

Vector Semantics



Why vector models of meaning? computing the similarity between words

“**fast**” is similar to “**rapid**”

“**tall**” is similar to “**height**”

Question answering:

*Q: “How **tall** is Mt. Everest?”*

*Candidate A: “The official **height** of Mount Everest is 29029 feet”*



Word similarity for plagiarism detection

MAINFRAMES

Mainframes **are primarily** referred to large computers with **rapid**, advanced processing capabilities that **can execute and** perform tasks **equivalent to many** Personal Computers (PCs) machines **networked together**. **It is characterized with high quantity** Random Access Memory (RAM), very large secondary storage devices, and **high-speed** processors to cater for the needs of the computers under its service.

Consisting of advanced components, mainframes have the capability of running multiple large applications required by **many and** most enterprises **and organizations**. **This is** one of its advantages. Mainframes are also suitable to cater for those applications **(programs)** or files that are of very **high**

MAINFRAMES

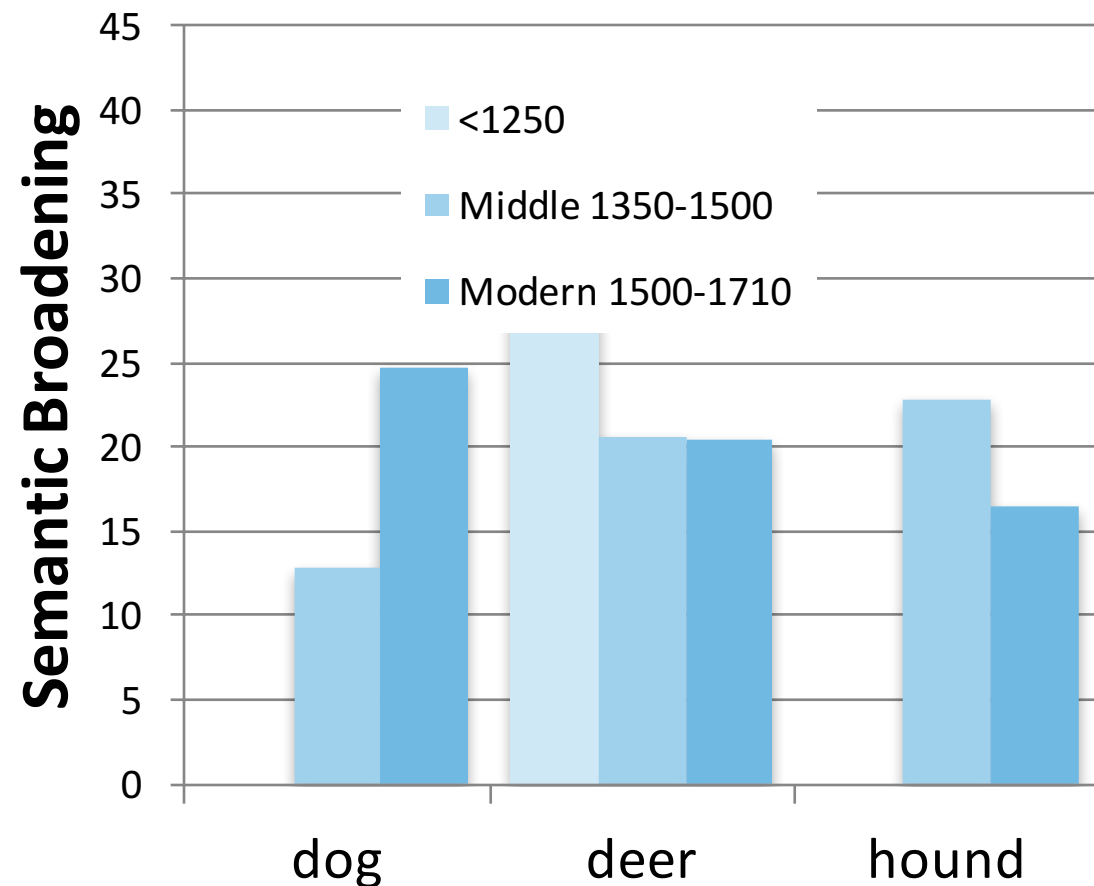
Mainframes **usually are** referred those computers with **fast**, advanced processing capabilities that **could perform by itself** tasks **that may require a lot of** Personal Computers (PC) Machines. **Usually mainframes would have lots of** RAMs, very large secondary storage devices, and **very fast** processors to cater for the needs of those computers under its service.

