
Phrase-Based Models

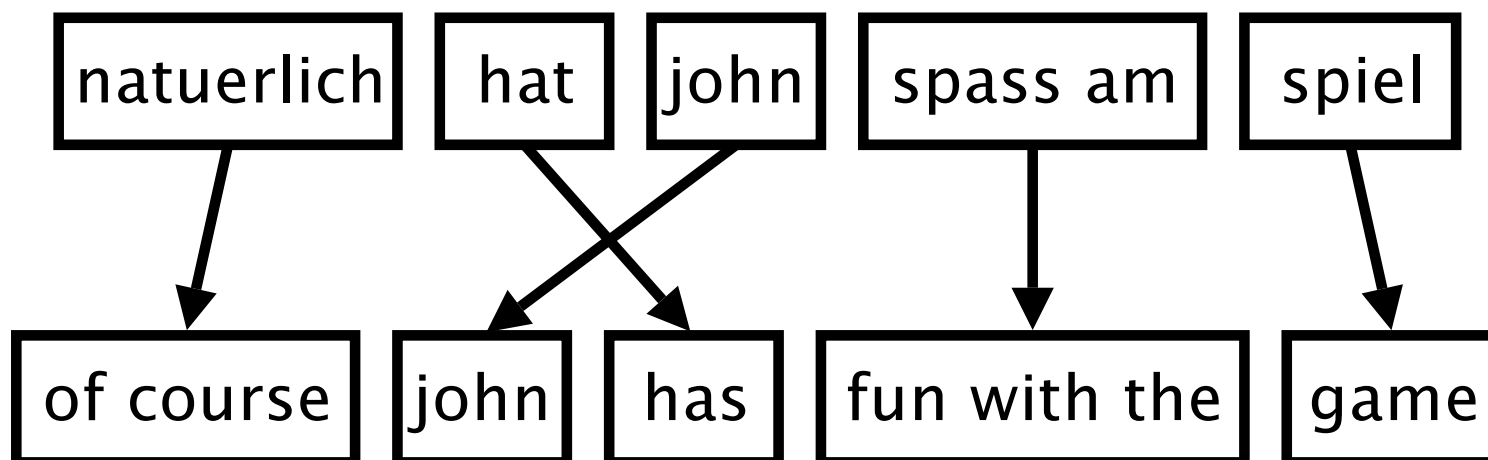
Philipp Koehn

14 September 2021



- Word-Based Models translate *words* as atomic units
- Phrase-Based Models translate *phrases* as atomic units
- Advantages:
 - many-to-many translation can handle non-compositional phrases
 - use of local context in translation
 - the more data, the longer phrases can be learned
- "Standard Model", used by Google Translate and others until about 2017

Phrase-Based Model



- Foreign input is segmented in phrases
- Each phrase is translated into English
- Phrases are reordered

Phrase Translation Table



- Main knowledge source: table with phrase translations and their probabilities
- Example: phrase translations for *natuerlich*

Translation	Probability $\phi(\bar{e} \bar{f})$
of course	0.5
naturally	0.3
of course ,	0.15
, of course ,	0.05

Real Example

- Phrase translations for **den Vorschlag** learned from the Europarl corpus:

English	$\phi(\bar{e} f)$	English	$\phi(\bar{e} f)$
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

- lexical variation (**proposal** vs **suggestions**)
- morphological variation (**proposal** vs **proposals**)
- included function words (**the**, **a**, ...)
- noise (**it**)

Linguistic Phrases?



- Model is not limited to linguistic phrases
(noun phrases, verb phrases, prepositional phrases, ...)
- Example non-linguistic phrase pair

spass am → fun with the

- Prior noun often helps with translation of preposition
- Experiments show that limitation to linguistic phrases hurts quality

