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# Lab 3: Language Modeling Fever

EECS E6870: Speech Recognition

Due: October 31, 2012 at 6:00pm

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SECTION 0

## Overview

The goal of this assignment is for you, the student, to implement basic algorithms for  $n$ -gram language modeling. This lab will involve counting  $n$ -grams and doing basic  $n$ -gram smoothing. For this lab, we will be working with *Switchboard* data. The Switchboard corpus is a collection of recordings of telephone conversations; participants were told to have a discussion on one of seventy topics (*e.g.*, pollution, gun control).

The lab consists of the following parts, all of which are required:

- ▶ **Part 1: Implement  $n$ -gram counting** — Given some text, collect all counts needed for building an  $n$ -gram language model.
- ▶ **Part 2: Implement  $+\delta$  smoothing** — Write code to compute LM probabilities for an  $n$ -gram model smoothed with  $+\delta$  smoothing.
- ▶ **Part 3: Implement Witten-Bell smoothing** — Write code to compute LM probabilities for an  $n$ -gram model smoothed with Witten-Bell smoothing.
- ▶ **Part 4: Evaluate various  $n$ -gram models on the task of  $N$ -best list rescoring** — See how  $n$ -gram order and smoothing affects WER when doing  $N$ -best list rescoring for Switchboard.

All of the files needed for the lab can be found in the directory `/user1/faculty/stanchen/e6870/lab3/`. Before starting the lab, please read the file `lab3.txt`; this includes all of the questions you will have to answer while doing the lab. Questions about the lab can be posted on Courseworks (<https://courseworks.columbia.edu/>); a discussion topic will be created for each lab.

SECTION 1

## Part 1: Implement $n$ -gram counting

### 1.1 The Big Picture

For this lab, we will be compiling the code you write into the program `lab3_lm` (or `Lab3Lm` for Java). Here is an outline of what this program does:

- ▶ Training phase.

- Reset all  $n$ -gram counts to 0.
- For each sentence in the training data:
  - Update  $n$ -gram counts (A).
- Evaluation phase.
  - For each sentence to be evaluated:
    - For each  $n$ -gram in the sentence:
      - Call smoothing routine to evaluate probability of  $n$ -gram given training counts (B).
  - Compute overall perplexity of evaluation data from  $n$ -gram probabilities.

In the first part of the lab, you'll be writing the code that does step (A). In the next two parts of the lab, you'll be writing step (B) for two different smoothing algorithms.

## 1.2 This Part

In this part, you will be writing code to collect all of the counts needed for building an  $n$ -gram model given some text. For example, consider trying to compute the probability of the word KING following the words OF THE. The maximum likelihood estimate of this trigram probability is:

$$P_{\text{MLE}}(\text{KING} \mid \text{OF THE}) = \frac{\text{count}(\text{OF THE KING})}{\sum_w \text{count}(\text{OF THE } w)} = \frac{\text{count}(\text{OF THE KING})}{\text{count}_{\text{hist}}(\text{OF THE})}$$

Thus, to compute this probability we need to collect the count of the trigram OF THE KING in the training data as well as the count of the bigram history OF THE. (The *history* is whatever words in the past we are conditioning on.) When building *smoothed* trigram LM's, we also need to compute bigram and unigram probabilities and thus also need to collect the relevant counts for these lower-order distributions.

Before we continue, let us clarify some terminology. Consider the maximum likelihood estimate for the bigram probability of the word THE following OF:

$$P_{\text{MLE}}(\text{THE} \mid \text{OF}) = \frac{\text{count}(\text{OF THE})}{\sum_w \text{count}(\text{OF } w)} = \frac{\text{count}(\text{OF THE})}{\text{count}_{\text{hist}}(\text{OF})}$$

Notice the term  $\text{count}(\text{OF THE})$  in this equation and the term  $\text{count}_{\text{hist}}(\text{OF THE})$  in the last equation. We refer to the former count as a regular bigram count and the latter count as a bigram *history* count. While these two counts will be the same for most pairs of words, they won't be the same for all pairs and so we distinguish between the two. Specifically, the history count is used for normalization, and so is defined as

$$\text{count}_{\text{hist}}(\text{OF THE}) \equiv \sum_w \text{count}(\text{OF THE } w)$$

