
1	1	0	$\approx 0$
1	1	1	$\approx 1$



$x_0$	$x_1$	$x_2$	$\neg x_1 \wedge \neg x_2$
1	0	0	$\approx 1$
1	0	1	$\approx 0$
1	1	0	$\approx 0$
1	1	1	$\approx 0$

# Function Composition



$x_0$	$x_1$	$x_2$	$\sigma(Z_1)$	$\sigma(Z_2)$	$\sigma(Z_3)$
1	0	0	$\approx 0$	$\approx 1$	$\sigma(1 * -10 + 0 * 20 + 1 * 20) = \sigma(10) \approx 1$
1	0	1	$\approx 0$	$\approx 0$	$\sigma(1 * -10 + 0 * 20 + 0 * 20) = \sigma(-10) \approx 0$
1	1	0	$\approx 0$	$\approx 0$	$\sigma(1 * -10 + 0 * 20 + 0 * 20) = \sigma(-10) \approx 0$
1	1	1	$\approx 1$	$\approx 0$	$\sigma(1 * -10 + 1 * 20 + 1 * 20) = \sigma(30) \approx 1$

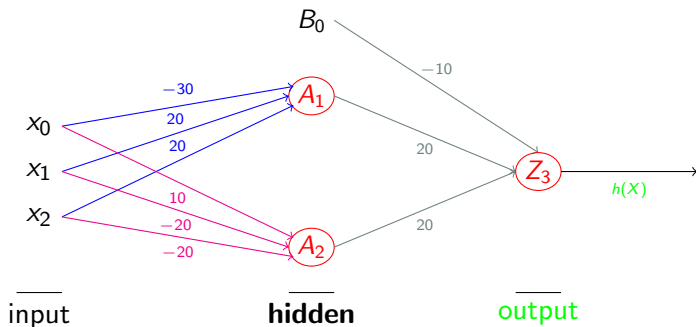
# Feedforward Neural Network

We just created a **feedforward neural network** with:

- 1 input layer  $X$  (feature vector)
- 2 weight matrices  $U = (\Theta_1, \Theta_2)$  and  $V = \Theta_3$
- 1 hidden layer  $H$  composed of:
  - ▶ 2 activations  $A_1 = \sigma(Z_1)$  and  $A_2 = \sigma(Z_2)$  where:
    - ★  $Z_1 = X \cdot \Theta_1$
    - ★  $Z_2 = X \cdot \Theta_2$
- 1 output unit  $h(X) = \sigma(Z_3)$  where:
  - ▶  $Z_3 = H \cdot \Theta_3$



# Feedforward Neural Network



Computation of hidden layer  $\mathbf{H}$ :

- $A_1 = \sigma(X \cdot \Theta_1)$
- $A_2 = \sigma(X \cdot \Theta_2)$
- $B_0 = 1$  (bias term)

Computation of output unit  $h(X)$ :

- $h(X) = \sigma(\mathbf{H} \cdot \Theta_3)$

# Feedforward Neural Network

**Classification task:** Do we have an **< time >** tag in the current position?

**Neural network:**  $h(X) = \sigma(\mathbf{H} \cdot \Theta_n)$ , with:

$$\mathbf{H} = \begin{bmatrix} B_0 = 1 \\ A_1 = \sigma(X \cdot \Theta_1) \\ A_2 = \sigma(X \cdot \Theta_2) \\ \dots \\ A_j = \sigma(X \cdot \Theta_j) \end{bmatrix}$$

**Prediction:** If  $h(X) > 0.5$ , yes. Otherwise, no.

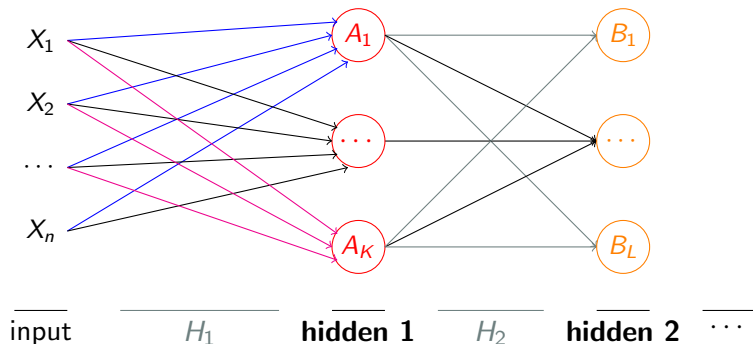
## Getting the right weights

**Training:** Find weight matrices  $U = (\Theta_1, \Theta_2)$  and  $V = \Theta_3$  such that  $h(X)$  is the **correct answer** as many times as possible.

