SFU NatLangLab

Natural Language Processing

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Part 1: Generative Models for Word Alignment

Statistical Machine Translation

Noisy Channel Model

$$\mathbf{e}^* = \arg\max_{\mathbf{e}} \underbrace{\Pr(\mathbf{e})}_{\textbf{Language Model}} \cdot \underbrace{\Pr(\mathbf{f} \mid \mathbf{e})}_{\textbf{Alignment Model}}$$

Alignment Task

$$\begin{array}{l} \mathbf{e} \searrow \\ \qquad \text{Program} \longrightarrow \Pr(\mathbf{e} \mid \mathbf{f}) \\ \mathbf{f} \nearrow \end{array}$$

Training Data

- **Alignment Model**: learn a mapping between **f** and **e**.
  Training data: lots of translation pairs between **f** and **e**.

Statistical Machine Translation

The IBM Models

- The first statistical machine translation models were developed at IBM Research (Yorktown Heights, NY) in the 1980s
- The models were published in 1993:
  Brown et. al. The Mathematics of Statistical Machine Translation.
  Computational Linguistics. 1993.
  `http://aclweb.org/anthology/J/J93/J93-2003.pdf`
- These models are the basic SMT models, called:
  IBM Model 1, IBM Model 2, IBM Model 3, IBM Model 4, IBM Model 5
  as they were called in the 1993 paper.
- We use **e** and **f** in the equations in honor of their system which translated from French to English.
  Trained on the Canadian Hansards (Parliament Proceedings)

Statistical Machine Translation

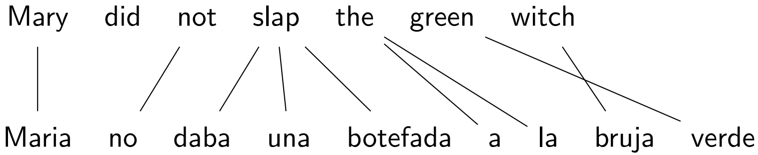
Generative Model of Word Alignment

- Word Alignments: IBM Model 3
- Word Alignments: IBM Model 1

Generative Model of Word Alignment

- English **e**: Mary did not slap the green witch
- "French" **f**: Maria no daba una botefada a la bruja verde
- Alignment **a**: $\{1, 3, 4, 4, 4, 5, 5, 7, 6\}$
  e.g. $(f_8, e_{a_8}) = (f_8, e_7) =$ (bruja, witch)

Visualizing alignment **a**



Generative Model of Word Alignment

Data Set

- Data set $\mathcal{D}$ of N sentences:
$$\mathcal{D} = \{(\mathbf{f}^{(1)}, \mathbf{e}^{(1)}), \ldots, (\mathbf{f}^{(N)}, \mathbf{e}^{(N)})\}$$
- French $\mathbf{f}$: $(f_1, f_2, \ldots, f_I)$
- English $\mathbf{e}$: $(e_1, e_2, \ldots, e_J)$
- Alignment $\mathbf{a}$: $(a_1, a_2, \ldots, a_I)$

Generative Model of Word Alignment

Find the best alignment for each translation pair

$$\mathbf{a}^* = \arg\max_{\mathbf{a}} \Pr(\mathbf{a} \mid \mathbf{f}, \mathbf{e})$$

Chain rule revisited

$$\begin{aligned} \Pr(\mathbf{f}, \mathbf{a}) &= \Pr(\mathbf{f}) \Pr(\mathbf{a} \mid \mathbf{f}) \\ \Pr(\mathbf{f}, \mathbf{a} \mid \mathbf{e}) &= \Pr(\mathbf{f} \mid \mathbf{e}) \Pr(\mathbf{a} \mid \mathbf{f}, \mathbf{e}) \end{aligned}$$