A related point that is worth mentioning is that it is useful to have the concept of a *0-gram* history. Just as we use unigram history counts in computing bigram probabilities, we use 0-gram history counts in computing unigram probabilities. We use the notation  $\text{count}_{\text{hist}}(\epsilon)$  to denote the 0-gram history count, and it is defined similarly as above, *i.e.*,

$$\text{count}_{\text{hist}}(\epsilon) \equiv \sum_w \text{count}(w)$$

In practice, instead of working directly with strings when collecting counts, all words are first converted to a unique integer index; *e.g.*, the words OF, THE, and KING might be encoded as the integers 1, 2, and 3, respectively. In this lab, the words in the training data have been converted to integers for you. To see the mapping from words to integers, check out the file `lab3.syms` (once you have copied over the files for the lab). In practice, it is much easier to fix the set of words that the LM assigns (nonzero) probabilities to beforehand (rather than allowing any possible word spelling); this set of words is called the *vocabulary*. When encountering a word outside the vocabulary, one typically maps this word to a distinguished word, the *unknown token*, which we call `<UNK>` in this lab. The unknown token is treated like any other word in the vocabulary, and the probability assigned to predicting the unknown token (in some context) can be interpreted as the sum of the probabilities of predicting any word not in the vocabulary (in that context).

To prepare for the exercise, create the relevant subdirectory and copy over the needed files:

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```
mkdir -p ~/e6870/lab3/
chmod 0700 ~/e6870/
cd ~/e6870/lab3/
cp -d /user1/faculty/stanthen/e6870/lab3/* .
```

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Be sure to use the `-d` flag with `cp` (so the symbolic links are copied over correctly).

Your job in this part is to fill in the sections between the markers `BEGIN_LAB` and `END_LAB` in the method `count_sentence_ngrams()` in the file `lang_model.C` (or `LangModel.java` for Java). Read this file to see what input and output structures need to be accessed. This routine corresponds to step (A) in the pseudocode listed in Section 1.1. In this function, you will be passed a sentence (expressed as an array of integer word indices) and will need to update all relevant regular  $n$ -gram counts (*e.g.*, trigram, bigram, and unigram counts for a trigram model) and all relevant history  $n$ -gram counts (*e.g.*, bigram, unigram, and 0-gram). All of these counts will be initialized to zero for you.

In addition, for Witten-Bell smoothing (to be implemented in Part 3), you will also need to compute how many unique words follow each bigram/unigram/0-gram history. We refer to this as a “1+” count, since this is the number of words with one or more counts following a history.

It is a little tricky to figure out exactly which  $n$ -grams to count in a sentence, namely at the sentence begins and ends. For more details, refer to slides 10–14 in the week 6 language modeling slides. Hint: If you’re building a trigram model, say, the trigram counts to update correspond one-to-one to the trigram probabilities used in computing the trigram probability of a sentence. Bigram history counts can be defined in terms of trigram counts using the equation described earlier. How to do counting for lower-order models is defined analogously.

In the lab, you’ll need to deal with the class `NGramCounter`:

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<http://www.ee.columbia.edu/~stanthen/fall09/e6870/classlib/classNGramCounter.html>

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Also,  $n$ -grams are represented using `vector<int>`’s (or `IntVector`’s in Java); see Lab 1 for some documentation and examples for vectors.

(Pedantic note: In this lab,  $n$ -gram counting is done in the constructor of the `LangModel` class, which is unusual in real life. In real life, one normally does counting offline, saves the LM to a file, and this LM file would be read in the constructor of the LM class. However, we

compress this stuff into a single program so we don't have to deal with reading and writing LM's, which can be nontrivial.)

### 1.3 Compiling and testing

Your code will be compiled into the program `lab3_lm` (or `Lab3Lm` for Java), which constructs an  $n$ -gram language model from training data and then uses this LM to evaluate the probability and perplexity of some test data. To compile this program with your code, type `make lab3_lm` for C++ or `make Lab3Lm` for Java in the directory containing your source files.

To run this program (training on 10 Switchboard sentences and evaluating on 10 other sentences), run