- Given a set  $T$  of training examples  $t_1, \dots, t_n$  with **correct labels**  $\mathbf{y}_i$ , find  $U = (\Theta_1, \Theta_2)$  and  $V = \Theta_3$  such that  $h(X) = \mathbf{y}_i$  for as many  $t_i$  as possible.
  - Computation of  $h(X)$  called **forward propagation**
  - $U = (\Theta_1, \Theta_2)$  and  $V = \Theta_3$  with error **back propagation**

# Network architectures

Depending on task, a particular network architecture can be chosen:



Note: Bias terms omitted for simplicity

# Multi-class classification

- More than two labels
- Instead of “yes” and “no”, predict  $c_i \in C = \{c_1, \dots, c_k\}$
- Not just `<time>` label but also `<etime>`, `<\etime>`, ...
- **Use  $k$  output units**, where  $k$  is number of classes
  - ▶ Output layer instead of unit
  - ▶ Use softmax to obtain value between 0 and 1 for each class
  - ▶ Highest value is right class

# A NEURAL LANGUAGE MODEL

# Neural language model

- Early application of neural networks (Bengio et al. 2003)
- Task: Given  $k$  previous words, predict the **current word**  
Estimate:  $P(w_t | w_{t-k}, \dots, w_{t-2}, w_{t-1})$

- Previous (non-neural) approaches:

**Problem:** Joint distribution of consecutive words difficult to obtain  
→ chose small history to reduce complexity ( $n=3$ )  
→ predict for unseen history through back-off to smaller history

**Drawbacks:**

Takes into account small context

**Does not model similarity between words**

# Word similarity for language modeling

- 1 The cat is walking in the bedroom
  - 2 The dog was running in a room
  - 3 A cat was running in a room
  - 4 A dog was walking in a bedroom
- Model similarity between (cat,dog), (room, bedroom)
- Generalize from 1 to 2 etc.



# Neural Language Model (LM)

- **Solution:**

Use **word embeddings** to represent each word in history

→ Each word is represented in relation to the others

→ Distributed word feature vector

Feed to a neural network to learn parameters for the LM task

# Feedforward Neural Network for LM

Training example: *The cat is walking in the **bedroom***

Neural network input:

Look at words preceding **bedroom**

→ The cat **is**<sub>-4</sub> **walking**<sub>-3</sub> **in**<sub>-2</sub> **the**<sub>-1</sub> **bedroom**

→ Create **word embedding** ( $LT_i$ ) for window

Give  $LT_i$  as input to Feedforward Neural Network

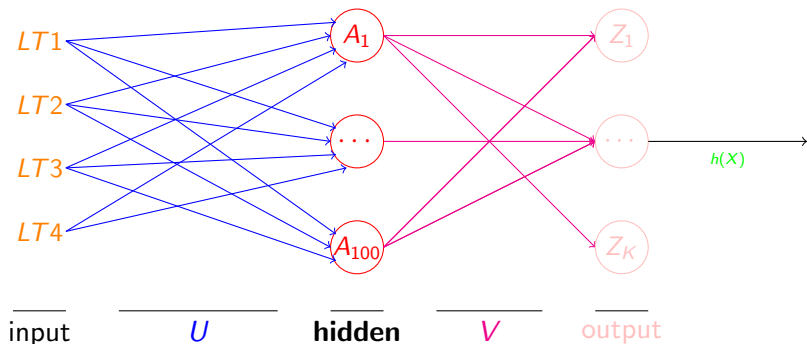
Neural network training:

Predict current word (forward propagation)

→ should be **bedroom**

Train weights by backpropagating error

# Feedforward Neural Network for LM



Input: word embeddings  $LT_i$

Output: predicted label (current word)

Note: Bias terms omitted for simplicity

# Feedforward Neural Network

**Input layer ( $X$ ):** Word features  $LT1, LT2, LT3, LT4$

**Weight matrices  $U, V$**

**Hidden layer ( $H$ ):**  $\sigma(X \cdot U + d)$

**Output layer ( $O$ ):**  $H \cdot V + b$

**Prediction:**  $h(X) = \text{softmax}(O)$

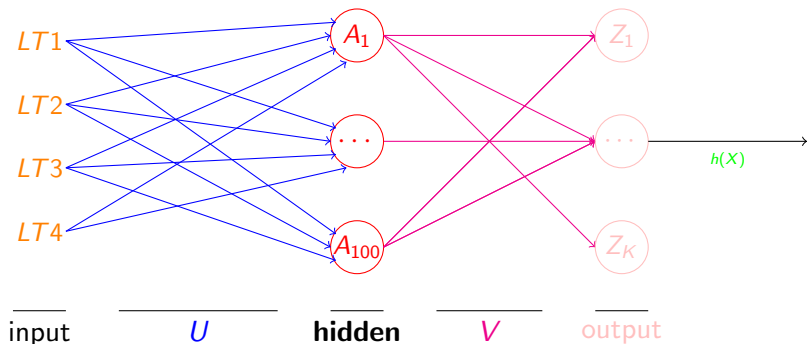
- Predicted class is the one with highest probability (given by softmax)

# Weight training

**Training:** Find weight matrices  $U$  and  $V$  such that  $h(X)$  is the **correct answer** as many times as possible.

