



## CMPT-413: Computational Linguistics

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## Cross-Entropy and Perplexity

### Smoothing $n$ -gram Models

- Add-one Smoothing

- Additive Smoothing

- Good-Turing Smoothing

- Backoff Smoothing

- Event Space for  $n$ -gram Models

# How good is a model

- ▶ So far we've seen the probability of a sentence:  $P(w_0, \dots, w_n)$
- ▶ What is the probability of a collection of sentences, that is what is the probability of a corpus
- ▶ Let  $T = s_0, \dots, s_m$  be a text corpus with sentences  $s_0$  through  $s_m$
- ▶ What is  $P(T)$ ?  
Let us assume that we trained  $P(\cdot)$  on some *training data*, and  $T$  is the *test data*

## How good is a model

- ▶  $T = s_0, \dots, s_m$  is the text corpus with sentences  $s_0$  through  $s_m$
- ▶  $P(T) = P(s_0, s_1, s_2, \dots, s_m)$  – but each sentence is independent from the other sentences
- ▶  $P(T) = P(s_0) \cdot P(s_1) \cdot P(s_2) \cdot \dots \cdot P(s_m) = \prod_{i=0}^m P(s_i)$
- ▶  $P(s_i) = P(w_0^i, \dots, w_n^i)$
- ▶ Let  $W_T$  be the length of the text  $T$  measured in words
- ▶ Then for the unigram model,  $P(T) = \prod_{w \in T} P(w)$
- ▶ A problem: we want to compare two different models  $P_1$  and  $P_2$  on  $T$
- ▶ To do this we use the *per word* perplexity of the model:

$$PP_P(T) = P(T)^{-\frac{1}{W_T}} = \sqrt[W_T]{\frac{1}{P(T)}}$$

# How good is a model

- ▶ The *per word* perplexity of the model is:

$$PP_P(T) = P(T)^{-\frac{1}{W_T}}$$

- ▶ Recall that  $PP_P(T) = 2^{H_P(T)}$  where  $H_P(T)$  is the cross-entropy of  $P$  for text  $T$ .
- ▶ Therefore,  $H_P(T) = \log_2 PP_P(T) = -\frac{1}{W_T} \log_2 P(T)$
- ▶ Above we use a unigram model  $P(w)$ , but the same derivation holds for bigram, trigram, ...

# How good is a model

- ▶ Lower cross entropy values and perplexity values are better  
Lower values mean that the model is *better*  
Correlation with performance of the language model in various applications
- ▶ Performance of a language model is its cross-entropy or perplexity on *test data* (unseen data)  
corresponds to the number bits required to encode that data
- ▶ On various real life datasets, typical perplexity values yielded by  $n$ -gram models on English text range from about 50 to almost 1000 (corresponding to cross entropies from about 6 to 10 bits/word)

## Cross-Entropy and Perplexity

### Smoothing $n$ -gram Models

- Add-one Smoothing

- Additive Smoothing

- Good-Turing Smoothing

- Backoff Smoothing

- Event Space for  $n$ -gram Models

# Bigram Models

- In practice:

$$P(\text{Mork read a book}) =$$

$$P(\text{Mork} \mid \langle \text{start} \rangle) \times P(\text{read} \mid \text{Mork}) \times$$

$$P(\text{a} \mid \text{read}) \times P(\text{book} \mid \text{a}) \times$$

$$P(\langle \text{stop} \rangle \mid \text{book})$$

- $P(w_i \mid w_{i-1}) = \frac{c(w_{i-1}, w_i)}{c(w_{i-1})}$

On unseen data,  $c(w_{i-1}, w_i)$  or worse  $c(w_{i-1})$  could be zero

$$\sum_{w_i} \frac{c(w_{i-1}, w_i)}{c(w_{i-1})} = ?$$



# Smoothing

- ▶ **Smoothing** deals with events that have been observed zero times
- ▶ Smoothing algorithms also tend to improve the accuracy of the model

$$P(w_i \mid w_{i-1}) = \frac{c(w_{i-1}, w_i)}{c(w_{i-1})}$$

- ▶ Not just unobserved events: what about events observed once?

