Weighted Automata in Statistical Machine Translation

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Machine Translation

Review translation [by Google Translate]

1. The room it is not narrowly was a simple, bathtub was also attached.
2. Wi-fi, TV and I was available.
3. Church looked When morning awake open the curtain.
4. When looking at often, wives, went out and is invited to try to go [...].
5. But was a little cold, morning walks was good.

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5. But was a little cold, morning walks was good.

Original [Japanese — © tripadvisor]

1. 部屋もシンプルでしたが狭くなく、バスタブもついていました。
2. Wi-fi、テレビも利用出来ました。
3. 朝起きてカーテンを開けると教会が見えました。
4. しばし眺めていると、妻たちは、[...]るから行こうとさそわれ出かけました。
5. ちょっと寒かったけれど、朝の散策はグッドでしたよ。

Danish-to-English Translation

Sample translation [by phrase-based Moses]

1. I think Danish is a hard language, though it looks like German.
2. Fortunately talking almost all Danes English, especially the young.
3. The boys come too late, but the girls come on time.

Danish-to-English Translation

Sample translation [by phrase-based Moses]

1. I think Danish is a hard language, though it looks like German.
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Original Danish

1. Jeg synes at dansk er et svært sprog, selvom det ligner tysk.
2. Heldigvis snakker næsten alle danskere engelsk, især de unge.
3. Drengene kom for sent, men pigerne kom til tiden.

Short History

Timeline

1960 – Dark age

- rule-based systems (e.g., SYSTRAN)
- Chomskyan approach (perfect translation, poor coverage)

1991 – Reformation

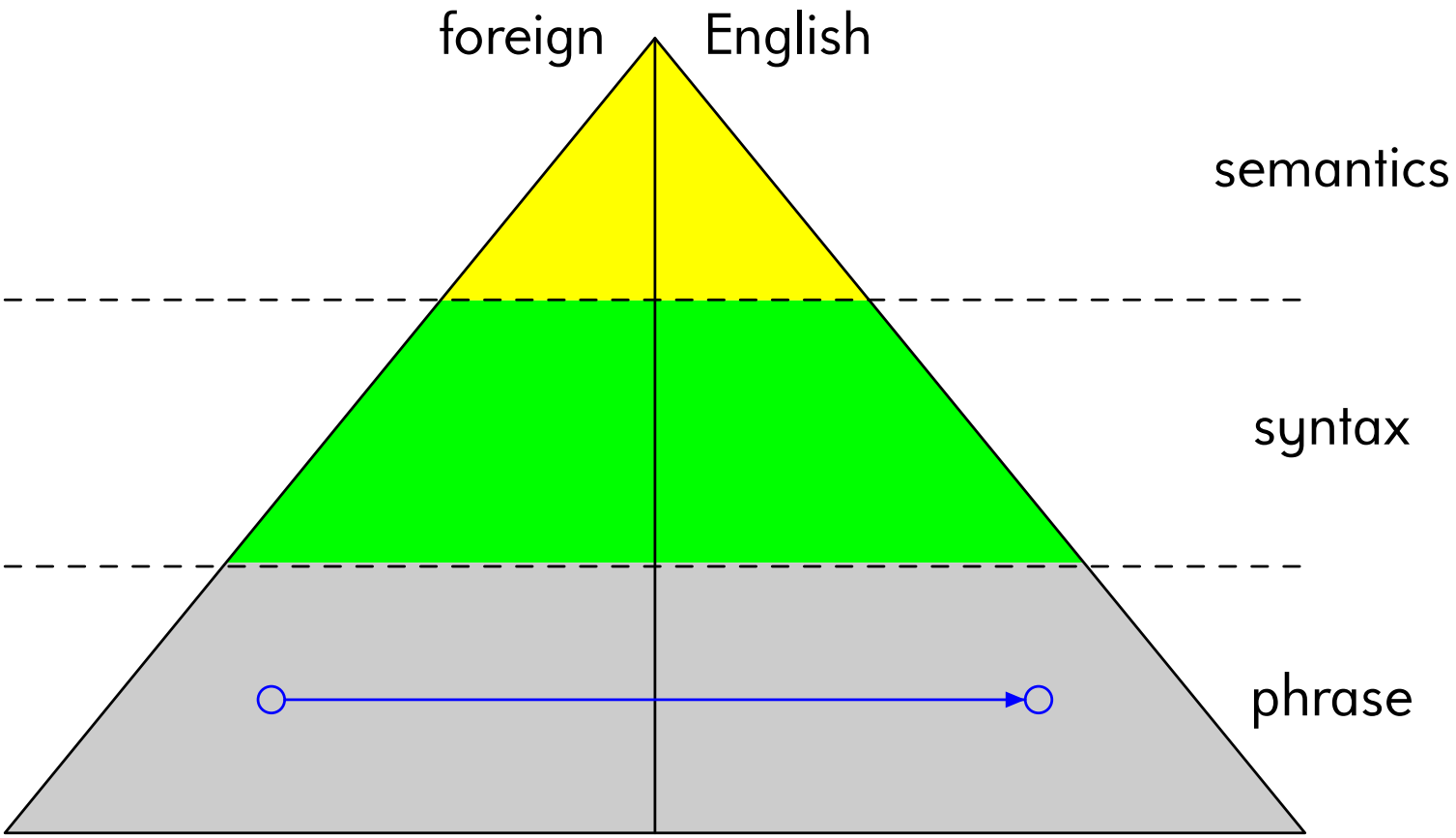
- phrase-based and syntax-based systems
- statistical approach (cheap, automatically trained)

