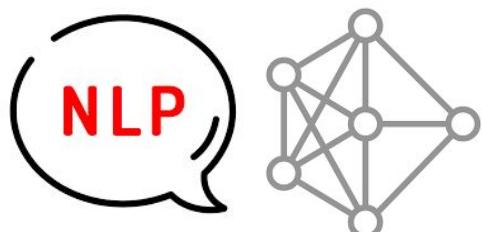




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COMPUTER



# Word Representations

2110572: Natural Language Processing Systems

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# Outline

- **1) How to represent words?**
  - Symbolic vs distributional word representations
- **2) Distributional: Sparse vector representations (discrete representation)**
  - Term-document matrix
  - Co-occurrence matrix
  - Positive Pointwise Mutual Information (PPMI)
  - TF-IDF
- **3) Distributional: Dense vector representations**
  - SVD-based method
  - Word2Vec
    - Skip-gram
    - CBOW
  - Word2Vec training methods
  - Pre-trained vector representations
    - Adaptation
    - Learned Semantic-Syntactic Relationships
    - Compositionality
- **4) Word2Vec Evaluation**
- **5) Advanced Topics**



# Part 1: How to represent words?

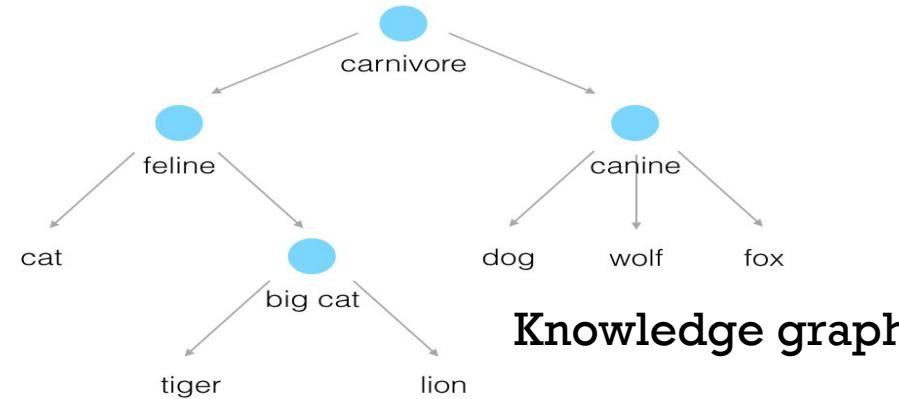
Symbolic vs distributional word representations



# How to represent words?

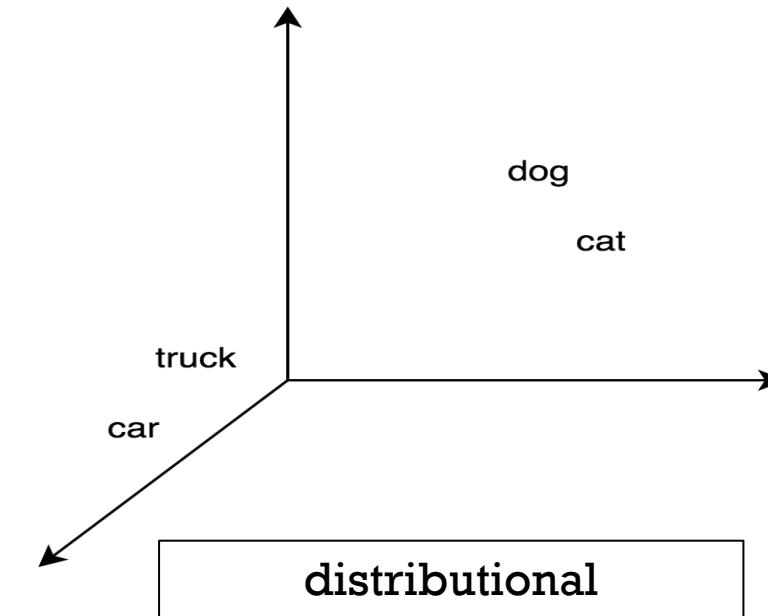
## Symbolic vs Distributional representations

- Representing words in computer is one of the most important tasks in NLP.
- Words = Input for our models



ເສື້ອ = [ 0 1 0 0 0 ... 0 0 ]  
One-hot model

symbolic





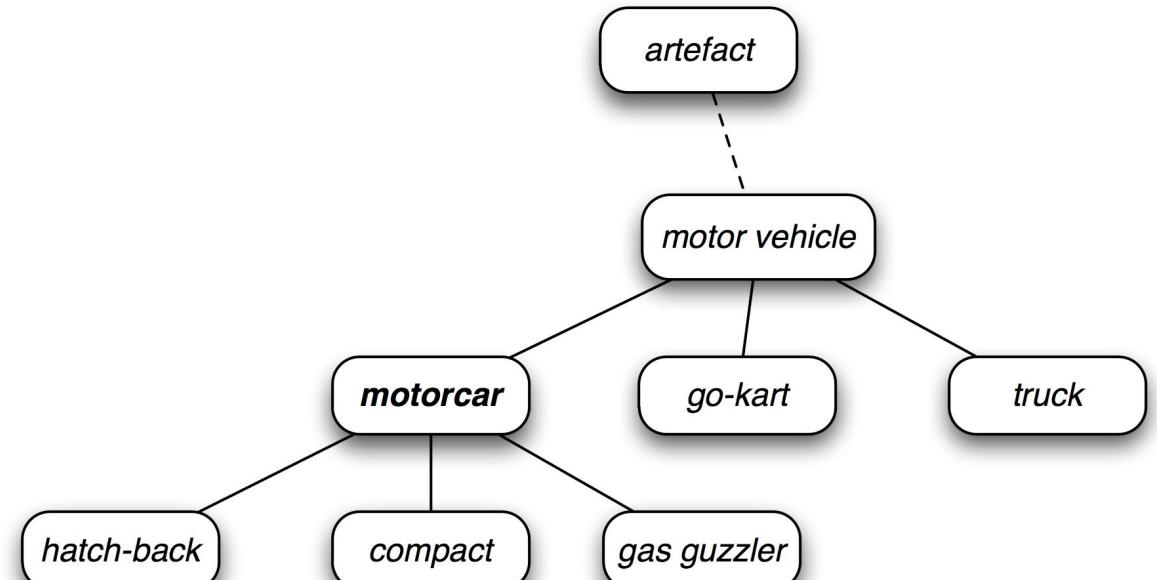
# How to represent words?

## Symbolic vs Distributional representations (cont.)

1

- Symbolic Representations

- A lexical database, such as WordNet that has hypernyms and synonyms
- Drawback:
  - Requires human labor to create and update
  - Missing new words, nuances
  - Hard to compute accurate word similarity



Knowledge graph



# How to represent words?

## Symbolic vs Distributional representations (cont.)

1

### ■ Symbolic Representations

- Earlier work in NLP, the vast majority of (rule-based and statistical) NLP models considered words as discrete atomic symbols.
- E.g. **One-hot model**

ເລື້ອ = [ 0 1 0 0 0 ... 0 0 ]

ສັຕິກິນເນື້ອ = [ 0 0 0 0 1 ... 0 0 ]

\* Each point in the vector represents each vocab.

- Drawback:

- **Cannot capture similarity between words**



# How to represent words?

## Symbolic vs Distributional representations (cont.)

2

- Distributed representations (aka distributional methods)
  - “You shall know a word by the company it keeps” (J. R. Firth 1957)
  - The meaning of a word is computed from the distribution of **words around it**.
  - **Can encode similarity between words!**

การลดจำนวนลงของ **ເສື່ອ** ທີ່ເປັນສັຕິກິນເນື້ອ ຈະສ່ວຍເລີດ  
ກະທົບຕ່ອງໂຄຮງສ້າງແລະຮະບັນນິເວສທັງໝາດ

**ເສື່ອ** ເປັນສັຕິໄລ້ຢູ່ລູກຄ້ວຍນມໃນວັນສຶກສິດທີ່ເປັນວັນທີເດືອນກັບແນວ

These words represent “**ເສື່ອ**”



# How to represent words?: Symbolic vs Distributional representations (cont.)

- Most modern NLP models use **distributional word representations** to represent words
- Word meaning as **a vector**
- In this class, we will examine the development of distributed word representations **before** the rise of deep learning, then we will introduce you to word representation techniques used in deep learning models.

+

## Part 2: Distributional: Sparse vector

Term-document matrix

Co-occurrence matrix

Positive Pointwise Mutual Information (PPMI)

TF-IDF



# Sparse vector representations in Distributional Representations

1. Term-Frequency (Raw Frequency)
2. Co-occurrence (Raw Frequency)
3. PPMI
4. TF-IDF



# Sparse vector representations: term-document matrix

1

- Each row represents a word in the vocabulary and term-document matrix
- Each column represents a document.

vocabulary

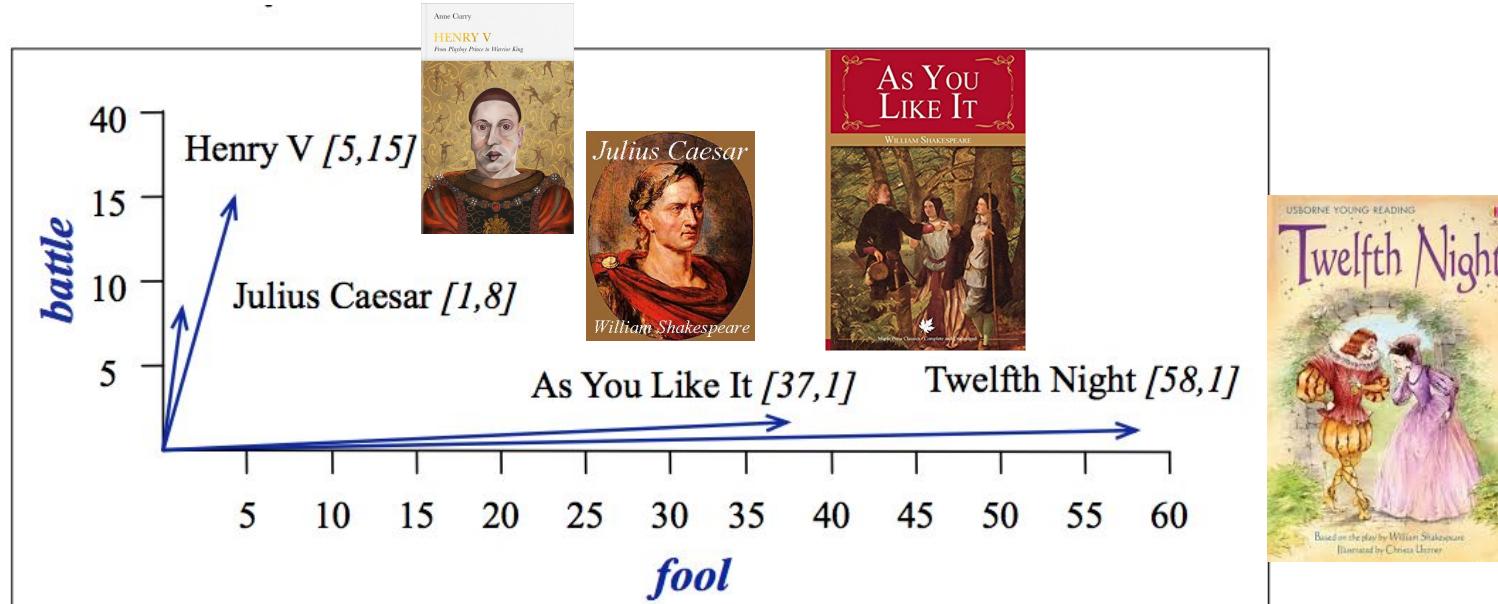
	<b>As You Like It</b>	<b>Twelfth Night</b>	<b>Julius Caesar</b>	<b>Henry V</b>	document
battle	1	1	8	15	
soldier	2	2	12	36	
fool	37	58	1	5	
clown	5	117	0	0	

**Figure 15.1** The term-document matrix for four words in four Shakespeare plays. Each cell contains the number of times the (row) word occurs in the (column) document.



# Sparse vector representations: term-document matrix (cont.)

- Application: Document Information Retrieval
  - Two documents that are similar tend to have similar words/vectors (**document similarity**)



**Figure 15.3** A spatial visualization of the document vectors for the four Shakespeare play documents, showing just two of the dimensions, corresponding to the words *battle* and *fool*. The comedies have high values for the *fool* dimension and low values for the *battle* dimension.



# Sparse vector representations: term-document matrix (cont.)

- Documents as vectors
- Two documents are similar if their vectors are similar (**document similarity**)

vocabulary	<b>As You Like It</b>	<b>Twelfth Night</b>	<b>Julius Caesar</b>	<b>Henry V</b>
battle	1	1	8	15
soldier	2	2	12	36
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# Sparse vector representations: term-document matrix (cont.)

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<b>fool</b>	37	58	1	5	
<b>clown</b>	5	117	0	0	

**Figure 15.1** The term-document matrix for four words in four Shakespeare plays. Each cell contains the number of times the (row) word occurs in the (column) document.



## Sparse vector representations: co-occurrence matrix (1)

2

- Word-word or word-context matrix
  - Instead of entire documents, use smaller contexts
- Two words are similar if their vectors are similar

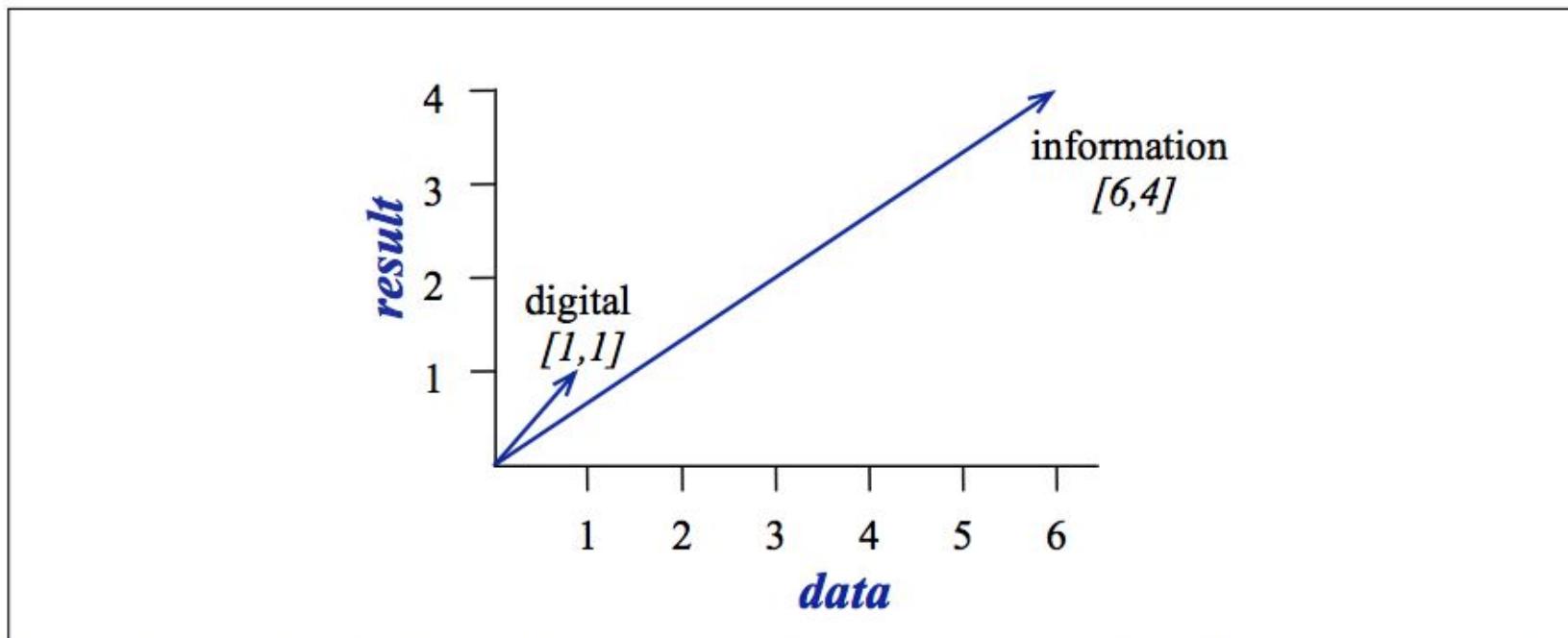
vocabulary ↓	aardvark	...	computer	data	pinch	result	sugar	...
apricot	0	...	0	0	1	0	1	
pineapple	0	...	0	0	1	0	1	
digital	0	...	2	1	0	1	0	
information	0	...	1	6	0	4	0	

**Figure 15.4** Co-occurrence vectors for four words, computed from the Brown corpus, showing only six of the dimensions (hand-picked for pedagogical purposes). The vector for the word *digital* is outlined in red. Note that a real vector would have vastly more dimensions and thus be much sparser.



# Sparse vector representations: co-occurrence matrix (2)

- Two similar words tend to have similar vectors (**word similarity**)



**Figure 15.5** A spatial visualization of word vectors for *digital* and *information*, showing just two of the dimensions, corresponding to the words *data* and *result*.

Reference: Jurafsky, Dan, and James H. Martin. Speech and language processing. 3<sup>rd</sup> edition draft, <https://web.stanford.edu/~jurafsky/slp3/>, August 2017



# Sparse vector representations: Positive Pointwise Mutual Information (PPMI)

3

- **Problems with raw frequency**
  - Very skewed (lots of 0)
  - Not very discriminative
    - Words such as “it, the, they” occur very frequently, **but are not very informative**
- **PPMI** incorporates the idea of mutual information to determine the informative context words
  - **We need a measure** which tells us which context words are informative about the target word



# Sparse vector representations: Positive Pointwise Mutual Information (PPMI) (cont.)

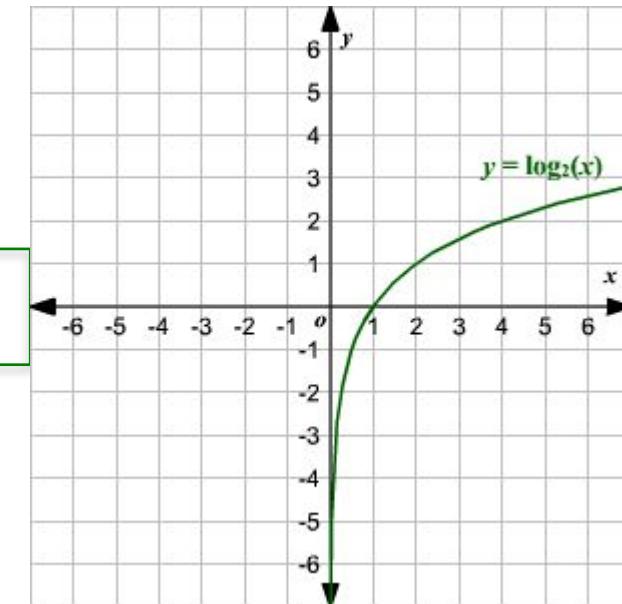
$$PMI(w, c) = \log_2 \frac{P(w, c)}{P(w)P(c)}$$

How often the two words occur together

How often the two words occur if they occur independently

w – target word  
c – context word

Do words “w” and “c” co-occur more than if they were independent?