Due to the advanced components mainframes have, **these computers** have the capability of running multiple large applications required by most enterprises, **which is** one of its advantage. Mainframes are also suitable to cater for those applications or files that are of very **large** demand

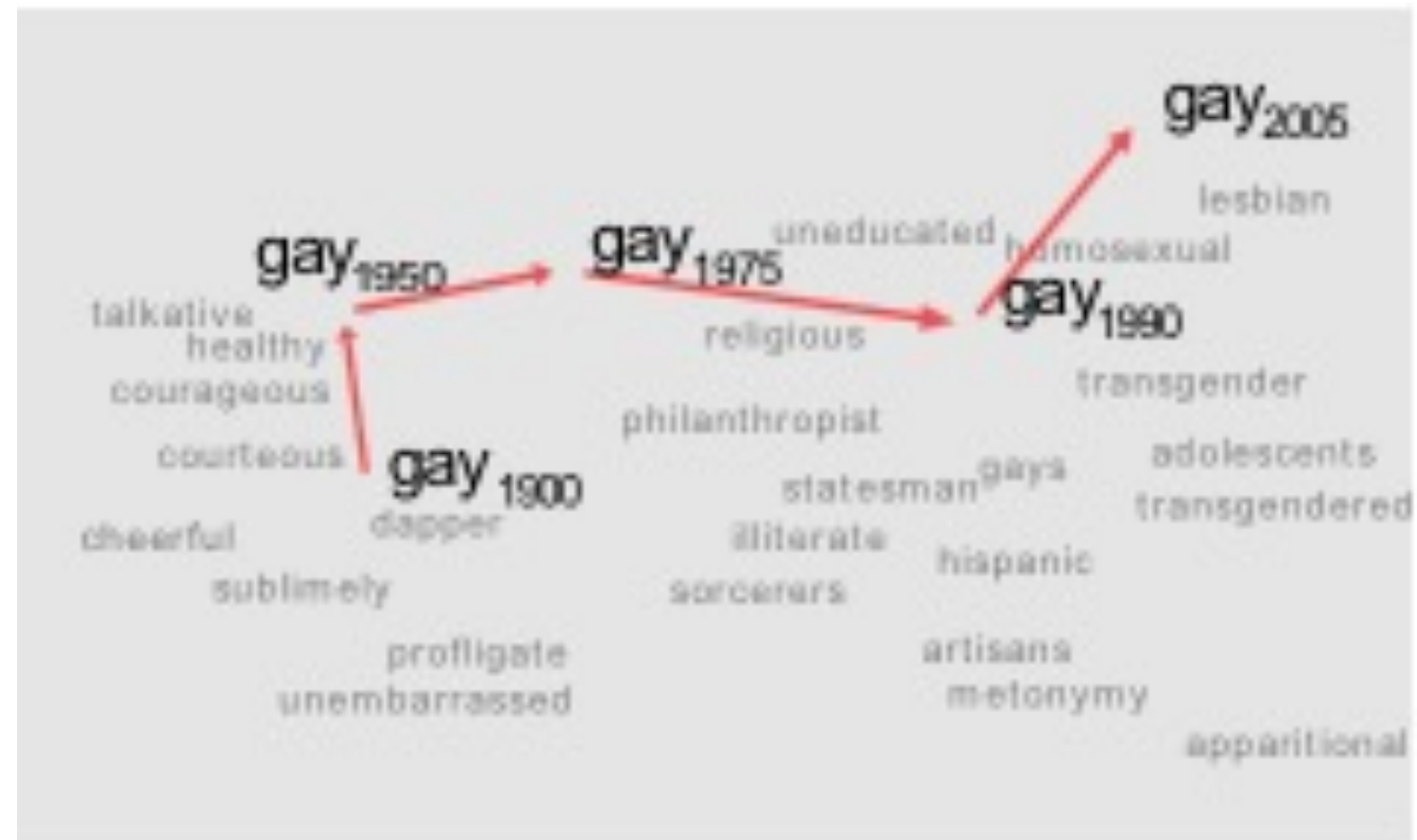


Word similarity for historical linguistics: semantic change over time

Sagi, Kaufmann Clark 2013



Kulkarni, Al-Rfou, Perozzi, Skiena 2015





Distributional models of meaning

= vector-space models of meaning

= vector semantics

Intuitions: Zellig Harris (1954):

- “oculist and eye-doctor ... occur in almost the same environments”
- “If A and B have almost identical environments we say that they are synonyms.”

Firth (1957):

- “You shall know a word by the company it keeps!”



Intuition of distributional word similarity

- Nida example:

A bottle of *tesgüino* is on the table
Everybody likes *tesgüino*
Tesgüino makes you drunk
We make *tesgüino* out of corn.

- From context words humans can guess *tesgüino* means
 - an alcoholic beverage like **beer**
- Intuition for algorithm:
 - Two words are similar if they have similar word contexts.



