Winter School

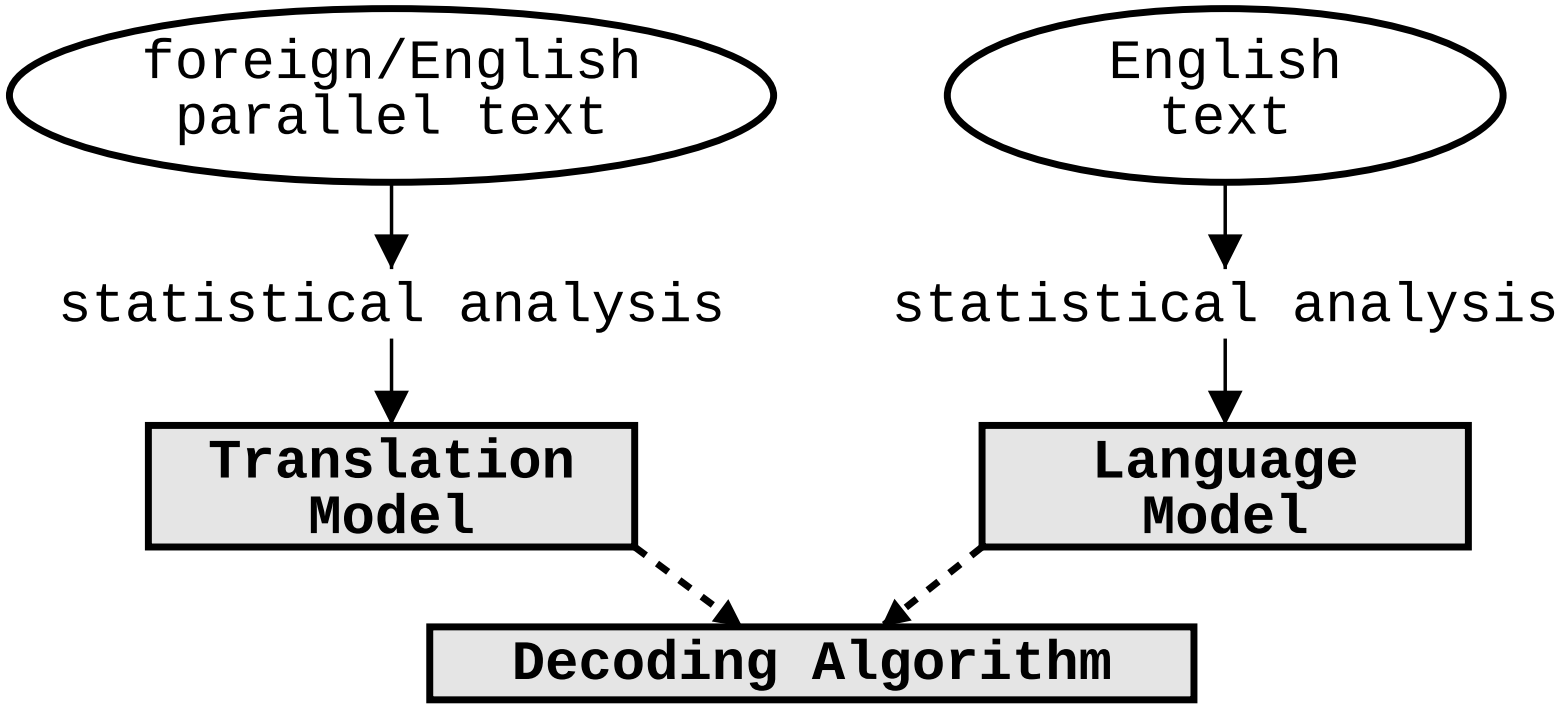
Day 3: Decoding / Phrase-based models

MT Marathon

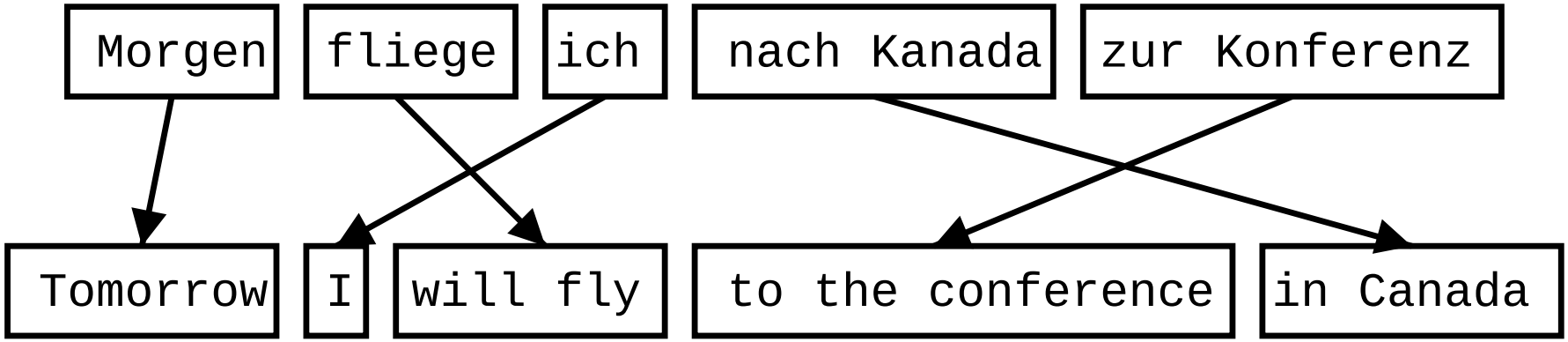
27 January 2010

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":

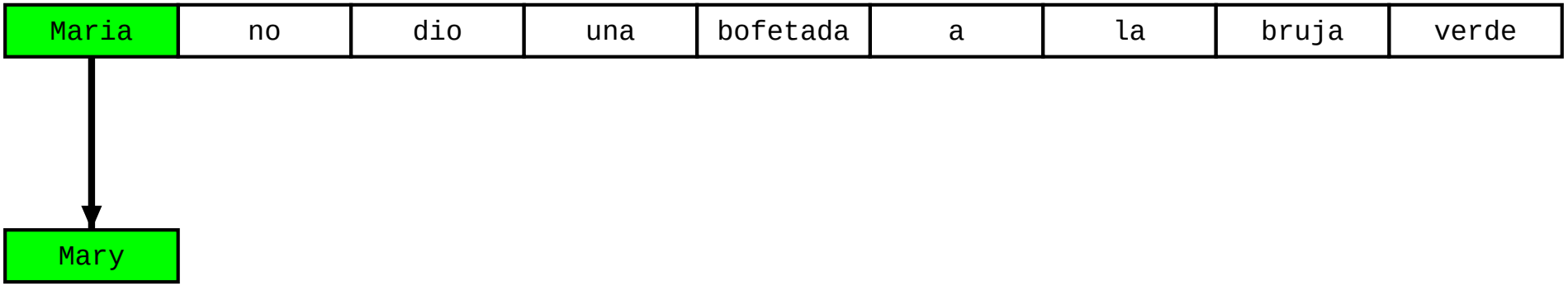
English	ϕ**(e|f)**	**English**	ϕ**(e|f)**
the proposal	0.6227	the suggestions	0.0114
's proposal	0.1068	the proposed	0.0114
a proposal	0.0341	the motion	0.0091
the idea	0.0250	the idea of	0.0091
this proposal	0.0227	the proposal ,	0.0068
proposal	0.0205	its proposal	0.0068
of the proposal	0.0159	it	0.0068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

