Winter School

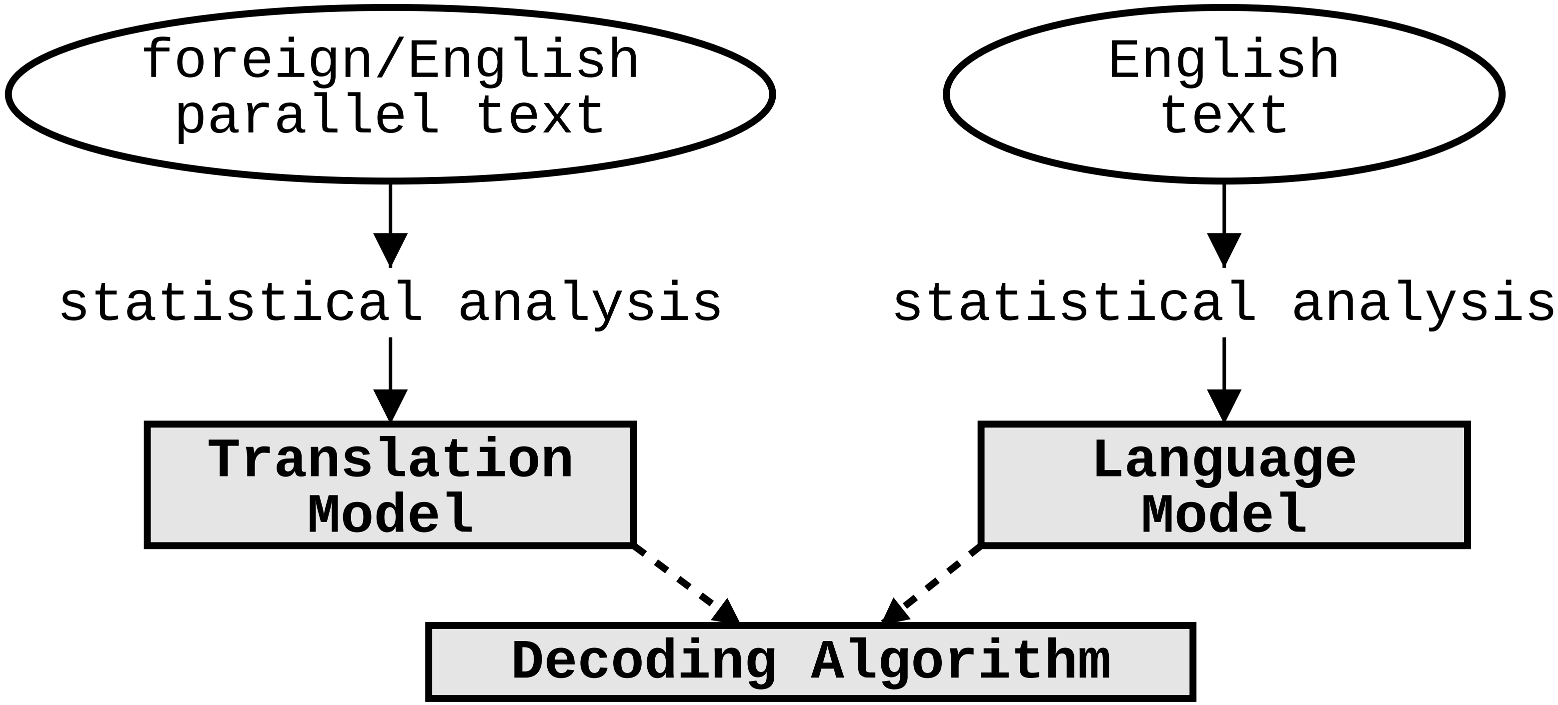
Day 3: Decoding / Phrase-based models

MT Marathon

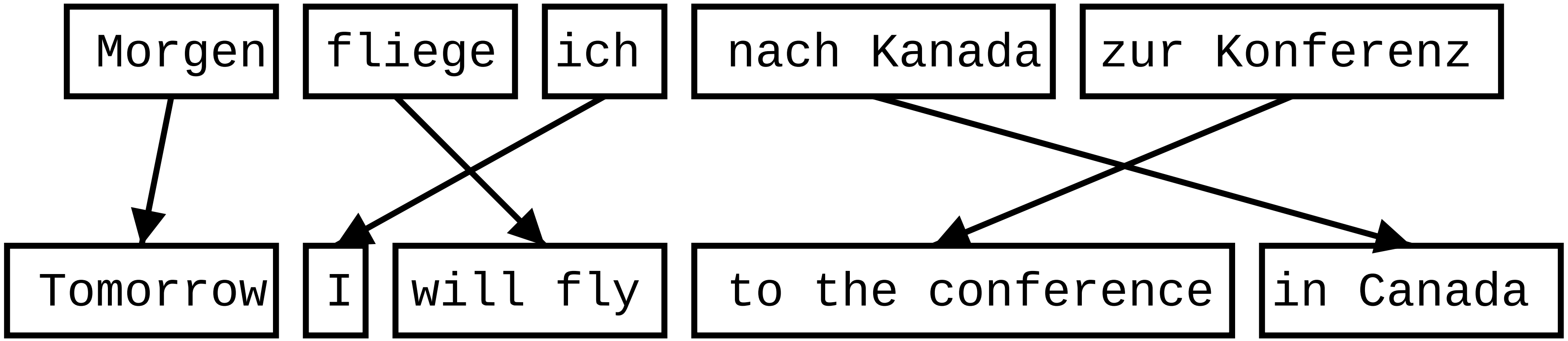
28 January 2009

Statistical Machine Translation

- Components: Translation model, language model, decoder



Phrase-Based Translation



- Foreign input is segmented in phrases
  - any sequence of words, not necessarily linguistically motivated
- Each phrase is translated into English
- Phrases are reordered

Phrase Translation Table

- Phrase Translations for "den Vorschlag":

English	$\phi(e\|f)$	English	$\phi(e\|f)$
the proposal	0.6227	the suggestions	0.0114
's proposal	0.1068	the proposed	0.0114
a proposal	0.0341	the motion	0.0091
the idea	0.0250	the idea of	0.0091
this proposal	0.0227	the proposal ,	0.0068
proposal	0.0205	its proposal	0.0068
of the proposal	0.0159	it	0.0068
the proposals	0.0159	...	...

Decoding Process

Maria	no	dio	una	bofetada	a	la	bruja	verde

- Build translation left to right
  - *select foreign* words to be translated

Decoding Process

- Build translation *left to right*
  - select foreign words to be translated
  - *find English* phrase translation
  - *add English* phrase to end of partial translation

Decoding Process

Maria	no	dio	una	bofetada	a	la	bruja	verde

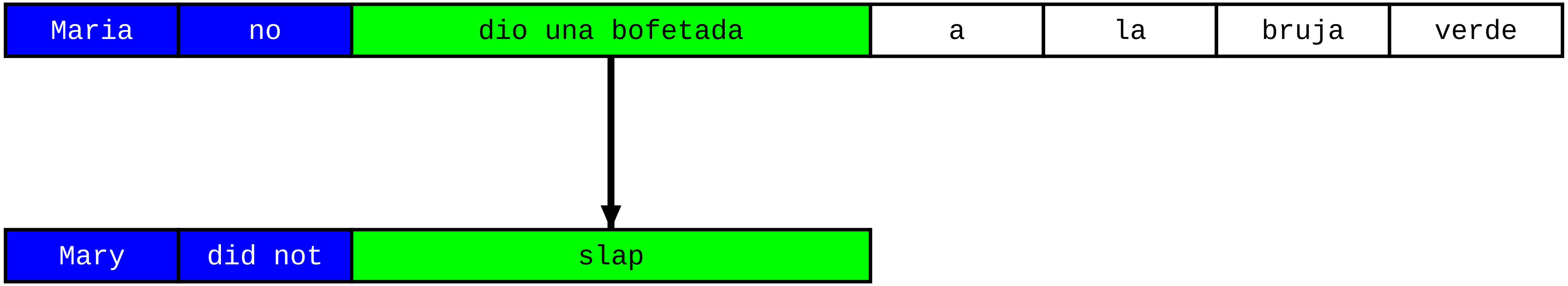
Mary

- Build translation left to right
  - select foreign words to be translated
  - find English phrase translation
  - add English phrase to end of partial translation
  - *mark foreign* words as translated

