Distributional Semantics, Pt. II

LING 571 — Deep Processing for NLP

November 16, 2020

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Announcements

- HW6 grades posted
- A note on ‘or’ and polymorphism (Partee and Rooth 1983)
  - They ate rice or they drank milk.
  - They ate rice or beans.
  - Walking or talking is their favorite thing.
  - …
- ‘or’_sentence: \p:<s,t> . \q:<s,t> . \w:s . p(w) = 1 or q(w) = 1
- ‘or’_IV: \v1:<e, t> . \v2:<e, t> . \x:e . v1(x) = 1 or v2(x) = 1
- Generally: reduce all others systematically to boolean ‘or’

Recap

- We can represent words as vectors
  - Each entry in the vector is a score for its correlation with another word
  - If a word occurs frequently with “tall” compared to other words, we might assume height is an important quality of the word
- In these extremely large vectors, most entries are zero

Roadmap

- Curse of Dimensionality
- Dimensionality Reduction
  - Principle Components Analysis (PCA)
  - Singular Value Decomposition (SVD) / LSA
- Prediction-based Methods
  - CBOW / Skip-gram (word2vec)
- Word Sense Disambiguation

The Curse of Dimensionality

The Problem with High Dimensionality

	tasty	delicious	disgusting	flavorful	tree
pear	0	1	0	0	0
apple	0	0	0	1	1
watermelon	1	0	0	0	0
paw_paw	0	0	1	0	0
family	0	0	0	0	1

The Problem with High Dimensionality

The cosine similarity for these words will be zero!

	tasty	delicious	disgusting	flavorful	tree
pear	0	1	0	0	0
apple	0	0	0	1	1
watermelon	1	0	0	0	0
paw_paw	0	0	1	0	0
family	0	0	0	0	1

The Problem with High Dimensionality

The cosine similarity for these words will be >0 (0.293)

	tasty	delicious	disgusting	flavorful	tree
pear	0	1	0	0	0
apple	0	0	0	1	1
watermelon	1	0	0	0	0
paw_paw	0	0	1	0	0
family	0	0	0	0	1

The Problem with High Dimensionality

But if we could collapse all of these into one "meta-dimension"…

	tasty	delicious	disgusting	flavorful	tree
pear	0	1	0	0	0
apple	0	0	0	1	1
watermelon	1	0	0	0	0
paw_paw	0	0	1	0	0
family	0	0	0	0	1

The Problem with High Dimensionality

Now, these things have "taste" associated with them as a concept

	$<taste>$	tree
pear	1	0
apple	1	1
watermelon	1	0
paw_paw	1	0
family	0	1

Curse of Dimensionality

- Vector representations are sparse, very high dimensional
  - # of words in vocabulary
  - # of relations × # words, etc

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Curse of Dimensionality

- Vector representations are sparse, very high dimensional
  - # of words in vocabulary
  - # of relations × # words, etc
- Google 1T 5-gram corpus:
  - In bigram 1M × 1M matrix: < 0.05% non-zero values
- Computationally hard to manage
  - Lots of zeroes
  - Can miss underlying relations

Roadmap

- Curse of Dimensionality
- **Dimensionality Reduction**
  - Principle Components Analysis (PCA)
  - Singular Value Decomposition (SVD) / LSA
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Reducing Dimensionality

- Can we use ***fewer*** features to build our matrices?

Reducing Dimensionality

- Can we use ***fewer*** features to build our matrices?
- Ideally with
  - **High** ***frequency*** — means fewer zeroes in our matrix
  - **High** ***variance*** — larger spread over values makes items easier to separate

Reducing Dimensionality

- One approach — ***filter*** out features
  - Can exclude terms with too few occurrences
  - Can include only top X most frequently seen features
  - χ^2 selection

Reducing Dimensionality

Reducing Dimensionality

- Things to watch out for:
  - Feature correlation — if features strongly correlated, give redundant information
  - Joint feature selection complex, computationally expensive

Reducing Dimensionality

- Approaches to project into lower-dimensional spaces
  - Principal Components Analysis (PCA)
  - Locality Preserving Projections (LPP) [link]
  - Singular Value Decomposition (SVD)

Reducing Dimensionality

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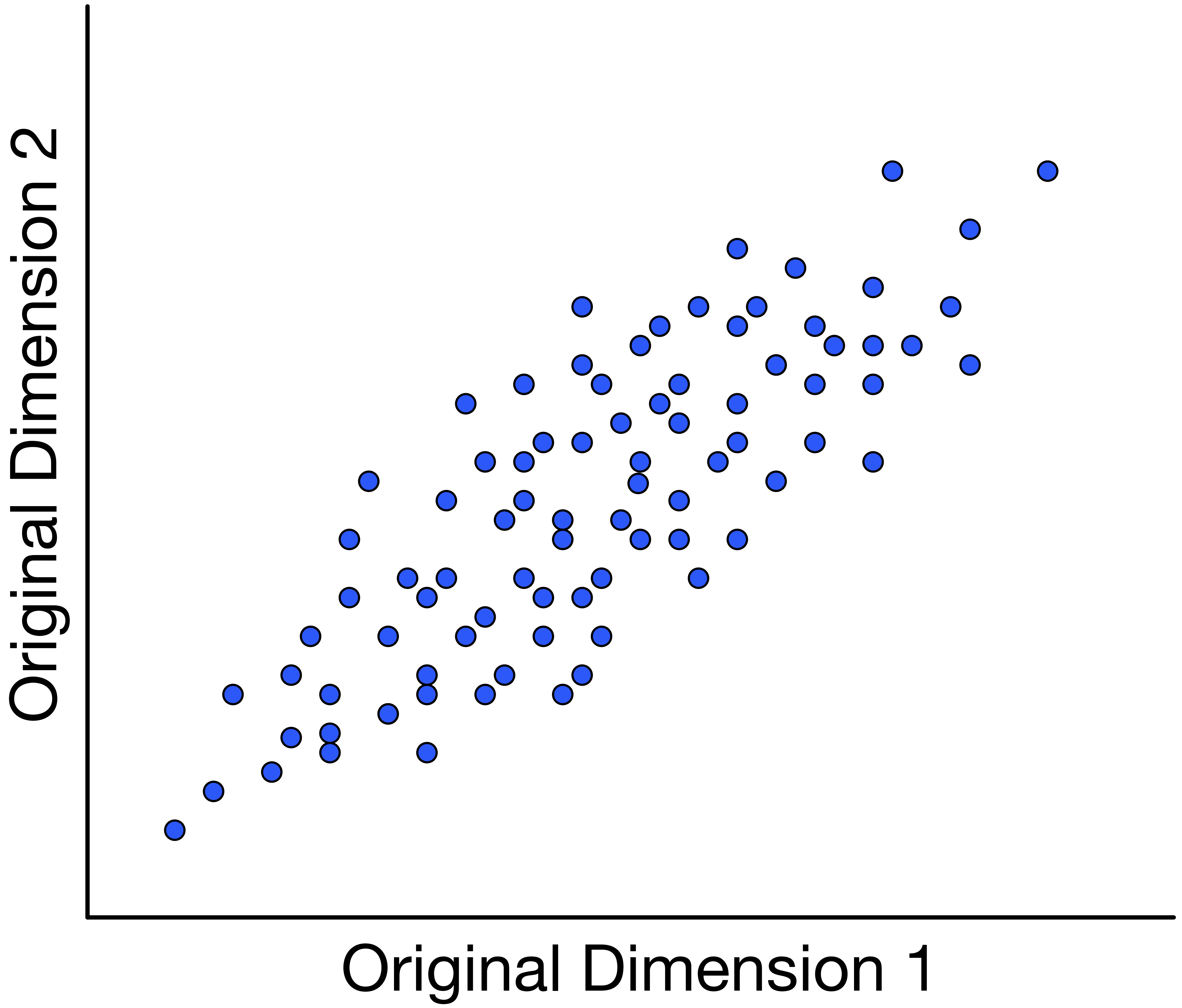
- All approaches create new lower dimensional space that
  - Preserves distances between data points
    - (Keep like with like)

Reducing Dimensionality

- All approaches create new lower dimensional space that
  - Preserves distances between data points
    - (Keep like with like)
- Approaches differ on exactly what is preserved

Principal Component Analysis (PCA)



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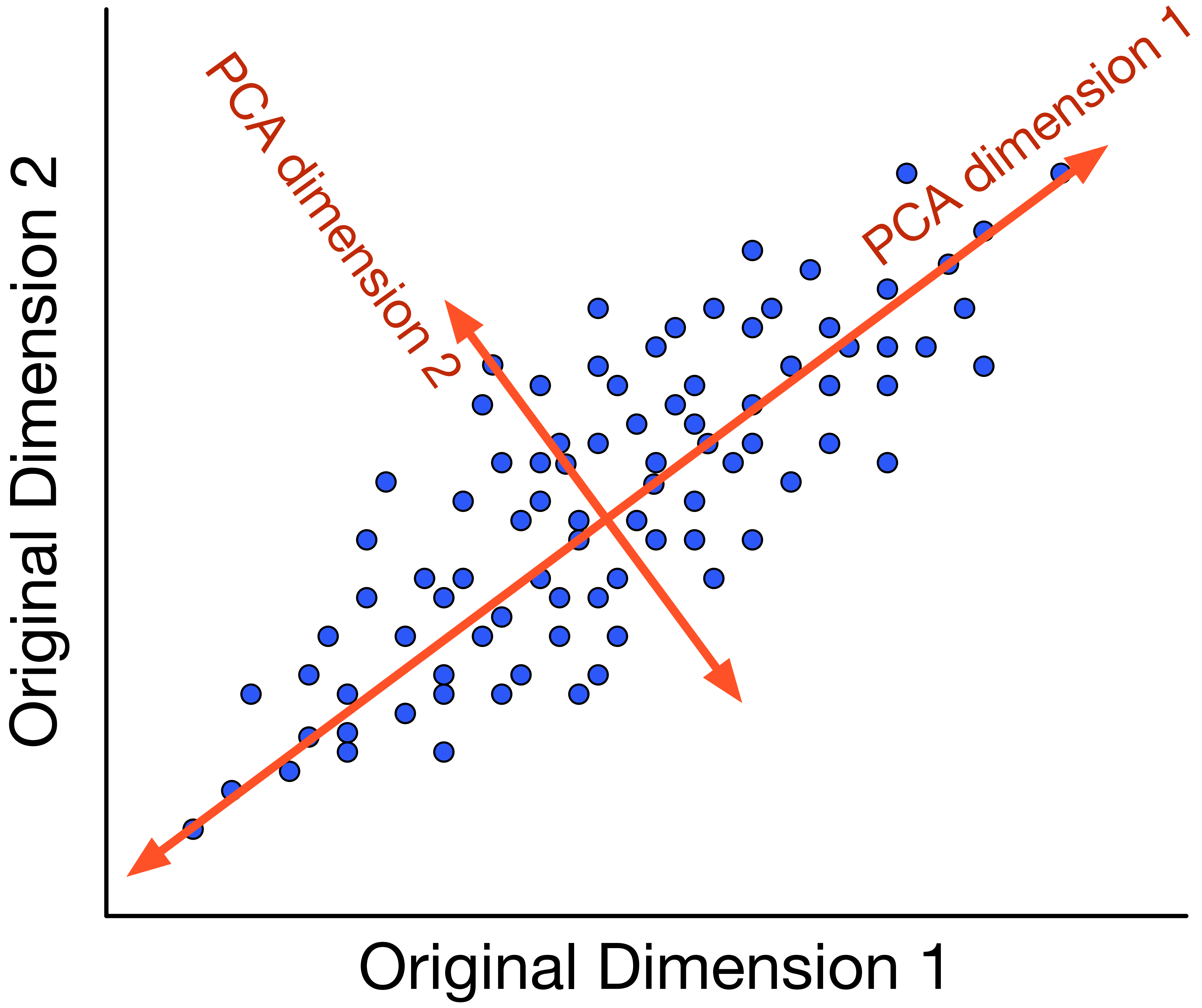