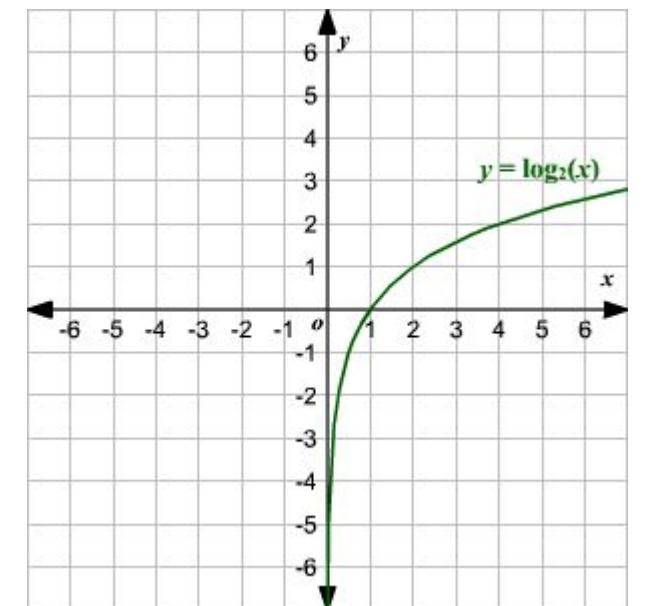


# Sparse vector representations: Positive Pointwise Mutual Information (PPMI) (cont.)

Negative PMI values tend to be unreliable.

It is common to replace all negative PMI values with zero

$$PPMI(w, c) = \max\left(\log_2 \frac{P(w, c)}{P(w)P(c)}, 0\right)$$



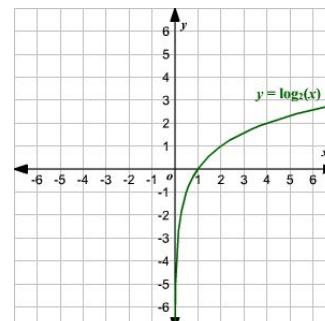


	aardvark	...	computer	data	pinch	result	sugar	...
apricot	0	...	0	0	1	0	1	
pineapple	0	...	0	0	1	0	1	
digital	0	...	2	1	0	1	0	
information	0	...	1	6	0	4	0	

	computer	data	pinch	result	sugar
apricot	0	0	2.25	0	2.25
pineapple	0	0	2.25	0	2.25
digital	1.66	0	0	0	0
information	0	0.57	0	0.47	0

**Figure 15.7** The PPMI matrix showing the association between words and context words, computed from the counts in Fig. 15.4 again showing five dimensions. Note that the 0 ppmi values are ones that had a negative pmi; for example  $\text{pmi}(\text{information}, \text{computer}) = \log 2(0.05 / (0.16 * 0.58)) = -0.618$ , meaning that *information* and *computer* co-occur in this mini-corpus slightly less often than we would expect by chance, and with ppmi we replace negative values by zero. Many of the zero ppmi values had a pmi of  $-\infty$ , like  $\text{pmi}(\text{apricot}, \text{computer}) = \log 2(0 / (0.16 * 0.11)) = \log 2(0) = -\infty$ .

Reference: Jurafsky, Dan, and James H. Martin. Speech and language processing. 3<sup>rd</sup> edition draft, <https://web.stanford.edu/~jurafsky/slp3/>, August 2017





# Sparse vector representations: TF-IDF

- Term Frequency (TF) – per each document

$$TF(w) = \frac{\text{Frequency of word } w \text{ in a document}}{\text{Total number of words in the document}}$$

- Inverse Document Frequency (IDF) – per corpus (all documents)

$$IDF(w) = \log_e \left( \frac{\text{Total number of documents}}{\text{Number of documents that contain word } w} \right)$$

- TF-IDF

$$TFIDF(w) = TF(w) * IDF(w)$$



# Sparse vector representations: TF-IDF (Cont.)

**tf-idf matrix**

	<b>As You Like It</b>	<b>Twelfth Night</b>	<b>Julius Caesar</b>	<b>Henry V</b>
<b>battle</b>	0.074	0	0.22	0.28
<b>good</b>	0	0	0	0
<b>fool</b>	0.019	0.021	0.0036	0.0083
<b>wit</b>	0.049	0.044	0.018	0.022

**Figure 6.8** A tf-idf weighted term-document matrix for four words in four Shakespeare plays, using the counts in Fig. 6.2. For example the 0.049 value for *wit* in *As You Like It* is the product of  $\text{tf} = \log_{10}(20 + 1) = 1.322$  and  $\text{idf} = .037$ . Note that the idf weighting has eliminated the importance of the ubiquitous word *good* and vastly reduced the impact of the almost-ubiquitous word *fool*.



## Sparse vector representations: TF-IDF (Cont.)

- A very popular way of weighting in Information Retrieval (**document similarity**)
- **Not** commonly used as a component to measure **word similarity** (it is designed **document similarity**)



## Part 3: Distributional: Dense vector representations

- SVD-based method
- Word2Vec
  - Skip-gram
  - CBOW
- Word2Vec training methods
- Pre-trained vector representations
  - Adaptation
- Learned Semantic-Syntactic Relationships
- Compositionality

# Dense vector representations

- **Sparse vector** representations such as PPMI vectors are:
  - Long (length of vector  $\approx$  20,000 to 50,000 )
  - Sparse (most elements are zero)
- **Dense vector** representations are introduced to:
  - Reduce length of vectors (length of vector  $\approx$  200 to 1,000 )
  - Reduce sparsity (hence the name “dense”; most elements are not zero)
  - **“Dense vectors work better in every NLP task than sparse vectors.” - Dan Jurafsky**



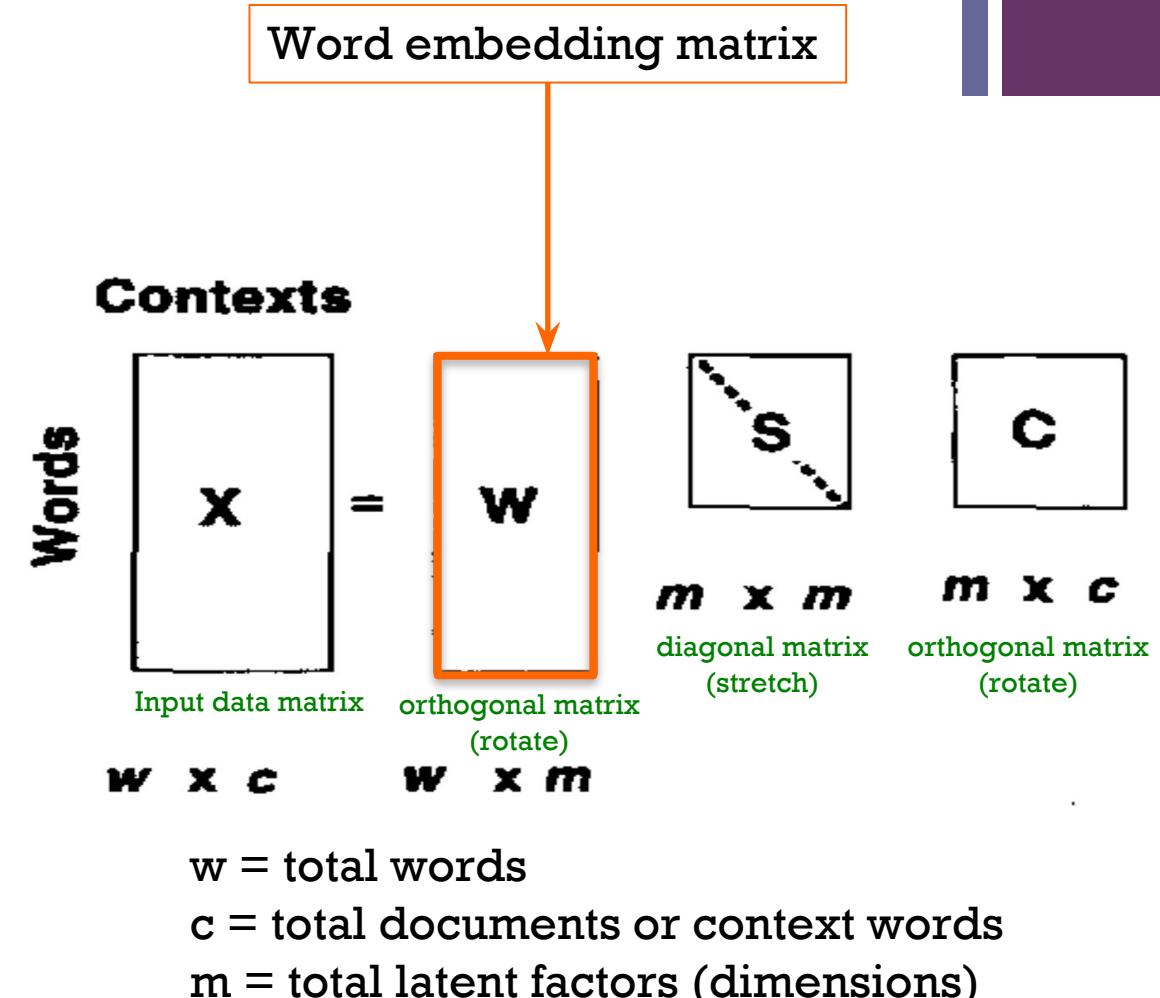
# Dense vector representations (cont.)

- **Advantages** of dense vector representation

- Less parameters to tune
- Generalize better
- Better at capturing synonymy

# Dense vector representations: SVD-based method (1)

- Single Value Decomposition (SVD)
  - dimensionality reduction
  - A way to **breakup a matrix** into 3 pieces
  - The use of SVD as a way to reduce large sparse vector spaces for word meaning was first applied in the context of information retrieval, often referred to as **LSA (Latent Semantic Analysis)**



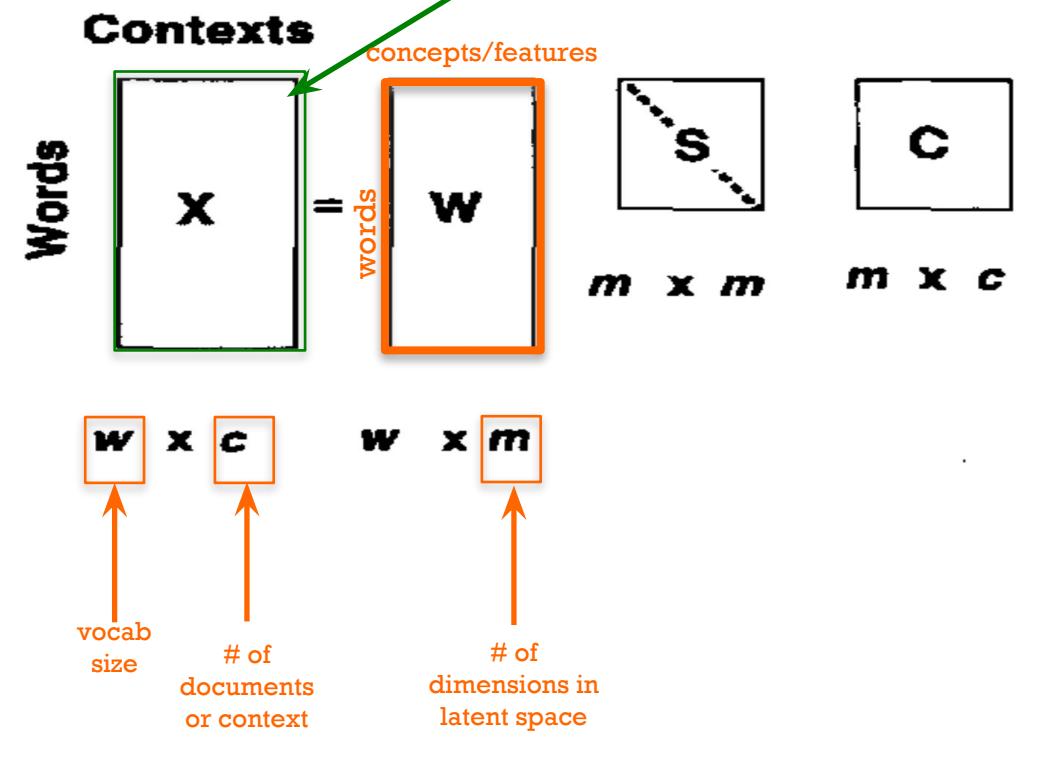
# Dense vector representations: SVD-based method (cont.)

- The matrix **X** is the product of 3 matrices:
  - W:** rows corresponding to original but **m** columns represents a dimension in a new latent space
  - m** column vectors are orthogonal to each other
  - Columns are ordered by the amount of **variance** in the dataset each new dimension accounts for

vocabulary	As You Like It	Twelfth Night	Julius Caesar	Henry V	document
battle	1	1	8	15	
soldier	2	2	12	36	
fool	37	58	1	5	
clown	5	117	0	0	

Figure 15.1 The term-document matrix for four words in four Shakespeare plays. Each cell contains the number of times the (row) word occurs in the (column) document.

The cells are commonly weighted by a product of two weights:  
 • Local weight: Log term frequency  
 • Global weight: either idf or an entropy measure

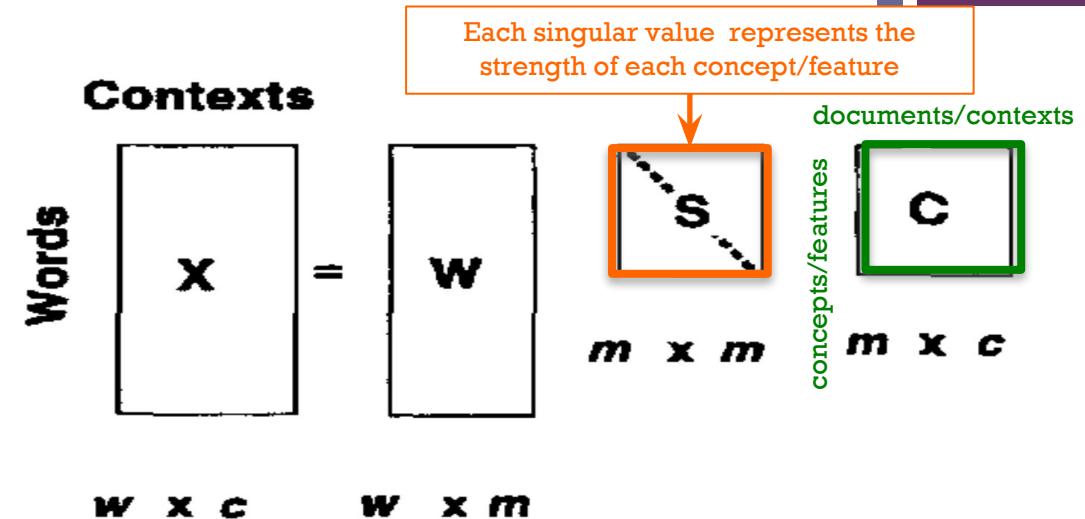


w = total words  
 c = total documents or context words  
 m = total latent factors (dimensions)



# Dense vector representations: SVD-based method (cont.)

- The matrix **X** is the product of 3 matrices:
  - S:** diagonal  $m \times m$  matrix of **singular values** expressing the **importance/strength** of each dimension
  - C:** columns corresponding to original but  $m$  rows corresponding to singular values



$w$  = total words

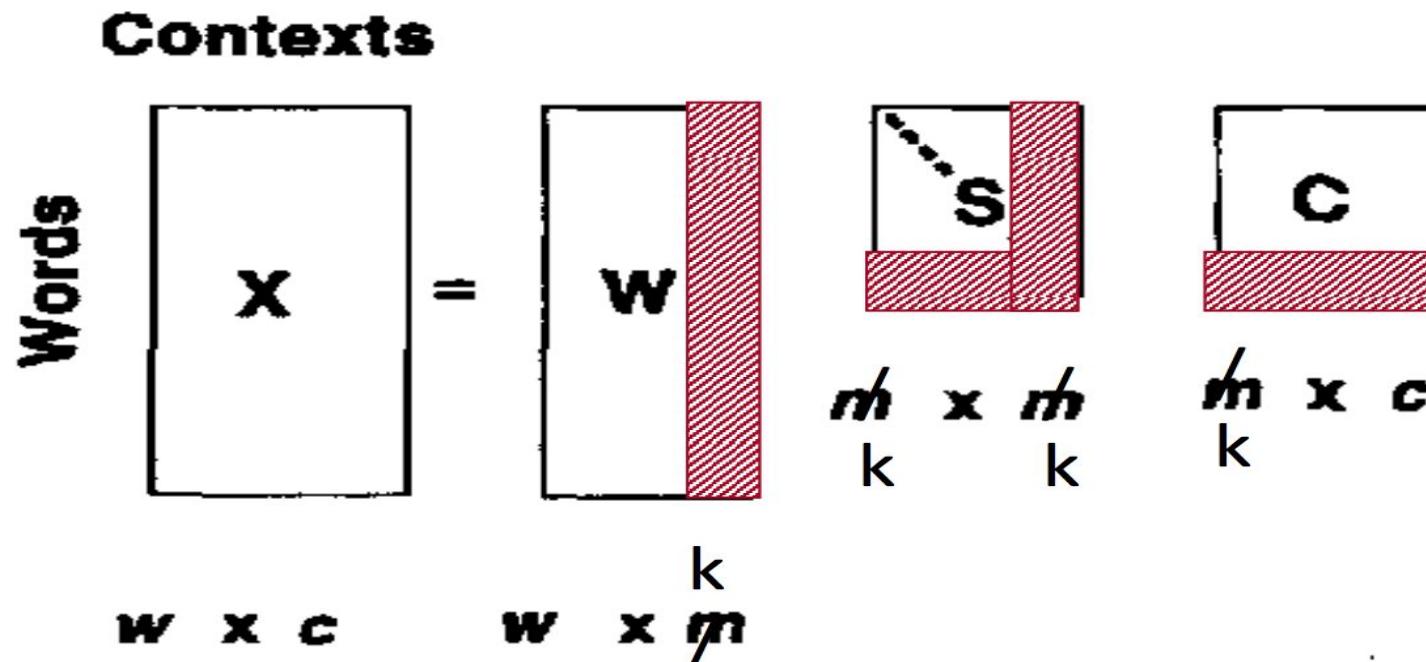
$c$  = total documents

$m$  = total latent factors (dimensions)



