Natural Language Processing Sequence Labeling and Hidden Markov Models

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May 7, 2024

Overview

- The Sequence Labeling (or Tagging) Problem
- Generative models, and the noisy-channel model, for supervised learning
- Hidden Markov Model (HMM) taggers
    - Basic definitions
    - Parameter estimation
    - The Viterbi algorithm

This slides are based on the course material by Michael Collins: `http://www.cs.columbia.edu/~mcollins/cs4705-spring2019/slides/tagging.pdf`

Sequence Labeling or Tagging Tasks

- Sequence Labeling or Tagging is a task in NLP different from document classification.
- Here the goal is to map a sentence represented as a sequence of tokens $x_1, x_2, \ldots, x_n$ into a sequence of tags or labels $y_1, y_2, \ldots, y_n$.
- Well known examples of this task are Part-of-Speech (POS) tagging and Named Entity Recognition (NER) to be presented next.

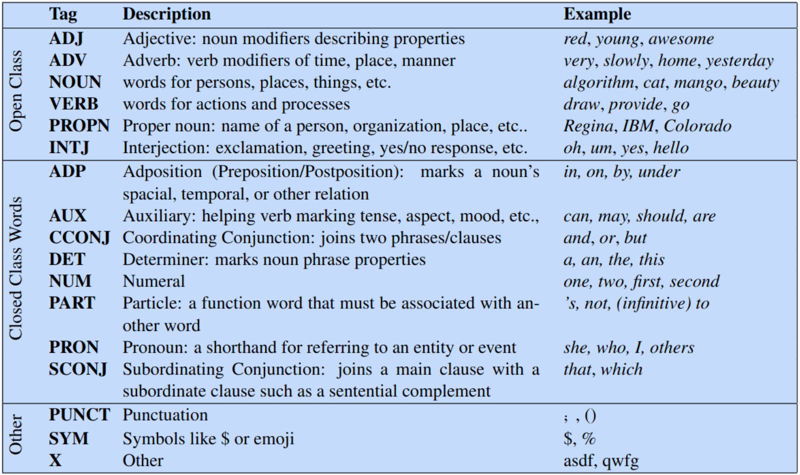
Part-of-Speech Tagging

INPUT: Profits soared at Boeing Co., easily topping forecasts on Wall Street, as their CEO Alan Mulally announced first quarter results.

OUTPUT: Profits/N soared/V at/P Boeing/N Co./N ,/, easily/ADV topping/V forecasts/N on/P Wall/N Street/N ,/, as/P their/POSS CEO/N Alan/N Mulally/N announced/V first/ADJ quarter/N results/N ./.

- N = Noun
- V = Verb
- P = Preposition
- Adv = Adverb
- Adj = Adjective
- ...

Part-of-Speech Tag Descriptions



	Tag	Description	Example
Open Class	**ADJ**	Adjective: noun modifiers describing properties	*red, young, awesome*
	ADV	Adverb: verb modifiers of time, place, manner	*very, slowly, home, yesterday*
	NOUN	words for persons, places, things, etc.	*algorithm, cat, mango, beauty*
	VERB	words for actions and processes	*draw, provide, go*
	PROPN	Proper noun: name of a person, organization, place, etc..	*Regina, IBM, Colorado*
	INTJ	Interjection: exclamation, greeting, yes/no response, etc.	*oh, um, yes, hello*
Closed Class Words	**ADP**	Adposition (Preposition/Postposition): marks a noun's spacial, temporal, or other relation	*in, on, by, under*
	AUX	Auxiliary: helping verb marking tense, aspect, mood, etc.,	*can, may, should, are*
	CCONJ	Coordinating Conjunction: joins two phrases/clauses	*and, or, but*
	DET	Determiner: marks noun phrase properties	*a, an, the, this*
	NUM	Numeral	*one, two, first, second*
	PART	Particle: a function word that must be associated with another word	*'s, not, (infinitive) to*
	PRON	Pronoun: a shorthand for referring to an entity or event	*she, who, I, others*
	SCONJ	Subordinating Conjunction: joins a main clause with a subordinate clause such as a sentential complement	*that, which*
Other	**PUNCT**	Punctuation	; , ()
	SYM	Symbols like $ or emoji	$, %
	X	Other	asdf, qwfg

Source: [Jurafsky and Martin, 2008]

Named Entity Recognition (NER)

A **named entity** is, roughly speaking, anything that can be referred to with a named entity proper name: a person, a location, an organization.

