

NLP: N-Grams

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1 Language Modeling Tasks

- Language identification / Authorship identification
- Machine Translation
- Speech recognition
- Optical character recognition (OCR)
- Context-sensitive spelling correction
- Predictive text (text messaging clients, search engines, etc)
- Generating spam
- Code-breaking (e.g. decipherment)

2 Kinds of Language Models

- Bag of words
- Sequences of words
- Sequences of tagged words
- Grammars
- Topic models

3 Language as a sequence of words

- What is the probability of seeing a particular sequence of words?
- Simplified model of language: words in order
- $p(\text{some words in sequence})$

- $p(\text{“an interesting story”})$?
- $p(\text{“a interesting story”})$?
- $p(\text{“a story interesting”})$?
- $p(\text{next} \mid \text{some sequence of previous words})$
 - $p(\text{“austin”} \mid \text{“university of texas at”})$?
 - $p(\text{“dallas”} \mid \text{“university of texas at”})$?
 - $p(\text{“giraffe”} \mid \text{“university of texas at”})$?

Use as a language model

- Language ID: This sequence is most likely to be seen in what language?
- Authorship ID: What is the most likely person to have produced this sequence of words?
- Machine Translation: Which sentence (word choices, ordering) seems most like the target language?
- Text Prediction: What’s the most likely next word in the sequence

Notation

- Probability of a sequence is a joint probability of words
- But the order of the words matters, so each gets its own feature
- $p(\text{“an interesting story”}) = p(w_1 = \text{an}, w_2 = \text{interesting}, w_3 = \text{story})$
- $p(\text{“austin”} \mid \text{“university of texas at”})$
 $= p(w_0 = \text{austin} \mid w_{-4} = \text{university}, w_{-3} = \text{of}, w_{-2} = \text{texas}, w_{-1} = \text{at})$
- So w_0 means “current word” and w_{-1} is “the previous word”.
- We will typically use the short-hand

4 Counting Words

- Terminology:
 - **Type:** Distinct word
 - **Token:** Particular occurrence of a word
 - “the man saw the saw”: 3 types, 5 tokens

What is a word? What do we count?

- Punctuation? Separate from neighboring words? Keep it at all?

- Stopwords?
- Lowercase everything?
- Distinct numbers vs. $\langle number \rangle$
- Hyphenated words?
- Lemmas only?
- Disfluencies? (um, uh)

5 Estimating Sequence Probabilities

- To build a statistical model, we need to set parameters.
- Our parameters: probabilities of various sequences of text
- Maximum Likelihood Estimate (MLE): of all the sequences of length N, what proportion are the relevant sequence?
- $p(\text{university of texas at austin})$
 $= p(w_1 = \text{university}, w_2 = \text{of}, w_3 = \text{texas}, w_4 = \text{at}, w_5 = \text{austin})$
 $= \frac{C(\text{"university of texas at austin"})}{C(\text{all 5-word sequences})} = \frac{3}{25,000,000}$
- $p(\text{a bank}) = \frac{C(\text{"a bank"})}{C(\text{all 2-word sequences})} = \frac{609}{50,000,000}$
- $p(\text{in the}) = \frac{C(\text{"in the"})}{C(\text{all 2-word sequences})} = \frac{312,776}{50,000,000}$
- Long sequences are unlikely to have any counts:
 $p(\text{the university of texas football team started the season off right by scoring a touchdown in the final seconds of play to secure a stunning victory over the out-of-town challengers})$
 $= \frac{C(\text{... that sentence ...})}{C(\text{all 30-word sequences})} = \mathbf{0.0}$
- Even shorter sentences may not have counts, even if they make sense, are perfectly grammatical, and not improbable that someone might say them:
 – “university of texas in amarillo”
- We need a way of estimating the probability of a long sequence, even though counts will be low.

Make a “naïve” assumption?

