Lecture 23: Phrase-based MT
Recap: IBM models for MT
The IBM models

Use the noisy channel (Bayes rule) to get the best (most likely) target translation \( e \) for source sentence \( f \):

\[
\arg \max_e P(e|f) = \arg \max_e P(f|e)P(e)
\]

The translation model \( P(f \mid e) \) requires alignments \( a \)

\[
P(f|e) = \sum_{a \in A(e,f)} P(f, a|e)
\]

Generate \( f \) and the alignment \( a \) with \( P(f, a \mid e) \):

\[
P(f, a|e) = \underbrace{P(m|e)}_{\text{Length: } |f|=m} \prod_{j=1}^m P(a_j|a_{1..j-1}, f_{1..j-1}, m, e) P(f_j|a_{1..j}f_{1..j-1}, e, m)
\]

\( m = \# \text{words in } f_j \)

probability of alignment \( a_j \)

probability of word \( f_j \)
Representing word alignments

<table>
<thead>
<tr>
<th>Position</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Foreign</td>
<td>Marie a traversé le lac à la nage</td>
<td></td>
<td></td>
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<tr>
<td>Alignment</td>
<td>1 3 3 4 5 0 0 2</td>
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</tr>
</tbody>
</table>

Every source word $f[i]$ is aligned to one target word $e[j]$ (incl. NULL). We represent alignments as a vector $a$ (of the same length as the source) with $a[i] = j$.
IBM model 1: Generative process

For each target sentence $e = e_1..e_n$ of length $n$:

1. Choose a **length $m$** for the source sentence (e.g. $m = 8$)

2. Choose an **alignment** $a = a_1...a_m$ for the source sentence
   
   Each $a_i$ corresponds to a word $e_i$ in $e$: $0 \leq a_i \leq n$

3. **Translate** each target word $e_{aj}$ into the source language
**Expectation-Maximization (EM)**

1. Initialize a first model, $M_0$

2. **Expectation (E) step:**
   Go through training data to gather expected counts
   $$\langle \text{count}(lac, lake) \rangle$$

3. **Maximization (M) step:**
   Use expected counts to compute a new model $M_{i+1}$
   $$P_{i+1}( lac \mid lake) = \langle \text{count}(lac, lake) \rangle / \langle \sum_w \text{count}(w, lake) \rangle$$

4. **Check for convergence:**
   Compute log-likelihood of training data with $M_{i+1}$
   If the difference between new and old log-likelihood smaller than a threshold, stop. Else go to 2.
The E-step

Compute the expected count $\langle c(f, e|f, e) \rangle$:

$$
\langle c(f, e|f, e) \rangle = \sum_{a \in A(f, e)} P(a|f, e) \cdot c(f, e|a, e, f)
$$

$$
P(a|f, e) = \frac{P(a, f|e)}{P(f|e)} = \frac{P(a, f|e)}{\sum_{a'} P(a', f|e)}
$$

$$
P(a, f|e) = \prod_{j} P(f_j|e_{a_j})
$$

$$
\langle c(f, e|f, e) \rangle = \sum_{a \in A(f, e)} \frac{\prod_{j} P(f_j|e_{a_j})}{\sum_{a'} \prod_{j} P(f_j|e_{a'_j})} \cdot c(f, e|a, e, f)
$$
Phrase-based translation models
Phrase-based translation models

Assumption: fundamental units of translation are phrases:

Phrase-based model of $P(F \mid E)$:
1. Split target sentence deterministically into phrases $ep_1...ep_n$
2. Translate each target phrase $ep_i$ into source phrase $fp_i$
   with translation probability $\varphi(fp_i \mid ep_i)$
3. Reorder foreign phrases with distortion probability
   $d(a_i-b_{i-1}) = c|a_i-b_{i-1} - 1|$

$a_i = $ start position of source phrase generated by $e_i$
$b_{i-1} = $ end position of source phrase generated by $e_{i-1}$
Phrase-based models of $P(f | e)$

Split target sentence $e = e_1..n$ into phrases $e_p_1..e_p_N$:

[The green witch] [is] [at home] [this week]

Translate each target phrase $e_p_i$ into source phrase $f_p_i$ with translation probability $P(f_p_i | e_p_i)$:

[The green witch] = [die grüne Hexe], ...