INPUT: Profits soared at Boeing Co., easily topping forecasts on Wall Street, as their CEO Alan Mulally announced first quarter results.

OUTPUT: Profits soared at [Company Boeing Co.], easily topping forecasts on [Location Wall Street], as their CEO [Person Alan Mulally] announced first quarter results.

- Since entities can span multiple words (i.e., a span recognition problem), we can use BIO tagging [**?**] to turn the problem into a sequence labeling problem.
- BIO tagging: use tags that capture both the boundary and the named entity type.

BIO tagging: NER as Sequence Labeling

INPUT: Profits soared at Boeing Co., easily topping forecasts on Wall Street, as their CEO Alan Mulally announced first quarter results.

OUTPUT: Profits/O soared/O at/O Boeing/B-C Co./I-C ,/O easily/O topping/O forecasts/O on/O Wall/B-L Street/I-L ,/O as/O their/O CEO/O Alan/B-P Mulally/I-P announced/O first/O quarter/O results/O ./O

- O = Outside (no entity)
- B-C = Begin Company
- I-C = Inside Company
- B-L = Begin Location
- I-L = Inside Location
- B-P = Begin Person
- I-P = Inside Person

Our Goal

Training set:

1. Pierre/NNP Vinken/NNP ,/, 61/CD years/NNS old/JJ ,/, will/MD join/VB the/DT board/NN as/IN a/DT nonexecutive/JJ director/NN Nov./NNP 29/CD ./.
2. Mr./NNP Vinken/NNP is/VBZ chairman/NN of/IN Elsevier/NNP N.V./NNP ,/, the/DT Dutch/NNP publishing/VBG group/NN ./.
3. Rudolph/NNP Agnew/NNP ,/, 55/CD years/NNS old/JJ and/CC chairman/NN of/IN Consolidated/NNP Gold/NNP Fields/NNP PLC/NNP ,/, was/VBD named/VBN a/DT nonexecutive/JJ director/NN of/IN this/DT British/JJ industrial/JJ conglomerate/NN ./.
4. ...

Our Goal: From the training set, induce a function/algorithm that maps new sentences to their tag sequences.

Two Types of Constraints

Influential/JJ members/NNS of/IN the/DT House/NNP Ways/NNP and/CC Means/NNP Committee/NNP introduced/VBD legislation/NN that/WDT would/MD restrict/VB how/WRB the/DT new/JJ savings-and-loan/NN bailout/NN agency/NN can/MD raise/VB capital/NN ./.

"Local":

- e.g., "can" is more likely to be a modal verb MD rather than a noun NN

"Contextual":

- e.g., a noun is much more likely than a verb to follow a determiner

Sometimes these preferences are in conflict:

- The trash can is in the garage

Sequence Labeling as Supervised Learning

- We have a sequence of inputs $x = (x_1, x_2, \ldots, x_n)$ and corresponding labels $y = (y_1, y_2, \ldots, y_n)$.
- Task is to learn a function f that maps input sequences to label sequences: $f(x_1, x_2, \ldots, x_n) = y_1, y_2, \ldots, y_n$.
- We have a training set of labeled sequences: $\{(x^{(1)}, y^{(1)}), (x^{(2)}, y^{(2)}), \ldots, (x^{(m)}, y^{(m)})\}$.

Generative Approach for Sequence Labeling

- Generative models such as Naive Bayes was used for classification can also be used for sequence labeling tasks in NLP.
- Approach:
  - Training: Learn the joint distribution $p(x_1, x_2, \ldots, x_n, y_1, y_2, \ldots, y_n)$ of input sequences.
  - Decoding: Use the learned distribution to predict label sequences for new input sequences.
- Decoding in sequence labeling involves finding the label sequence with the highest joint probability: $\arg\max_{y_1, y_2, \ldots, y_n} p(x_1, x_2, \ldots, x_n, y_1, y_2, \ldots, y_n)$.