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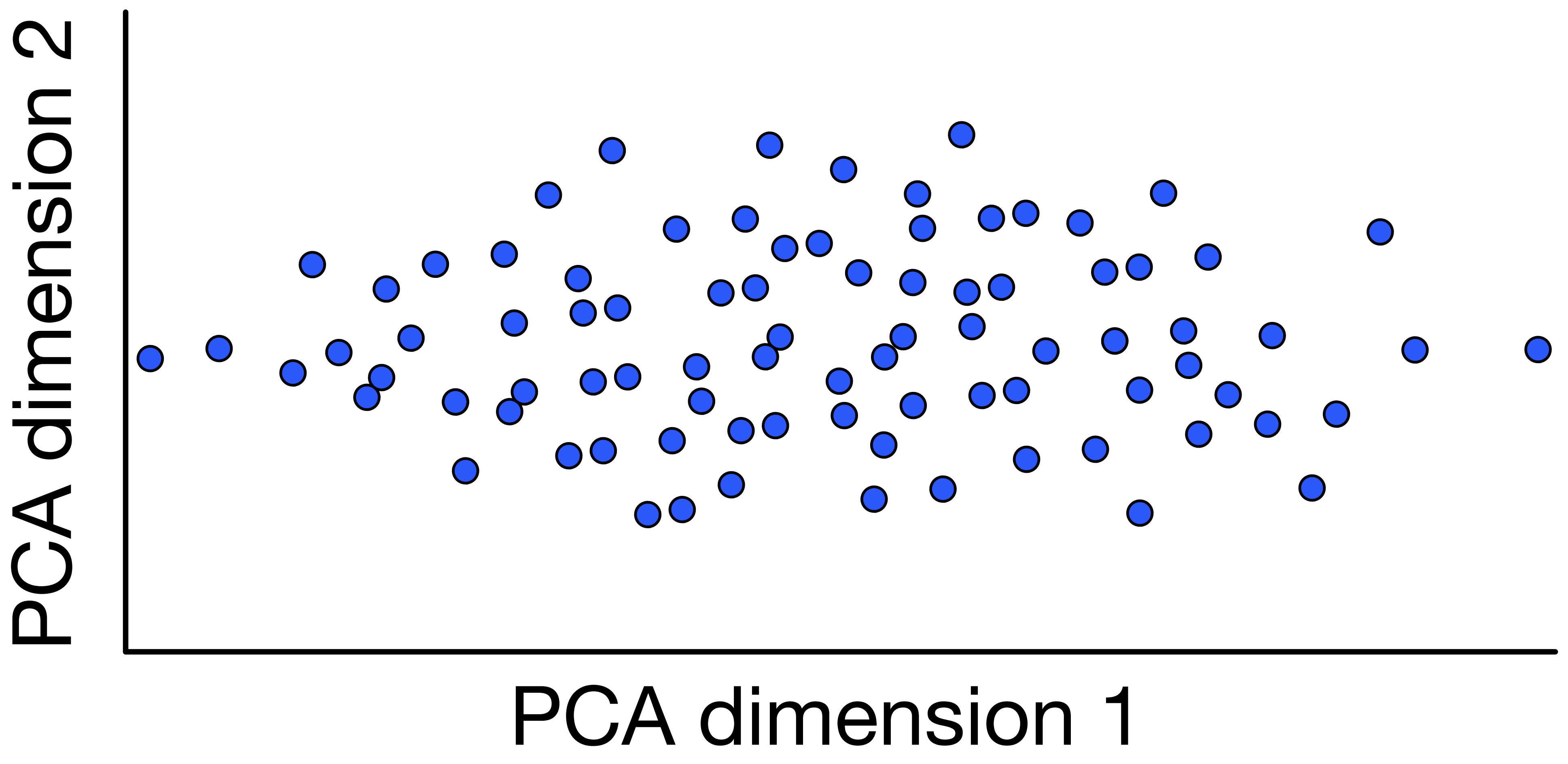

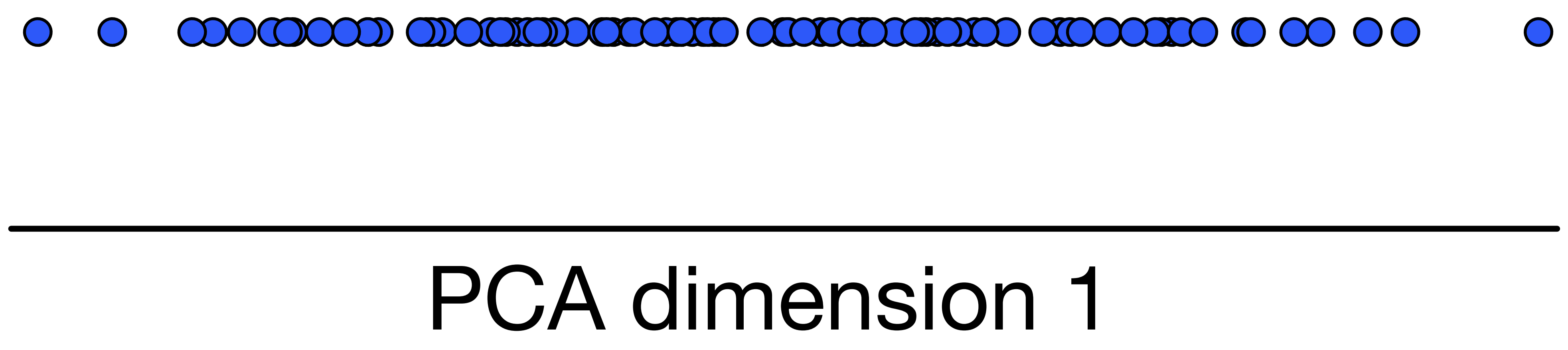

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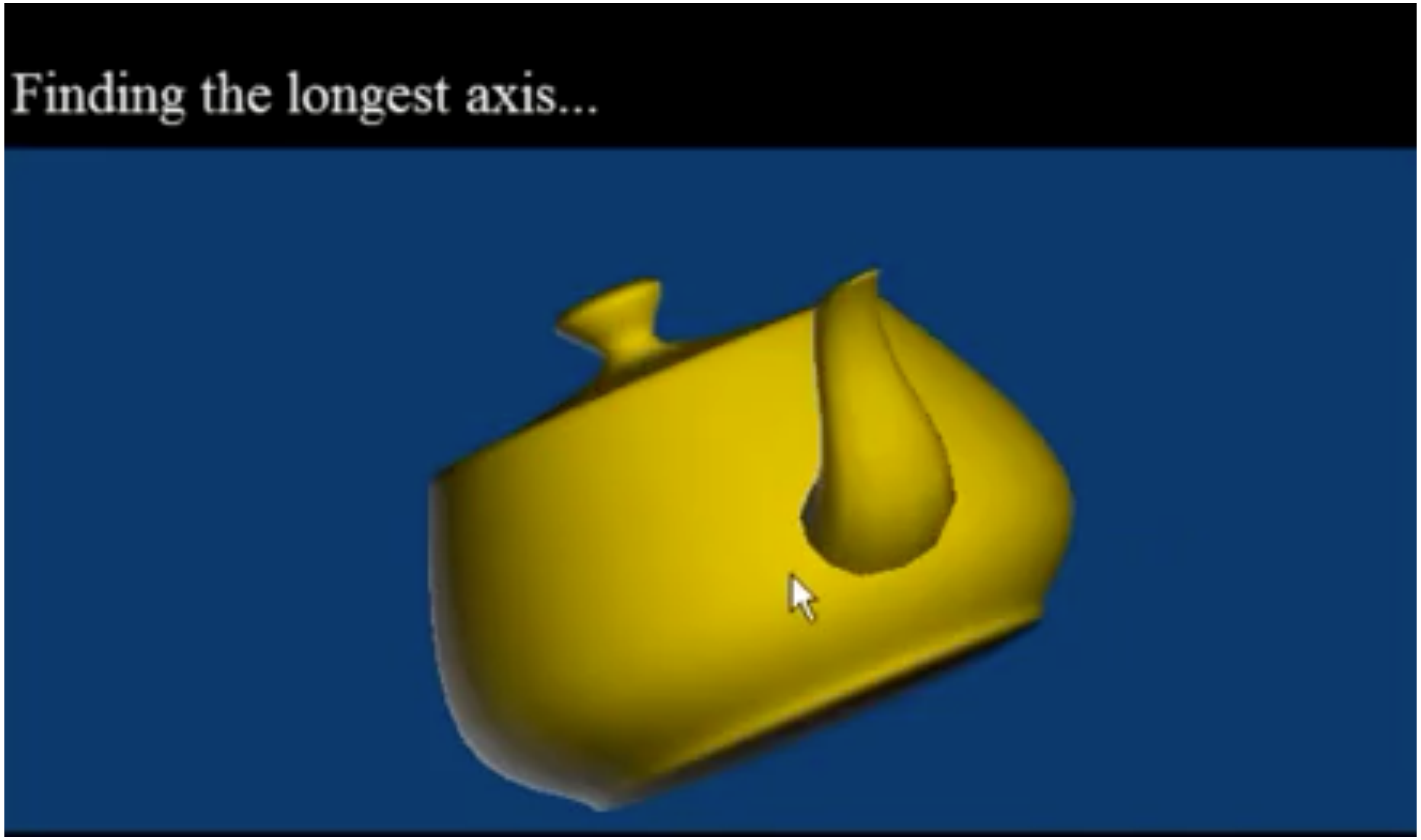
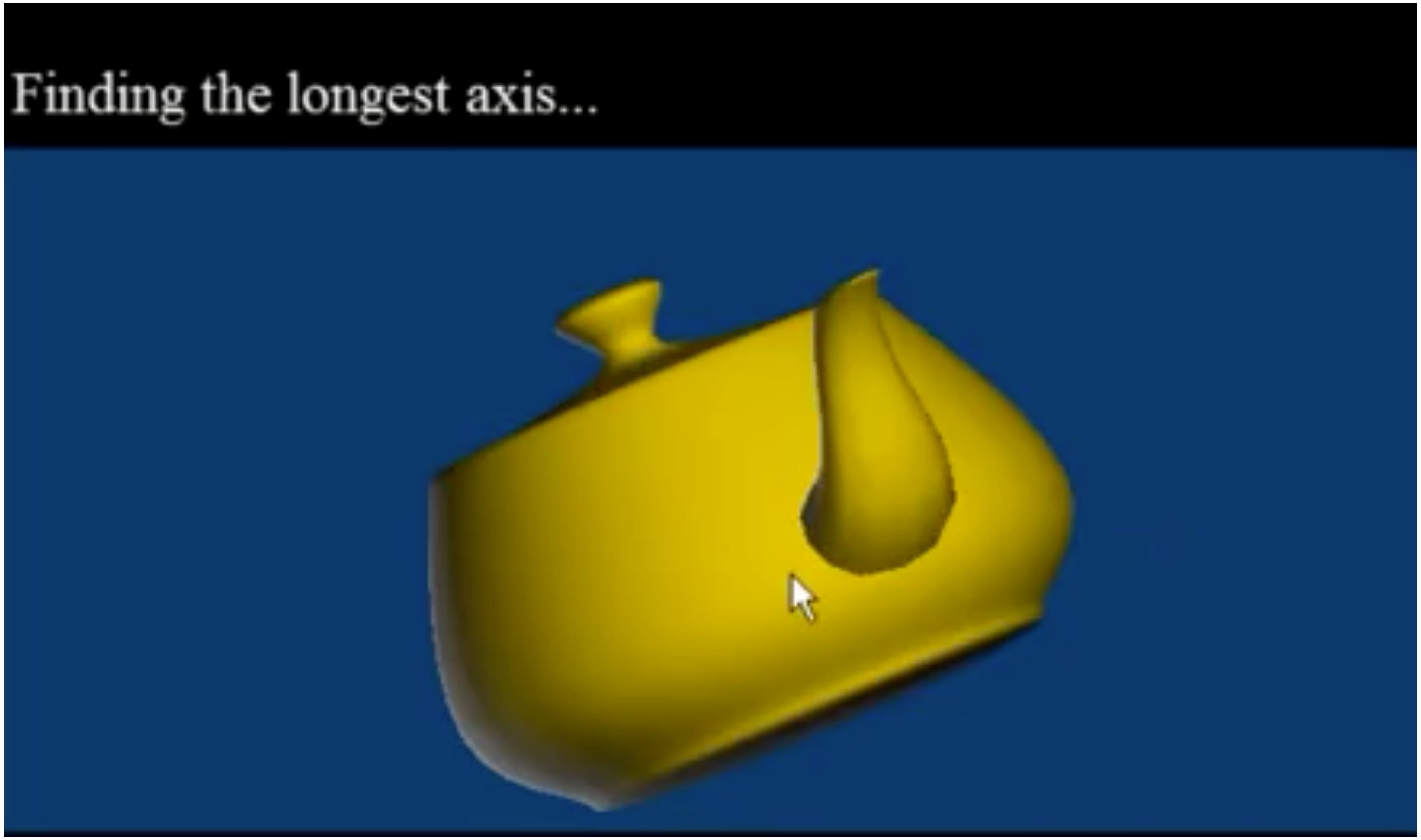


via [A layman's introduction to PCA]

Principal Component Analysis (PCA)