modeling

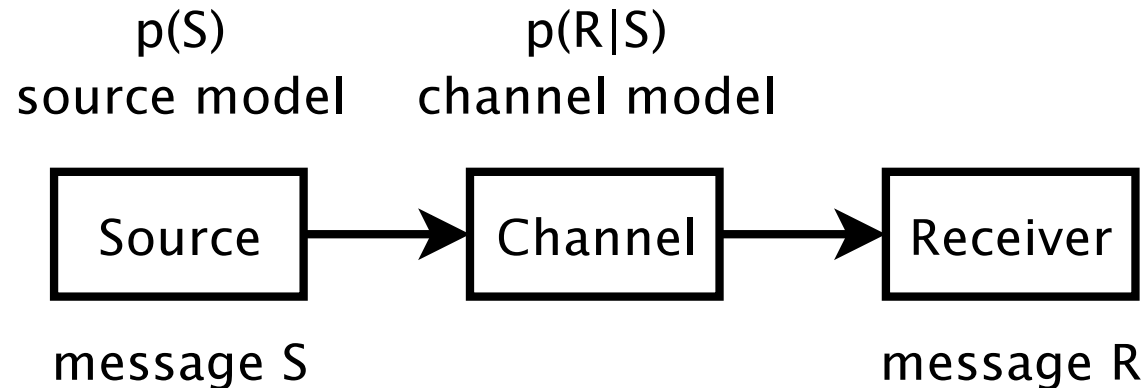
Noisy Channel Model



- We would like to integrate a language model
- Bayes rule

$$\begin{aligned}\operatorname{argmax}_{\mathbf{e}} p(\mathbf{e}|\mathbf{f}) &= \operatorname{argmax}_{\mathbf{e}} \frac{p(\mathbf{f}|\mathbf{e}) p(\mathbf{e})}{p(\mathbf{f})} \\ &= \operatorname{argmax}_{\mathbf{e}} p(\mathbf{f}|\mathbf{e}) p(\mathbf{e})\end{aligned}$$

Noisy Channel Model



- Applying Bayes rule also called noisy channel model
 - we observe a distorted message R (here: a foreign string **f**)
 - we have a model on how the message is distorted (here: translation model)
 - we have a model on what messages are probably (here: language model)
 - we want to recover the original message S (here: an English string **e**)

- Bayes rule

$$\begin{aligned} \mathbf{e}_{\text{best}} &= \operatorname{argmax}_{\mathbf{e}} p(\mathbf{e}|\mathbf{f}) \\ &= \operatorname{argmax}_{\mathbf{e}} p(\mathbf{f}|\mathbf{e}) p_{\text{LM}}(\mathbf{e}) \end{aligned}$$

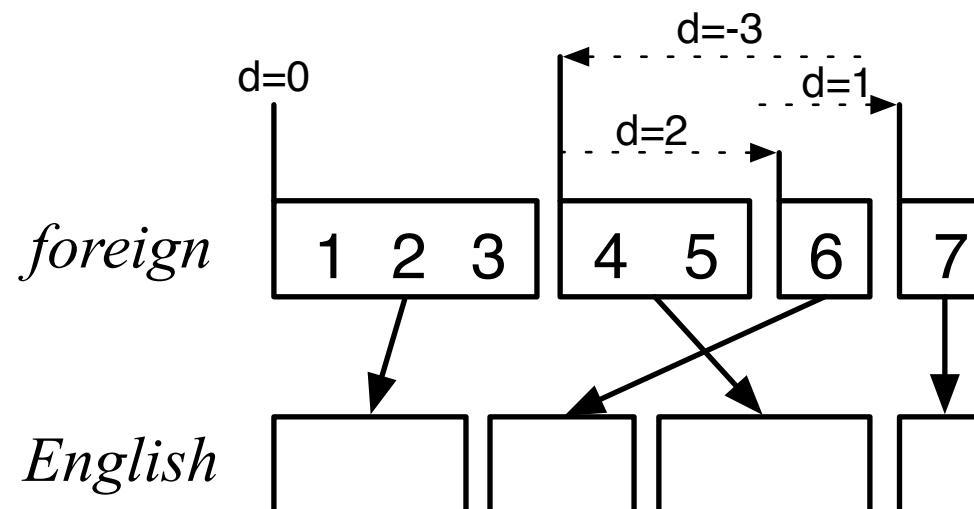
- translation model $p(\mathbf{f}|\mathbf{e})$
- language model $p_{\text{LM}}(\mathbf{e})$

