

Dan Jurafsky and James Martin  
Speech and Language Processing

Chapter 6:  
Vector Semantics, Part II



Tf-idf and PPMI are  
sparse representations

**tf-idf and PPMI vectors are**

- **long** (length  $|V| = 20,000$  to  $50,000$ )
- **sparse** (most elements are zero)



# Alternative: dense vectors

vectors which are

- **short** (length 50-1000)
- **dense** (most elements are non-zero)

# Sparse versus dense vectors

## Why dense vectors?

- Short vectors may be easier to use as **features** in machine learning (less weights to tune)
- Dense vectors may **generalize** better than storing explicit counts
- They may do better at capturing synonymy:
  - *car* and *automobile* are synonyms; but are distinct dimensions
    - a word with *car* as a neighbor and a word with *automobile* as a neighbor should be similar, but aren't
- **In practice, they work better**

# Dense embeddings you can download!



**Word2vec** (Mikolov et al.)

<https://code.google.com/archive/p/word2vec/>

**Fasttext** <http://www.fasttext.cc/>

**Glove** (Pennington, Socher, Manning)

<http://nlp.stanford.edu/projects/glove/>





Word2vec

Popular embedding method

Very fast to train

Code available on the web

Idea: **predict** rather than **count**

# Word2vec

- Instead of **counting** how often each word  $w$  occurs near "*apricot*"
- Train a classifier on a binary **prediction** task:
  - Is  $w$  likely to show up near "*apricot*"?
- We don't actually care about this task
  - But we'll take the learned classifier weights as the word embeddings

# Brilliant insight: Use running text as implicitly supervised training data!

- A word  $s$  near *apricot*
  - Acts as gold ‘correct answer’ to the question
  - “Is word  $w$  likely to show up near *apricot*?”
- No need for hand-labeled supervision
- The idea comes from **neural language modeling**
  - Bengio et al. (2003)
  - Collobert et al. (2011)



# Word2Vec: Skip-Gram Task

Word2vec provides a variety of options. Let's do

- "skip-gram with negative sampling" (SGNS)

# Skip-gram algorithm

1. Treat the target word and a neighboring context word as positive examples.
2. Randomly sample other words in the lexicon to get negative samples
3. Use logistic regression to train a classifier to distinguish those two cases
4. Use the weights as the embeddings

# Skip-Gram Training Data

Training sentence:

... lemon, a **tablespoon of apricot jam** a pinch ...

c1            c2 target c3    c4

Assume context words are those in +/- 2  
word window

# Skip-Gram Goal

Given a tuple  $(t,c)$  = target, context

- (*apricot*, *jam*)
- (*apricot*, *aardvark*)

Return probability that  $c$  is a real context word:

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

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

# How to compute $p(+ | t, c)$ ?

Intuition:

- Words are likely to appear near similar words
- Model similarity with dot-product!
- $\text{Similarity}(t, c) \propto t \cdot c$

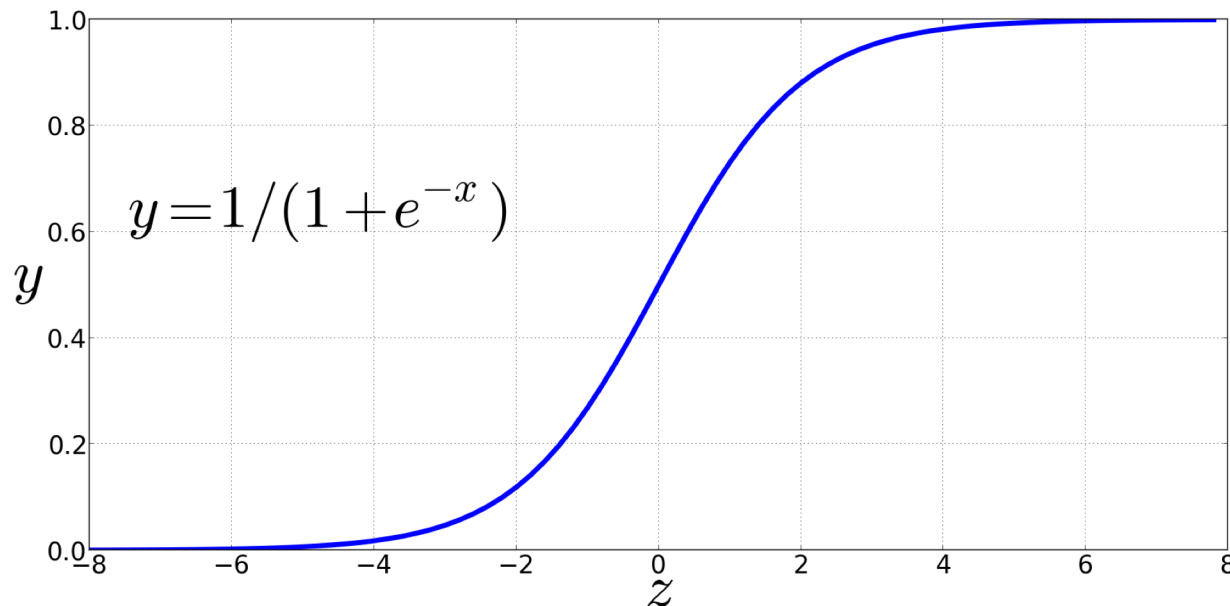
*Problem:*

- *Dot product is not a probability!*
  - *(Neither is cosine)*

# Turning dot product into a probability

The sigmoid lies between 0 and 1:

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



# Turning dot product into a probability

$$P(+|t, c) = \frac{1}{1 + e^{-t \cdot c}}$$

$$\begin{aligned} P(-|t, c) &= 1 - P(+|t, c) \\ &= \frac{e^{-t \cdot c}}{1 + e^{-t \cdot c}} \end{aligned}$$

For all the context words:

Assume all context words are independent

$$P(+|t, c_{1:k}) = \prod_{i=1}^{\kappa} \frac{1}{1 + e^{-t \cdot c_i}}$$

$$\log P(+|t, c_{1:k}) = \sum_{i=1}^k \log \frac{1}{1 + e^{-t \cdot c_i}}$$



# Skip-Gram Training Data

Training sentence:

... lemon, a **tablespoon of apricot jam** a pinch ...

c1                  c2    t                  c3    c4

Training data: input/output pairs centering  
on *apricot*

Assume a +/- 2 word window

# Skip-Gram Training

Training sentence:

... lemon, a **tablespoon of apricot jam** a pinch ...

c1

c2

t

c3

c4

**positive examples +**

t

c

---

apricot    tablespoon

apricot    of

apricot    preserves

apricot    or

- For each positive example, we'll create  $k$  negative examples.
- Using *noise* words
- Any random word that isn't  $t$

# Skip-Gram Training

Training sentence:

... lemon, a **tablespoon of apricot jam** a pinch ...

c1                    c2   t                    c3   c4

**positive examples +**

t                    c

---

apricot    tablespoon

apricot    of

apricot    preserves

apricot    or

**negative examples -**

<sup>k=2</sup>

t                    c                    t                    c

---

apricot    aardvark    apricot    twelve

apricot    puddle      apricot    hello

apricot    where       apricot    dear

apricot    coaxial     apricot    forever

# Choosing noise words

Could pick  $w$  according to their unigram frequency  $P(w)$

More common to chosen then according to  $p_\alpha(w)$

$$P_\alpha(w) = \frac{\text{count}(w)^\alpha}{\sum_w \text{count}(w)^\alpha}$$

$\alpha = \frac{3}{4}$  works well because it gives rare noise words slightly higher probability

To show this, imagine two events  $p(a) = .99$  and  $p(b) = .01$ :

$$P_\alpha(a) = \frac{.99^{.75}}{.99^{.75} + .01^{.75}} = .97$$

$$P_\alpha(b) = \frac{.01^{.75}}{.99^{.75} + .01^{.75}} = .03$$

# Setup

Let's represent words as vectors of some length (say 300), randomly initialized.

So we start with  $300 * V$  random parameters

Over the entire training set, we'd like to adjust those word vectors such that we

- Maximize the similarity of the **target word, context word** pairs (t,c) drawn from the positive data
- Minimize the similarity of the (t,c) pairs drawn from the negative data.



# Learning the classifier

Iterative process.

We'll start with 0 or random weights

Then adjust the word weights to

- make the positive pairs more likely
- and the negative pairs less likely

over the entire training set:

# Objective Criteria

We want to maximize...

