CS 6120/CS 4120: Natural Language Processing
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Outline
• What is part-of-speech (POS) and POS tagging?
• Hidden Markov Model (HMM) for POS tagging
• Learning an HMM
• Prediction with an learned HMM (inference)

Parts of Speech
• Perhaps starting with Aristotle in the West (384–322 BCE), there was the idea of having parts of speech (POS)
  • a.k.a lexical categories, word classes, "tags"
  • Lowest level of syntactic analysis

English Parts of Speech (POS) Tagsets
• Original Brown corpus used a large set of 87 POS tags.
• Most common in NLP today is the Penn Treebank set of 45 tags.
  • Tagset used in the slides.
  • Reduced from the Brown set for use in the context of a parsed corpus (i.e. Penn Treebank).

English Parts of Speech
• Noun (person, place or thing)
  • Singular (NN): dog, fork
  • Plural (NNs): dogs, forks
  • Proper (NNS, NNPS): John, Springfields
  • Personal pronoun (PRP): I, you, he, she, it
  • Wh-pronoun (WP): who, what
• Verb (actions and processes)
  • Base, infinitive (VB): eat
  • Past tense (VBD): ate
  • Gerund (VBN): eating
  • Past participle (VBN): eaten
  • 3rd person singular present tense (VBZ): eats
  • Modal (MD): should, can
  • To (TO): to (to eat)

English Parts of Speech (cont.)
• Adjective (modify nouns)
  • Basic (JJ): red, tall
  • Comparative (JRP): redder, taller
  • Superlative (JJS): reddest, tallest
• Adverb (modify verbs)
  • Basic (RB): quickly
  • Comparative (RBR): quicker
  • Superlative (RBS): quickest
• Preposition (IN): on, in, by, to, with
• Determiner:
  • Basic (DT): a, an, the
  • WH-determiner (WDT): which, that
• Coordinating Conjunction (CC): and, but, or,
• Particle (RP): off (took off), up (put up)
Open vs. Closed classes

- Open vs. Closed classes
  - Closed:
    - determiners: a, an, the
    - pronouns: she, he, I
    - prepositions: on, under, over, near, by, ...
  - Why "closed"?
  - Open:
    - Nouns, Verbs, Adjectives, Adverbs.

Ambiguity in POS Tagging

- "Like" can be a verb or a preposition
  - I like/VBP candy.
  - Time flies like/IN an arrow.
- "Around" can be a preposition, particle, or adverb
  - I bought it at the shop around/IN the corner.
  - I never got around/RP to getting a car.
  - A new Prius costs around/RB $25K.

POS Tagging

- Input:
  - plays well/NN with others
- Ambiguity: NNS/VBZ UH/JJ/NN/RB IN NNS
- Output:
  - Plays/VBZ well/RB with/IN others/NNS
- Uses:
  - Text-to-speech (how do we pronounce "lead"?)
  - Can write regexps over the output for phrase extraction
  - Noun phrase: (Det) Adv* N+
  - As input to or to speed up a full parser
POS tagging performance

- How many tags are correct? (Tag accuracy)
  - About 97% currently
  - But baseline is already 90%
    - Baseline is performance of stupidest possible method
    - Take an annotated corpus (or a dictionary), tag every word with
      its most frequent tag
    - Many words are unambiguous
    - You get points for them (the, a, etc.) and for punctuation
      marks!

- Partly easy because

How difficult is POS tagging?

- Word types: roughly speaking, unique words
  - About 11% of the word types in the Brown corpus
    are ambiguous with regard to part of speech
    - But they tend to be very common words. E.g., that
      - I know that he is honest = IN (preposition)
      - Yes, that play was nice = DT (determiner)
      - You can’t go that far = RB (adverb)
      - 40% of the word tokens are ambiguous

Sources of information

- What are the main sources of information for POS tagging? “Bill saw that man yesterday”
  - Contextual: Knowledge of neighboring words
    - Bill saw that man yesterday
    - NNP NN DT NN NN
    - VB VB(IN) IN VB NN
  - Local: Knowledge of word probabilities
    - man is rarely used as a verb...
    - The latter proves the most useful, but the former also helps
    - Sometimes these preferences are in conflict:
      - The trash can is in the garage

