

Natural Language Processing for Law and Social Science

5. Word Embeddings

Catching Up

- ▶ In-Class Presentation: Ash, Jacobs, MacLeod, Naidu, and Stammbach (2020)
“Unsupervised extraction of rights and duties from collective bargaining agreements”

What have we been doing? *Learning representations* of the data

- ▶ Dictionary methods: document is represented as a count over the lexicon
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 - ▶ the vector of features, \mathbf{x}_i , is itself a compressed representation of the unprocessed document \mathcal{D}_i .
- ▶ Further: the learned parameters $\hat{\theta}$ can also be understood as a **learned compressed representation of the whole dataset**:
 - ▶ it contains information about the training corpus, the text features, and the outcome classes.

Information in $\hat{\theta}$

Say we train a multinomial logistic regression on a bag-of-words representation \mathbf{x}_i to predict classes \mathbf{y}_i :

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- ▶ θ is an interesting object. How can we use it?
- ▶ e.g.:
 - ▶ cluster the column vectors \rightarrow which outcome classes are similar/related.
 - ▶ cluster the row vectors \rightarrow which input features are similar/related.

$\hat{\theta}$ Contains Word Embeddings

θ = matrix of parameters learned from logit, relating words to outcomes.

- ▶ If \mathbf{x} is a bag-of-words representation for a document consisting of a list of tokens $\{w_1, \dots, w_t, \dots, w_n\}$, we can write

$$\mathbf{x} = \frac{1}{n} \sum_{t=1}^n \mathbf{x}_t$$

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- ▶ We can construct a **document vector**

$$\vec{\mathbf{d}} = \frac{1}{n} \sum_{t=1}^{n_i} \theta_t$$

the sum of the n_y -dimensional word representations (the row vectors from above).

- ▶ this is called the “continuous bag of words (CBOW)” representation (Goldberg 2017).
- ▶ Note that $\vec{\mathbf{d}} = \theta \cdot \mathbf{x}$, we thus call θ a **word embedding matrix**.

Outline

Word Embedding without Neural Nets

Embedding Layers

Word Embedding with Neural Nets

Exercises and Practice

Word Embedding with Local Context

- ▶ “Word embeddings” often refer to Word2Vec or GloVe – these are particular (popular) models for producing word embeddings.
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 - ▶ these models get good performance on a range of similarity, analogy, and prediction tasks.
- ▶ “You shall know a word by the company it keeps”:
 - ▶ “He filled the **wampimuk**, passed it around and we all drunk some.”
 - ▶ “We found a little, hairy **wampimuk** sleeping behind the tree.”

Words and Contexts

A long line of NLP research aims to capture the distributional properties of words using a **word-context matrix** M :

- ▶ each row w represents a **word** (e.g. “income”), each column c represents a linguistic **context** in which words can occur (e.g. “corporate ____ tax”).
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 - ▶ A matrix entry $M_{[w,c]}$ quantifies the strength of association between a word and a context in a large corpus.
- ▶ each word (row) $M_{[w,:]}$ gives a distribution over contexts.
 - ▶ different definitions of contexts and different measures of association → different types of **word vectors**.
 - ▶ these vectors often have a **spatial interpretation** → geometric distances between word vectors reflect semantic distances between words.

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 - ▶ ...
- ▶ Etc.

Defining an Association Measure

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- ▶ e.g. **counts**: $f_M(w, c) = \#(w, c)$, the number of times w appeared along with context c , or **document frequencies**: $f_M(w, c) = \frac{\#(w, c)}{n_D}$
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- ▶ Better: **Point-wise mutual information** (PMI):

$$f_M(w, c) = \frac{\Pr(w, c)}{\Pr(w)\Pr(c)} = \frac{\frac{\#(w, c)}{n_D}}{\frac{\#(w)}{n_D} \frac{\#(c)}{n_D}} = \frac{n_D \#(w, c)}{\#(w) \#(c)}$$

where $\#(w)$ and $\#(c)$ are the corpus counts for w and c , respectively.