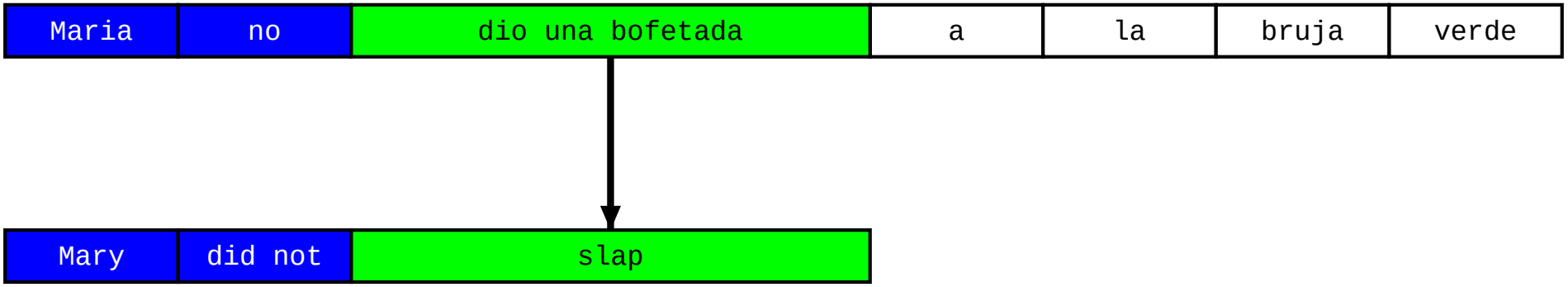
Mary

- 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

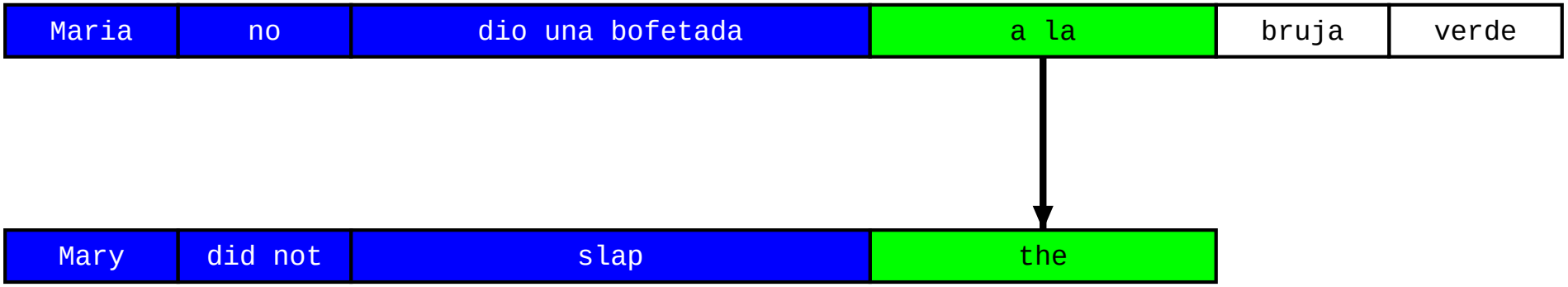
- *One to many* translation

Decoding Process



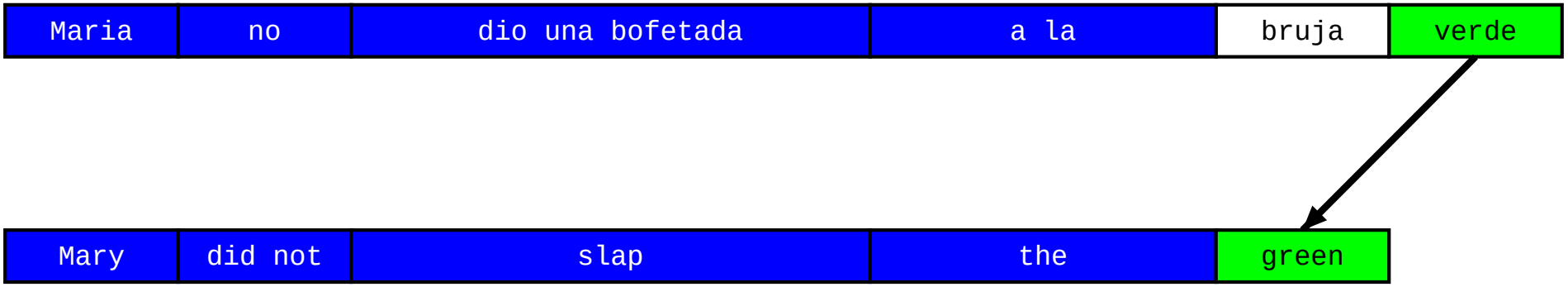
- Many to one translation

Decoding Process



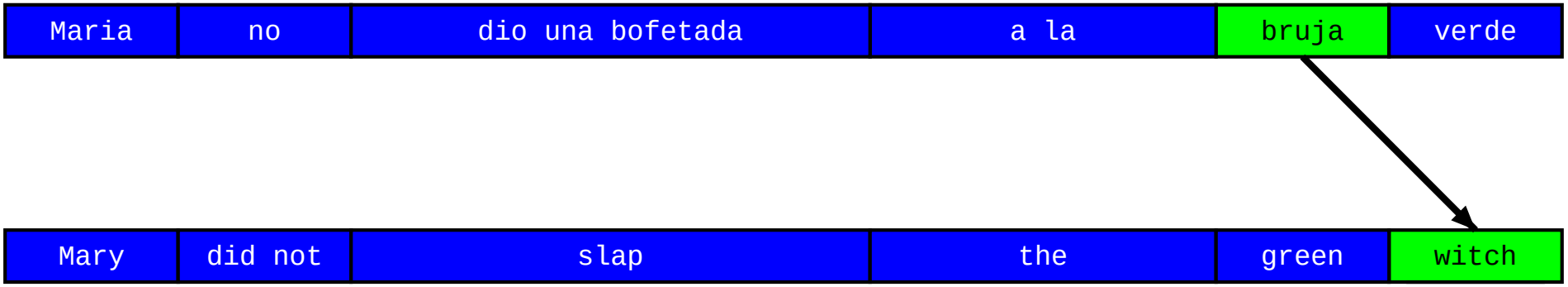
- *Many to one* translation

Decoding Process



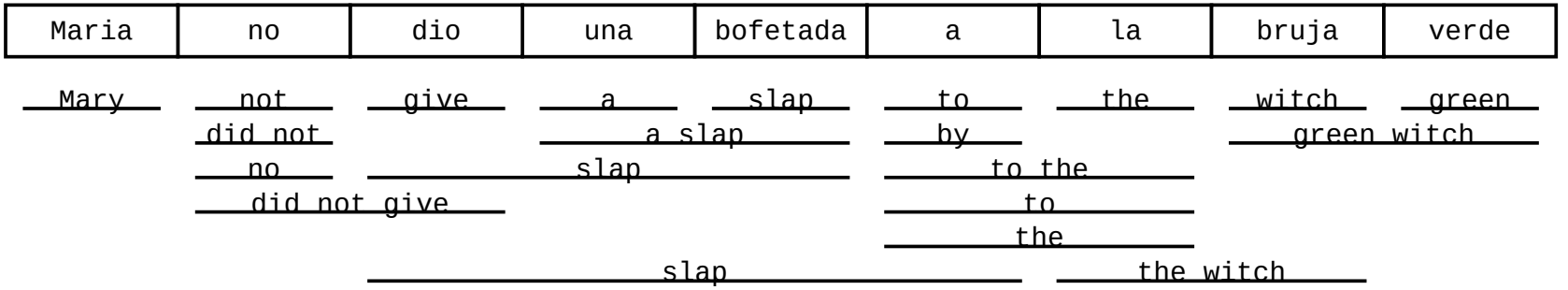
- *Reordering*

Decoding Process



- Translation *finished*

Translation Options

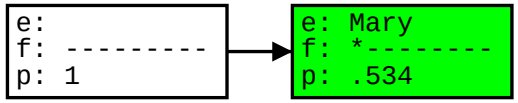


- Look up *possible phrase translations*
  - many different ways to *segment* words into phrases
  - many different ways to *translate* each phrase

