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Human Language Technologies

Session 12: Vector semantics, word2vec

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About Jatin Khilnani (TA)

- 2nd year Computer Science PhD student
- Research interests
 - Machine Learning
 - Natural Language Processing
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Assessments

- Project proposal is due **this Fri Feb 27**
- Homework 2 on text classification has been released, is due **Mar 17**
 - Implement a logistic regression classifier to detect if someone is lying in the ‘Diplomacy’ game

Structure of this course

MODULE 1

Prerequisite skills for NLP

text normalization, linear alg., prob., machine learning

Approaches

How text is represented

NLP tasks

MODULE 2

statistical machine learning

n-grams

language modeling
text classification

MODULE 3

neural networks

static word vectors

text classification

MODULE 4

language modeling
text classification
sentiment labeling

MODULE 5

NLP applications and ethics

Overview: vector semantics, static word embeddings

- Coding activity: clickbait classification evaluation and error analysis
- Vector semantics
- Distributional semantics
- Types of word vectors
- Word2vec
- Bias in word vectors
- Coding activity: explore word vectors

Coding activity: clickbait classifier evaluation and error analysis

Notebook: clickbait classifier evaluation and error analysis

1. Go to this [nbgitpuller link](#) (also available on course website)
2. Start a server with **TEACH – 6 CPUs, 48 GB**
3. Load custom environment at `/ix1/cs1671-2026s/class_env`
4. Open `session11_clickbait_error_analysis.ipynb`

Vector semantics

Semantics: the study of meaning

Word representations in NLP draw on 2 areas of semantics

- a. Vector semantics
- b. Distributional semantics

Vector semantics

Modeling semantics as points in vector space

- Words or other text segments are represented by vectors
- Multiple dimensions
- Nearer = more similar words

Term-document matrix: word vectors

Two words are similar if their vectors are similar.



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	6	117	0	0

Pairs of similar words?

Similarity and relatedness

- Synonyms: big/large, couch/sofa, automobile/car
- Similar: sharing some element of meaning
 - coffee/tea, car/bicycle, cow/horse
- Related: by a semantic field
 - coffee/cup, scalpel/surgeon



Distributional semantics

Distributional semantics

"The meaning of a word is its use in the language" [Wittgenstein 1953]



"You shall know a word by the company it keeps" [Firth 1957]



"If A and B have almost identical environments we say that they are synonyms" [Harris 1954]



Distributional semantics

Define the meaning of a word by its **distribution in language use**: its neighboring words or grammatical environments.

You Learn Words by Using Distributional Similarity



Consider

- A bottle of **pocarisweat** is on the table.
- Everybody likes **pocarisweat**.
- **Pocarisweat** makes you feel refreshed.
- They make **pocarisweat** out of ginger.

What does **pocarisweat** mean?

You Know Pocarisweat by the Company It Keeps



From context words humans can guess *pocarisweat* means a beverage like **coke**.

How do you know?

- Other words can occur in the same context
- Those other words are often for beverages (that you drink cold)
- You assume that *pocarisweat* is probably similar

So the intuition is that **two words are similar if they have similar word contexts.**

Sample Contexts of ± 7 Words

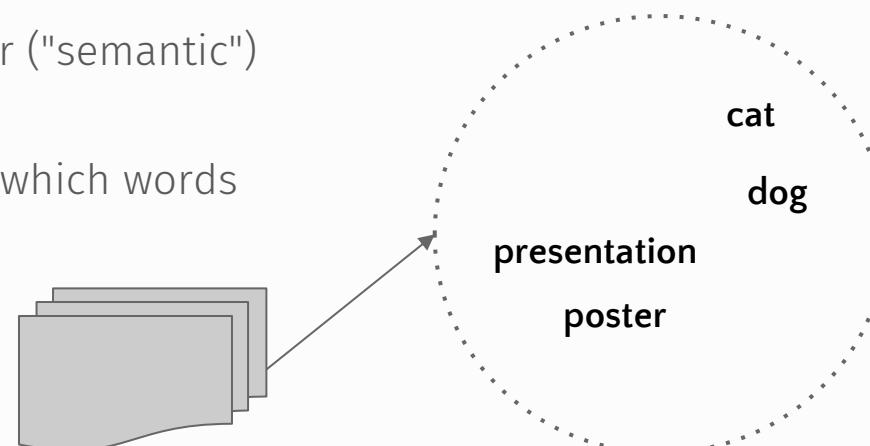
sugar, a sliced lemon, a tablespoonful of their enjoyment. Cautiously she sampled her first well suited to programming on the digital for the purpose of gathering data and **apricot** **pineapple** **computer**. In finding the optimal R-stage policy from necessary for the study authorized in the preserve or jam, a pinch each of, and another fruit whose taste she likened

	aardvark	computer	data	pinch	result	sugar ...
:						
<i>apricot</i>	0	0	0	1	0	1
<i>pineapple</i>	0	0	0	1	0	1
<i>digital</i>	0	2	1	0	1	0
<i>information</i>	0	1	6	0	4	0
:						

