statistical machine translation
Today

• Overview of IBM-2, IBM-3, and phrase-based methods.
• Decoding for SMT.
• Evaluation of MT systems.
Practical note on programming IBM-1

- If you were to code the EM algorithm for IBM-1, you would **not** initialize $P(f | e)$ uniformly over the entire vocabulary.
  - Don’t make a $V_F \times V_E$ table with $P(f | e) = 1/\|V_E\|$.
  - This structure would be too large.
    - Probabilities would be too small.
    - It would take too much work to update.

- Rather, initialize a hash table over possible alignments, $\mathcal{M}$. For every English $e$, only consider French words $f$ in sentences **aligned** with English sentences containing $e$.
  - e.g., structure $P(e. f := P(f | e) = 1/\|\mathcal{M}\|$
Higher IBM models

<table>
<thead>
<tr>
<th>IBM Model</th>
<th>Feature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model 1</td>
<td>lexical translation</td>
</tr>
<tr>
<td>Model 2</td>
<td>adds absolute re-ordering model</td>
</tr>
<tr>
<td>Model 3</td>
<td>adds fertility model</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>

- Only IBM Model 1 training reaches a *global maximum*
- Training of each IBM model extends the **next lowest** model.

- **Higher models** become computationally expensive.
IBM-2

• **Unlike** IBM Model-1, the placement of a word in French depends on where its **equivalent** word was in English.
• IBM-2 captures the intuition that translations should lie roughly “along the diagonal”.

<table>
<thead>
<tr>
<th></th>
<th>Buenos</th>
<th>dias</th>
<th>,</th>
<th>me</th>
<th>gusta</th>
<th>papas</th>
<th>frías</th>
</tr>
</thead>
<tbody>
<tr>
<td>Good</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>day</td>
<td></td>
<td>X</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>,</td>
<td></td>
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</tr>
<tr>
<td>I</td>
<td></td>
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<td>X</td>
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<tr>
<td>like</td>
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<td>X</td>
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<td>cold</td>
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<td></td>
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<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>potatoes</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>X</td>
</tr>
</tbody>
</table>
IBM-2

- IBM Model 2 builds on Model 1 by adding a re-ordering model defined by distortion parameters regardless of actual words.

\[
D(e_i|f_j, \mathcal{L}_E, \mathcal{L}_F) = \text{the probability that the } i^{th} \text{ English word is aligned to the } j^{th} \text{ French word, given sentence lengths } \mathcal{L}_E \text{ and } \mathcal{L}_F.
\]

- In IBM Model 2:

\[
P(a|E, \mathcal{L}_E, \mathcal{L}_F) = \prod_{j=1}^{\mathcal{L}_F} D(a_j|f_j, \mathcal{L}_E, \mathcal{L}_F)
\]

- Recall that in IBM Model 1,

\[
P(a|E, \mathcal{L}_E, \mathcal{L}_F) = \frac{P(\mathcal{L}_F)}{(\mathcal{L}_E + 1)^{\mathcal{L}_F}}
\]
IBM-2 – Probability of alignment

• $E = \text{And the program has been implemented}$
• $F = \text{Le programme a été mis en application}$
• $\mathcal{L}_E = 6$
• $\mathcal{L}_F = 7$
• $\alpha = \{2, 3, 4, 5, 6, 6, 6\}$ (i.e., $F_1 \leftarrow E_2, F_2 \leftarrow E_3, \ldots$)

$$P(\alpha|E, \mathcal{L}_E, \mathcal{L}_F) = D(2|1, 6, 7) \times D(3|2, 6, 7) \times D(4|3, 6, 7) \times D(5|4, 6, 7) \times D(6|5, 6, 7) \times D(6|6, 6, 7) \times D(6|7, 6, 7)$$
IBM-2: generation

- To **generate** a French sentence $F$ from English $E$:
  1. **Pick an alignment** with probability
     \[
     \prod_{j=1}^{L_F} D(a_j | j, \mathcal{L}_E, \mathcal{L}_F)
     \]
  3. **Sample** French words with probability
     \[
     P(F | a, E) = \prod_{j=1}^{L_F} P(f_j | e_{a_j})
     \]

So,
\[
P(F, a | E) = P(a | E)P(F | a, E) = \prod_{j=1}^{L_F} D(a_j | j, \mathcal{L}_E, \mathcal{L}_F) P(f_j | e_{a_j})
\]

This is the same $P(f | e)$ as in IBM-1.
IBM-2: training

• We use EM, as before with IBM-1 except that we need to take the distortion into account when computing the probability of an alignment.