- Given a set  $T$  of training examples  $t_1, \dots, t_n$  with **correct labels**  $y_i$ , find  $U$  and  $V$  such that  $h(X) = y_i$  for as many  $t_i$  as possible.
- Computation of  $h(X)$  with **forward propagation**
- $U$  and  $V$  with error **back propagation**

# Forward Propagation



**Forward propagation:**

→ Perform all operations to get  $h(X)$  from input  $LT$ .

# Forward Propagation

**Input layer ( $X$ ):** Word features  $LT1, LT2, LT3, LT4$

**Weight matrices  $U, V$**

**Hidden layer ( $H$ ):**  $\sigma(X \cdot U + d)$

**Output layer ( $O$ ):**  $H \cdot V + b$

**Prediction:**  $h(X) = \text{softmax}(O)$

- Predicted class is the one with highest probability (given by softmax)

# Backpropagation

Goal of training: adjust weights such that **correct label is predicted**

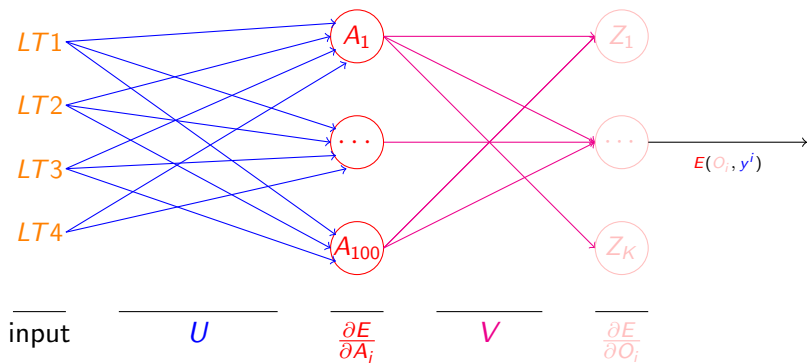
→ **Error** between **correct label** and **prediction** is minimal

Sketch:

- Compute **derivative** of **Error** w.r.t. **prediction**
- Compute **derivatives** in each **hidden layer** from **layer above**
  - ▶ **Backpropagate** the error derivative with respect to the output of a unit
- Use derivatives w.r.t **the activations** to get error derivatives w.r.t **incomming weights**



# Backpropagation



## Backpropagation:

→ Compute  $E$

→ Compute  $\frac{\partial E}{\partial O_i}$

# Backpropagation 1

Compute **error at output E**:

Compare **output unit** with  $y^i$

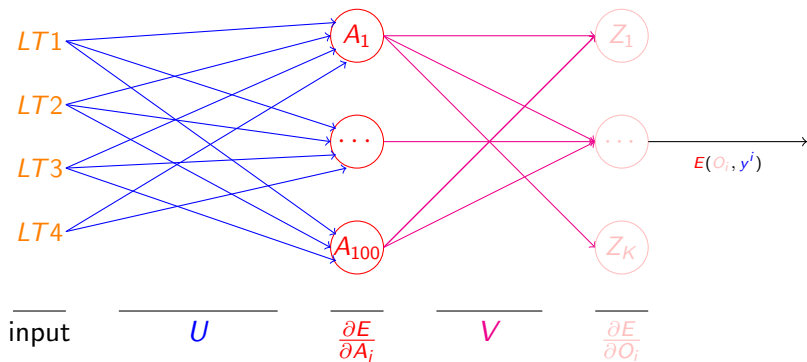
▶  $y^i$  vector with 1 in correct class, 0 otherwise

$$E = \frac{1}{2} \sum_{i=1}^n (y_i - O_i)^2 \text{ (mean squared)}$$

Compute  $\frac{\partial E}{\partial O_i}$ :

$$\frac{\partial E}{\partial O_i} = -(y_i - O_i)$$

# Backpropagation



Backpropagation:

→ Compute  $\frac{\partial E}{\partial A_j}$

## Backpropagation 2

Compute **derivatives** in each hidden layer from **layer above**:

Compute derivative of **error** w.r.t **logit**

$$\frac{\partial E}{\partial Z_i} = \frac{\partial E}{\partial O_i} \frac{\partial O_i}{\partial Z_i} = \frac{\partial E}{\partial O_i} O_i(1 - O_i) \quad (\text{Note: } O_i = \frac{1}{1+e^{-Z_i}})$$

Compute derivative of **error** w.r.t **previous hidden unit**

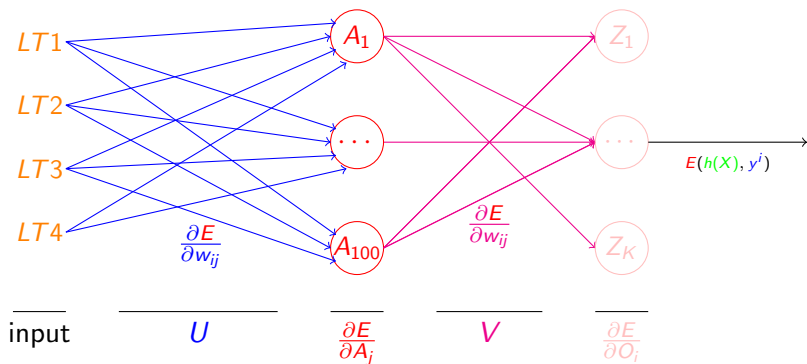
$$\frac{\partial E}{\partial A_j} = \sum_i \frac{\partial Z_i}{\partial A_j} \frac{\partial E}{\partial Z_i} = \sum_i w_{ji} \frac{\partial E}{\partial Z_i}$$

Compute derivative w.r.t. **weights**

$$\frac{\partial E}{\partial w_{ji}} = \frac{\partial Z_i}{\partial w_{ji}} \frac{\partial E}{\partial Z_i} = O_j \frac{\partial E}{\partial Z_i}$$

→ Use **recursion** to do this **for every layer**

# Backpropagation



# Weight training

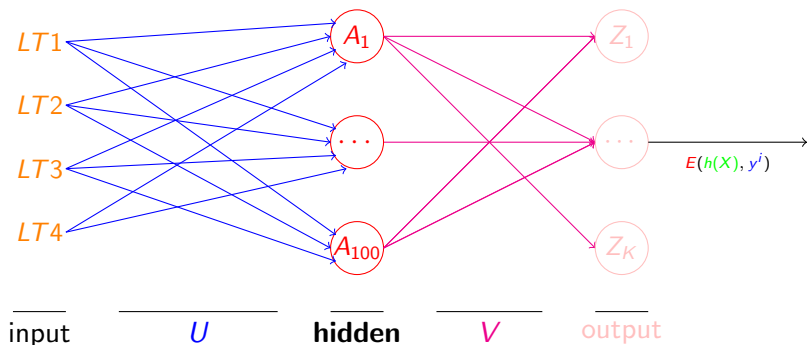
**Training:** Find weight matrices  $U$  and  $V$  such that  $h(X)$  is the **correct answer** as many times as possible.

- Computation of  $h(X)$  with **forward propagation**
- $U$  and  $V$  with error **back propagation**

For each batch of training examples

- 1 Forward propagation to get predictions
- 2 Backpropagation of error
  - ▶ Gives gradient of  $E$  given **input**
- 3 Modify weights (gradient descent)
- 4 Goto 1 until convergence

# Word Embedding Layer



# Word Embedding Layer

- Each word encoded into index vector  $w_i = \begin{bmatrix} 0 \\ 1 \\ 0 \\ 0 \\ 0 \end{bmatrix}$
- $LT_i$  is dot product of **weight matrix  $C$**  with index of  $w_i$   
→  $C$  is **shared** among all words



## Dot product with (trained) weight vector

$W = \{\text{the, cat, on, table, chair}\}$

$$w_{\text{table}} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \\ 0 \end{bmatrix} \quad C = \begin{bmatrix} 0.02 & 0.1 & 0.05 & 0.03 & 0.01 \\ 0.15 & 0.2 & 0.01 & 0.02 & 0.11 \\ 0.03 & 0.1 & 0.04 & 0.04 & 0.12 \end{bmatrix}$$

$$LT_{\text{table}} = w_{\text{table}} \cdot C^T = \begin{bmatrix} 0.03 \\ 0.02 \\ 0.04 \end{bmatrix}$$

