Natural Language Processing

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Part 1: Classification tasks in NLP

Classification tasks in NLP

Naive Bayes Classifier

Log linear models

Tagging tasks in NLP

Log-linear models for Tagging

Prepositional Phrases

- noun attach: *I bought the shirt with pockets*
- verb attach: *I washed the shirt with soap*
- As in the case of other attachment decisions in parsing: it depends on the meaning of the entire sentence – needs world knowledge, etc.
- Maybe there is a simpler solution: we can attempt to solve it using heuristics or associations between words

Ambiguity Resolution: Prepositional Phrases in English

- Learning Prepositional Phrase Attachment: Annotated Data

v	n_1	p	n_2	Attachment
join	board	as	director	V
is	chairman	of	N.V.	N
using	crocidolite	in	filters	V
bring	attention	to	problem	V
is	asbestos	in	products	N
making	paper	for	filters	N
including	three	with	cancer	N
⋮	⋮	⋮	⋮	⋮

Prepositional Phrase Attachment

Method	Accuracy
Always noun attachment	59.0
Most likely for each preposition	72.2
Average Human (4 head words only)	88.2
Average Human (whole sentence)	93.2

Back-off Smoothing

- Random variable a represents attachment.
- $a = n_1$ or $a = v$ (two-class classification)
- We want to compute probability of noun attachment: $p(a = n_1 \mid v, n_1, p, n_2)$.
- Probability of verb attachment is $1 - p(a = n_1 \mid v, n_1, p, n_2)$.

Back-off Smoothing

1. If $f(v, n_1, p, n_2) > 0$ and $\hat{p} \neq 0.5$

$$\hat{p}(a_{n_1} \mid v, n_1, p, n_2) = \frac{f(a_{n_1}, v, n_1, p, n_2)}{f(v, n_1, p, n_2)}$$

2. Else if $f(v, n_1, p) + f(v, p, n_2) + f(n_1, p, n_2) > 0$ and $\hat{p} \neq 0.5$

$$\hat{p}(a_{n_1} \mid v, n_1, p, n_2) = \frac{f(a_{n_1}, v, n_1, p) + f(a_{n_1}, v, p, n_2) + f(a_{n_1}, n_1, p, n_2)}{f(v, n_1, p) + f(v, p, n_2) + f(n_1, p, n_2)}$$

3. Else if $f(v, p) + f(n_1, p) + f(p, n_2) > 0$

$$\hat{p}(a_{n_1} \mid v, n_1, p, n_2) = \frac{f(a_{n_1}, v, p) + f(a_{n_1}, n_1, p) + f(a_{n_1}, p, n_2)}{f(v, p) + f(n_1, p) + f(p, n_2)}$$

4. Else if $f(p) > 0$ (try choosing attachment based on preposition alone)

$$\hat{p}(a_{n_1} \mid v, n_1, p, n_2) = \frac{f(a_{n_1}, p)}{f(p)}$$

5. Else $\hat{p}(a_{n_1} \mid v, n_1, p, n_2) = 1.0$

Prepositional Phrase Attachment: Results

- **Results (Collins and Brooks 1995)**: 84.5% accuracy
  with the use of some limited word classes for dates, numbers, etc.
- **Toutanova, Manning, and Ng, 2004**:
  use sophisticated smoothing model for PP attachment
  86.18% with words & stems; with word classes: 87.54%
- **Merlo, Crocker and Berthouzoz, 1997**:
  test on multiple PPs, generalize disambiguation of 1 PP to 2-3 PPs
  1PP: 84.3% 2PP: 69.6% 3PP: 43.6%
  Note that this is still not the real problem faced in parsing natural language

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Part 2: Probabilistic Classifiers

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Naive Bayes Classifier

- $\mathbf{x}$ is the input that can be represented as d independent features f_j, $1 \leq j \leq d$
- y is the output classification
- $P(y \mid \mathbf{x}) = \frac{P(y) \cdot P(\mathbf{x}|y)}{P(\mathbf{x})}$ (Bayes Rule)
- $P(\mathbf{x} \mid y) = \prod_{j=1}^{d} P(f_j \mid y)$
- $P(y \mid \mathbf{x}) = P(y) \cdot \prod_{j=1}^{d} P(f_j \mid y)$