• We also need to learn the distortion function.
IBM-3

- **IBM Model 3** extends Model 2 by adding a **fertility model** that describes how many French words each English word can produce.
  - In the example below, *implemented* appears to be **more fertile** than *program*. 

```
\[ e_0 \quad e_1 \quad e_2 \quad e_3 \quad e_4 \quad e_5 \quad e_6 \]
\[ \emptyset \quad \text{Canada} \quad \text{‘s} \quad \text{program} \quad \text{has} \quad \text{been} \quad \text{implemented} \]
```

```
\[ f_1 \quad f_2 \quad f_3 \quad f_4 \quad f_5 \quad f_6 \quad f_7 \quad f_8 \quad f_9 \]
\[ \text{Le} \quad \text{programme} \quad \text{du} \quad \text{Canada} \quad \text{a} \quad \text{été} \quad \text{mis} \quad \text{en} \quad \text{application} \]
```
IBM-3: The generation model

- First, we replicate each word according to a new hidden parameter, $N(n|e)$, which is the probability that word $e$ produces $n$ words.
- We then translate and re-order (with distortion) as we did in IBM-2.
## IBM models

<table>
<thead>
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</tr>
<tr>
<td>IBM Model 3</td>
<td>adds <strong>fertility model</strong></td>
</tr>
</tbody>
</table>
No more words

I want to see phrases
Phrase-based statistical MT

• **Phrase-based** statistical MT involves segmenting sentences into contiguous blocks or segments.
  • Each phrase is probabilistically **translated**.
    e.g., \( P(\text{zu Hausse} | \text{at home}) \)
  • Each phrase is probabilistically **re-ordered**.

```
The green witch is at home this week
```
```
Diese Woche ist die grüne Hexe zu Hausse
```
Phrase-based statistical MT

• Phrase-based SMT allows **many-to-many** word mappings.

• Larger context allows for some disambiguation that is not possible in word-based alignment.
  • E.g.,
    \[
    P(\text{intérêt} | \text{interest}) \\
    \text{vs.} \\
    P(\text{taux d’intérêt} | \text{interest rate}) > P(\text{taux d’intérêt} | \text{interest in})
    \]
Learning phrase-translations

• Typically, we use **alignment templates** (Och et al., 1999).
• Start with a **word-alignment**, then build **phrases**.

```
<table>
<thead>
<tr>
<th>Maria</th>
<th>no</th>
<th>dió</th>
<th>una</th>
<th>bofetada</th>
<th>a</th>
<th>la</th>
<th>bruja</th>
<th>verde</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mary</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>did</td>
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<td>not</td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>slap</td>
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<tr>
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<td></td>
<td></td>
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<tr>
<td>green</td>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>witch</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
```

This **word-alignment** is produced by a model like IBM-3
Learning phrase-translations

• A phrase alignment **must** contain **all** word alignments for each of its rows and columns.

• Collect **all** phrase alignments that are **consistent** with the **word alignment**, e.g.

```
<table>
<thead>
<tr>
<th>Maria</th>
<th>no</th>
<th>dió</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mary</td>
<td></td>
<td></td>
</tr>
<tr>
<td>did</td>
<td></td>
<td></td>
</tr>
<tr>
<td>not</td>
<td></td>
<td></td>
</tr>
<tr>
<td>slap</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
```

Consistent  Inconsistent  Inconsistent
Learning phrase-translations

- Given word-alignments (produced automatically or otherwise), we do not need to do EM training. E.g.,

\[ P(f_1 f_2 | e_1 e_2 e_3) = \frac{\text{Count}(f_1 f_2, e_1 e_2 e_3)}{\text{Count}(e_1 e_2 e_3)} \]
Phrase-based translation in practice

Google translate

What is the legal drinking age in Quebec?

Quel est l’âge légal pour boire au Québec?
No more models

I want to see decoding
Decoding

- **Decoding** is the act of translating a ‘foreign’ language into your native language.
  - Decoding is an NP-complete problem (Knight, 1999).

- IBM Models often decoded with *stack decoding* or *A* search.