Words get mapped to lower dimension

→ Hyperparameter to be set

## Dot product with (initial) weight vector

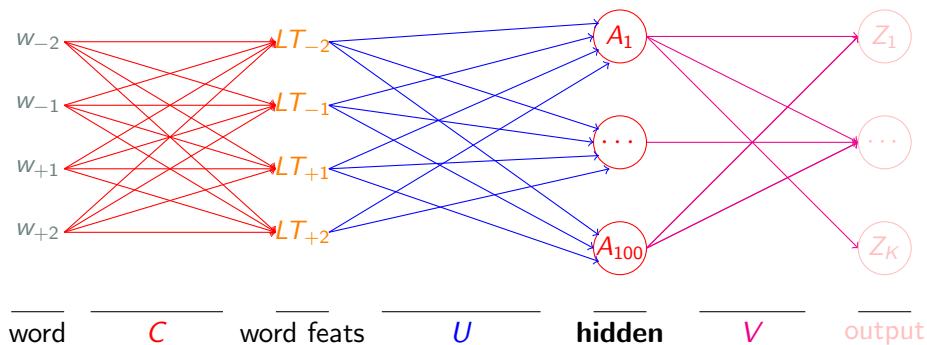
$W = \{\text{the,cat,on,table,chair}\}$

$$w_{table} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \\ 0 \end{bmatrix} \quad C = \begin{bmatrix} 0.01 & 0.01 & 0.01 & 0.01 & 0.01 \\ 0.01 & 0.01 & 0.01 & 0.01 & 0.01 \\ 0.01 & 0.01 & 0.01 & 0.01 & 0.01 \end{bmatrix}$$

$$LT_{table} = w_{table} \cdot C^T = \begin{bmatrix} 0.01 \\ 0.01 \\ 0.01 \end{bmatrix}$$

Feature vectors same for all words.

# Feedforward Neural Network with Lookup Table



Note: Bias terms omitted for simplicity

# Weight training

**Training:** Find weight matrices  $C$ ,  $U$  and  $V$  such that  $h(X)$  is the **correct answer** as many times as possible.

- Given a set  $T$  of training examples  $t_1, \dots, t_n$  with **correct labels**  $\mathbf{y}_i$ , find  $C$ ,  $U$  and  $V$  such that  $h(X) = \mathbf{y}_i$  for as many  $t_i$  as possible.
- Computation of  $h(X)$  with **forward propagation**
- $C$ ,  $U$  and  $V$  with error **back propagation**

## Dot product with (trained) weight vector

$W = \{\text{the, cat, on, table, chair}\}$

$$w_{table} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \\ 0 \end{bmatrix} \quad C = \begin{bmatrix} 0.02 & 0.1 & 0.05 & 0.03 & 0.01 \\ 0.15 & 0.2 & 0.01 & 0.02 & 0.11 \\ 0.03 & 0.1 & 0.04 & 0.04 & 0.12 \end{bmatrix}$$

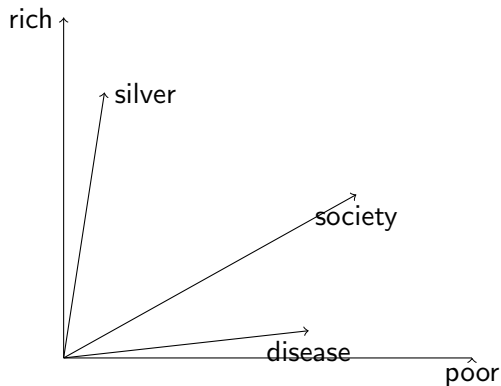
$$LT_{table} = w_{table} \cdot C^T = \begin{bmatrix} 0.03 \\ 0.02 \\ 0.04 \end{bmatrix}$$

Each word gets a **specific** feature vector

# WORD EMBEDDINGS

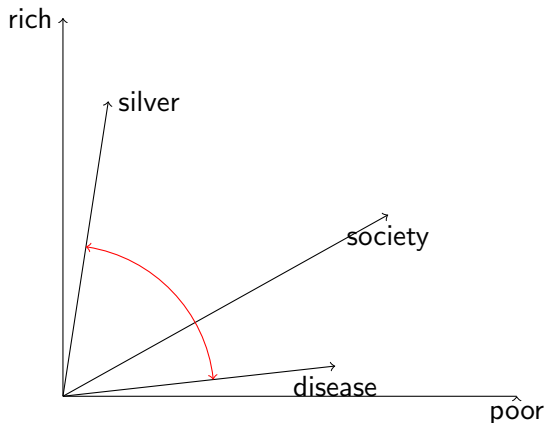
# Word Embeddings

- Representation of words in vector space



# Word Embeddings

- Similar words are close to each other  
→ Similarity is the cosine of the angle between two word vectors





# Underlying thoughts

- Assume the equivalence of:
  - ▶ Two words are **semantically similar**.
  - ▶ Two words occur in **similar contexts** (Miller & Charles, roughly).
  - ▶ Two words have **similar word neighbors** in the corpus.
- Elements of this are from Leibniz, Harris, Firth, and Miller.
- Strictly speaking, similarity of neighbors is neither necessary nor sufficient for semantic similarity.
- But perhaps this is **good enough**.