Decoding Process

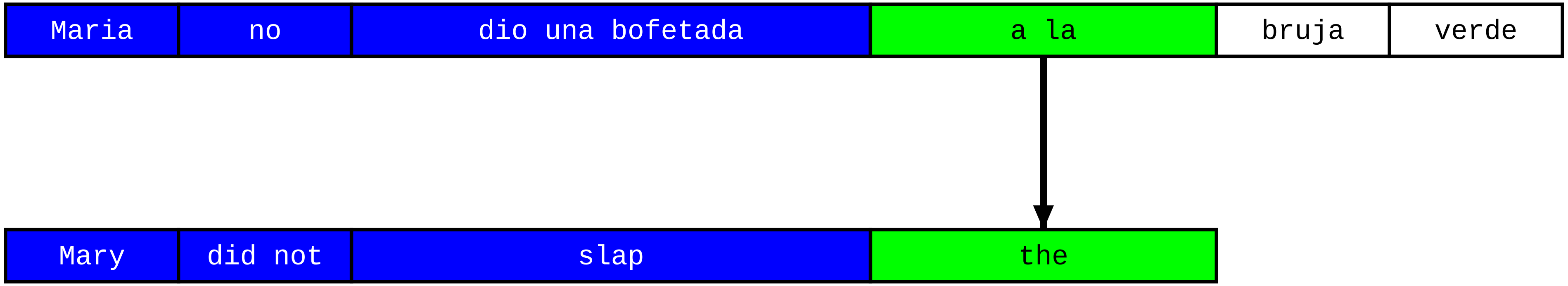
- *One to many* translation

Decoding Process



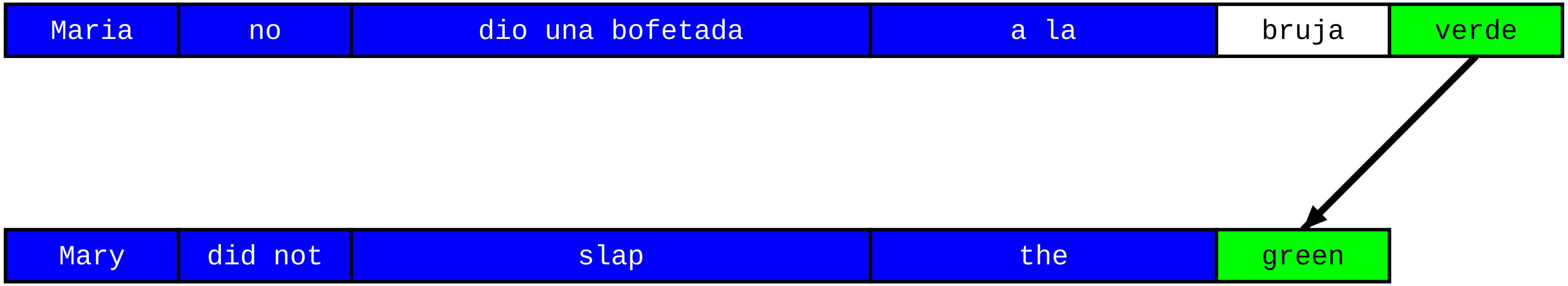
- Many to one translation

Decoding Process



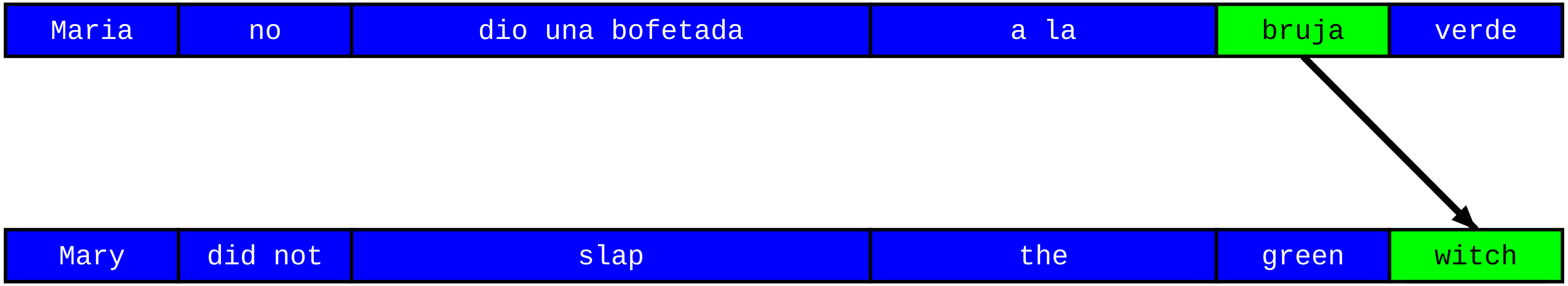
- *Many to one* translation

Decoding Process



- *Reordering*

Decoding Process



- Translation *finished*

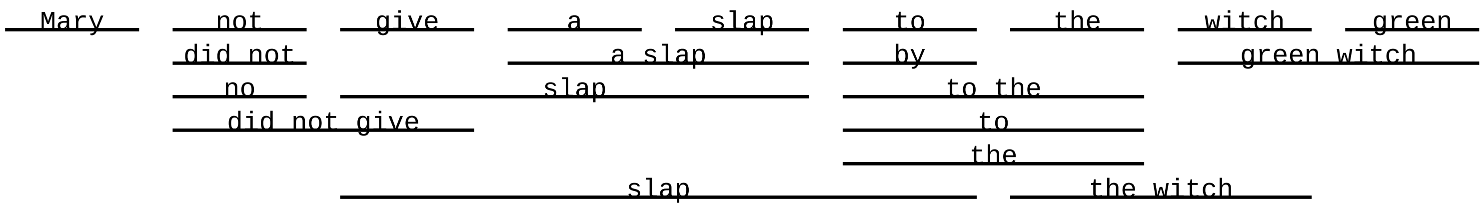
Translation Options

<table>
<tr><th>Maria</th><th>no</th><th>dio</th><th>una</th><th>bofetada</th><th>a</th><th>la</th><th>bruja</th><th>verde</th></tr>
<tr><td>Mary</td><td>not</td><td>give</td><td>a</td><td>slap</td><td>to</td><td>the</td><td>witch</td><td>green</td></tr>
<tr><td></td><td>did not</td><td></td><td colspan="2">a slap</td><td>by</td><td></td><td colspan="2">green witch</td></tr>
<tr><td></td><td>no</td><td colspan="3">slap</td><td colspan="2">to the</td><td></td><td></td></tr>
<tr><td></td><td colspan="2">did not give</td><td></td><td></td><td colspan="2">to</td><td></td><td></td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td colspan="2">the</td><td></td><td></td></tr>
<tr><td></td><td></td><td colspan="4">slap</td><td colspan="2">the witch</td><td></td></tr>
</table>

- Look up *possible phrase translations*
  - many different ways to *segment* words into phrases
  - many different ways to *translate* each phrase

Hypothesis Expansion

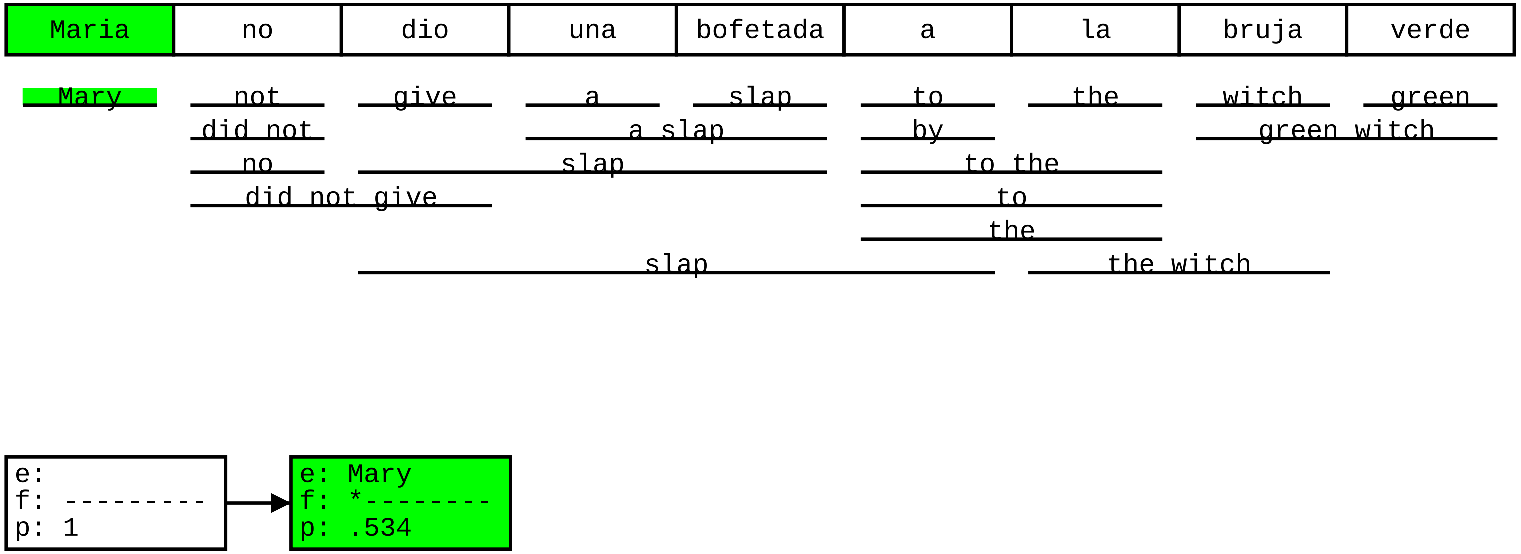
Maria	no	dio	una	bofetada	a	la	bruja	verde



e:
f: ---------
p: 1

- Start with **empty hypothesis**
  - e: no English words
  - f: no foreign words covered
  - p: probability 1