- Decomposition of the translation model

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

- phrase translation probability ϕ
- reordering probability d

Distance-Based Reordering



phrase	translates	movement	distance
1	1–3	start at beginning	0
2	6	skip over 4–5	+2
3	4–5	move back over 4–6	-3
4	7	skip over 6	+1

Scoring function: $d(x) = \alpha^{|x|}$ — exponential with distance



training

Learning a Phrase Translation Table

- Task: learn the model from a parallel corpus
- Three stages:
 - word alignment: using IBM models or other method
 - extraction of phrase pairs
 - scoring phrase pairs

Word Alignment

13



	michael	geht	davon	aus	,	dass	er	im	haus	bleibt
michael										
assumes										
that										
he										
will										
stay										
in										
the										
house										

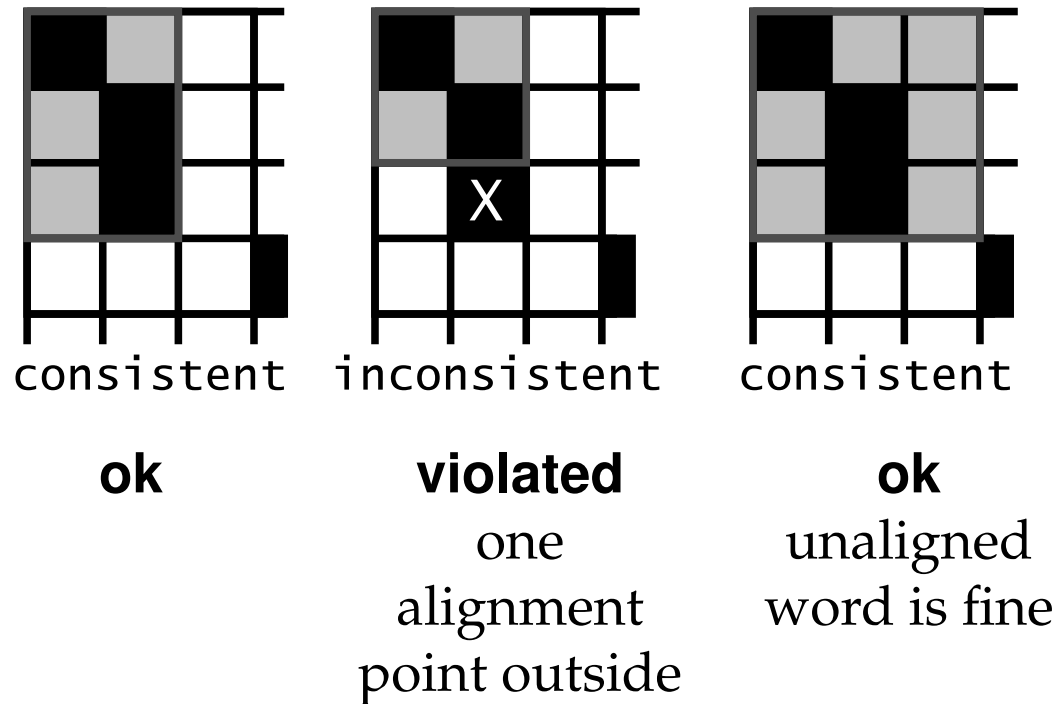
Extracting Phrase Pairs

	michael	geht	davon	aus	,	dass	er	im	haus	bleibt
michael										
assumes										
that										
he										
will										
stay										
in										
the										
house										