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Log-linear models for Tagging

Log linear model

- Let there be m features, $f_k(\mathbf{x}, y)$ for $k = 1, \ldots, m$
- Define a parameter vector $\mathbf{w} \in \mathbb{R}^m$
- Each $(\mathbf{x}, y)$ pair is mapped to score:

$$s(\mathbf{x}, y) = \sum_k w_k \cdot f_k(\mathbf{x}, y)$$

- Using inner product notation:

$$\begin{aligned} \mathbf{w} \cdot \mathbf{f}(\mathbf{x}, y) &= \sum_k w_k \cdot f_k(\mathbf{x}, y) \\ s(\mathbf{x}, y) &= \mathbf{w} \cdot \mathbf{f}(\mathbf{x}, y) \end{aligned}$$

- To get a probability from the score: Renormalize!

$$\Pr(y \mid \mathbf{x}, \mathbf{w}) = \frac{exp\left(s(\mathbf{x}, y)\right)}{\sum_{y'} exp\left(s(\mathbf{x}, y')\right)}$$

Log linear model

- The name 'log-linear model' comes from:

$$\log \Pr(y \mid \mathbf{x}, \mathbf{w}) = \underbrace{\mathbf{w} \cdot \mathbf{f}(\mathbf{x}, y)}_{\text{linear term}} - \underbrace{\log \sum_{y'} exp\left(\mathbf{w} \cdot \mathbf{f}(\mathbf{x}, y')\right)}_{\text{normalization term}}$$

- Once the weights are learned, we can perform predictions using these features.
- The goal: to find $\mathbf{w}$ that maximizes the log likelihood $L(\mathbf{w})$ of the labeled training set containing $(\mathbf{x}_i, y_i)$ for $i = 1 \ldots n$

$$\begin{aligned} L(\mathbf{w}) &= \sum_i \log \Pr(y_i \mid \mathbf{x}_i, \mathbf{w}) \\ &= \sum_i \mathbf{w} \cdot \mathbf{f}(\mathbf{x}_i, y_i) - \sum_i \log \sum_{y'} exp\left(\mathbf{w} \cdot \mathbf{f}(\mathbf{x}_i, y')\right) \end{aligned}$$

Log linear model

- Maximize:

$$L(\mathbf{w}) = \sum_i \mathbf{w} \cdot \mathbf{f}(\mathbf{x}_i, y_i) - \sum_i \log \sum_{y'} exp\left(\mathbf{w} \cdot \mathbf{f}(\mathbf{x}_i, y')\right)$$

- Calculate gradient:

$$\left.\frac{dL(\mathbf{w})}{d\mathbf{w}}\right|_{\mathbf{w}}$$

$$= \sum_i \mathbf{f}(\mathbf{x}_i, y_i) - \sum_i \frac{1}{\sum_{y''} exp\left(\mathbf{w} \cdot \mathbf{f}(x_i, y'')\right)} \sum_{y'} \mathbf{f}(\mathbf{x}_i, y') \cdot exp\left(\mathbf{w} \cdot \mathbf{f}(\mathbf{x}_i, y')\right)$$

$$= \sum_i \mathbf{f}(\mathbf{x}_i, y_i) - \sum_i \sum_{y'} \mathbf{f}(\mathbf{x}_i, y') \frac{exp\left(\mathbf{w} \cdot \mathbf{f}(\mathbf{x}_i, y')\right)}{\sum_{y''} exp\left(\mathbf{w} \cdot \mathbf{f}(x_i, y'')\right)}$$

$$= \underbrace{\sum_i \mathbf{f}(\mathbf{x}_i, y_i)}_{\text{Observed counts}} - \underbrace{\sum_i \sum_{y'} \mathbf{f}(\mathbf{x}_i, y') \Pr(y' \mid \mathbf{x}_i, \mathbf{w})}_{\text{Expected counts}}$$

Log linear model

- Init: $\mathbf{w}^{(0)} = \mathbf{0}$
- $t \leftarrow 0$
- Iterate until convergence:
  - Calculate: $\Delta = \left.\frac{dL(\mathbf{w})}{d\mathbf{w}}\right|_{\mathbf{w}=\mathbf{w}^{(t)}}$
  - Find $\beta^* = \arg\max_\beta L(\mathbf{w}^{(t)} + \beta\Delta)$
  - Set $\mathbf{w}^{(t+1)} \leftarrow \mathbf{w}^{(t)} + \beta^*\Delta$

