Basics in Language and Probability

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Quotes

It must be recognized that the notion "probability of a sentence" is an entirely useless one, under any known interpretation of this term.
Noam Chomsky, 1969

Whenever I fire a linguist our system performance improves.
Frederick Jelinek, 1988
Conflicts?

- rationalist vs. empiricist
- scientist vs. engineer
- insight vs. data analysis
- explaining language vs. building applications
language
A Naive View of Language

- Language needs to name
  - nouns: objects in the world (dog)
  - verbs: actions (jump)
  - adjectives and adverbs: properties of objects and actions (brown, quickly)

- Relationship between these have to specified
  - word order
  - morphology
  - function words
A Bag of Words

quick

fox

brown

lazy

jump

dog
Relationships

quick
fox
lazy
brown
jump
dog
Marking of Relationships: Word Order

quick brown fox jump lazy dog
Marking of Relationships: Function Words

quick brown fox jump over lazy dog
Marking of Relationships: Morphology

quick brown fox jumps over lazy dog
the quick brown fox jumps over the lazy dog
Marking of Relationships: Agreement

- From Catullus, First Book, first verse (Latin):

  Cui dono lepidum novum libellum arida modo pumice expolitum?
  Whom I-present lovely new little-book dry manner pumice polished?

  (To whom do I present this lovely new little book now polished with a dry pumice?)

- Gender (and case) agreement links adjectives to nouns
Marking of Relationships to Verb: Case

- German:

  \[
  \text{Die Frau} \quad \text{gibt} \quad \text{dem Mann} \quad \text{den Apfel} \\
  \text{The woman} \quad \text{gives} \quad \text{the man} \quad \text{the apple}
  \]

  \[
  \text{Der Frau} \quad \text{gibt} \quad \text{der Mann} \quad \text{den Apfel} \\
  \text{The woman} \quad \text{gives} \quad \text{the man} \quad \text{the apple}
  \]

- Case inflection indicates role of noun phrases
Case Morphology vs. Prepositions

• Two different word orderings for English:
  – The woman gives the man the apple
  – The woman gives the apple to the man

• Japanese:

  女の人は 男の人に リンゴを あげます
  woman TOPIC  man OBJ2  apple OBJ1  give

• Is there a real difference between prepositions and noun phrase case inflection?
This is a simple sentence
This is a simple sentence

be
3sg
present

WORDS
MORPHOLOGY
Parts of Speech

This is a simple sentence

be
3sg
present
Syntax

This is a simple sentence

be
3sg
present

PART OF SPEECH

WORDS

MORPHOLOGY

SYNTAX

This is a simple sentence

be
3sg
present

PART OF SPEECH

WORDS

MORPHOLOGY

SYNTAX
This is a simple sentence.
This is a simple sentence

But it is an instructive one.

This is a simple sentence

be 3sg present

SIMPLE1 having few parts

SENTENCE1 string of words satisfying the grammatical rules of a language

But it is an instructive one.

This is a simple sentence

be 3sg present

SIMPLE1 having few parts

SENTENCE1 string of words satisfying the grammatical rules of a language

But it is an instructive one.
Why is Language Hard?

- Ambiguities on many levels
- Rules, but many exceptions
- No clear understand how humans process language
- Can we learn everything about language by automatic data analysis?
data
Data: Words

• Definition: strings of letters separated by spaces

• But how about:
  – punctuation: commas, periods, etc. typically separated (tokenization)
  – hyphens: high-risk
  – clitics: Joe’s
  – compounds: website, Computerlinguistikvorlesung

• And what if there are no spaces:
  伦敦每日快报指出,两台记载黛安娜王妃一九九七年巴黎死亡车祸调查资料的手提电脑,被从前大都会警察总长的办公室里偷走.
Word Counts