# Dense vector representations: SVD-based method (cont.)

- **Latent Semantic Analysis** (Deerwester et al. (1988))
  - instead of keeping all  $m$  dimensions, we just keep the top  $k$  singular values. ( $k=300$  is common)

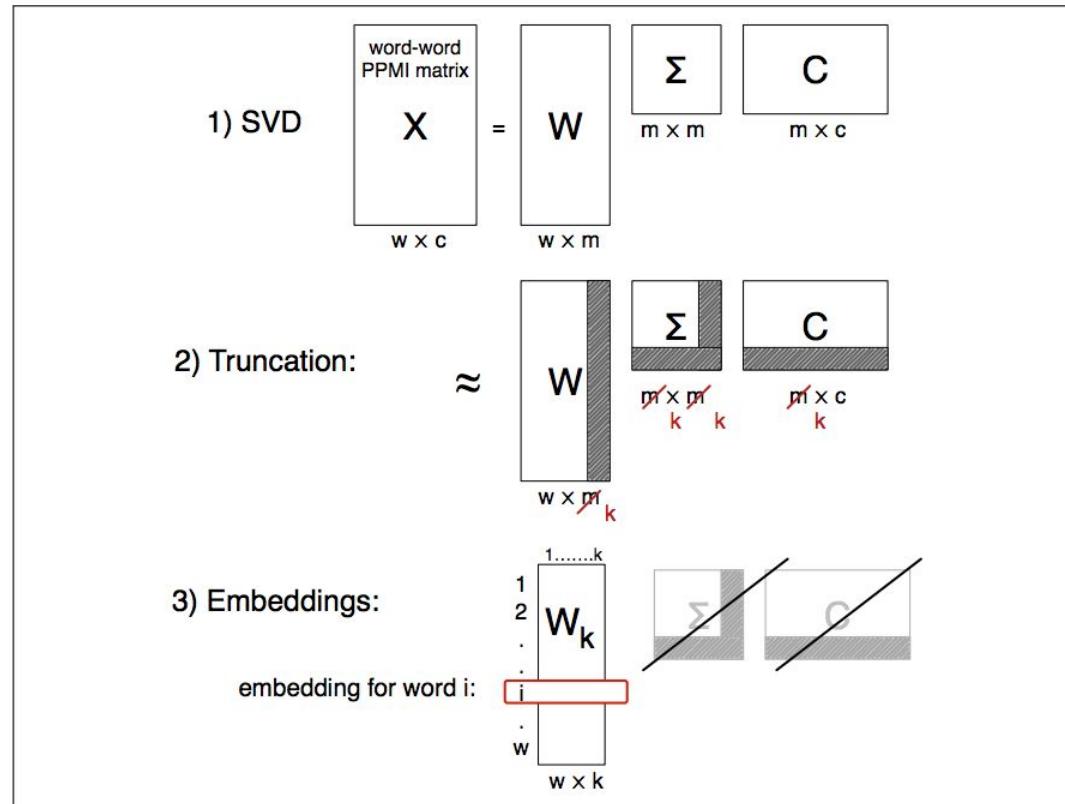




# Dense vector representations: SVD-based method (cont.)

- SVD applied to  
**word-word/word-context matrices**
- In this version the context dimensions  
are words rather than documents
- The only difference is that we are  
using a **PPMI-weighted word-word  
matrix** as an input data matrix

	computer	data	pinch	result	sugar
apricot	0	0	2.25	0	2.25
pineapple	0	0	2.25	0	2.25
digital	1.66	0	0	0	0
information	0	0.57	0	0.47	0



**Figure 16.3** Sketching the use of SVD to produce a dense embedding of dimensionality  $k$  from a sparse PPMI matrix of dimensionality  $c$ . The SVD is used to factorize the word-word PPMI matrix into a  $W$ ,  $\Sigma$ , and  $C$  matrix. The  $\Sigma$  and  $C$  matrices are discarded, and the  $W$  matrix is truncated giving a matrix of  $k$ -dimensionality embedding vectors for each word.



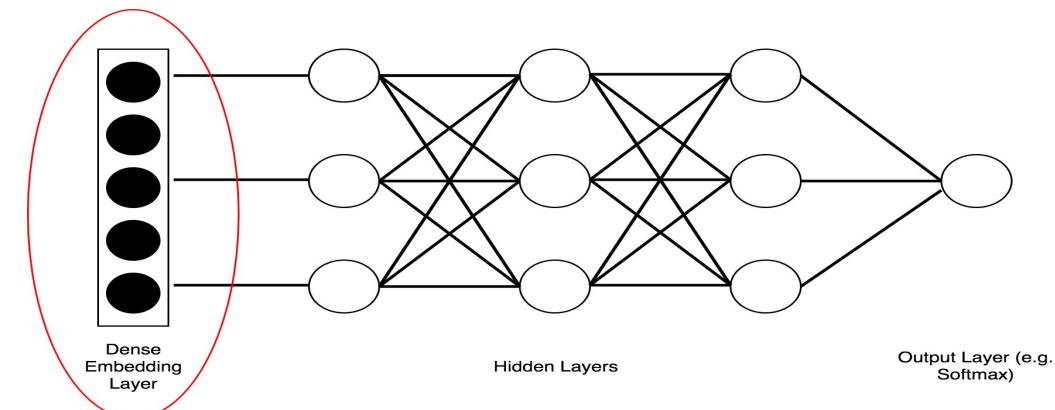
## Dense vector representations: SVD-based method (cont.)

- We can apply SVD/LSA to one of the sparse vector representations to yield a word representation with smaller dimensionality.
- Advantages:
  - Generalize better on unseen data
  - Reduce low-order dimensions that may represent unimportant information
  - Less parameters to tune

# 2 Dense vector representations : neural networks

How do we train embeddings in neural networks?

1. **Pre-train** on unsupervised task (e.g. LM: skip-gram, CBOW)
  - a. we will learn how to do this today
2. **Pre-train** on supervised task
  - a. e.g. train on POS tagging task and use it on other tasks
3. **Initialize randomly** and train it on a your target task.





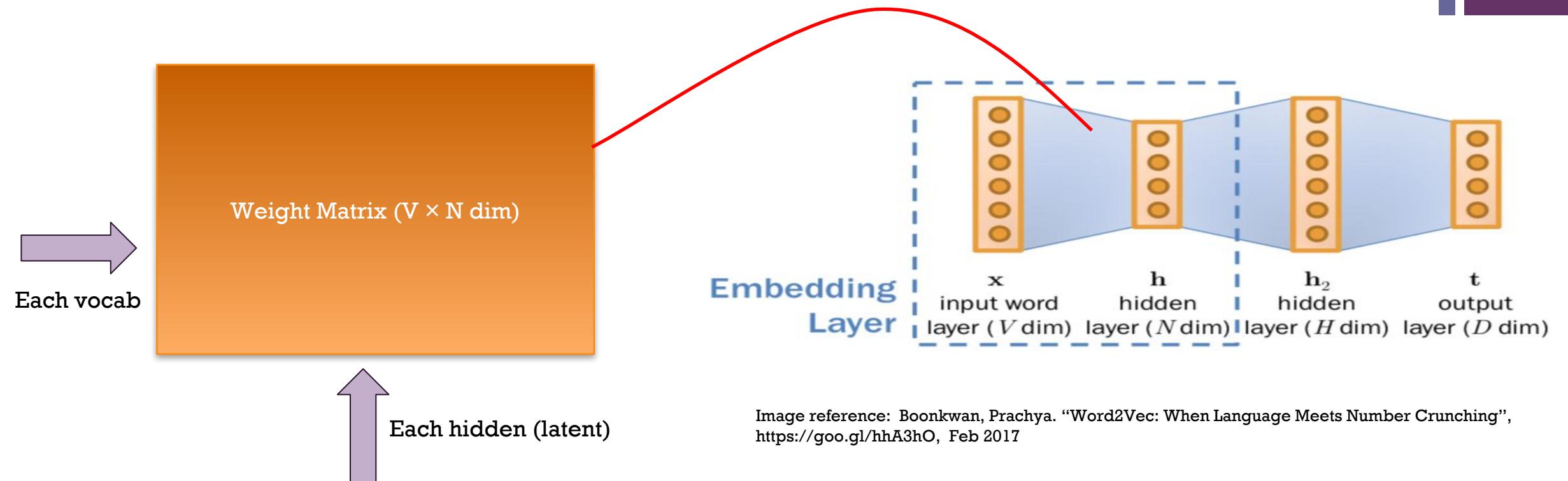
# Dense vector representations : neural networks (cont.)

- Tomas Mikolov introduced **Skip-gram** and **CBOW** in 2013
- Train a neural network to predict neighboring words
- Word representation can be learned as a part of the process of **word prediction**.
- **Part of a neural network (embedding layer)** can be used as word representation in various NLP tasks
- **Advantages:**
  - Faster than SVD
  - Pre-trained word representations are available online!



**Tomas Mikolov**  
RESEARCH SCIENTIST

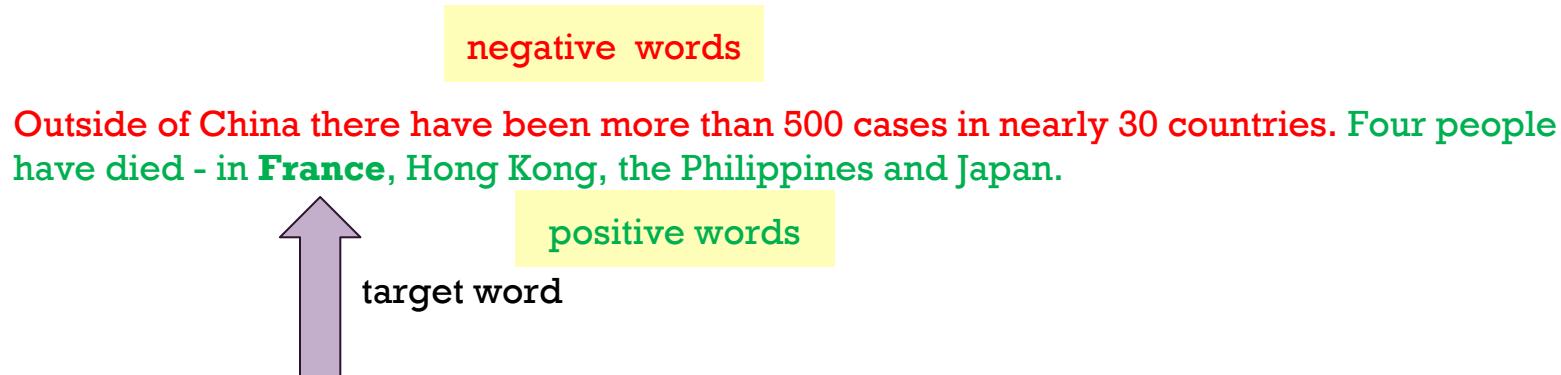
# + Dense vector representations : neural networks (cont.)





# Dense vector representations : neural networks (cont.)

- CBOW and Skip-Gram intuition: Iteratively make the embeddings for a word
  - (positive class) **more like** the embeddings of its **neighbors** and
  - (negative class) **less like** the embeddings of **other words**.

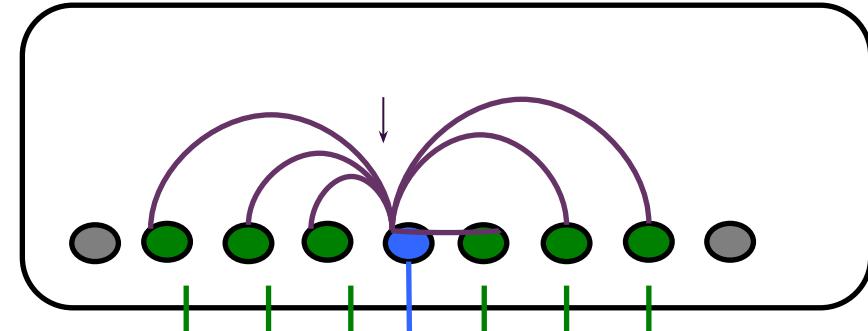
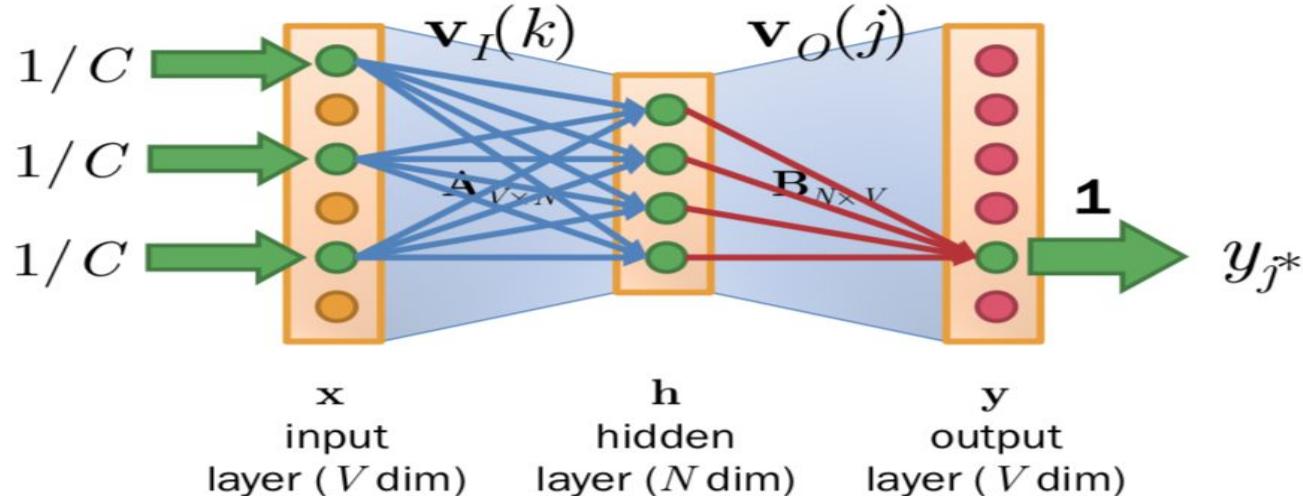


Reference: Jurafsky, Dan, and James H. Martin. Speech and language processing. 3<sup>rd</sup> edition draft, <https://web.stanford.edu/~jurafsky/slp3/>, August 2017



# Dense vector representations : CBOW

- Continuous Bag-of-Words (CBOW)
- In CBOW neural language model, **ONE target word** is predicted from **SEVERAL context words**.

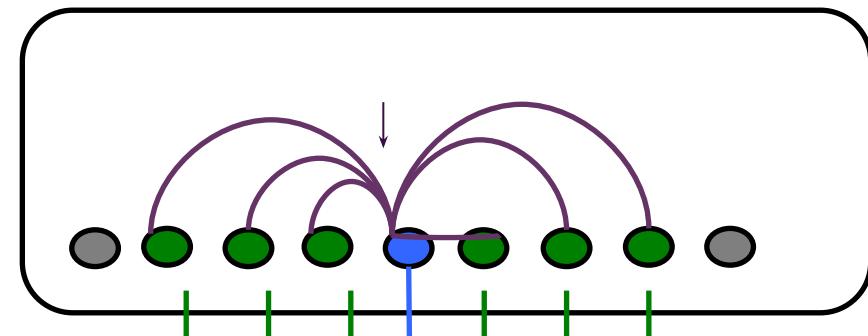
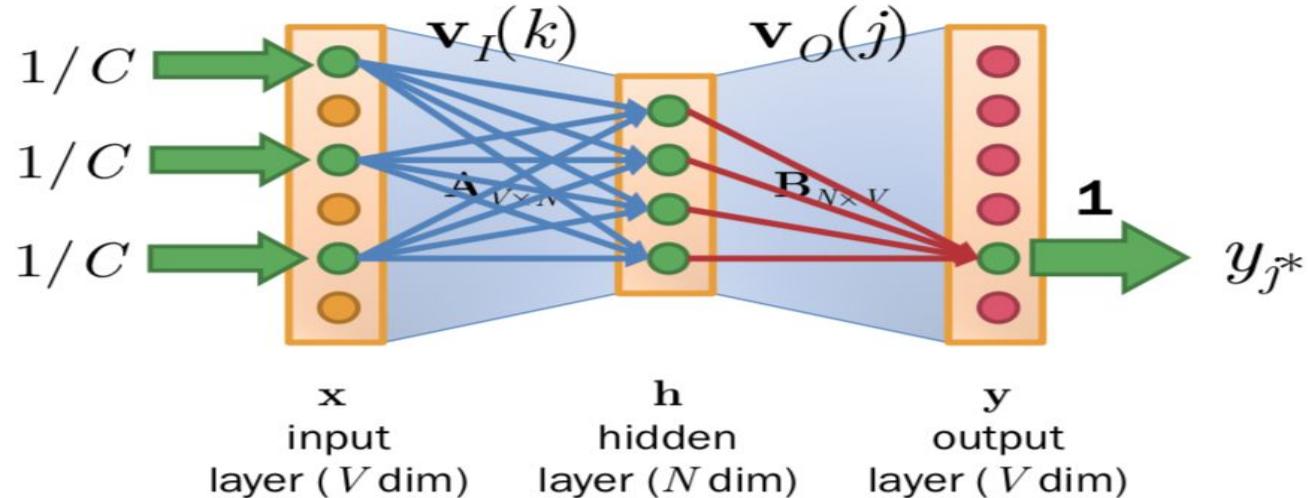