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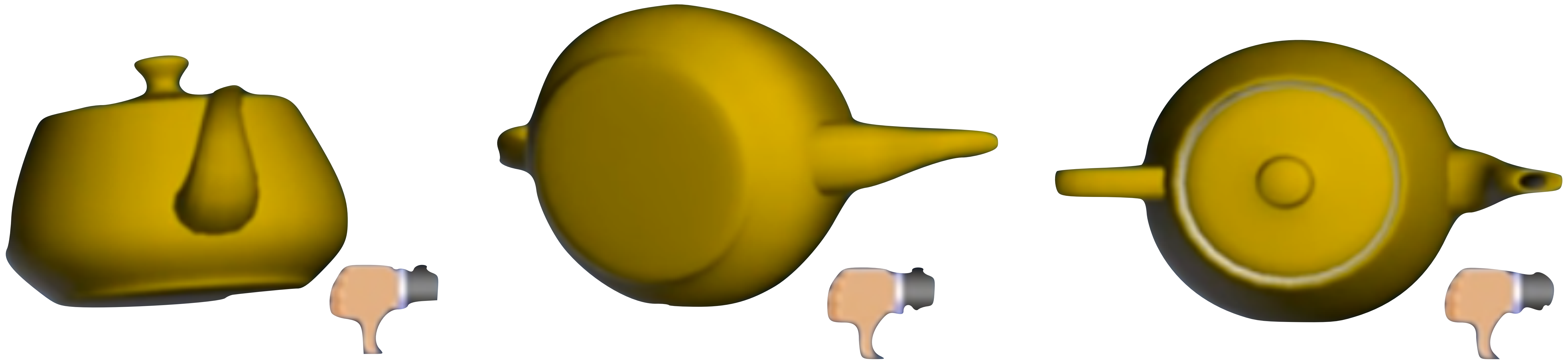
Principal Component Analysis (PCA)

This →

Preserves more information than

These →



via [A layman's introduction to PCA]

Singular Value Decomposition (SVD)

- Enables creation of reduced dimension model
  - Low rank approximation of of original matrix
  - Best-fit at that rank (in least-squares sense)

Singular Value Decomposition (SVD)

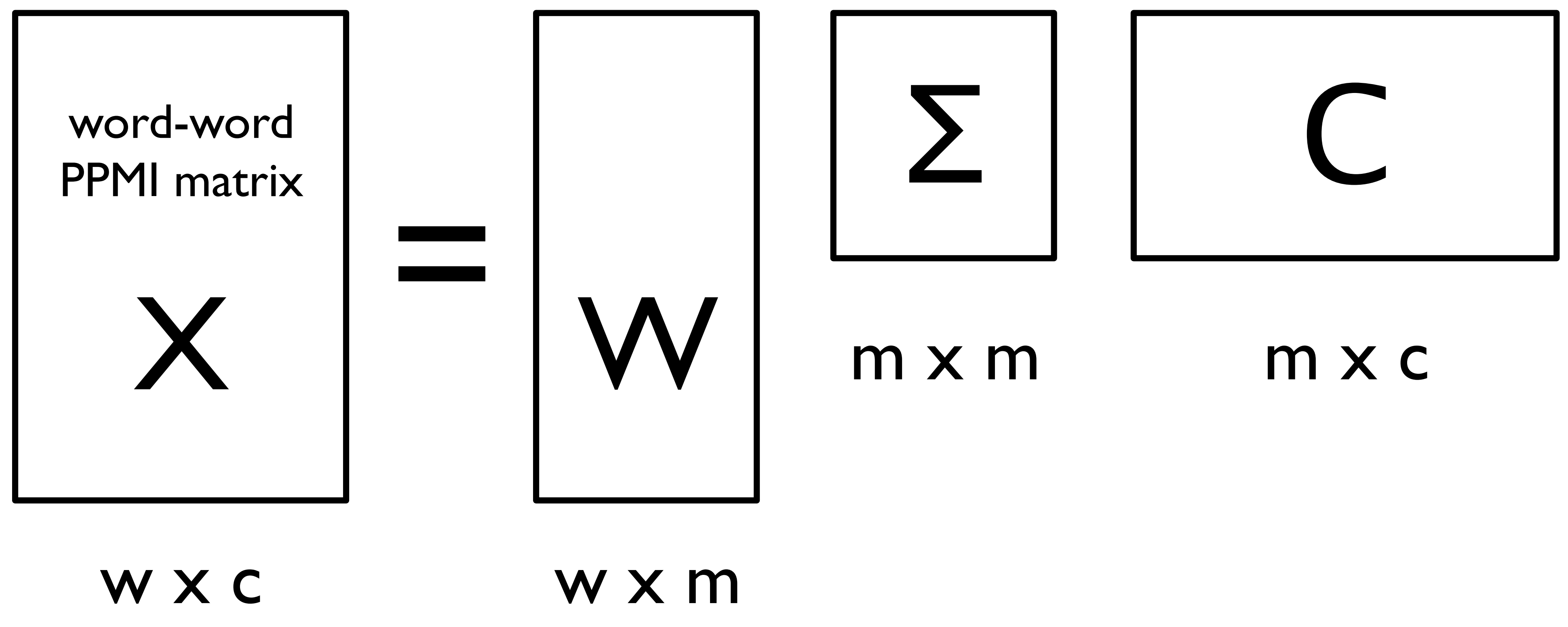
- Original matrix: high dimensional, sparse
  - Similarities missed due to word choice, etc
- Create new, projected space
  - More compact, better captures important variation
- Landauer et al (1998) argue identifies underlying “concepts”
  - Across words with related meanings

Latent Semantic Analysis (LSA)

- Apply SVD to $|\boldsymbol{V}| \times \boldsymbol{c}$ term-document matrix $\boldsymbol{X}$
  - $\boldsymbol{V}$ → Vocabulary
  - $\boldsymbol{c}$ → documents
  - $\boldsymbol{X}$
    - *row* → word
    - *column* → document
    - *cell* → count of word/document

Latent Semantic Analysis (LSA)

- Factor $\boldsymbol{X}$ into three new matrices:
  - $W \rightarrow$ one row per word, but columns are now arbitrary m dimensions
  - $\Sigma \rightarrow$ Diagonal matrix, where every (1,1) (2,2) etc… is the *rank* for m
  - $C^T \rightarrow$ arbitrary m dimensions, as spread across c documents



SVD
Animation

youtu.be/R9UoFyqJca8

Enjoy some 3D Graphics from 1976!

SVD
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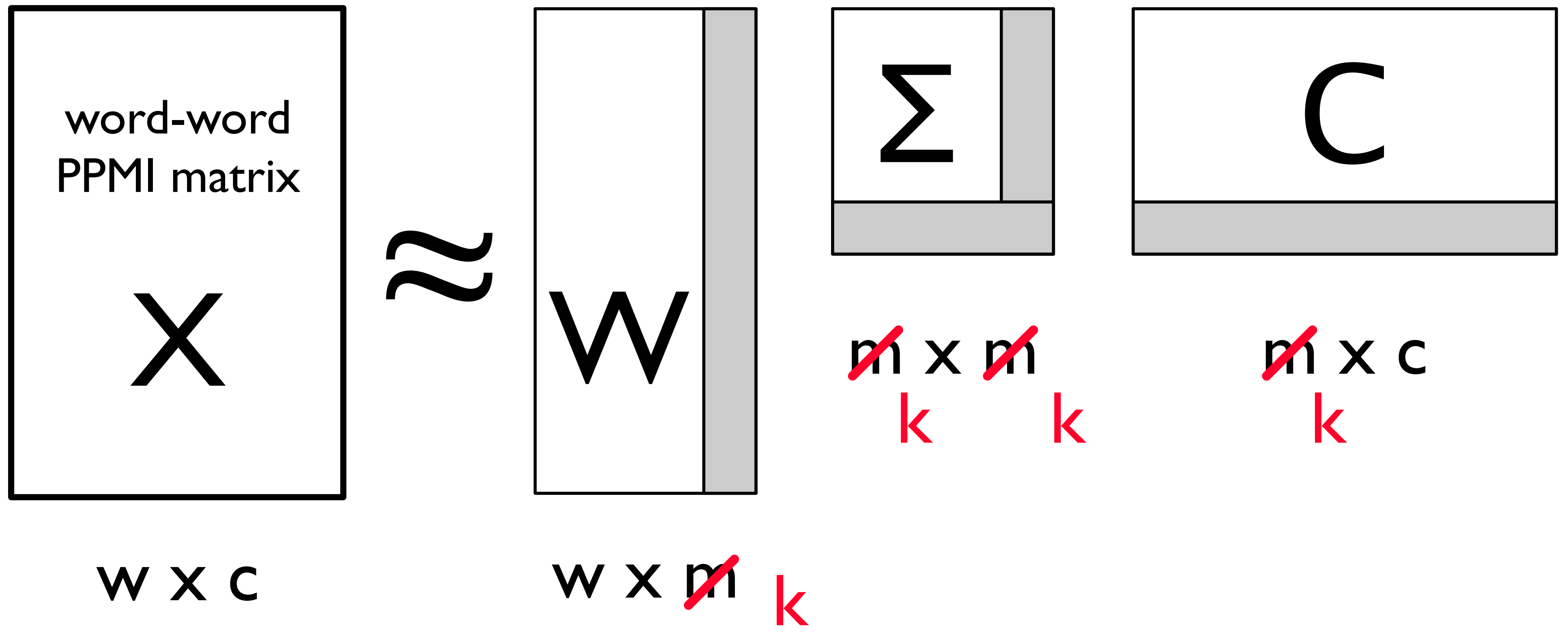
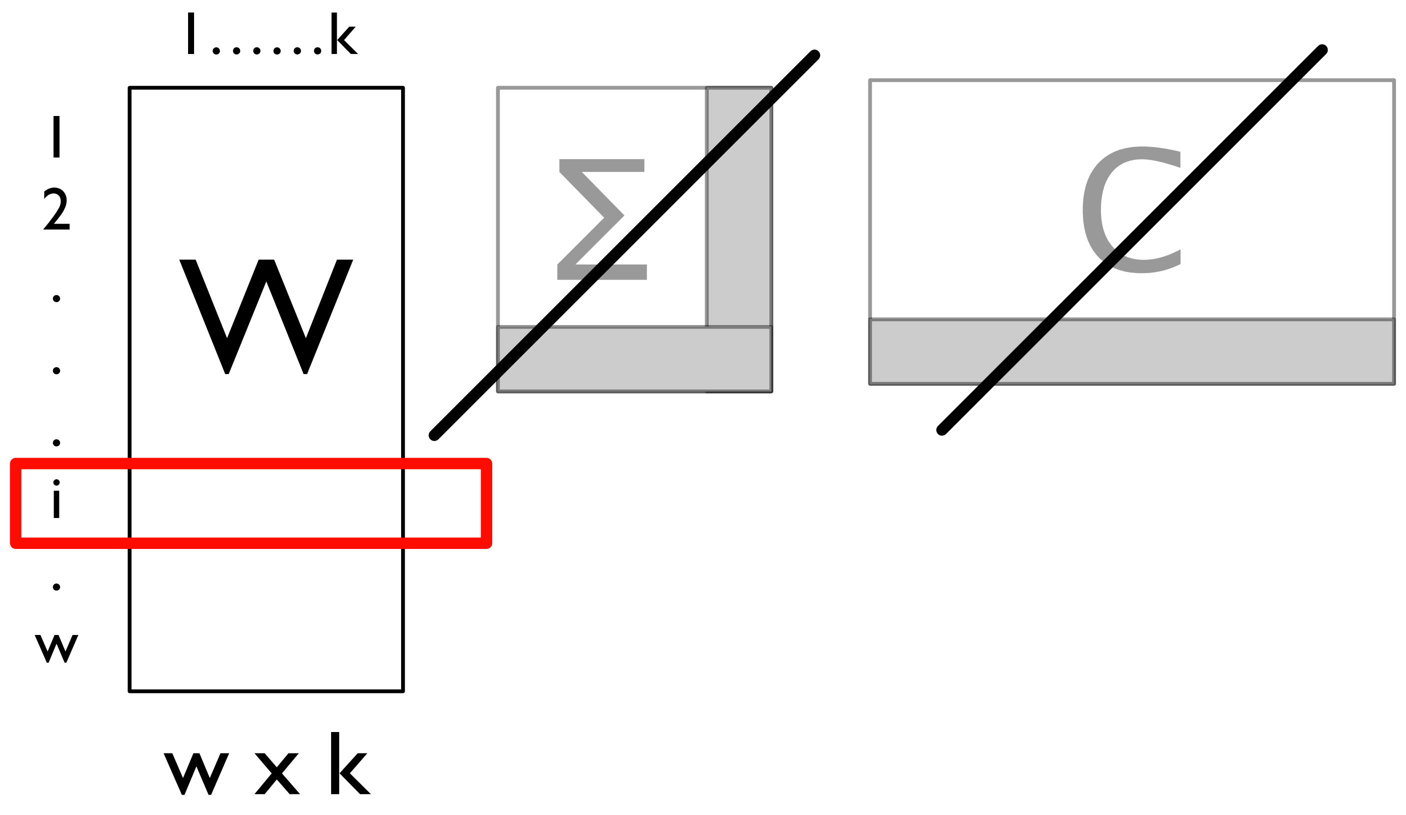
Latent Semantic Analysis (LSA)

- LSA implementations typically:
  - ***truncate*** initial m dimensions to top k



Latent Semantic Analysis (LSA)