Hypothesis Expansion

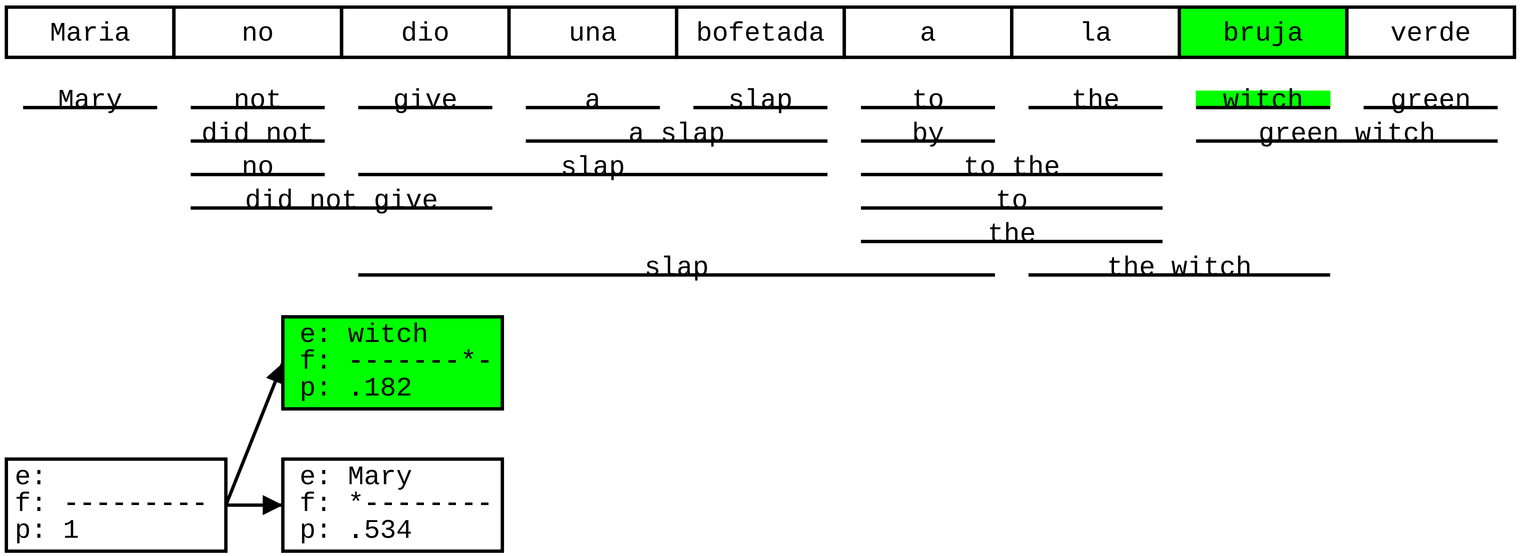


- Pick *translation option*
- Create *hypothesis*
  - e: add English phrase `Mary`
  - f: first foreign word covered
  - p: probability 0.534

A Quick Word on Probabilities

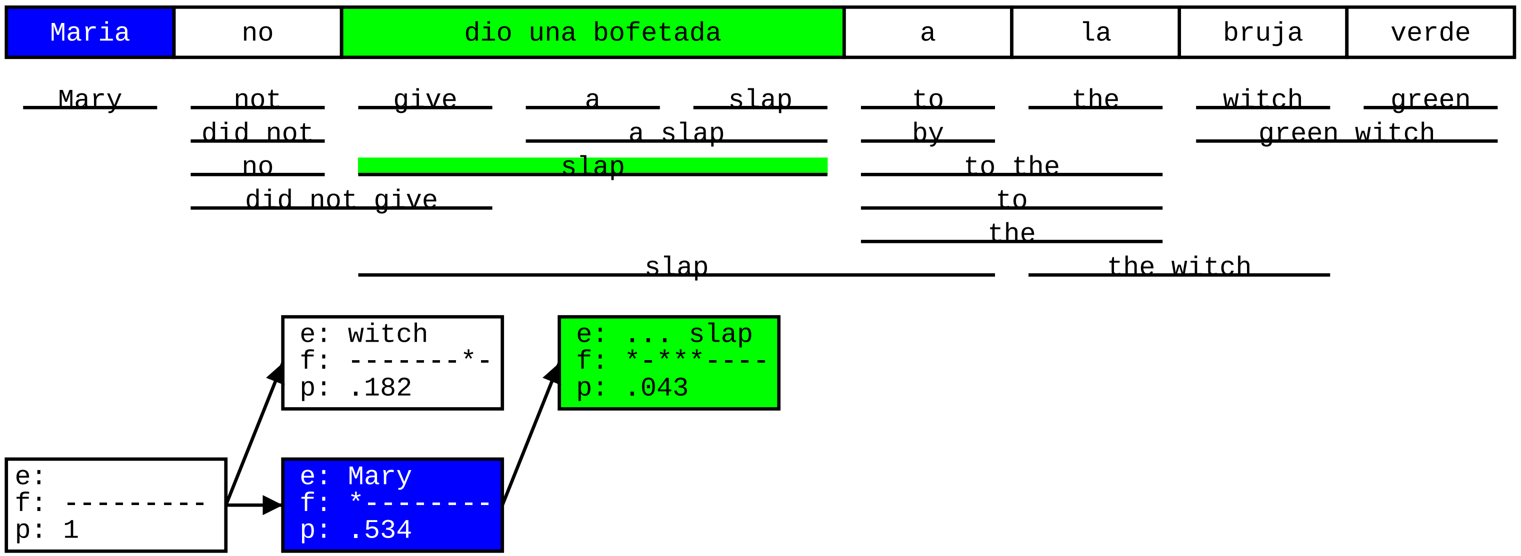
- Not going into detail here, but...
- *Translation Model*
  - phrase translation probability p(Mary|Maria)
  - reordering costs
  - phrase/word count costs
  - ...
- *Language Model*
  - uses trigrams:
  - p(Mary did not) $=$
    p(Mary|START) $\times p$(did|Mary,START) $\times$ p(not|Mary did)