$$\mathbf{h}_{\text{ctx}} = \frac{1}{C} \sum_{q=1}^C \mathbf{v}_I(q)$$



# Dense vector representations : CBOW (cont.)

- We simply average the encoding vectors



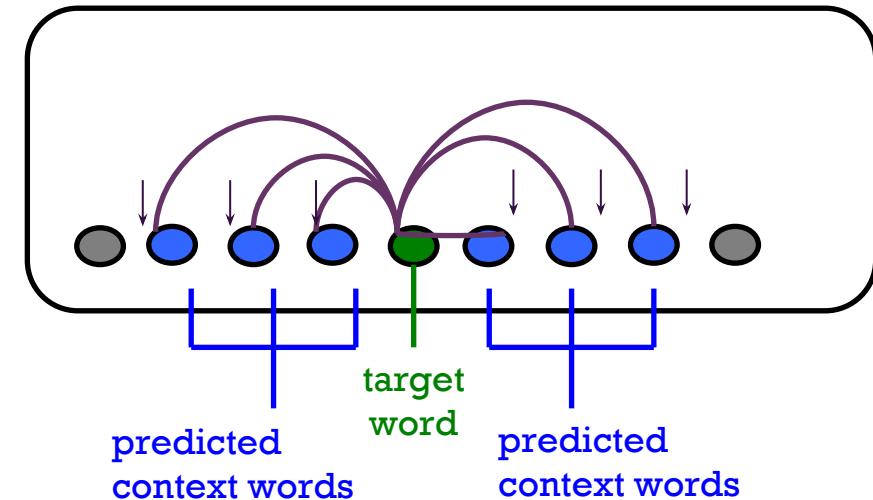
context words  
predicted target word

$$\mathbf{h}_{\text{ctx}} = \frac{1}{C} \sum_{q=1}^C \mathbf{v}_I(q)$$



# Dense vector representations : Skip-gram

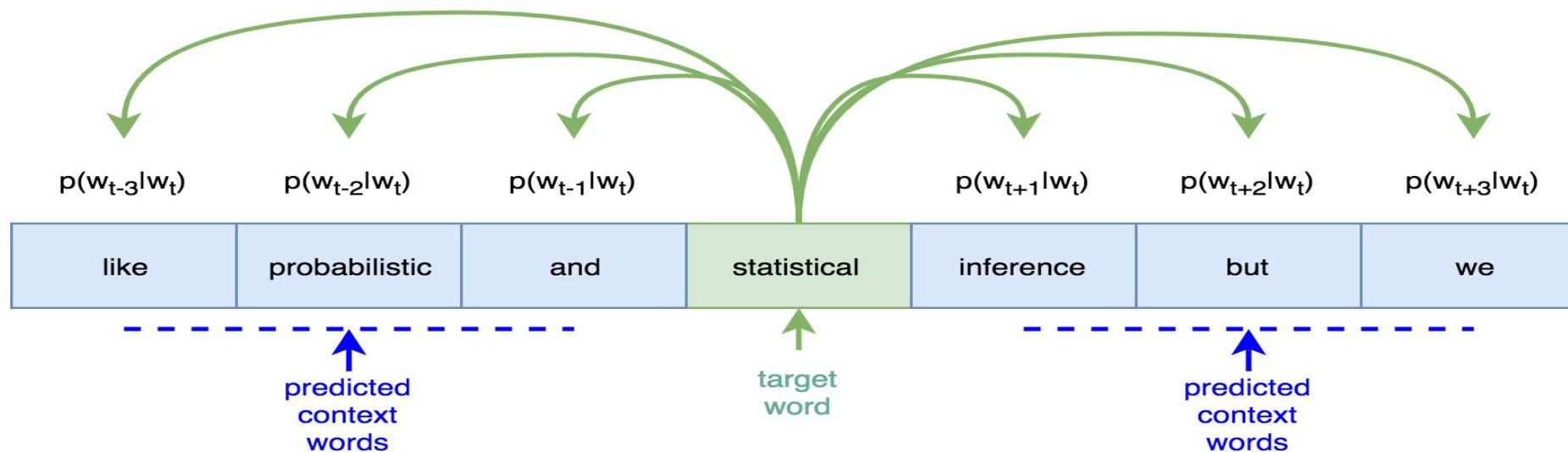
- In skip-gram neural language model, **SEVERAL context words** are predicted from **ONE target word**.
- In “Efficient Estimation of Word Representations in Vector Space”, Mikolov shows that **skip-gram performs better than CBOW** in several tasks. BUT skip-gram model requires **more training time**.
- In this lecture, we will show you how skip-gram works





# Dense vector representations : Skip-gram (cont.)

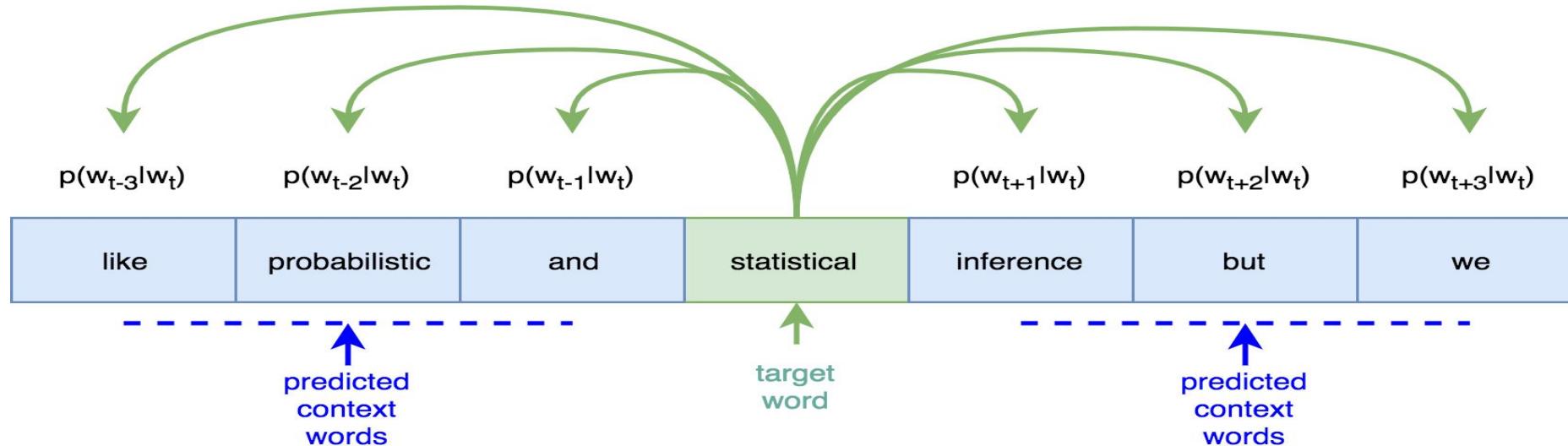
- Skip-gram prediction
- Consider the following passage:
  - “I think it is much more likely that human language learning involves something like probabilistic and statistical inference but we just don't know yet.”





# Dense vector representations : Skip-gram (cont.)

- For each word  $t = 1 \dots T$ , predict its surrounding context words (next  $m$  words and previous  $m$  words)
- “ $m$ ” is the window size





# Dense vector representations : Skip-gram (cont.)

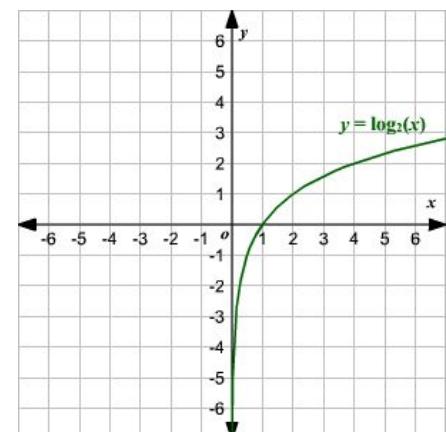
- Likelihood function: Given the target word (aka center word), **maximize** the probability of each context word

$$J'(\theta) = \prod_{t=1}^T \prod_{-m \leq j \leq m; j \neq 0} p(w_{t+j} | w_t; \theta)$$

$j = -m$  → previous words  
 $j = +m$  → next words  
 $j = 0$  → the input word ( $w_t$ )

- Cost/Loss Function (**Negative Log-Likelihood**): (**minimize**)

$$J(\theta) = -\frac{1}{T} \sum_{t=1}^T \sum_{-m \leq j \leq m; j \neq 0} \log p(w_{t+j} | w_t; \theta)$$





# Dense vector representations : Skip-gram (cont.)

- How to calculate  $p(w_{t+j} | w_t; \theta)$  ?
  - for each word  $w$ , we will use two vectors
    - $v$  when  $w$  is a target/center word
    - $u$  when  $w$  is a context word

- Then for a center word 'c' and a context word 'o'

Dot product compares similarity of o and c.  
Larger dot product = larger probability

$$p(o|c) = \frac{\exp(u_o^T v_c)}{\sum_{w \in V} \exp(u_w^T v_c)}$$

Dot product compares similarity of o and c.  
Larger dot product = larger probability

After taking exponent, normalize over entire vocabulary



# Dense vector representations : Skip-gram (cont.)

$$p(o|c) = \frac{\exp(u_o^T v_c)}{\sum_{w \in V} \exp(u_w^T v_c)}$$

- This is basically a softmax function

$$\text{softmax}(x_i) = \frac{\exp(x_i)}{\sum_{j=1}^n \exp(x_j)} = p_i$$

- The softmax function maps arbitrary values  $x_i$  to a probability distribution  $p_i$ 
  - “max”** because amplifies probability of largest  $x_i$
  - “soft”** because still assigns some probability to smaller  $x_i$



# Dense vector representations : Skip-gram (cont.)

- Negative Log-Likelihood of **Skip-gram model**:

$$J(\theta) = -\frac{1}{T} \sum_{t=1}^T \sum_{-m \leq j \leq m; j \neq 0} \log p(w_{t+j}|w_t; \theta)$$

- Notice the difference** between skip-gram's cost function and the cost function of neural language model from the last lecture

Predict context words



# Neural Language Model (cont.)

- Recurrent Neural Network (RNN)

- Cost function:

- $$J = -\frac{1}{T} \sum_{t=1}^T \sum_{j=1}^{|V|} y_{t,j} \log \hat{y}_{t,j}$$

- Where

- V = Number of unique words in corpus
- T = Number of total words in corpus
- y = Target next word
- $\hat{y}$  = Distribution of predicted next word



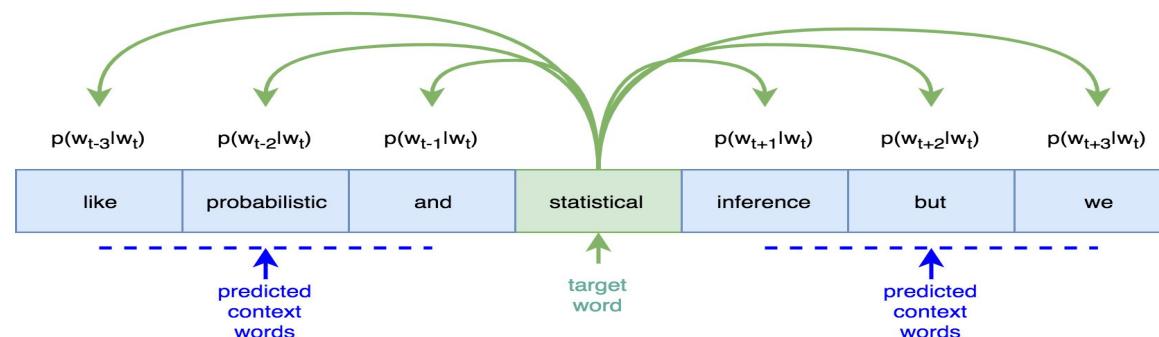
Predict the next word



# Dense vector representations : Skip-gram (cont.)

## Skip-gram model step-by-step:

1. Generate a one hot input vector for the target word (center word)
2. Get the embedded vector for the target center word
3. Generate  $2*m$  score vectors (where  $m$  is the window size)
4. Turn the score vectors into probabilities
5. We desire our probability vector generated to match the true probabilities which are the one hot vectors of the actual output.



Reference:[http://web.stanford.edu/class/cs224n/lecture\\_notes/cs224n-2017-notes1.pdf](http://web.stanford.edu/class/cs224n/lecture_notes/cs224n-2017-notes1.pdf)



# Dense vector representations : Skip-gram (cont.)

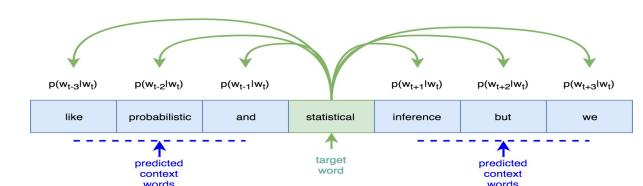
- 1. Generate a one hot input vector  $x$  for of the target word (center word)

statistical = [0 0 1 ... 0 0]



$$x \in \mathbb{R}^{|V|}$$

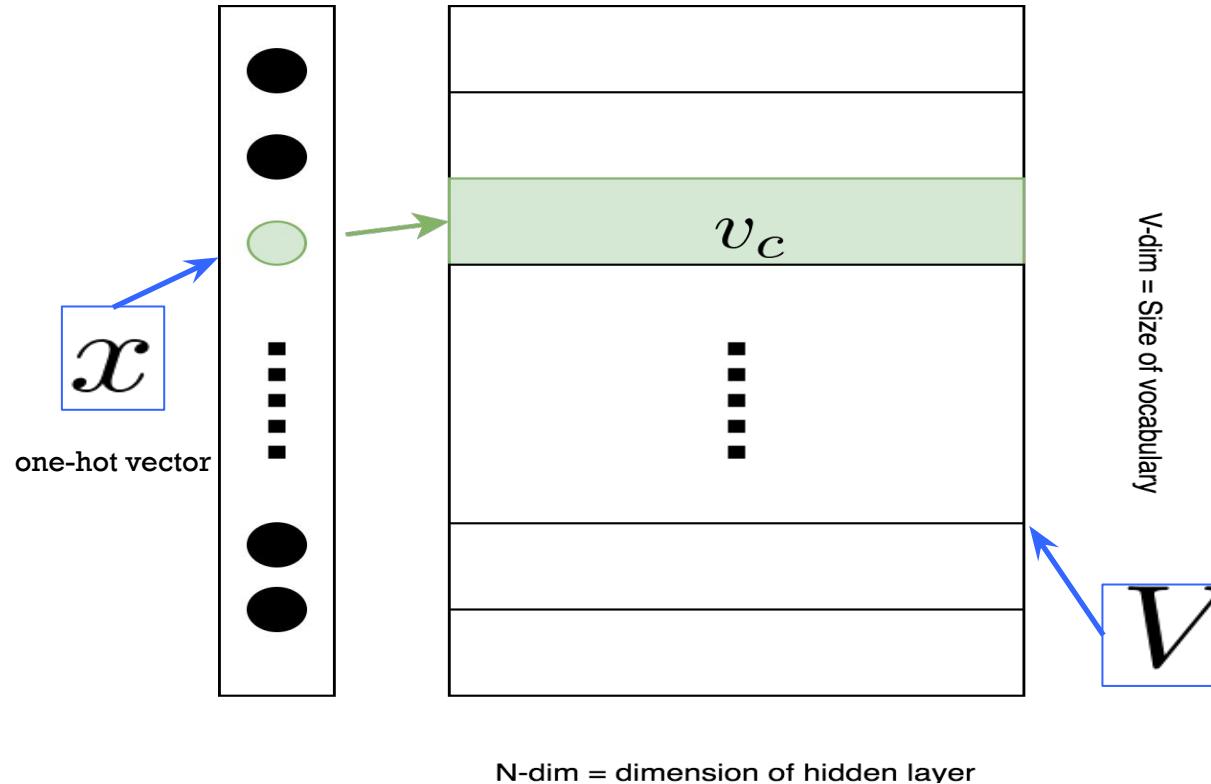
V-Dim = size of the vocabulary





# Dense vector representations : Skip-gram (cont.)

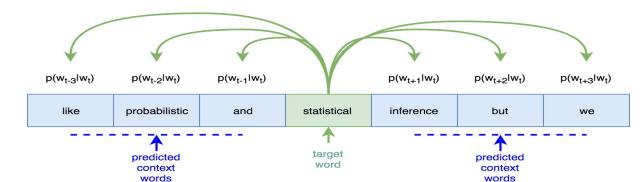
- 2. Get the embedded vector for the target center word



$$v_c = Vx \in \mathbb{R}^n$$

Note that the weight matrix in the embedding layer can be think of as a **look-up table**

Reference:[http://web.stanford.edu/class/cs224n/lecture\\_notes/cs224n-2017-notes1.pdf](http://web.stanford.edu/class/cs224n/lecture_notes/cs224n-2017-notes1.pdf)