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- ▶ \mathbf{M} is $n_w \times n_c$
 - ▶ if c is drawn from the vocabulary of a reasonably large corpus, the associated word vectors $\{v_1 = \mathbf{M}_{[w_1, :]}, v_2 = \mathbf{M}_{[w_2, :]}, \dots\}$ are too high-dimensional to be useful.

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- ▶ Going back to dimension reduction: can use singular value decomposition (SVD):
 - ▶ factorize $M \in \mathbb{R}^{n_w \times n_c}$ into a word matrix $W \in \mathbb{R}^{n_w \times n_E}$ and context matrix $C \in \mathbb{R}^{n_c \times n_E}$
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- ▶ **similarity measures between rows of W approximate similarity measures between rows of M**

GloVe Embeddings

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- ▶ Input: C_{ij} = local co-occurrence counts between words $i, j \in \{1, \dots, n_w\}$ within some co-occurrence window, e.g. ten words.

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Learn word vectors $\mathbf{w} = (w_1, \dots, w_i, \dots, w_{n_w})$, initialized randomly and $w_i \in (-1, 1)^{n_E}$, to solve

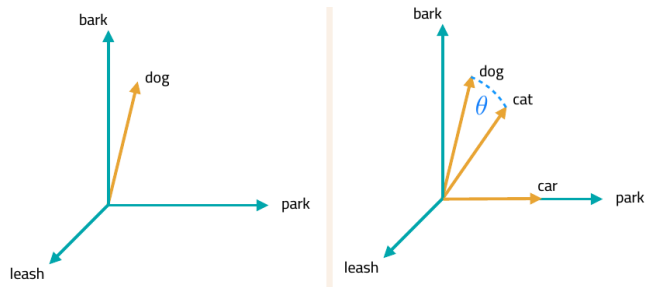
$$\min_{\mathbf{w}} \sum_{i,j} f(C_{ij}) \left(w_i^T w_j - \log(C_{ij}) \right)^2$$

where $f(\cdot)$ is weighting function to down-weight frequent words.

- ▶ Minimizes **squared difference** between:
 - ▶ **dot product of word vectors**, $w_i^T w_j$
 - ▶ **empirical co-occurrence**, $\log(C_{ij})$
[Arora et al (2016) put the PMI here instead of co-occurrence counts]
- ▶ Intuitively: words that co-occur should have high correlation (dot product)

Word Similarity

- ▶ Once words are represented as vectors, we can use linear algebra to understand the relationships between words:
 - ▶ Words that are geometrically close to each other are similar: e.g. “dog” and “cat”:



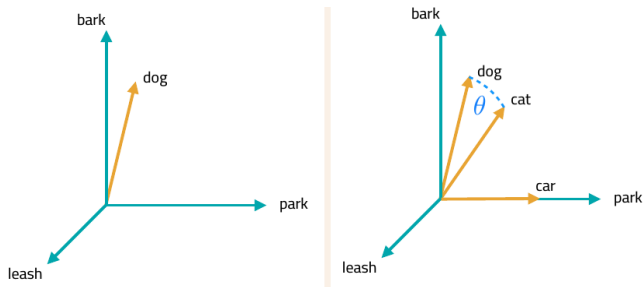
- ▶ The standard metric for comparing vectors is cosine similarity:

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- ▶ alternatives include e.g. Jaccard similarity (Goldberg 2017)
- ▶ Thanks to linearity, can compute similarities between groups of words by averaging the groups.

In-Class Presentation: Gennaro and Ash (EJ 2022)

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Exercises and Practice

What is an Embedding?

- ▶ In a broad sense, “**embedding**” refers to a lower-dimensional dense vector representation of a higher-dimensional object.
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- ▶ Not embeddings:
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- ▶ Embeddings:
 - ▶ PCA reductions of the word count vectors
 - ▶ LDA topic shares

Categorical Embeddings = dense representations of categorical variables

Say we have a binary classification problem with outcome Y :

- ▶ we have a high-dimensional categorical variable (e.g. area of law with 1000 categories)
- ▶ including dummy variables A for each category in your ML model is computationally expensive.

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(2) is similar to what embedding layers do in neural nets.