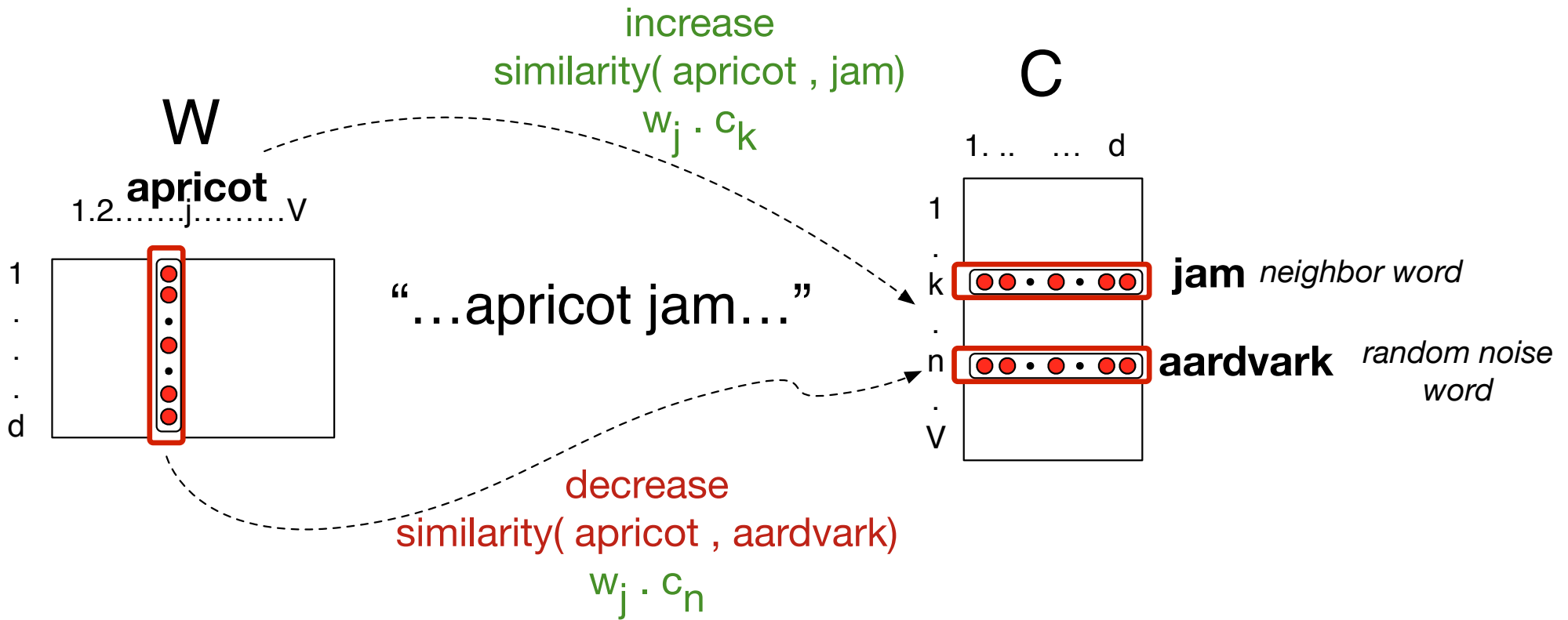
$$\sum_{(t,c) \in +} \log P(+|t, c) + \sum_{(t,c) \in -} \log P(-|t, c)$$

Maximize the + label for the pairs from the positive training data, and the – label for the pairs sample from the negative data.

Focusing on one target word  $t$ :

$$\begin{aligned} L(\theta) &= \log P(+|t, c) + \sum_{i=1} \log P(-|t, n_i) \\ &= \log \sigma(c \cdot t) + \sum_{i=1}^k \log \sigma(-n_i \cdot t) \\ &= \log \frac{1}{1 + e^{-c \cdot t}} + \sum_{i=1}^k \log \frac{1}{1 + e^{n_i \cdot t}} \end{aligned}$$







# Train using gradient descent

Actually learns two separate embedding matrices  $W$  and  $C$

Can use  $W$  and throw away  $C$ , or merge them somehow

# Summary: How to learn word2vec (skip-gram) embeddings

Start with  $V$  random 300-dimensional vectors as initial embeddings

Use logistic regression, the second most basic classifier used in machine learning after naïve bayes

- Take a corpus and take pairs of words that co-occur as positive examples
- Take pairs of words that don't co-occur as negative examples
- Train the classifier to distinguish these by slowly adjusting all the embeddings to improve the classifier performance
- Throw away the classifier code and keep the embeddings.

# Evaluating embeddings

Compare to human scores on word similarity-type tasks:

- WordSim-353 (Finkelstein et al., 2002)
- SimLex-999 (Hill et al., 2015)
- Stanford Contextual Word Similarity (SCWS) dataset (Huang et al., 2012)
- TOEFL dataset: *Levied is closest in meaning to: imposed, believed, requested, correlated*

# Properties of embeddings

Similarity depends on window size  $C$

$C = \pm 2$  The nearest words to *Hogwarts*:

- *Sunnydale*
- *Evernight*

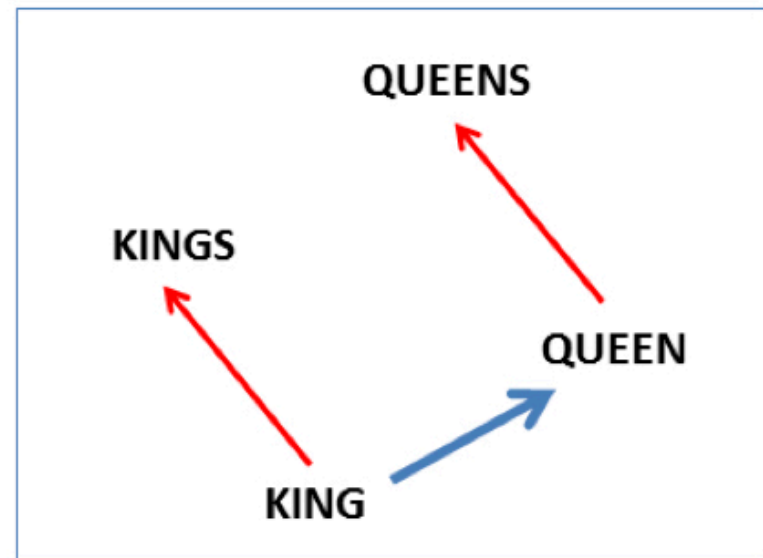
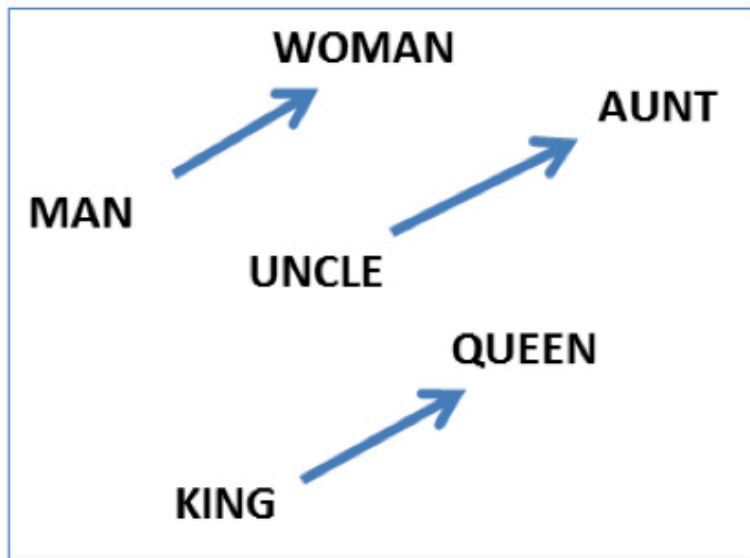
$C = \pm 5$  The nearest words to *Hogwarts*:

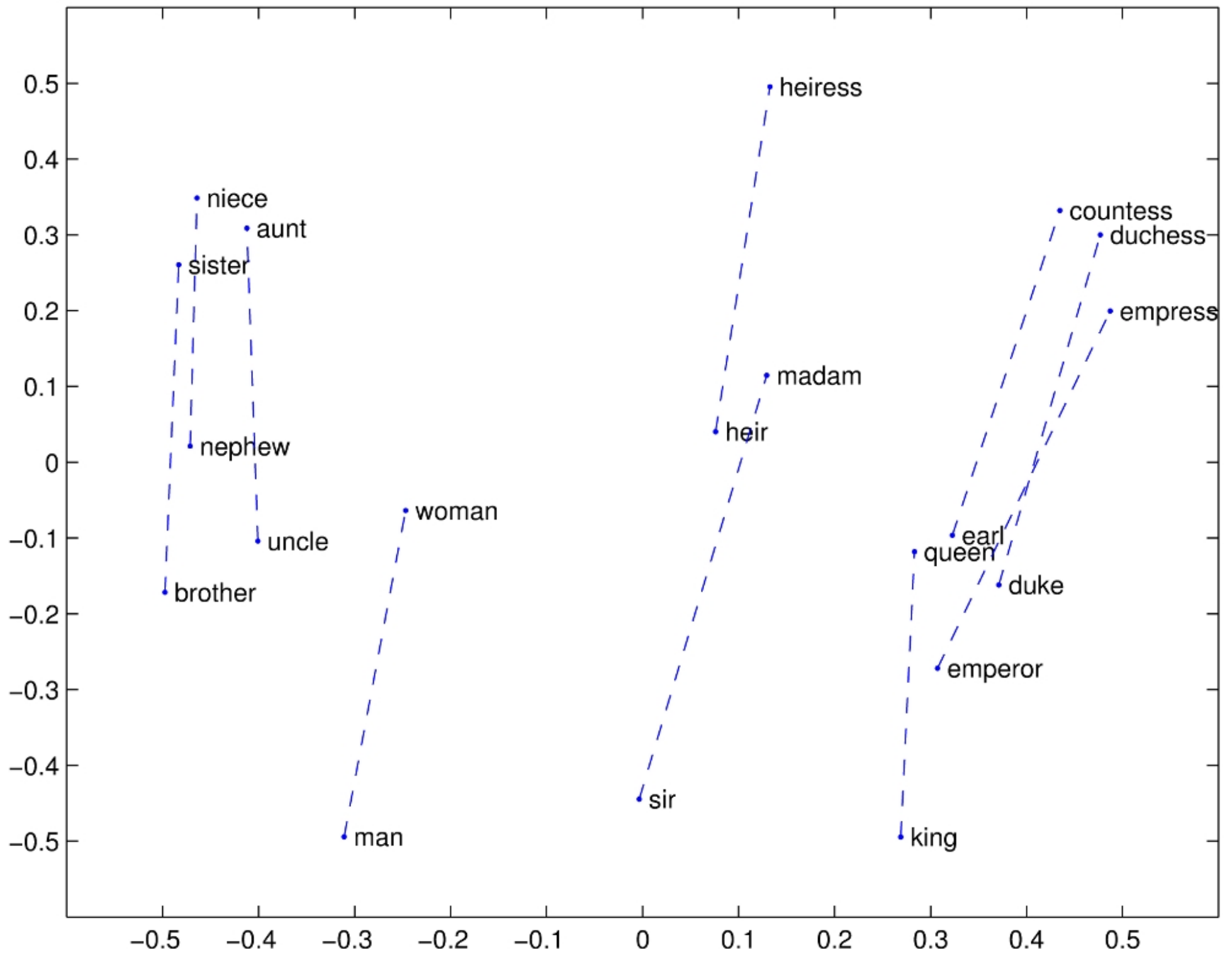
- *Dumbledore*
- *Malfoy*
- *halfblood*

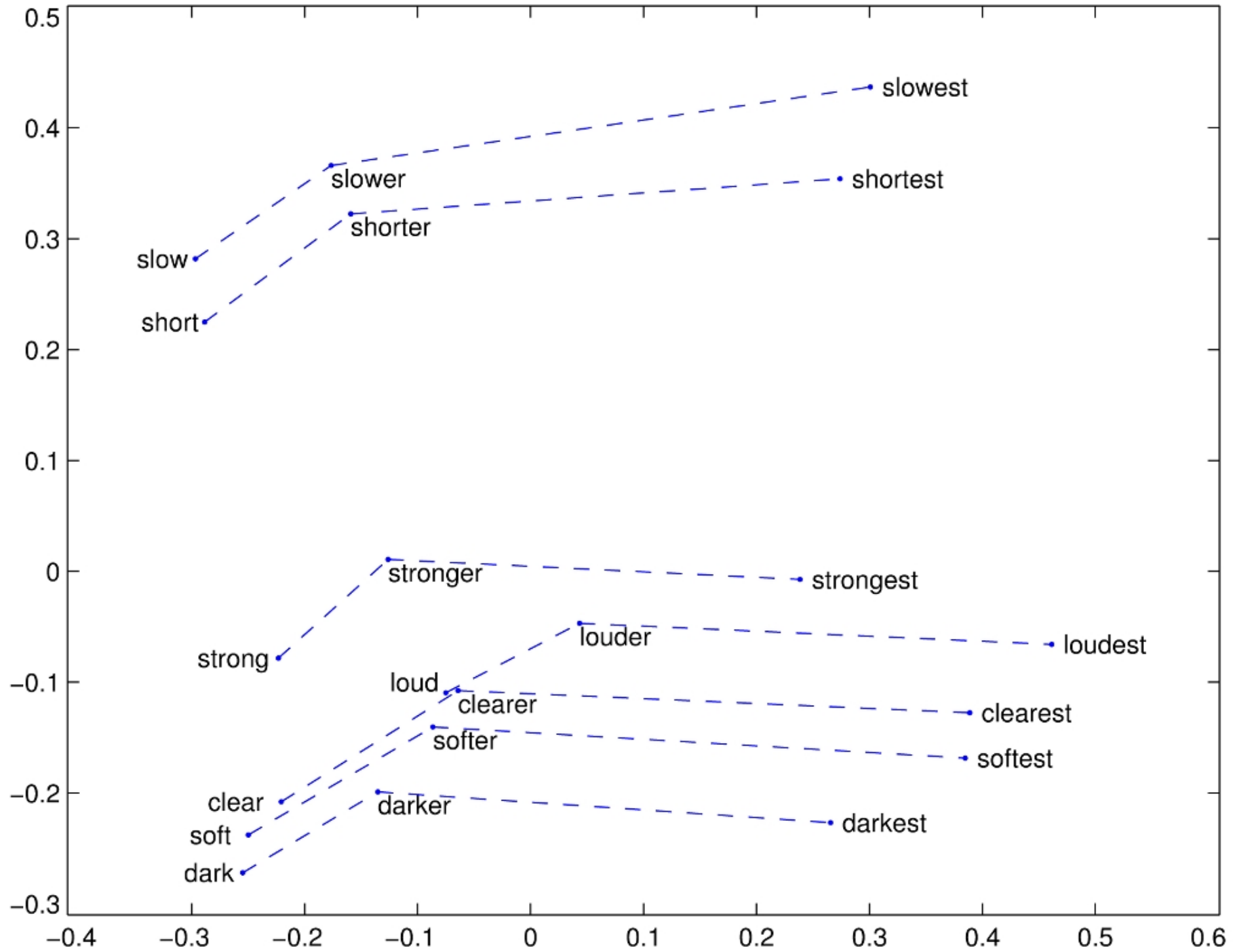
# Analogy: Embeddings capture relational meaning!

$\text{vector}(\textit{king}) - \text{vector}(\textit{man}) + \text{vector}(\textit{woman}) \approx \text{vector}(\textit{queen})$

$\text{vector}(\textit{Paris}) - \text{vector}(\textit{France}) + \text{vector}(\textit{Italy}) \approx \text{vector}(\textit{Rome})$