  - Introduces **greedy decoding** – start with a solution and incrementally try to **improve** it.
First stage of greedy method

• For each French word $f_j$, pick the English word $e^*$ such that

$$e^* = \arg\max_{e} P(f_j|e)$$

• This gives an initial alignment, e.g.,

<table>
<thead>
<tr>
<th>Bien</th>
<th>intendu</th>
<th>,</th>
<th>il</th>
<th>parole</th>
<th>d’</th>
<th>une</th>
<th>belle</th>
<th>victoire</th>
</tr>
</thead>
<tbody>
<tr>
<td>Well</td>
<td>heard</td>
<td>,</td>
<td>it</td>
<td>talking</td>
<td>Ø</td>
<td>a</td>
<td>beautiful</td>
<td>victory</td>
</tr>
</tbody>
</table>

(Better: quite naturally, he talks about a great victory)
Some transformations

• **Change**(\(j, e\)): sets translation of \(f_j\) to \(e\)
  • Usually we only consider English words \(e\) that are in the top \(N\) ranked translations for \(f_j\).

• **Change2**(\(j_1, e_1, j_2, e_2\)): sets translation of \(f_{j_1}\) to \(e_1\) and translation of \(f_{j_2}\) to \(e_2\)
  • Like performing **two** **Change** transformations in sequence, but **without** evaluating the intermediate string.

• **ChangeAndInsert**(\(j, e_1, e_2\)): sets translation of \(f_j\) to \(e_1\) and inserts \(e_2\) at its most likely position.
Transformation functions

- **RemoveInfertile(\(i\))**: Removes \(e_i\) if \(e_i\) is aligned with no French words.

- **SwapSeg(\(i_1, i_2, j_1, j_2\))**: Swaps segment \(e_{i_1:i_2}\) with segment \(e_{j_1:j_2}\) such that segments do not overlap.

- **JoinWords(\(i_1, i_2\))**: Removes \(e_{i_1}\) and aligns all French words that were aligned to \(e_{i_1}\) to \(e_{i_2}\).
Greedy transformations

• We have an initial pair \((E^{(0)}, a^{(0)})\).

• Use local transformations to map \((E, a)\) to new pairs, \((E', a')\).

• At each iteration, \(k\), take the highest probability pair from all possible transformations

  • i.e., if \(\mathcal{R}(E^{(k)}, a^{(k)})\) is the set of all \((E, a)\) ‘reachable’ from \((E^{(k)}, a^{(k)})\), then at each iteration:

\[
(E^{(k+1)}, a^{(k+1)}) = \arg\max_{(E,a) \in \mathcal{R}(E^{(k)}, a^{(k)})} P(E)P(F, a | E)
\]
Example of greedy search

Bien   intendu ,  il  parle  d’  une  belle  victoire
Well   heard ,  it  **talking**  ∅  a  **beautiful**  victory

```
Change2(5, talks, 8, great)
```

<table>
<thead>
<tr>
<th>Bien</th>
<th>intendu</th>
<th>,</th>
<th>il</th>
<th>parle</th>
<th>d’</th>
<th>une</th>
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<td>Well</td>
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<td>,</td>
<td>it</td>
<td><strong>talking</strong></td>
<td>∅</td>
<td>a</td>
<td><strong>beautiful</strong></td>
<td>victory</td>
</tr>
</tbody>
</table>
Example of greedy search

Bien  entendu, il parle d'une belle victoire
Well  heard, it talks a great victory

Change2(2, understood, 6, about)

Bien  entendu, il parle d'une belle victoire
Well  understood, it talks about a great victory
Example of greedy search

<table>
<thead>
<tr>
<th>Bien</th>
<th>intendu</th>
<th>,</th>
<th>il</th>
<th>parole</th>
<th>d’</th>
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<th>victoire</th>
</tr>
</thead>
<tbody>
<tr>
<td>Well</td>
<td>understood</td>
<td>,</td>
<td>it</td>
<td>talks</td>
<td>about</td>
<td>a</td>
<td>great</td>
<td>victory</td>
</tr>
</tbody>
</table>

Change(4, he)

<table>
<thead>
<tr>
<th>Bien</th>
<th>intendu</th>
<th>,</th>
<th>il</th>
<th>parole</th>
<th>d’</th>
<th>une</th>
<th>belle</th>
<th>victoire</th>
</tr>
</thead>
<tbody>
<tr>
<td>Well</td>
<td>understood</td>
<td>,</td>
<td>he</td>
<td>talks</td>
<td>about</td>
<td>a</td>
<td>great</td>
<td>victory</td>
</tr>
</tbody>
</table>
**Example of greedy search**