Hypothesis Expansion

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

Hypothesis Expansion

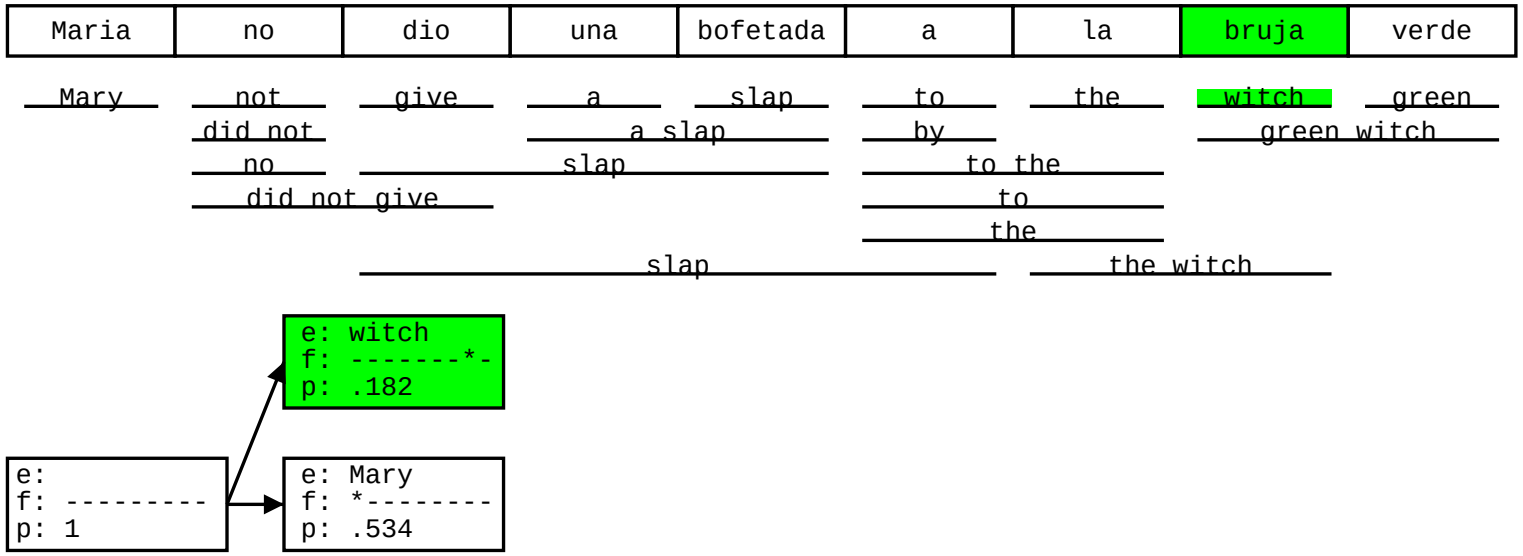


- Pick *translation option*
- Create *hypothesis*
  - e: add English phrase `Mary`
  - f: first foreign word covered
  - p: probability 0.534

A Quick Word on Probabilities

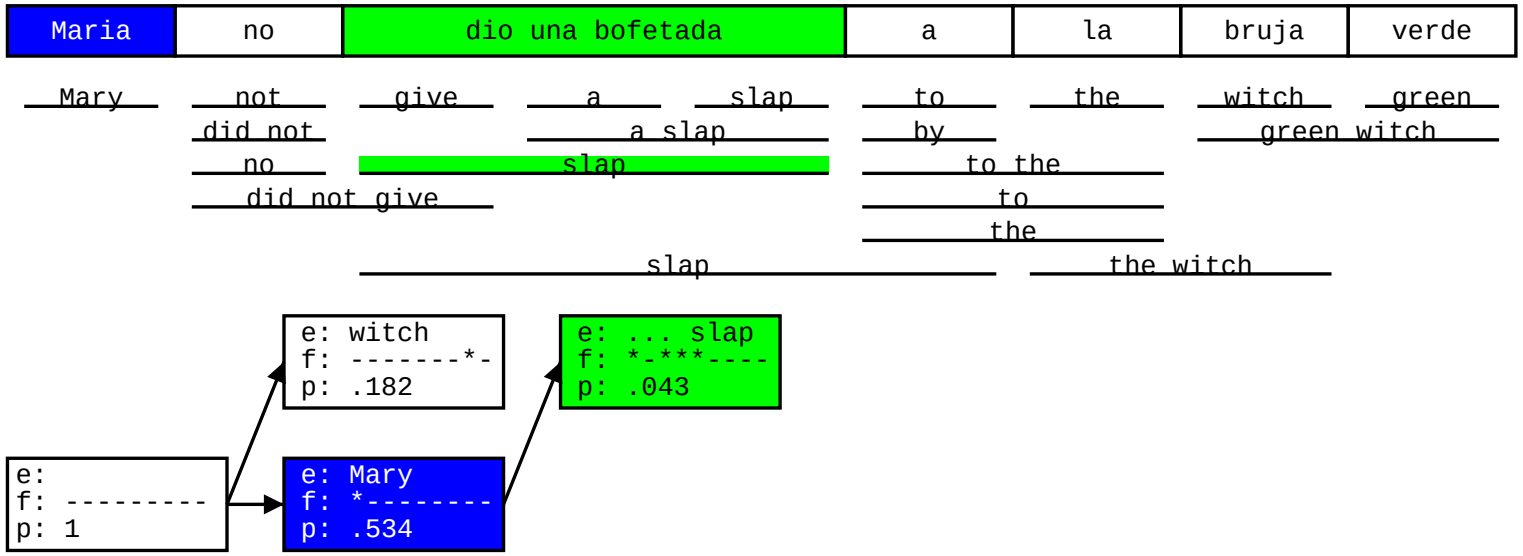
- Not going into detail here, but...
- *Translation Model*
  - phrase translation probability p(Mary|Maria)
  - reordering costs
  - phrase/word count costs
  - ...
- *Language Model*
  - uses trigrams:
  - p(Mary did not) = p(Mary|START) $\times p$(did|Mary,START) $\times$ p(not|Mary did)