*Adapted slide from Hinrich Schütze*

# Learning word embeddings

## Count-based methods:

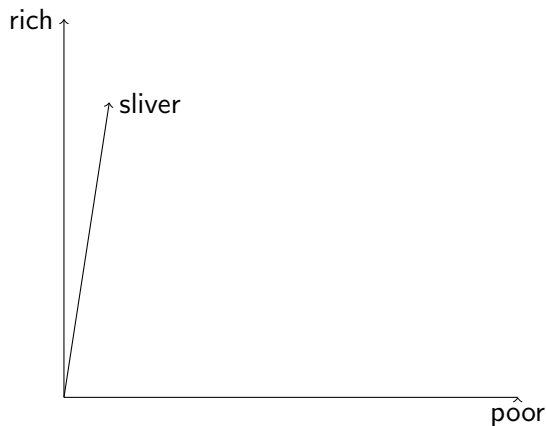
- Compute cooccurrence statistics
- Learn high-dimensional representation
- Map sparse high-dimensional vectors to small dense representation

# Word cooccurrence in Wikipedia

- corpus = English Wikipedia
- cooccurrence defined as **occurrence within  $k = 10$  words** of each other
  - ▶  $\text{cooc.}(\text{rich}, \text{silver}) = 186$
  - ▶  $\text{cooc.}(\text{poor}, \text{silver}) = 34$
  - ▶  $\text{cooc.}(\text{rich}, \text{disease}) = 17$
  - ▶  $\text{cooc.}(\text{poor}, \text{disease}) = 162$
  - ▶  $\text{cooc.}(\text{rich}, \text{society}) = 143$
  - ▶  $\text{cooc.}(\text{poor}, \text{society}) = 228$

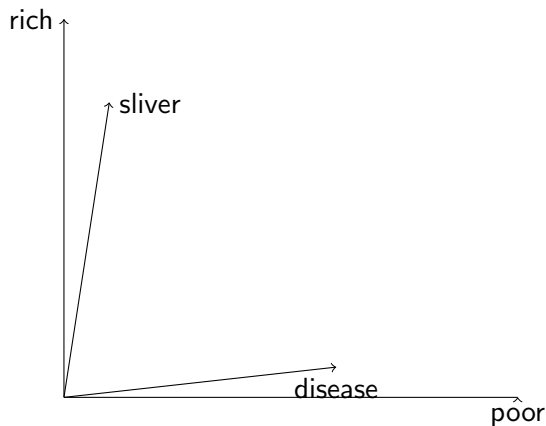
*Adapted slide from Hinrich Schütze*

## Cooccurrence-based Word Space



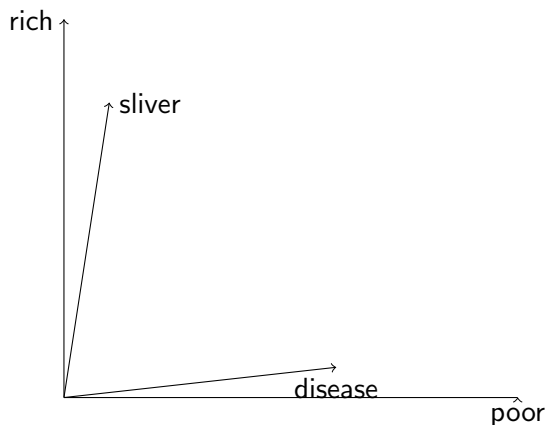
$$\text{cooc.}(\text{poor}, \text{silver}) = 34, \text{cooc.}(\text{rich}, \text{silver}) = 186$$

# Cooccurrence-based Word Space



$\text{cooc.}(\text{poor}, \text{disease}) = 162, \text{cooc.}(\text{rich}, \text{disease}) = 17.$

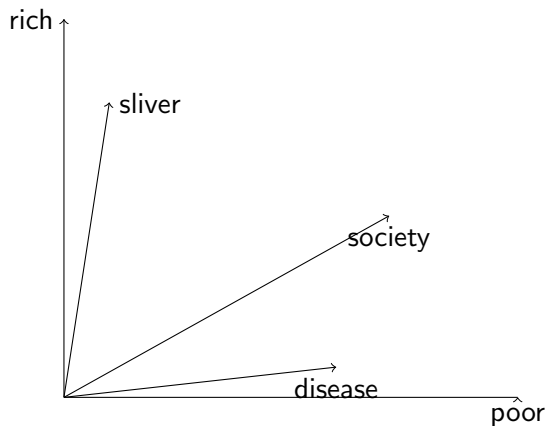
## Exercise



$\text{cooc.}(\text{poor}, \text{society})=228$ ,  $\text{cooc.}(\text{rich}, \text{society})=143$

How is it represented?