Four kinds of vector models

Sparse vector representations

1. Mutual-information weighted word co-occurrence matrices

Dense vector representations:

2. Singular value decomposition (and Latent Semantic Analysis)
3. Neural-network-inspired models (skip-grams, CBOW)
4. Brown clusters



Shared intuition

- Model the meaning of a word by “embedding” in a vector space.
- The meaning of a word is a vector of numbers
 - Vector models are also called “**embeddings**”.
- Contrast: word meaning is represented in many computational linguistic applications by a vocabulary index (“word number 545”)
- Old philosophy joke:
Q: What’s the meaning of life?
A: LIFE’



Term-document matrix

- Each cell: count of term t in a document d : $tf_{t,d}$
 - Each document is a **count vector** in \mathbb{N}^v : a column below

	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



Term-document matrix

- Two documents 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



The words in a term-document matrix

- Each word is a **count vector** in \mathbb{N}^D : a row below

	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



The words in a term-document matrix

- 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



Term-context matrix for word similarity

- Two **words** are similar in meaning if their context vectors are similar

	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	



The word-word or word-context matrix

- Instead of entire documents, use smaller contexts
 - Paragraph
 - Window of ± 4 words
- A word is now defined by a vector over counts of context words
- Instead of each vector being of length D
- Each vector is now of length $|V|$
- The word-word matrix is $|V| \times |V|$



Word-Word matrix

Sample contexts ± 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. information** preserve or jam, a pinch each of, and another fruit whose taste she likened In finding the optimal R-stage policy from necessary for the study authorized in the

	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	
...	...						



Word-word matrix

- We showed only 4x6, but the real matrix is 50,000 x 50,000
 - So it's very **sparse**
 - Most values are 0.
 - That's OK, since there are lots of efficient algorithms for sparse matrices.
- The size of windows depends on your goals
 - The shorter the windows, the more **syntactic** the representation
 - $\pm 1-3$ very syntactic
 - The longer the windows, the more **semantic** the representation
 - $\pm 4-10$ more semantic



2 kinds of co-occurrence between 2 words

(Schütze and Pedersen, 1993)

- First-order co-occurrence (**syntagmatic association**):
 - They are typically nearby each other.
 - *wrote* is a first-order associate of *book* or *poem*.
- Second-order co-occurrence (**paradigmatic association**):
 - They have similar neighbors.
 - *wrote* is a second- order associate of words like *said* or *remarked*.



Vector Semantics

Positive Pointwise Mutual Information (PPMI)



Problem with raw counts

- Raw word frequency is not a great measure of association between words
 - It's very skewed
 - "the" and "of" are very frequent, but maybe not the most discriminative
- We'd rather have a measure that asks whether a context word is **particularly informative** about the target word.
 - Positive Pointwise Mutual Information (PPMI)



Pointwise Mutual Information

Pointwise mutual information:

Do events x and y co-occur more than if they were independent?

$$\text{PMI}(X, Y) = \log_2 \frac{P(x, y)}{P(x)P(y)}$$

PMI between two words: (Church & Hanks 1989)

Do words x and y co-occur more than if they were independent?

$$\text{PMI}(\text{word}_1, \text{word}_2) = \log_2 \frac{P(\text{word}_1, \text{word}_2)}{P(\text{word}_1)P(\text{word}_2)}$$



Positive Pointwise Mutual Information

- PMI ranges from $-\infty$ to $+\infty$
- But the negative values are problematic
 - Things are co-occurring **less than** we expect by chance
 - Unreliable without enormous corpora
 - Imagine w_1 and w_2 whose probability is each 10^{-6}
 - Hard to be sure $p(w_1, w_2)$ is significantly different than 10^{-12}
 - Plus it's not clear people are good at "unrelatedness"
- So we just replace negative PMI values by 0
- Positive PMI (PPMI) between word1 and word2:

$$\text{PPMI}(\text{word}_1, \text{word}_2) = \max\left(\log_2 \frac{P(\text{word}_1, \text{word}_2)}{P(\text{word}_1)P(\text{word}_2)}, 0\right)$$



Computing PPMI on a term-context matrix

- Matrix F with W rows (words) and C columns (contexts)
- f_{ij} is # of times w_i occurs in context c_j

$$p_{ij} = \frac{f_{ij}}{\sum_{i=1}^W \sum_{j=1}^C f_{ij}}$$

$$p_{i*} = \frac{\sum_{j=1}^C f_{ij}}{\sum_{i=1}^W \sum_{j=1}^C f_{ij}}$$

$$p_{*j} = \frac{\sum_{i=1}^W f_{ij}}{\sum_{i=1}^W \sum_{j=1}^C f_{ij}}$$

apricot
pineapple
digital
information

	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

$$pmi_{ij} = \log_2 \frac{p_{ij}}{p_{i*} p_{*j}}$$

$$ppmi_{ij} = \begin{cases} pmi_{ij} & \text{if } pmi_{ij} > 0 \\ 0 & \text{otherwise} \end{cases}$$



$$p_{ij} = \frac{f_{ij}}{\sum_{i=1}^W \sum_{j=1}^C f_{ij}}$$

apricot
pineapple
digital
information

Count(w,context)