Hypothesis Expansion



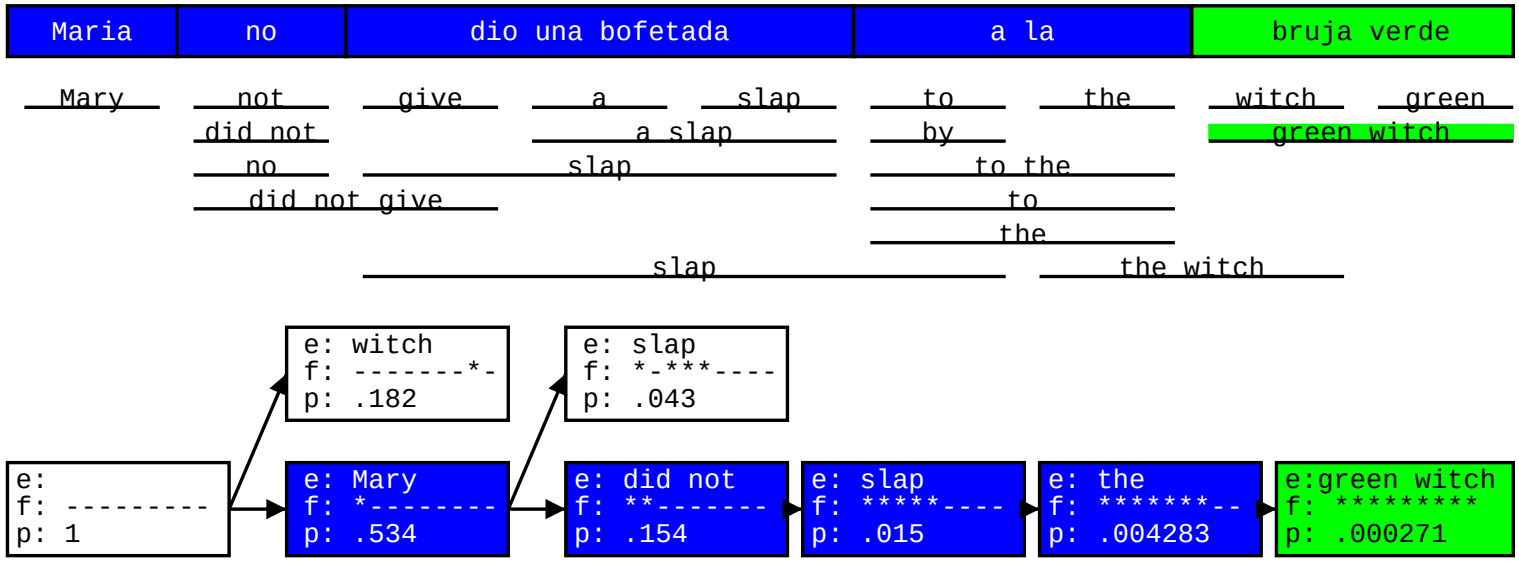
- Add another *hypothesis*

Hypothesis Expansion



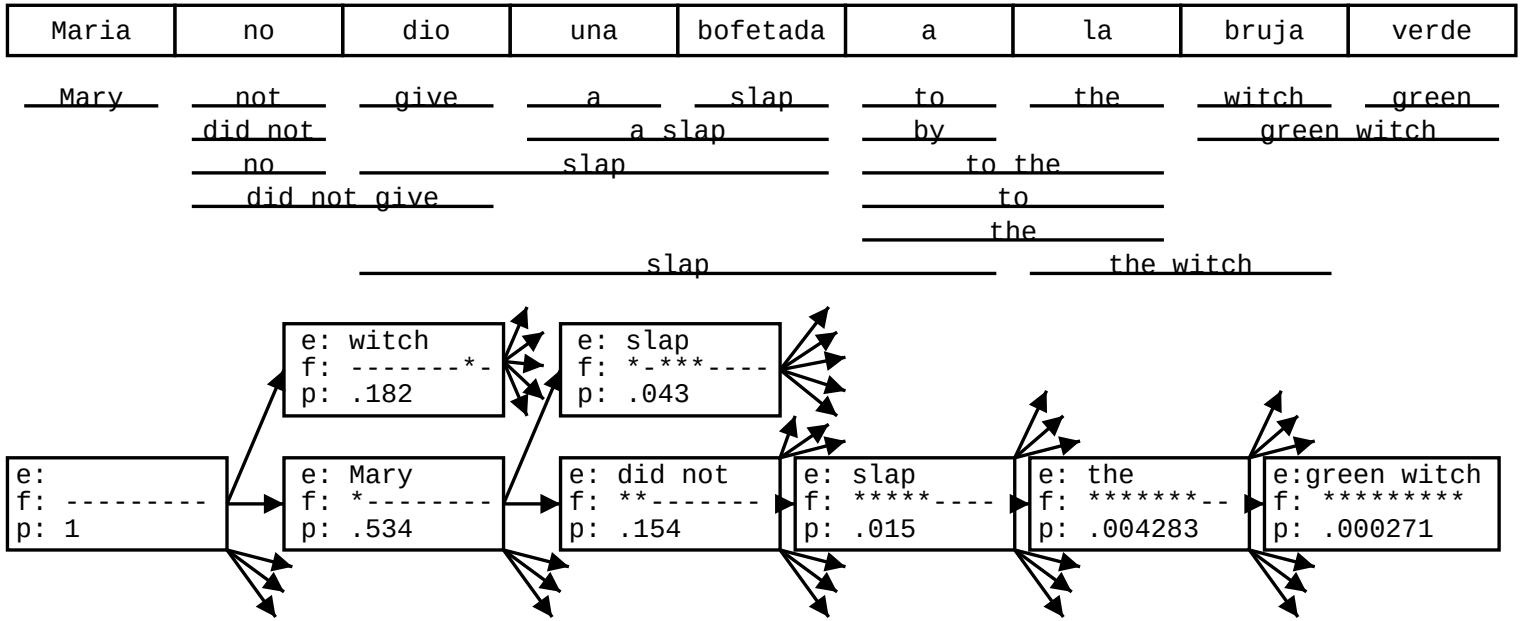
- Further *hypothesis expansion*

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

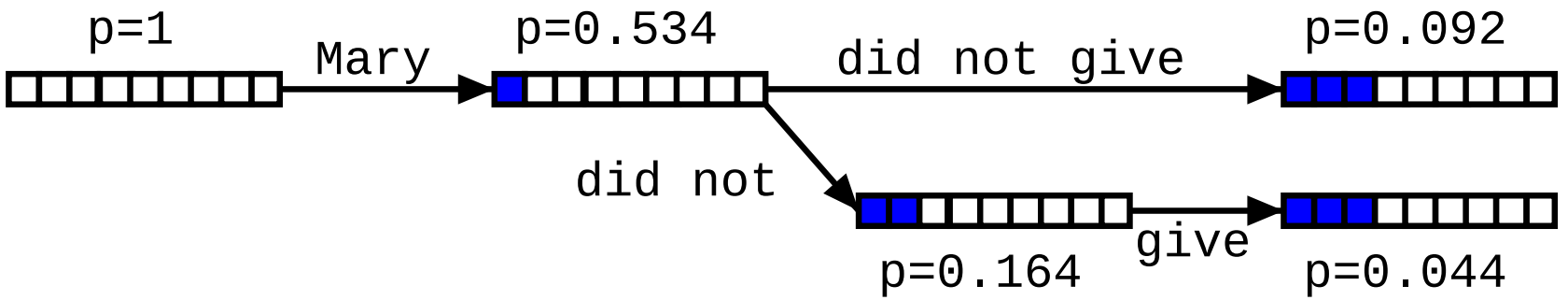
- Number of hypotheses is *exponential* with respect to sentence length

$\Rightarrow$ Decoding is NP-complete [Knight, 1999]

$\Rightarrow$ Need to *reduce search space*

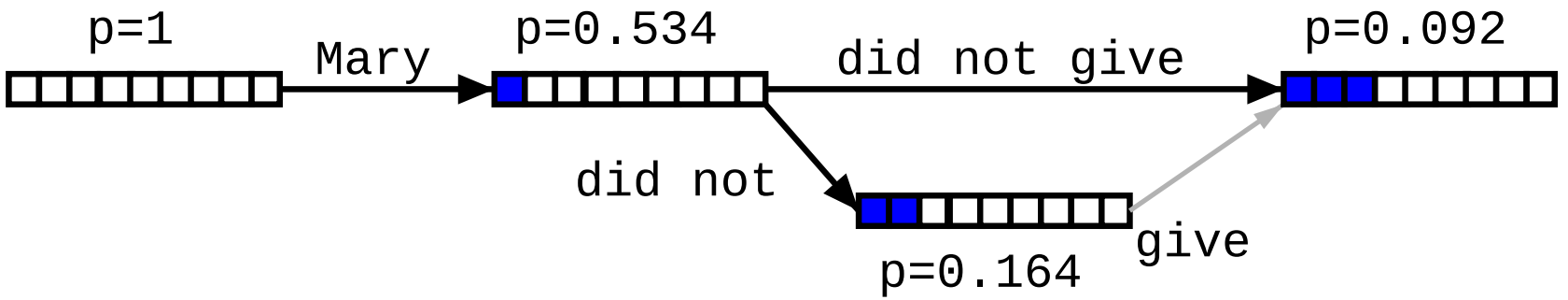
  - risk free: hypothesis **recombination**
  - risky: **histogram/threshold pruning**