- With naïve Bayes, we dealt with this problem by assuming that all features were independent.
- $p(w_1 = \text{university}, w_2 = \text{of}, w_3 = \text{texas}, w_4 = \text{in}, w_5 = \text{amarillo}) =$
 $p(w = \text{university}) \cdot p(w = \text{of}) \cdot p(w = \text{texas}) \cdot p(w = \text{in}) \cdot p(w = \text{amarillo})$

- But this loses the difference between “university of texas in amarillo”, which seems likely, and “university texas amarillo in of”, which does not
- This amounts to a “bag of words” model

Use Chain Rule?

- Long sequences are sparse, short sequences are less so
- Break down long sequences using the chain rule
- $p(\text{university of texas in amarillo}) = p(\text{university}) \cdot p(\text{of} \mid \text{university}) \cdot p(\text{texas} \mid \text{university of}) \cdot p(\text{in} \mid \text{university of texas}) \cdot p(\text{amarillo} \mid \text{university of texas in})$
- “p(seeing ‘university’) times p(seeing ‘of’ given that the previous word was ‘university’) times p(seeing ‘texas’ given that the previous two words were ‘university of’) ...”
- $p(\text{university}) = \frac{C(\text{university})}{\sum_x C(x)} = \frac{C(\text{university})}{C(\text{all words})}$; easy to estimate
- $p(\text{of} \mid \text{university}) = \frac{C(\text{university of})}{\sum_w C(\text{university of } w)} = \frac{C(\text{university of})}{C(\text{university})}$; easy to estimate
- $p(\text{texas} \mid \text{university of}) = \frac{C(\text{university of texas})}{\sum_w C(\text{university of } w)} = \frac{C(\text{university of texas})}{C(\text{university of})}$; easy to estimate
- $p(\text{in} \mid \text{university of texas}) = \frac{C(\text{university of texas in})}{\sum_w C(\text{university of texas } w)} = \frac{C(\text{university of texas in})}{C(\text{university of texas})}$; easy to estimate
- $p(\text{amarillo} \mid \text{university of texas in}) = \frac{C(\text{university of texas in amarillo})}{\sum_w C(\text{university of texas in } w)} = \frac{C(\text{university of texas in amarillo})}{C(\text{university of texas in})}$; **same problem**
- So this doesn’t help us at all.

6 N-Grams

- We don’t necessarily want a “fully naïve” solution
 - Partial independence: limit how far back we look
- “Markov assumption”: future behavior depends only on recent history
 - k^{th} -order Markov model: depend only on k most recent states
- **n-gram**: sequence of n words
- **n-gram model**: statistical model of word sequences using n-grams.
- $p(\text{university of texas in amarillo})$
 - 5+ -gram:

$$p(\text{university}) \cdot p(\text{of} \mid \text{university}) \cdot p(\text{texas} \mid \text{university of}) \cdot p(\text{in} \mid \text{university of texas}) \cdot p(\text{amarillo} \mid \text{university of texas in})$$
 - 3-gram (trigram):

$$p(\text{university}) \cdot p(\text{of} \mid \text{university}) \cdot p(\text{texas} \mid \text{university of}) \cdot p(\text{in} \mid \text{of texas}) \cdot p(\text{amarillo} \mid \text{texas in})$$

- 2-gram (bigram):
 $p(\text{university}) \cdot p(\text{of} \mid \text{university}) \cdot p(\text{texas} \mid \text{of}) \cdot p(\text{in} \mid \text{texas}) \cdot p(\text{amarillo} \mid \text{in})$
- 1-gram (unigram) / bag-of-words model / full independence:
 $p(\text{university}) \cdot p(\text{of}) \cdot p(\text{texas}) \cdot p(\text{in}) \cdot p(\text{amarillo})$

- Idea: reduce necessary probabilities to an estimatable size.

