HW Assignment 2 (Due by 9am on Oct 3)

In this assignment you will implement a person name recognizer using sequence tagging with CRFs. The assignment (write-up and code) was created by Greg Durrett for his NLP course at UT Austin. The following rules apply:

- Turn in a hard copy of your homework report at the beginning of class on the due date. Electronically submit on Blackboard a hw02.zip file that contains a hw02 folder with the code and the report. On a Linux system, creating the archive can be done using the command:
  
  > zip -r hw02.zip hw02.

- Non-EECS students are allowed to use external CRF packages to implement this assignment. EECS students must implement it from scratch using the skeleton code provided.

- Structure, indent, and format your code well. Use adequate comments, both block and in-line to document your code.

- You receive a budget of 5 slip days to use throughout the semester. Any number of these days can be applied to any homework assignment to extend the deadline for that assignment. For example, you can turn the first assignment in 2 days late and the fourth assignment 3 days late. After your slip days are exhausted, each day of lateness will incur a 20% penalty to that assignment’s grade. Plan your slip day budget accordingly, e.g., be sure to save them up if you know you’ll be traveling for a conference around a due date for a later project. Additional extensions may be granted in cases of medical or other types of emergencies, but must be agreed on with me before the project’s original due date.
### CS388 Project 1: Sequential CRF for NER

**Due date:** October 3, 2019 at 9:00am

**Collaboration:** As stated in the syllabus, you are free to discuss the homework assignments with other students and work towards solutions together. However, all of the code you write must be your own! Your extension should also be distinct from those of your classmates and your writeup should be your own as well. **Please list your collaborators at the top of your written submission.**

**Goal:** In this project you’ll implement a CRF sequence tagger for NER. You’ll implement the Viterbi algorithm on a fixed model first (an HMM), then generalize that to forward-backward and implement learning and decoding for a feature-based CRF as well. The primary goal of this assignment is to expose you to inference and learning for a simple structured model where exact inference is possible. Secondarily, you will learn some of the engineering factors that need to be considered when implementing a model like this.

The expectation in this project is that you understand CRFs and HMMs from scratch using the code we give you. **You should not call existing CRF libraries in your solution to this project.**

### Background

Named entity recognition is the task of identifying references to named entities of certain types in text. We use data presented in the CoNLL 2003 Shared Task (Tjong Kim Sang and De Meulder, 2003). An example of the data is given below:

<table>
<thead>
<tr>
<th>Word</th>
<th>POS</th>
<th>Chunk</th>
<th>Tag</th>
</tr>
</thead>
<tbody>
<tr>
<td>Singapore</td>
<td>NNP</td>
<td>I-NP</td>
<td>B-ORG</td>
</tr>
<tr>
<td>Refining</td>
<td>NNP</td>
<td>I-NP</td>
<td>I-ORG</td>
</tr>
<tr>
<td>Company</td>
<td>NNP</td>
<td>I-NP</td>
<td>I-ORG</td>
</tr>
<tr>
<td>expected</td>
<td>VBD</td>
<td>I-VP</td>
<td>O</td>
</tr>
<tr>
<td>to</td>
<td>TO</td>
<td>I-VP</td>
<td>O</td>
</tr>
<tr>
<td>shut</td>
<td>VB</td>
<td>I-VP</td>
<td>O</td>
</tr>
<tr>
<td>CDU</td>
<td>NNP</td>
<td>I-NP</td>
<td>B-ORG</td>
</tr>
<tr>
<td>3</td>
<td>CD</td>
<td>I-NP</td>
<td>I-ORG</td>
</tr>
<tr>
<td>.</td>
<td>O</td>
<td>NONE</td>
<td>O</td>
</tr>
</tbody>
</table>

There are four columns here: the word, the POS tag, the chunk bit (a form of shallow parsing—you can ignore this), and the column containing the NER tag. NER labels are given in a BIO tag scheme: beginning, inside, outside. In the example above, two named entities are present: Singapore Refining Company and CDU 3. O tags denote text not part of a named entity. B tags indicate the start of a named entity, and I tags indicate the continuation of the previous named entity. Both B and I tags are hyphenated and contain a type after the hyphen, which in this dataset is one of PER, ORG, LOC, or MISC. A B tag can immediately follow another B tag in the case where a one-word entity is followed immediately by another entity. However, note that an I tag can only follow an I tag or B tag of the same type.

An NER system’s job is to predict the NER chunks of an unseen sentence, i.e., predict the last column given the others. Output is typically evaluated according to chunk-level F-measure.\(^1\) To evaluate a single sentence, let \(C\) denote the predicted set of labeled chunks represented by a tuple of (label, start index, end index) and let \(C^*\) denote the gold set of chunks. We compute precision, recall, and \(F_1\) as follows:

\[
\text{Precision} = \frac{|C \cap C^*|}{|C|}; \quad \text{Recall} = \frac{|C \cap C^*|}{|C^*|}; \quad F_1 = \frac{1}{\frac{1}{2}(\text{Precision} + \text{Recall})}
\]

\(^1\)Tag-level accuracy isn’t used because of the prevalence of the O class—always predicting O would give extremely high accuracies!
The gold labeled chunks from the example above are (ORG, 0, 3) and (ORG, 6, 8) using 0-based indexing and semi-inclusive notation for intervals.