Learning the weights: $\mathbf{w}$: Generalized Iterative Scaling

$f^{\#} = max_{x,y} \sum_j f_j(x, y)$
(the maximum possible feature value; needed for scaling)
Initialize $\mathbf{w}^{(0)}$
For each iteration t
    `expected[j]` $\leftarrow$ 0 for j $= 1$ .. # of features
    For i $= 1$ to $|$ training data $|$
        For each feature f_j
            `expected[j]` $+= f_j(x_i, y_i) \cdot P(y_i \mid x_i, \mathbf{w}^{(t)})$
    For each feature $f_j(x, y)$
        `observed[j]` $= f_j(x, y) \cdot \frac{c(x,y)}{|\text{training data}|}$
    For each feature $f_j(x, y)$
        $w_j^{(t+1)} \leftarrow w_j^{(t)} \cdot \sqrt[f^{\#}]{\frac{\texttt{observed[j]}}{\texttt{expected[j]}}}$

cf. Goodman, NIPS '01

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Part 3: Linear models for Tagging

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Tagging Tasks

Tagged Sequences

a b e e a f h j $\Rightarrow$ a/Y b/Z e/Y e/Y a/Z f/X h/Z j/Y

Example 1: Part-of-speech tagging

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 ./.

Example 2: Named Entity Recognition

Profits/O soared/O at/O Boeing/B-CO Co./I-CO ,/O easily/O
topping/O forecasts/O on/O Wall/B-LOC Street/I-LOC ,/O as/O
their/O CEO/O Alan/B-PER Mulally/I-PER announced/O first/O
quarter/O results/O ./O

Notation for Tagging Tasks

- Set of possible input words: $\mathcal{V}$
- Set of possible tags: $\mathcal{T}$
- Word sequence: $x_{[1:n]} = [x_1, \ldots, x_n]$
- Tag sequence: $t_{[1:n]} = [t_1, \ldots, t_n]$
- Training data is N tagged sentences, the i^{th} sentence has length n_i:

$$(x^{(i)}_{[1:n]}, t^{(i)}_{[1:n]}) \text{ for } i = 1, \ldots, n$$

Independence Assumptions for Tagging

Chain Rule

$$P(t_{[1:n]} \mid x_{[1:n]}) = \prod_{j=1}^{n} P(t_j \mid t_{j-1}, \ldots, t_1, x_{[1:n]}, j)$$

Make independence assumptions

$$P(t_{[1:n]} \mid x_{[1:n]}) \approx \prod_{j=1}^{n} P(t_j \mid t_{j-1}, x_{[1:n]}, j)$$

j is the word being tagged.

We model the conditional probability directly: no Bayes Rule here.

Questions

- Split up $P(t_j \mid t_{j-1}, x_{[1:n]}, j)$ into parameters?
- How to find $\arg\max_{t_{[1:n]}} P(t_{[1:n]} \mid x_{[1:n]})$?

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Representation: finding the right parameters

Problem: Predict ?? using context, $P(?? \mid \texttt{context})$

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

Representation: history

- A history is a 3-tuple: $(t_{-1}, x_{[1:n]}, i)$
- t_{-1} is the previous tag (we are assuming a bigram model)
- $x_{[1:n]}$ are the n words in the input
- i is the index of the word being tagged
- For example, for $x_4 =$ Boeing:
  - $t_{-1} =$ P
  - $x_{[1:n]} =$ (Profits, soared, ..., results, .)
  - $i = 4$

Feature-vectors over history-tag pairs

Take a history, tag pair (h, t)

$f_k(h, t)$ for $k = 1, \ldots, m$ are **feature functions** representing the tagging decision.