- Estimating trigrams:

$$\begin{aligned}
 & p(\text{university}) \cdot p(\text{of} \mid \text{university}) \cdot p(\text{texas} \mid \text{university of}) \cdot p(\text{in} \mid \text{of texas}) \\
 & \quad \cdot p(\text{amarillo} \mid \text{texas in}) \\
 &= \frac{C(\text{university})}{\sum_x C(x)} \cdot \frac{C(\text{university of})}{\sum_x C(\text{university } x)} \cdot \frac{C(\text{university of texas})}{\sum_x C(\text{university of } x)} \cdot \frac{C(\text{of texas in})}{\sum_x C(\text{of texas } x)} \cdot \frac{C(\text{texas in amarillo})}{\sum_x C(\text{texas in } x)} \\
 &= \frac{C(\text{university})}{C(\text{all words})} \cdot \frac{C(\text{university of})}{C(\text{university})} \cdot \frac{C(\text{university of texas})}{C(\text{university of})} \cdot \frac{C(\text{of texas in})}{C(\text{of texas})} \cdot \frac{C(\text{texas in amarillo})}{C(\text{texas in})}
 \end{aligned}$$

- All of these should be easy to estimate!

7 N-Gram Model of Sentences

- Sentences are sequences of words, but with starts and ends.
- We also want to model the likelihood of words being at the beginning/end of a sentence.
- Append special “words” to the sentence

- $n-1$ ‘ $\langle S \rangle$ ’ symbols to beginning
- only one ‘ $\langle E \rangle$ ’ to then end needed
- * $p(\langle E \rangle \mid \cdot \langle E \rangle) = 1.0$ since $\langle E \rangle$ would always be followed by $\langle E \rangle$.

- “the man walks the dog .” (trigrams)

- Becomes “ $\langle S \rangle \langle S \rangle$ the man walks the dog . $\langle E \rangle$ ”
- $p(\langle S \rangle \langle S \rangle \text{ the man walks the dog . } \langle E \rangle) =$
 $p(\text{the} \mid \langle S \rangle \langle S \rangle)$
 $\cdot p(\text{man} \mid \langle S \rangle \text{ the})$
 $\cdot p(\text{walks} \mid \text{the man})$
 $\cdot p(\text{the} \mid \text{man walks})$
 $\cdot p(\text{dog} \mid \text{walks the})$
 $\cdot p(\cdot \mid \text{the dog})$
 $\cdot p(\langle E \rangle \mid \text{dog } \cdot)$

- Can be generalized to model longer texts: paragraphs, documents, etc:

- Good: can model ngrams that cross sentences (e.g. $p(w_0 \mid \cdot)$ or $p(w_0 \mid ?)$)
- Bad: more sparsity on $\langle S \rangle$ and $\langle E \rangle$

8 Sentence Likelihood Examples

Example dataset:

```
<S> the dog runs . <E>
<S> the dog walks . <E>
<S> the man walks . <E>
<S> a man walks the dog . <E>
<S> the cat walks . <E>
<S> the dog chases the cat . <E>
```

Sentence Likelihood with Bigrams:

$$\begin{aligned}
 & p(\langle S \rangle \text{ the dog walks } . \langle E \rangle) \\
 &= p(\text{the} \mid \langle S \rangle) \cdot p(\text{dog} \mid \text{the}) \cdot p(\text{walks} \mid \text{dog}) \cdot p(. \mid \text{walks}) \cdot p(\langle E \rangle \mid .) \\
 &= \frac{C(\langle S \rangle \text{ the})}{\sum_x C(\langle S \rangle x)} \cdot \frac{C(\text{the dog})}{\sum_x C(\text{the } x)} \cdot \frac{C(\text{dog walks})}{\sum_x C(\text{dog } x)} \cdot \frac{C(\text{walks } .)}{\sum_x C(\text{walks } x)} \cdot \frac{C(. \langle E \rangle)}{\sum_x C(. x)} \\
 &= \frac{C(\langle S \rangle \text{ the})}{C(\langle S \rangle)} \cdot \frac{C(\text{the dog})}{C(\text{the})} \cdot \frac{C(\text{dog walks})}{C(\text{dog})} \cdot \frac{C(\text{walks } .)}{C(\text{walks})} \cdot \frac{C(. \langle E \rangle)}{C(.)} \\
 &= \frac{5}{6} \cdot \frac{4}{7} \cdot \frac{1}{4} \cdot \frac{3}{4} \cdot \frac{6}{6} = 0.83 \cdot 0.57 \cdot 0.25 \cdot 0.75 \cdot 1.0 = \mathbf{0.089}
 \end{aligned}$$