More and Better Features ➔ Feature-based tagger

- Can do surprisingly well just looking at a word by itself:
  - Word
    - the: the → DT
  - Lowercased word
    - Importantly: importantly → RB
  - Prefixes
    - unfathomable: un → JJ
  - Suffixes
    - Importantly: ly → RB
  - Capitalization
    - Meridian: CAP → NNP
  - Word shapes
    - 35-year: d-x → JJ

POS Tagging Approaches

- Rule-Based: Human crafted rules based on lexical and other linguistic knowledge.
- Learning-Based: Trained on human annotated corpora like the Penn Treebank.
  - Statistical models: Hidden Markov Model (HMM) – this lecture!
    - Maximum Entropy Markov Model (MEMM), Conditional Random Field (CRF)
  - Rule learning: Transformation Based Learning (TBL)
  - Neural networks: Recurrent networks like Long Short Term Memory (LSTMs)
  - Generally, learning-based approaches have been found to be more effective overall, taking into account the total amount of human expertise and effort involved.
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Hidden Markov Model

Markov Model / Markov Chain

• A finite state machine with probabilistic state transitions.
• Makes Markov assumption that next state only depends on the current state and independent of previous history.

Sample Markov Model for POS (a finite state machine)

Sample Markov Model for POS

Hidden Markov Model

• Probabilistic generative model for sequences.
• Assume an underlying set of hidden (unobserved) states in which the model can be (e.g., part-of-speech).
• Assume probabilistic transitions between states over time (e.g., transition from POS to another POS as sequence is generated).
• Assume a probabilistic generation of tokens from states (e.g., words generated for each POS).
Formally, Markov Sequences

- Consider a sequence of random variables \( X_1, X_2, \ldots, X_m \) where \( m \) is the length of the sequence.
- Each variable \( X_i \) can take any value in \( \{1, 2, \ldots, k\} \).
- How do we model the joint distribution

\[
P(X_1 = x_1, X_2 = x_2, \ldots, X_m = x_m)
\]
The Markov Assumption

\[
P(X_1 = x_1, X_2 = x_2, \ldots, X_m = x_m) = P(X_1 = x_1) \prod_{j=2}^{m} P(X_j = x_j | X_1 = x_1, \ldots, X_{j-1} = x_{j-1})
\]

\[
P(X_1 = x_1) \prod_{j=2}^{m} P(X_j = x_j | X_{j-1} = x_{j-1})
\]

- The first equality is exact (by the chain rule).
- The second equality follows from the Markov assumption: for all \( j = 2 \ldots m, \)

\[
P(X_j = x_j | X_1 = x_1, \ldots, X_{j-1} = x_{j-1}) = P(X_j = x_j | X_{j-1} = x_{j-1})
\]

Homogeneous Markov Chains

- In a homogeneous Markov chain, we make an additional assumption, that for \( j = 2 \ldots m, \)

\[
P(X_j = x_j | X_{j-1} = x_{j-1}) = q(x_j | x_{j-1})
\]

where \( q(x') | x) \) is some function

- Idea behind this assumption: the transition probabilities do not depend on the position in the Markov chain (do not depend on the index \( j \))

Markov Models

- Our model is then as follows:

\[
p(x_1, x_2, \ldots, x_m; \theta) = q(x_1) \prod_{j=2}^{m} q(x_j | x_{j-1})
\]

Parameters in the model:

- \( q(x) \) for \( x = \{1, 2, \ldots, k\} \)
  - Constraints: \( q(x) \geq 0 \) and \( \sum_{x=1}^{k} q(x) = 1 \)
- \( q(x' | x) \) for \( x = \{1, 2, \ldots, k\} \) and \( x' = \{1, 2, \ldots, k\} \)
  - Constraints: \( q(x' | x) \geq 0 \) and \( \sum_{x'=}^{k} q(x' | x) = 1 \)

Probabilistic Models for Sequence Pairs – words and POS tags

- We have two sequences of random variables: \( X_1, X_2, \ldots, X_m \) and \( S_1, S_2, \ldots, S_m \)

- Intuitively, each \( X_i \) corresponds to an “observation” and each \( S_i \) corresponds to an underlying “state” that generated the observation. Assume that each \( S_i \) is in \( \{1, 2, \ldots, k\} \), and each \( X_i \) is in \( \{1, 2, \ldots, o\} \)