Types of word vectors

Shared Intuition: Words are Vectors of Numbers Representing Meaning

- Model the meaning of a word by “embedding” it in a vector space.
- The meaning of a word is a vector of numbers:
 - Vector models are also called **embeddings**
 - Often, the word *embedding* is reserved for *dense* vector representations
- In contrast, word meaning is represented in many (early) NLP applications by a vocabulary index (“word number 545”; compare to **one-hot representations**)
- Similar words are nearby in vector (“semantic”) space
- Build “semantic space” by seeing which words are nearby in text



There are Two Kinds of Vector Models

- **Sparse embeddings** (vectors from term-document matrix)
 - long (length of 20,000 to 50,000)
 - sparse: most elements are 0
- **Dense embeddings** (Word2vec)
 - short (length of 50-1000)
 - dense (most elements are non-zero)

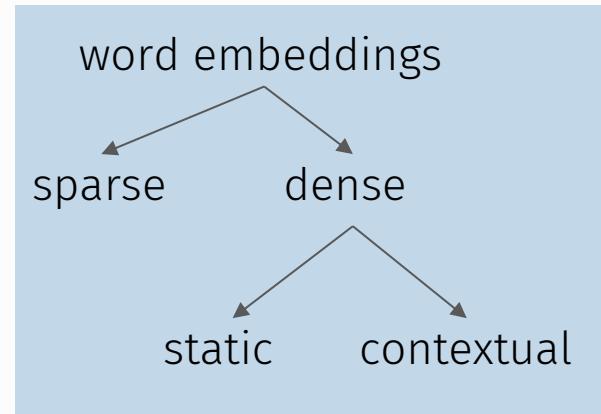


Dense Vectors Have Three Advantages over Sparse Vectors

1. Short vectors may be **easier to use as features** in machine learning (less weights to tune).
2. Dense vectors may **generalize better** than storing explicit counts.
3. They may do **better at capturing synonymy**:
 - *car* and *automobile* are synonyms
 - But, in sparse vectors, they are represented as distinct dimensions
 - This fails to capture similarity between a word with *car* as a **neighbor** and a word with *automobile* as a **neighbor**

Methods for learning short, dense word embeddings

- Static, neural embeddings
 - Fixed embeddings for word types
 - Word2Vec, GloVe
- Contextual embeddings
 - Embeddings for words vary by context
 - ELMo, BERT, LLMs



Word2vec

Word2vec [Mikolov et al. 2013]

- Instead of counting words, train a classifier on a binary prediction task
 - Is w_1 likely to show up near w_2 ?

Word2vec [Mikolov et al. 2013]

- Instead of counting words, train a classifier on a binary prediction task
 - Is w_1 likely to show up near *apricot?*



Word2vec [Mikolov et al. 2013]

- Instead of counting words, train a classifier on a binary prediction task
 - Is w_1 likely to show up near *apricot?*
- Take the learned classifier weights as the word embeddings



Word2vec [Mikolov et al. 2013]

- Instead of counting words, train a classifier on a binary prediction task
 - Is w_1 likely to show up near *apricot?*
- Take the learned classifier weights as the word embeddings
- Training techniques: skip-gram and CBOW



Word2vec: training supervision

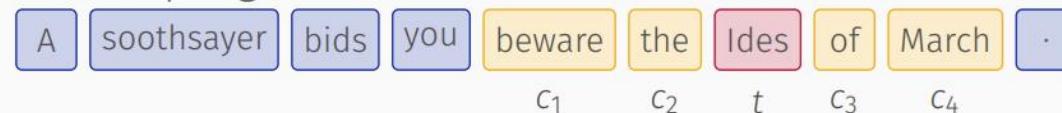
- **Self-supervision** [Bengio et al. 2003, Collobert et al. 2011]
- Use naturally occurring text as labels
- A word c that occurs near *apricot* in the corpus counts as the gold "correct answer" for supervised learning

Word2vec training overview

1. Positive examples: the target word w and a neighboring context word c_{pos}
2. Negative examples: Randomly sample other words c_{neg} in the lexicon to pair with w
3. Use logistic regression to train a classifier to distinguish those two cases
4. Use the learned weights (W, C) as the word embeddings

Training for Embeddings

- We do not know what W and C are. So we learn them through an iterative process.
- We use a large corpus as a training data
- We also randomly sample the corpus to find words that are NOT in the context—negative sampling.