$$\begin{aligned}
 & p(\langle S \rangle \text{ the cat walks the dog } . \langle E \rangle) \\
 &= p(\text{the} \mid \langle S \rangle) \cdot p(\text{cat} \mid \text{the}) \cdot p(\text{walks} \mid \text{cat}) \cdot p(\text{the} \mid \text{walks}) \cdot p(\text{dog} \mid \text{the}) \cdot p(. \mid \text{dog}) \cdot p(\langle E \rangle \mid .) \\
 &= \frac{C(\langle S \rangle \text{ the})}{\sum_x C(\langle S \rangle x)} \cdot \frac{C(\text{the cat})}{\sum_x C(\text{the } x)} \cdot \frac{C(\text{cat walks})}{\sum_x C(\text{cat } x)} \cdot \frac{C(\text{walks the})}{\sum_x C(\text{walks } x)} \cdot \frac{C(\text{the dog})}{\sum_x C(\text{the } x)} \cdot \frac{C(\text{dog } .)}{\sum_x C(\text{dog } x)} \cdot \frac{C(. \langle E \rangle)}{\sum_x C(. x)} \\
 &= \frac{C(\langle S \rangle \text{ the})}{C(\langle S \rangle)} \cdot \frac{C(\text{the cat})}{C(\text{the})} \cdot \frac{C(\text{cat walks})}{C(\text{cat})} \cdot \frac{C(\text{walks the})}{C(\text{walks})} \cdot \frac{C(\text{the dog})}{C(\text{the})} \cdot \frac{C(\text{dog } .)}{C(\text{dog})} \cdot \frac{C(. \langle E \rangle)}{C(.)} \\
 &= \frac{5}{6} \cdot \frac{1}{7} \cdot \frac{1}{1} \cdot \frac{1}{4} \cdot \frac{4}{7} \cdot \frac{1}{4} \cdot \frac{6}{6} = 0.83 \cdot 0.14 \cdot 1.0 \cdot 0.25 \cdot 0.57 \cdot 0.25 \cdot 1.0 = \mathbf{0.004}
 \end{aligned}$$

$$\begin{aligned}
 & p(\langle S \rangle \text{ the cat runs } . \langle E \rangle) \\
 &= p(\text{the} \mid \langle S \rangle) \cdot p(\text{cat} \mid \text{the}) \cdot p(\text{runs} \mid \text{cat}) \cdot p(. \mid \text{runs}) \cdot p(\langle E \rangle \mid .) \\
 &= \frac{C(\langle S \rangle \text{ the})}{\sum_x C(\langle S \rangle x)} \cdot \frac{C(\text{the cat})}{\sum_x C(\text{the } x)} \cdot \frac{C(\text{cat runs})}{\sum_x C(\text{cat } x)} \cdot \frac{C(\text{runs } .)}{\sum_x C(\text{runs } x)} \cdot \frac{C(. \langle E \rangle)}{\sum_x C(. x)} \\
 &= \frac{C(\langle S \rangle \text{ the})}{C(\langle S \rangle)} \cdot \frac{C(\text{the cat})}{C(\text{the})} \cdot \frac{C(\text{cat runs})}{C(\text{cat})} \cdot \frac{C(\text{runs } .)}{C(\text{runs})} \cdot \frac{C(. \langle E \rangle)}{C(.)} \\
 &= \frac{5}{6} \cdot \frac{1}{7} \cdot \frac{0}{1} \cdot \frac{1}{1} \cdot \frac{6}{6} = 0.83 \cdot 0.14 \cdot \mathbf{0.0} \cdot 1.0 \cdot 1.0 = \mathbf{0.000}
 \end{aligned}$$

- Longer sentences have lower likelihoods.
 - This makes sense because longer sequences are harder to match exactly.
- Zeros happen when an n-gram isn't seen.

9 Handling Sparsity

How big of a problem is sparsity?