- How do we model the joint distribution

\[
P(X_1 = x_1, \ldots, X_m = x_m, S_1 = s_1, \ldots, S_m = s_m)
\]

Probabilistic Models for Sequence Pairs – words and POS tags

- We have two sequences of random variables: \( X_1, X_2, \ldots, X_m \) and \( S_1, S_2, \ldots, S_m \)

Words Part-of-Speech tags

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- How do we model the joint distribution

\[
P(X_1 = x_1, \ldots, X_m = x_m, S_1 = s_1, \ldots, S_m = s_m)
\]
Firstly, why would we want to model the joint distribution?

\[ P(X_1 = x_1, \ldots, X_m = x_m, S_1 = s_1, \ldots, S_m = s_m) \]

Hidden Markov Models (HMMs)

- In HMMs, we assume that:

\[ P(X_1 = x_1, \ldots, X_m = x_m, S_1 = s_1, \ldots, S_m = s_m) = P(S_1 = s_1) \prod_{j=2}^{m} P(S_j = s_j | S_{j-1} = s_{j-1}) \prod_{j=1}^{m} P(X_j = x_j | S_j = s_j) \]

Independence Assumptions in HMMs

- By the chain rule, the following equality is exact:

\[ P(X_1 = x_1, \ldots, X_m = x_m, S_1 = s_1, \ldots, S_m = s_m) = P(S_1 = s_1, \ldots, S_m = s_m) \times P(X_1 = x_1, \ldots, X_m = x_m | S_1 = s_1, \ldots, S_m = s_m) \]

- Assumption 1: the state sequence forms a Markov chain

\[ P(S_1 = s_1, \ldots, S_m = s_m) = P(S_1 = s_1) \prod_{j=2}^{m} P(S_j = s_j | S_{j-1} = s_{j-1}) \]

e.g. Part-of-Speech tags

\[ P(X_1 = x_1, \ldots, X_m = x_m, S_1 = s_1, \ldots, S_m = s_m) = P(S_1 = s_1) \prod_{j=2}^{m} P(S_j = s_j | S_{j-1} = s_{j-1}) \prod_{j=1}^{m} P(X_j = x_j | S_j = s_j) \]

Formally

- The model takes the following form:

\[ p(x_1 \ldots x_m, s_1 \ldots s_m) = t(s_1) \prod_{j=2}^{m} t(s_j | s_{j-1}) \prod_{j=1}^{m} \epsilon(x_j | s_j) \]

- Parameters in the model:

1. Initial state parameters \( t(s) \) for \( s \in \{1, 2, \ldots, k\} \)
2. Transition parameters \( t(s'|s) \) for \( s, s' \in \{1, 2, \ldots, k\} \)
3. Emission parameters \( \epsilon(x|s) \) for \( s \in \{1, 2, \ldots, k\} \) and \( x \in \{1, 2, \ldots, c\} \)

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Parameter Estimation with Fully Observed Data

We’ll now discuss parameter estimates in the case of fully observed data: for $i = 1 \ldots n$, we have pairs of sequences $x_{i,j}$ for $j = 1 \ldots m$ and $s_{i,j}$ for $j = 1 \ldots m$. (i.e., we have $n$ training examples, each of length $m$.)

- Assume we have fully observed data: for $i = 1 \ldots n$, we have pairs of sequences $x_{i,j}$ for $j = 1 \ldots m$ and $s_{i,j}$ for $j = 1 \ldots m$.
- Define $\text{count}(i, s \rightarrow s')$ to be the number of times state $s'$ follows state $s$ in the $i$th training example. More formally:

$$\text{count}(i, s \rightarrow s') = \sum_{j=1}^{m} [s_{i,j} = s \land s_{i,j+1} = s']$$

(We define $[\pi]$ to be 1 if $\pi$ is true, 0 otherwise.)