Hidden Markov Models

- Hidden Markov Models (HMMs) provide a principled way to handle sequence labeling problems using generative modeling and efficient decoding algorithms.
- We have an input sentence $x = x_1, x_2, \ldots, x_n$ (x_i is the i-th word in the sentence).
- We have a tag sequence $y = y_1, y_2, \ldots, y_n$ (y_i is the i-th tag in the sentence).
- We'll use an HMM to define $p(x_1, x_2, \ldots, x_n, y_1, y_2, \ldots, y_n)$ for any sentence $x_1, \ldots, x_n$ and tag sequence $y_1, \ldots, y_n$ of the same length. [Kupiec, 1992]
- Then, the most likely tag sequence for x is:

$$\arg \max_{y_1, \ldots, y_n} p(x_1, \ldots, x_n, y_1, \ldots, y_n)$$

Trigram Hidden Markov Models (Trigram HMMs)

For any sentence $x_1, \ldots, x_n$ where $x_i \in V$ for $i = 1, \ldots, n$, and any tag sequence $y_1, \ldots, y_{n+1}$ where $y_i \in S$ for $i = 1, \ldots, n$, and $y_{n+1} = \text{STOP}$, the joint probability of the sentence and tag sequence is:

$$p(x_1, \ldots, x_n, y_1, \ldots, y_{n+1}) = \prod_{i=1}^{n+1} q(y_i | y_{i-2}, y_{i-1}) \prod_{i=1}^{n} e(x_i | y_i)$$

where we have assumed that $x_0 = x_{-1} = *$.

Parameters of the Model

- $q(s|u, v)$ for any $s \in \mathcal{S} \cup \{\text{STOP}\}$, $u, v \in \mathcal{S} \cup \{*\}$
  - The value for $q(s|u, v)$ can be interpreted as the probability of seeing the tag s immediately after the bigram of tags (u, v).
- $e(x|s)$ for any $s \in \mathcal{S}$, $x \in \mathcal{V}$
  - The value for $e(x|s)$ can be interpreted as the probability of seeing observation x paired with state s.

An Example

If we have $n = 3$, x_1, x_2, x_3 equal to the sentence ”the dog laughs”, and y_1, y_2, y_3, y_4 equal to the tag sequence ”D N V STOP”, then:

$$\begin{aligned} p(x_1, \ldots, x_n, y_1, \ldots, y_{n+1}) = & q(D|*, *) \times q(N|*, D) \\ & \times q(V|D, N) \times q(\text{STOP}|N, V) \\ & \times e(\text{the}|D) \times e(\text{dog}|N) \times e(\text{laughs}|V) \end{aligned}$$

- STOP is a special tag that terminates the sequence.
- We take $y_0 = y_{-1} = *$, where $*$ is a special ”padding” symbol.

Independence Assumptions in Trigram HMMs

- Trigram Hidden Markov Models (HMMs) are derived by making specific independence assumptions in the model.
- Consider two sequences of random variables: $X_1, \ldots, X_n$ and $Y_1, \ldots, Y_n$, where n is the length of the sequences.
- Each X_i can take any value in a finite set V of words, and each Y_i can take any value in a finite set K of possible tags (e.g., $K = \{D, N, V \ldots\}$).
- Our goal is to model the joint probability:

$$
\begin{aligned}
P(x_1, x_2, \ldots, x_n,& y_1, \ldots, y_n) \\
&= p(y_1) \times p(y_2|y_1) \\
&\quad \times \ldots \\
&\quad \times p(y_n|y_{n-1}, y_{n-2}, \ldots y_1) \\
&\quad \times p(x_1|y_n, y_{n-1}, \ldots y_1) \\
&\quad \times p(x_2|x_1, y_n, y_{n-1}, \ldots y_1) \\
&\quad \times p(x_n|x_{n-1}, \ldots, x_1, y_n, y_{n-1}, \ldots y_1)
\end{aligned}
$$

- We define an additional random variable Y_{n+1} that always takes the value "STOP."

Independence Assumptions in Trigram HMMs

- The key idea in HMMs is the factorization of the joint probability:

$$P(X_1 = x_1, \ldots, X_n = x_n, Y_1 = y_1, \ldots, Y_{n+1} = y_{n+1})$$

$$= \prod_{i=1}^{n+1} P(Y_i = y_i | Y_{i-2} = y_{i-2}, Y_{i-1} = y_{i-1}) \times \prod_{i=1}^{n} P(X_i = x_i | Y_i = y_i)$$

- We first assume that:

$$P(Y_i = y_i | Y_{i-2} = y_{i-2}, Y_{i-1} = y_{i-1}) = q(y_i | y_{i-2}, y_{i-1})$$

- This assumes that the sequence $Y_1, \ldots, Y_{n+1}$ is a second-order Markov sequence, where each state depends only on the previous two states.
- And we also assume that:

$$P(X_i = x_i | Y_i = y_i) = e(x_i | y_i)$$

- This assumes that the value of the random variable X_i depends only on the value of Y_i.
- These independence assumptions allow for the derivation of the joint probability equation.