```
lab3_pla.sh
```

This shell script starts the executable `lab3_lm` located in the current directory with the appropriate flags (or `Lab3Lm.class` if `lab3_lm` is absent). You can examine this script to see what arguments are being provided to `lab3_lm`. The final cross-entropy/perplexity output will be bogus, since the code for computing LM probabilities won't be filled in until later in the lab. However, this script also outputs all collected counts to the file `pla.counts`. The file first contains all regular counts, then history counts, and then 1+ counts; each line contains a single  $n$ -gram followed by its count. The target output can be found in `pla.counts.ref`; your output should match the target output exactly. The training data used by the script can be found in `minitrain2.txt`.

The instructions in `lab3.txt` will ask you to run the script `lab3_plb.sh`, which does the same thing as `lab3_pla.sh` except training on 100 rather than 10 sentences.

## SECTION 2

### Part 2: Implement $+\delta$ smoothing

In this part, you will write code to compute LM probabilities for an  $n$ -gram model smoothed with  $+\delta$  smoothing. This is just like *add-one* smoothing in the readings, except instead of adding one count to each trigram, say, we will add  $\delta$  counts to each trigram for some small  $\delta$  (e.g.,  $\delta = 0.0001$  in this lab). This is just about the simplest smoothing algorithm around, and this can actually work acceptably in some situations (though not in large-vocabulary ASR). To estimate the probability of a trigram  $P_{+\delta}(w_i|w_{i-2}w_{i-1})$  with this smoothing, we take

$$P_{+\delta}(w_i|w_{i-2}w_{i-1}) = \frac{c(w_{i-2}w_{i-1}w_i) + \delta}{c_h(w_{i-2}w_{i-1}) + \delta \times |V|}$$

where  $|V|$  is the size of the vocabulary. (Note: in the above equation and the rest of the document, we abbreviate `count( $\cdot$ )` as  $c(\cdot)$  and `counthist( $\cdot$ )` as  $c_h(\cdot)$ .)

Your job in this part is to fill in the method `get_prob_plus_delta()`. This function should return the value  $P_{+\delta}(w_i|w_{i-2}w_{i-1})$  given a trigram  $w_{i-2}w_{i-1}w_i$  (if  $n=3$ ). You will be provided with the vocabulary size and all of the counts you computed in Part 1. This routine corresponds to step (B) in the pseudocode listed in Section 1.1.

Your code will again be compiled into the program `lab3_lm`. To compile, type `make lab3_lm` for C++ or `make Lab3Lm` for Java. To run this program on a 100-sentence Switchboard training set and 10-sentence test set, run

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```
lab3_p2a.sh
```

---

This does three runs, corresponding to unigram, bigram, and trigram models. Here is the target output:

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```
408.6994 PP (66 words)
397.5355 PP (66 words)
1052.6901 PP (66 words)
```

---

It also writes the probability of each word to a file; the corresponding files for each run are `p2a.1.probs`, `p2a.2.probs`, and `p2a.3.probs`. The target output can be found in files of the same name with the extension `.ref` appended. Again, you should try to match the target output just about exactly.

The instructions in `lab3.txt` will ask you to run the script `lab3_p2b.sh`, which does the same thing as `lab3_p2a.sh` except on a 100-sentence test set and only for trigrams.

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SECTION 3

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### Part 3: Implement Witten-Bell smoothing

Witten-Bell smoothing is this smoothing algorithm that was invented by some dude named Moffat, but dudes named Witten and Bell have generally gotten credit for it. It is significant in the field of text compression and is relatively easy to implement, and that's good enough for us.

Here's a rough motivation for this smoothing algorithm: One of the central problems in smoothing is how to estimate the probability of  $n$ -grams with zero count. For example, let's say we're building a bigram model and the bigram  $w_{i-1}w_i$  has zero count, so  $P_{\text{MLE}}(w_i|w_{i-1}) = 0$ . According to the Good-Turing estimate, the total mass of counts belonging to things with zero count in a distribution is the number of things with exactly one count. In other words, the probability mass assigned to the backoff distribution should be around  $\frac{N_1(w_{i-1})}{c_h(w_{i-1})}$ , where  $N_1(w_{i-1})$  is the number of words  $w'$  following  $w_{i-1}$  exactly once in the training data (*i.e.*, the number of bigrams  $w_{i-1}w'$  with exactly one count). This suggests the following smoothing algorithm

$$P_{\text{WB}}(w_i|w_{i-1}) \stackrel{?}{=} \lambda P_{\text{MLE}}(w_i|w_{i-1}) + \frac{N_1(w_{i-1})}{c_h(w_{i-1})} P_{\text{backoff}}(w_i)$$

where  $\lambda$  is set to some value so that this probability distribution sums to 1, and  $P_{\text{backoff}}(w_i)$  is some unigram distribution that we can backoff to.

However,  $N_1(w_{i-1})$  is kind of a finicky value; *e.g.*, it can be zero even for distributions with lots of counts. Thus, we replace it with  $N_{1+}(w_{i-1})$ , the number of words following  $w_{i-1}$  at least once (rather than exactly once), and we fiddle with some of the other terms. Long story short, we get

$$P_{\text{WB}}(w_i|w_{i-1}) = \frac{c_h(w_{i-1})}{c_h(w_{i-1}) + N_{1+}(w_{i-1})} P_{\text{MLE}}(w_i|w_{i-1}) + \frac{N_{1+}(w_{i-1})}{c_h(w_{i-1}) + N_{1+}(w_{i-1})} P_{\text{backoff}}(w_i)$$

For the backoff distribution, we can use an analogous equation:

$$P_{\text{backoff}}(w_i) = P_{\text{WB}}(w_i) = \frac{c_h(\epsilon)}{c_h(\epsilon) + N_{1+}(\epsilon)} P_{\text{MLE}}(w_i) + \frac{N_{1+}(\epsilon)}{c_h(\epsilon) + N_{1+}(\epsilon)} \frac{1}{|V|}$$

The term  $c_h(\epsilon)$  is the 0-gram history count defined earlier, and  $N_{1+}(\epsilon)$  is the number of different words with at least one count. For the backoff distribution for the unigram model, we use the uniform distribution  $P_{\text{unif}}(w_i) = \frac{1}{|V|}$ . Trigram models are defined analogously.

If a particular distribution has no history counts, then just use the backoff distribution directly. For example, if when computing  $P_{\text{WB}}(w_i|w_{i-1})$  you find that the history count  $c_h(w_{i-1})$  is zero, then just take  $P_{\text{WB}}(w_i|w_{i-1}) = P_{\text{WB}}(w_i)$ . Intuitively, if a history  $h$  has no counts, the MLE distribution  $P_{\text{MLE}}(w|h)$  is not meaningful and should be ignored.

Your job in this part is to fill in the method `get_prob_witten_bell()`. This function should return the value  $P_{\text{WB}}(w_i|w_{i-2}w_{i-1})$  given a trigram  $w_{i-2}w_{i-1}w_i$  (for  $n=3$ ). You will be provided with all of the counts that you computed in Part 1. Again, this routine corresponds to step (B) in the pseudocode listed in Section 1.1.

Your code will again be compiled into the program `lab3_lm`. To compile, type `make lab3_lm` for C++ or `make Lab3Lm` for Java. To run this program on a 100-sentence Switchboard training set and 10-sentence test set, run

```
lab3_p3a.sh
```

This does three runs, corresponding to unigram, bigram, and trigram models. Here is the target output:

```
242.2294 PP (66 words)
99.3588 PP (66 words)
103.1958 PP (66 words)
```

It also writes the probability of each word to a file; the corresponding files for each run are `p3a.1.probs`, `p3a.2.probs`, and `p3a.3.probs`. The target output can be found in files of the same name with the extension `.ref` appended. Again, you should try to match the target output just about exactly. Due to the recursive nature of the algorithm, it's best to try to match the unigram model output first, then the bigram model, etc.

The instructions in `lab3.txt` will ask you to run the script `lab3_p3b.sh`, which does the same thing as `lab3_p3a.sh` except on a 100-sentence test set and only for trigrams.

#### SECTION 4

### Part 4: Evaluate various $n$ -gram models on the task of $N$ -best list rescoring

In this section, we use the code you wrote in the earlier parts of this lab to build various language models on the full original Switchboard training set (about 3 million words). We will investigate how  $n$ -gram order (*i.e.*, the value of  $n$ ) and smoothing affect WER's using the paradigm of  *$N$ -best list rescoring*. First, if you're running C++, it's a good idea to recompile with optimization, like so:

---

```
make clean
OPTFLAGS=-O2 make lab3_lm
```

---

If you're running Java, our condolences.

In ASR, it is sometimes convenient to do recognition in a two-pass process. In the first pass, we may use a relatively small LM (to simplify the decoding process) and for each utterance output the  $N$  best-scoring hypotheses, where  $N$  is typically around 100 or larger. Then, we can use a more complex LM to replace the LM scores for these hypotheses (retaining the acoustic scores) to compute a new best-scoring hypothesis for each utterance. To see an example  $N$ -best list, type

---