Hypothesis Expansion



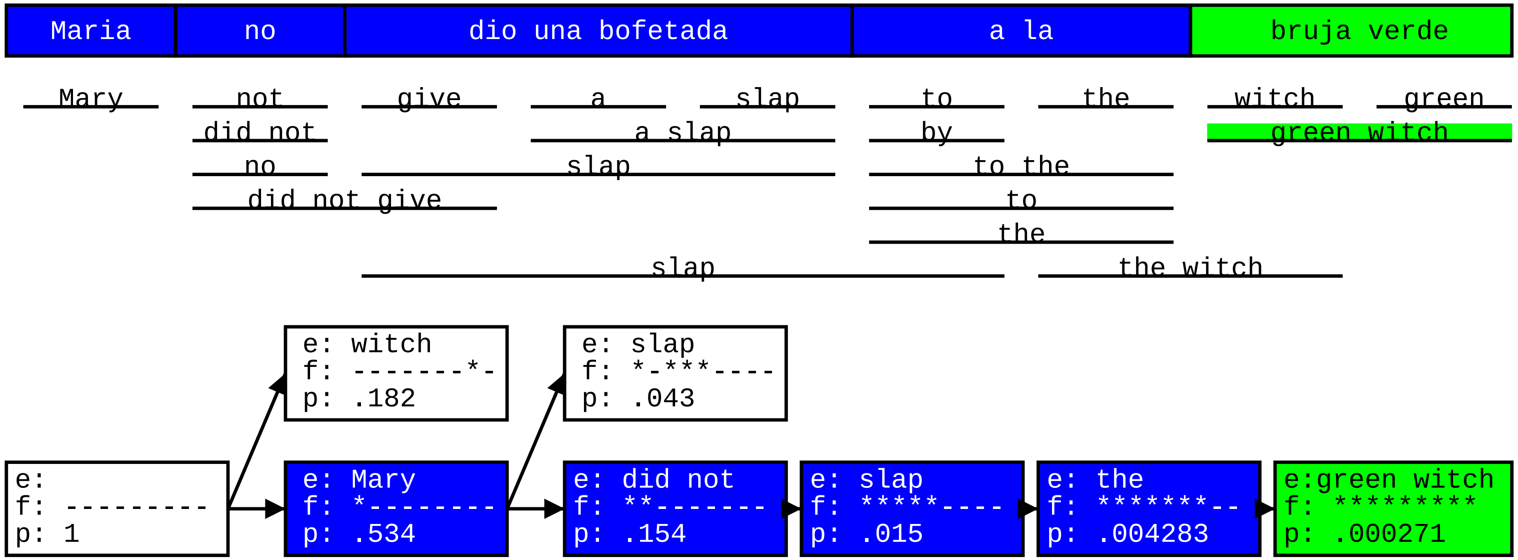
- Add another *hypothesis*

Hypothesis Expansion



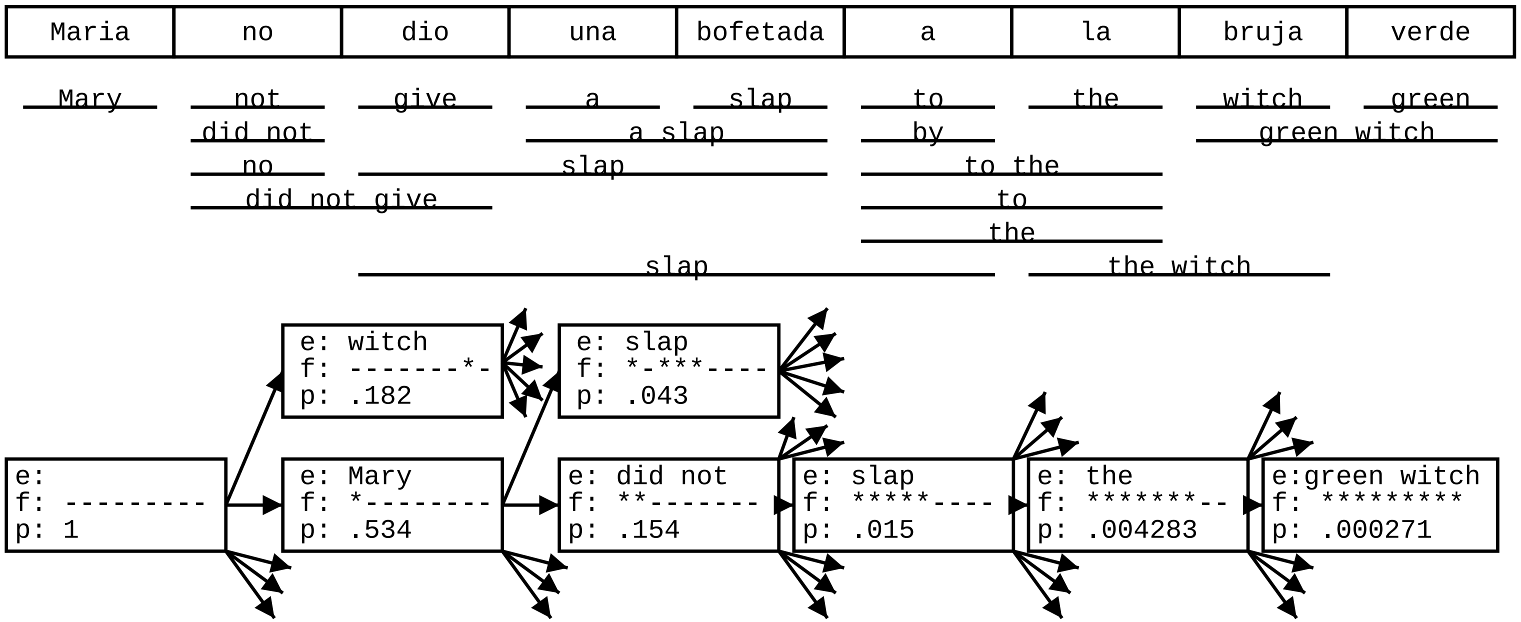
- Further *hypothesis expansion*

Hypothesis Expansion



- ... until all foreign words *covered*
  - find *best hypothesis* that covers all foreign words
  - *backtrack* to read off translation

Hypothesis Expansion



- Adding more hypothesis

⇒ *Explosion* of search space

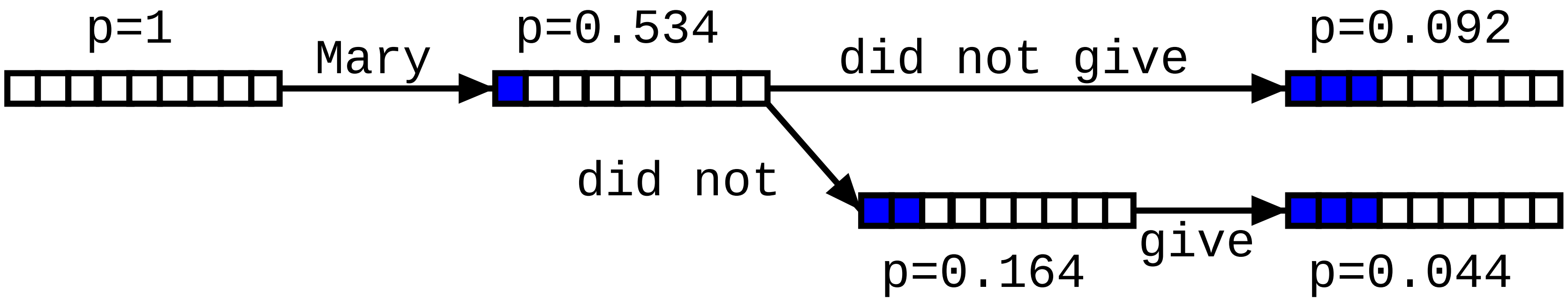
Explosion of Search Space

- Number of hypotheses is *exponential* with respect to sentence length

⇒ Decoding is NP-complete [Knight, 1999]

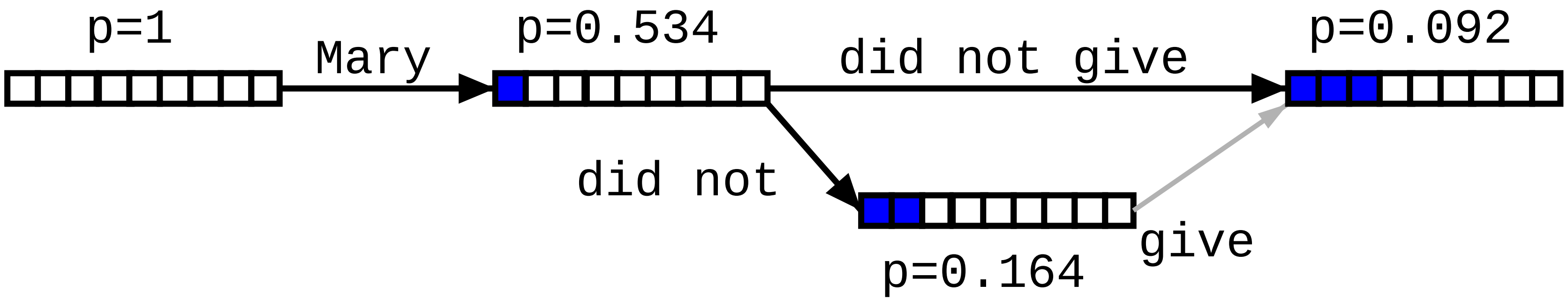
⇒ Need to *reduce search space*
  - risk free: hypothesis **recombination**
  - risky: **histogram/threshold pruning**