- LSA implementations typically:
  - ***truncate*** initial m dimensions to top k
  - then ***discard*** Σ and C matrices
    - Leaving matrix W
    - Each row is now an “embedded” representation of each w across k dimensions



Singular Value Decomposition (SVD)

Original Matrix X (zeroes blank)

	Avengers	Star Wars	Iron Man	Titanic	The Notebook
User1	1	1	1		
User2	3	3	3		
User3	4	4	4		
User4	5	5	5		
User5		2		4	4
User6				5	5
User7		1		2	2

Singular Value Decomposition (SVD)

W $(w \times m)$

	m1	m2	m3
User1	0.13	0.02	-0.01
User2	0.41	0.07	-0.03
User3	0.55	0.09	-0.04
User4	0.68	0.11	-0.05
User5	0.15	-0.59	0.65
User6	0.07	-0.73	-0.67
User7	0.07	-0.29	-0.32

Σ $(m \times m)$

	m1	m2	m3
m1	12.4		
m2		9.5	
m3			1.3

C $(m \times c)$

	Avengers	Star Wars	Iron Man	Titanic	The Notebook
m1	0.56	0.59	0.56	0.09	0.09
m2	0.12	-0.02	0.12	-0.69	-0.69
m3	0.40	-0.80	0.40	0.09	0.09

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$\Sigma \ (m \times m)$

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m3			1.3

"Sci-fi-ness"

$C \ (m \times c)$

	Avengers	Star Wars	Iron Man	Titanic	The Notebook
m1	0.56	0.59	0.56	0.09	0.09
m2	0.12	-0.02	0.12	-0.69	-0.69
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$\Sigma \ (m \times m)$

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m3			1.3

"Romance-ness"

$C \ (m \times c)$

	Avengers	Star Wars	Iron Man	Titanic	The Notebook
m1	0.56	0.59	0.56	0.09	0.09
m2	0.12	-0.02	0.12	-0.69	-0.69
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$\Sigma\ (m{\times}m)$

	m1	m2	m3
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Catchall (noise)

$C\ (m{\times}c)$

	Avengers	Star Wars	Iron Man	Titanic	The Notebook
m1	0.56	0.59	0.56	0.09	0.09
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LSA Document Contexts

- Deerwester et al, 1990: "*Indexing by Latent Semantic Analysis*"
  - Titles of scientific articles

c1	***Human*** machine ***interface*** for ABC ***computer*** applications
c2	A ***survey*** of ***user*** opinion of ***computer system response time***
c3	The ***EPS user interface*** management *system*
c4	***System*** and ***human system*** engineering testing of ***EPS***
c5	Relation of ***user*** perceived ***response time*** to error measurement
m1	The generation of random, binary, ordered ***trees***
m2	The intersection ***graph*** of paths in ***trees***
m3	***Graph minors*** IV: Widths of ***trees*** and well-quasi-ordering
m4	***Graph minors***: A ***survey***

Document Context Representation

- Term x document:
  - $corr$(human, user) $=$ -0.38; $corr$(human, minors)$=$-0.29

	c1	c2	c3	c4	c5	m1	m2	m3	m4
human	1	0	0	1	0	0	0	0	0
interface	1	0	1	0	0	0	0	0	0
computer	1	1	0	0	0	0	0	0	0
user	0	1	1	0	1	0	0	0	0
system	0	1	1	2	0	0	0	0	0
response	0	1	0	0	1	0	0	0	0
time	0	1	0	0	1	0	0	0	0
EPS	0	0	1	1	0	0	0	0	0
survey	0	1	0	0	0	0	0	0	1
trees	0	0	0	0	0	1	1	1	0
graph	0	0	0	0	0	0	1	1	1
minors	0	0	0	0	0	0	0	1	1

Improved Representation

- Reduced dimension projection:
  - $corr(\text{human, user}) = 0.98; \quad corr(\text{human, minors}) = -0.83$

	c1	c2	c3	c4	c5	m1	m2	m3	m4
human	0.16	0.40	0.38	0.47	0.18	-0.05	-0.12	-0.16	-0.09
interface	0.14	0.37	0.33	0.40	0.16	-0.03	-0.07	-0.10	-0.04
computer	0.15	0.51	0.36	0.41	0.24	0.02	0.06	0.09	0.12
user	0.26	0.84	0.61	0.70	0.39	0.03	0.08	0.12	0.19
system	0.45	1.23	1.05	1.27	0.56	-0.07	-0.15	-0.21	-0.05
response	0.16	0.58	0.38	0.42	0.28	0.05	0.13	0.19	0.22
time	0.16	0.58	0.38	0.42	0.28	0.06	0.13	0.19	0.22
EPS	0.22	0.55	0.51	0.63	0.24	-0.07	-0.14	-0.20	-0.11
survey	0.10	0.53	0.23	0.21	0.27	0.14	0.31	0.33	0.42
trees	-0.06	0.23	-0.14	-0.27	0.14	0.24	0.55	0.77	0.66
graph	-0.06	0.34	-0.15	-0.30	0.20	0.31	0.69	0.98	0.85
minors	-0.04	0.25	-0.10	-0.21	0.15	0.22	0.50	0.71	0.62

Python Tutorial for LSA

- For those interested in seeing how LSA works in practice:
  - technowiki.wordpress.com/2011/08/27/latent-semantic-analysis-lsa-tutorial/

Dimensionality Reduction for Visualization

- “I see well in many dimensions as long as the dimensions are around two.”
  - —Martin Shubek
- Even with ‘dense’ embeddings, techniques like PCA are useful for visualization
- Another popular one: t-SNE
- Useful for exploratory analysis

Prediction-Based Models

Prediction-based Embeddings

- LSA models: good, but expensive to compute

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Prediction-based Embeddings

- LSA models: good, but expensive to compute
- *Skip-gram* and *Continuous Bag of Words* (CBOW) models
- Intuition:
  - Words with similar meanings share similar contexts
  - Train language models to learn to predict context words
  - Models train embeddings that make current word more like nearby words and less like distance words
  - Provably related to PPMI models under SVD

Embeddings: Skip-Gram vs. Continuous Bag of Words

- Continuous Bag of Words (CBOW):
  - $P(\boldsymbol{word} \,|\, \boldsymbol{context})$
  - Input: $(w_{t\text{-}1},\ w_{t\text{-}2},\ w_{t+1},\ wt_{+2}\ \ldots)$
  - Output: $p(\boldsymbol{w_t})$

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  - Output: $p(w_t)$
- Skip-gram:
  - $P(context \mid word)$
  - Input: w_t
  - Output: $p(w_{t\text{-}1},\ w_{t\text{-}2},\ w_{t+1},\ w_{t+2}\ \ldots)$

Embeddings:
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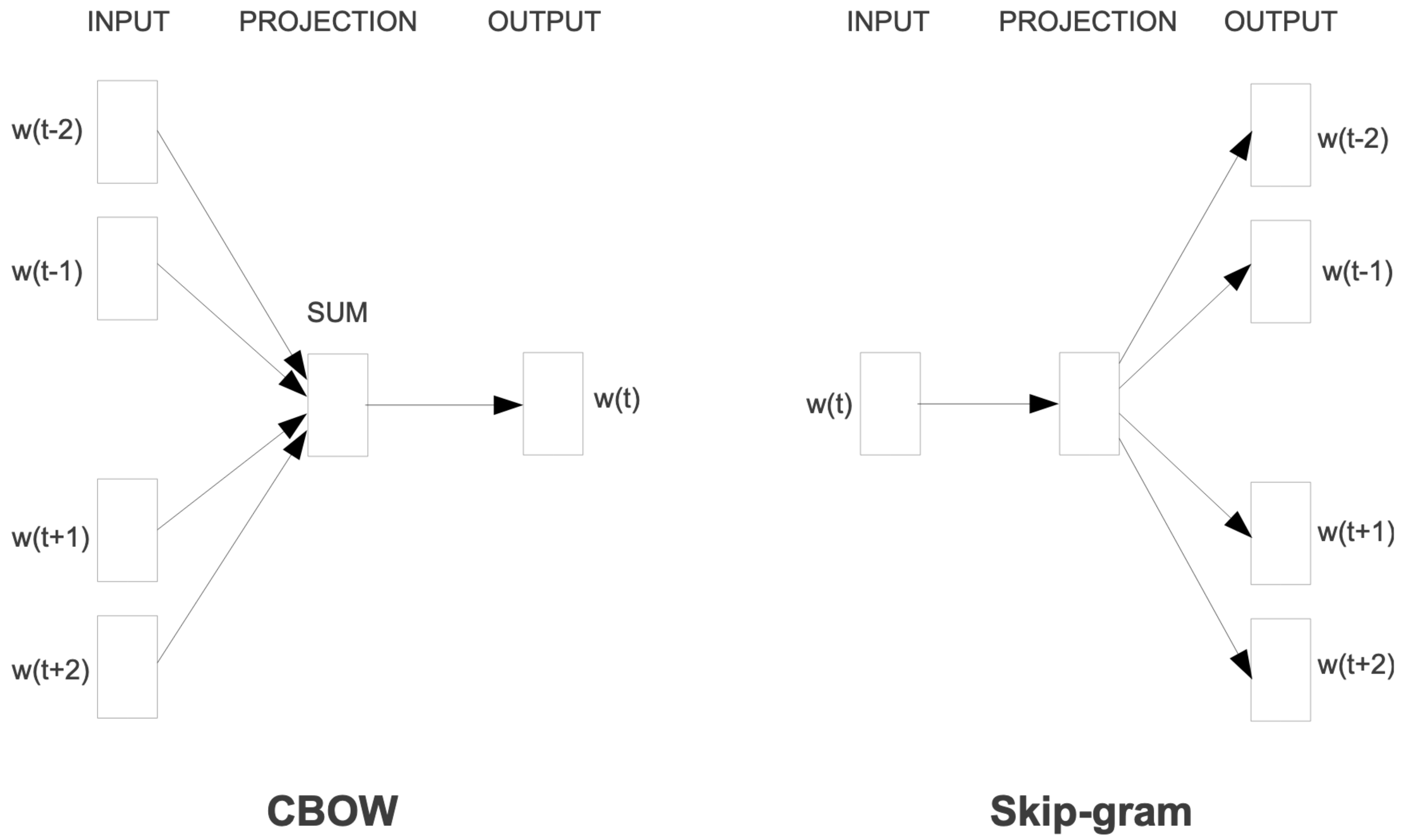


Mikolov et al 2013a (the OG `word2vec` paper)

Skip-Gram Model

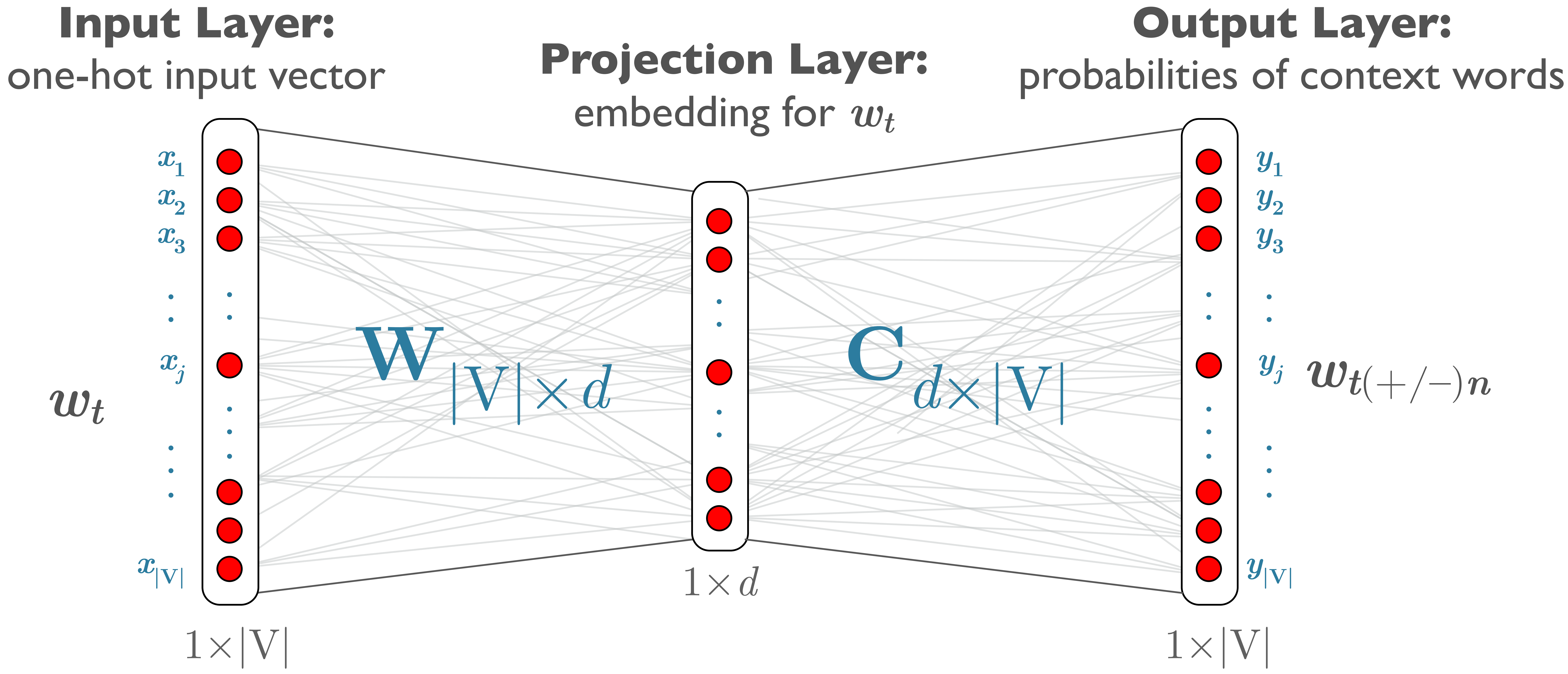
- Learns two embeddings
  - W : word
  - C : context of some fixed dimension