In deep learning, an embedding layer is matrix multiplication:

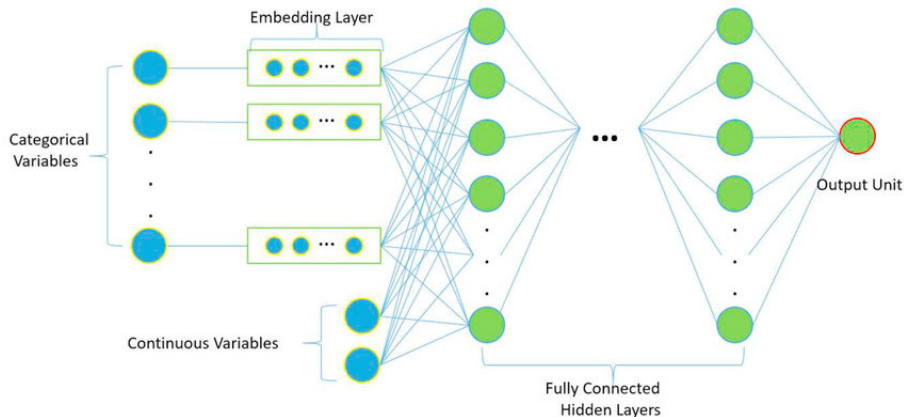
$$\underbrace{h_1}_{n_E \times 1} = \underbrace{\omega_E}_{n_E \times n_w} \cdot \underbrace{x}_{n_x \times 1}$$

- ▶ x = a categorical variable (e.g., representing a word)
 - ▶ one-hot vector with a single item equaling one. Input to the embedding layer.
- ▶ ω_E = the matrix of learnable parameters.
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The embedding matrix ω_E encodes predictive information about the categories, has a spatial interpretation when projected to two dimensions.

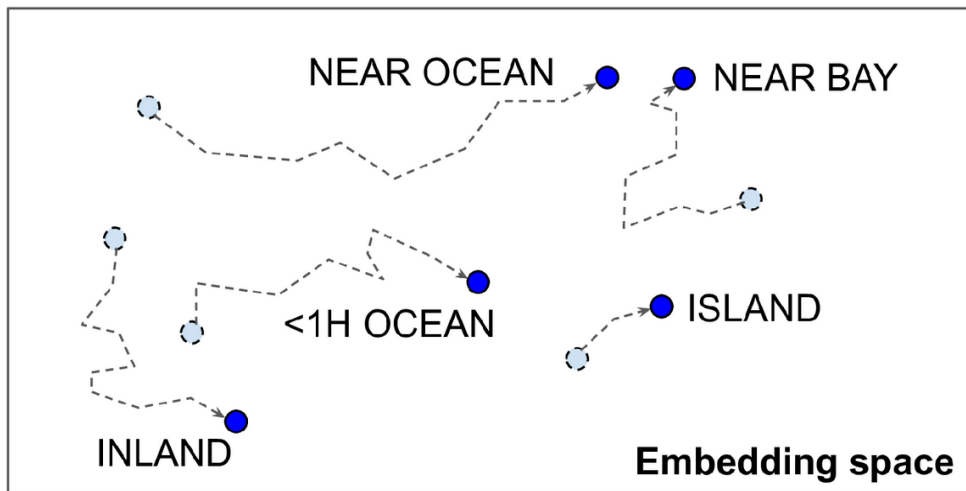


Figure 13-4. Embeddings will gradually improve during training

Embedding Layers versus Dense Layers

- ▶ An embedding layer is statistically equivalent to a fully-connected dense layer with one-hot vectors as input and linear activation.
 - ▶ dense layers might fit the data better, since you can use ReLU activation.
 - ▶ embedding layers are much faster; should use them when you have 10 or more categories.