Hypothesis Recombination



- Different paths to the *same* partial translation

Hypothesis Recombination

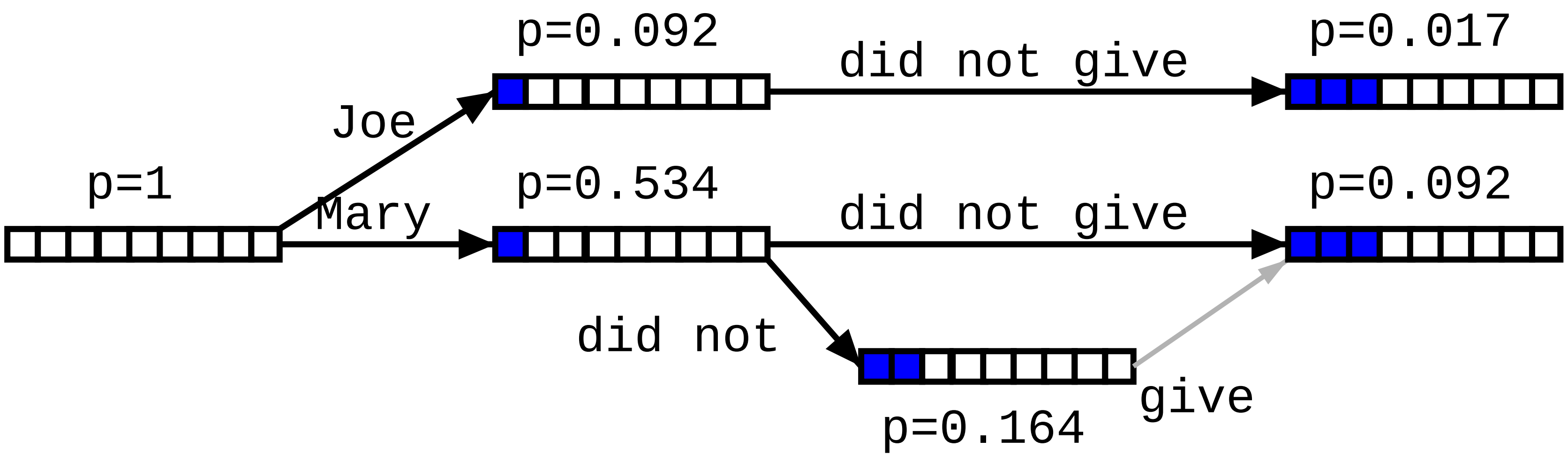


- Different paths to the same partial translation

⇒ *Combine paths*

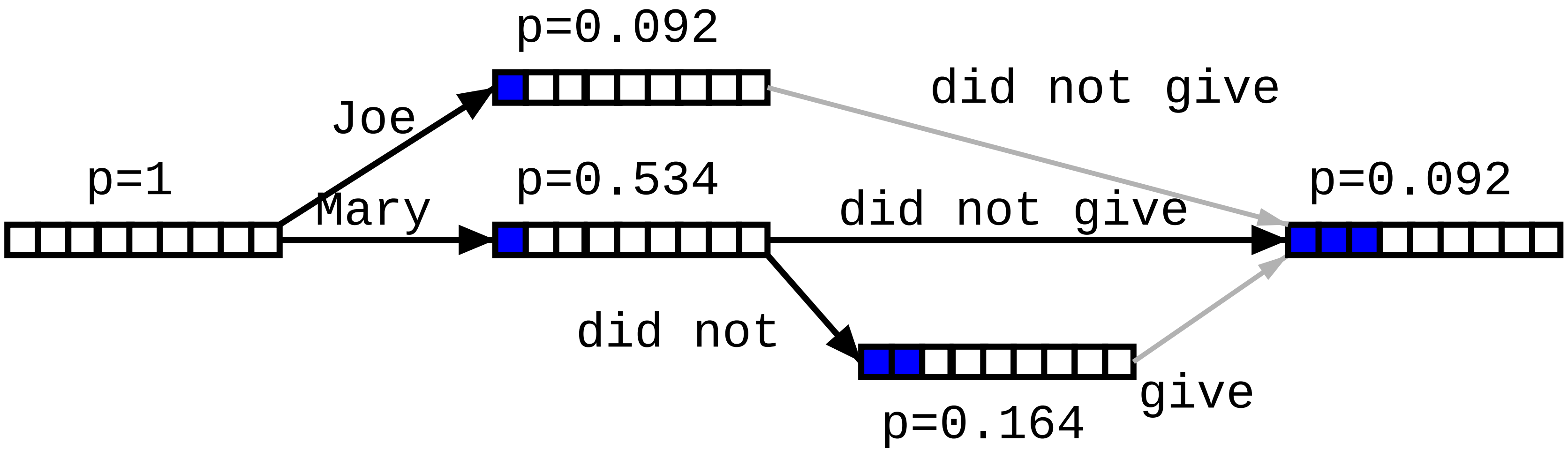
  - *drop weaker* path
  - keep pointer from weaker path (for lattice generation)

Hypothesis Recombination



- Recombined hypotheses do *not* have to *match completely*
- No matter what is added, weaker path can be dropped, if:
  - *last two English words* match (matters for language model)
  - *foreign word coverage* vectors match (effects future path)

Hypothesis Recombination



- Recombined hypotheses do not have to match completely
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⇒ *Combine paths*

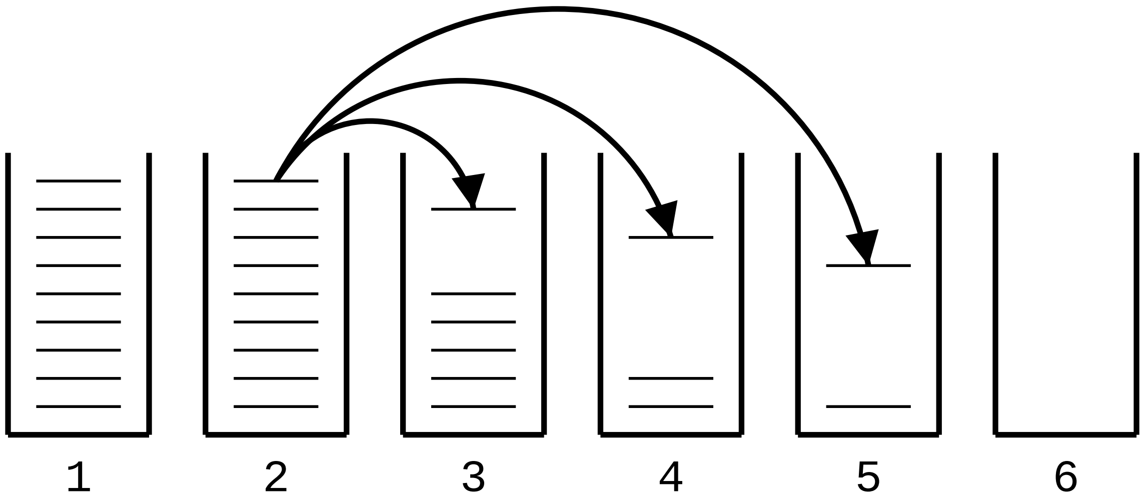
Pruning

- Hypothesis recombination is *not sufficient*

⇒ Heuristically *discard* weak hypotheses early

- Organize Hypothesis in **stacks**, e.g. by
  - *same* foreign words covered
  - *same number* of foreign words covered
- Compare hypotheses in stacks, discard bad ones
  - **histogram pruning**: keep top n hypotheses in each stack (e.g., n=100)
  - **threshold pruning**: keep hypotheses that are at most α times the cost of best hypothesis in stack (e.g., $\alpha = 0.001$)

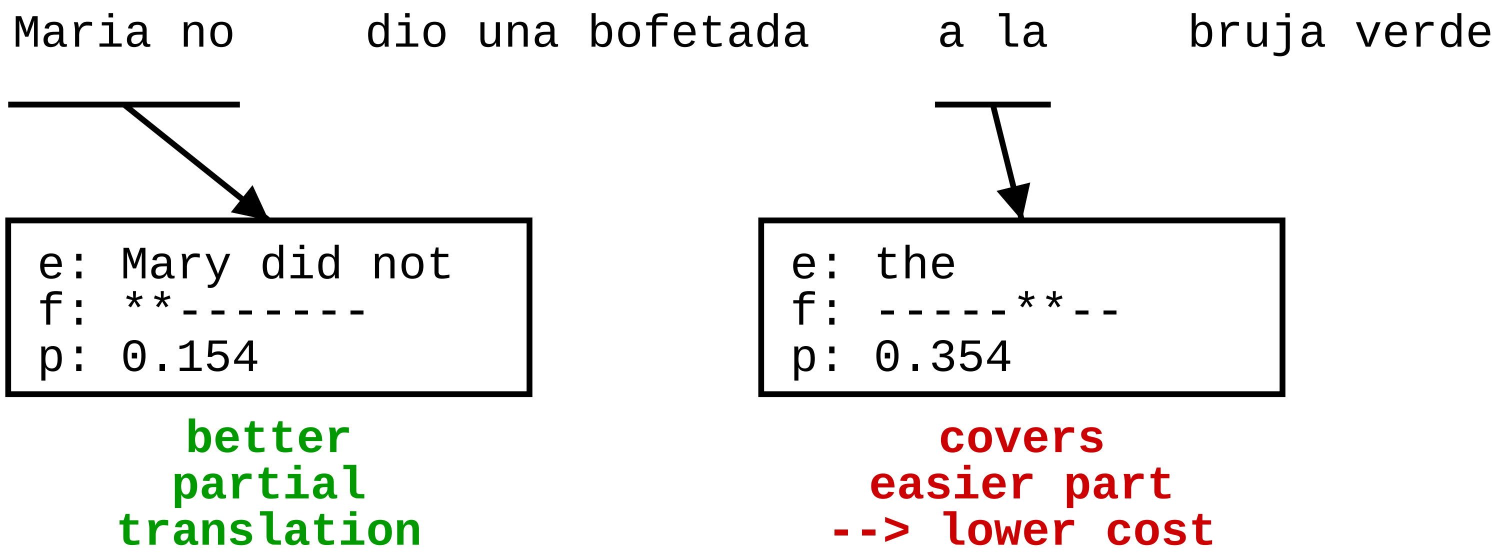
Hypothesis Stacks



- Organization of hypothesis into stacks
  - here: based on *number of foreign words* translated
  - during translation all hypotheses from one stack are expanded
  - expanded Hypotheses are placed into stacks

Comparing Hypotheses

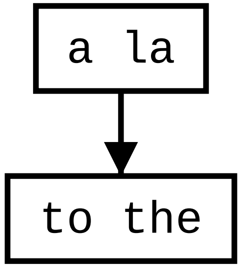
- Comparing hypotheses with *same number of foreign words* covered