<table>
<thead>
<tr>
<th>Bien</th>
<th>intendu</th>
<th>,</th>
<th><em>il</em></th>
<th>parole</th>
<th>d’</th>
<th>une</th>
<th>belle</th>
<th>victoire</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Well</em></td>
<td><em>understood</em></td>
<td>,</td>
<td><em>he</em></td>
<td><em>talks</em></td>
<td><em>about</em></td>
<td>a</td>
<td><em>great</em></td>
<td><em>victory</em></td>
</tr>
</tbody>
</table>

*Change 2*(1, *quite*, 2, *naturally*)

<table>
<thead>
<tr>
<th>Bien</th>
<th>intendu</th>
<th>,</th>
<th><em>il</em></th>
<th>parole</th>
<th>d’</th>
<th>une</th>
<th>belle</th>
<th>victoire</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Quite</em></td>
<td><em>naturally</em></td>
<td>,</td>
<td><em>he</em></td>
<td><em>talks</em></td>
<td><em>about</em></td>
<td>a</td>
<td><em>great</em></td>
<td><em>victory</em></td>
</tr>
</tbody>
</table>
Greedy transformations

• At each iteration, we try *each possible* transformation.

• For each possible transformation, we evaluate

\[ P(E)P(F, a | E') \]

• We choose the transformation that gives the highest probability.
No more decoding

I want to see evaluation
### Evaluation of MT systems

<table>
<thead>
<tr>
<th>Human</th>
<th>According to the data provided today by the Ministry of Foreign Trade and Economic Cooperation, as of November this year, China has actually utilized 46.959B US dollars of foreign capital, including 40.007B US dollars of direct investment from foreign businessmen.</th>
</tr>
</thead>
<tbody>
<tr>
<td>IBM4</td>
<td>The Ministry of Foreign Trade and Economic Cooperation, including foreign direct investment 40.007B US dollars today provide data include that year to November China actually using foreign 46.959B US dollars and</td>
</tr>
<tr>
<td>Yamada/Knight</td>
<td>Today’s available data of the Ministry of Foreign Trade and Economic Cooperation shows that China’s actual utilization of November this year will include 40.007B US dollars for the foreign direct investment among 46.959B US dollars in foreign capital.</td>
</tr>
</tbody>
</table>

How can we objectively compare the quality of two translations?
Automatic evaluation

• We want an automatic and effective method to objectively rank competing translations.
  • **Word Error Rate (WER)** measures the number of erroneous word insertions, deletions, substitutions in a translation.
  • E.g., Reference: *how to recognize speech*
    Translation: *how understand a speech*

• **Problem**: There are many possible valid translations.
  (There’s no need for an exact match)
Challenges of evaluation

• **Human judges:** expensive, slow, non-reproducible (different judges – different biases).

• **Multiple valid translations,** e.g.:
  
  • **Source:** *Il s’agit d’un guide qui assure que l’armée sera toujours fidèle au Parti*
  
  • **T1:** *It is a guide to action that ensures that the military will forever heed Party commands*
  
  • **T2:** *It is the guiding principle which guarantees the military forces always being under command of the Party*
BLEU evaluation

- **BLEU (BiLingual Evaluation Understudy)** is an automatic and popular method for evaluating MT.
  - It uses *multiple* human reference translations, and looks for local matches, allowing for phrase movement.

- **Candidate**: *n.* a translation produced by a machine.

- There are a few parts to a **BLEU score**...
Example of BLEU evaluation

• **Reference 1**: It is a guide to action that ensures that the military will forever heed Party commands
• **Reference 2**: It is the guiding principle which guarantees the military forces always being under command of the Party
• **Reference 3**: It is the practical guide for the army always to heed the directions of the party

• **Candidate 1**: It is a guide to action which ensures that the military always obeys the commands of the party
• **Candidate 2**: It is to insure the troops forever hearing the activity guidebook that party direct
BLEU: Unigram precision

• The **unigram precision** of a candidate is
  \[ \frac{C}{N} \]
  where \( N \) is the number of words in the **candidate** and \( C \) is the number of words in the **candidate** which are in **at least one reference**.

• e.g., **Candidate 1**: *It is a guide to action which ensures that the military always obeys the commands of the party*
  • **Unigram precision** = \( \frac{17}{18} \)
    *(obeys appears in none of the three references)*.
BLEU: Modified unigram precision

- **Reference 1**: *The lunatic is on the grass*
- **Reference 2**: *There is a lunatic upon the grass*
- **Candidate**: *The the the the the the the the*
  - Unigram precision $= \frac{7}{7} = 1$

- **Capped unigram precision**:
  A candidate word type $w$ can only be correct a **maximum** of $\text{cap}(w)$ times.
  - e.g., with $\text{cap}(\text{the}) = 2$, the above gives $p_1 = \frac{2}{7}$
BLEU: Generalizing to $N$-grams

• Generalizes to higher-order $N$-grams.