# Add-one Smoothing

$$P(w_i \mid w_{i-1}) = \frac{c(w_{i-1}, w_i)}{c(w_{i-1})}$$

- ▶ Add-one Smoothing:

$$P(w_i \mid w_{i-1}) = \frac{1 + c(w_{i-1}, w_i)}{V + c(w_{i-1})}$$

- ▶ Let  $V$  be the number of words in our vocabulary  
Assign count of 1 to unseen bigrams

# Add-one Smoothing

$$\begin{aligned} P(\text{Mindy read a book}) = & \\ & P(\text{Mindy} \mid \langle \text{start} \rangle) \times P(\text{read} \mid \text{Mindy}) \times \\ & P(\text{a} \mid \text{read}) \times P(\text{book} \mid \text{a}) \times \\ & P(\langle \text{stop} \rangle \mid \text{book}) \end{aligned}$$

- ▶ Without smoothing:

$$P(\text{read} \mid \text{Mindy}) = \frac{c(\text{Mindy, read})}{c(\text{Mindy})} = 0$$

- ▶ With add-one smoothing (assuming  $c(\text{Mindy}) = 1$  but  $c(\text{Mindy, read}) = 0$ ):

$$P(\text{read} \mid \text{Mindy}) = \frac{1}{V + 1}$$

## Additive Smoothing: (Lidstone 1920, Jeffreys 1948)

$$P(w_i \mid w_{i-1}) = \frac{c(w_{i-1}, w_i)}{c(w_{i-1})}$$

- ▶ Add-one smoothing works horribly in practice. Seems like 1 is too large a count for unobserved events.
- ▶ Additive Smoothing:

$$P(w_i \mid w_{i-1}) = \frac{\delta + c(w_{i-1}, w_i)}{(\delta \times V) + c(w_{i-1})}$$

- ▶  $0 < \delta \leq 1$   
Still works horribly in practice, but better than add-one smoothing.

## Good-Turing Smoothing: (Good, 1953)

$$P(w_i \mid w_{i-1}) = \frac{c(w_{i-1}, w_i)}{c(w_{i-1})}$$

- ▶ Imagine you're sitting at a sushi bar with a conveyor belt.
- ▶ You see going past you 10 plates of tuna, 3 plates of unagi, 2 plates of salmon, 1 plate of shrimp, 1 plate of octopus, and 1 plate of yellowtail
- ▶ Chance you will observe a new kind of seafood:  $\frac{3}{18}$
- ▶ How likely are you to see another plate of salmon: should be  $< \frac{2}{18}$

# Good-Turing Smoothing

- ▶ How many types of seafood (words) were seen once? Use this to predict probabilities for unseen events

Let  $n_1$  be the number of events that occurred once:  $p_0 = \frac{n_1}{N}$

- ▶ The Good-Turing estimate states that for any  $n$ -gram that occurs  $r$  times, we should pretend that it occurs  $r^*$  times

$$r^* = (r + 1) \frac{n_{r+1}}{n_r}$$

- ▶  $n_r$ : number of different objects seen  $r$  times

# Good-Turing Smoothing

- ▶ 10 tuna, 3 unagi, 2 salmon, 1 shrimp, 1 octopus, 1 yellowtail
- ▶ How likely is new data? Let  $n_1$  be the number of items occurring once, which is 3 in this case.  $N$  is the total, which is 18.

$$p_0 = \frac{n_1}{N} = \frac{3}{18} = 0.166$$

# Good-Turing Smoothing

- ▶ 10 tuna, 3 unagi, 2 salmon, 1 shrimp, 1 octopus, 1 yellowtail
- ▶ How likely is *octopus*? Since  $c(\text{octopus}) = 1$  The GT estimate is  $1^*$ .

$$r^* = (r + 1) \frac{n_{r+1}}{n_r}$$

$$p_{GT} = \frac{r^*}{N}$$

- ▶ To compute  $1^*$ , we need  $n_1 = 3$  and  $n_2 = 1$

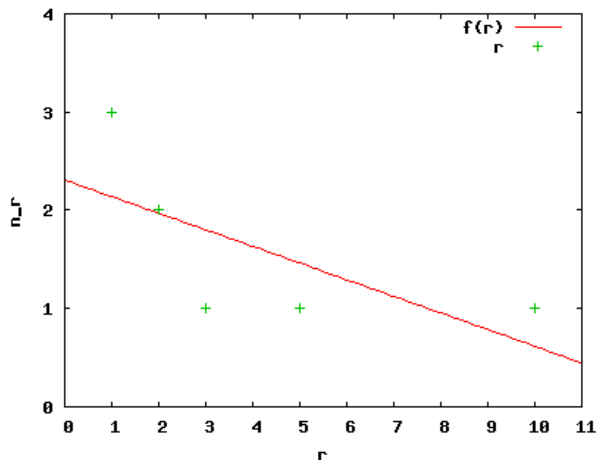
$$1^* = 2 \times \frac{1}{3} = \frac{2}{3}$$

$$p_1 = \frac{1^*}{18} = 0.037$$

- ▶ What happens when  $n_{r+1} = 0$ ? (smoothing before smoothing)