Arrange the set of source phrases $\{f_p_i\}$ to get $s$ with distortion probability $P(f_p | \{f_p_i\})$:

[Diese Woche] [ist] [die grüne Hexe] [zuhause]

$$P(f | e = \langle e_p_1, ..., e_p_l \rangle) = \prod_i P(f_p_i | e_p_i)P(f_p | \{f_p_i\})$$
Translation probability $P(fp_i \mid ep_i)$

Phrase translation probabilities can be obtained from a phrase table:

<table>
<thead>
<tr>
<th>EP</th>
<th>FP</th>
<th>count</th>
</tr>
</thead>
<tbody>
<tr>
<td>green witch</td>
<td>grüne Hexe</td>
<td>…</td>
</tr>
<tr>
<td>at home</td>
<td>zuhause</td>
<td>10534</td>
</tr>
<tr>
<td>at home</td>
<td>daheim</td>
<td>9890</td>
</tr>
<tr>
<td>is</td>
<td>ist</td>
<td>598012</td>
</tr>
<tr>
<td>this week</td>
<td>diese Woche</td>
<td>….</td>
</tr>
</tbody>
</table>

This requires phrase alignment
### Word alignment

<table>
<thead>
<tr>
<th></th>
<th>Diese</th>
<th>Woche</th>
<th>ist</th>
<th>die</th>
<th>grüne</th>
<th>Hexe</th>
<th>zuhause</th>
</tr>
</thead>
<tbody>
<tr>
<td>The</td>
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</tbody>
</table>

The green witch is at home this week.
### Phrase alignment

<table>
<thead>
<tr>
<th></th>
<th>Diese</th>
<th>Woche</th>
<th>ist</th>
<th>die</th>
<th>grüne</th>
<th>Hexe</th>
<th>zuhause</th>
</tr>
</thead>
<tbody>
<tr>
<td>The</td>
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<td>witch</td>
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</table>
Obtaining phrase alignments

We’ll skip over details, but here’s the basic idea:

For a given parallel corpus (F-E)
1. Train two word aligners, \((F \rightarrow E \text{ and } E \rightarrow F)\)
2. Take the intersection of these alignments to get a high-precision word alignment
3. Grow these high-precision alignments until all words in both sentences are included in the alignment.
   Consider any pair of words in the union of the alignments, and incrementally add them to the existing alignments
4. Consider all phrases that are consistent with this improved word alignment
Decoding
(for phrase-based MT)
Phrase-based models of $P(f | e)$

Split target sentence $e = e_1..n$ into phrases $e_p_1..e_p_N$:

[The green witch] [is] [at home] [this week]

Translate each target phrase $e_p_i$ into source phrase $f_p_i$ with translation probability $P(f_p_i | e_p_i)$:

[The green witch] = [die grüne Hexe], ...  

Arrange the set of source phrases $\{f_p_i\}$ to get $s$ with distortion probability $P(f | \{f_p\})$:

[Diese Woche] [ist] [die grüne Hexe] [zuhause]

$$P(f | e = \langle e_p_1, ..., e_p_l \rangle) = \prod_i P(f_p_i | e_p_i) P(f_p | \{f_p_i\})$$
Translating

How do we translate a foreign sentence (e.g. “Diese Woche ist die grüne Hexe zuhause”) into English?