```
gzip -cd nbest/0001.nbest.gz
```

---

The correct transcript for this utterance is DARN; each line contains a hypothesis word sequence and an acoustic logprob at the end (*i.e.*,  $\log P(\mathbf{x}|\omega)$ ).

To give a little more detail, recall the fundamental equation of speech recognition

$$\text{class}(\mathbf{x}) \approx \arg \max_{\omega} P(\omega)^{\alpha} P(\mathbf{x}|\omega) = \arg \max_{\omega} [\alpha \log P(\omega) + \log P(\mathbf{x}|\omega)]$$

where  $\mathbf{x}$  is the acoustic feature vector,  $\omega$  is a word sequence, and  $\alpha$  is the language model weight. In  $N$ -best list rescoring, for each hypotheses  $\omega$  in an  $N$ -best list, we compute  $\log P(\omega)$  for our new language model and combine it with the acoustic model score  $\log P(\mathbf{x}|\omega)$  computed earlier. Then, we compute the above argmax over the hypotheses in the  $N$ -best list to produce a new best-scoring hypothesis.

For this part of the lab, we have created 100-best lists for each of 100 utterances of a Switchboard test set, and we will calculate the WER over these utterances when rescoring using various language models. Because the LM used in creating the 100-best lists prevents really bad hypotheses (from an LM perspective) from making it onto the lists, WER differences between good and bad LM's will be muted when doing  $N$ -best list rescoring as compared to when using the LM's directly in one-pass decoding. However,  $N$ -best list rescoring is very easy and cheap to do so we use it here.

So, all you have to do in this part is run:

---

```
lab3_p4.sh | tee p4.out
```

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This does a bunch of different rescoring runs, varying  $n$ -gram order, smoothing algorithm, and training set size. In each rescoring run, the script first calls the script `p018p1.rescore.py`. What this does is take all of the hypotheses in each  $N$ -best list in the directory `nbest/` and collects them into a single big text file. Then, `lab3_lm` (or `Lab3Lm.java`) is run using this file as the test set and the total log probability of each hypothesis is output. Then, `p018p1.rescore.py` combines these LM scores with the acoustic model scores already in the  $N$ -best lists to compute the total score of each hypothesis, and the highest-scoring hypothesis is output for each utterance. Finally, the program `p018h1.calc-wer.sh` is called to compute the WER of the output hypotheses.

Rescoring runs are done using unigram, bigram, and trigram models; with no smoothing, plus-delta smoothing, and Witten-Bell smoothing; and with training set sizes of 2000, 20000,

and 200000 sentences. With no smoothing, we assign a small nonzero floor probability to trigram probabilities that have an MLE of zero. (This will make some conditional distributions sum to slightly more than 1, but we don't care in  $N$ -best list rescoring.) To create the smaller training sets, we just take the prefix of the full Switchboard corpus of that length. In case you were wondering, there are about 13 words per sentence on average in Switchboard data.

Pedantic notes:

- ▶ We use a language model weight of 4 for all runs. We have no recollection of how that value was chosen.
- ▶ Before computing word-error rates, we normalize hypotheses to better match the conventions of the reference transcript. For example, we expand all contractions, *e.g.*, AIN'T is changed to IS NOT; and we change hesitation sounds (*e.g.*, UH) to the token (%HESITATION). To do this, we use a *finite-state transducer* (see the file `filter.fsm`); these will be covered later in the class.
- ▶ Before sending all the hypotheses in the  $N$ -best lists to be scored by `lab3_lm`, we remove all silence tokens from the hypotheses. Instead, we assign each silence a probability of 0.1 (which is the approximate frequency of silence in actual speech) and manually add these probabilities into the final LM scores. This technique is known as treating silence as a *transparent* word, because silences can be thought of as being invisible to the  $n$ -gram model.

## SECTION 5

### What is to be handed in

You should have a copy of the ASCII file `lab3.txt` in your current directory. Fill in all of the fields in this file and submit this file using the provided script.

Incidentally, if you find that your forehead is becoming warm as you do this assignment, do not be alarmed: you probably have *language modeling fever*. It should recede by itself within a day, but if it does not, go see a doctor and tell them that you have language modeling fever; they'll know what to do.