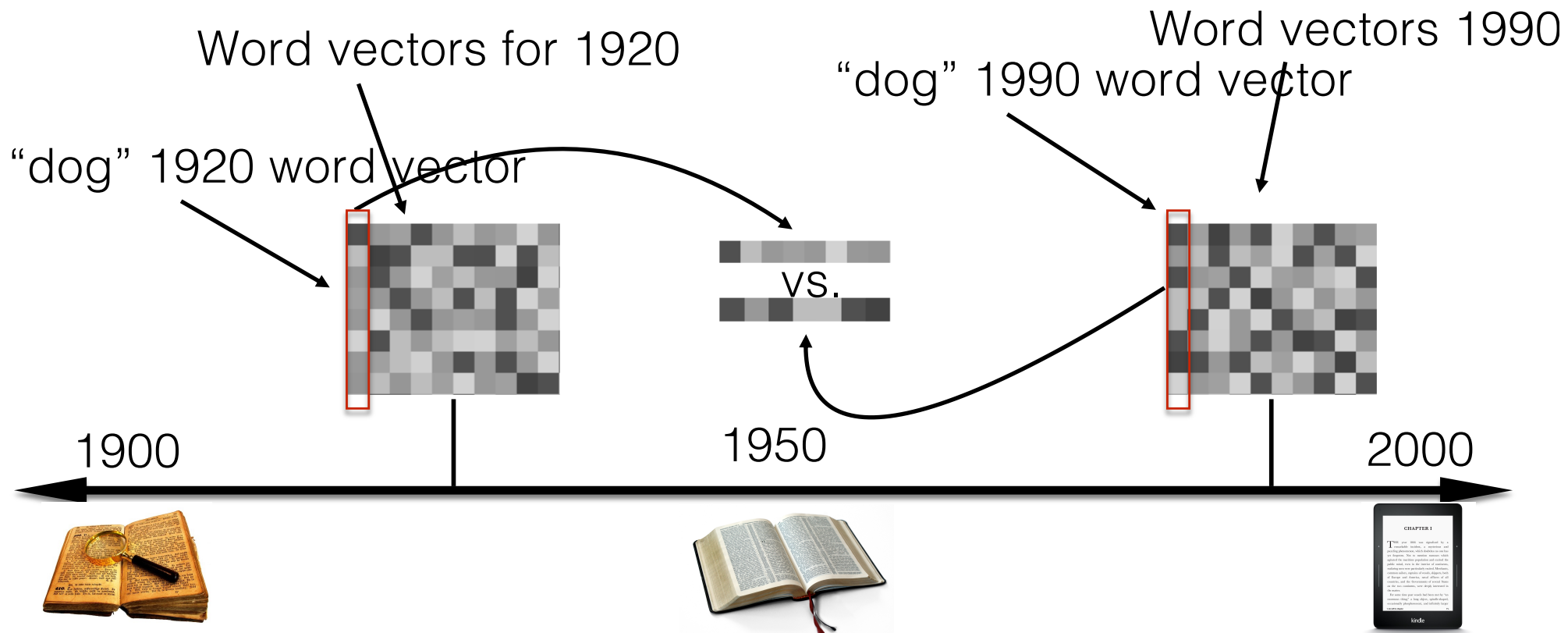
Embeddings can help study  
word history!

Train embeddings on old books to study  
changes in word meaning!!



Will Hamilton

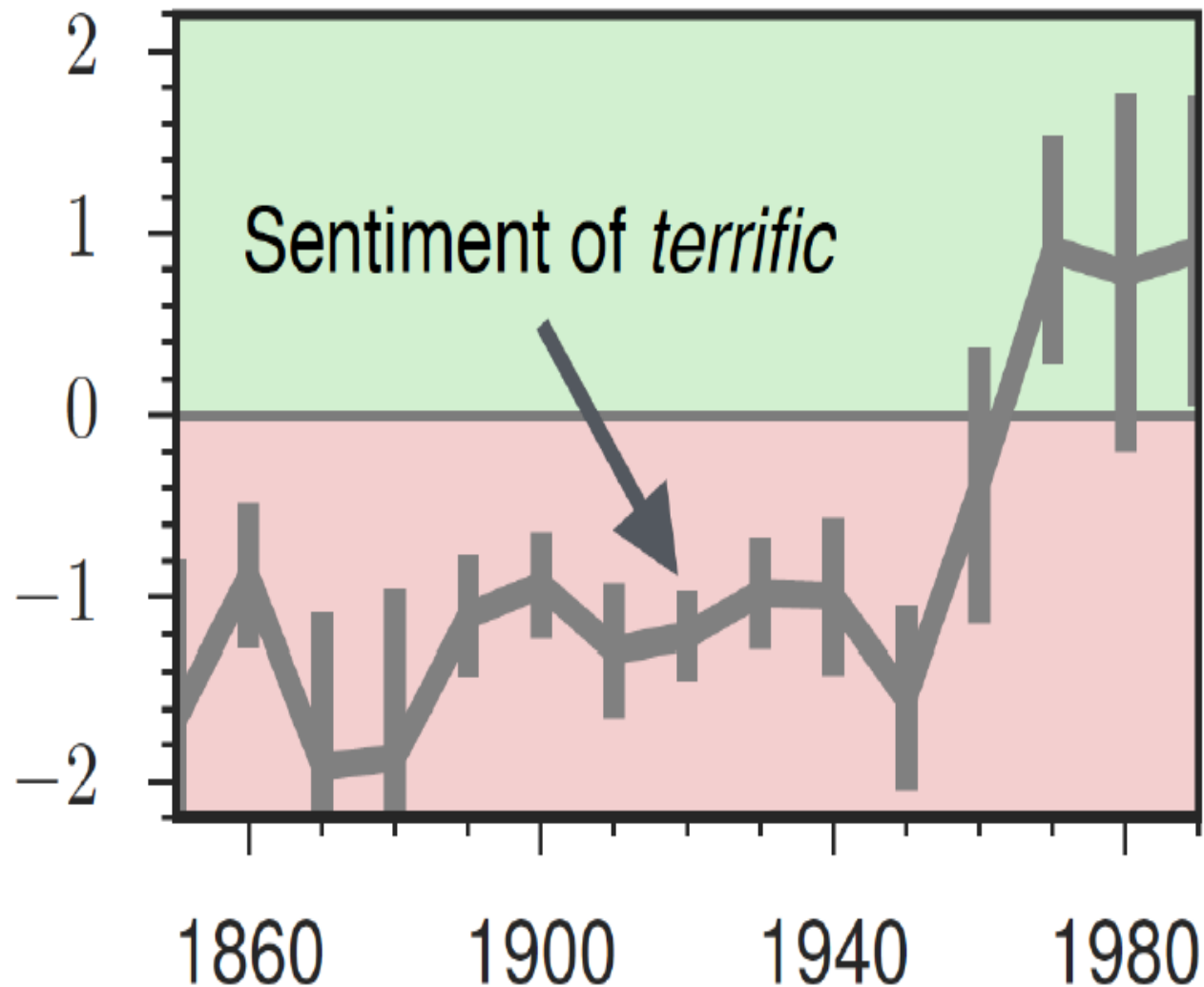
# Diachronic word embeddings for studying language change!