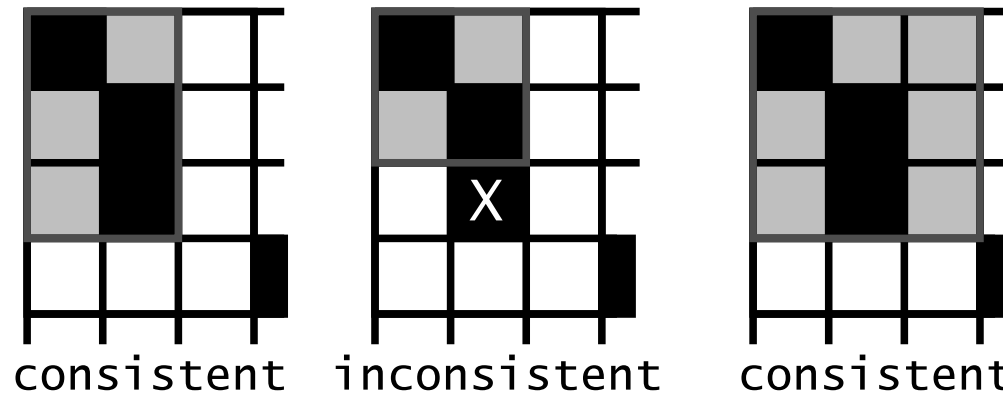
extract phrase pair consistent with word alignment:

assumes that / geht davon aus , dass

Consistent



All words of the phrase pair have to align to each other.



Phrase pair (\bar{e}, \bar{f}) consistent with an alignment A , if all words f_1, \dots, f_n in \bar{f} that have alignment points in A have these with words e_1, \dots, e_n in \bar{e} and vice versa:

(\bar{e}, \bar{f}) consistent with $A \Leftrightarrow$

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

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

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

Phrase Pair Extraction

	michael	geht	davon	aus	,	dass	er	im	haus	bleibt
michael	■									
assumes		■	■	■						
that						■				
he							■			
will										■
stay										■
in								■		
the								■		
house									■	

Smallest phrase pairs:

michael — michael

assumes — geht davon aus / geht davon aus ,

that — dass / , dass

he — er

will stay — bleibt

in the — im

house — haus

unaligned words (here: German comma) lead to multiple translations

Larger Phrase Pairs

	michael	geht	davon	aus	,	dass	er	im	haus	bleibt
michael	■									
assumes		■	■	■						
that						■				
he							■			
will										■
stay										■
in								■		
the								■		
house									■	

michael assumes — michael geht davon aus / michael geht davon aus ,
 assumes that — geht davon aus , dass ; assumes that he — geht davon aus , dass er
 that he — dass er / , dass er ; in the house — im haus
 michael assumes that — michael geht davon aus , dass
 michael assumes that he — michael geht davon aus , dass er
 michael assumes that he will stay in the house — michael geht davon aus , dass er im haus bleibt
 assumes that he will stay in the house — geht davon aus , dass er im haus bleibt
 that he will stay in the house — dass er im haus bleibt ; dass er im haus bleibt ,
 he will stay in the house — er im haus bleibt ; will stay in the house — im haus bleibt

Scoring Phrase Translations

- Phrase pair extraction: collect all phrase pairs from the data
- Phrase pair scoring: assign probabilities to phrase translations
- Score by relative frequency:

$$\phi(\bar{f}|\bar{e}) = \frac{\text{count}(\bar{e}, \bar{f})}{\sum_{\bar{f}_i} \text{count}(\bar{e}, \bar{f}_i)}$$

EM Training of the Phrase Model

- We presented a heuristic set-up to build phrase translation table (word alignment, phrase extraction, phrase scoring)
- Alternative: align phrase pairs directly with EM algorithm
 - initialization: uniform model, all $\phi(\bar{e}, \bar{f})$ are the same
 - expectation step:
 - * estimate likelihood of all possible phrase alignments for all sentence pairs
 - maximization step:
 - * collect counts for phrase pairs (\bar{e}, \bar{f}) , weighted by alignment probability
 - * update phrase translation probabilities $p(\bar{e}, \bar{f})$
- However: method easily overfits (learns very large phrase pairs, spanning entire sentences)

Size of the Phrase Table

- Phrase translation table typically bigger than corpus
... even with limits on phrase lengths (e.g., max 7 words)

→ Too big to store in memory?