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

p(w=information,c=data) = 6/19 = .32

p(w=information) = 11/19 = .58

p(c=data) = 7/19 = .37

$$p(w_i) = \frac{\sum_{j=1}^C f_{ij}}{N}$$

$$p(c_j) = \frac{\sum_{i=1}^W f_{ij}}{N}$$

p(w,context)

p(w)

	computer	data	pinch	result	sugar	
apricot	0.00	0.00	0.05	0.00	0.05	0.11
pineapple	0.00	0.00	0.05	0.00	0.05	0.11
digital	0.11	0.05	0.00	0.05	0.00	0.21
information	0.05	0.32	0.00	0.21	0.00	0.58
p(context)	0.16	0.37	0.11	0.26	0.11	



$$pmi_{ij} = \log_2 \frac{p_{ij}}{p_i p_j}$$

apricot
pineapple
digital
information

p(context)

p(w,context)

computer

data

pinch

result

sugar

p(w)

0.00

0.00

0.05

0.00

0.05

0.11

0.00

0.00

0.05

0.00

0.05

0.11

0.11

0.05

0.00

0.05

0.00

0.21

0.05

0.32

0.00

0.21

0.00

0.58

0.16

0.37

0.11

0.26

0.11

- pmi(information,data) = $\log_2 (.32 / (.37 * .58)) = .58$

(.57 using full precision)

PPMI(w,context)

computer

data

pinch

result

sugar

apricot

-

-

2.25

-

2.25

pineapple

-

-

2.25

-

2.25

digital

1.66

0.00

-

0.00

-

information

0.00

0.57

-

0.47

-



Weighting PMI

- PMI is biased toward infrequent events
 - Very rare words have very high PMI values
- Two solutions:
 - Give rare words slightly higher probabilities
 - Use add-one smoothing (which has a similar effect)



Weighting PMI: Giving rare context words slightly higher probability

- Raise the context probabilities to $\alpha = 0.75$:

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

$$P_{\alpha}(c) = \frac{\text{count}(c)^{\alpha}}{\sum_c \text{count}(c)^{\alpha}}$$

- This helps because $P_{\alpha}(c) > P(c)$ for rare c
- Consider two events, $P(a) = .99$ and $P(b) = .01$

$$P_{\alpha}(a) = \frac{.99^{.75}}{.99^{.75} + .01^{.75}} = .97 \quad P_{\alpha}(b) = \frac{.01^{.75}}{.01^{.75} + .01^{.75}} = .03$$



Use Laplace (add-1) smoothing



	Add-2 Smoothed Count(w,context)				
	computer	data	pinch	result	sugar
apricot	2	2	3	2	3
pineapple	2	2	3	2	3
digital	4	3	2	3	2
information	3	8	2	6	2

	p(w,context) [add-2]					p(w)
	computer	data	pinch	result	sugar	
apricot	0.03	0.03	0.05	0.03	0.05	0.20
pineapple	0.03	0.03	0.05	0.03	0.05	0.20
digital	0.07	0.05	0.03	0.05	0.03	0.24
information	0.05	0.14	0.03	0.10	0.03	0.36
p(context)	0.19	0.25	0.17	0.22	0.17	



PPMI versus add-2 smoothed PPMI

PPMI(w,context)

	computer	data	pinch	result	sugar
apricot	-	-	2.25	-	2.25
pineapple	-	-	2.25	-	2.25
digital	1.66	0.00	-	0.00	-
information	0.00	0.57	-	0.47	-

PPMI(w,context) [add-2]

	computer	data	pinch	result	sugar
apricot	0.00	0.00	0.56	0.00	0.56
pineapple	0.00	0.00	0.56	0.00	0.56
digital	0.62	0.00	0.00	0.00	0.00
information	0.00	0.58	0.00	0.37	0.00



Vector Semantics

Measuring similarity: the cosine



Measuring similarity

- Given 2 target words v and w
- We'll need a way to measure their similarity.
- Most measure of vectors similarity are based on the:
- **Dot product** or **inner product** from linear algebra

$$\text{dot-product}(\vec{v}, \vec{w}) = \vec{v} \cdot \vec{w} = \sum_{i=1}^N v_i w_i = v_1 w_1 + v_2 w_2 + \dots + v_N w_N$$

- High when two vectors have large values in same dimensions.
- Low (in fact 0) for **orthogonal vectors** with zeros in complementary distribution