- The maximum-likelihood estimates of transition probabilities are then

$$t(s'|s) = \frac{\sum_{i=1}^{n} \text{count}(i, s \rightarrow s')}{\sum_{i=1}^{n} \sum_{s'} \text{count}(i, s \rightarrow s')}$$
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Parameter Estimation: Initial State Parameters

• Assume we have fully observed data: for \(i = 1 \ldots n\), we have pairs of sequences \(x_{ij}\) for \(j = 1 \ldots m\) and \(s_{ij}\) for \(j = 1 \ldots m\)
• Define \(\text{count}(i, s \rightarrow x)\) to be the number of times state \(s\) is paired with emission \(x\). More formally:
  \[
  \text{count}(i, s \rightarrow x) = \sum_{j=1}^{m} [(s_{ij} = s) \land (x_{ij} = x)]
  \]
• The maximum-likelihood estimates of emission probabilities are then
  \[
  e(x | s) = \frac{\sum_{i=1}^{n} \text{count}(i, s \rightarrow x)}{\sum_{i=1}^{n} \sum_{x} \text{count}(i, s \rightarrow x)}
  \]

John gave the dog an apple.

Det Noun PropNoun Verb

The Viterbi Algorithm

• Goal: for a given input sequence \(x_1, \ldots, x_m\), find
  \[
  \arg \max_{s_1, \ldots, s_m} p(x_1, \ldots, x_m, s_1, \ldots, s_m | \theta)
  \]
• This is the most likely state sequence \(s_1 \ldots s_m\) for the given input sequence \(x_1 \ldots x_m\)

HMM

• Parameter estimation
  • Inference: Viterbi algorithm (dynamic programming)

Most Likely State Sequence

• Given an observation sequence, \(X\), and a model, what is the most likely state sequence, \(S=s_1, s_2, \ldots, s_m\), that generated this sequence from this model?
• Used for sequence labeling, assuming each state corresponds to a tag, it determines the globally best assignment of tags to all tokens in a sequence using a principled approach grounded in probability theory.
Most Likely State Sequence

- Given an observation sequence, $X$, and a model, what is the most likely state sequence, $S = s_1, s_2, \ldots, s_m$, that generated this sequence from this model?
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Det Noun PropNoun Verb
The Viterbi Algorithm

- Goal: for a given input sequence \( x_1, \ldots, x_m \), find
  \[
  \arg \max_{\pi_1, \ldots, \pi_m} p(x_1 \ldots x_m, \pi_1 \ldots \pi_m; \theta)
  \]

- The Viterbi algorithm is a dynamic programming algorithm. Basic data structure:
  \[
  \pi[j, s]
  \]
  will be a table entry that stores the maximum probability for any state sequence ending in state \( s \) at position \( j \). More formally:
  \[
  \pi[1, s] = \lambda(s)(x_1 | s), \quad \text{and for } j > 1,
  \]

Viterbi Backpointers

Viterbi Backtrace

- Most likely Sequence: \( S_0 \) \( S_0 \) \( S_1 \) \( S_2 \ldots S_2 \) \( S_2 \)

- The algorithm runs in \( O(mk^2) \) time
The Viterbi Algorithm: Backpointers

- Initialization: for $s = 1 \ldots k$
  $$\pi[1, s] = t(s) \cdot e(x_1 | s)$$

- For $j = 2 \ldots m$, $s = 1 \ldots k$:
  $$\pi[j, s] = \max_{s' \in \{1 \ldots k\}} \{ \pi[j-1, s'] \times t(s'|s') \times e(x_j | s') \}$$
  and
  $$bp[j, s] = \arg \max_{s' \in \{1 \ldots k\}} \{ \pi[j-1, s'] \times t(s'|s') \times e(x_j | s') \}$$

- The $bp$ entries are backpointers that will allow us to recover the identity of the highest probability state sequence

Homework

- Reading J&M Ch5.1-5.5, Ch6.1-6.5
- For 3rd Edition:
  
- HMM notes
- Start thinking about course project and find a team.

- Highest probability for any sequence of states is
  $$\max_s \pi[m, s]$$

- To recover identity of highest-probability sequence:
  $$s_m = \arg \max_s \pi[m, s]$$
  and for $j = m \ldots 2$,
  $$s_{j-1} = bp[j, s_j]$$

- The sequence of states $s_1 \ldots s_m$ is then
  $$\arg \max_{s_1 \ldots s_m} p(x_1 \ldots x_m, s_1 \ldots s_m; \theta)$$