- Hypothesis that covers *easy part* of sentence is preferred

⇒ Need to consider **future cost** of uncovered parts

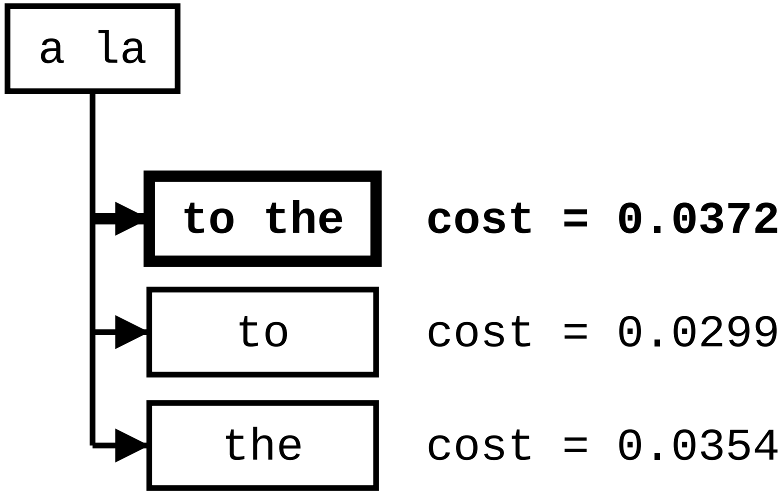
Future Cost Estimation



- *Estimate cost* to translate remaining part of input
- Step 1: estimate future cost for each *translation option*
  - look up translation model cost
  - estimate language model cost (no prior context)
  - ignore reordering model cost

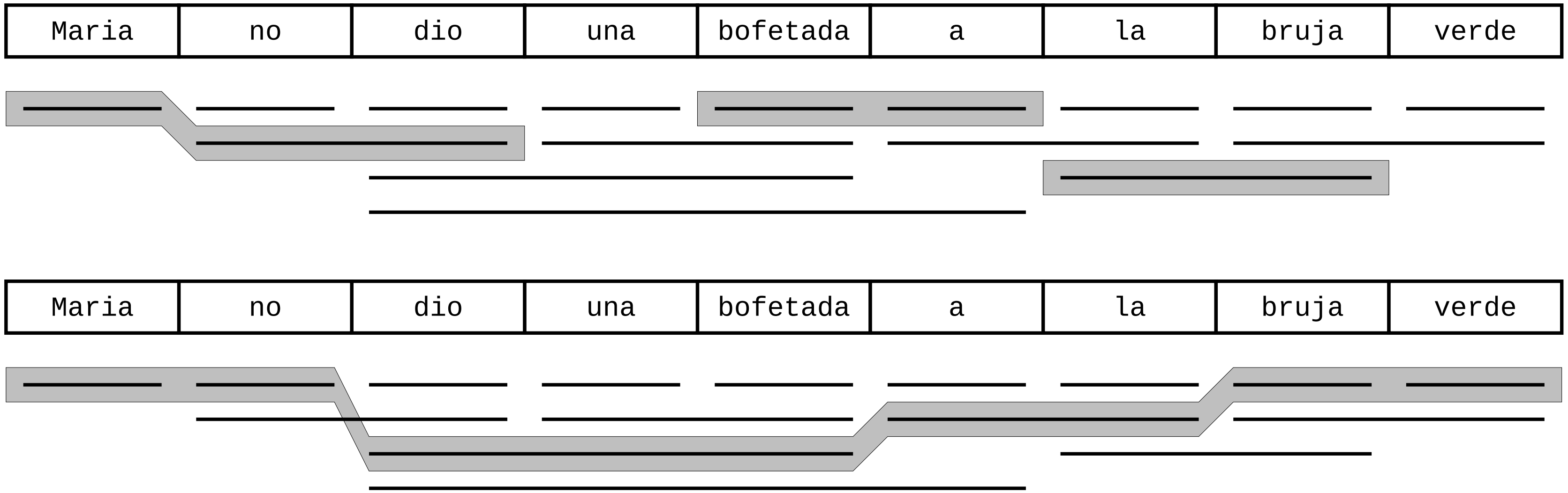
  $\rightarrow$ LM * TM = p(to) * p(the|to) * p(to the|a la)

Future Cost Estimation: Step 2



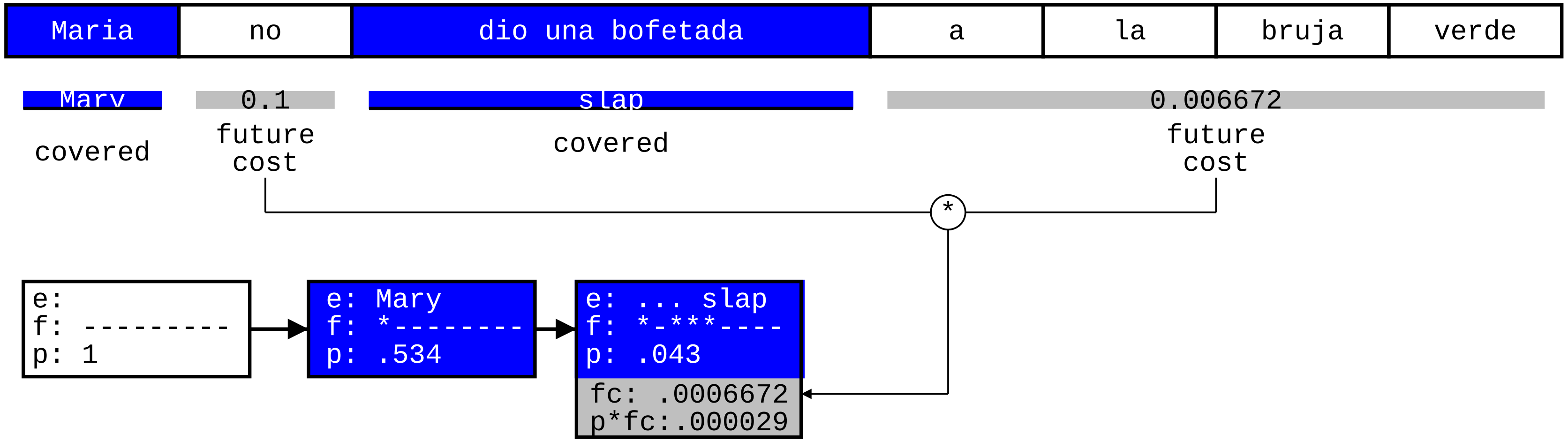
- Step 2: find *cheapest cost* among translation options

Future Cost Estimation: Step 3



- Step 3: find *cheapest future cost path* for each span
  - can be done *efficiently* by dynamic programming
  - future cost for every span can be *pre-computed*

Future Cost Estimation: Application



- Use future cost estimates when *pruning* hypotheses
- For each *uncovered contiguous span*:
  - look up *future costs* for each maximal contiguous uncovered span
  - *add* to actually accumulated cost for translation option for pruning

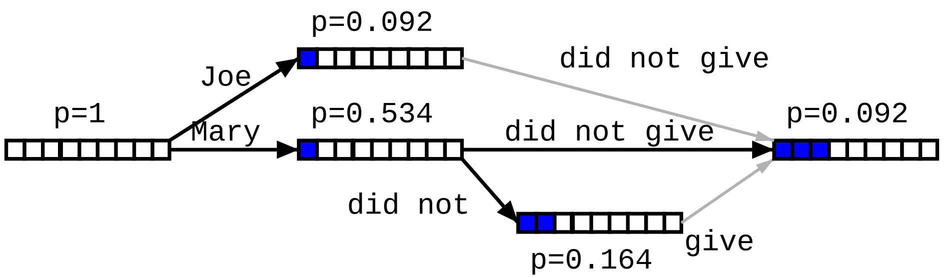
A* search

- Pruning might drop hypothesis that lead to the best path (**search error**)
- **A* search**: safe pruning
  - future cost estimates have to be accurate or underestimates
  - **lower bound** for probability is established early by **depth first search**: compute cost for one complete translation
  - if cost-so-far and future cost are worse than *lower bound*, hypothesis can be safely discarded
- Not commonly done, since not aggressive enough

Limits on Reordering

- Reordering may be **limited**
  - **Monotone** Translation: No reordering at all
  - Only phrase movements of at most n words
- Reordering limits *speed* up search (polynomial instead of exponential)
- Current reordering models are weak, so limits *improve* translation quality

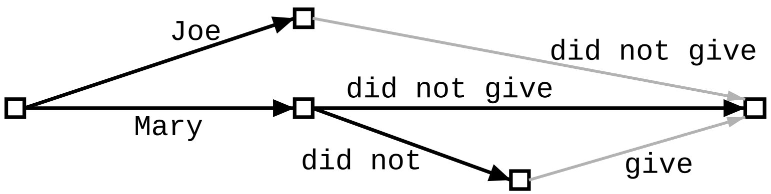
Word Lattice Generation



- **Search graph** can be easily converted into a **word lattice**
  - can be further mined for **n-best lists**