To generalize to corpus-level evaluation, the numerators and denominators of precision and recall are aggregated across the corpus. State-of-the-art systems can get above 90 F1 on this dataset; we’ll be aiming to get close to this and build systems that can get in at least the mid-80s.

Your Task

You will be building a CRF NER system. This is broken down for you into a few steps:

1. Implementing Viterbi decoding for a generative HMM.
2. Generalizing your Viterbi decoding to forward-backward to compute marginals, then using those to train a simple feature-based CRF for this task.
3. Extending the CRF for NER somehow.

Getting Started

Download the data and code from Canvas. You will need Python 3 and numpy. Try running

```
python ner.py
```

This will run a very bad NER system, one which simply outputs the most common tag for every token, or O if it hasn’t been seen before. The system will print a bunch of warnings on the dev set—this baseline doesn’t even produce consistent tag sequences.

Data  eng.train is the training set, eng.testa is the standard NER development set, and eng.testb.blind is a blind test set you will submit results on. The deu* files are German data that you can experiment with in your extension, but you’re not required to do anything with these.

Code  We provide

```
ner.py: Contains the implementation of BadNerModel and the main function which reads the data, trains the appropriate model, and evaluates it on the test set.

nerdata.py: Utilities for reading NER data, evaluation code, and functions for converting from BIO to chunk representation and back. The main abstraction to pay attention to here is LabeledSentence, which contains a sequence of Token objects (wrappers around words, POS tags, and chunk information) and a set of Chunk objects representing a labeling. Gold examples are LabeledSentence and this is also what your system will return as predictions.

utils.py: Same as in Mini 1: Indexer and Counter are the as before, with Indexer additionally being useful for mapping between labels and indices in dynamic programming. A Beam data structure is also provided, but you won’t need that in this project unless you choose to do beam search as your extension.
```

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2If you don’t have numpy, see https://www.scipy.org/install.html. We recommend that you install with anaconda, since this will provide an easy way to create virtual environments for later deep learning projects.
optimizers.py: Same as in HW1: three optimizer classes implementing SGD, unregularized Adagrad, and L1-regularized Adagrad. These wrap the weight vector, exposing access and score methods to use it, and are updated by apply_gradient_update, which takes as input a Counter of feature values for this gradient as well as the size of the batch the gradient was computed on.

models.py: You should feel free to modify anything in this file as you need, but the scaffolding will likely serve you well. We will describe the code here in more detail in the following sections.

Next, try running
```
python ner.py --model HMM
```
This will crash with an error message. You have to implement Viterbi decoding as the first step to make the HMM work.

**Part 1: Viterbi Decoding**

Look in models.py. `train_hmm` model estimates initial state, transition, and emission probabilities from the labeled data and returns a new `HmmNerModel` with these probabilities. Your task is to implement Viterbi decoding in this model so it can return `LabeledSentence` predictions in `decode`.

We’ve provided an abstraction for you in `ProbabilisticSequenceScorer`. This abstraction is meant to help you build inference code that can work for both generative and probabilistic scoring as well as feature-based scoring. `score_init` scores the initial HMM state, `score_transition` scores an HMM state transition, and `score_emission` scores the HMM emission. All of these are implemented as log probabilities. Note that this abstraction operates in terms of indexed tags, where the indices have been produced by `tag_indexer`. This allows you to score tags directly in the dynamic programming state space without converting back and forth to strings all the time.

You should implement the Viterbi algorithm with scores that come from log probabilities to find the highest log-probability path.

\[
P(y_1, \ldots, y_n | x_1, \ldots, x_n) \propto P(y_1, \ldots, y_n, x_1, \ldots, x_n) = P(y_1) \prod_{i=2}^{n} P(y_i | y_{i-1}) \prod_{i=1}^{n} P(x_i | y_i)
\]

\[
\arg \max_{y_1, \ldots, y_n} P(y_1, \ldots, y_n | x_1, \ldots, x_n) = \arg \max_{y_1, \ldots, y_n} \log P(y_1) + \sum_{i=2}^{n} \log P(y_i | y_{i-1}) + \sum_{i=1}^{n} \log P(x_i | y_i)
\]

If you’re not sure about the interface to the code, take a look at `BadNerModel` decoding and use that as a template.

The instructors’ reference implementation of Viterbi decoding for the HMM gets 76.89 F1 on the development set, though yours may differ slightly.

**Implementation tips**

- Python data structures like lists and dictionaries can be pretty inefficient. Consider using numpy arrays in dynamic programs.