- Solution for training
 - extract to disk, sort, construct for one source phrase at a time
- Solutions for decoding
 - on-disk data structures with index for quick look-ups
 - suffix arrays to create phrase pairs on demand

advanced modeling

Weighted Model

- Described standard model consists of three sub-models
 - phrase translation model $\phi(\bar{f}|\bar{e})$
 - reordering model d
 - language model $p_{LM}(e)$

$$e_{\text{best}} = \operatorname{argmax}_e \prod_{i=1}^I \phi(\bar{f}_i|\bar{e}_i) d(\text{start}_i - \text{end}_{i-1} - 1) \prod_{i=1}^{|\mathbf{e}|} p_{LM}(e_i|e_1\dots e_{i-1})$$

- Some sub-models may be more important than others
- Add weights $\lambda_\phi, \lambda_d, \lambda_{LM}$

$$e_{\text{best}} = \operatorname{argmax}_e \prod_{i=1}^I \phi(\bar{f}_i|\bar{e}_i)^{\lambda_\phi} d(\text{start}_i - \text{end}_{i-1} - 1)^{\lambda_d} \prod_{i=1}^{|\mathbf{e}|} p_{LM}(e_i|e_1\dots e_{i-1})^{\lambda_{LM}}$$

Log-Linear Model

- Such a weighted model is a log-linear model:

$$p(x) = \exp \sum_{i=1}^n \lambda_i h_i(x)$$

- Our feature functions
 - number of feature function $n = 3$
 - random variable $x = (e, f, start, end)$
 - feature function $h_1 = \log \phi$
 - feature function $h_2 = \log d$
 - feature function $h_3 = \log p_{\text{LM}}$

Weighted Model as Log-Linear Model

$$p(e, a|f) = \exp(\lambda_\phi \sum_{i=1}^I \log \phi(\bar{f}_i|\bar{e}_i) + \\ \lambda_d \sum_{i=1}^I \log d(a_i - b_{i-1} - 1) + \\ \lambda_{LM} \sum_{i=1}^{|e|} \log p_{LM}(e_i|e_1 \dots e_{i-1}))$$

More Feature Functions

- Bidirectional alignment probabilities: $\phi(\bar{e}|\bar{f})$ and $\phi(\bar{f}|\bar{e})$
- Rare phrase pairs have unreliable phrase translation probability estimates
→ lexical weighting with word translation probabilities

	geht	nicht	davon	aus	NULL
does					
not					
assume					

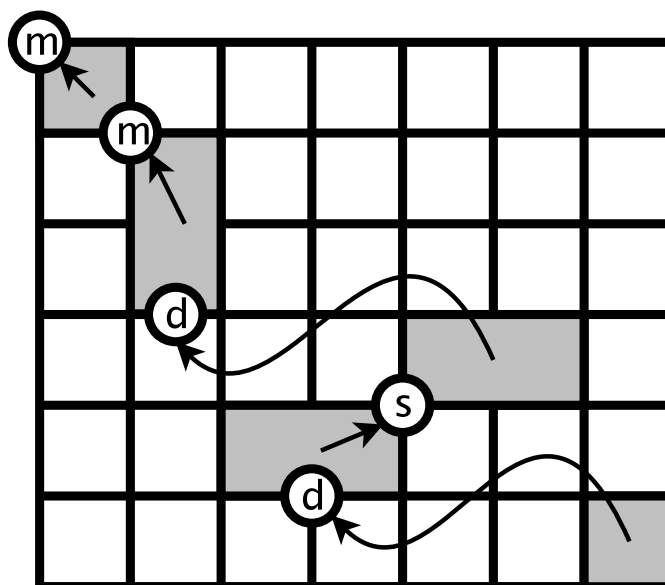
$$\text{lex}(\bar{e}|\bar{f}, a) = \prod_{i=1}^{\text{length}(\bar{e})} \frac{1}{|\{j | (i, j) \in a\}|} \sum_{\forall (i, j) \in a} w(e_i | f_j)$$