- Alice's Adventures in Wonderland
 - Vocabulary (all word types) size: $V = 3,569$
 - Distinct bigrams: 17,149; $\frac{17,149}{|V|^2}$, or 99.8% of possible bigrams unseen
 - Distinct trigrams: 28,540; $\frac{17,149}{|V|^3}$, or 99.9999994% of possible trigrams unseen
- If a sequence contains an unseen ngram, it will have likelihood zero: an impossible sequence.
- Many legitimate ngrams will simply be absent from the corpus.
- This does not mean they are impossible.
- Even ungrammatical/nonsense ngrams should not cause an entire sequence's likelihood to be zero.
- Many others will be too infrequent to estimate well.

Add- λ Smoothing

- Add some constant λ to every count, including unseen ngrams
- V is the Vocabulary — all word types — including $\langle E \rangle$ (if necessary $n > 1$)
 - Don't need $\langle S \rangle$ because it will never be the 'next word'
- $$p(w_0 | w_{1-n} \dots w_{-1}) = \frac{C(w_{1-n} \dots w_{-1} w_0) + 1}{\sum_x (C(w_{1-n} \dots w_{-1} x) + 1)} = \frac{C(w_{1-n} \dots w_{-1} w_0) + 1}{(\sum_x C(w_{1-n} \dots w_{-1} x)) + |V|} = \frac{C(w_{1-n} \dots w_{-1} w_0) + 1}{C(w_{1-n} \dots w_{-1}) + |V|}$$
- Add $|V|$ to the denominator to account for the fact that there is an extra count for every x
- In practice it over-smoothes, even when $\lambda < 1$
- Example dataset:
 - `<S> <S> the dog runs . <E>`
 - `<S> <S> the dog walks . <E>`
 - `<S> <S> the man walks . <E>`
 - `<S> <S> a man walks the dog . <E>`
 - `<S> <S> the cat walks . <E>`
 - `<S> <S> the dog chases the cat . <E>`

$V = \{a, cat, chases, dog, man, runs, the, walks, ., \langle E \rangle\}$
 $|V| = 9$

Sentence Likelihood with Trigrams:

$$\begin{aligned} & p(\langle S \rangle \text{ the cat runs . } \langle E \rangle) \\ &= p(\text{the} | \langle S \rangle \langle S \rangle) \cdot p(\text{cat} | \langle S \rangle \text{ the}) \cdot p(\text{runs} | \text{the cat}) \cdot p(. | \text{cat runs}) \cdot p(\langle E \rangle | \text{runs .}) \end{aligned}$$

$$\begin{aligned}
&= \frac{C(\langle S \rangle \langle S \rangle \text{ the})}{\sum_x (C(\langle S \rangle \langle S \rangle x) + 1)} \cdot \frac{C(\langle S \rangle \text{ the cat}) + 1}{\sum_x (C(\langle S \rangle \text{ the } x) + 1)} \cdot \frac{C(\text{the cat runs}) + 1}{\sum_x (C(\text{the cat } x) + 1)} \cdot \frac{C(\text{cat runs } .) + 1}{\sum_x (C(\text{cat runs } x) + 1)} \cdot \frac{C(\text{runs } . \langle E \rangle) + 1}{\sum_x (C(\text{runs } . x) + 1)} \\
&= \frac{C(\langle S \rangle \langle S \rangle \text{ the}) + 1}{C(\langle S \rangle \langle S \rangle) + (|V| - 1)} \cdot \frac{C(\langle S \rangle \text{ the cat}) + 1}{C(\langle S \rangle \text{ the}) + |V|} \cdot \frac{C(\text{the cat runs}) + 1}{C(\text{the cat}) + |V|} \cdot \frac{C(\text{cat runs } .) + 1}{C(\text{cat runs}) + |V|} \cdot \frac{C(\text{runs } . \langle E \rangle) + 1}{C(\text{runs } .) + |V|} \\
&= \frac{5+1}{6+9} \cdot \frac{1+1}{5+10} \cdot \frac{0+1}{2+10} \cdot \frac{0+1}{0+10} \cdot \frac{1+1}{1+10} \\
&= 0.40 \cdot 0.13 \cdot \mathbf{0.08} \cdot \mathbf{0.10} \cdot 0.18 = \mathbf{0.000081}
\end{aligned}$$