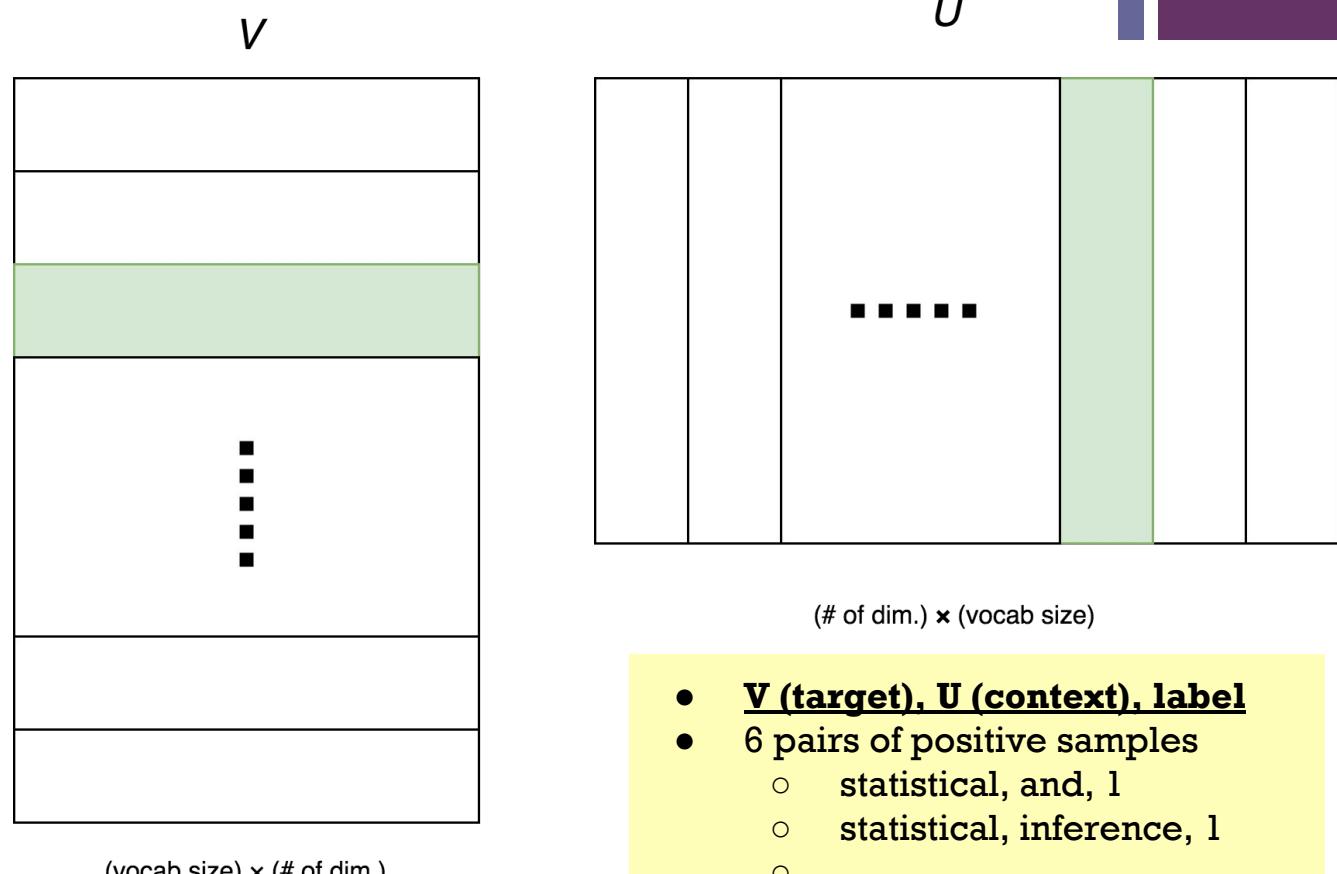
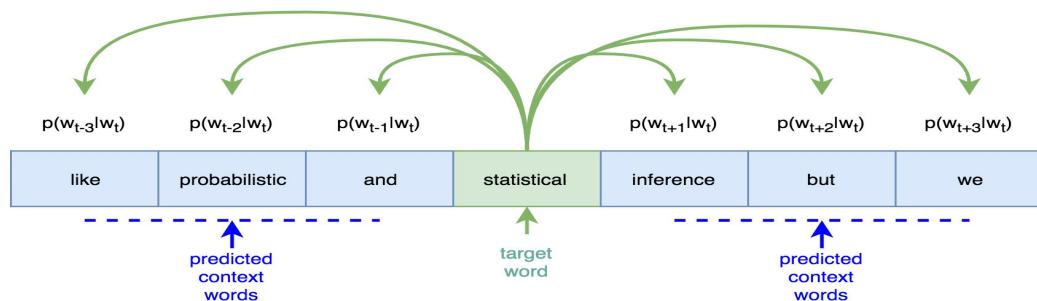


# Dense vector representations : Skip-gram (cont.)

- 3. Generate a score vector

$$z = U v_c$$

- Note that  $\text{similarity}(v_c, u_o) = v_c \cdot u_o$ 
  - $v_c$  = center (target),  $u_o$  = other (context)



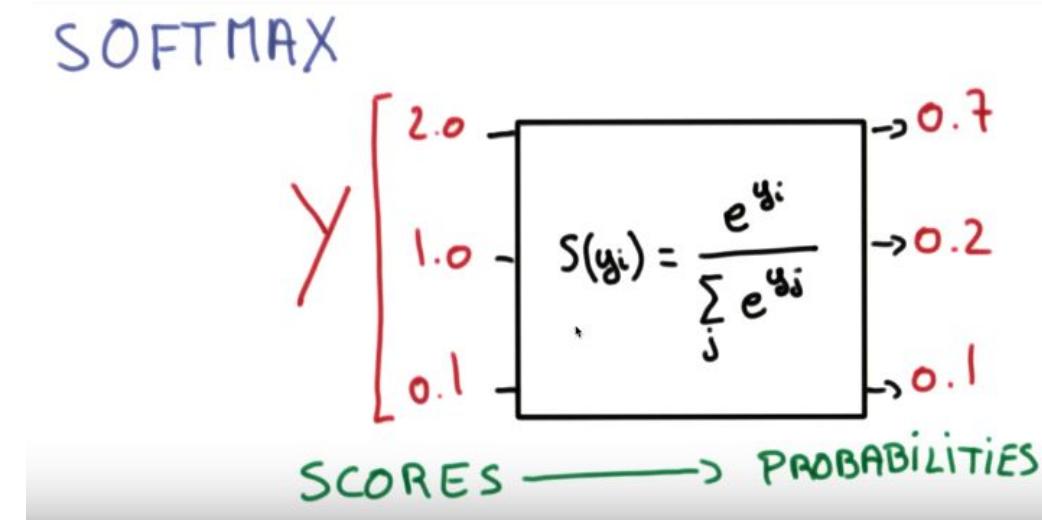


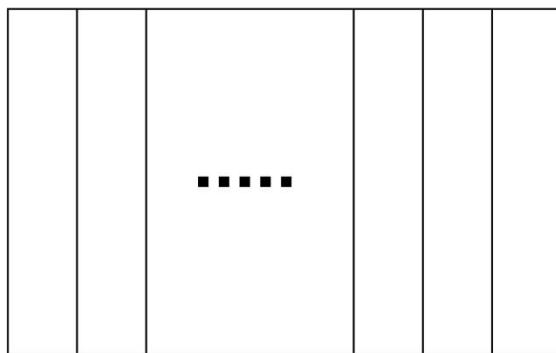
# Dense vector representations : Skip-gram (cont.)

- 4. Turn score into probabilities

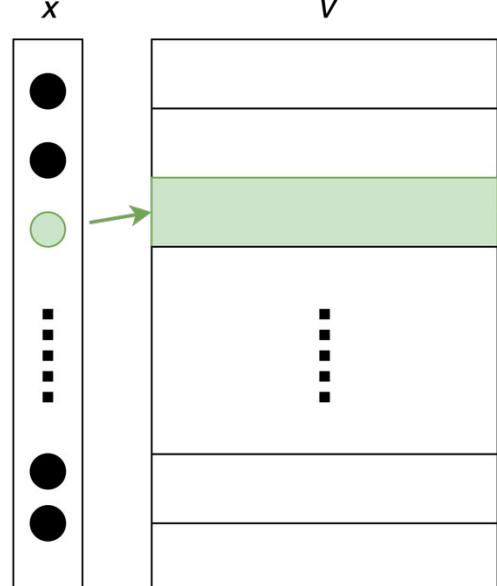
$$\hat{y} = \text{softmax}(z)$$

- 5. We desire our probability vector generated to match the true probabilities which are the one hot vectors of the actual output

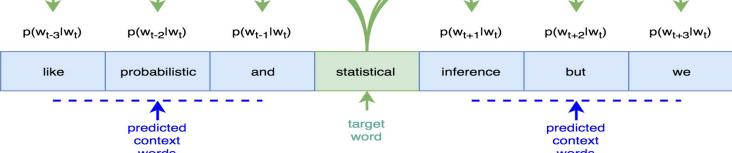


*U*

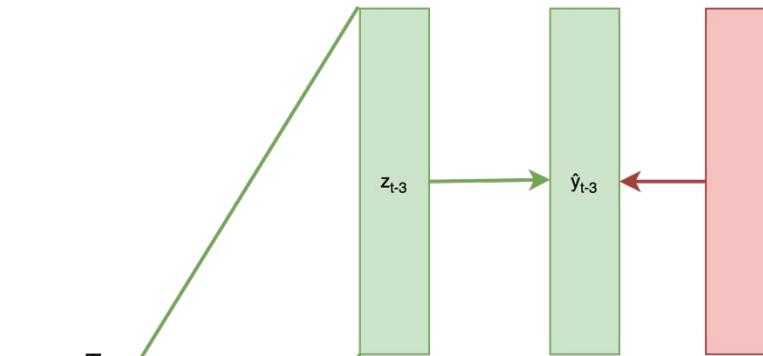
(# of dimensions)  $\times$  (vocab size)  
context word embeddings

*V*

(vocab size)  $\times$  (# of dim.)  
target/center word  
embeddings

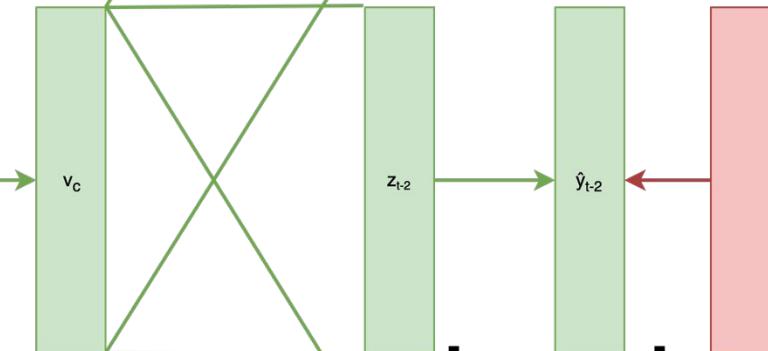


$$z = U^T v_c \quad \hat{y} = \text{softmax}(z) \quad \text{Truth}$$



$$v_c = V^T x$$

(# of dim.)  $\times$  1



(# of dim.)  $\times$  (vocab size)  
context word embeddings

(vocab size)  $\times$  1  
score vector

(vocab size)  $\times$  1  
prob. vector

(vocab size)  $\times$  1  
one-hot vector

**The size of output layer  
= vocab**



# Word2Vec training methods

- Softmax is **not** very efficient (slow)
- Computational Cost :  $O(|V|)$
- **Solution:** Two efficient training methods
  - Hierarchical Softmax:  $O(\log(|V|))$  – **not cover**
  - Negative Sampling



# Word2Vec training methods :

## Solution1: Hierarchical Softmax

- Softmax as **tree traversal**
- Hierarchical softmax uses a **binary tree** to represent words
- Each leaf is a word
  - There's a unique path from root to leaf
- The probability of each word is the **product** of **branch selection decisions** from the root to the word's leaf

$P(\cdot | e)$

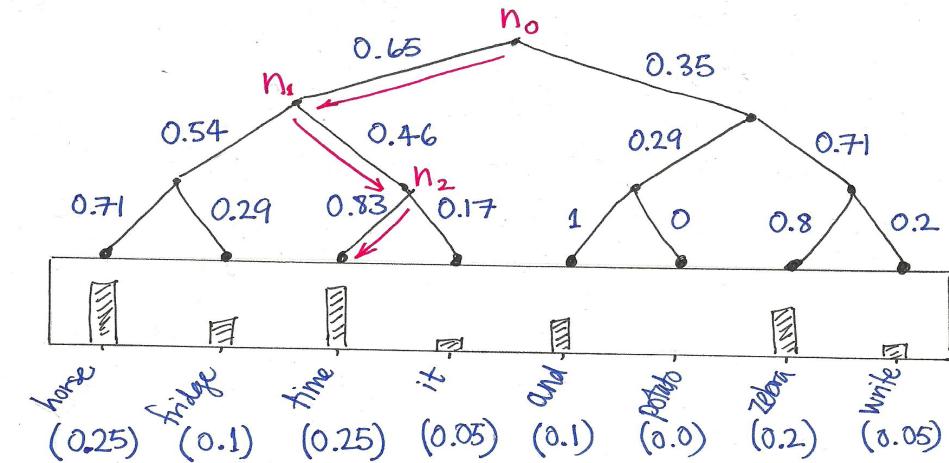


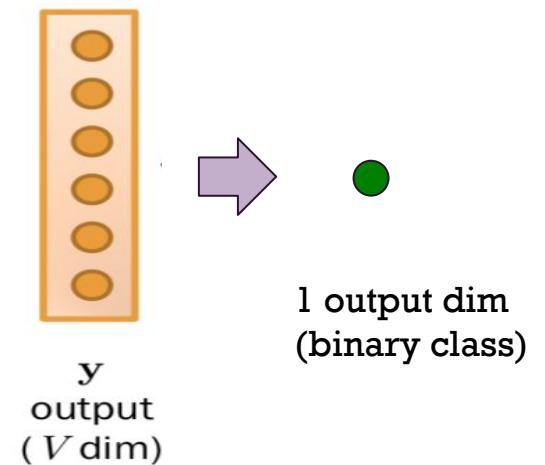
Image reference:

<http://building-babylon.net/2017/08/01/hierarchical-softmax/>



# Word2Vec training methods : Solution2: Negative Sampling (1)

- We assume that the dataset is noisy containing:
  - **Positive examples**: correct output words
  - **Negative examples**: incorrect output words
- How to reduce computational cost?
  - The **positive examples** should be kept
  - Only **k negative examples** are sampled from a distribution



$$P^{\frac{3}{4}}(w) = \frac{(w)^{\frac{3}{4}}}{\sum_{w'} (w')^{\frac{3}{4}}}$$



# Word2Vec training methods : Solution2: Negative Sampling (2)

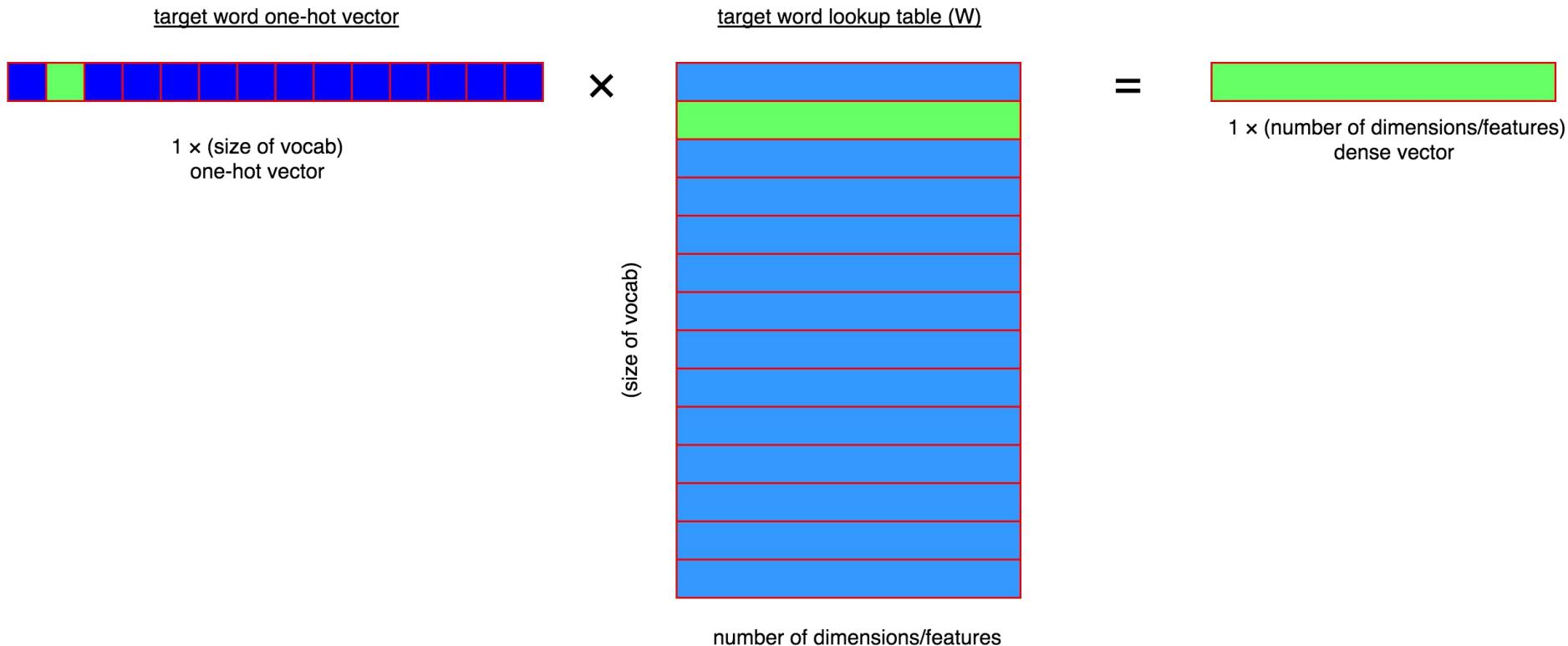
- Why  $\frac{3}{4}$ ?
  - Chosen based on **empirical experiments**
- Intuition:
  - ที่:  $0.9^{3/4} = 0.92$
  - ชานา:  $0.09^{3/4} = 0.16$
  - ตถາຕາ:  $0.01^{3/4} = 0.032$
  - **A rare word** such as ‘ตถາຕາ’ is now 3x more likely to be sampled
  - While the probability of a frequent word ที่ only went up marginally

$$P^{\frac{3}{4}}(w) = \frac{(w)^{\frac{3}{4}}}{\sum_{w'}(w')^{\frac{3}{4}}}$$



# Dense vector representations : Skip-gram (Negative Sampling)

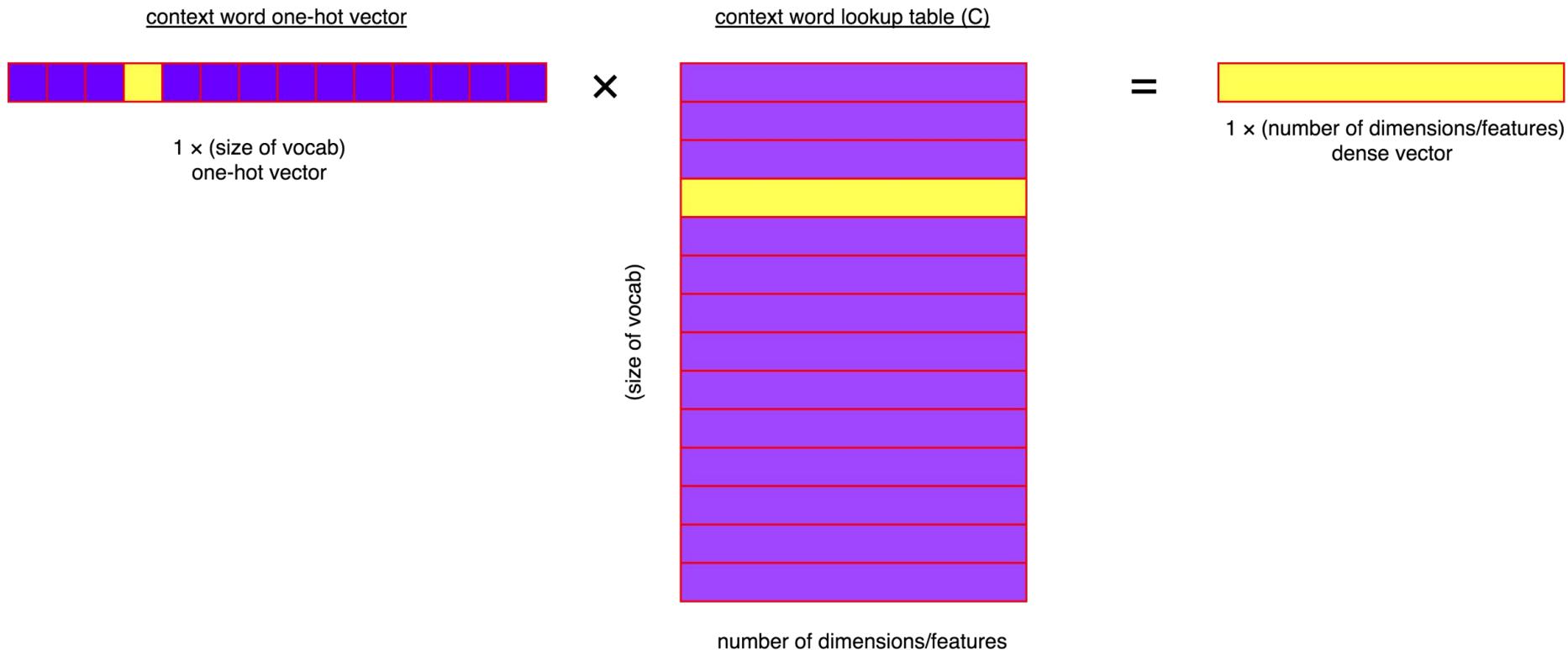
Step1: select the embedding of the target word from W





# Dense vector representations : Skip-gram (Negative Sampling) (cont.)

Step2: select the embedding of the context word from C





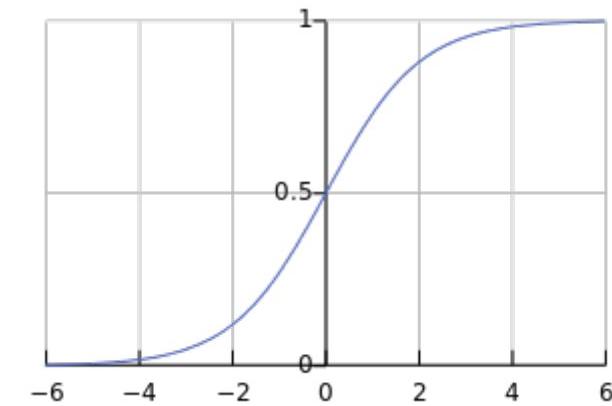
# Dense vector representations : Skip-gram (Negative Sampling) (cont.)