Hypothesis Recombination



- Different paths to the *same* partial translation

Hypothesis Recombination

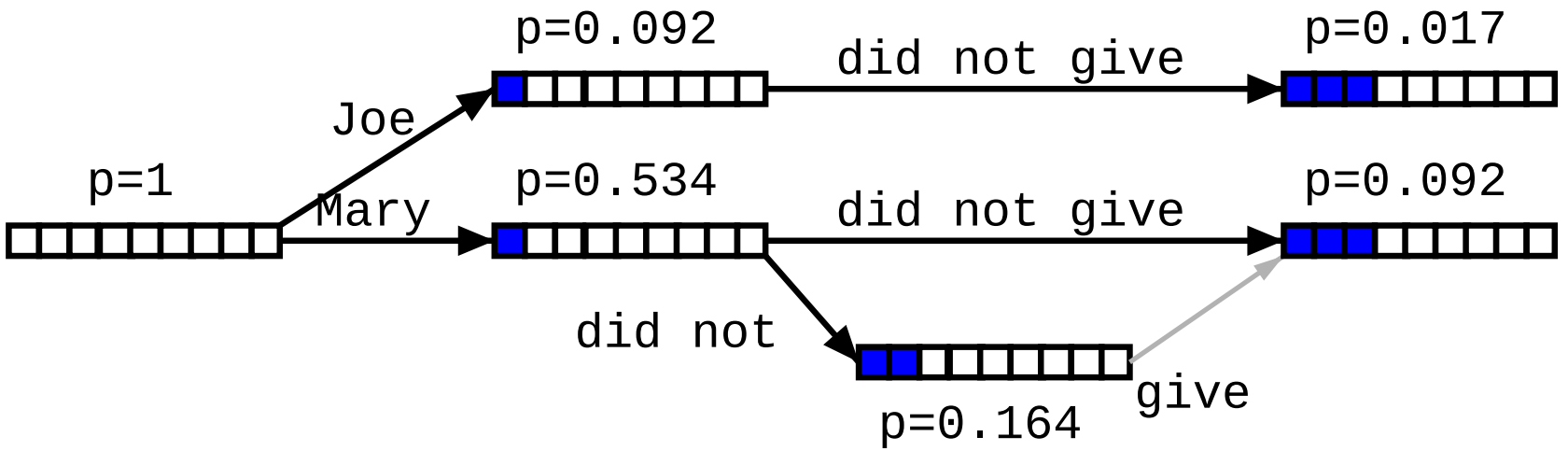


- Different paths to the same partial translation

⇒ *Combine paths*

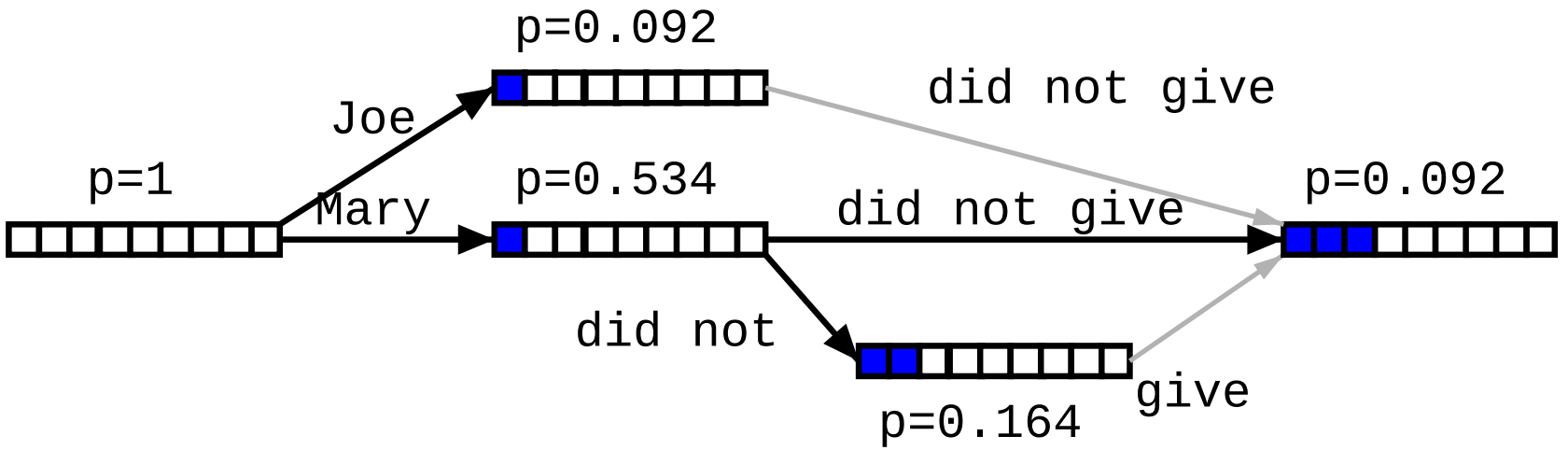
  - *drop weaker* path
  - keep pointer from weaker path (for lattice generation)

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
- 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)

⇒ *Combine paths*

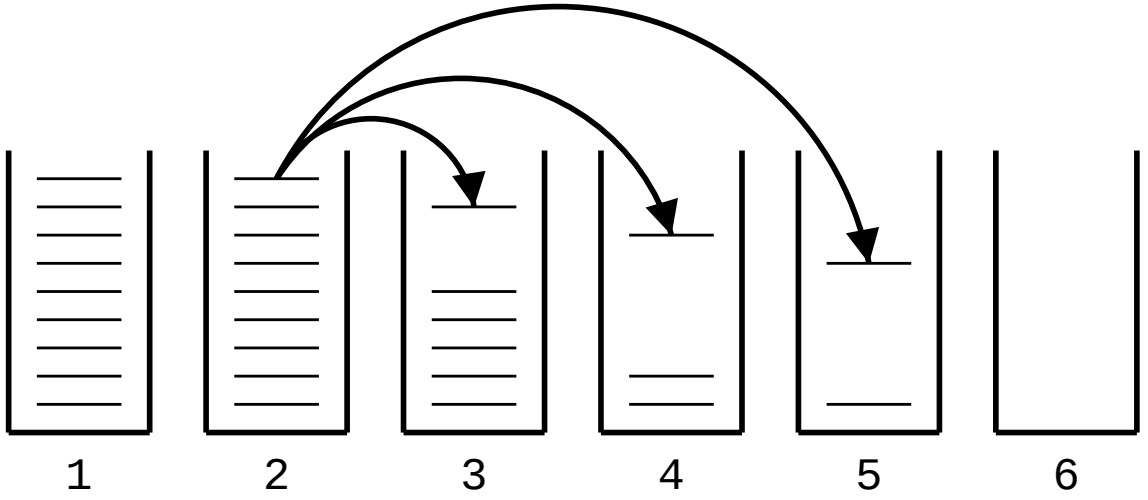
Pruning

- 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., $\alpha = 0.001$)