Alignment probability

$$\Pr(\mathbf{a} \mid \mathbf{f}, \mathbf{e}) = \frac{\Pr(\mathbf{f}, \mathbf{a} \mid \mathbf{e})}{\Pr(\mathbf{f} \mid \mathbf{e})} = \frac{\Pr(\mathbf{f}, \mathbf{a} \mid \mathbf{e})}{\sum_{\mathbf{a}} \Pr(\mathbf{f}, \mathbf{a} \mid \mathbf{e})}$$

Statistical Machine Translation

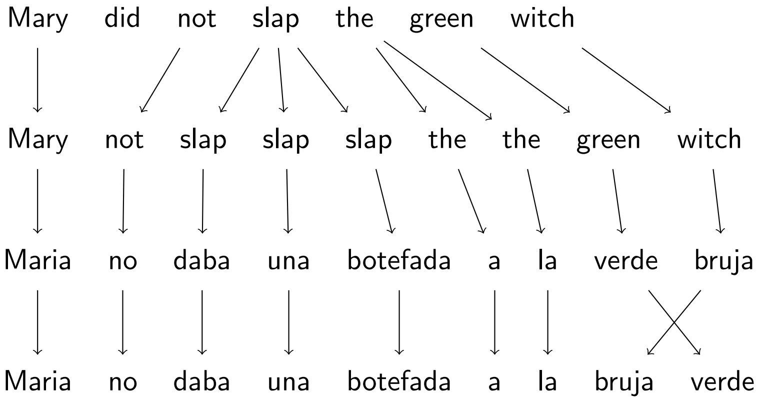
Generative Model of Word Alignment

Word Alignments: IBM Model 3

Word Alignments: IBM Model 1

Word Alignments: IBM Model 3

Generative "story" for $P(\mathbf{a} \mid \mathbf{f}, \mathbf{e})$



Word Alignments: IBM Model 3

Fertility parameter

$$n(\phi_j \mid e_j) : n(3 \mid slap)$$

Translation parameter

$$t(f_i \mid e_j) : t(bruja \mid witch)$$

Distortion parameter

$$d(f_{pos} \mid e_{pos}, I, J) : d(8 \mid 7, 8, 6)$$

Word Alignments: IBM Model 1

Alignment probability

$$\Pr(\mathbf{a} \mid \mathbf{f}, \mathbf{e}) = \frac{\Pr(\mathbf{f}, \mathbf{a} \mid \mathbf{e})}{\sum_{\mathbf{a}} \Pr(\mathbf{f}, \mathbf{a} \mid \mathbf{e})}$$

Example alignment

1	2	3	4
das	Haus	ist	klein
|	|	|	|
1	2	3	4
the	house	is	small

$$\Pr(\mathbf{f}, \mathbf{a} \mid \mathbf{e}) = \prod_{i=1}^{I} t(f_i \mid e_{a_i})$$

$$\begin{aligned}\Pr(\mathbf{f}, \mathbf{a} \mid \mathbf{e}) = \\ & t(\text{das} \mid \text{the}) \times \\ & t(\text{Haus} \mid \text{house}) \times \\ & t(\text{ist} \mid \text{is}) \times \\ & t(\text{klein} \mid \text{small})\end{aligned}$$

Word Alignments: IBM Model 1

Sum over all alignments

$$\sum_{\mathbf{a}} \Pr(\mathbf{f}, \mathbf{a} \mid \mathbf{e}) \quad = \quad \sum_{a_1=1}^{J} \sum_{a_2=1}^{J} \ldots \sum_{a_I=1}^{J} \prod_{i=1}^{I} t(f_i \mid e_{a_i})$$

Assume (f_1, f_2, f_3) and (e_1, e_2)

$$\sum_{a_1=1}^{2} \sum_{a_2=1}^{2} \sum_{a_3=1}^{2} t(f_1 \mid e_{a_1}) \times t(f_2 \mid e_{a_2}) \times t(f_3 \mid e_{a_3})$$