## Cooccurrence-based Word Space



$\text{cooc.}(\text{poor}, \text{society})=228$ ,  $\text{cooc.}(\text{rich}, \text{society})=143$

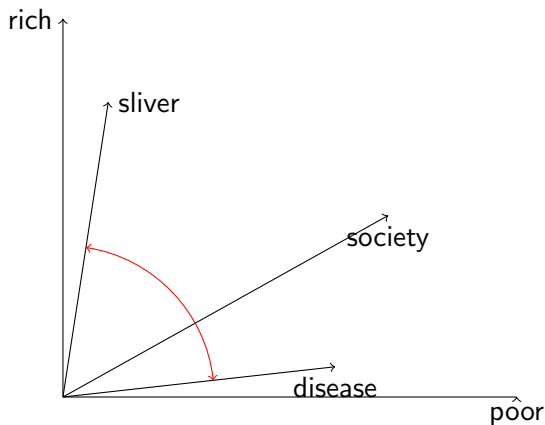
# Dimensionality of word space

- Up to now we've only used two dimension words: rich and poor.
- Do this for all possible words in a corpus → **high-dimensional space**
- Formally, there is no difference to a two-dimensional space with three vectors.
- Note: a word can have a **dual role** in word space.
  - ▶ Each word can, in principle, be a **dimension word**, an axis of the space.
  - ▶ But each word is also a **vector** in that space.

*Adapted slide from Hinrich Schütze*



# Semantic similarity



Similarity is the cosine of the angle between two word vectors

# Learning word embeddings

## Count-based methods:

- Compute cooccurrence statistics
- Learn high-dimensional representation
- Map sparse high-dimensional vectors to small dense representation

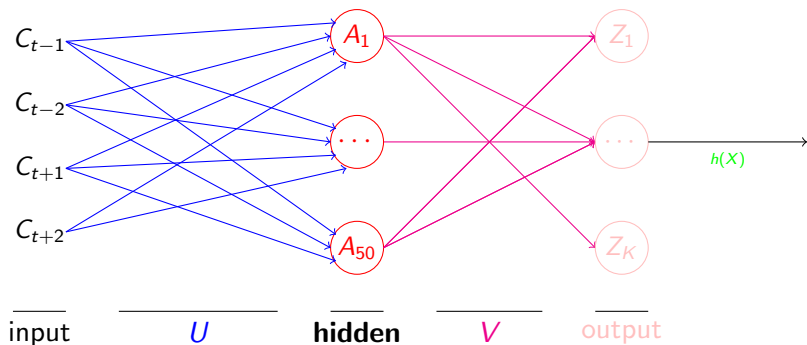
## Neural networks:

- Predict a word from its neighbors
- Learn (small) embedding vectors

# Word vectors with Neural Networks

- LM Task: Given  $k$  previous words, predict the current word
  - For each word  $w$  in  $V$ , model  $P(w_t | w_{t-1}, w_{t-2}, \dots, w_{t-n})$
  - **Learn embeddings  $C$  of words**
  - Input for task
  
- Task: Given  $k$  context words, predict the current word
  - **Learn embeddings  $C$  of words**

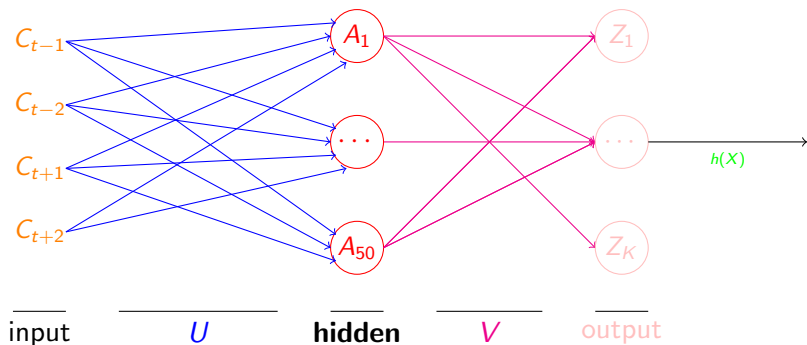
# Network architecture



Given words  $w_{t-2}$ ,  $w_{t-1}$ ,  $w_{t+1}$  and  $w_{t+2}$ , predict  $w_t$