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- ▶ Embedding layer replaces the list of sparse one-hot vectors with a list of n_E -dimensional ($n_E \ll n_w$) dense vectors

$$\mathbf{X} = \begin{bmatrix} x_1 & \dots & x_L \end{bmatrix}$$

where

$$\underbrace{x_j}_{n_E \times 1} = \underbrace{\mathbf{E}}_{n_E \times n_w} \cdot \underbrace{w_j}_{n_w \times 1}$$

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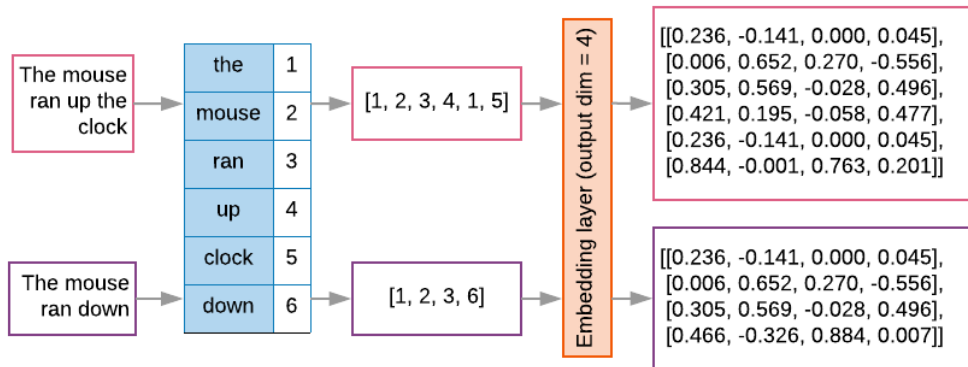
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$$\underbrace{x_j}_{n_E \times 1} = \underbrace{\mathbf{E}}_{n_E \times n_w} \cdot \underbrace{w_j}_{n_w \times 1}$$

- ▶ \mathbf{E} is a matrix of word vectors. The column associated with the word at j is selected by dot-product with one-hot vector w_j .
- ▶ \mathbf{X} is flattened into an $L * n_E$ vector for input to the next layer.

Illustration



Word2Vec

- ▶ “Word2Vec” is a neural net model that, instead of predicting some metadata (such as classifying topic labels), predicts the co-occurrence of neighboring words.
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 - ▶ an example of “**self-supervision**”
- ▶ How does it learn the meaning of the word “fox”?
 - ▶ By comparing true instances of the word fox (“The quick brown **fox** jumps over the lazy dog”)
 - ▶ to fake (randomly sampled) ones (“The prescription of **fox** is advised for this diagnosis”)

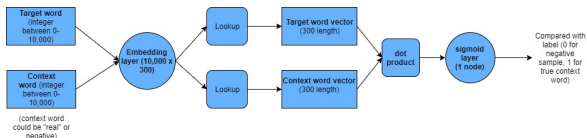
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 - ▶ By comparing true instances of the word fox (“The quick brown **fox** jumps over the lazy dog”)
 - ▶ to fake (randomly sampled) ones (“The prescription of **fox** is advised for this diagnosis”)
- ▶ Word2Vec learns embedding vectors for the target word (“fox”) and context words (neighbors of “fox”) to distinguish true from false samples.

Word2Vec Negative Sampling Objective

The dataset is a collection of context pairs indexed by i :

- ▶ $y_i = 1$ means correct (it appeared in the corpus)
- ▶ $y_i = 0$ means incorrect (it was randomly drawn \rightarrow **negative sample**).
- ▶ Both words are looked up in the same embedding matrix.
- ▶ The concatenated embeddings $[\mathbf{w}; \mathbf{c}]$ are input to a dense layer (no activation) then to sigmoid output:



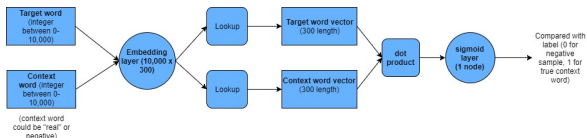
$$\hat{y}(w, c) = \text{sigmoid}(([\mathbf{w}; \mathbf{c}] \cdot \omega_0) \cdot \omega_1)$$

which gives the predicted probability of a correct rather than random pair.

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- ▶ Word2Vec minimizes the binary cross-entropy

$$\min_{\mathbf{w}, \mathbf{c}, \omega} L(\mathbf{w}, \mathbf{c}, \omega) = - \sum_{i=1}^{n_D} [y_i \log \hat{y}_i(\mathbf{w}, \mathbf{c}, \omega) + [1 - y_i] \log(1 - \hat{y}_i(\mathbf{w}, \mathbf{c}, \omega))]$$

How does Word2Vec relate to the \mathbf{M} matrix?