Word Alignments: IBM Model 1

Assume (f_1, f_2, f_3) and (e_1, e_2): $I = 3$ and $J = 2$

$$\sum_{a_1=1}^{2} \sum_{a_2=1}^{2} \sum_{a_3=1}^{2} t(f_1 \mid e_{a_1}) \times t(f_2 \mid e_{a_2}) \times t(f_3 \mid e_{a_3})$$

$J^I = 2^3$ terms to be added:

$t(f_1 \mid e_1)$	$\times$	$t(f_2 \mid e_1)$	$\times$	$t(f_3 \mid e_1)$	$+$
$t(f_1 \mid e_1)$	$\times$	$t(f_2 \mid e_1)$	$\times$	$t(f_3 \mid e_2)$	$+$
$t(f_1 \mid e_1)$	$\times$	$t(f_2 \mid e_2)$	$\times$	$t(f_3 \mid e_1)$	$+$
$t(f_1 \mid e_1)$	$\times$	$t(f_2 \mid e_2)$	$\times$	$t(f_3 \mid e_2)$	$+$
$t(f_1 \mid e_2)$	$\times$	$t(f_2 \mid e_1)$	$\times$	$t(f_3 \mid e_1)$	$+$
$t(f_1 \mid e_2)$	$\times$	$t(f_2 \mid e_1)$	$\times$	$t(f_3 \mid e_2)$	$+$
$t(f_1 \mid e_2)$	$\times$	$t(f_2 \mid e_2)$	$\times$	$t(f_3 \mid e_1)$	$+$
$t(f_1 \mid e_2)$	$\times$	$t(f_2 \mid e_2)$	$\times$	$t(f_3 \mid e_2)$	$+$

Word Alignments: IBM Model 1

Factor the terms:

$$\begin{array}{lcll}
(t(f_1 \mid e_1) \times t(f_2 \mid e_1)) & \times & (t(f_3 \mid e_1) + t(f_3 \mid e_2)) & + \\
(t(f_1 \mid e_1) \times t(f_2 \mid e_2)) & \times & (t(f_3 \mid e_1) + t(f_3 \mid e_2)) & + \\
(t(f_1 \mid e_2) \times t(f_2 \mid e_1)) & \times & (t(f_3 \mid e_1) + t(f_3 \mid e_2)) & + \\
(t(f_1 \mid e_2) \times t(f_2 \mid e_2)) & \times & (t(f_3 \mid e_1) + t(f_3 \mid e_2)) &
\end{array}$$

$$(t(f_3 \mid e_1) + t(f_3 \mid e_2)) \left(\begin{array}{lcll}
t(f_1 \mid e_1) & \times & t(f_2 \mid e_1) & + \\
t(f_1 \mid e_1) & \times & t(f_2 \mid e_2) & + \\
t(f_1 \mid e_2) & \times & t(f_2 \mid e_1) & + \\
t(f_1 \mid e_2) & \times & t(f_2 \mid e_2) &
\end{array} \right)$$

$$(t(f_3 \mid e_1) + t(f_3 \mid e_2)) \left(\begin{array}{lcll}
t(f_1 \mid e_1) & \times & (t(f_2 \mid e_1) + t(f_2 \mid e_2)) & + \\
t(f_1 \mid e_2) & \times & (t(f_2 \mid e_1) + t(f_2 \mid e_2)) &
\end{array} \right)$$

Word Alignments: IBM Model 1

Assume (f_1, f_2, f_3) and (e_1, e_2): $I = 3$ and $J = 2$

$$\prod_{i=1}^{3} \sum_{a_i=1}^{2} t(f_i \mid e_{a_i})$$

$I \times J = 2 \times 3$ terms to be added:

$$\begin{array}{ccccc}
(t(f_1 \mid e_1) & + & t(f_1 \mid e_2)) & \times \\
(t(f_2 \mid e_1) & + & t(f_2 \mid e_2)) & \times \\
(t(f_3 \mid e_1) & + & t(f_3 \mid e_2)) &
\end{array}$$

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