## Simple Good-Turing: linear interpolation for missing $n_{r+1}$



$$f(r) = a + b * r$$

$$a = 2.3$$

$$b = -0.17$$

$r$	$n_r = f(r)$
1	2.14
2	1.97
3	1.80
4	1.63
5	1.46
6	1.29
7	1.12
8	0.95
9	0.78
10	0.61
11	0.44

## Comparison between Add-one and Good-Turing

freq $r$	num with freq $r$ $n_r$	NS $p_r$	Add1 $p_r$	SGT $p_r$
0	0	0	0.0294	0.12
1	3	0.04	0.0588	0.03079
2	2	0.08	0.0882	0.06719
3	1	0.12	0.1176	0.1045
5	1	0.2	0.1764	0.1797
10	1	0.4	0.3235	0.3691

- ▶  $N = (1 * 3) + (2 * 2) + 3 + 5 + 10 = 25$
- ▶  $V = 1 + 3 + 2 + 1 + 1 + 1 = 9$
- ▶ Important: we added a new word type for unseen words. Let's call it UNK, the unknown word.
- ▶ Check that:  $1.0 == \sum_r n_r \times p_r$   
 $0.12 + (3 * 0.03079) + (2 * 0.06719) + 0.1045 + 0.1797 + 0.3691 = 1.0$

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- ▶ NS = No smoothing:  $p_r = \frac{r}{N}$
- ▶ Add1 = Add-one smoothing:  $p_r = \frac{1+r}{V+N}$
- ▶ SGT = Simple Good-Turing:  $p_0 = \frac{n_1}{N}$ ,  $p_r = \frac{(r+1)^{\frac{n_{r+1}}{n_r}}}{N}$   
with linear interpolation for missing values where  $n_{r+1} = 0$   
(Gale and Sampson, 1995) <http://www.grsampson.net/AGtf1.html>

## Simple Backoff Smoothing: incorrect version

$$P(w_i \mid w_{i-1}) = \frac{c(w_{i-1}, w_i)}{c(w_{i-1})}$$

- ▶ In add-one or Good-Turing:  
 $P(\text{the} \mid \text{string}) = P(\text{Fonz} \mid \text{string})$
- ▶ If  $c(w_{i-1}, w_i) = 0$ , then use  $P(w_i)$  (back off)
- ▶ Works for trigrams: back off to bigrams and then unigrams
- ▶ Works better in practice, but probabilities get mixed up (unseen bigrams, for example will get higher probabilities than seen bigrams)

## Backoff Smoothing: Jelinek-Mercer Smoothing

$$P_{ML}(w_i \mid w_{i-1}) = \frac{c(w_{i-1}, w_i)}{c(w_{i-1})}$$

- ▶  $P_{JM}(w_i \mid w_{i-1}) = \lambda P_{ML}(w_i \mid w_{i-1}) + (1 - \lambda)P_{ML}(w_i)$   
where,  $0 \leq \lambda \leq 1$
- ▶ Notice that  $P_{JM}(\text{the} \mid \text{string}) > P_{JM}(\text{Fonz} \mid \text{string})$  as we wanted
- ▶ Jelinek-Mercer (1980) describe an elegant form of this **interpolation**:

$$P_{JM}(n\text{gram}) = \lambda P_{ML}(n\text{gram}) + (1 - \lambda)P_{JM}(n - 1\text{gram})$$

- ▶ What about  $P_{JM}(w_i)$ ?  
For missing unigrams:  $P_{JM}(w_i) = \lambda P_{ML}(w_i) + (1 - \lambda)\frac{\delta}{V}$

## Backoff Smoothing: Many alternatives

$$P_{JM}(n\text{gram}) = \lambda P_{ML}(n\text{gram}) + (1 - \lambda)P_{JM}(n - 1\text{gram})$$

- ▶ Different methods for finding the values for  $\lambda$  correspond to variety of different smoothing methods
- ▶ Katz Backoff (include Good-Turing with Backoff Smoothing)

$$P_{katz}(y \mid x) = \begin{cases} \frac{c^*(xy)}{c(x)} & \text{if } c(xy) > 0 \\ \alpha(x)P_{katz}(y) & \text{otherwise} \end{cases}$$

- ▶ where  $\alpha(x)$  is chosen to make sure that  $P_{katz}(y \mid x)$  is a proper probability

$$\alpha(x) = 1 - \sum_y \frac{c^*(xy)}{c(x)}$$

## Backoff Smoothing: Many alternatives

$$P_{JM}(ngram) = \lambda P_{ML}(ngram) + (1 - \lambda)P_{JM}(n - 1gram)$$

- ▶ Deleted Interpolation (Jelinek, Mercer)  
compute  $\lambda$  values to minimize cross-entropy on **held-out** data  
which is **deleted** from the initial set of training data
- ▶ Improved JM smoothing, a separate  $\lambda$  for each  $w_{i-1}$ :

$$P_{JM}(w_i \mid w_{i-1}) = \lambda(w_{i-1})P_{ML}(w_i \mid w_{i-1}) + (1 - \lambda(w_{i-1}))P_{ML}(w_i)$$

$$\text{where } \sum_i \lambda(w_i) = 1 \text{ because } \sum_{w_i} P(w_i \mid w_{i-1}) = 1$$