Positive Examples		Negative Examples			
t	c	t	c	t	c
ides	beware	ides	aardvark	ides	twelve
ides	of	ides	puddle	ides	hello
ides	March	ides	where	ides	dear
ides	the	ides	coaxial	ides	forever

Word2vec: learning embeddings

- Start with randomly initialized context C and target word W matrices
- Go through the positive and negative training pairs, adjusting word vectors such that we:
 - Maximize the similarity of the target word, context word pairs (w, c_{pos}) drawn from the positive data
 - Minimize the similarity of the (w, c_{neg}) pairs drawn from the negative data.

Skip-gram classifier

Classifier input pairs:

(target word w , context word c)

Classifier output: probabilities that w occurs with c

$$P(+|w, c)$$

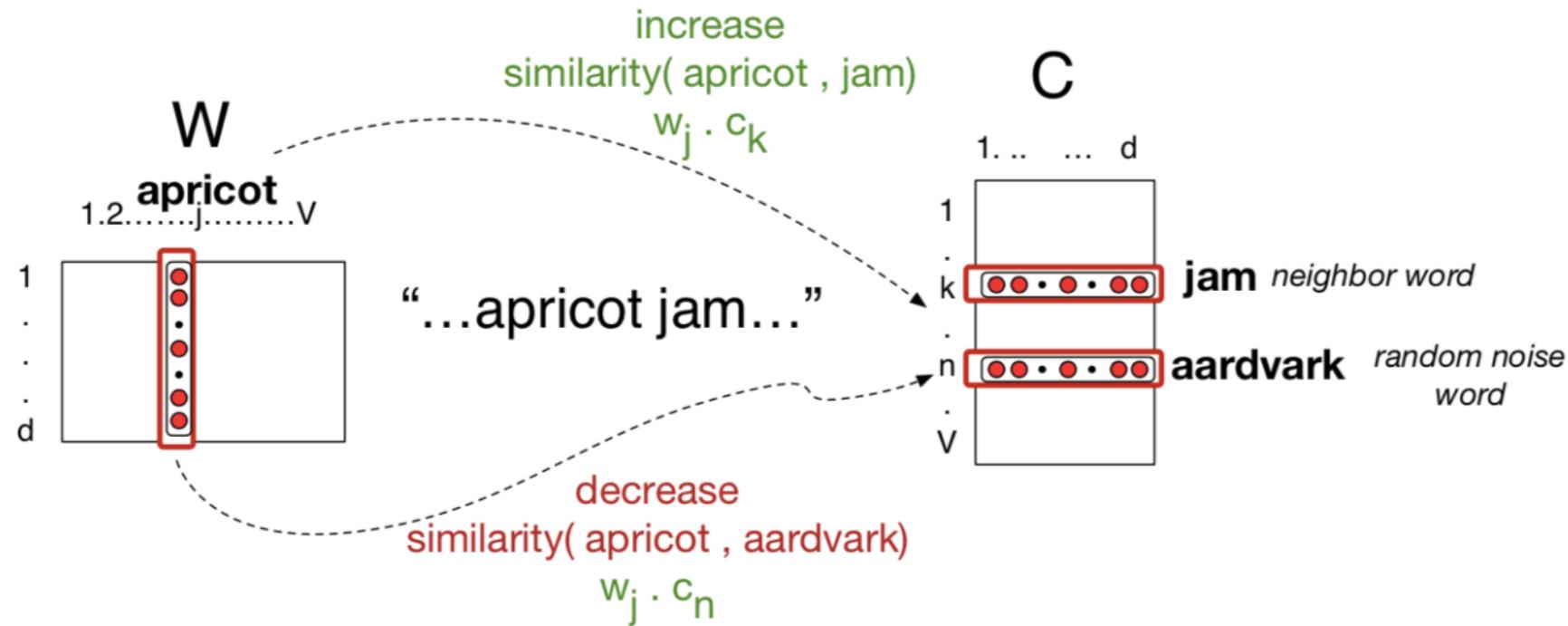
$$P(-|w, c) = 1 - P(+|w, c)$$

Skip-gram classifier: calculating probabilities

- From input vectors, need to compare for similarity
- Start with dot product: $\text{sim}(w, c) \approx w \cdot c$
- To turn this into a probability, use the sigmoid function from logistic regression:

$$P(+|w, c) = \sigma(c \cdot w) = \frac{1}{1 + \exp(-c \cdot w)}$$

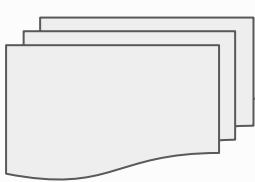
Training for Embeddings



Reminder: one step of gradient descent

- Direction: We move in the reverse direction from the gradient of the loss function
- Magnitude: we move the value of this gradient $d/dw L(P(+|w,c) + P(-|w,c))$ weighted by a learning rate η
- Higher learning rate means move w faster

Summary: How to learn word2vec embeddings



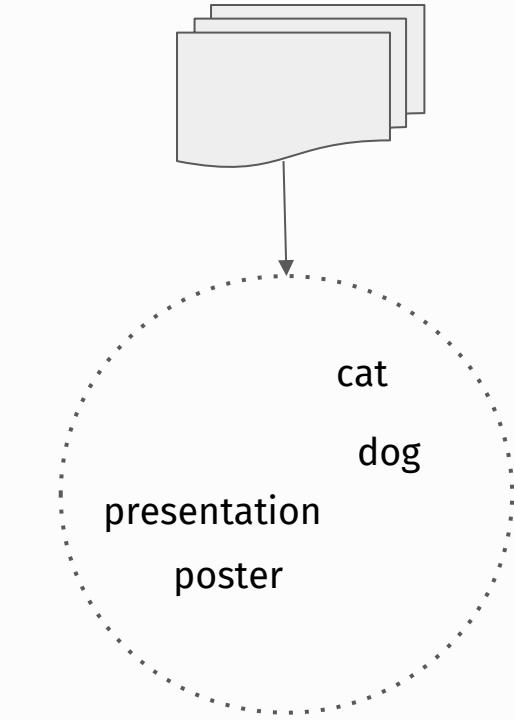
cat	[0.31, 0.24, 0.07, 0.65 ...]
dog	[0.37, 0.29, 0.06, 0.63 ...]
presentation	[0.65, 0.93, 0.16, 0.78 ...]
poster	[0.57, 0.82, 0.21, 0.73 ...]

Summary: How to learn word2vec embeddings

1. Start with randomly initialized word embeddings
2. From a corpus, extract pairs of words that co-occur (positive)
3. Extract pairs of words that don't co-occur (negative)
4. Train a classifier to distinguish between positive and negative examples by slowly adjusting all the embeddings to improve the classifier performance
5. Keep the weights as our word embeddings

Final embeddings

- Can add representations for a word in W and in C together for final word vector for w_i
- Can just keep W and throw away C
- Can find "nearest neighbors" of certain words with cosine similarity in embedding space



There are Tools and Resources Available for Training and Using Embeddings

- Pretrained embeddings
 - Skip-gram
 - CBOW
 - fastText
 - GloVe
- Training your own embeddings
 - You can easily train skip-gram, CBOW, and fastText embeddings with `gensim`
 - Straightforward Python interface

Embeddings reflect cultural biases [Bolukbasi et al. 2016]

- Paris : France :: Tokyo : *Japan*
- Sexist occupational stereotypes
 - father : doctor :: mother : *nurse*
 - man : computer programmer :: woman : *homemaker*
- Would be problematic to use embeddings in hiring searches for programmers

Conclusion: vector semantics, static word embeddings

- NLP typically represents words as vectors in spaces where distance \approx semantic similarity
- Word2vec learns static embeddings (vectors) for words by predicting which words occur together in training data
- These embeddings are effective in downstream NLP tasks, but also reflect social biases of training data text

Coding activity

Notebook: examine word2vec embeddings

1. Go to this [nbgitpuller link](#) (also available on course website)
2. Start a server with **TEACH – 6 CPUs, 48 GB**
3. Load custom environment at `/ix1/cs1671-2026s/class_env`
4. Open `session12_word2vec.ipynb`