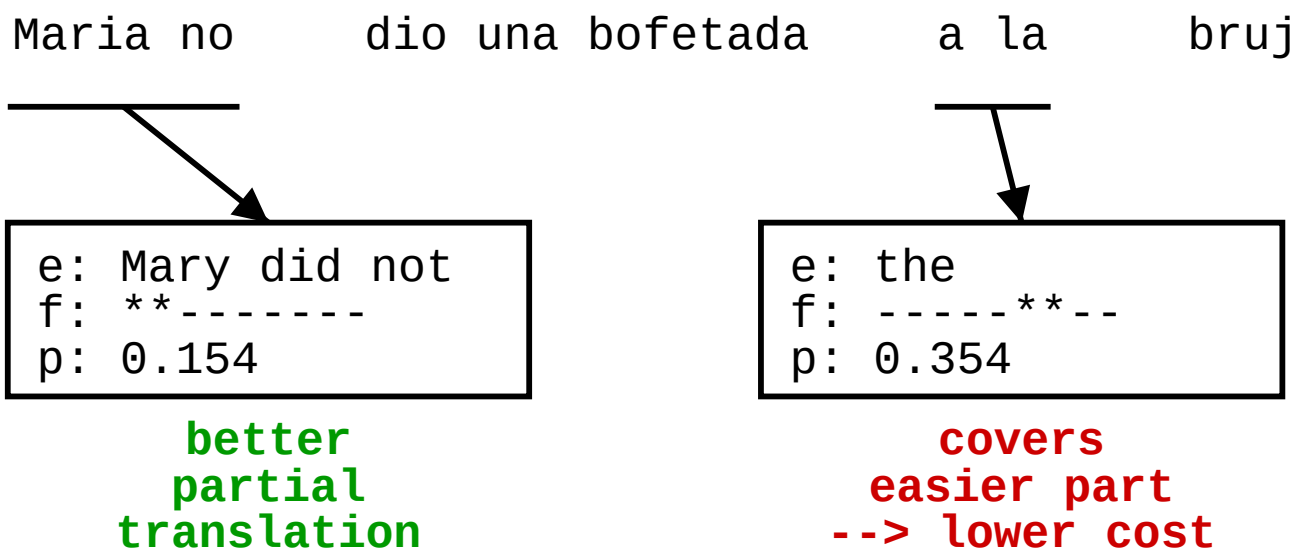
Hypothesis Stacks



- 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

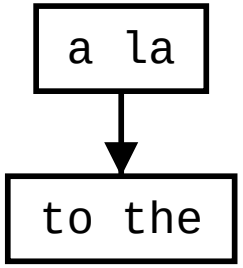
- Comparing hypotheses with *same number of foreign words* covered



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

$\Rightarrow$ Need to consider **future cost** of uncovered parts

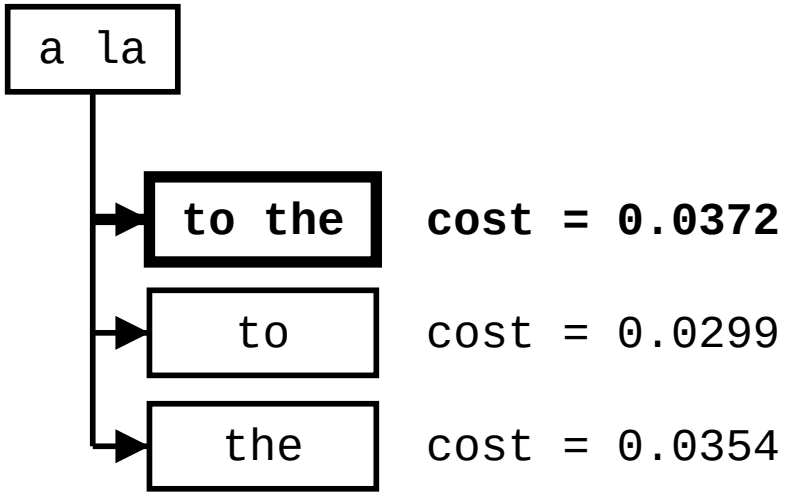
Future Cost Estimation



- *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

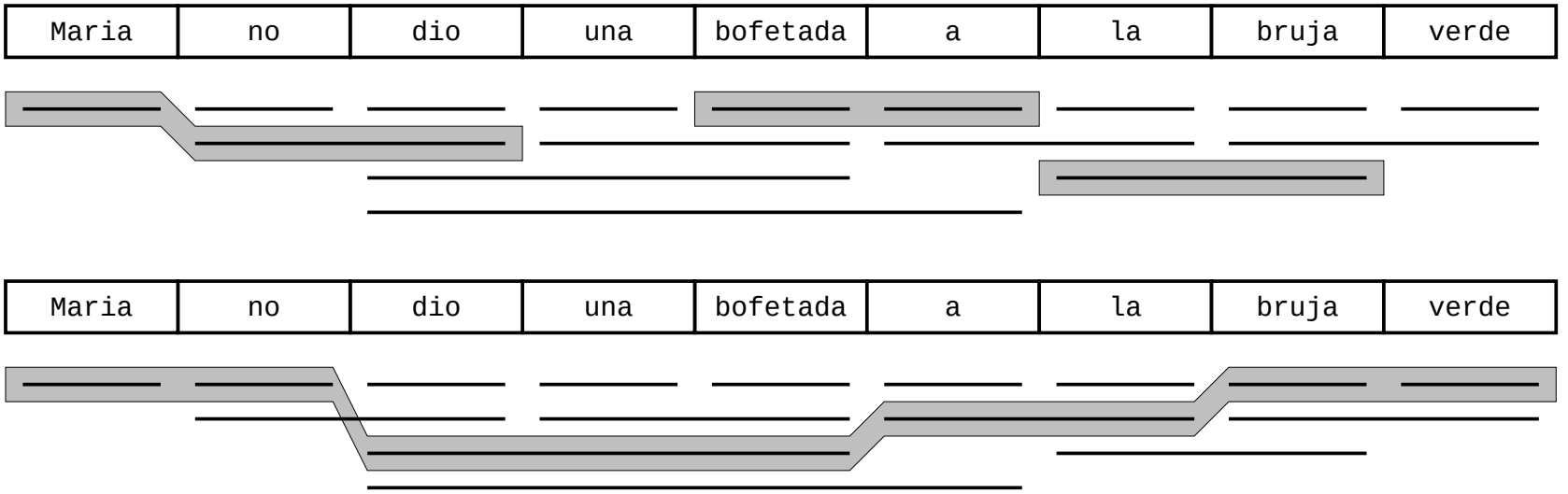
  $\rightarrow$ LM * TM = p(to) * p(the|to) * p(to the|a la)

Future Cost Estimation: Step 2



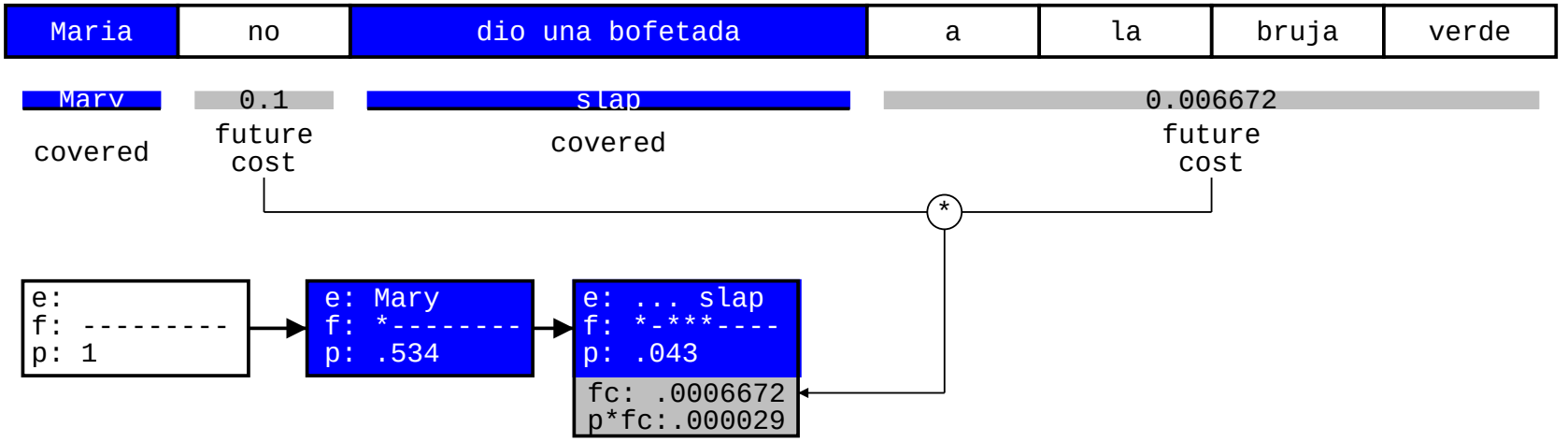
- Step 2: find *cheapest cost* among translation options