Note: Bias terms omitted for simplicity

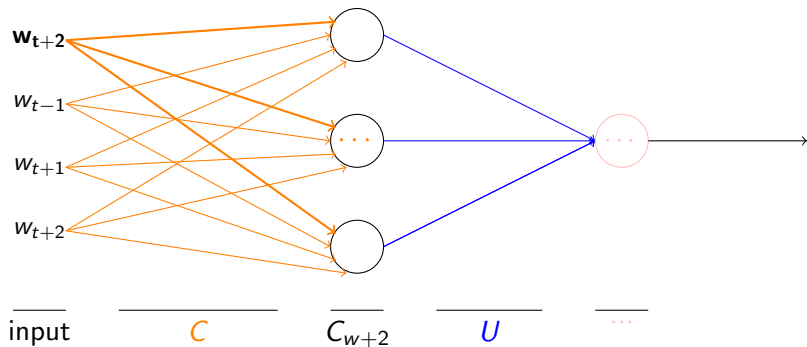
# Network architecture



We want the **context vectors**  $\rightarrow$  embed words in shared space

Note: Bias terms omitted for simplicity

# Getting the Word Embeddings

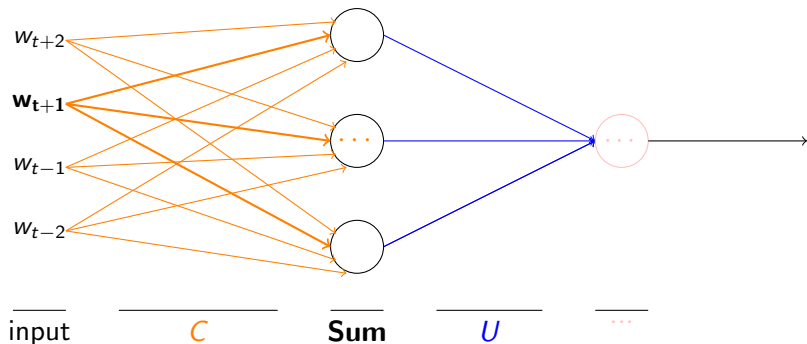


Note: Bias terms omitted for simplicity

# Simplifications

- Remove hidden layer
- Sum over all projections

# Simplifications



Remove hidden layer and sum over context

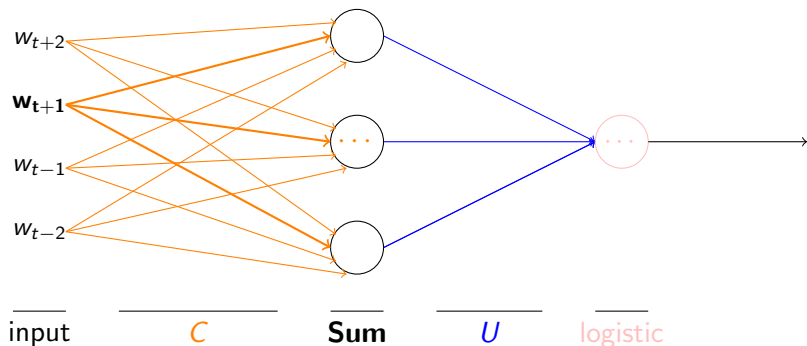
Note: Bias terms omitted for simplicity



# Simplifications

- Single **logistic unit** instead of output layer
  - No need for distribution over words (only vector representation)
  - Task as binary classification problem:
    - ▶ Given input and weight matrix say if  $w_t$  is current word
    - ▶ We know the correct  $w_t$ , how do we get the wrong ones?
      - **negative sampling**

# Simplifications



Remove hidden layer and sum over context

Note: Bias terms omitted for simplicity

- BOW model (Mikolov. 2013)
- Skip-gram model:
  - ▶ Input is  $w_t$
  - ▶ Prediction is  $w_{t+2}$ ,  $w_{t+1}$ ,  $w_{t-1}$  and  $w_{t-2}$

# Applications

## Semantic similarity:

- How similar are the words:
  - ▶ *coast* and *shore*; *rich* and *money*; *happiness* and *disease*; *close* and *open*
- WordSim-353 (Finkelstein et al. 2002)
  - ▶ Measure associations
- SimLex-999
  - ▶ Only measure semantic similarity

## Other tasks:

- Use word embeddings as input features for other tasks (e.g. sentiment analysis, language modeling)

# Recap

- Cannot fit data with **non-linear** decision boundary with linear models

**Solution:** compose non-linear functions with **neural networks**

→ Successful in many NLP applications:

- ▶ Language modeling
  - ▶ Learning word embeddings
- Feeding word embeddings into neural networks has proven successful in many NLP tasks
    - ▶ Sentiment analysis
    - ▶ Named Entity Recognition

Thank you !