Skip-Gram Model

- Learns two embeddings
  - W : word
  - C : context of some fixed dimension
- Prediction task:
  - Given a word, predict each neighbor word in window
  - Compute $p(w_k|w_j)$ represented as $c_k \cdot v_j$
    - For each context position
  - Convert to probability via softmax

$$p(w_k|w_j) = \frac{\exp(c_k \cdot v_j)}{\sum_{i \in |V|} \exp(c_i \cdot v_j)}$$

Skip-Gram Network Visualization



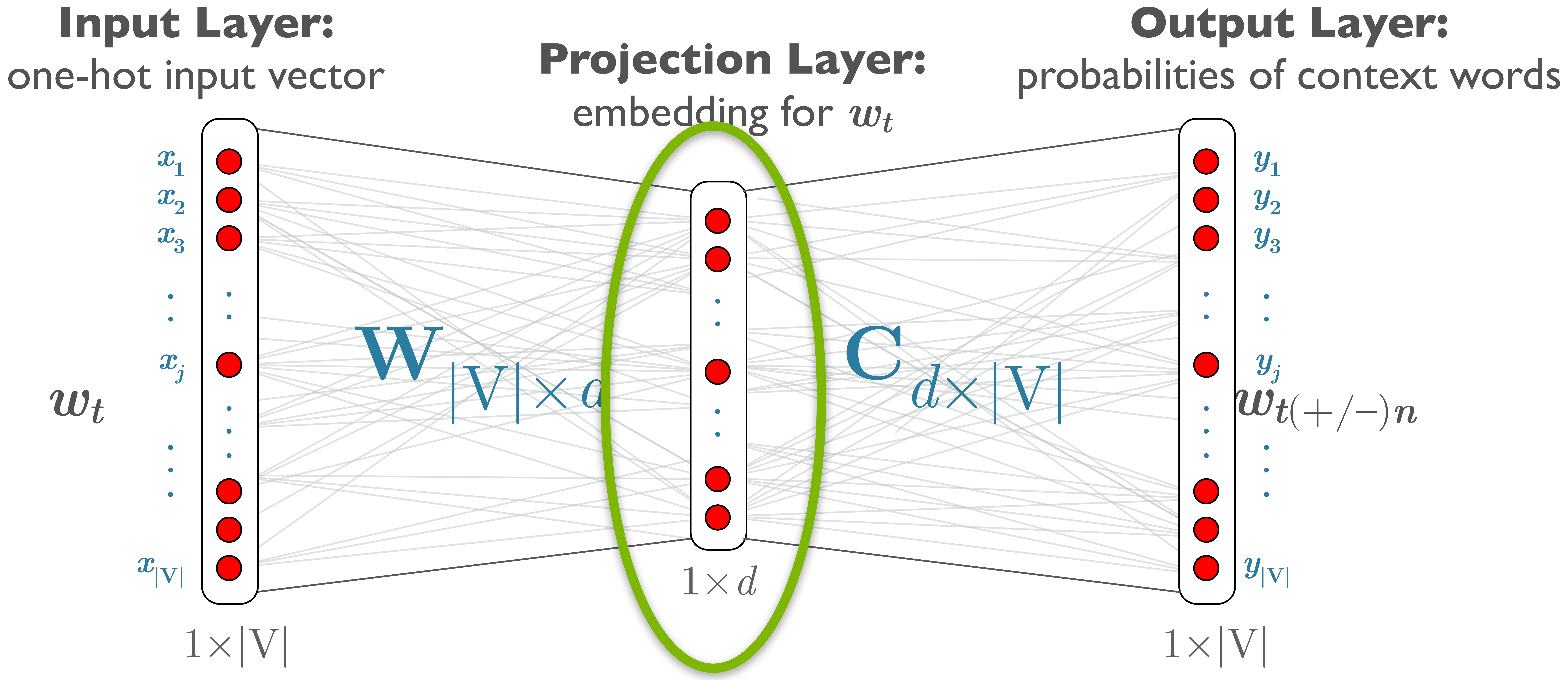
Training The Model

- Issue:
  - Denominator computation is very expensive
- Strategy:
  - Approximate by negative sampling (efficient approximation to Noise Contrastive Estimation):
    - + example: true context word
    - – example: k other words, sampled

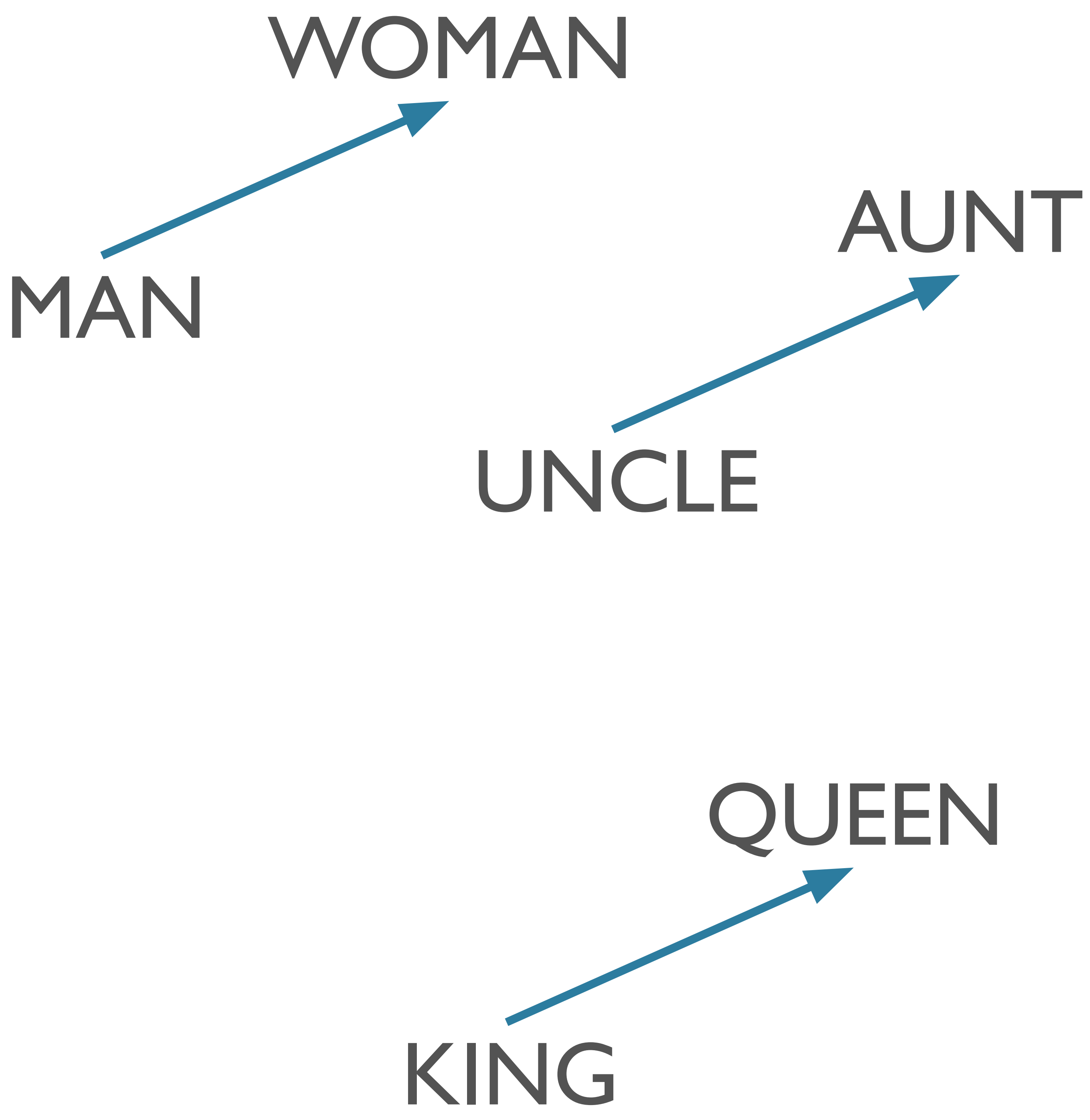
Training The Model

- Approach:
  - Randomly initialize W, C
  - Iterate over corpus, update w/ stochastic gradient descent
  - Update embeddings to improve loss function
- Use trained embeddings directly as word representations