- ▶ Word2Vec produces embedding matrices \mathbf{W} and \mathbf{C} .
 - ▶ generally, context embeddings are discarded after training.
- ▶ Levy and Goldberg (2014):
 - ▶ If we take $\tilde{\mathbf{M}} = \mathbf{WC}'$, word2vec is equivalent to factorizing a matrix \mathbf{M} with items

$$\mathbf{M}_{[w,c]} = \text{PMI}(w, c) - \log a$$

where a is a constant calibrating the amount of negative sampling.

Word Embeddings Encode Linguistic Relations

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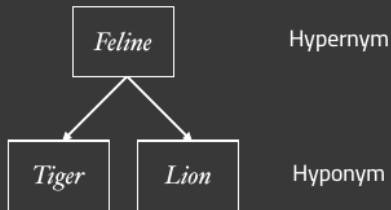
Synonymy



Antonymy



Hyponymy



Similarity vs. Relatedness (Budansky and Hirst, 2006)

- ▶ Semantic **similarity**: words sharing salient attributes / features
 - ▶ synonymy (car / automobile)
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- ▶ Word embeddings will recover one or both of these relations, depending on how contexts and associated are constructed.

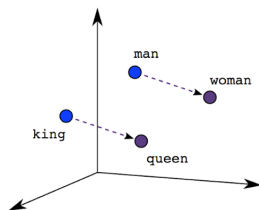
Most similar words to dog, depending on context window size

	2-word window	30-word window	
More paradigmatic		<u>kennel</u>	More syntagmatic
	cat	puppy	
	horse	pet	
	fox	bitch	
	pet	terrier	
	rabbit	rottweiler	
	pig	canine	
	animal	cat	
	mongrel	<u>bark</u>	
	sheep	alsatian	
	pigeon		

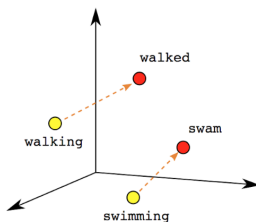
- ▶ Small windows pick up substitutable words; large windows pick up topics.

Vector Directions \leftrightarrow Meaning

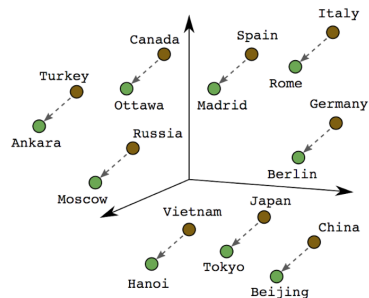
- ▶ Intriguingly, word2vec algebra can depict conceptual, analogical relationships between words:



Male-Female



Verb Tense



Country-Capital

Word Embeddings for Analogies

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

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$$\arg \max_{b_2 \in V} \cos(b_2, a_2 - a_1 + b_1)$$

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- ▶ Often works better with normalized vectors (so that one long vector doesn't wash out the others)
- ▶ Levy and Goldberg (2014) recommend the following “CosMul” metric which tends to perform better:

$$\arg \max_{b_2 \in V} \frac{\cos(b_2, a_2) \cos(b_2, b_1)}{\cos(b_2, a_1) + \epsilon}$$

- ▶ requires normalized, non-negative vectors (can transform using $(x+1)/2$)
- ▶ ϵ is a small smoothing parameter.

Pre-trained word embeddings

- ▶ In many settings (e.g. a small corpus), better to use pre-trained embeddings.
- ▶ e.g, spaCy's GloVe embeddings:
 - ▶ one million vocabulary entries
 - ▶ 300-dimensional vectors
 - ▶ trained on the Common Crawl corpus
- ▶ Can initialize models with pre-trained embeddings, can fine-tune as needed.

Parts of Speech and Phrases

- ▶ In the default model multiple senses of a word are merged.
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- ▶ Can improve the quality of embeddings in these cases by attaching the POS to the word (e.g. “like:verb”, “like:prep”) before training.
- ▶ The default model only works by word, but “new york \neq ”new” + “york”
 - ▶ can tokenize phrases together (see Week 2 lecture) before training.