Why the Name?

$$\begin{aligned} p(x_1, \ldots, x_n, y_1, \ldots, y_n) =& q(\text{STOP}|y_{n-1}, y_n) \\ & \times \prod_{j=1}^{n} q(y_j|y_{j-2}, y_{j-1}) \\ & \times \prod_{j=1}^{n} e(x_j|y_j) \end{aligned}$$

- Markov Chain component:

$$q(\text{STOP}|y_{n-1}, y_n) \times \prod_{j=1}^{n} q(y_j|y_{j-2}, y_{j-1})$$

  These transitions are not directly observed for a given sequence of words $(x_1, \ldots, x_n)$, hence the name “hidden”.

- Observed component:

$$\prod_{j=1}^{n} e(x_j|y_j)$$

  The observed component of HMMs models the emission probabilities of observed symbols (x’s) conditioned on the corresponding hidden states (y’s).

Smoothed Estimation

$$
\begin{aligned}
q(Vt|DT, JJ) =& \lambda_1 \times \frac{\text{Count}(Dt, JJ, Vt)}{\text{Count}(Dt, JJ)} \\
&+ \lambda_2 \times \frac{\text{Count}(JJ, Vt)}{\text{Count}(JJ)} \\
&+ \lambda_3 \times \frac{\text{Count}(Vt)}{\text{Count}()}
\end{aligned}
$$

where $\lambda_1 + \lambda_2 + \lambda_3 = 1$, and for all i, $\lambda_i \geq 0$.

$$
e(\text{base}|Vt) = \frac{\text{Count}(Vt, \text{base})}{\text{Count}(Vt)}
$$

Dealing with Low-Frequency Words

A common method is as follows:

- Step 1: Split vocabulary into two sets
  - Frequent words = words occurring $\geq$ 5 times in training
  - Low frequency words = all other words
- Step 2: Map low frequency words into a small, finite set, depending on prefixes, suffixes, etc.

Dealing with Low-Frequency Words: An Example

Below is an example of word classes for named entity recognition [Bikel et al., 1999]:

Word class	Example	Intuition
twoDigitNum	90	Two-digit year
fourDigitNum	1990	Four-digit year
containsDigitAndAlpha	$A8956 - 67$	Product code
containsDigitAndDash	$09 - 96$	Date
containsDigitAndSlash	$11/9/89$	Date
containsDigitAndComma	$23, 000.00$	Monetary amount
containsDigitAndPeriod	1.00	Monetary amount, percentage
othernum	456789	Other number
allCaps	BBN	Organization
capPeriod	$M.$	Person name initial
firstWord	First word of sentence	No useful capitalization information
initCap	Sally	Capitalized word
lowercase	can	Uncapitalized word
other	,	Punctuation marks, all other words

Dealing with Low-Frequency Words: An Example

Original Sentence: Profits/O soared/O at/O Boeing/B-C Co./I-C ,/O easily/O topping/O forecasts/O on/O Wall/B-L Street/I-L ,/O as/O their/O CEO/O Alan/B-P Mulally/I-P announced/O first/O quarter/O results/O ./O

Transformed Sentence:
firstword/O soared/O at/O initCap/B-C Co./I-C ,/O easily/O lowercase/O forecasts/O on/O initCap/B-L Street/I-L ,/O as/O their/O CEO/O Alan/B-P initCap/I-P announced/O first/O quarter/O results/O ./O

- O = Outside (no entity)
- B-C = Begin Company
- I-C = Inside Company
- B-L = Begin Location
- I-L = Inside Location
- B-P = Begin Person
- I-P = Inside Person

Decoding Problem

Decoding Problem: For an input $x_1 \ldots x_n$, find

$$\arg \max_{y_1 \ldots y_{n+1}} p(x_1 \ldots x_n, y_1 \ldots y_{n+1})$$

where the $\arg\max$ is taken over all sequences $y_1 \ldots y_{n+1}$ such that $y_i \in S$ for $i = 1 \ldots n$, and $y_{n+1} = \text{STOP}$.
We assume that p takes the form:

$$p(x_1 \ldots x_n, y_1 \ldots y_{n+1}) = \prod_{i=1}^{n+1} q(y_i | y_{i-2}, y_{i-1}) \prod_{i=1}^{n} e(x_i | y_i)$$

Recall that we have assumed in this definition that $y_0 = y_{-1} = *$, and $y_{n+1} = \text{STOP}$.