Skip-Gram Network Visualization

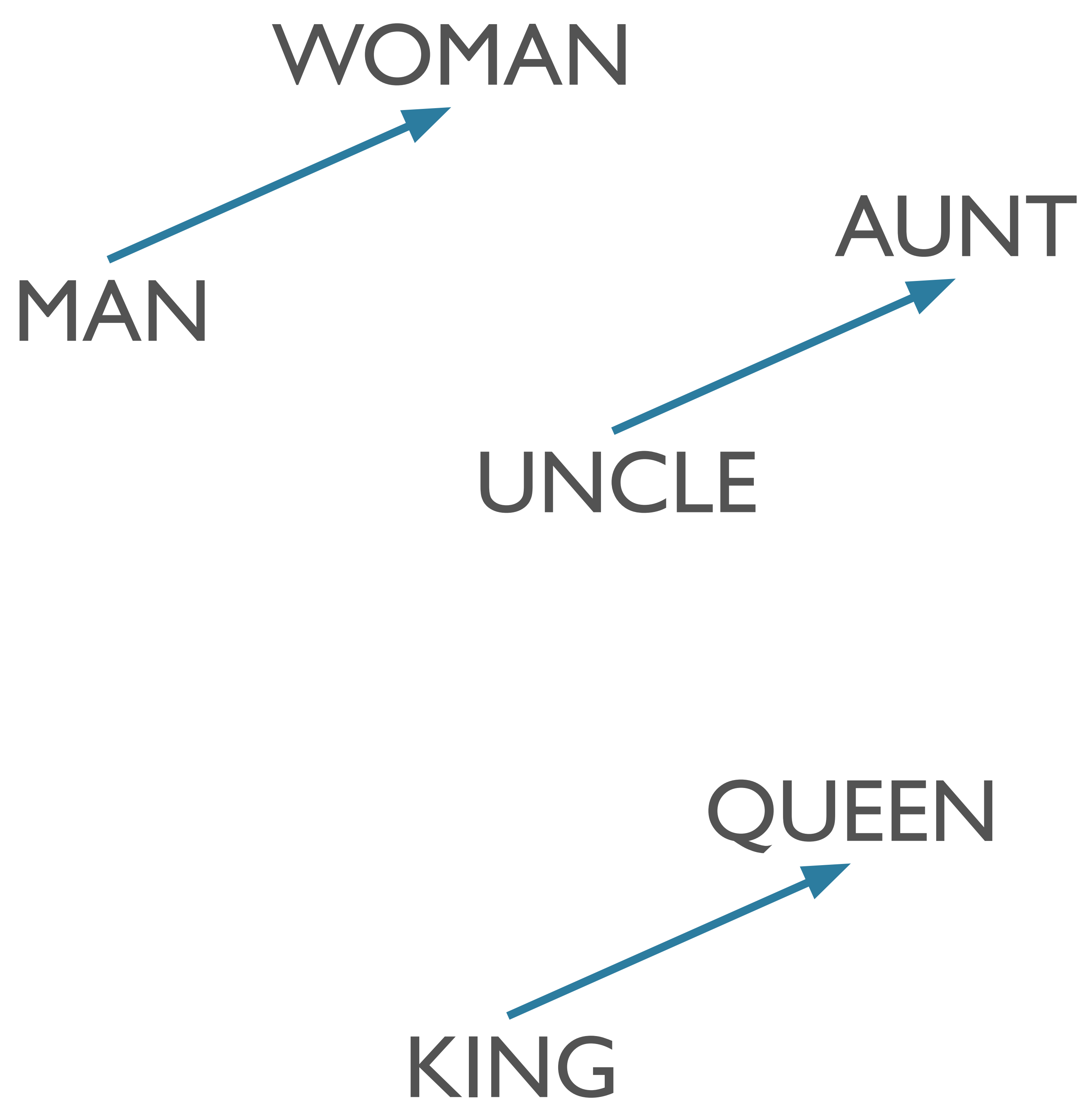


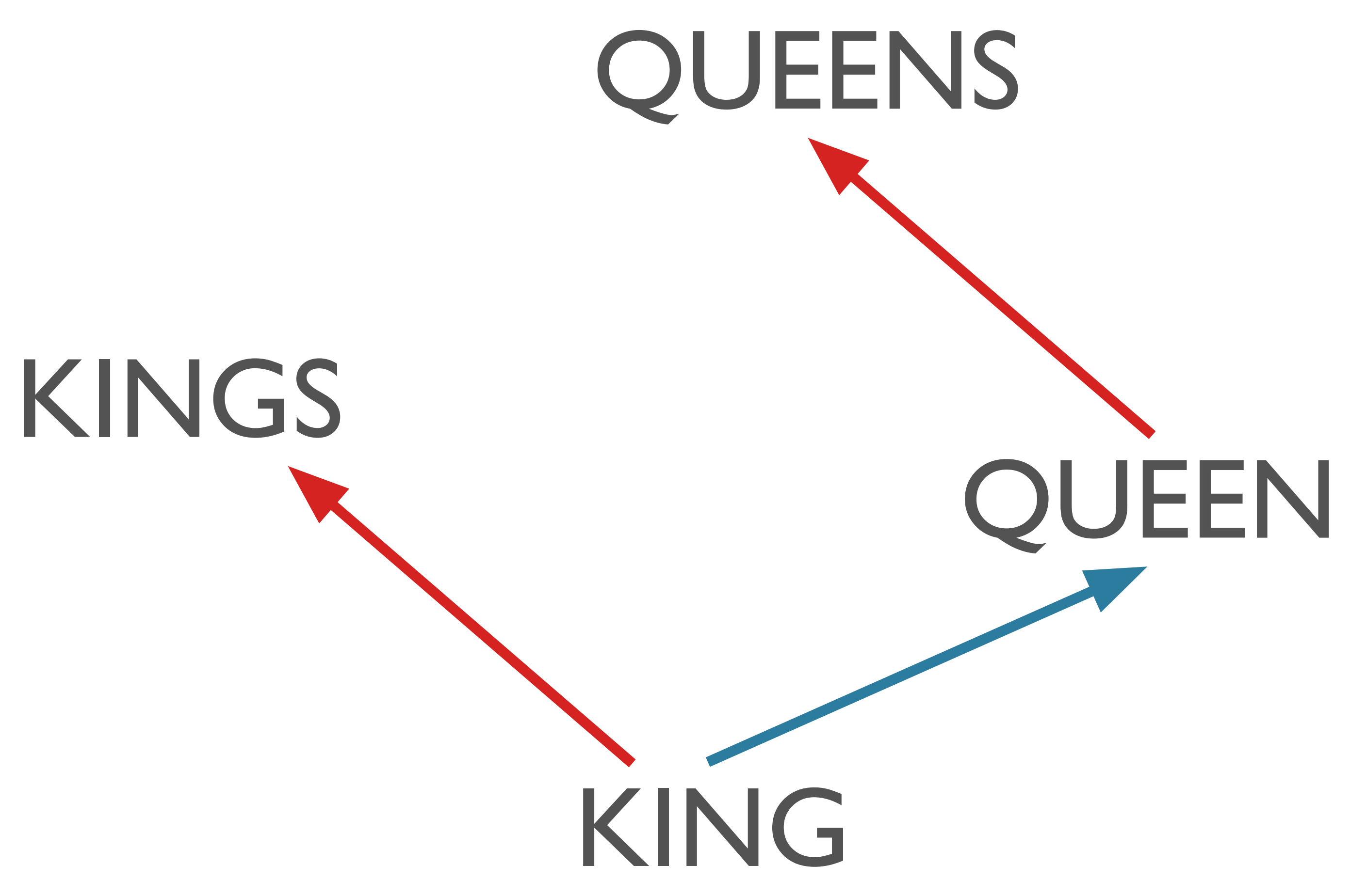
Relationships via Offsets



Mikolov et al 2013b

Relationships via Offsets





Mikolov et al 2013b

One More Example

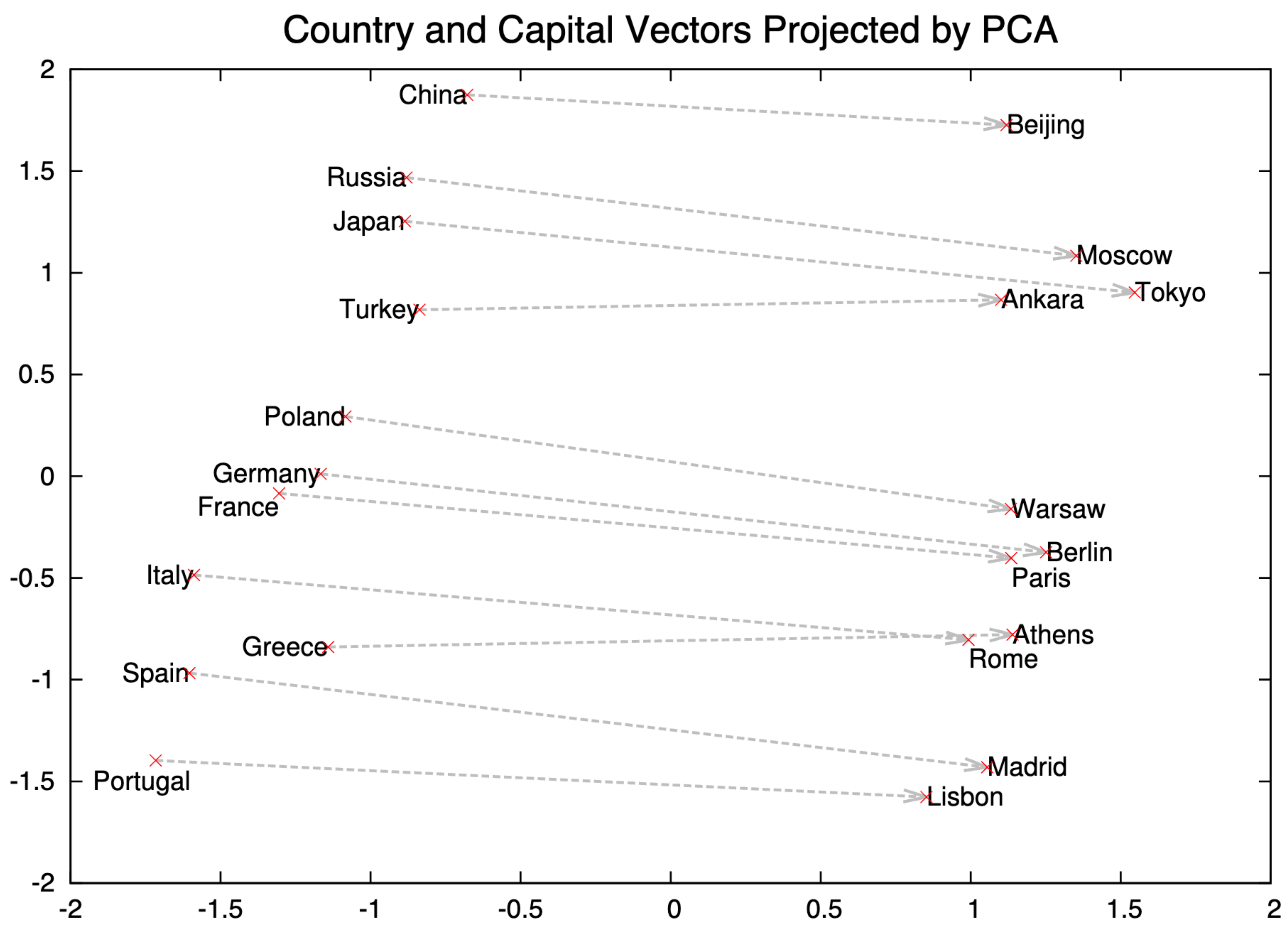
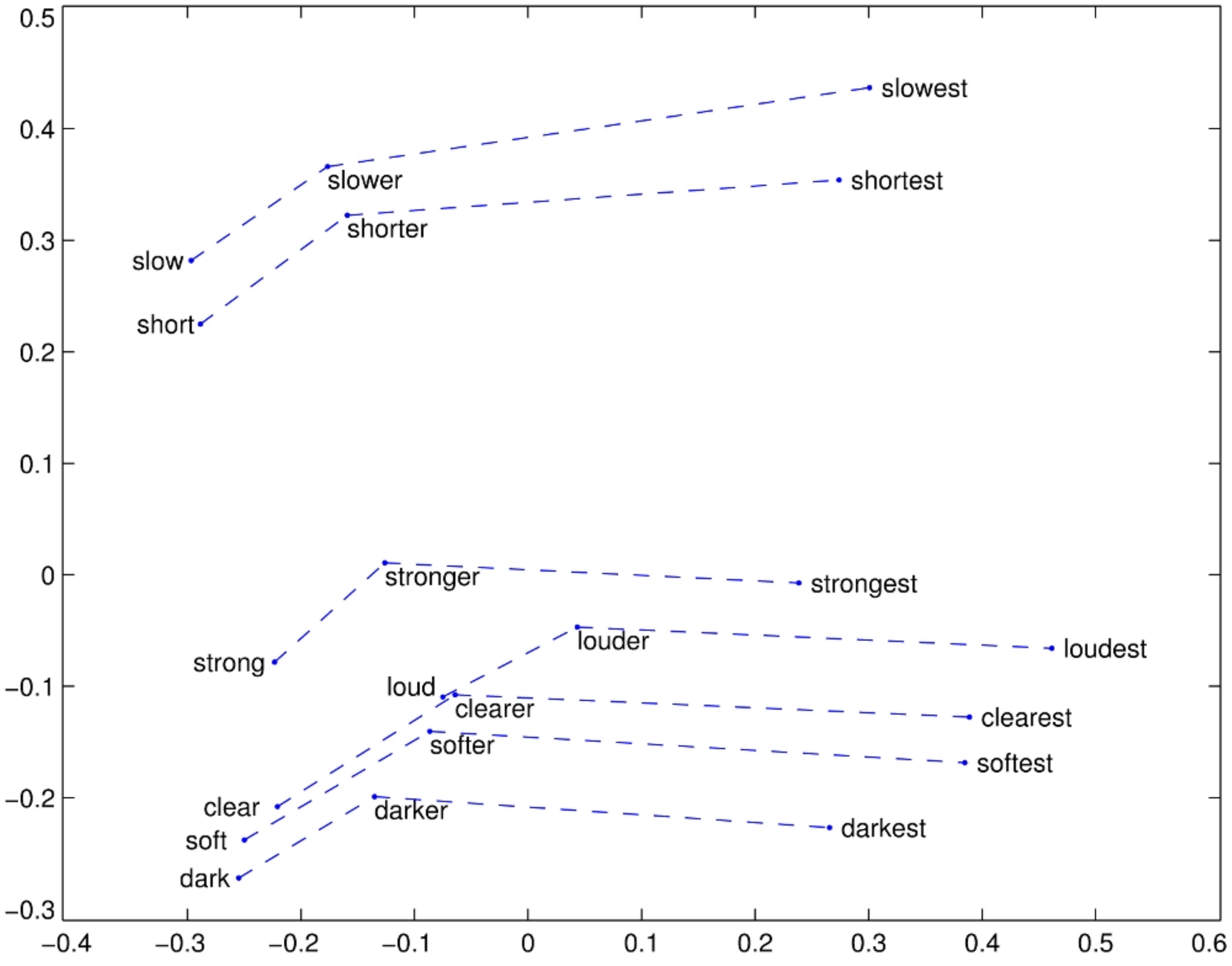


Figure 2: Two-dimensional PCA projection of the 1000-dimensional Skip-gram vectors of countries and their capital cities. The figure illustrates ability of the model to automatically organize concepts and learn implicitly the relationships between them, as during the training we did not provide any supervised information about what a capital city means.

Mikolov et al 2013c

One More Example



Caveat Emptor

Issues in evaluating semantic spaces using word analogies

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Abstract

The offset method for solving word analogies has become a standard evaluation tool for vector-space semantic models: it is considered desirable for a space to represent semantic relations as consistent vector offsets. We show that the method's reliance on cosine similarity conflates offset consistency with largely irrelevant neighborhood structure, and propose simple baselines that should be used to improve the utility of the method in vector space evaluation.