More Feature Functions

- Language model has a bias towards short translations
→ word count: $wc(e) = \log |e|^\omega$
- We may prefer finer or coarser segmentation
→ phrase count $pc(e) = \log |I|^\rho$
- Multiple language models
- Multiple translation models
- Other knowledge sources

reordering

Lexicalized Reordering

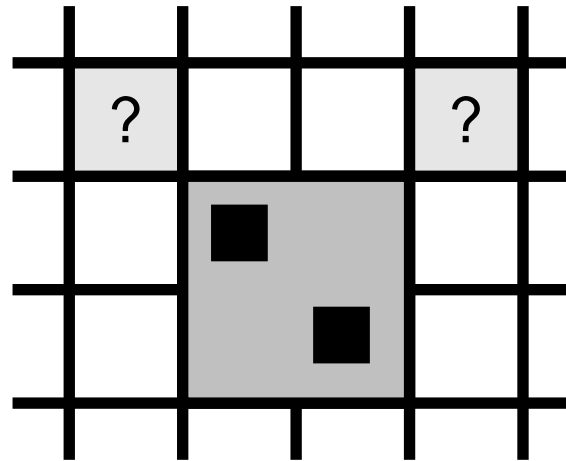


- Distance-based reordering model is weak
→ learn reordering preference for each phrase pair
- Three orientations types: (m) monotone, (s) swap, (d) discontinuous

orientation $\in \{m, s, d\}$

$p_o(\text{orientation} | \bar{f}, \bar{e})$

Learning Lexicalized Reordering



- Collect orientation information during phrase pair extraction
 - if word alignment point to the top left exists → **monotone**
 - if a word alignment point to the top right exists → **swap**
 - if neither a word alignment point to top left nor to the top right exists → neither monotone nor swap → **discontinuous**

- Estimation by relative frequency

$$p_o(\text{orientation}) = \frac{\sum_{\bar{f}} \sum_{\bar{e}} \text{count}(\text{orientation}, \bar{e}, \bar{f})}{\sum_o \sum_{\bar{f}} \sum_{\bar{e}} \text{count}(o, \bar{e}, \bar{f})}$$

- Smoothing with unlexicalized orientation model $p(\text{orientation})$ to avoid zero probabilities for unseen orientations

$$p_o(\text{orientation} | \bar{f}, \bar{e}) = \frac{\sigma p(\text{orientation}) + \text{count}(\text{orientation}, \bar{e}, \bar{f})}{\sigma + \sum_o \text{count}(o, \bar{e}, \bar{f})}$$

operation sequence model

A Critique: Phrase Segmentation is Arbitrary³³



- If multiple segmentations possible - why chose one over the other?

spass am spiel vs. spass am spiel

- When choose larger phrase pairs or multiple shorter phrase pairs?