Naive Brute Force Method

The naive, brute force method for finding the highest scoring tag sequence is to enumerate all possible tag sequences $y_1, \ldots, y_{n+1}$, score them under the function p, and select the sequence with the highest score.

- Example:
    - Input sentence: *the dog barks*
    - Set of possible tags: $K = \{D, N, V\}$
- Enumerate all possible tag sequences:
    - *D D D STOP*
    - *D D N STOP*
    - *D D V STOP*
    - *D N D STOP*
    - *D N N STOP*
    - *D N V STOP*
    - ...

Naive Brute Force Method

- In this case, there are $3^3 = 27$ possible sequences.
- However, for longer sentences, this method becomes inefficient.
- For an input sentence of length n, there are $|K|^n$ possible tag sequences.
- The exponential growth makes brute-force search infeasible for reasonable length sentences.

Viterbi Decoding Dynamic Programming

- The algorithm used by HMMs to perform efficient decoding is called Viterbi decoding.
- Viterbi decoding uses dynamic programming.
- Dynamic programming is a technique for solving optimization problems by breaking them down into overlapping subproblems.
- It stores the solutions to these subproblems in a table so that they do not have to be recalculated.
- Dynamic programming can greatly improve the efficiency of algorithms.
- Next, we show how dynamic programming works with two examples: Factorial and Fibonacci

Factorial

- Recursive implementation:

```python
def recur_factorial(n):
    # Base case
    if n == 1:
        return n
    else:
        return n * recur_factorial(n-1)
```

- Dynamic programming implementation:

```python
def dynamic_factorial(n):
    table = [0 for i in range(0, n+1)]

    # Base case
    table[0] = 1

    for i in range(1, len(table)):
        table[i] = i * table[i-1]

    return table[n]
```

Fibonacci

- Recursive implementation:

```python
def recur_fibonacci(n):
    if n == 1 or n == 0:
        return 1
    else:
        return recur_fibonacci(n-1) + recur_fibonacci(n-2)
```

- Dynamic programming implementation:

```python
def dynamic_fibonacci(n):
    table = [0 for i in range(0, n+1)]

    # Base case
    table[0] = 1
    table[1] = 1

    for i in range(2, len(table)):
        table[i] = table[i-1] + table[i-2]

    return table[n]
```

Complexity

- In recursive implementations, the complexity can be quite high due to repeated calculations of the same subproblems.
- However, dynamic programming can significantly reduce the complexity by storing the solutions to subproblems in a table or array and reusing them when needed.
- This approach eliminates the redundant calculations and allows for a more efficient computation.
- For the case of Fibonacci the complexity is reduced from exponential to linear.

The Viterbi Algorithm

The Viterbi algorithm efficiently computes the maximum probability of a tag sequence by using dynamic programming.

Definitions:

- Define n as the length of the sentence.
- Define S_k for $k = -1 \ldots n$ as the set of possible tags at position k: $S_{-1} = S_0 = \{*\}$, $S_k = S$ for $k \in \{1 \ldots n\}$.
- Define a truncated version of the probability encoded by the HMM until position k, $r(y_{-1}, y_0, y_1, \ldots, y_k)$ as:

$$r(y_{-1}, y_0, y_1, \ldots, y_k) = \prod_{i=1}^{k} q(y_i|y_{i-2}, y_{i-1}) \prod_{i=1}^{k} e(x_i|y_i)$$

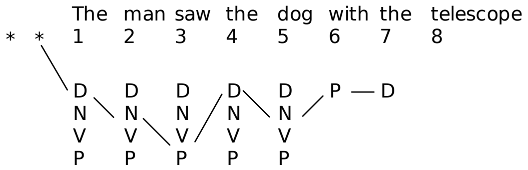
- Define a dynamic programming table $\pi(k, u, v)$ as the maximum probability of a tag sequence ending in tags u, v at position k:

$$\pi(k, u, v) = \max_{y_{-1}, y_0, y_1, \ldots, y_k : y_{k-1}=u, y_k=v} r(y_{-1}, y_0, y_1, \ldots, y_k)$$

An Example

Recall that $\pi(k, u, v)$ is maximum probability of a tag sequence ending in tags u, v at position k

$$S = \{D, N, P, V\}$$



The man saw the dog with the telescope

* * 1 2 3 4 5 6 7 8

D D D D D P — D

N N N N N

V V V V V

P P P P P

- There are many possible sequences of tags.
- Each of them has a probability calculated from the parameters q and e.
- $\pi(7, P, D)$ is the maximum probability that one of these tag sequences ends in P D at position 7.
- The path represents the sequence with the maximum probability.