Problem with dot product

$$\text{dot-product}(\vec{v}, \vec{w}) = \vec{v} \cdot \vec{w} = \sum_{i=1}^N v_i w_i = v_1 w_1 + v_2 w_2 + \dots + v_N w_N$$

- Dot product is longer if the vector is longer. Vector length:

$$|\vec{v}| = \sqrt{\sum_{i=1}^N v_i^2}$$

- Vectors are longer if they have higher values in each dimension
- That means more frequent words will have higher dot products
- That's bad: we don't want a similarity metric to be sensitive to word frequency



Solution: cosine

- Just divide the dot product by the length of the two vectors!

$$\frac{\vec{a} \cdot \vec{b}}{|\vec{a}| |\vec{b}|}$$

- This turns out to be the cosine of the angle between them!

$$\vec{a} \cdot \vec{b} = |\vec{a}| |\vec{b}| \cos \theta$$

$$\frac{\vec{a} \cdot \vec{b}}{|\vec{a}| |\vec{b}|} = \cos \theta$$



Cosine for computing similarity

Dot product

Unit vectors

$$\cos(\vec{v}, \vec{w}) = \frac{\vec{v} \cdot \vec{w}}{|\vec{v}| |\vec{w}|} = \frac{\vec{v}}{|\vec{v}|} \cdot \frac{\vec{w}}{|\vec{w}|} = \frac{\sum_{i=1}^N v_i w_i}{\sqrt{\sum_{i=1}^N v_i^2} \sqrt{\sum_{i=1}^N w_i^2}}$$

v_i is the PPMI value for word v in context i

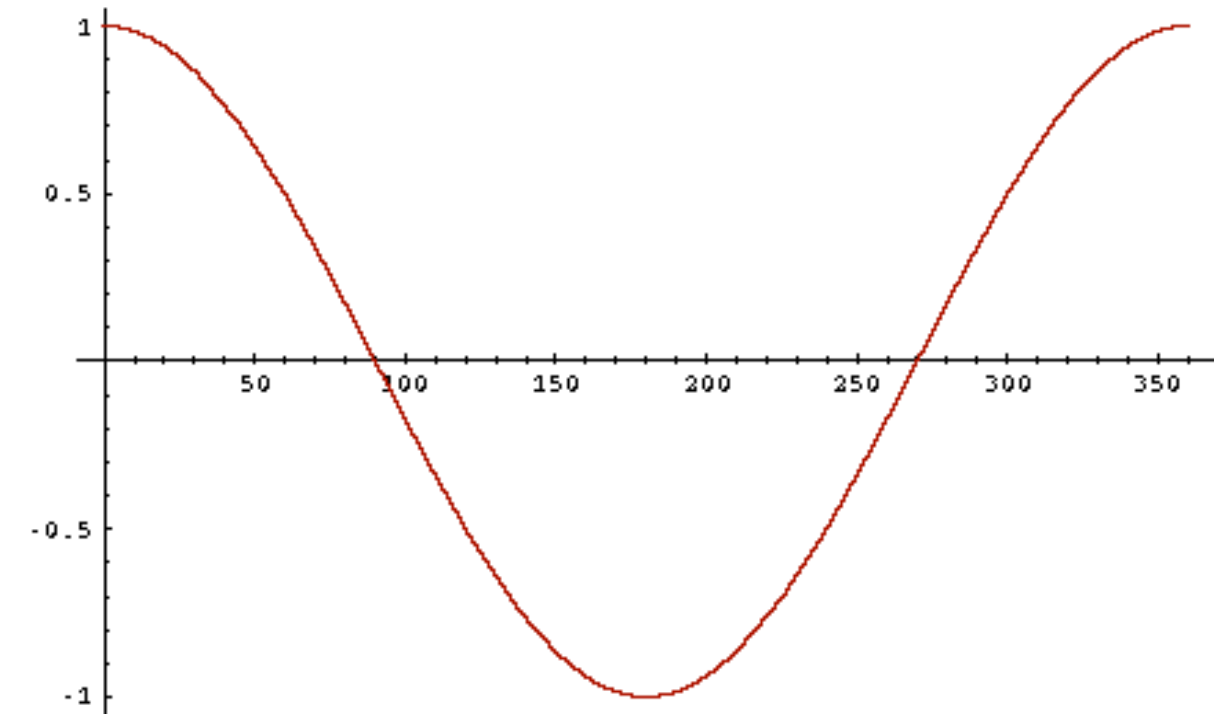
w_i is the PPMI value for word w in context i .