- We need to find $\hat{e} = \text{argmax}_e P(f \mid e)P(e)$
- There is an exponential number of candidate translations $e$
- But we can look up phrase translations $ep$ and $P(fp \mid ep)$ in the phrase table:

<table>
<thead>
<tr>
<th>diese</th>
<th>Woche</th>
<th>ist</th>
<th>die</th>
<th>grüne</th>
<th>Hexe</th>
<th>zuhause</th>
</tr>
</thead>
<tbody>
<tr>
<td>this 0.2</td>
<td>week 0.7</td>
<td>is 0.8</td>
<td>the 0.3</td>
<td>green 0.3</td>
<td>witch 0.5</td>
<td>home 1.00</td>
</tr>
<tr>
<td>these 0.5</td>
<td></td>
<td></td>
<td></td>
<td>the green 0.4</td>
<td>sorceress 0.6</td>
<td></td>
</tr>
<tr>
<td>this week 0.6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>green witch 0.7</td>
<td></td>
</tr>
<tr>
<td>is this week 0.4</td>
<td></td>
<td></td>
<td></td>
<td>the green witch 0.7</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Generating a (random) translation

1. Pick the first Target phrase $ep_1$ from the candidate list.
   \[ P := P_{LM}(<s> \ ep_1)P_{Trans}(fp_1 | ep_1) \]
   \[ E = \text{the}, \ F = <\ldots\text{die}\ldots> \]

2. Pick the next target phrase $ep_2$ from the candidate list
   \[ P := P \times P_{LM}(ep_2 | ep_1)P_{Trans}(fp_2 | ep_2) \]
   \[ E = \text{the green witch}, \ F = <\ldots\text{die grüne Hexe}\ldots> \]

3. Keep going: pick target phrases $ep_i$ until the entire source sentence is translated
   \[ P := P \times P_{LM}(ep_i | ep_1\ldots i-1)P_{Trans}(fp_i | ep_i) \]
   \[ E = \text{the green witch is}, \ F = <\ldots\text{ist die grüne Hexe}\ldots> \]
Finding the best translation

How can we find the best translation efficiently?
There is an exponential number of possible translations.

We will use a heuristic search algorithm
We cannot guarantee to find the best (= highest-scoring) translation, but we’re likely to get close.

We will use a “stack-based” decoder
(If you’ve taken Intro to AI: this is A* (“A-star”) search)
We will score partial translations based on how good we expect the corresponding completed translation to be.
Or, rather: we will score partial translations on how bad we expect the corresponding complete translation to be.
That is, our scores will be costs (high=bad, low=good)
Scoring partial translations

Assign expected costs to partial translations \((E, F)\):
\[
\text{expected\_cost}(E,F) = \text{current\_cost}(E,F) + \text{future\_cost}(E,F)
\]

The current cost is based on the score of the partial translation \((E, F)\)

The (estimated) future cost is an upper bound on the actual cost of completing the partial translation \((E, F)\):
\[
\text{true\_cost}(E,F) \; (= \text{current\_cost}(E,F) + \text{actual\_future\_cost}(E,F)) \leq \text{expected\_cost}(E,F) \; (= \text{current\_cost}(E,F) + \text{future\_cost}(E,F))
\]
because \text{actual\_future\_cost}(E,F) \leq \text{future\_cost}(E,F)
Stack-based decoding

Maintain a **priority queue** (=’stack’) of **partial translations**
(hypotheses) with their **expected costs**.
Each element on the stack is **open** (we haven’t yet pursued this hypothesis) or **closed** (we have already pursued this hypothesis)

At each step:
- **Expand** the best open hypothesis (the open translation with the lowest expected cost) in all possible ways.
- These new translations become **new open elements** on the stack.
- **Close** the best open hypothesis.

**Additional Pruning** (**n-best / beam search**):
Only keep the *n* best open hypotheses around
Stack-based decoding

E: current translation
F: which words in F have we covered?
E: these
F: d******
Cost:.852
...
E: the
F: ***d***
Cost:.500
...
E: at home
F: ******z
Cost:.993
Stack-based decoding

E: these
F: d******
Cost:.852

...}

E: the
F: ***d***
Cost:.500

...}

E: at home
F: ******z
Cost:.993

We’re done with this node now (all continuations have a lower cost)
Stack-based decoding

E: these
F: d******
Cost:.852

E: the
F: ***d***
Cost:.500

E: at home
F: *****z
Cost:.993

Expand one of these new yellow nodes next
Stack-based decoding

Expand the yellow node with the lowest cost
Stack-based decoding

Expand the next node with the lowest cost
Stack-based decoding

E: these
F: d******
Cost:.852

E: the
F: ***d***
Cost:.500

E: at home
F: ******z
Cost:.993

E: the witch
F: ***d*H*
Cost:.700

E: the green witch
F: ***dgH*
Cost:.560

E: the at home
F: ***d*H*
Cost:.1236
Stack-based decoding

We always expand the best (lowest-cost) node, even if it’s not the last one introduced.