The black sheep problem

- ▶ The trivial or obvious features of a word are not mentioned in standard corpora.
- ▶ For example, although most sheep are white, you rarely see the phrase “white sheep”.
 - ▶ so word2vec sometimes tells you $\text{sim}(\text{black}, \text{sheep}) > \text{sim}(\text{white}, \text{sheep})$.

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 - ▶ so word2vec sometimes tells you $\text{sim}(\text{black}, \text{sheep}) > \text{sim}(\text{white}, \text{sheep})$.
- ▶ This is really important when interpreting results using embeddings to analyze beliefs/attitudes.
- ▶ Relatedly, antonyms are often rated similarly, have to be careful with that.

Review: NLP “Bias” is statistical bias

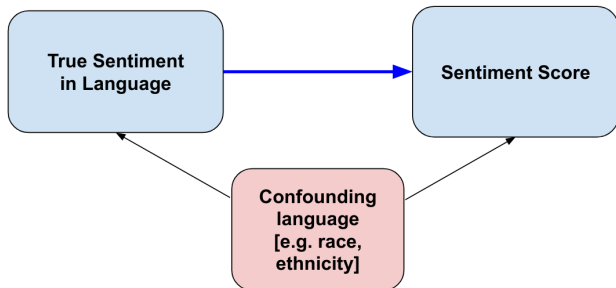
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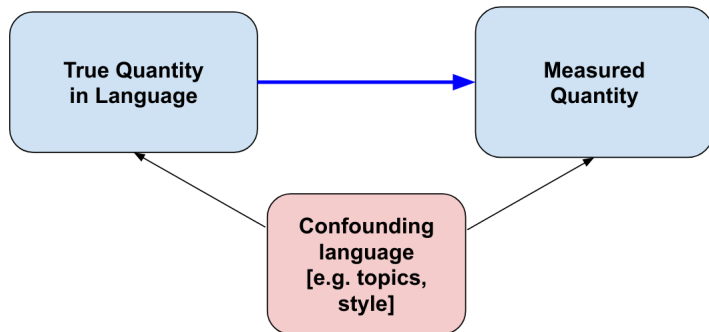
- ▶ Self-supervised learning algorithms like Word2Vec learn **all** dimensions of word associations; not just ones we are most interested in.
 - ▶ e.g., true expressions of attitudes or perceptions.
- ▶ e.g., using embeddings to scale social group words in a positive-to-negative dimension can learn correlated associations, not just sincere expressions of such attitudes:

```
text_to_sentiment("Let's go get Italian food")  
2.0429166109  
text_to_sentiment("Let's go get Chinese food")  
1.4094033658  
text_to_sentiment("Let's go get Mexican food")  
0.3880198556
```

```
text_to_sentiment("My name is Emily")  
2.2286179365  
text_to_sentiment("My name is Heather")  
1.3976291151  
text_to_sentiment("My name is Yvette")  
0.9846380213  
text_to_sentiment("My name is Shaniqua")  
-0.4704813178
```



Self-Supervised Models Learn Confounders



- ▶ self-supervised language models like Word2Vec learn all linguistic associations in language.
 - ▶ the measured associations might reflect attitudes/perceptions, or might reflect something else.

In-Class Presentation: Caliskan, Bryson, and Narayanan (*Science* 2017)

Steps for de-biasing

- ▶ Language features that are often confounded with the quantity of interest:
 - ▶ stopwords
 - ▶ named entities: person/organization/place names
- ▶ These can be dropped during pre-processing to reduce the influence of confounders in subsequent measurements.
- ▶ Can control for topic or style features or other potential confounders in regressions, or shuffle named entities.

De-Biasing Word Embeddings

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- ▶ Bolukbasi et al (NIPS 2016):
 - ▶ “Geometrically, **gender bias is first shown to be captured by a direction in the word embedding.**”
 - ▶ “Second, gender neutral words are shown to be linearly separable from gender definition words in the word embedding.”
 - ▶ “Using these properties, we provide a methodology for modifying an embedding to remove gender stereotypes, such as the association between the words receptionist and female, while maintaining desired associations such as between the words queen and female.”