Example: Part-of-speech tagging [Ratnaparkhi 1996]

$$f_{100}(h, t) = \begin{cases} 1 & \text{if current word } x_i \text{ is } \texttt{Boeing} \text{ and } t = \texttt{N} \\ 0 & \text{otherwise} \end{cases}$$

$$f_{101}(h, t) = \begin{cases} 1 & \text{if } t_{-1} \text{ is } \texttt{P} \text{ and } t = \texttt{N} \\ 0 & \text{otherwise} \end{cases}$$

Log linear model for Tagging

- Let there be m features, $f_k(\mathbf{x}, \mathbf{y})$ for $k = 1, \ldots, m$
- $\mathbf{x} = x_{[1:n]}$ and $\mathbf{y} = t_{[1:n]}$
- Define a parameter vector $\mathbf{w} \in \mathbb{R}^m$
- Each $(\mathbf{x}, \mathbf{y})$ pair is mapped to score:

$$s(\mathbf{x}, \mathbf{y}) = \sum_k w_k \cdot f_k(\mathbf{x}, \mathbf{y})$$

- Using inner product notation:

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- To get a probability from the score: Renormalize!

$$\Pr(\mathbf{y} \mid \mathbf{x}, \mathbf{w}) = \frac{exp\left(s(\mathbf{x}, \mathbf{y})\right)}{\sum_{\mathbf{y}'} exp\left(s(\mathbf{x}, \mathbf{y}')\right)}$$

Feature functions for Tagging

Problem

- We have defined a log-linear model using feature functions: **f(x,y)**
- We have defined parameters using a history h so feature functions are: $\mathbf{f}(h, t)$

Locally normalized log-linear taggers

Conditional Distribution over history, tag pair (h, t)

$$\log \Pr(t \mid h) = \mathbf{w} \cdot \mathbf{f}(h, t) - log \sum_{t'} \exp\left(\mathbf{w} \cdot \mathbf{f}(h, t')\right)$$

- $\mathbf{f}(h, t)$ is a vector of feature functions
- $\mathbf{w}$ is the weight vector

Local normalization for tagging

- Word sequence: $x_{[1:n]}$ and tag sequence: $t_{[1:n]}$
- Histories $h_i = (t_{i-1}, x_{[1:n]}, i)$

$$\log \Pr(t_{[1:n]} \mid x_{[1:n]}) = \sum_{i=1}^{n} \log \Pr(t_i \mid h_i)$$

Globally normalized log-linear taggers

Global feature function $\mathbf{\Phi}(\mathbf{x}, \mathbf{y})$

- Word sequence: $\mathbf{x} = x_{[1:n]}$ and tag sequence: $\mathbf{y} = t_{[1:n]}$
- From *local* histories $h_i = (t_{i-1}, x_{[1:n]}, i)$ to global Φ values:

$$\Phi_k(x_{[1:n]}, t_{[1:n]}) = \sum_{i=1}^{n} f_k(h_i, t_i)$$

- $\mathbf{\Phi}(\mathbf{x}, \mathbf{y}) = (\Phi_1, \Phi_2, \ldots, \Phi_m)$ is a *global* feature vector
- $\mathbf{w}$ is the weight vector for $\mathbf{\Phi}$

Global normalization for tagging

$$\log \Pr(\mathbf{y} \mid \mathbf{x}, \mathbf{w}) = \mathbf{w} \cdot \mathbf{\Phi}(\mathbf{x}, \mathbf{y}) - \log \sum_{\mathbf{y'}} exp\left(\mathbf{w} \cdot \mathbf{\Phi}(\mathbf{x}, \mathbf{y'})\right)$$

Conditional Random Field

Global normalization for tagging

$$\log \Pr(\mathbf{y} \mid \mathbf{x}, \mathbf{w}) = \mathbf{w} \cdot \mathbf{\Phi}(\mathbf{x}, \mathbf{y}) - \log \sum_{\mathbf{y'}} exp\left(\mathbf{w} \cdot \mathbf{\Phi}(\mathbf{x}, \mathbf{y'})\right)$$

- This model is also called a conditional random field (CRF)

Algorithms for training and decoding

- Global normalization could be expensive: requires sum over exponentially many terms $\mathbf{y'}$
- Finding $\arg\max_{\mathbf{y}} \log \Pr(\mathbf{y} \mid \mathbf{x})$ can be accomplished using the Viterbi algorithm.
- Training: finding the weight vector $\mathbf{w}$ can be done using a variant of the Forward algorithm.

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