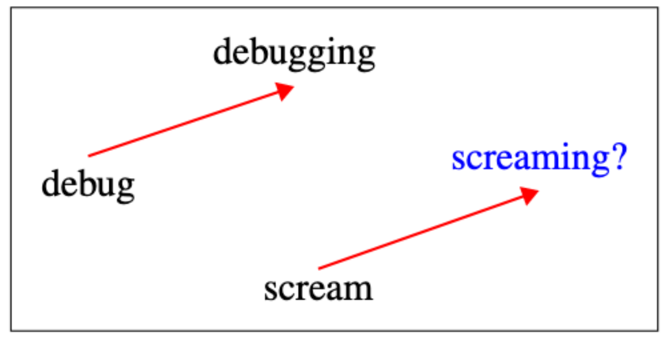


Figure 1: Using the vector offset method to solve the analogy task (Mikolov et al., 2013c).

cosine similarity to the landing point. Formally, if the analogy is given by

$$a : a^* :: b : \_\_\_ \tag{1}$$

Linzen 2016, a.o.

Diverse Applications

- Unsupervised POS tagging
- Word Sense Disambiguation
- Essay Scoring
- Document Retrieval
- Unsupervised Thesaurus Induction
- Ontology/Taxonomy Expansion
- Analogy Tests, Word Tests
- Topic Segmentation

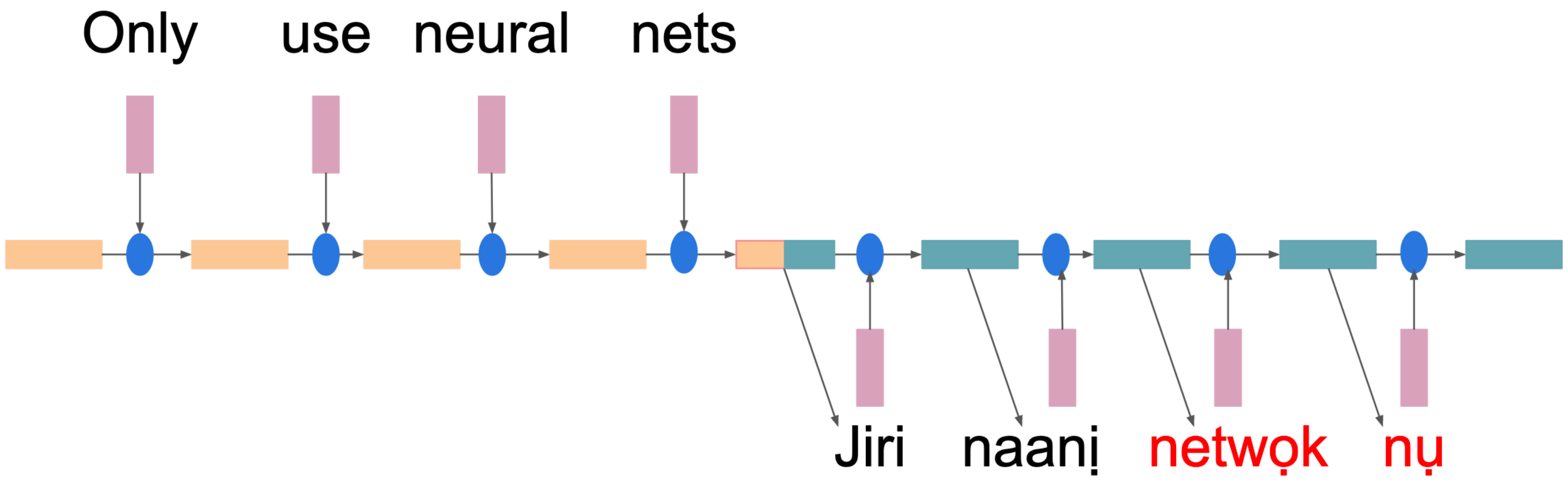
General Recipe

General Recipe

- Embedding layer (~300-dimensions):
  - download pre-trained embeddings
  - Use as look-up table for every word
  - Then feed those vectors into model of choice

General Recipe

- Embedding layer (~300-dimensions):
  - download pre-trained embeddings
  - Use as look-up table for every word
  - Then feed those vectors into model of choice



Depiction of seq2seq NMT architecture
c/o Hewitt & Kriz

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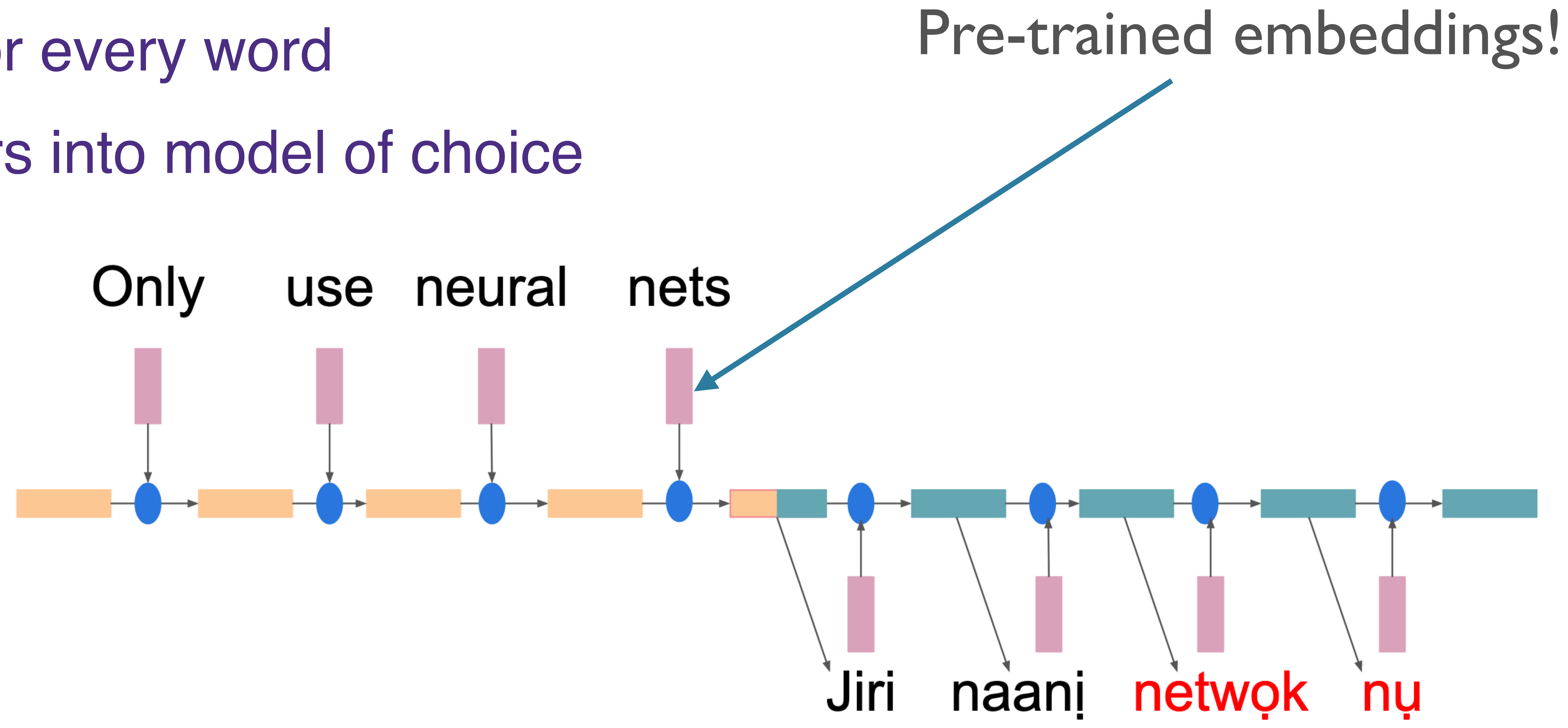

Depiction of seq2seq NMT architecture
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General Recipe

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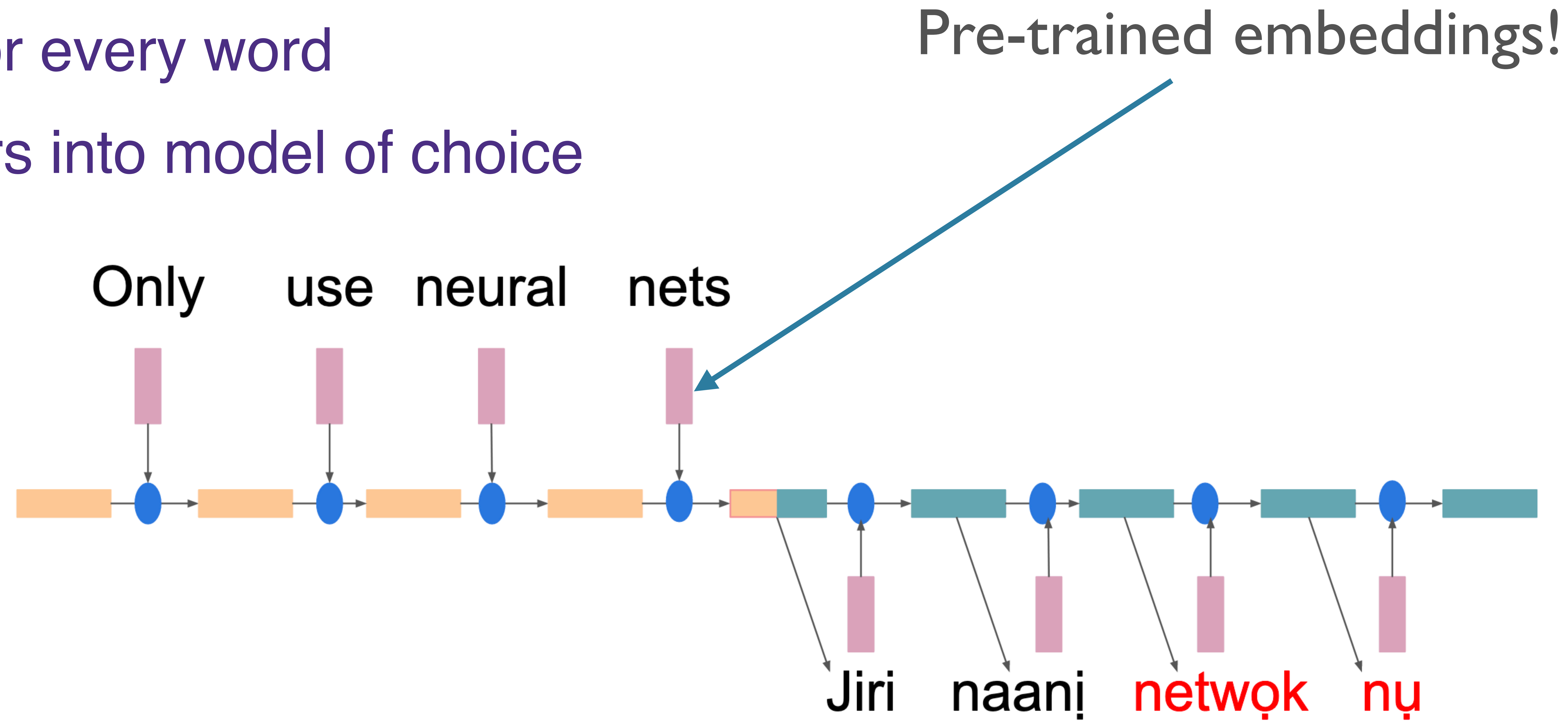
- Newer embeddings:
  - [fastText]
  - [GloVe]

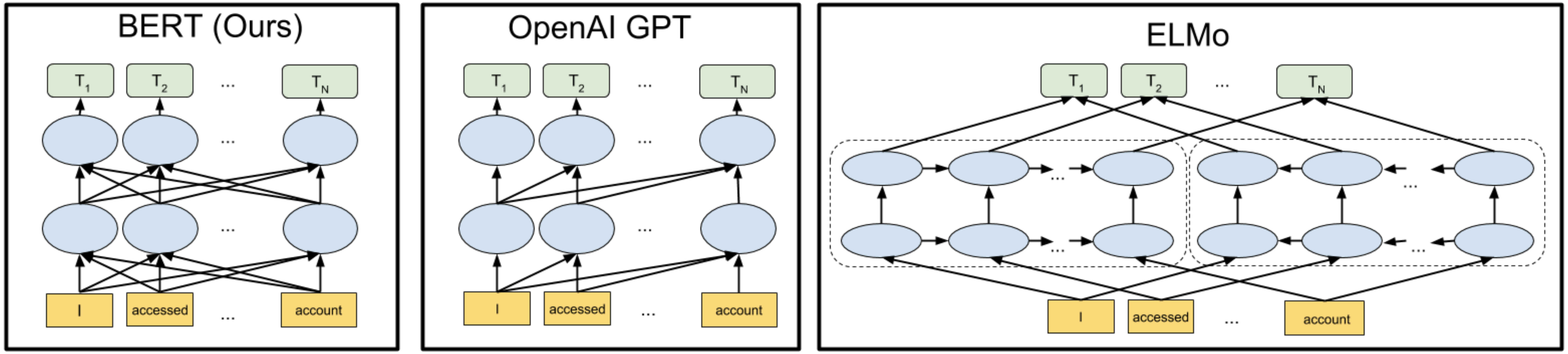


Depiction of seq2seq NMT architecture
c/o [Hewitt & Kriz]