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- ▶ But: Gonen and Goldberg (2019):
 - ▶ *“... we argue that this removal is superficial. While the bias is indeed substantially reduced according to the provided bias definition, the actual effect is mostly hiding the bias, not removing it. The gender bias information is still reflected in the distances between ‘gender-neutralized’ words in the debiased embeddings, and can be recovered from them...”*

Tokenizing for Word Embeddings

- ▶ capitalization?
- ▶ punctuation?
- ▶ stopwords/function-words?
- ▶ can add special tokens for start of sentence and end of sentence
- ▶ for out-of-vocab words, substitute a special token or replace with part-of-speech tag
 - ▶ or use FastText embeddings (more below)

Can cluster word embeddings to produce topics

Cluster #	Top 10 Words
174	complicate, depend, crucial, illustrate, elusive, focus, important, straightforward, elide, critical
134	implausible, problematic, exaggeration, skeptical, ascribe, discredit, contradictory, weak, exaggerate, supportable
75	reverse, AFFIRM, affirm, vacate, reversed, REMANDED, forego, foregoing, forgoing, remands
70	importation, import, ecstasy, marihuana, illicit, opium, distilled, export, phencyclidine, narcotic
178	perverse, sensible, tempt, unlikely, unwise, anomalous, would, easy, costly, attractive
32	phrase, meaning, word, synonymous, language, interpret, noun, wording, verb, adjective
169	circumscribe, endow, unfettered, vest, unlimited, boundless, broad, constrain, exercise, unbounded
85	hundred, thousand, many, million, huge, massive, large, enormous, most, dozen
28	emphasis, bracket, alteration, citation, footnote, italic, ellipsis, petcitation, idcitation, punctuation
138	logo, symbol, stylized, imprint, emblem, grille, prefix, lettering, suffix, crosshair
181	wilful, carelessness, recklessness, careless, intentional, wilful, conscious, reckless, unintentional, wantonness
158	rigorous, demanding, heightened, reasonableness, rigid, heighten, objective, deferential, flexible, particular
55	agreement, contract, contractual, promise, novation, repudiate, guaranty, enforceable, novate, repurchase
197	summation, admonish, sidebar, prosecutor, admonishment, mistrial, curative, questioning, remark, recess
120	scrivener, typographical, reversible, plain, harmless, clerical, invited, clear, requiresthe, instructional
15	adjudicatory, adjudicative, adversarial, judicial, rulemaking, decisionmaking, administrative, meaningful, rulemake, agency

Clustered word embeddings in judicial opinions, from Ash and Nikolaus (2020)

“Enriching word vectors with subword information” (Bojanowski et al 2017)

- ▶ each word is represented as a bag of (hashed) character n-grams. (e.g., spicy = (spi, pic, icy)).
- ▶ learn embeddings for the character segments, and construct word embedding by summing over the segment embeddings

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- ▶ learn embeddings for the character segments, and construct word embedding by summing over the segment embeddings
- ▶ competitive with word2vec in standard tasks; better in some languages.
- ▶ produces good embeddings for unseen words.

Standard word embeddings (e.g. word2vec/glove) have a number of limitations:

- ▶ **polysemy**: you get one vector for multiple senses of a word
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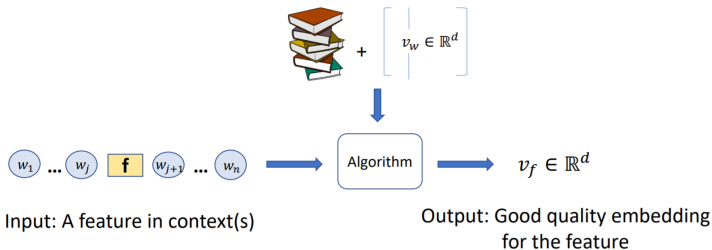
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- ▶ Goal of Khodak et al (2018): produce embeddings “a la carte” given a context:

Given: Text corpus and high quality word embeddings trained on it



A la carte embeddings

- ▶ Given a target word f and its context c , define

$$v_f^{avg} = \frac{1}{|c|} \sum_{w \in c} v_w$$

the average vector for the words in the context.