# The evolution of sentiment words

Negative words change faster than positive words





# Embeddings and bias

# Embeddings reflect cultural bias

Bolukbasi, Tolga, Kai-Wei Chang, James Y. Zou, Venkatesh Saligrama, and Adam T. Kalai. "Man is to computer programmer as woman is to homemaker? debiasing word embeddings." In *Advances in Neural Information Processing Systems*, pp. 4349-4357. 2016.

Ask “Paris : France :: Tokyo : x”

- x = Japan

Ask “father : doctor :: mother : x”

- x = nurse

Ask “man : computer programmer :: woman : x”

- x = homemaker

# Embeddings reflect cultural bias

Caliskan, Aylin, Joanna J. Brusson and Arvind Narayanan. 2017. Semantics derived automatically from language corpora contain human-like biases. *Science* 356:6334, 183-186.

Implicit Association test (Greenwald et al 1998): How associated are

- concepts (*flowers, insects*) & attributes (*pleasantness, unpleasantness*)?
- Studied by measuring timing latencies for categorization.

Psychological findings on US participants:

- African-American names are associated with unpleasant words (more than European-American names)
- Male names associated more with math, female names with arts
- Old people's names with unpleasant words, young people with pleasant words.

Caliskan et al. replication with embeddings:

- African-American names (*Leroy, Shaniqua*) had a higher GloVe cosine with unpleasant words (*abuse, stink, ugly*)
- European American names (*Brad, Greg, Courtney*) had a higher cosine with pleasant words (*love, peace, miracle*)

Embeddings reflect and replicate all sorts of pernicious biases.

# Directions

## Debiasing algorithms for embeddings

- Bolukbasi, Tolga, Chang, Kai-Wei, Zou, James Y., Saligrama, Venkatesh, and Kalai, Adam T. (2016). Man is to computer programmer as woman is to homemaker? debiasing word embeddings. In *Advances in Neural Information Processing Systems*, pp. 4349–4357.

Use embeddings as a historical tool to study bias



# Embeddings as a window onto history

Garg, Nikhil, Schiebinger, Londa, Jurafsky, Dan, and Zou, James (2018). Word embeddings quantify 100 years of gender and ethnic stereotypes. *Proceedings of the National Academy of Sciences*, 115(16), E3635–E3644

## Use the Hamilton historical embeddings

The cosine similarity of embeddings for decade X for occupations (like teacher) to male vs female names

- Is correlated with the actual percentage of women teachers in decade X

# History of biased framings of women

Garg, Nikhil, Schiebinger, Londa, Jurafsky, Dan, and Zou, James (2018). Word embeddings quantify 100 years of gender and ethnic stereotypes. *Proceedings of the National Academy of Sciences*, 115(16), E3635–E3644