- Once you run your dynamic program, you still need to extract the best answer. Typically this is done by either storing a backpointer for each cell to know how that cell’s value was derived or by using a backward pass over the chart to reconstruct the sequence.
Part 2: CRF Training

In the CRF training phase, you will implement learning and inference for a CRF sequence tagger with a fixed feature set. We provide a simple CRF feature set with emission features only. While you’ll need to impose some kind of sequential constraints in the model, transition features are often slow to learn: you should be able to get good performance by constraining the model to only produce valid BIO sequences (prohibiting a transition to I-X from anything except I-X and B-X).

We provide a code skeleton in CrfNerModel and train_crf_model. The latter calls feature extraction in extract_emission_features and builds a cache of features for each example—you can feel free to use this cache or not.

You should take the following steps to implement your CRF:

1. Generalize your Viterbi code to forward-backward.

2. Extend your forward-backward code to use a scorer based on features—perhaps you might write a FeatureBasedSequenceScorer with an interface similar to ProbabilisticSequenceScorer for this purpose.

3. Compute the stochastic gradient of the feature vector for a sentence.

4. Use the stochastic gradient in a learning loop to learn feature weights for the NER system.

To get full credit on the assignment, you should get a score of at least 85 F₁ on the development set. Assignments falling short of this will be judged based on completeness and awarded partial credit accordingly: if you at least get 75-80, for example, we can see that your implementation may be mostly working and you will receive substantial credit. The instructors’ reference implementation was able to get 88.2 F₁ using the given emission features and unregularized Adagrad as the optimizer—see if you can beat that!

Implementation Tips

- Make sure that your probabilities from forward-backward normalize correctly! You should be able to sum the forward x backward chart values at each sentence index and get the same value (the normalizing constant). You can check your forward-backward implementation in the HMM model if that’s useful.

- When implementing forward-backward, you’ll probably want to do so in log space rather than real space. (+, x) in real space translates to (log-sum-exp, +) in log space. Use numpy.logaddexp.

- Remember that the NER tag definition has hard constraints in it (only B-X or I-X can transition to I-X), so be sure to build these into your inference procedure. You can also incorporate features on tag pairs, but this is substantially more challenging and not necessary to get good performance.

- If your code is too slow, try (a) making use of the feature cache to reduce computation and (b) exploiting sparsity in the gradients (Counter is a good class for maintaining sparse maps). Run your code with python -m cProfile ner.py to print a profile and help identify bottlenecks.

- Implement things in baby steps! First make sure that your marginal probabilities look correct on a single example. Then make sure that your optimizer can fit a very small training set (10 examples); you might want to write a small amount of extra code to compute log-likelihood and check that this goes up, along with train accuracy. Then work on scaling things up to more data and optimizing for development performance.
Part 3: Extensions

Here are some possibilities for extensions, but feel free to investigate anything else that you might find interesting. Grading of the extension will be assessed on the basis of how sophisticated your extension is, how thorough your analysis is, and how much evidence there is of substantial effort. A simple extension with fleshed-out analysis can receive full credit.

Training  Try using structured SVM instead of a CRF. You can use Viterbi decoding instead of forward-backward now, but remember to incorporate loss augmentation! Compare these two algorithms and see if they differ in how quickly they learn and how robust they are to changes in the optimizer.

Features  Try features on POS tags and other improvements to the feature set. If you do this, you should do more than just add some a few new features—add detailed quantitative analysis and cite some examples showing what helps and what doesn’t.

Speed  Try making the system faster. This might consist of speeding up feature extraction (is there a way to handle parallel features across tags more effectively?), inference (can we use beam search and structured perceptron training to train the system faster?), or training (are there better optimizers that converge more quickly?).

German  You also have access to German NER data—does the system perform well on this data? Can you add features or change it to get better performance? Note that simply running your model on this dataset and reporting results does not constitute a substantial extension.

Submission and Grading

You should submit on Blackboard as three file uploads:

1. Your code as a .zip or .tgz file

2. Your CRF’s output on the testb blind test set in CoNLL format. Uncomment the appropriate line in the file to produce this.

3. A report of around 2-3 pages, not including references, though you aren’t expected to reference many papers. Your report should list your collaborators, briefly restate the core problem and what you are doing, describe relevant details of your implementation, present results from both your basic CRF model as well as with different system variants as part of your extension, and optionally discuss error cases addressed by your extension or describe how the system could be further improved. Your report should be written in the tone and style of an ACL/NeurIPS conference paper. Any LaTeX format with reasonably small (1” margins) is fine, including the ACL style files or any other one- or two-column format with equivalent density.

Grading  Your assignment is judged roughly 60% on the basis of your existing implementation, 20% on the report, and 20% on the extension.

3Available at http://acl2017.org/calls/papers/
**Slip Days**  You may apply slip days to this project as described in the syllabus.

**References**