$\longrightarrow$ enables **reranking** approaches

$\longrightarrow$ enables **discriminative training**



Sample N-Best List

- Simple **N-best list**:

```
Translation ||| Reordering LM TM WordPenalty ||| Score
this is a small house ||| 0 -27.0908 -1.83258 -5 ||| -28.9234
this is a little house ||| 0 -28.1791 -1.83258 -5 ||| -30.0117
it is a small house ||| 0 -27.108 -3.21888 -5 ||| -30.3268
it is a little house ||| 0 -28.1963 -3.21888 -5 ||| -31.4152
this is an small house ||| 0 -31.7294 -1.83258 -5 ||| -33.562
it is an small house ||| 0 -32.3094 -3.21888 -5 ||| -35.5283
this is an little house ||| 0 -33.7639 -1.83258 -5 ||| -35.5965
this is a house small ||| -3 -31.4851 -1.83258 -5 ||| -36.3176
this is a house little ||| -3 -31.5689 -1.83258 -5 ||| -36.4015
it is an little house ||| 0 -34.3439 -3.21888 -5 ||| -37.5628
it is a house small ||| -3 -31.5022 -3.21888 -5 ||| -37.7211
this is an house small ||| -3 -32.8999 -1.83258 -5 ||| -37.7325
it is a house little ||| -3 -31.586 -3.21888 -5 ||| -37.8049
this is an house little ||| -3 -32.9837 -1.83258 -5 ||| -37.8163
the house is a little ||| -7 -28.5107 -2.52573 -5 ||| -38.0364
the is a small house ||| 0 -35.6899 -2.52573 -5 ||| -38.2156
is it a little house ||| -4 -30.3603 -3.91202 -5 ||| -38.2723
the house is a small ||| -7 -28.7683 -2.52573 -5 ||| -38.294
it 's a small house ||| 0 -34.8557 -3.91202 -5 ||| -38.7677
this house is a little ||| -7 -28.0443 -3.91202 -5 ||| -38.9563
it 's a little house ||| 0 -35.1446 -3.91202 -5 ||| -39.0566
this house is a small ||| -7 -28.3018 -3.91202 -5 ||| -39.2139
```

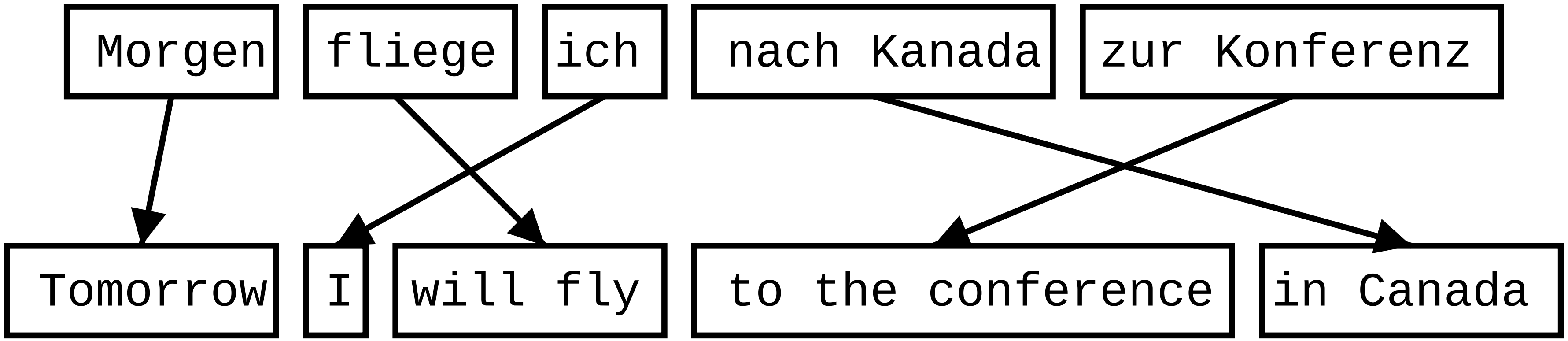
Moses: Open Source Toolkit

- **Open source** statistical machine translation system (developed from scratch 2006)
  - state-of-the-art *phrase-based* approach
  - novel methods: *factored translation models*, *confusion network decoding*
  - support for *very large models* through *memory-efficient* data structures

- Documentation, source code, binaries **available** at `http://www.statmt.org/moses/`
- Development also **supported by**
  - EC-funded *TC-STAR* project
  - *US* funding agencies DARPA, NSF
  - universities (Edinburgh, Maryland, MIT, ITC-irst, RWTH Aachen, ...)

Phrase-based models

Phrase-based translation



- Foreign input is segmented in phrases
  - any sequence of words, not necessarily linguistically motivated
- Each phrase is translated into English
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Phrase-based translation model

- Major components of phrase-based model
  - **phrase translation model** $\phi(\mathbf{f}|\mathbf{e})$
  - **reordering model** $\omega^{d(\text{start}_i - \text{end}_{i-1} - 1)}$
  - **language model** $p_{\text{LM}}(\mathbf{e})$
- Bayes rule

$$\begin{aligned} \text{argmax}_{\mathbf{e}} p(\mathbf{e}|\mathbf{f}) &= \text{argmax}_{\mathbf{e}} p(\mathbf{f}|\mathbf{e}) p(\mathbf{e}) \\ &= \text{argmax}_{\mathbf{e}} \phi(\mathbf{f}|\mathbf{e})\ p_{\text{LM}}(\mathbf{e})\ \omega^{d(\text{start}_i - \text{end}_{i-1} - 1)} \end{aligned}$$

- Sentence $\mathbf{f}$ is decomposed into I phrases $\bar{f}_1^I = \bar{f}_1, ..., \bar{f}_I$
- Decomposition of $\phi(\mathbf{f}|\mathbf{e})$

$$\phi(\bar{f}_1^I|\bar{e}_1^I) = \prod_{i=1}^{I} \phi(\bar{f}_i|\bar{e}_i)\ \omega^{d(\text{start}_i - \text{end}_{i-1} - 1)})$$

Advantages of phrase-based translation

- *Many-to-many* translation can handle non-compositional phrases
- Use of *local context* in translation
- The more data, the *longer phrases* can be learned

Phrase translation table

- Phrase translations for *den Vorschlag*

English	$\phi(e\|f)$	**English**	$\phi(e\|f)$
the proposal	0.6227	the suggestions	0.0114
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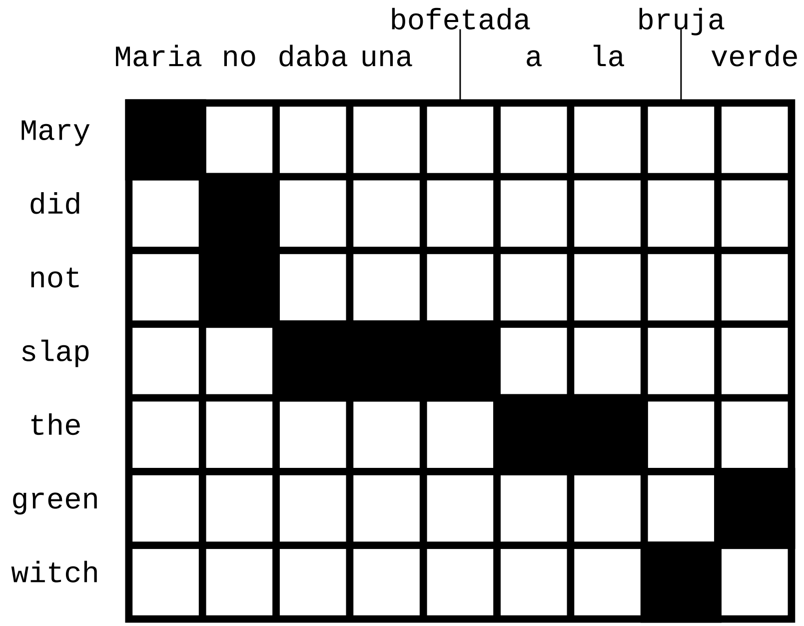
proposal	0.0205	its proposal	0.0068
of the proposal	0.0159	it	0.0068
the proposals	0.0159	...	...

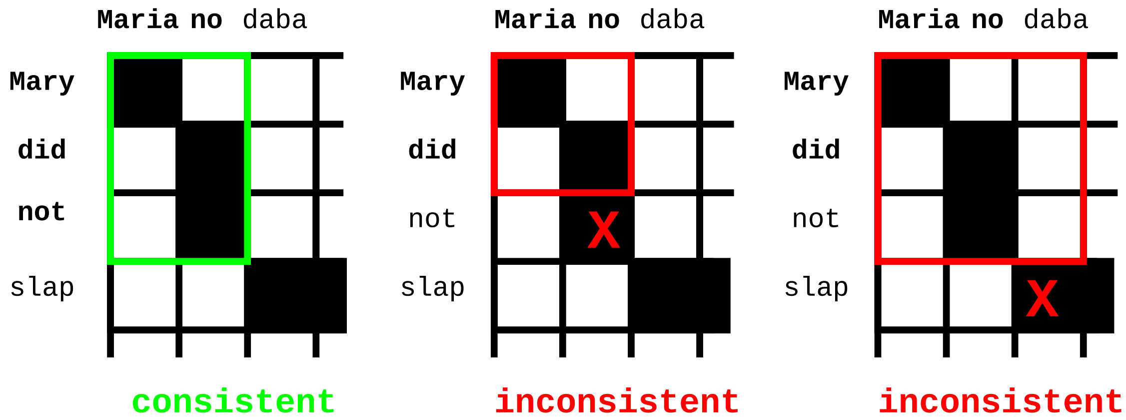
How to learn the phrase translation table?