A Recursive Definition

Base case:

$$\pi(0, *, *) = 1$$

Recursive definition: For any $k \in \{1 \ldots n\}$, for any $u \in S_{k-1}$ and $v \in S_k$:

$$\pi(k, u, v) = \max_{w \in S_{k-2}} \left(\pi(k-1, w, u) \times q(v|w, u) \times e(x_k|v)\right)$$

Justification for the Recursive Definition

For any $k \in \{1 \dots n\}$, for any $u \in S_{k-1}$ and $v \in S_k$:

$$\pi(k, u, v) = \max_{w \in S_{k-2}} (\pi(k-1, w, u) \times q(v|w, u) \times e(x_k|v))$$

				D			
				$\boxed{\text{N}}$			
				V			
				P	P	D	
The	man	saw	the	dog	with	the	telescope
1	2	3	4	5	6	7	8

$$\mathcal{S}_5 = \mathcal{S} = \{D, N, V, P\}$$

$$\Pi(7, P, D) = \max_{w \in \mathcal{S}_5} (\Pi(6, w, P) \times q(D|w, P) \times e(\text{the}|D))$$

- Let's consider an arbitrary tag sequence that ends with tags *P* and *D* at position 7.
- It must contain some tag at position 5.
- We are basically searching for the tag that maximizes the probability at position 5.

The Viterbi Algorithm

Algorithm 1: Viterbi Algorithm

```
Input: a sentence $x_1 \ldots x_n$, parameters $q(s|u,v)$ and $e(x|s)$
Initialization: Set $\pi(0,*,*) = 1$; $S_{-1} = S_0 = \{*\}$, $S_k = S$
                for $k \in \{1 \ldots n\}$.

for $k = 1$ to $n$ do
    for $u \in S_{k-1}, v \in S_k$ do
        $\pi(k,u,v) = \max_{w \in S_{k-2}} (\pi(k-1,w,u) \times q(v|w,u) \times e(x_k|v))$
    end
end
return ($\max_{u \in S_{n-1}, v \in S_n} (\pi(n,u,v) \times q(STOP|u,v))$)
```

The Viterbi Algorithm with Backpointers

Algorithm 2: Viterbi Algorithm with Backpointers

Input: a sentence $x_1 \ldots x_n$, parameters $q(s|u, v)$ and $e(x|s)$

Initialization: Set $\pi(0, *, *) = 1$; $S_{-1} = S_0 = \{*\}$, $S_k = S$ for $k \in \{1 \ldots n\}$.

```
for $k = 1$ to $n$ do
    for $u \in S_{k-1}, v \in S_k$ do
        $\pi(k, u, v) = \max_{w \in S_{k-2}} (\pi(k-1, w, u) \times q(v|w, u) \times e(x_k|v))$
        $\text{bp}(k, u, v) = \arg\max_{w \in S_{k-2}} (\pi(k-1, w, u) \times q(v|w, u) \times e(x_k|v))$
    end
end
$(y_{n-1}, y_n) = \arg\max_{(u,v)} (\pi(n, u, v) \times q(\text{STOP}|u, v))$ ;    // Find maximum probability and corresponding tags
for $k = (n-2)$ to 1 do
    $y_k = \text{bp}(k+2, y_{k+1}, y_{k+2})$ ;    // Retrieve tag sequence using backpointers
end
return(the tag sequence $y_1 \ldots y_n$) ;  // Return the final tag sequence
```

The Viterbi Algorithm: Running Time

- $O(n|S|^3)$ time to calculate $q(s|u,v) \times e(x_k|s)$ for all k, s, u, v.
- $n|S|^2$ entries in π to be filled in.
- $O(|S|)$ time to fill in one entry.

$\Rightarrow O(n|S|^3)$ time in total.

Pros and Cons

- Hidden Markov Model (HMM) taggers are simple to train (compile counts from training corpus).
- They perform relatively well (over 90% performance on named entity recognition).
- Main difficulty is modeling $e(\text{word}|\text{tag})$, which can be very complex if ”words” are complex.

Questions?

Thanks for your Attention!

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