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- ▶ The “induction matrix” A can be learned with a least-squares (linear regression) objective

$$A^* = \arg \min_A \sum_w |v_w - A v_w^{avg}|_2^2$$

where w indexes over all the tokens in the corpus.

- ▶ empirically:

$$\text{cosine}(v_f, A^* v_f^{avg}) \geq 0.9$$

In-Class Presentation: Kozlowski, Evans, and Taddy (ASR 2019)

Outline

Word Embedding without Neural Nets

Embedding Layers

Word Embedding with Neural Nets

Exercises and Practice

Social Science with Embeddings

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- ▶ In what domains is this relevant?
 - ▶ social media, news media, politics, legal, scientific, ...
- ▶ Does language matter?
 - ▶ Djourelova (2020): style change from “illegal” to “undocumented” immigrant softened attitudes toward immigration.

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- ▶ Policy priorities → predicted probability of speeches/laws being about a particular policy topic.

confounders?

When is measurement confounding important?

- ▶ By itself, producing measurements that are biased by confounders might not be a problem.
- ▶ e.g.:
 - ▶ an NLP-based essay grading system that learns confounders → not a problem unless students learn about it and strategically alter their essays.

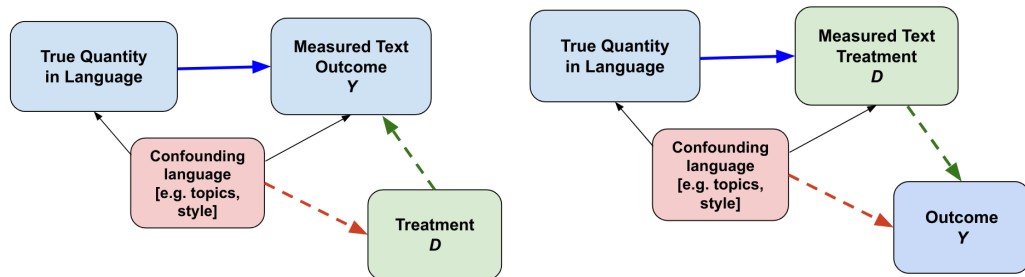
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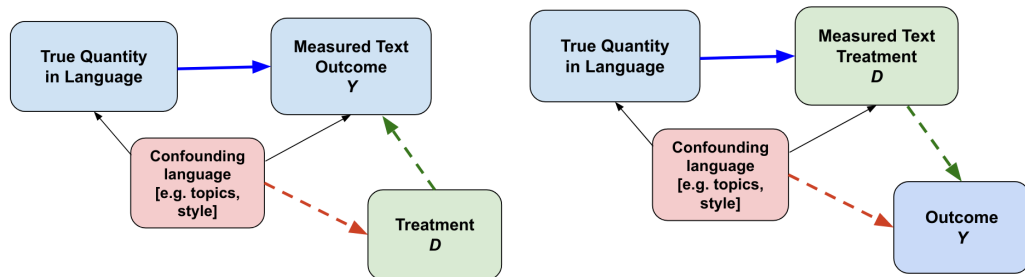
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 - ▶ but would matter a lot for summary statistics in a new domain
- ▶ even in-domain, will matter for assessing the causal effect of a treatment, e.g. the electoral cycle:
 - ▶ elections might cause politicians to focus on social issues rather than economic issues,
 - ▶ if social/economic issues are confounded with partisanship, the resulting estimates are biased.

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 - ▶ e.g.: estimating the effect of politician speech sentiment on his/her reelection chances?

Check for Understanding

1. What is the difference/connection between an embedding layer and a word embedding?
2. What does negative sampling mean in general, and in the case of Word2Vec?
3. What are the main differences between Word2Vec and GloVe?

Check for Understanding

1. How would it affect my word embeddings to use co-occurrence within paragraph, rather than within sentence?
2. How would it my embeddings to drop function words in a pre-processing step?
3. What is the black sheep problem in the context of word embeddings?
4. Think of a setting (and explain) where:
 - ▶ using pre-trained embeddings would not work.
 - ▶ using embeddings with subword information would help a lot
 - ▶ using a la carte embeddings is necessary