$\cos(\vec{v}, \vec{w})$ is the cosine similarity of \vec{v} and \vec{w}



Cosine as a similarity metric

- -1: vectors point in opposite directions
 - +1: vectors point in same directions
 - 0: vectors are orthogonal
-
- Raw frequency or PPMI are non-negative, so cosine range 0-1





$$\cos(\vec{v}, \vec{w}) = \frac{\vec{v} \cdot \vec{w}}{|\vec{v}| |\vec{w}|} = \frac{\vec{v}}{|\vec{v}|} \cdot \frac{\vec{w}}{|\vec{w}|} = \frac{\sum_{i=1}^N v_i w_i}{\sqrt{\sum_{i=1}^N v_i^2} \sqrt{\sum_{i=1}^N w_i^2}}$$

	large	data	computer
apricot	2	0	0
digital	0	1	2
information	1	6	1

Which pair of words is more similar?

$$\text{cosine}(\text{apricot}, \text{information}) = \frac{2 + 0 + 0}{\sqrt{2 + 0 + 0} \sqrt{1 + 36 + 1}} = \frac{2}{\sqrt{2} \sqrt{38}} = .23$$

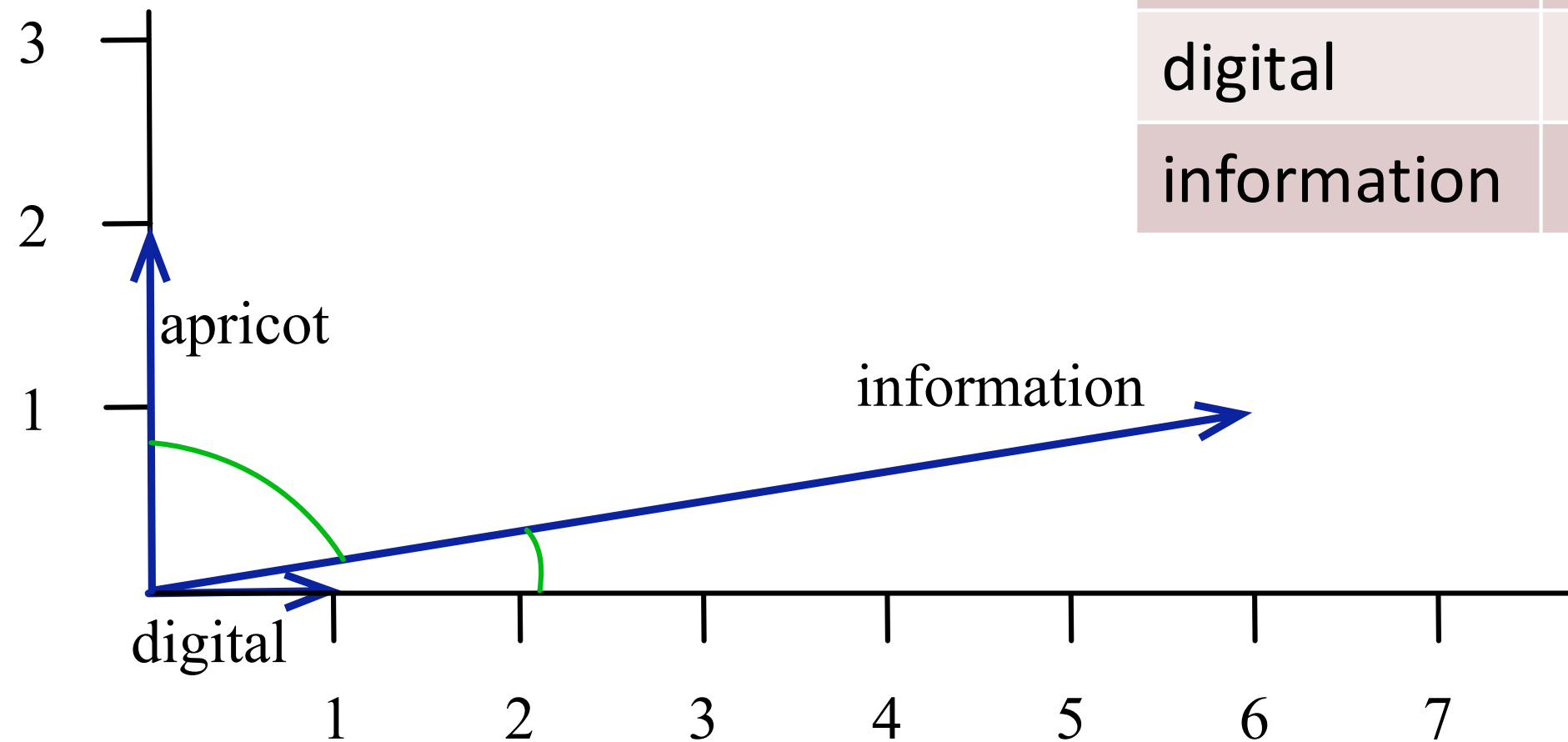
$$\text{cosine}(\text{digital}, \text{information}) = \frac{0 + 6 + 2}{\sqrt{0 + 1 + 4} \sqrt{1 + 36 + 1}} = \frac{8}{\sqrt{5} \sqrt{38}} = .58$$

$$\text{cosine}(\text{apricot}, \text{digital}) = \frac{0 + 0 + 0}{\sqrt{1 + 0 + 0} \sqrt{0 + 1 + 4}} = 0$$