Most frequent words in the English Europarl corpus

<table>
<thead>
<tr>
<th>any word</th>
<th>Frequency in text</th>
<th>Token</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1,929,379</td>
<td>the</td>
</tr>
<tr>
<td></td>
<td>1,297,736</td>
<td>,</td>
</tr>
<tr>
<td></td>
<td>956,902</td>
<td>.</td>
</tr>
<tr>
<td></td>
<td>901,174</td>
<td>of</td>
</tr>
<tr>
<td></td>
<td>841,661</td>
<td>to</td>
</tr>
<tr>
<td></td>
<td>684,869</td>
<td>and</td>
</tr>
<tr>
<td></td>
<td>582,592</td>
<td>in</td>
</tr>
<tr>
<td></td>
<td>452,491</td>
<td>that</td>
</tr>
<tr>
<td></td>
<td>424,895</td>
<td>is</td>
</tr>
<tr>
<td></td>
<td>424,552</td>
<td>a</td>
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<table>
<thead>
<tr>
<th>nouns</th>
<th>Frequency in text</th>
<th>Content word</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>129,851</td>
<td>European</td>
</tr>
<tr>
<td></td>
<td>110,072</td>
<td>Mr</td>
</tr>
<tr>
<td></td>
<td>98,073</td>
<td>commission</td>
</tr>
<tr>
<td></td>
<td>71,111</td>
<td>president</td>
</tr>
<tr>
<td></td>
<td>67,518</td>
<td>parliament</td>
</tr>
<tr>
<td></td>
<td>64,620</td>
<td>union</td>
</tr>
<tr>
<td></td>
<td>58,506</td>
<td>report</td>
</tr>
<tr>
<td></td>
<td>57,490</td>
<td>council</td>
</tr>
<tr>
<td></td>
<td>54,079</td>
<td>states</td>
</tr>
<tr>
<td></td>
<td>49,965</td>
<td>member</td>
</tr>
</tbody>
</table>
Word Counts

But also:

There is a large tail of words that occur only once. 33,447 words occur once, for instance

- cornflakes
- mathematicians
- Tazhikhistan
Zipf’s law

\[ f \times r = k \]

\( f \) = frequency of a word

\( r \) = rank of a word (if sorted by frequency)

\( k \) = a constant
Zipf’s law as a graph

Why a line in log-scale?

\[ fr = k \Rightarrow f = \frac{k}{r} \Rightarrow \log f = \log k - \log r \]
statistics
Given word counts we can estimate a probability distribution:

\[ P(w) = \frac{\text{count}(w)}{\sum_{w'} \text{count}(w')} \]

This type of estimation is called *maximum likelihood estimation*. Why? We will get to that later.

Estimating probabilities based on frequencies is called the *frequentist approach* to probability.

This probability distribution answers the question: If we randomly pick a word out of a text, how likely will it be word \( w \)?
• We introduce a **random variable** \( W \).

• We define a **probability distribution** \( p \), that tells us how likely the variable \( W \) is the word \( w \):

\[
\text{prob}(W = w) = p(w)
\]
Joint Probabilities

• Sometimes, we want to deal with two random variables at the same time.

• Example: Words $w_1$ and $w_2$ that occur in sequence (a bigram)
  We model this with the distribution: $p(w_1, w_2)$

• If the occurrence of words in bigrams is independent, we can reduce this to $p(w_1, w_2) = p(w_1)p(w_2)$. Intuitively, this not the case for word bigrams.

• We can estimate joint probabilities over two variables the same way we estimated the probability distribution over a single variable:

  $p(w_1, w_2) = \frac{\text{count}(w_1, w_2)}{\sum_{w_1', w_2'} \text{count}(w_1', w_2')}$
Conditional Probabilities

- Another useful concept is **conditional probability**
  
  \[ p(w_2|w_1) \]

  It answers the question: If the random variable \( W_1 = w_1 \), how what is the value for the second random variable \( W_2 \)?

- Mathematically, we can define conditional probability as
  
  \[ p(w_2|w_1) = \frac{p(w_1, w_2)}{p(w_1)} \]

- If \( W_1 \) and \( W_2 \) are independent: \( p(w_2|w_1) = p(w_2) \)
Chain Rule

- A bit of math gives us the chain rule:

\[ p(w_2 \mid w_1) = \frac{p(w_1, w_2)}{p(w_1)} \]

\[ p(w_1) \ p(w_2 \mid w_1) = p(w_1, w_2) \]

- What if we want to break down large joint probabilities like \( p(w_1, w_2, w_3) \)?