Step3: compute the dot product: $w^*c$

$$\begin{matrix} \text{[Red rectangle]} \\ 1 \times (\text{number of dimensions/features}) \end{matrix} * \begin{matrix} \text{[Yellow rectangle]} \\ (\text{number of dimensions/features}) \times 1 \end{matrix} = \begin{matrix} \text{[Blue square]} \\ \text{scalar} \\ 1 \times 1 \end{matrix}$$

Step4: normalize dot products into probability

$$\sigma(\text{[Blue square]})$$



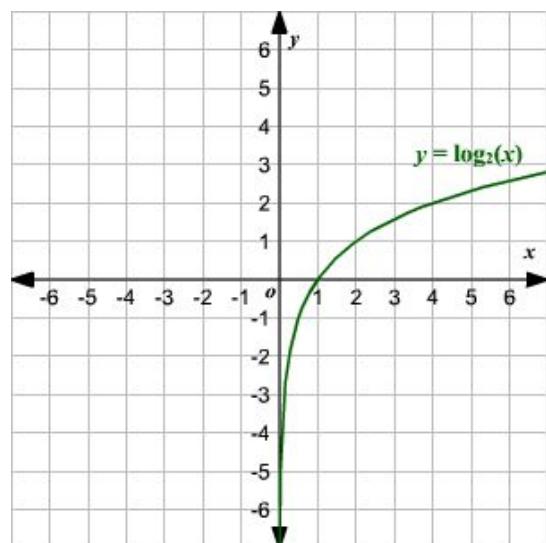
$$\sigma(x) = \frac{1}{1+e^{-x}}$$



# Dense vector representations : Skip-gram (Negative Sampling) (cont.)

- The objective function for skip-gram with negative sampling:

$$J_t(\theta) = \log \sigma(u_o^T v_c) + \sum_{i=1}^k \mathbb{E}_{j \sim P(w)} [\log \sigma(-u_j^T v_c)]$$



Context word

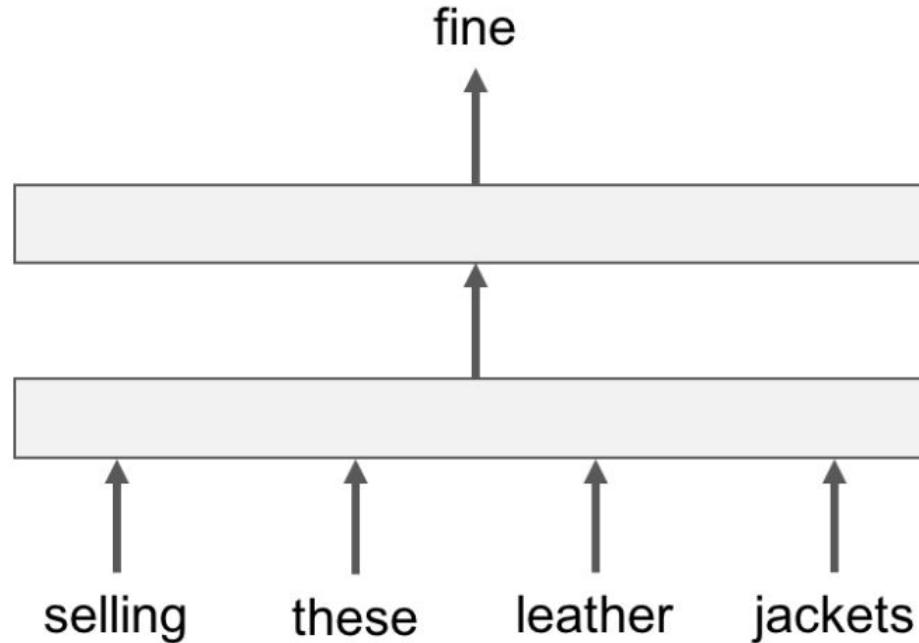
$\sigma$  = sigmoid

Negative samples

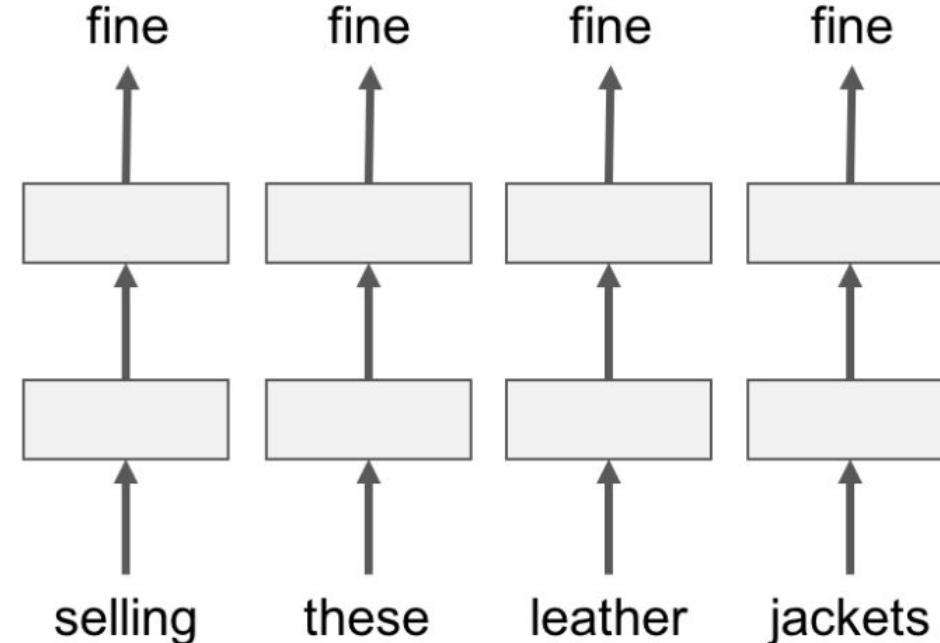


# Summary: CBOW vs Skip-gram (recap)

CBOW



SKIPGRAM



I am selling these **fine** leather jackets

# Pre-trained Word2Vec

- **1) Non-contextualized Word Embeddings (fixed vector)**
- GloVe (Stanford)
  - <https://nlp.stanford.edu/projects/glove/>
- fastText [Available in Thai language] (Facebook)
  - <https://github.com/facebookresearch/fastText>
- **2) Contextualized Word Embeddings**
- thai2fit
  - ULMFit
  - <https://github.com/cstorm125/thai2fit/>
- BERT [Available in Thai language] (Google)
  - <https://github.com/google-research/bert>



# Pre-trained Word2Vec: GloVe

- **GloVe is an unsupervised learning algorithm** for obtaining vector representations for words.
- Training is performed on aggregated global **word-word co-occurrence** statistics from a corpus, and the resulting representations showcase interesting linear substructures of the word vector space
- Pre-trained word vectors from **different domains** are available (Wikipedia+Gigaword, Common Crawl, Twitter)

## GloVe: Global Vectors for Word Representation

Jeffrey Pennington, Richard Socher, Christopher D. Manning

### Introduction

GloVe is an unsupervised learning algorithm for obtaining vector representations for words. Training is performed on aggregated global word-word co-occurrence statistics from a corpus, and the resulting representations showcase interesting linear substructures of the word vector space.

## GloVe: Global Vectors for Word Representation

**Jeffrey Pennington, Richard Socher, Christopher D. Manning**  
 Computer Science Department, Stanford University, Stanford, CA 94305  
 jpennin@stanford.edu, richard@socher.org, manning@stanford.edu

Reference: Pennington, Jeffrey, Richard Socher, and Christopher Manning. "Glove: Global vectors for word representation." Proceedings of the 2014 conference on empirical methods in natural language processing (EMNLP). 2014.



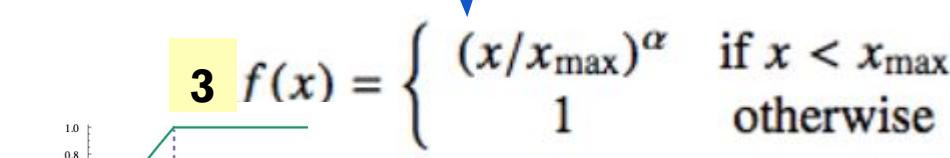
# Pre-trained Word2Vec: GloVe (cont.)

<https://www.aclweb.org/anthology/D14-1162>

- Main Ideas

- capture **meaning** in vector space
- Takes **advantage of co-occurrence statistics** instead of only local information

$$2 \quad F(w_i, w_j, \tilde{w}_k) = \frac{P_{ik}}{P_{jk}}$$



$$J = \sum_{i,j=1}^V f(X_{ij}) \left( w_i^T \tilde{w}_j + b_i + \tilde{b}_j - \log X_{ij} \right)^2$$

weighting function      prediction term

4) weight = average of all **k** words

1

i="ice", j="steam"

Probability and Ratio	$k = solid$	$k = gas$	$k = water$	$k = fashion$
$P(k ice)$	$1.9 \times 10^{-4}$	$6.6 \times 10^{-5}$	$3.0 \times 10^{-3}$	$1.7 \times 10^{-5}$
$P(k steam)$	$2.2 \times 10^{-5}$	$7.8 \times 10^{-4}$	$2.2 \times 10^{-3}$	$1.8 \times 10^{-5}$
$P(k ice)/P(k steam)$	8.9	$8.5 \times 10^{-2}$	1.36	0.96

word co-occurrence matrix

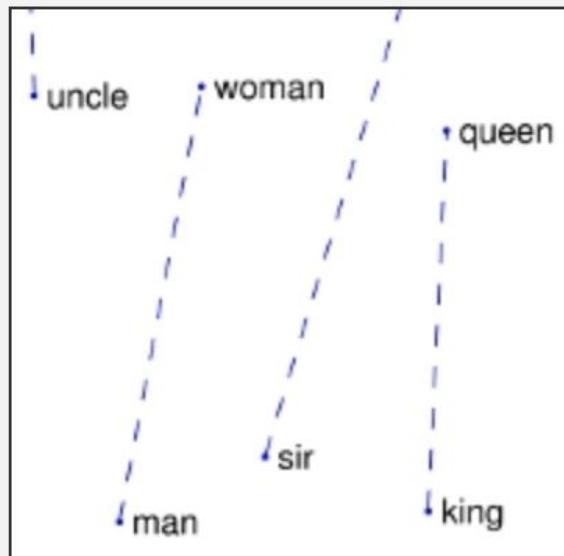
	As You Like It	Twelfth Night	Julius Caesar	Henry V
battle	1	1	8	15
soldier	2	2	12	36
fool	37	58	1	5
clown	5	117	0	0

Figure 15.1 The term-document matrix for four words in four Shakespeare plays. Each cell contains the number of times the (row) word occurs in the (column) document.

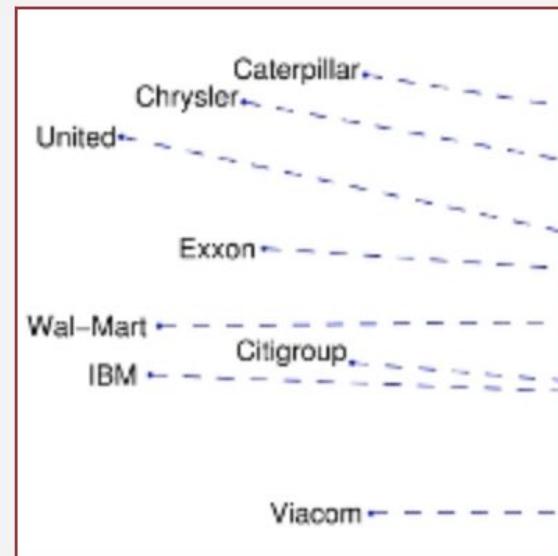


# Pre-trained Word2Vec: GloVe (cont.)

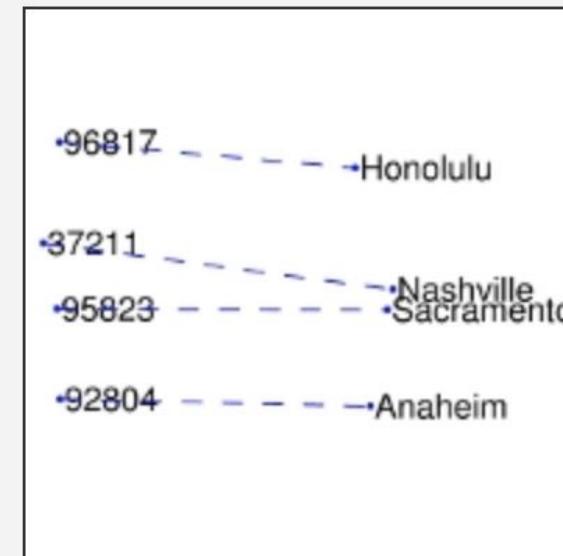
- Linear substructures



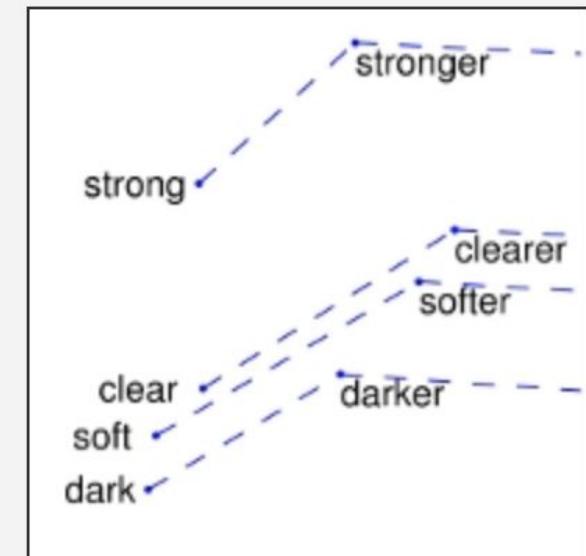
man - woman



company - ceo



city - zip code



comparative - superlative



# Pre-trained Word2Vec: fastText

*Skip-Gram (or CBOW) of “sum of subwords (char n-grams)”*

- fastText is a library for efficient learning of **word representations** and **sentence classification**.
- **Character n-grams** as additional features to capture some partial information about the local word order.
  - Good for **rare words**, since rare words can share these n-grams with common words
- Pre-trained word vectors for 294 languages (**including Thai**) trained on **Wikipedia**.

<where>. <wh, whe, her, ere, re>

Reference: Bojanowski, Piotr, et al. "Enriching word vectors with subword information." arXiv preprint arXiv:1607.04606 (2016).

Joulin, Armand, et al. "Bag of tricks for efficient text classification." arXiv preprint arXiv:1607.01759 (2016).

## Resources

English word vectors

Word vectors for 157 languages

Wiki word vectors

Aligned word vectors

Supervised models

Language identification

Datasets

# Word vectors for 157 languages

We distribute pre-trained word vectors for 157 languages, trained on *Common Crawl* and *Wikipedia* using fastText. These models were trained using CBOW with position-weights, in dimension 300, with character n-grams of length 5, a window of size 5 and 10 negatives. We also distribute three new word analogy datasets, for French, Hindi and Polish.

## Download directly with command line or from python

In order to download with command line or from python code, you must have installed the python package as described here.