- If the context was never seen, then the distribution is uniform:

$$\begin{aligned}
p_{+\lambda}(w_0 \mid w_{-2}, w_{-1}) &= \frac{C(w_{-2} w_{-1} w_0) + \lambda}{(\sum_x C(w_{-2} w_{-1} x)) + \lambda \cdot |V|} \\
&= \frac{0 + \lambda}{(\sum_x 0) + \lambda \cdot |V|} \\
&= \frac{0 + \lambda}{0 + \lambda \cdot |V|} = \frac{\lambda}{\lambda \cdot |V|} = \frac{1}{1 \cdot |V|} = \frac{1}{|V|}
\end{aligned}$$

- Since $\langle S \rangle$ can never be followed by $\langle E \rangle$
 - $p(\langle E \rangle \mid \langle S \rangle \langle S \rangle) = 0$
 - The denominator $\sum_x C(\langle S \rangle \langle S \rangle x)$ only gets $|V|-1$ smoothing counts
- $\langle S \rangle$ not included in V because we can't transition to it.

Good-Turing Smoothing

- Estimate counts of things you haven't seen from counts of things you have
- Estimate probability of things which occur c times with the probability of things which occur $c + 1$ times
- $c^* = (c + 1) \frac{N_{c+1}}{N_c}$
- $p_{GT}^*(\text{things with freq } 0) = \frac{N_1}{N}$
- $p_{GT}(w_0 \mid w_{1-n} \dots w_{-1}) = \frac{C^*(w_{1-n} \dots w_{-1} w_0)}{C^*(w_{1-n} \dots w_{-1})}$

Stupid Backoff

- If $p(\text{n-gram})=0$, use $p((\text{n-1})\text{-gram})$
- Works shockingly well for huge datasets

Interpolation

- Mix n-gram probability with probabilities from lower-order models

$$\begin{aligned}
\hat{p}(w_0 \mid w_{-2} w_{-1}) &= \lambda_3 \cdot p(w_0 \mid w_{-2} w_{-1}) \\
&\quad + \lambda_2 \cdot p(w_0 \mid w_{-1}) \\
&\quad + \lambda_1 \cdot p(w_0)
\end{aligned}$$

- λ_i terms used to decide how much to smooth
- $\sum_i \lambda_i = 1$, because they are proportions
- Use *dev* dataset to tune λ hyperparameters
- Also useful for combining models trained on different data:
 - Can interpolate “customized” models with “general” models
 - Baseline English + regional English + user-specific English
 - Little in-domain data, lots of out-of-domain

Knesser-Ney Smoothing

- Intuition: interpolate based on “openness” of the context
- Words seen in more contexts are more likely to appear in others
- Even if we haven’t seen w_0 following the context, if the context is “open” (supports a wide variety of “next words”), then it is more likely to support w_0
- Boost counts based on $|\{x : C(w_{1-n} \dots w_{-1} x) > 0\}|$, the number of different “next words” seen after $w_{1-n} \dots w_{-1}$

10 Out-of-Vocabulary Words (OOV)

Add- λ

- If ngram contains OOV item, assume count of λ , just like for all other ngrams.
- Probability distributions become invalid. We can’t know the full vocabulary size, so we can’t normalize counts correctly.

$\langle unk \rangle$

- Create special token $\langle unk \rangle$
- Create a fixed lexicon L
 - All types in some subset of training data?
 - All types appearing more than k times?
- $V = L + \langle unk \rangle$, $|V| = |L| + 1$
- Before training, change any word not in L to $\langle unk \rangle$
- Then train as usual as if $\langle unk \rangle$ was a normal word
- For new sentence, again replace words not in L with $\langle unk \rangle$ before using model

- Probabilities containing $\langle unk \rangle$ measure likelihood with *some rare word*
- Problem: the “rare” word is no longer rare since there are many $\langle unk \rangle$ tokens
 - Ngrams with $\langle unk \rangle$ will have higher probabilities than those with any particular rare word
 - Not so bad when comparing same sequence under multiple models. All will have inflated probabilities.
 - More problematic when comparing probabilities of different sequences under the same model
 - * $p(i \text{ **totes** know}) < p(i \text{ **totally** know}) < p(i \langle \textbf{unk} \rangle \text{ know})$