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

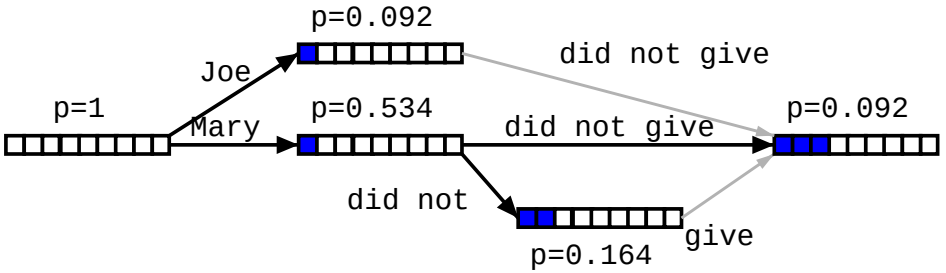
A* search

- 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

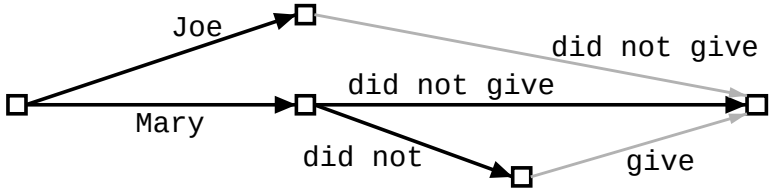
Word Lattice Generation



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

  → enables **reranking** approaches

  → 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
```

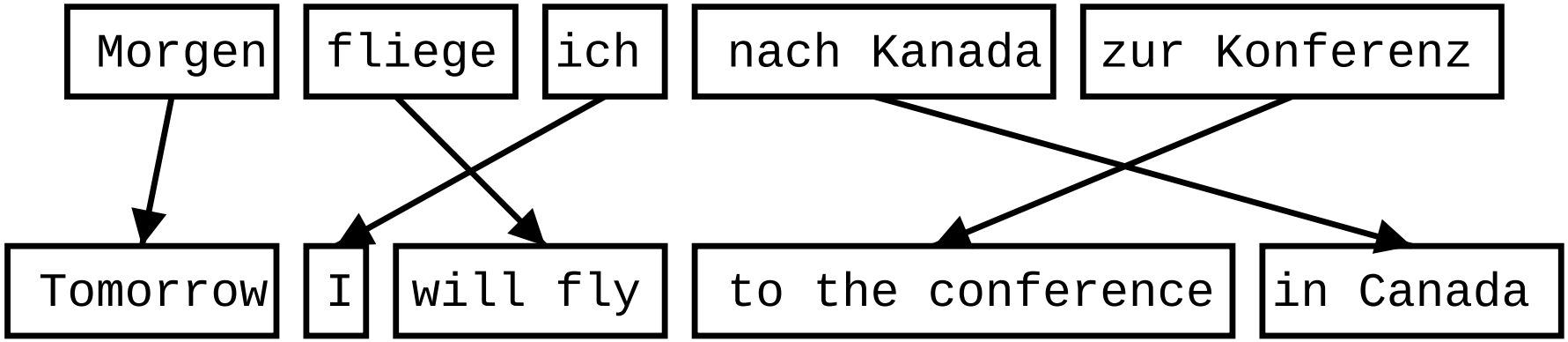
Moses: Open Source Toolkit

- **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
- Phrases are reordered

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

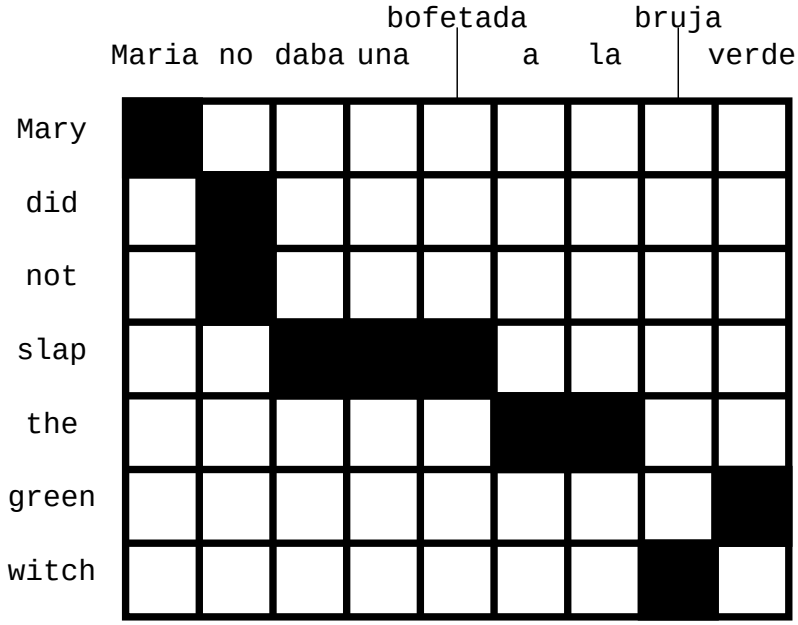
Phrase translation table

- Phrase translations for *den Vorschlag*

English	ϕ**(e|f)**	**English**	ϕ**(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	...	...

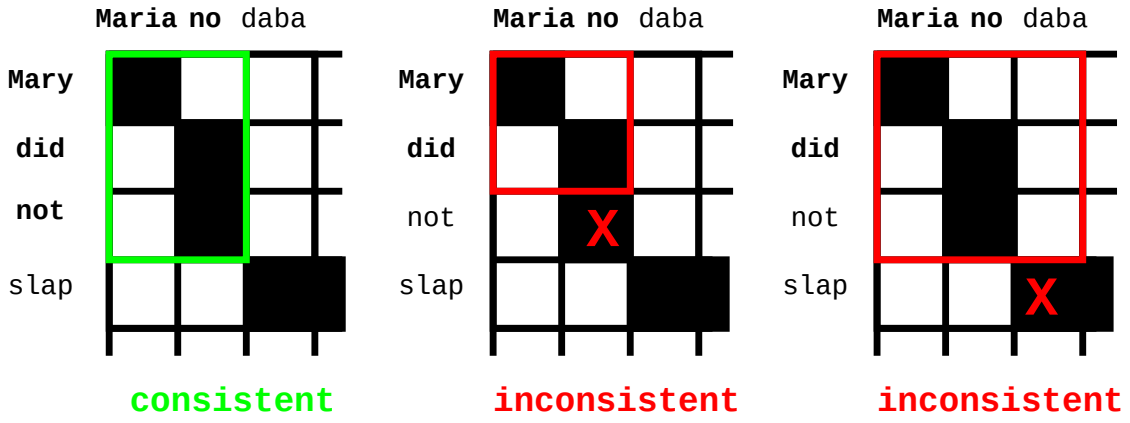
How to learn the phrase translation table?

- Start with the *word alignment*:



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

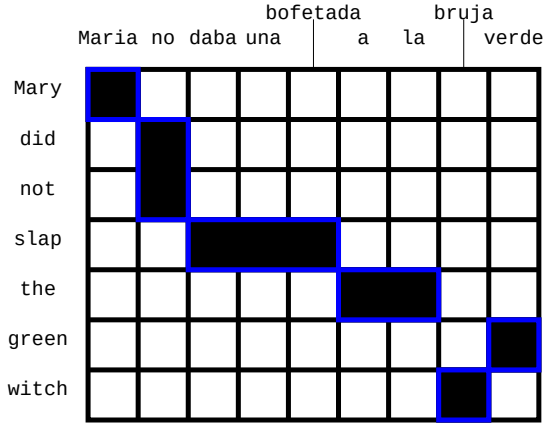
Consistent with word alignment



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

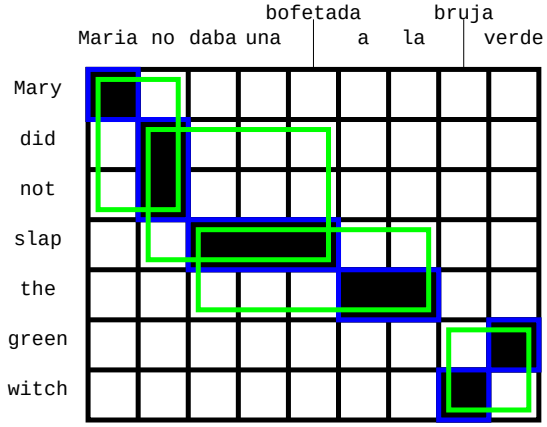
$$(\overline{e}, \overline{f}) \in BP \Leftrightarrow \quad \forall e_i \in \overline{e} : (e_i, f_j) \in A \rightarrow f_j \in \overline{f}$$
$$\text{AND} \quad \forall f_j \in \overline{f} : (e_i, f_j) \in A \rightarrow e_i \in \overline{e}$$

Word alignment induced phrases



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