Embeddings for competence adjectives are biased toward men

- *Smart, wise, brilliant, intelligent, resourceful, thoughtful, logical, etc.*

This bias is slowly decreasing

# Embeddings reflect ethnic stereotypes over time

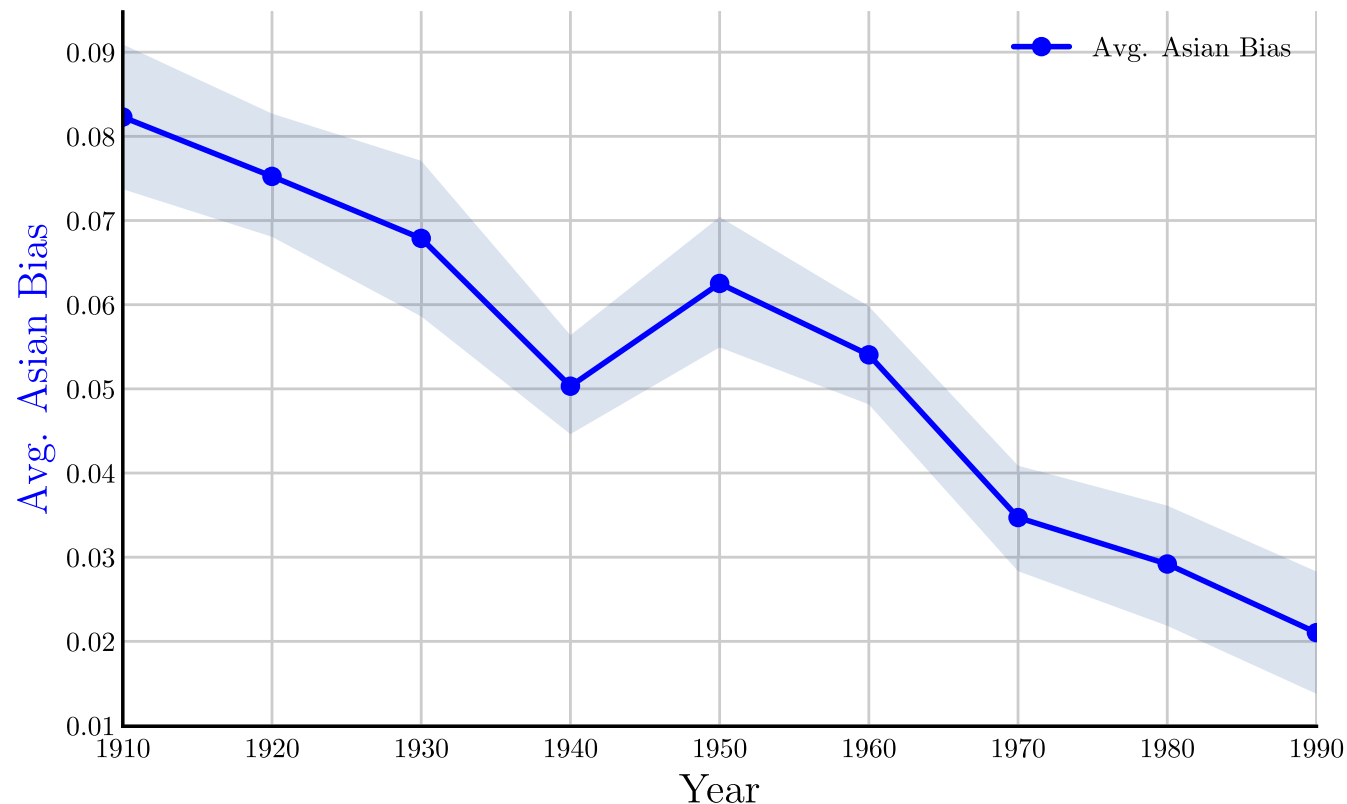
Garg, Nikhil, Schiebinger, Londa, Jurafsky, Dan, and Zou, James (2018). Word embeddings quantify 100 years of gender and ethnic stereotypes. *Proceedings of the National Academy of Sciences*, 115(16), E3635–E3644

- Princeton trilogy experiments
- Attitudes toward ethnic groups (1933, 1951, 1969) scores for adjectives
  - *industrious, superstitious, nationalistic, etc*
- Cosine of Chinese name embeddings with those adjective embeddings correlates with human ratings.

# Change in linguistic framing 1910-1990

Garg, Nikhil, Schiebinger, Londa, Jurafsky, Dan, and Zou, James (2018). Word embeddings quantify 100 years of gender and ethnic stereotypes. *Proceedings of the National Academy of Sciences*, 115(16), E3635–E3644

Change in association of Chinese names with adjectives framed as "othering" (*barbaric, monstrous, bizarre*)



# Changes in framing: adjectives associated with Chinese

Garg, Nikhil, Schiebinger, Londa, Jurafsky, Dan, and Zou, James (2018). Word embeddings quantify 100 years of gender and ethnic stereotypes. *Proceedings of the National Academy of Sciences*, 115(16), E3635–E3644

1910	1950	1990
Irresponsible	Disorganized	Inhibited
Envious	Outrageous	Passive
Barbaric	Pompous	Dissolute
Aggressive	Unstable	Haughty
Transparent	Effeminate	Complacent
Monstrous	Unprincipled	Forceful
Hateful	Venomous	Fixed
Cruel	Disobedient	Active
Greedy	Predatory	Sensitive
Bizarre	Boisterous	Hearty

# Conclusion

## **Concepts** or word senses

- Have a complex many-to-many association with **words** (homonymy, multiple senses)
- Have relations with each other
  - Synonymy, Antonymy, Superordinate
- But are hard to define formally (necessary & sufficient conditions)

## **Embeddings** = vector models of meaning

- More fine-grained than just a string or index
- Especially good at modeling similarity/analogy
  - Just download them and use cosines!!
- Can use sparse models (tf-idf) or dense models (word2vec, GLoVE)
- Useful in practice but know they encode cultural stereotypes