## Backoff Smoothing: Many alternatives

$$P_{JM}(n\text{gram}) = \lambda P_{ML}(n\text{gram}) + (1 - \lambda) P_{JM}(n - 1\text{gram})$$

- ▶ Witten-Bell smoothing  
use the  $n - 1$  gram model when the  $n$  gram model has too few unique words **in the  $n$  gram context**
- ▶ Absolute discounting (Ney, Essen, Kneser)

$$P_{abs}(y \mid x) = \begin{cases} \frac{c(xy) - D}{c(x)} & \text{if } c(xy) > 0 \\ \alpha(x) P_{abs}(y) & \text{otherwise} \end{cases}$$

compute  $\alpha(x)$  as was done in Katz smoothing



# Backoff Smoothing: Many alternatives

$$P_{JM}(n\text{gram}) = \lambda P_{ML}(n\text{gram}) + (1 - \lambda)P_{JM}(n - 1\text{gram})$$

- ▶ Kneser-Ney smoothing

$$P(\text{Francisco} \mid \text{eggplant}) > P(\text{stew} \mid \text{eggplant})$$

- ▶ *Francisco* is common, so interpolation gives  $P(\text{Francisco} \mid \text{eggplant})$  a high value
- ▶ But *Francisco* occurs in few contexts (only after *San*)
- ▶ *stew* is common, **and** occurs in many contexts
- ▶ Hence weight the interpolation based on number of contexts for the word using discounting

# Backoff Smoothing: Many alternatives

$$P_{JM}(n\text{gram}) = \lambda P_{ML}(n\text{gram}) + (1 - \lambda)P_{JM}(n - 1\text{gram})$$

- ▶ Modified Kneser-Ney smoothing (Chen and Goodman)  
multiple discounts for one count, two counts and three or more counts
- ▶ Finding  $\lambda$ : use Generalized line search (Powell search) or the Expectation-Maximization algorithm

# Trigram Models

- ▶ Revisiting the trigram model:

$$P(w_1, w_2, \dots, w_n) = \\ P(w_1) \times P(w_2 \mid w_1) \times P(w_3 \mid w_1, w_2) \times P(w_4 \mid w_2, w_3) \times \\ \dots P(w_i \mid w_{i-2}, w_{i-1}) \dots \times P(w_n \mid w_{n-2}, \dots, w_{n-1})$$

- ▶ Notice that the length of the sentence  $n$  is variable
- ▶ What is the event space?

# The stop symbol

- ▶ Let  $\Sigma = \{a, b\}$  and the language be  $\Sigma^*$   
so  $L = \{\epsilon, a, b, aa, bb, ab, ba \dots\}$
- ▶ Consider a unigram model:  $P(a) = P(b) = 0.5$
- ▶  $P(a) = 0.5, P(b) = 0.5, P(aa) = 0.5^2 = 0.25, P(bb) = 0.25$   
and so on.
- ▶ But  $P(a) + P(b) + P(aa) + P(bb) = 1.5 !!$

$$\sum_w P(w) = 1$$

# The stop symbol

- ▶ What went wrong?  
No probability for  $P(\epsilon)$
- ▶ Add a special stop symbol:

$$P(a) = P(b) = 0.25$$

$$P(\text{stop}) = 0.5$$

- ▶  $P(\text{stop}) = 0.5$ ,  
 $P(a \text{ stop}) = P(b \text{ stop}) = 0.25 \times 0.5 = 0.125$ ,  
 $P(aa \text{ stop}) = 0.25^2 \times 0.5 = 0.03125$  (now the sum is no longer greater than one)

# The stop symbol

- ▶ With this new stop symbol we can show that  $\sum_w P(w) = 1$   
Notice that the probability of any sequence of length  $n$  is  $0.25^n \times 0.5$   
Also there are  $2^n$  sequences of length  $n$

$$\begin{aligned}\sum_w P(w) &= \\&= \sum_{n=0}^{\infty} 2^n \times 0.25^n \times 0.5 \\&= \sum_{n=0}^{\infty} 0.5^n \times 0.5 = \sum_{n=0}^{\infty} 0.5^{n+1} \\&= \sum_{n=1}^{\infty} 0.5^n = 1\end{aligned}$$