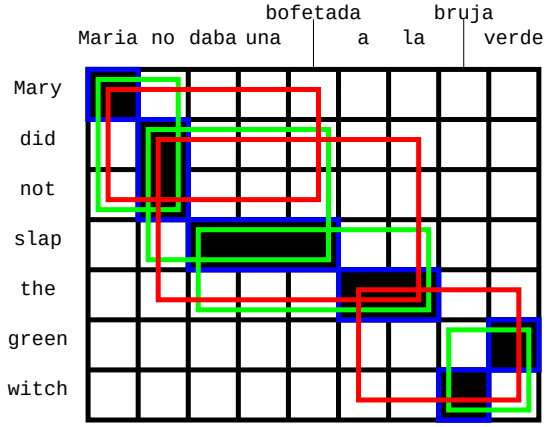
Word alignment induced phrases



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

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

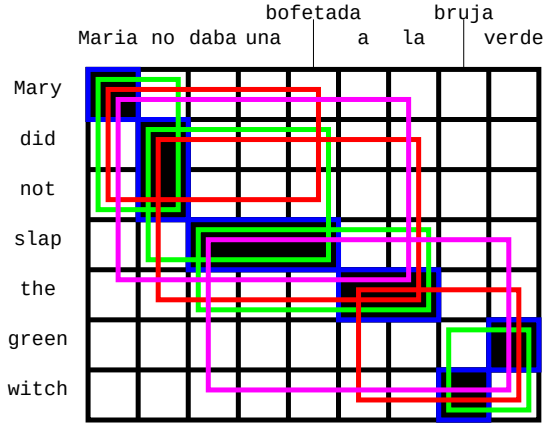
Word alignment induced phrases



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

(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



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

(Maria no, Mary did not), (no daba una bofetada, did not slap), (daba una bofetada a la, slap the),

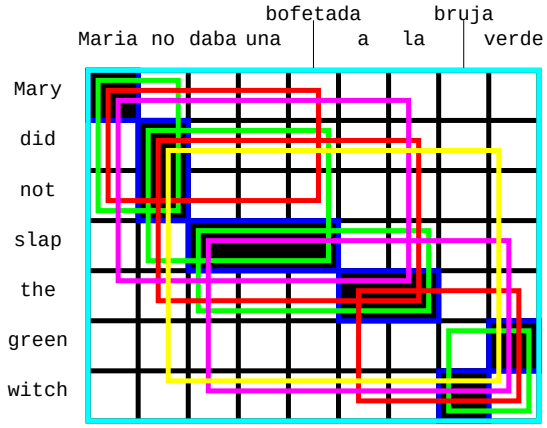
(bruja verde, green witch), (Maria no daba una bofetada, Mary did not slap),

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

(Maria no daba una bofetada a la, Mary did not slap the),

(daba una bofetada a la bruja verde, slap the green witch)

Word alignment induced phrases (5)



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

$\Rightarrow$ Possible *choices*

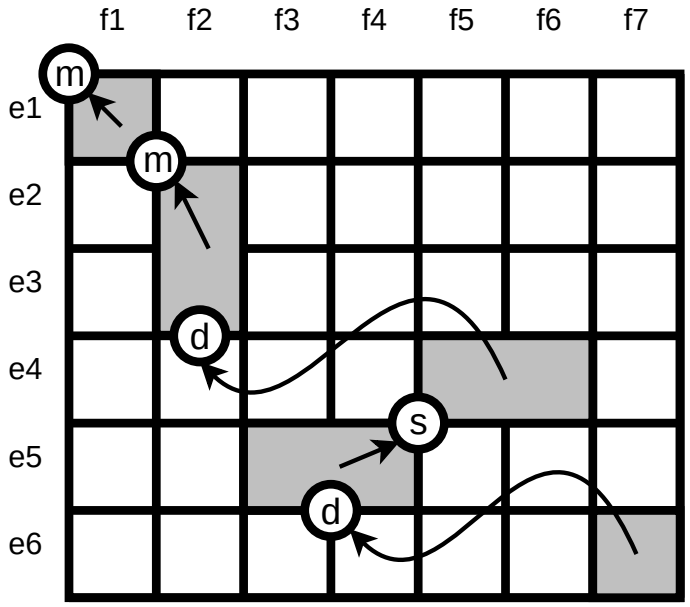
  - *relative frequency* of collected phrases: $\phi(\overline{f}|\overline{e}) = \frac{\text{count}(\overline{f},\overline{e})}{\sum_{\overline{f}} \text{count}(\overline{f},\overline{e})}$
  - or, conversely $\phi(\overline{e}|\overline{f})$
  - use *lexical translation probabilities*

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

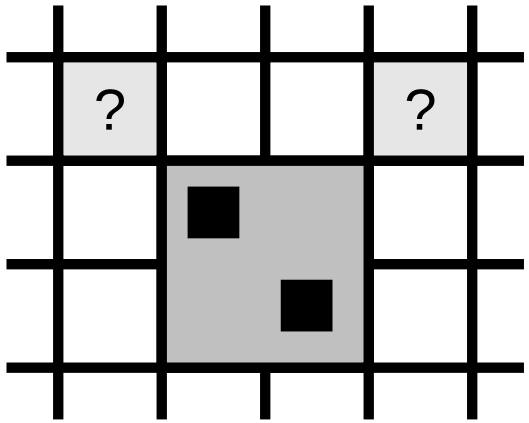
Lexicalized reordering models



[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]