  We can repeatedly apply the chain rule:

\[ p(w_1, w_2, w_3) = p(w_1) \ p(w_2 \mid w_1) \ p(w_3 \mid w_1, w_2) \]
• Finally, another important rule: **Bayes rule**

\[ p(x|y) = \frac{p(y|x) p(x)}{p(y)} \]

• It can easily derived from the chain rule:

\[ p(x, y) = p(x, y) \]

\[ p(x|y) p(y) = p(y|x) p(x) \]

\[ p(x|y) = \frac{p(y|x) p(x)}{p(y)} \]
Expectation

• We introduced the concept of a random variable $X$
\[ \text{prob}(X = x) = p(x) \]

• Example: Roll of a dice. There is a $\frac{1}{6}$ chance that it will be 1, 2, 3, 4, 5, or 6.

• We define the **expectation** $E(X)$ of a random variable as:
\[ E(X) = \sum_x p(x) \times x \]

• Roll of a dice:
\[ E(X) = \frac{1}{6} \times 1 + \frac{1}{6} \times 2 + \frac{1}{6} \times 3 + \frac{1}{6} \times 4 + \frac{1}{6} \times 5 + \frac{1}{6} \times 6 = 3.5 \]
Variance

- **Variance** is defined as

\[
Var(X) = E((X - E(X))^2) = E(X^2) - E^2(X)
\]

\[
Var(X) = \sum_x p(x) (x - E(X))^2
\]

- Intuitively, this is a measure how far events diverge from the mean (expectation)

- Related to this is **standard deviation**, denoted as \(\sigma\).

\[
Var(X) = \sigma^2
\]

\[
E(X) = \mu
\]
Variance

- Roll of a dice:

\[
\text{Var}(X) = \frac{1}{6}(1 - 3.5)^2 + \frac{1}{6}(2 - 3.5)^2 + \frac{1}{6}(3 - 3.5)^2 \\
+ \frac{1}{6}(4 - 3.5)^2 + \frac{1}{6}(5 - 3.5)^2 + \frac{1}{6}(6 - 3.5)^2 \\
= \frac{1}{6}((-2.5)^2 + (-1.5)^2 + (-0.5)^2 + 0.5^2 + 1.5^2 + 2.5^2) \\
= \frac{1}{6}(6.25 + 2.25 + 0.25 + 0.25 + 2.25 + 6.25) \\
= 2.917
\]
Standard Distributions

- **Uniform**: all events equally likely
  - \( \forall x, y : p(x) = p(y) \)
  - example: roll of one dice

- **Binomial**: a series of trials with only two outcomes
  - probability \( p \) for each trial, occurrence \( r \) out of \( n \) times:
    \[
    b(r; n, p) = \binom{n}{r} p^r (1 - p)^{n-r}
    \]
  - a number of coin tosses
• **Normal**: common distribution for continuous values
  
  – value in the range \([- \infty, x]\), given expectation \(\mu\) and standard deviation \(\sigma\):
  \[
n(x; \mu, \sigma) = \frac{1}{\sqrt{2\pi\sigma}} e^{-\frac{(x-\mu)^2}{2\sigma^2}}
  \]
  
  – also called **Bell curve**, or **Gaussian**
  
  – examples: heights of people, IQ of people, tree heights, ...
Estimation Revisited

• We introduced previously an estimation of probabilities based on frequencies:

\[ P(w) = \frac{\text{count}(w)}{\sum_{w'} \text{count}(w')} \]

• Alternative view: Bayesian: what is the most likely model given the data

\[ p(M|D) \]

• Model and data are viewed as random variables
  – model \( M \) as random variable
  – data \( D \) as random variable
Bayesian Estimation

• Reformulation of $p(M|D)$ using Bayes rule:

$$p(M|D) = \frac{p(D|M) p(M)}{p(D)}$$

$$\arg\max_M p(M|D) = \arg\max_M p(D|M) p(M)$$

• $p(M|D)$ answers the question: What is the most likely model given the data

• $p(M)$ is a prior that prefers certain models (e.g. simple models)

• The frequentist estimation of word probabilities $p(w)$ is the same as Bayesian estimation with a uniform prior (no bias towards a specific model), hence it is also called the **maximum likelihood estimation**
• An important concept is entropy:

\[ H(X) = \sum_x -p(x) \log_2 p(x) \]