Cost: .999
Cost: .852
Cost: .500
Cost: .993

Cost: .700
Cost: .560

Cost: .1236
Cost: .732
Cost: .705
Cost: .800

Cost: .1236

We always expand the best (lowest-cost) node, even if it’s not the last one introduced.
MT evaluation
Automatic evaluation: BLEU

Evaluate candidate translations against several reference translations.

C1: It is a guide to action which ensures that the military always obeys the commands of the party.
C2: It is to insure the troops forever hearing the activity guidebook that party direct
R1: It is a guide to action that ensures that the military will forever heed Party commands.
R2: It is the guiding principle which guarantees the military forces always being under the command of the Party.
R3: It is the practical guide for the army always to heed the directions of the party.

The **BLEU score** is based on **N-gram precision**:
How many n-grams in the candidate translation occur also in one of the reference translation?
BLEU details

For \( n \in \{1, \ldots, 4\} \), compute the (modified) precision of all \( n \)-grams:

\[
Prec_n = \frac{\sum_{c \in C} \sum_{n\text{-gram} \in c} \text{MaxFreq}_{\text{ref}}(n\text{-gram})}{\sum_{c \in C} \sum_{n\text{-gram} \in c} \text{Freq}_c(n\text{-gram})}
\]

MaxFreq\(_{\text{ref}}\)(‘the party’) = max. count of ‘the party’ in one reference translation.
Freq\(_c\)(‘the party’) = count of ‘the party’ in candidate translation \( c \).

Penalize short candidate translations by a brevity penalty \( BP \)

c = length (number of words) of the whole candidate translation corpus
r = Pick for each candidate the reference translation that is closest in length; sum up these lengths.

Brevity penalty \( BP = \exp(1-c/r) \) for \( c \leq r \); \( BP = 1 \) for \( c > r \)
(BP ranges from \( e \) for \( c=0 \) to 1 for \( c=r \))
BLEU score

The BLEU score is the geometric mean of the precision of the unigrams, bigrams, trigrams, quadrigrams, weighted by the brevity penalty BP.

\[
\text{BLEU} = BP \times \exp \left( \frac{1}{N} \sum_{n=1}^{N} \log \text{Prec}_n \right)
\]
Human evaluation

We want to know whether the translation is “good” English, and whether it is an accurate translation of the original.

- Ask human raters to judge the fluency and the adequacy of the translation (e.g. on a scale of 1 to 5)
- Correlated with fluency is accuracy on cloze task: Give rater the sentence with one word replaced by blank. Ask rater to guess the missing word in the blank.
- Similar to adequacy is informativeness
  Can you use the translation to perform some task (e.g. answer multiple-choice questions about the text)
Summary:
Machine Translation
Machine translation models

Current MT models all rely on statistics.

Many current models do estimate $P(E \mid F)$ directly, but may use features based on language models (capturing $P(E)$) and IBM-style translation models ($P(F \mid E)$) internally.

There are a number of syntax-based models, e.g. using synchronous context-free grammars, which consist of pairs of rules for the two languages in which each RHS NT in language A corresponds to a RHS NT in language B:

Language A: $XP \rightarrow YP \ ZP$  
Language B: $XP \rightarrow ZP \ YP$
More recent developments

Neural network-based approaches:

  Recurrent neural networks (RNN) can model sequences (e.g. strings, sentences, etc.)
  Use one RNN (the encoder) to process the input in the source language
  Pass its output to another RNN (the decoder) to generate the output in the target language

See e.g. [http://www.tensorflow.org/tutorials/seq2seq/index.md#sequence-to-sequence_basics](http://www.tensorflow.org/tutorials/seq2seq/index.md#sequence-to-sequence_basics)