Contextual Word Representations

- Global embeddings: single fixed word-vector look-up table
- Contextual embeddings:
  - Get a different vector for every occurrence of every word
- A recent revolution in NLP
- Here's a nice "contextual introduction"

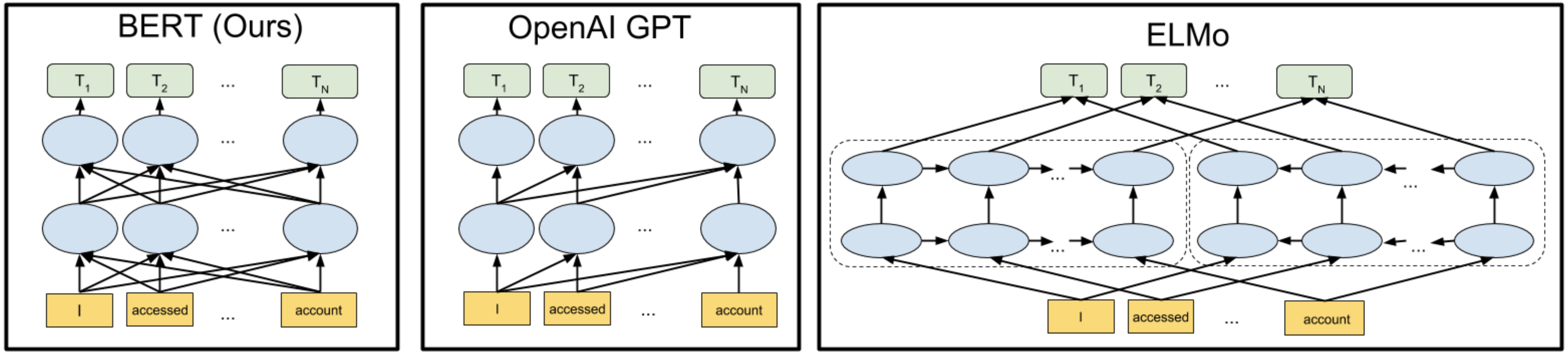
Contextual Word Representations



Devlin et al 2018 | Radford et al 2019 | Peters et al 2018

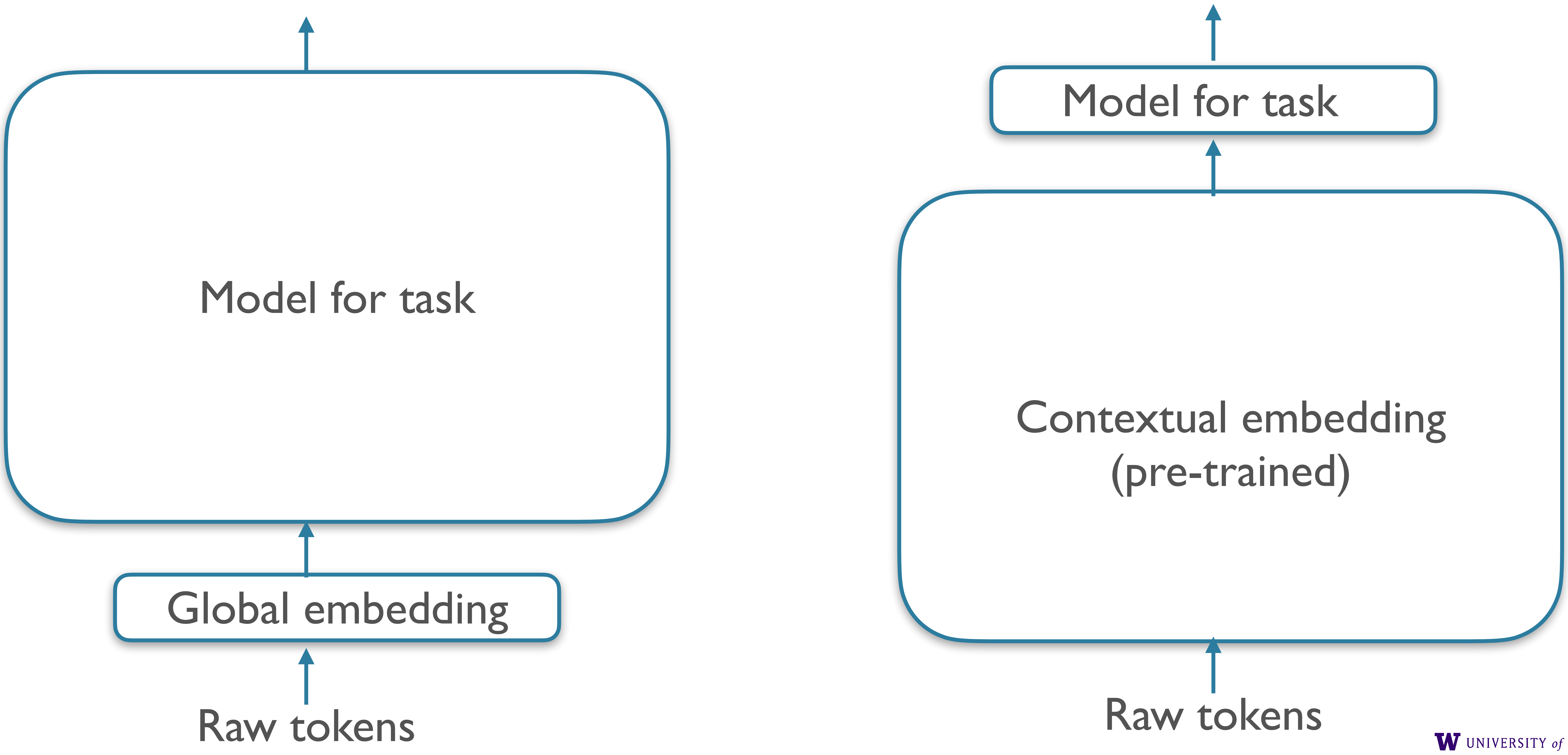
Contextual Word Representations

“Embeddings from Language Models”



[Devlin et al 2018](#) [Radford et al 2019](#) [Peters et al 2018](#)

Global vs Contextual Representations



Ethical Issues Around Embeddings

- Models that learn representations from reading human-produced raw text also learn our biases

Man is to Computer Programmer as Woman is to Homemaker? Debiasing Word Embeddings

Tolga Bolukbasi[1], **Kai-Wei Chang**[2], **James Zou**[2], **Venkatesh Saligrama**[1,2], **Adam Kalai**[2]
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Abstract

The blind application of machine learning runs the risk of amplifying biases present in data. Such a danger is facing us with *word embedding*, a popular framework to represent text data as vectors which has been used in many machine learning and natural language processing tasks. We show that even word embeddings trained on Google News articles exhibit female/male gender stereotypes to a disturbing extent. This raises concerns because their widespread use, as we describe, often tends to amplify these biases. 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*. Using crowd-worker evaluation as well as standard benchmarks, we

Boukbasi et al 2016

Distributional Similarity for Word Sense Disambiguation

There are more kinds of **plants** and animals in the rainforests than anywhere else on Earth. Over half of the millions of known species of **plants** and animals live in the rainforest. Many are found nowhere else. There are even **plants** and animals in the rainforest that we have not yet discovered.

Biological Example

The Paulus company was founded in 1938. Since those days the product range has been the subject of constant expansions and is brought up continuously to correspond with the state of the art. We're engineering, manufacturing and commissioning world-wide ready-to-run **plants** packed with our comprehensive know-how. Our Product Range includes pneumatic conveying systems for carbon, carbide, sand, lime and many others. We use reagent injection in molten metal for the…

Industrial Example

Label the First Use of "Plant"

Word Representation

- 2nd Order Representation:
  - Identify words in context of w
  - For each x in context of w:
    - Compute x vector representation
  - Compute centroid of these $\vec{x}$ vector representations

Computing Word Senses

- Compute context vector for each occurrence of word in corpus

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- Cluster centroid represents word sense
- Link to specific sense?
  - Pure unsupervsed: no sense tag, just i^{th} sense
  - Some supervision: hand label clusters, or tag training

Disambiguating Instances

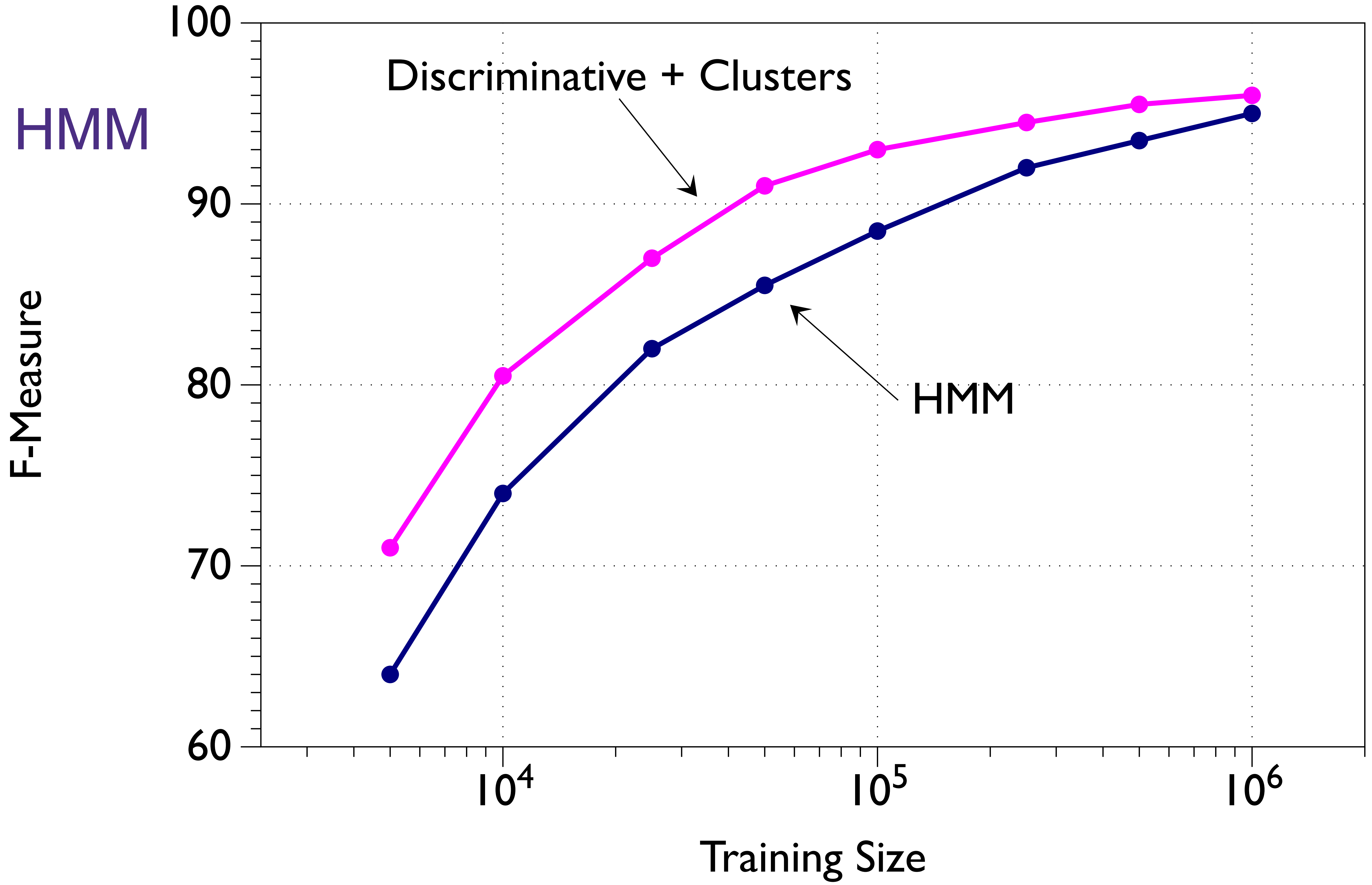
- To disambiguate an instance ***t*** of ***w***:
  - Compute context vector for instance
  - Retrieve all senses of ***w***
  - Assign ***w*** sense with closest centroid to ***t***

Local Context Clustering

- "Brown" (aka IBM) clustering (1992)
  - Generative model over adjacent words
  - Each w_i has class c_i
    - $\log P(W) = \sum_i \log P(w_i|c_i) + \log P(c_i|c_{i-1})$
  - Greedy clustering
    - Start with each word in own cluster
    - Merge clusters based on log prob of text under model
      - Merge those which maximize $P(W)$

Clustering Impact

- Improves downstream tasks
  - Named Entity Recognition vs. HMM
    - Miller et al ’04



Distributional Models: Summary

- Upsurge in distributional compositional
  - Embeddings:
    - Discriminatively trained, “low”-dimensional representations
    - e.g. word2vec
      - skipgrams, etc. over large corpora
  - Composition?
    - Methods for combining word vector models
    - Capture phrasal, sentential meanings