• A measure for the degree of disorder
Entropy Example

One event

\[ p(a) = 1 \]
\[ H(X) = -1 \log_2 1 \]
\[ = 0 \]
Entropy Example

2 equally likely events:

\[ p(a) = 0.5 \]
\[ p(b) = 0.5 \]

\[ H(X) = -0.5 \log_2 0.5 - 0.5 \log_2 0.5 \]
\[ = - \log_2 0.5 \]
\[ = 1 \]
Entropy Example

4 equally likely events:

\[ p(a) = 0.25 \]
\[ p(b) = 0.25 \]
\[ p(c) = 0.25 \]
\[ p(d) = 0.25 \]

\[ H(X) = -0.25 \log_2 0.25 - 0.25 \log_2 0.25 \]
\[ -0.25 \log_2 0.25 - 0.25 \log_2 0.25 \]
\[ = - \log_2 0.25 \]
\[ = 2 \]
Entropy Example

4 events, one more likely than the others:

\[
p(a) = 0.7 \\
p(b) = 0.1 \\
p(c) = 0.1 \\
p(d) = 0.1
\]

\[
H(X) = -0.7 \log_2 0.7 - 0.1 \log_2 0.1 \\
- 0.1 \log_2 0.1 - 0.1 \log_2 0.1 \\
= -0.7 \log_2 0.7 - 0.3 \log_2 0.1 \\
= -0.7 \times -0.5146 - 0.3 \times -3.3219 \\
= 0.36020 + 0.99658 \\
= 1.35678
\]
Entropy Example

4 events, one much more likely than the others:

\[
p(a) = 0.97 \\
p(b) = 0.01 \\
p(c) = 0.01 \\
p(d) = 0.01
\]

\[
H(X) = -0.97 \log_2 0.97 - 0.01 \log_2 0.01 \\
- 0.01 \log_2 0.01 - 0.01 \log_2 0.01 \\
= -0.97 \log_2 0.97 - 0.03 \log_2 0.01 \\
= -0.97 \times -0.04394 - 0.03 \times -6.6439 \\
= 0.04262 + 0.19932 \\
= 0.24194
\]
Examples

\[ H(X) = 0 \]
\[ H(X) = 1 \]
\[ H(X) = 2 \]
\[ H(X) = 3 \]
\[ H(X) = 1.35678 \]
\[ H(X) = 0.24194 \]
Intuition Behind Entropy

• A good model has low entropy
→ it is more certain about outcomes

• For instance a translation table

| e   | f   | \( p(e|f) \) |
|-----|-----|--------------|
| the | der | 0.8          |
| that| der | 0.2          |

is better than

| e   | f   | \( p(e|f) \) |
|-----|-----|--------------|
| the | der | 0.02         |
| that| der | 0.01         |

• A lot of statistical estimation is about reducing entropy
• Assume that we want to encode a sequence of events $X$

• Each event is encoded by a sequence of bits

• For example
  – Coin flip: heads = 0, tails = 1
  – 4 equally likely events: $a = 00$, $b = 01$, $c = 10$, $d = 11$
  – 3 events, one more likely than others: $a = 0$, $b = 10$, $c = 11$
  – Morse code: $e$ has shorter code than $q$

• Average number of bits needed to encode $X \geq$ entropy of $X$
The Entropy of English

• We already talked about the probability of a word $p(w)$

• But words come in sequence. Given a number of words in a text, can we guess the next word $p(w_n|w_1, ..., w_{n-1})$?

• Assuming a model with a limited window size

<table>
<thead>
<tr>
<th>Model</th>
<th>Entropy</th>
</tr>
</thead>
<tbody>
<tr>
<td>0th order</td>
<td>4.76</td>
</tr>
<tr>
<td>1st order</td>
<td>4.03</td>
</tr>
<tr>
<td>2nd order</td>
<td>2.8</td>
</tr>
<tr>
<td>human, unlimited</td>
<td>1.3</td>
</tr>
</tbody>
</table>
Next Lecture: Language Models

• Next time, we will expand on the idea of a model of English in the form

\[ p(w_n | w_1, \ldots, w_{n-1}) \]

• Despite its simplicity, a tremendously useful tool for NLP

• Nice machine learning challenge
  – sparse data
  – smoothing
  – back-off and interpolation