• **Reference 1:** *It is a guide to action that ensures that the military will forever heed Party commands*

• **Reference 2:** *It is the guiding principle which guarantees the military forces always being under command of the Party*

• **Reference 3:** *It is the practical guide for the army always to heed the directions of the party*

• **Candidate 1:** *It is a guide to action which ensures that the military always obeys the commands of the party*

• **Candidate 2:** *It is to insure the troops forever hearing the activity guidebook that party direct*

Bigram precision, $p_2$

\[ p_2 = 10/17 \]

\[ p_2 = 1/13 \]
BLEU: Precision is not enough

- **Reference 1:** It is a guide to action that ensures that the military will forever heed Party commands
- **Reference 2:** It is the guiding principle which guarantees the military forces always being under command of the Party
- **Reference 3:** It is the practical guide for the army always to heed the directions of the party

- **Candidate 1:** of the

Unigram precision, $p_1 = \frac{2}{2} = 1$  
Bigram precision, $p_2 = \frac{1}{1} = 1$
BLEU: Brevity

- Solution: Penalize brevity.
- Step 1: for each candidate, find the reference most similar in length.
- Step 2: $c_i$ is the length of the $i^{th}$ candidate, and $r_i$ is the nearest length among the references,

$$brevity_i = \frac{r_i}{c_i}$$

- Step 3: the brevity penalty, $BP$, is

$$BP = \begin{cases} 1 & \text{if brevity} < 1 \\ e^{1-brevity} & \text{if brevity} \geq 1 \end{cases} \quad (r_i < c_i) \quad (r_i \geq c_i)$$

Bigger = too brief
BLEU: Final score

- On slide 39, $r_1 = 16$, $r_2 = 17$, $r_3 = 16$, and $c_1 = 18$ and $c_2 = 14$, 

  \[
  \text{brevity}_1 = \frac{17}{18} \quad \text{BP}_1 = 1 \\
  \text{brevity}_2 = \frac{16}{14} \quad \text{BP}_2 = e^{1-\left(\frac{8}{7}\right)} = 0.8669
  \]

- **Final score** of candidate $C$:

  \[
  \text{BLEU} = \text{BP}_C \times (p_1p_2 \ldots p_n)^{1/n}
  \]

  where $p_n$ is the $n$-gram precision. (You can set $n$ empirically)
Example: Final BLEU score

- Reference 1: I am afraid Dave
- Reference 2: I am scared Dave
- Reference 3: I have fear David
- Candidate: I fear David

- brevity = $\frac{4}{3} \geq 1$ so $BP = e^{1 - \left(\frac{4}{3}\right)}$

- $p_1 = \frac{1+1+1}{3} = 1$
- $p_2 = \frac{1}{2}$

- $\text{BLEU} = BP(p_1p_2)^{\frac{1}{2}} = e^{1 - \left(\frac{4}{3}\right)} \left(\frac{1}{2}\right)^{\frac{1}{2}} \approx 0.5067$

Assume $cap(\cdot) = 2$ for all $N$-grams

Also assume BLEU order $n = 2$
BLEU: summary

• BLEU is a geometric mean over $n$-gram precisions.
  • These precisions are capped to avoid strange cases.
    • E.g., the translation “the the the the” is not favoured.
  • This geometric mean is weighted so as not to favour unrealistically short translations, e.g., “the”

• Initially, evaluations showed that BLEU predicted human judgements very well, but:
  • People started optimizing MT systems to maximize BLEU. Correlations between BLEU and humans decreased.
Reading


• **Useful reading on IBM Model-1**: Section 25.5 of the 2nd edition of the Jurafsky & Martin text.
  • 1st edition available at Robarts library.

• **Other**: Manning & Schütze Sections 13.1.2 (Gale&Church), 13.1.3 (Church), 13.3
Announcements – assignment 2

• We’ve placed an alternative decoder, decode2.m, on CDF at /u/cs401/A2_SMT/code/decode2.m.
• For Task 5 you can use either decoder, or improve either, or write your own – it’s all equivalent – just be sure to say which decoder you use and submit any changes you make.
Announcements

• **Assignment 1** marks/comments will be emailed individually.

• **Not-for-marks midterm** on Monday 24 February.