spass am spiel vs. spass am spiel vs. spass am spiel

- None of this has been properly addressed

A Critique: Strong Independence Assumptions



- Lexical context considered only within phrase pairs

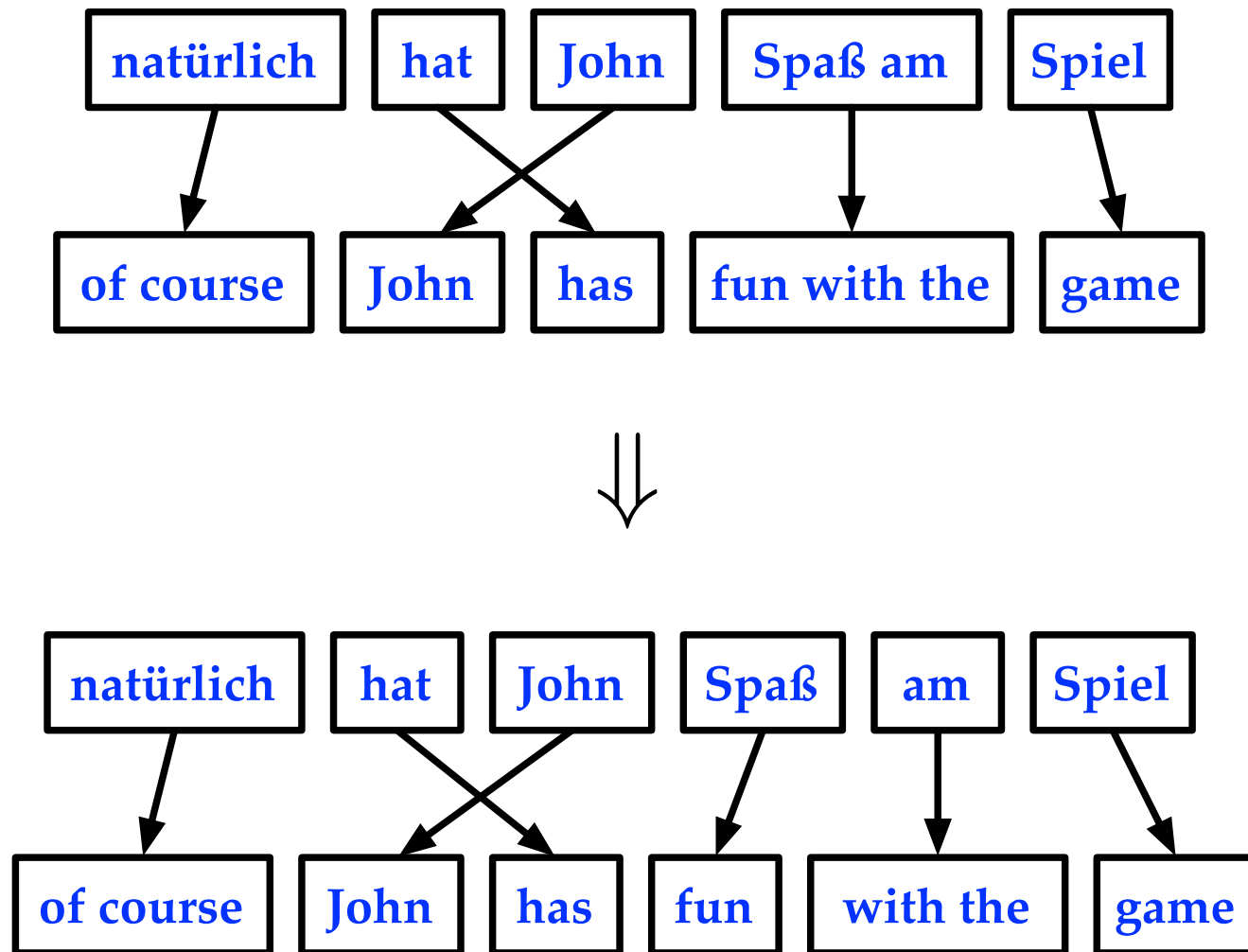
spass am → fun with

- No context considered between phrase pairs

? spass am ? → ? fun with ?

- Some phrasal context considered in lexicalized reordering model
... but not based on the identity of neighboring phrases

Segmentation? Minimal Phrase Pairs



Independence?

Consider Sequence of Operations

o_1	Generate(natürlich, of course)	natürlich ↓ of course
o_2	Insert Gap	natürlich ↓ <input type="text"/> John
o_3	Generate (John, John)	of course John
o_4	Jump Back (1)	natürlich hat ↓ John
o_5	Generate (hat, has)	of course John has
o_6	Jump Forward	natürlich hat John ↓ of course John has
o_7	Generate(natürlich, of course)	natürlich hat John Spaß ↓ of course John has fun
o_8	Generate(am, with)	natürlich hat John Spaß am ↓
o_9	GenerateTargetOnly(the)	of course John has fun with the
o_{10}	Generate(Spiel, game)	natürlich hat John Spaß am Spiel ↓ of course John has fun with the game

Operation Sequence Model

- Operations
 - generate (phrase translation)
 - generate target only
 - generate source only
 - insert gap
 - jump back
 - jump forward
- N-gram sequence model over operations, e.g., 5-gram model:

$$p(o_1) p(o_2|o_1) p(o_3|o_1, o_2) \dots p(o_{10}|o_6, o_7, o_8, o_9)$$

- Operation Sequence Model used as additional feature function
 - Significant improvements over phrase-based baseline
- State-of-the-art systems include such a model

- Phrase Model
- Training the model
 - word alignment
 - phrase pair extraction
 - phrase pair scoring
 - EM training of the phrase model
- Log linear model
 - sub-models as feature functions
 - lexical weighting
 - word and phrase count features
- Lexicalized reordering model
- Operation sequence model