11 Evaluation

Extrinsic

- Use the model in some larger task. See if it helps.
- More realistic
- Harder

Intrinsic

- Evaluate on a test corpus
- Easier

Perplexity

- Intrinsic measure of model quality
- How well does the model “fit” the test data?
- How “perplexed” is the model whe it sees the test data?
- Measure the probability of the test corpus, normalize for number of words.
- $PP(W) = \frac{1}{|W|} \sqrt{\frac{1}{p(w_1 \ w_2 \ ... \ w_{|W|})}}$
- With individual sentences: $PP(s_1, s_2, ...) = \frac{1}{(\sum_i |s_i|)} \sqrt{\frac{1}{\prod_i p(s_i)}}$

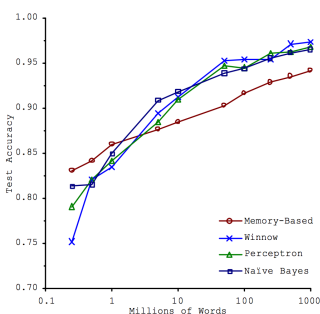
12 How much data?

Choosing n

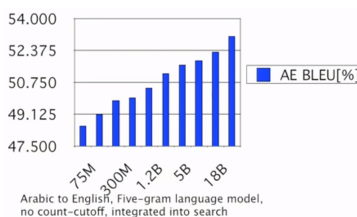
- Large n
 - More context for probabilities:
 $p(\text{phone})$ vs
 $p(\text{phone} \mid \text{cell})$ vs
 $p(\text{phone} \mid \text{your cell})$ vs
 $p(\text{phone} \mid \text{off your cell})$ vs
 $p(\text{phone} \mid \text{turn off your cell})$
 - Long-range dependencies
- Small n
 - Better generalization
 - Better estimates
 - Long-range dependencies

How much training data?

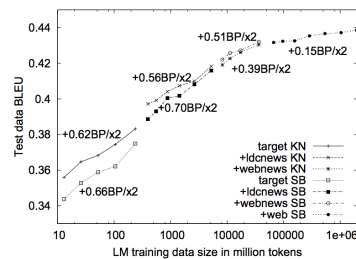
- *As much as possible.*
- More data means better estimates
- Google N-Gram corpus uses 10-grams



(a) Data size matters more than algorithm (Banko and Brill, 2001)



(b) Results keep improving with more data (Norvig: Unreasonable ...)



(c) With enough data, stupid backoff approaches Knesser-Ney accuracy (Brants et al., 2007)

13 Generative Models

- Generative models are designed to model how the data *could have been generated*.
- The best parameters are those that would most likely generate the data.

- MLE maximizes that likelihood that the training data was generated by the model.
- As such, we can *actually generate* data from a model.
- Trigram model:
 - General:

For each sequence:

 1. Sample a word w_0 according to $w_0 \sim p(w_0)$
 2. Sample a second word w_1 according to $w_1 \sim p(w_1 | w_0)$
 3. Sample a next word w_k according to $w_k \sim p(w_k | w_{k-2} w_{k-1})$
 4. Repeat step 3 until you feel like stopping.
 - Sentences:

For each sentence:

 1. Sample a word w_0 according to $w_0 \sim p(w_0 | \langle S \rangle \langle S \rangle)$
 2. Sample a second word w_1 according to $w_1 \sim p(w_1 | w_0 \langle S \rangle)$
 3. Sample a next word w_k according to $w_k \sim p(w_k | w_{k-2} w_{k-1})$
 4. Repeat until $\langle E \rangle$ is drawn.
- Longer n generates more coherent text
- Too-large n just ends up generating sentences from the training data because most counts will be 1 (no choice of next word).
- Naïve Bayes was a generative model too!

For each instance:

 1. Sample a label l according to $l \sim p(\text{Label} = l)$
 2. For each feature F : sample a value v according to $v \sim p(F = v | \text{Label} = l)$
- We will see many more generative models throughout this course

14 Citations

Some content adapted from:

- http://courses.washington.edu/ling570/gina_fall11/slides/ling570_class8_smoothing.pdf