Visualizing vectors and angles

Dimension 1: 'large'

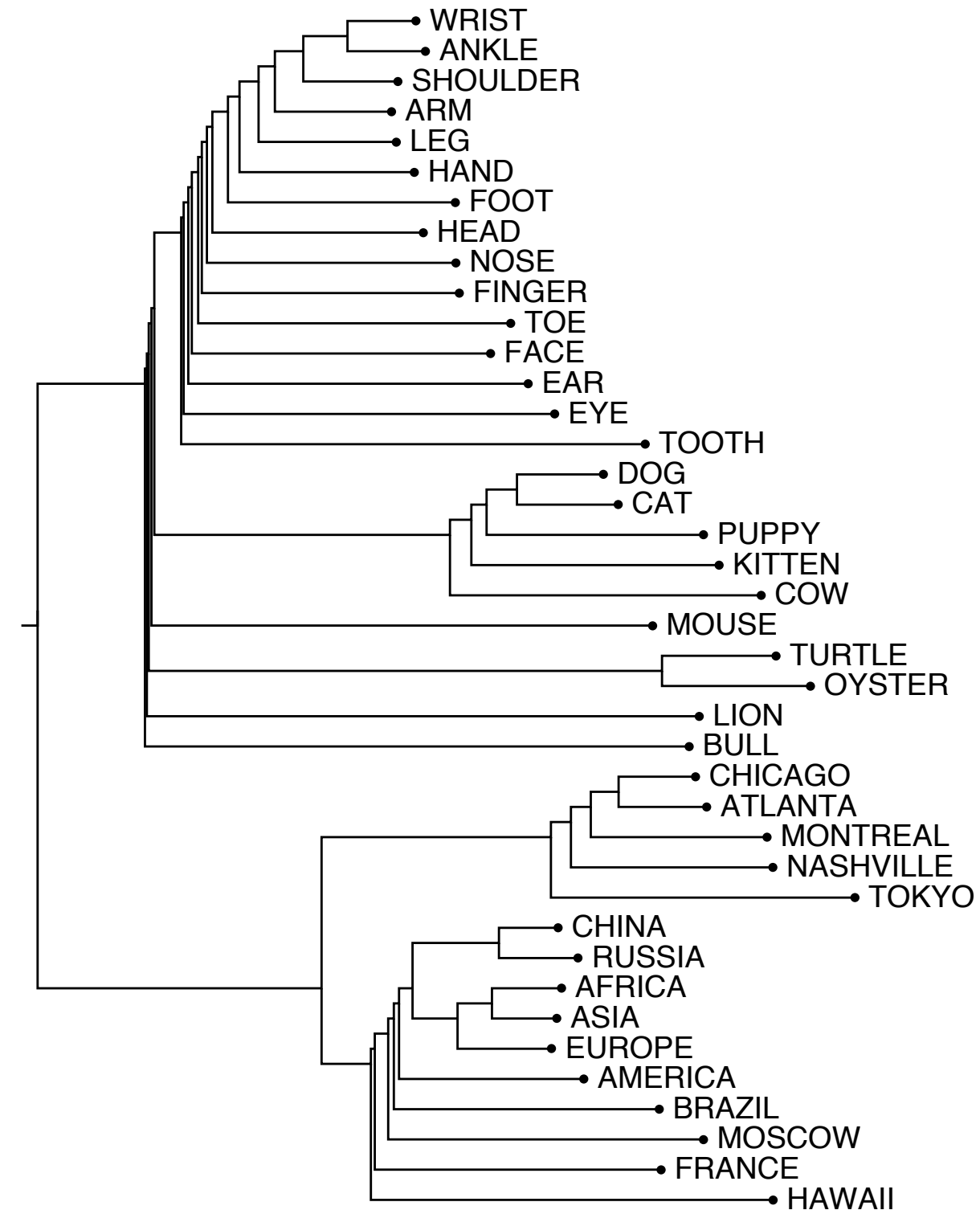


	large	data
apricot	2	0
digital	0	1
information	1	6

Dimension 2: 'data'



Clustering vectors to visualize similarity in co-occurrence matrices



Rohde et al. (2006)