Command line

Python

```
$ ./download_model.py en      # English  
Downloading https://dl.fbaipublicfiles.com/fasttext/vectors-crawl/cc.en.300.bin.gz  
(19.78%) [=====>] ]
```



# Pre-trained Word2Vec: Universal Language Model Fine-tuning (ULMFiT)

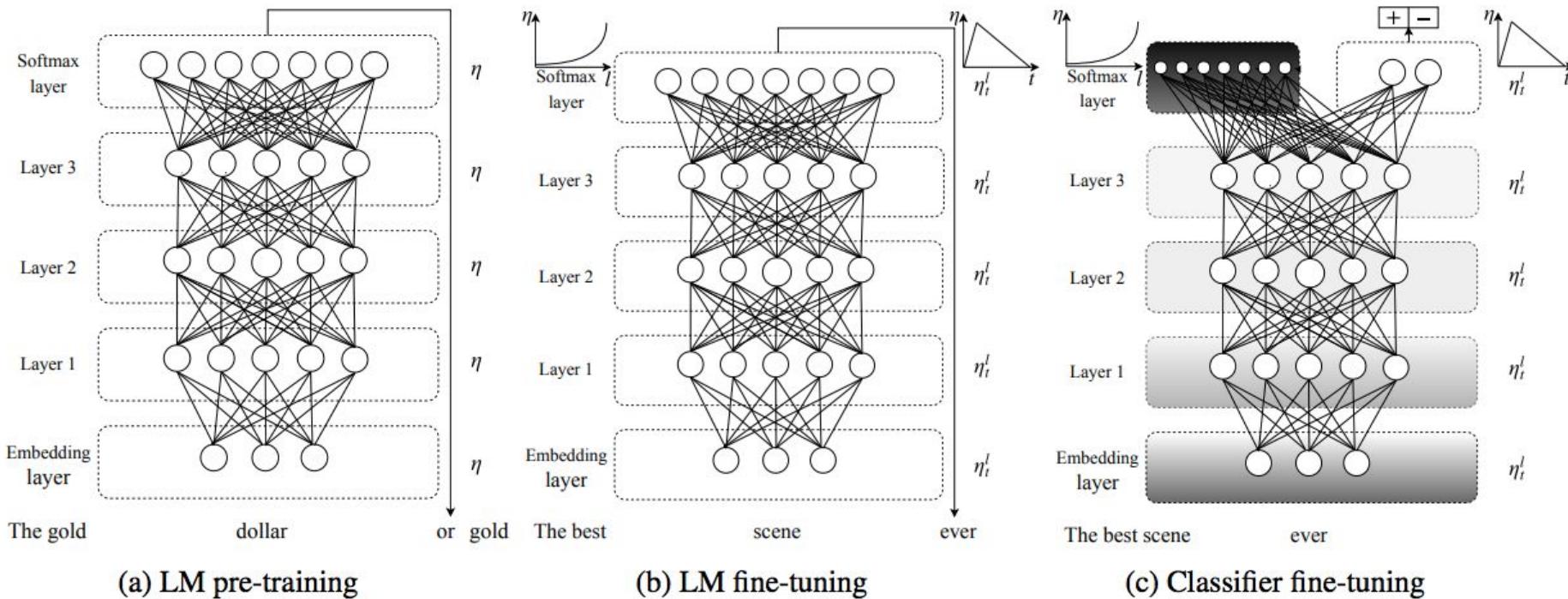


Figure 1: ULMFiT consists of three stages: a) The LM is trained on a general-domain corpus to capture general features of the language in different layers. b) The full LM is fine-tuned on target task data using discriminative fine-tuning ('*Discr*') and slanted triangular learning rates (STLR) to learn task-specific features. c) The classifier is fine-tuned on the target task using gradual unfreezing, '*Discr*', and STLR to preserve low-level representations and adapt high-level ones (shaded: unfreezing stages; black: frozen).



# Benefit of Pre-trained Word Embedding: Adaptation (1) on parsing (blue vs red)

- Weights from word embedding layer can be used as pre-trained weights in other NLP applications

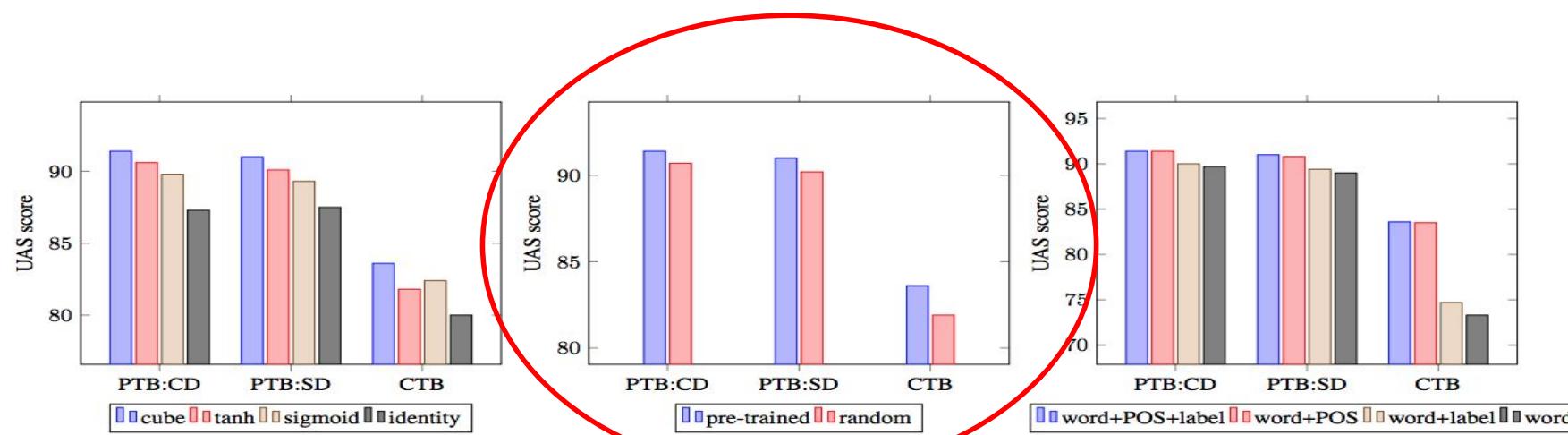


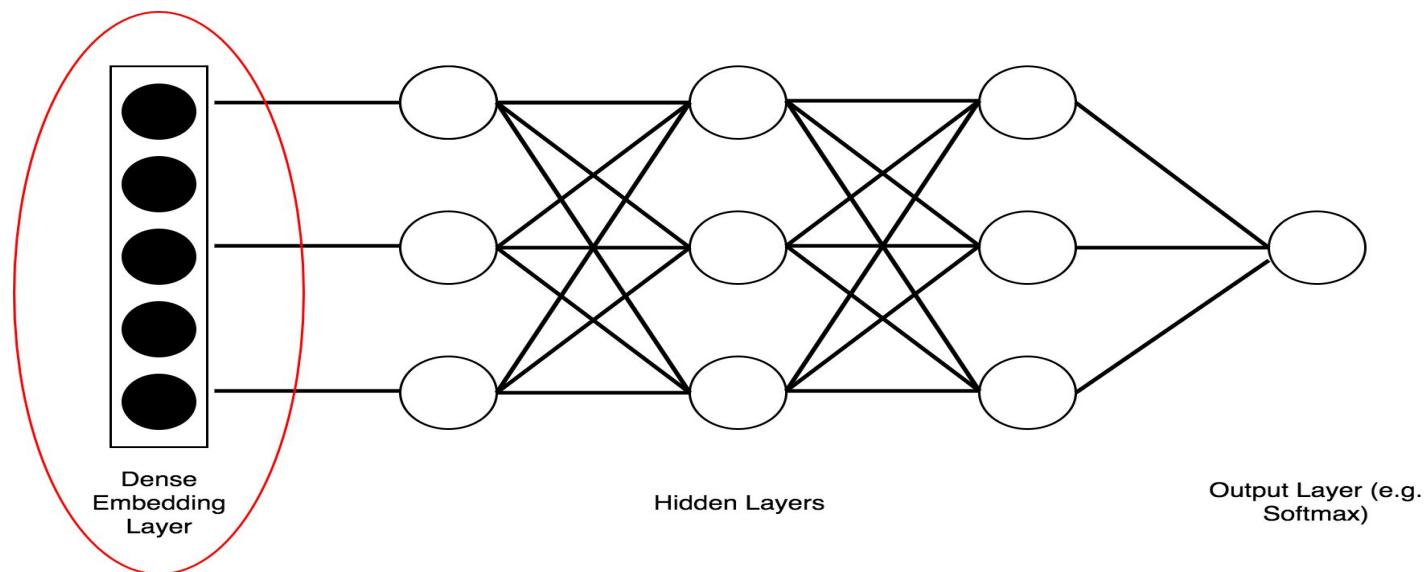
Figure 4: Effects of different parser components. Left: comparison of different activation functions. Middle: comparison of pre-trained word vectors and random initialization. Right: effects of POS and label embeddings.

Image reference: Chen, Danqi, and Christopher Manning. "A fast and accurate dependency parser using neural networks." Proceedings of the 2014 conference on empirical methods in natural language processing (EMNLP). 2014. APA



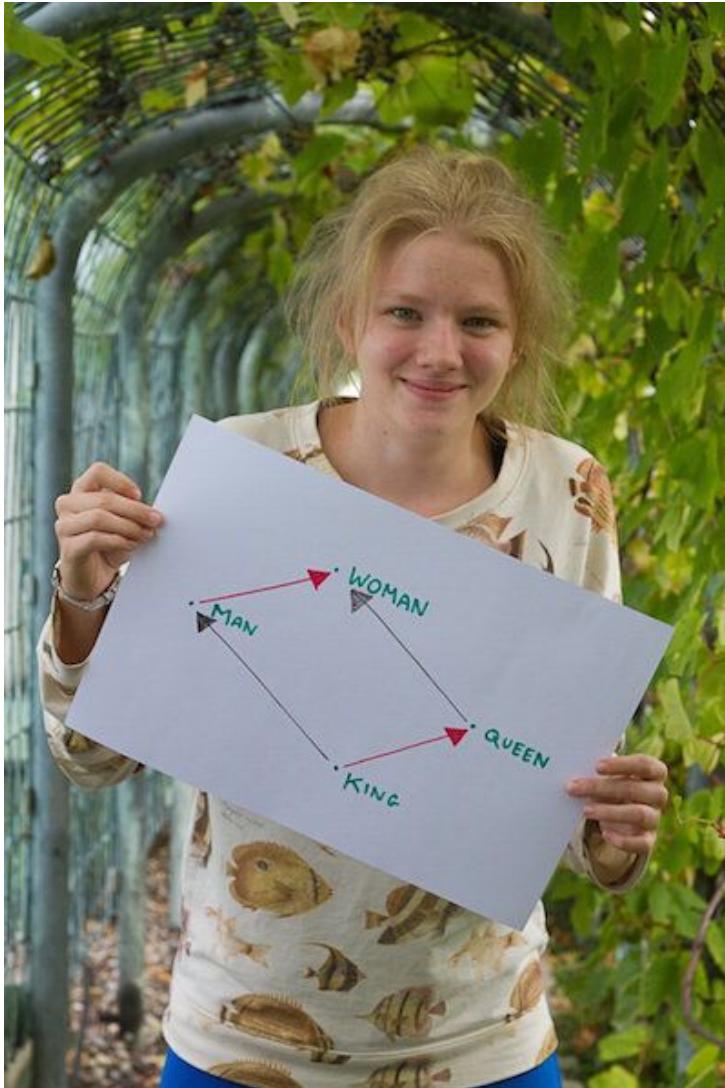
# Adaptation (2)

- Classification Model with pre-trained word embedding
- You already know how to create a classification model
  - In **homework 2**, word segmentation is a classification task
- In your homework ☺, you will be asked to create a classification model using pre-trained weights from the skip-gram model





# Learned Semantic-Syntactic Relationships



- Word Embedding can also capture semantic & syntactic relationships between words
- **king – queen = man – woman**
- We can ask “what is the word that is similar to **king** in the same sense as **woman** is similar to **man** ?”
- $X = \text{king} - \text{man} + \text{woman}$
- We then search for word that is closest to X (cosine distance)



# Compositionality

- Now, we know how to create a dense vector representation for a word
  - What about larger linguistic units? (e.g. phrase, sentence)
- We can combine smaller units into a larger unit

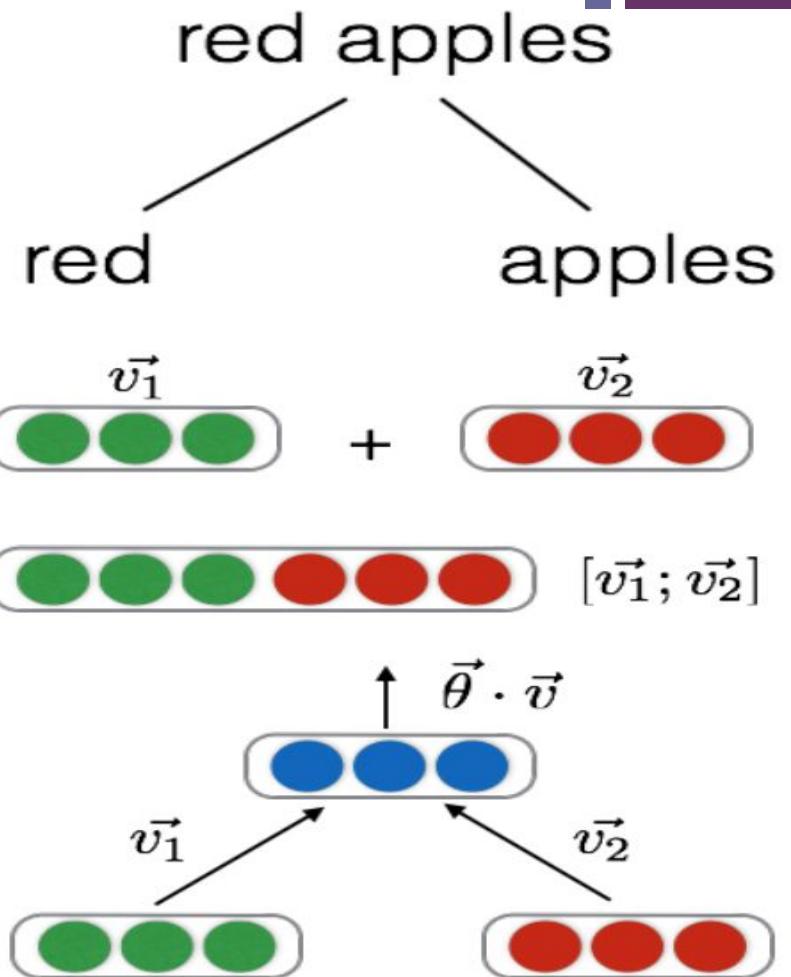


Image ref: Prof. Regina Barzilay , NLP@MIT



## Part 4: Word2Vec Evaluation

Extrinsic  
Intrinsic



# Evaluation for word vectors (1)

- Extrinsic Evaluation:
  - Use pre-trained word vectors to initialize or concatenate as extra features
  - Then **evaluate on real tasks (other tasks)** (e.g. Part-of-speech tagging, Named entity recognition, sentimental analysis, etc. )



# Evaluation for word vectors (2)

- Intrinsic Evaluation:
  - Evaluate on **specific subtasks** (e.g. Analogy completion)

City 1 : State containing City 1 :: City 2 : State containing City 2

Input	Result Produced
Chicago : Illinois : : Houston	Texas
Chicago : Illinois : : Philadelphia	Pennsylvania
Chicago : Illinois : : Phoenix	Arizona
Chicago : Illinois : : Dallas	Texas
Chicago : Illinois : : Jacksonville	Florida
Chicago : Illinois : : Indianapolis	Indiana
Chicago : Illinois : : Austin	Texas
Chicago : Illinois : : Detroit	Michigan
Chicago : Illinois : : Memphis	Tennessee
Chicago : Illinois : : Boston	Massachusetts



# Evaluation for word vectors (3)

- Intrinsic Evaluation
- Tasks:
  - **Relatedness:** Correlation between word vectors similarity and **human judgment** of word similarity
  - **Analogy:** The goal is to find a term x for a given term y so that **x : y** best resembles a sample relationship **a : b**
  - **Categorization:** Word vectors are **clustered**, then measure the purity of cluster based on the labeled dataset
  - **Selectional Preference (word function):** The goal is to determine how typical a noun is for a verb either as a **subject** or as an **object** (e.g., people eat, but we rarely eat people)



# Summary

- One-hot vectors do not represent similarity between words
- Distributional representations can capture similarity between words
- Word2Vec is faster than SVD; pre-trained Word2Vec parameters are available online.
- Two main Word2Vec models:
  - Skip-gram
  - CBOW
- Efficient training methods
  - Hierarchical Softmax
  - Negative Sampling
- Adaptation
- Learned Semantic-Syntactic Relationships
- Compositionality
- Word2Vec evaluation: extrinsic evaluation and intrinsic evaluation



## Part 5: Advanced Topics

Doc2Vec

Limitations of word embeddings and possible improvements



# Doc2Vec (Le and Mikolov 2014)

- Document representation
    - also work with variable-length pieces of texts, such as sentences, paragraphs, documents, etc.
- 

## Distributed Representations of Sentences and Documents

---

Quoc Le

Tomas Mikolov

Google Inc, 1600 Amphitheatre Parkway, Mountain View, CA 94043

QVL@GOOGLE.COM

TMIKOLOV@GOOGLE.COM



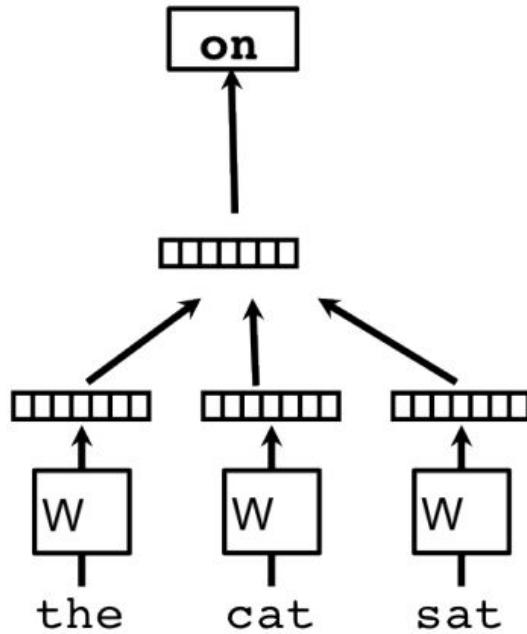
# Doc2Vec (cont.)