- Start with the *word alignment*:



- Collect all phrase pairs that are **consistent** with the word alignment

Consistent with word alignment

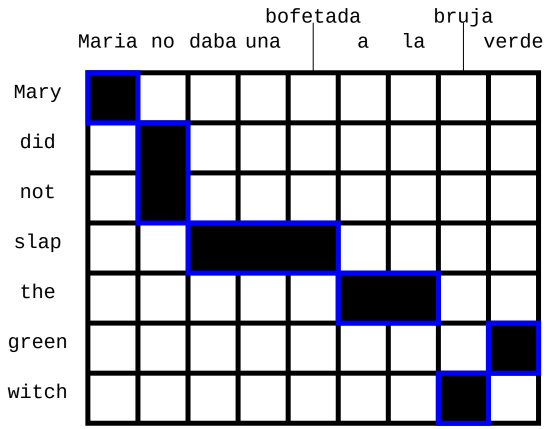


- **Consistent with the word alignment** :=
  phrase alignment has to *contain all alignment points* for all covered words

$$(\bar{e}, \bar{f}) \in BP \Leftrightarrow \quad \forall e_i \in \bar{e} : (e_i, f_j) \in A \rightarrow f_j \in \bar{f}$$

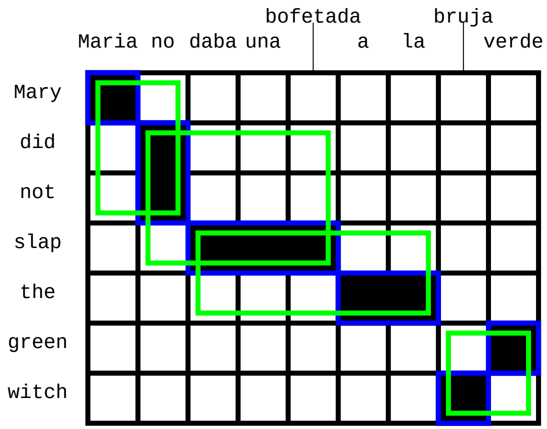
$$\text{AND} \quad \forall f_j \in \bar{f} : (e_i, f_j) \in A \rightarrow e_i \in \bar{e}$$

Word alignment induced phrases



(Maria, Mary), (no, did not), (slap, daba una bofetada), (a la, the), (bruja, witch), (verde, green)

Word alignment induced phrases



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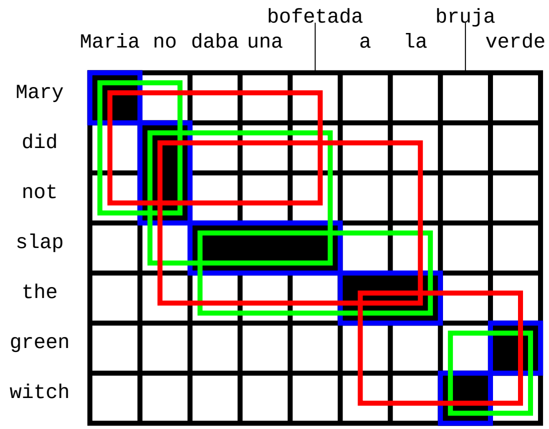
(Maria no, Mary did not), (no daba una bofetada, did not slap), (daba una bofetada a la, slap the), (bruja verde, green witch)

Word alignment induced phrases



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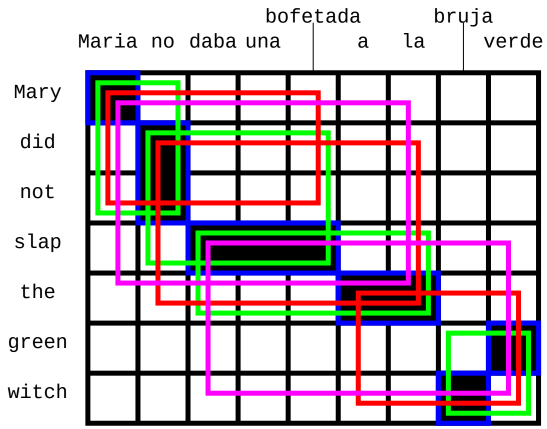
(Maria no, Mary did not), (no daba una bofetada, did not slap), (daba una bofetada a la, slap the),
(bruja verde, green witch), (Maria no daba una bofetada, Mary did not slap),
(no daba una bofetada a la, did not slap the), (a la bruja verde, the green witch)

Word alignment induced phrases



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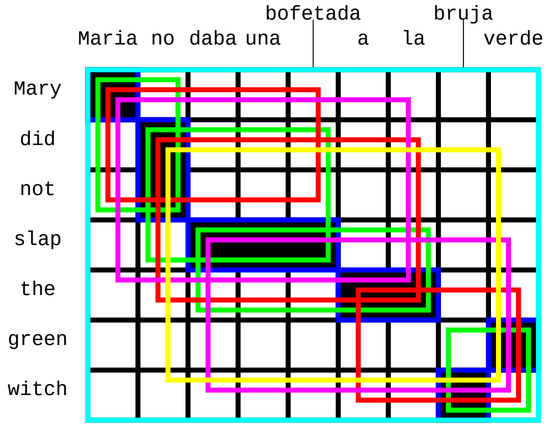
Word alignment induced phrases (5)



(Maria, Mary), (no, did not), (slap, daba una bofetada), (a la, the), (bruja, witch), (verde, green),

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(Maria no daba una bofetada a la, Mary did not slap the), (daba una bofetada a la bruja verde, slap the green witch), (no daba una bofetada a la bruja verde, did not slap the green witch),

(Maria no daba una bofetada a la bruja verde, Mary did not slap the green witch)

Probability distribution of phrase pairs

- We need a **probability distribution** $\phi(\overline{f}|\overline{e})$ over the collected phrase pairs

⇒ Possible *choices*

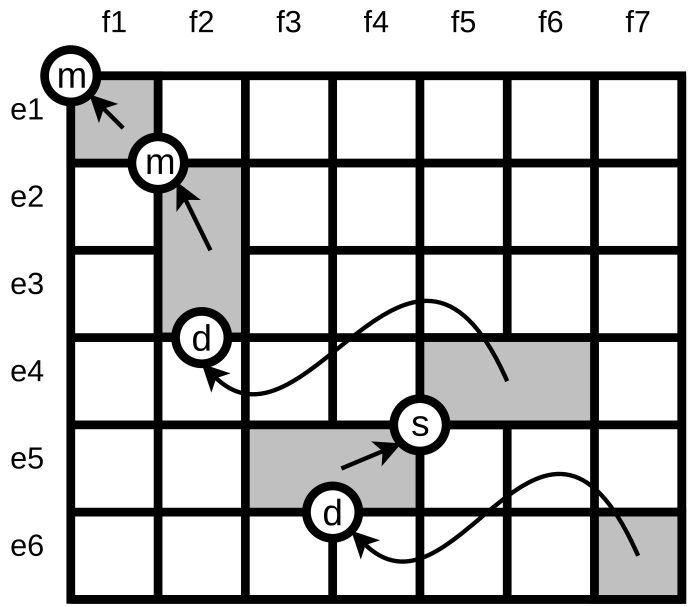
- *relative frequency* of collected phrases: $\phi(\overline{f}|\overline{e}) = \frac{\text{count}(\overline{f},\overline{e})}{\sum_{\overline{f}} \text{count}(\overline{f},\overline{e})}$
- or, conversely $\phi(\overline{e}|\overline{f})$
- use *lexical translation probabilities*

Reordering

- *Monotone* translation
  - do not allow any reordering

  $\longrightarrow$ worse translations
- *Limiting* reordering (to movement over max. number of words) helps
- *Distance-based* reordering cost
  - moving a foreign phrase over n words: cost ω^n
- *Lexicalized* reordering model

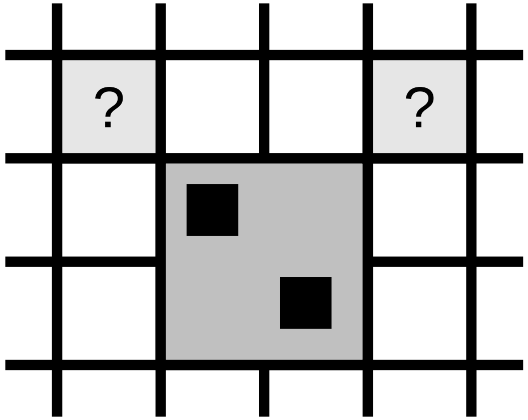
Lexicalized reordering models



[from Koehn et al., 2005, IWSLT]

- Three **orientation** types: **monotone**, **swap**, **discontinuous**
- Probability $p(swap|e, f)$ depends on foreign (and English) *phrase* involved

Learning lexicalized reordering models



[from Koehn et al., 2005, IWSLT]

- Orientation type is *learned during phrase extractions*
- *Alignment point* to the *top left* (monotone) or *top right* (swap)?
- For more, see [Tillmann, 2003] or [Koehn et al., 2005]