Other possible similarity measures

$$\text{sim}_{\text{cosine}}(\vec{v}, \vec{w}) = \frac{\vec{v} \cdot \vec{w}}{|\vec{v}| |\vec{w}|} = \frac{\sum_{i=1}^N v_i \times w_i}{\sqrt{\sum_{i=1}^N v_i^2} \sqrt{\sum_{i=1}^N w_i^2}}$$

$$\text{sim}_{\text{Jaccard}}(\vec{v}, \vec{w}) = \frac{\sum_{i=1}^N \min(v_i, w_i)}{\sum_{i=1}^N \max(v_i, w_i)}$$

$$\text{sim}_{\text{Dice}}(\vec{v}, \vec{w}) = \frac{2 \times \sum_{i=1}^N \min(v_i, w_i)}{\sum_{i=1}^N (v_i + w_i)}$$

$$\text{sim}_{\text{JS}}(\vec{v} || \vec{w}) = D(\vec{v} | \frac{\vec{v} + \vec{w}}{2}) + D(\vec{w} | \frac{\vec{v} + \vec{w}}{2})$$



Vector Semantics

Measuring similarity: the cosine



Using syntax to define a word's context

- Zellig Harris (1968)
 “The meaning of entities, and the meaning of grammatical relations among them, is related to the restriction of combinations of these entities relative to other entities”
- **Two words are similar if they have similar syntactic contexts**

Duty and **responsibility** have similar syntactic distribution:

**Modified by
adjectives**

additional, administrative, assumed, collective,
congressional, constitutional ...

Objects of verbs

assert, assign, assume, attend to, avoid, become, breach..



Co-occurrence vectors based on syntactic dependencies

Dekang Lin, 1998 "Automatic Retrieval and Clustering of Similar Words"

- Each dimension: a context word in one of R grammatical relations
 - Subject-of- "absorb"
- Instead of a vector of $|V|$ features, a vector of $R/V|$
- Example: counts for the word *cell* :

	subj-of, absorb	subj-of, adapt	subj-of, behave	...	pobj-of, inside	pobj-of, into	...	nmod-of, abnormality	nmod-of, anemia	nmod-of, architecture	...	obj-of, attack	obj-of, call	obj-of, come from	obj-of, decorate	...	nmod, bacteria	nmod, body	nmod, bone marrow
cell	1	1	1		16	30		3	8	1		6	11	3	2		3	2	2



Syntactic dependencies for dimensions

- Alternative (Padó and Lapata 2007):
 - Instead of having a $|V| \times R|V|$ matrix
 - Have a $|V| \times |V|$ matrix
 - But the co-occurrence counts aren't just counts of words in a window
 - But counts of words that occur in one of R dependencies (subject, object, etc).
 - So $M(\text{"cell"}, \text{"absorb"}) = \text{count}(\text{subj}(\text{cell}, \text{absorb})) + \text{count}(\text{obj}(\text{cell}, \text{absorb})) + \text{count}(\text{pobj}(\text{cell}, \text{absorb})), \text{ etc.}$



PMI applied to dependency relations

Hindle, Don. 1990. Noun Classification from Predicate-Argument Structure. ACL

Object of “drink”	Count	PMI
tea	2	11.8
liquid	2	10.5
wine	2	9.3
anything	3	5.2
it	3	1.3

- “Drink it” more common than “drink wine”
- But “wine” is a better “drinkable” thing than “it”



Alternative to PPMI for measuring association

- **tf-idf** (that's a hyphen not a minus sign)
- The combination of two factors
 - **Term frequency** (Luhn 1957): frequency of the word (can be logged)
 - **Inverse document frequency** (IDF) (Sparck Jones 1972)
 - N is the total number of documents
 - df_i = "document frequency of word i "
 - = # of documents with word i
- w_{ij} = word i in document j

$$idf_i = \log \left(\frac{N}{df_i} \right)$$

$$w_{ij} = tf_{ij} idf_i$$



tf-idf not generally used for word-word similarity

- But is by far the most common weighting when we are considering the relationship of words to documents



Vector Semantics

Evaluating similarity



Evaluating similarity

- Extrinsic (task-based, end-to-end) Evaluation:
 - Question Answering
 - Spell Checking
 - Essay grading
- Intrinsic Evaluation:
 - Correlation between algorithm and human word similarity ratings
 - Wordsim353: 353 noun pairs rated 0-10. $sim(plane, car) = 5.77$
 - Taking TOEFL multiple-choice vocabulary tests
 - Levied is closest in meaning to:
imposed, believed, requested, correlated



Summary

- Distributional (vector) models of meaning
 - **Sparse** (PPMI-weighted word-word co-occurrence matrices)
 - **Dense:**
 - Word-word SVD 50-2000 dimensions
 - Skip-grams and CBOW
 - Brown clusters 5-20 binary dimensions.