A framework for learning word vector

Classifier

Average/Concatenate

Word Matrix

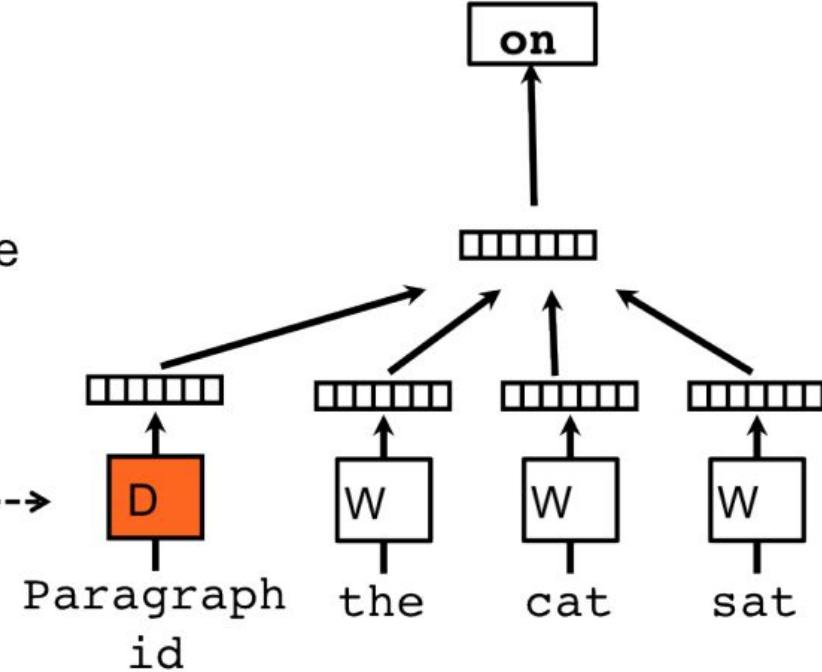


A framework for learning document vector

Classifier

Average/Concatenate

Paragraph Matrix----->

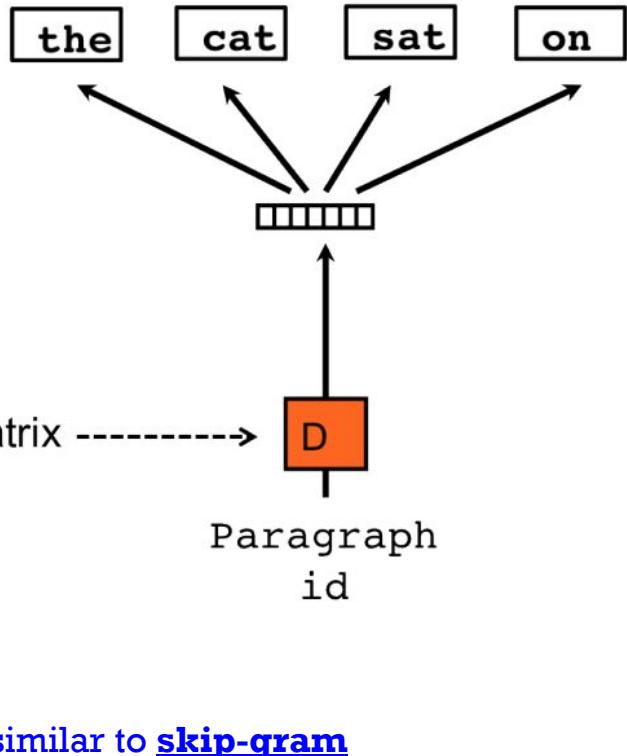


similar to [CBOW](#)



## Doc2Vec (cont.)

Classifier



Model	Error rate (Positive/ Negative)	Error rate (Fine- grained)
Naïve Bayes (Socher et al., 2013b)	18.2 %	59.0%
SVMs (Socher et al., 2013b)	20.6%	59.3%
Bigram Naïve Bayes (Socher et al., 2013b)	16.9%	58.1%
Word Vector Averaging (Socher et al., 2013b)	19.9%	67.3%
Recursive Neural Network (Socher et al., 2013b)	17.6%	56.8%
Matrix Vector-RNN (Socher et al., 2013b)	17.1%	55.6%
Recursive Neural Tensor Network (Socher et al., 2013b)	14.6%	54.3%
Paragraph Vector	<b>12.2 %</b>	<b>51.3%</b>

# Unknown words

- Why do we need a UNK token?
  - Not all words are available in training data
  - Larger vocab size = more memory/computation time
- Common ways:
  - Frequency threshold
    - if word count  $\leq 1$ , then UNK
  - Rank threshold: only include top 50,000 words, the rest are UNK



# Limitations of word embeddings

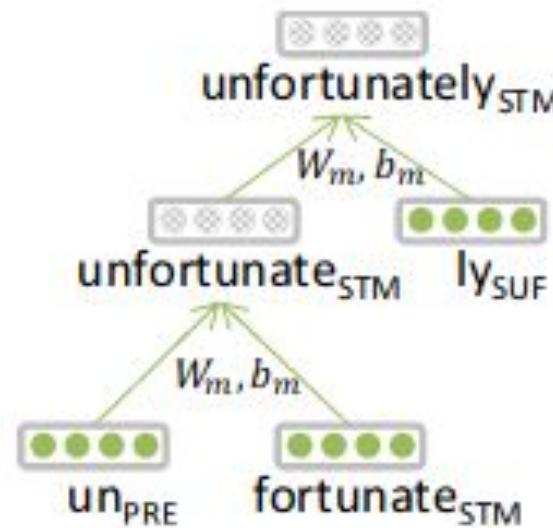
- Problem1) Sensitive to **subtle**/superficial morphological differences → **Solution: Subwords**
  - student vs students
- Problem2) Only has one representation for all **unknown** words → **Solution: Subwords**
- Problem3) Insensitive to **context** → **Solution: Contextualized word representations**
  - baseball bat  vs bat can fly 
- Problem4) Interpretability → **Solution: Sparse Embeddings**
  - what does each dimension of a word embeddings represent?
- Problem5) Bias → **Solution: debias algorithm**
  - racial discrimination and gender bias



# Solutions 1,2: Subwords Embeddings

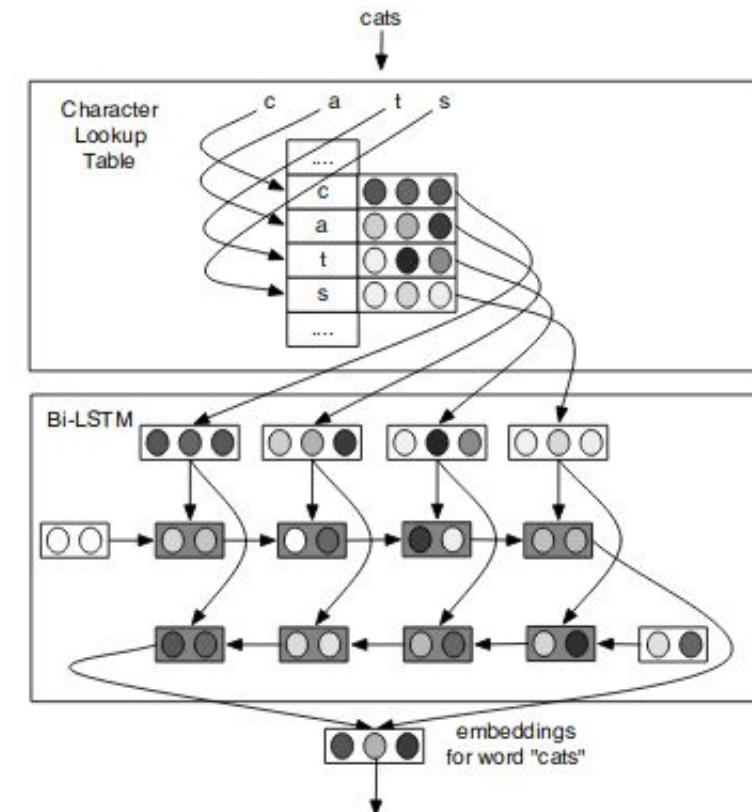
- Morpheme-based ([Luong et al. 2013](#))

recursive neural net!



- Character-based ([Ling et al. 2015](#))

- compositional character to word model





# Solutions 1,2: Subwords Embeddings (cont.)

- Character n-grams ([Wieting et al. 2016](#))
- add vectors of character n-grams together followed by an elementwise nonlinearity
- Best version uses <2,3,4,5,6>-grams

sweet → <sw, swe, we, wee, ee, eet, et >

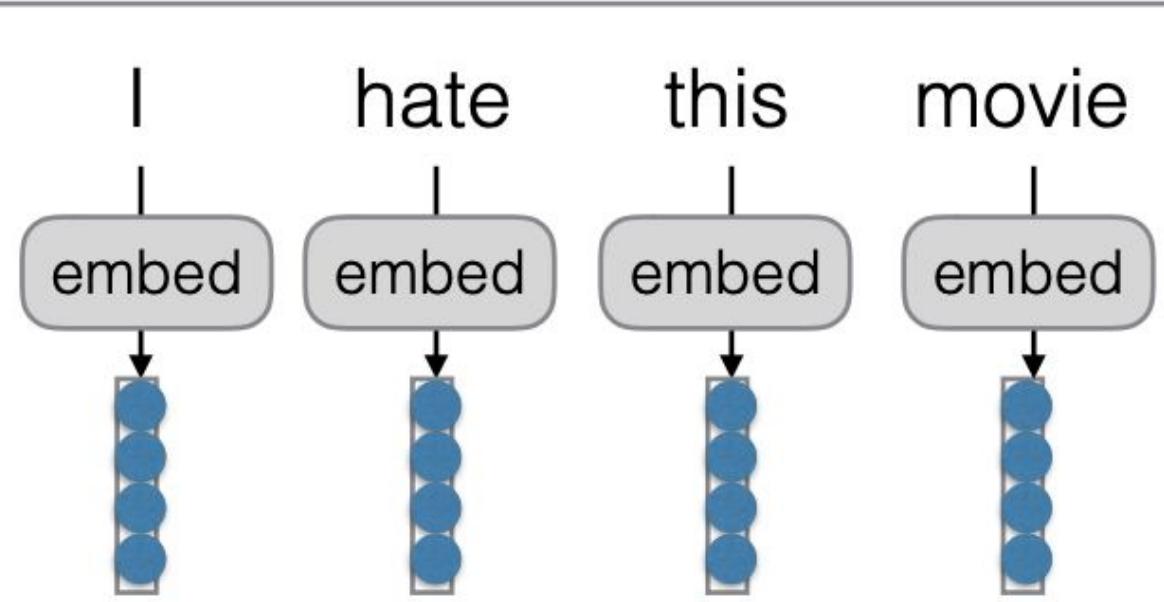
$$g_{\text{CHAR}}(x) = h \left( \mathbf{b} + \sum_{i=1}^{m+1} \sum_{j=1+i-k}^i \mathbb{I}[x_j^i \in V] W^{x_j^i} \right)$$

- Byte-Pair Encoding (BPE)
  - aaabdaaaabac
  - **ZabdZabac**
    - **Z=aa**
  - **ZYdZYac**
    - **Y=ab**
    - Z=aa
  - **XdXac**
    - **X=ZY**
    - Y=ab
    - Z=aa
- reference: [https://en.wikipedia.org/wiki/Byte\\_pair\\_encoding](https://en.wikipedia.org/wiki/Byte_pair_encoding)

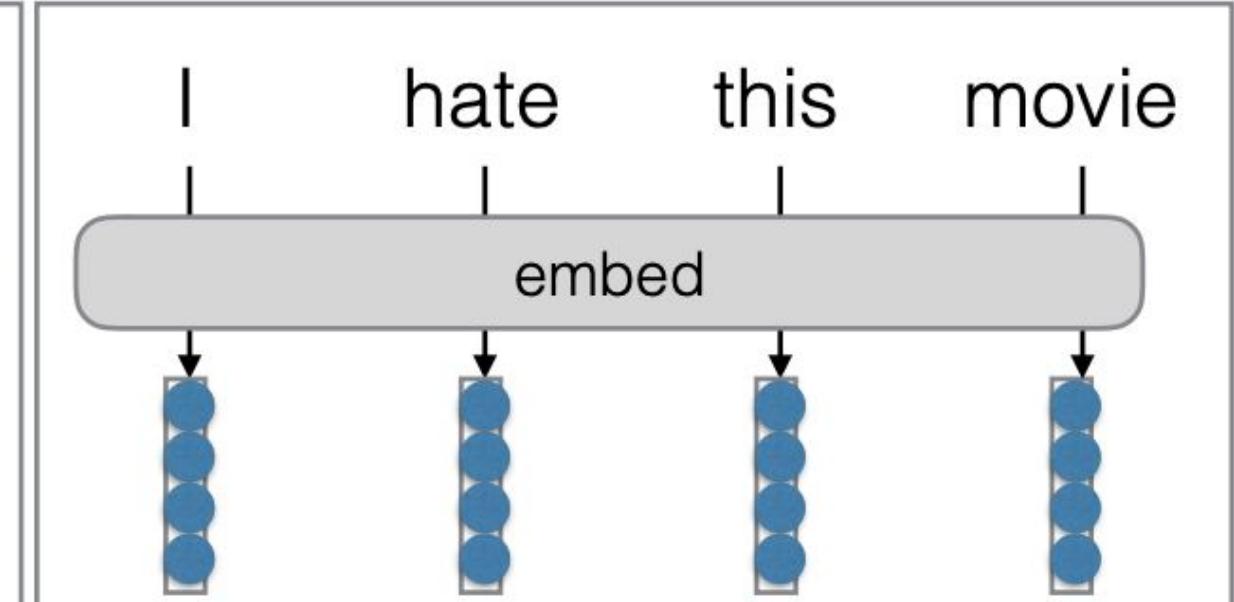


# Solution3: Contextualized word representation

## Non-contextualized Representations



## Contextualized Representations



# Solution3: Contextualized word representation (cont.)

- The representation for each word depends on the entire context in which it is used: (these are state-of-the-art models)
  - ELMo[pretrained weights and code are available]
  - BERT [pretrained weights and code are available]

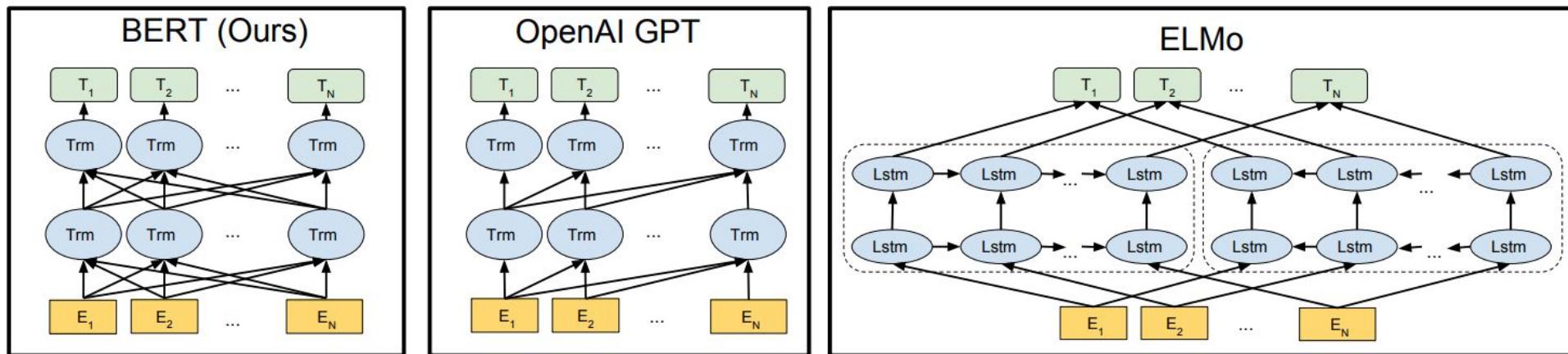


Figure 1: Differences in pre-training model architectures. BERT uses a bidirectional Transformer. OpenAI GPT uses a left-to-right Transformer. ELMo uses the concatenation of independently trained left-to-right and right-to-left LSTM to generate features for downstream tasks. Among three, only BERT representations are jointly conditioned on both left and right context in all layers.



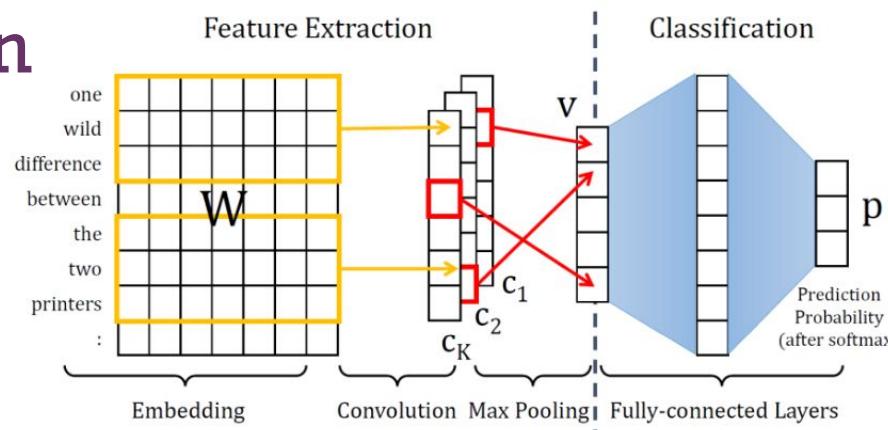
## Solution4: Sparse Embeddings (Murphy et al. 2012) [interpretation issue]

- Increase the **interpretability of each dimension** of a word embedding
  - constrained matrix factorization technique
    - Non-Negative Sparse Embedding (NNSE)
  - add **sparsity** constraint
    - most of the dimensions are zeros
    - therefore **increase the information content of non-zero dimensions** for each word

Model	Top 5 Words (per dimension)
$\text{SVD}_{300}$	well, long, if, year, watch plan, engine, e, rock, very get, no, features, music, via features, by, links, free, down works, sound, video, building, section
$\text{NNSE}_{1000}$	inhibitor, inhibitors, antagonists, receptors, inhibition bristol, thames, southampton, brighton, poole delhi, india, bombay, chennai, madras pundits, forecasters, proponents, commentators, observers nosy, averse, leery, unsympathetic, snotty

# Neural based interpretation

## Gradient Analysis



- Sensitivity Analysis (Arras et al., 2016)
  - The effect of  $w_i$  towards the prediction of class  $j$  ( $E_{j,w_i}$ )
 
$$E_{j,w_i} = \sum_d \left( \frac{\partial FC(v)_j}{\partial w_{i,d}} \right)^2$$
- Grad-CAM-Text (Lertvittayakumjorn & Toni, 2019)
  - $E_{j,N(k)}$  : the effect of an **n-gram** selected by the  $k^{th}$  filter towards the prediction of class  $j$ :  $E_{j,N(k)} = \left| \max\left(\frac{\partial FC(v)_j}{\partial v_k}, 0\right) \right| \times v_k$
  - $E_{j,w_i} = \sum_k (\mathbb{I}[w_i \in N(k)] \times E_{j,N(k)})$



# Solution5: Debiasing word embeddings (Bolukbasi et al. 2016) [gender bias issue]

- What if we want to use ML model to make a very important decision?
- Word embeddings reflect undesirable biases of text in the training corpus
  - Man:Woman as King:Queen (**we want this**) ✓
  - Man:Programmer as Woman:Homemaker (**we don't want this**) ✗
  - He:She as Professor:Associate\_Professor (**we don't want this**) ✗
- **Transform the space** while preserving useful relationships
- Steps:
  - 1. Identify bias direction
  - 2. Neutralize: For every word that is not definitional, project to get rid of biases
  - 3. Equalize pairs