2016 – Potential future

- semantics-based systems (e.g., FrameNet-based)
- semi-supervised, statistical approach
- basic understanding of (translated) text

Machine Translation

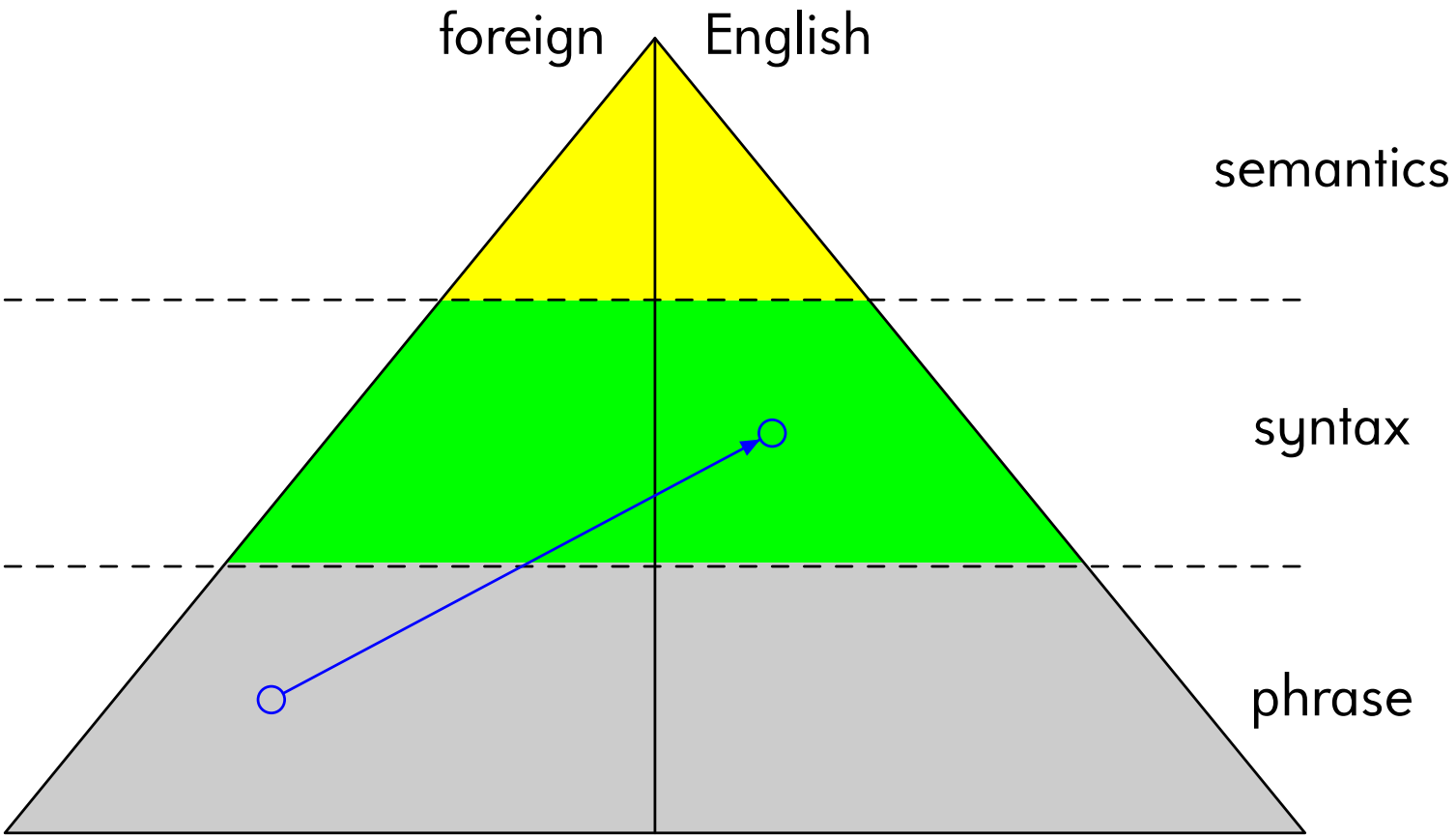
Vauquois triangle:



Translation model: string-to-string

Machine Translation

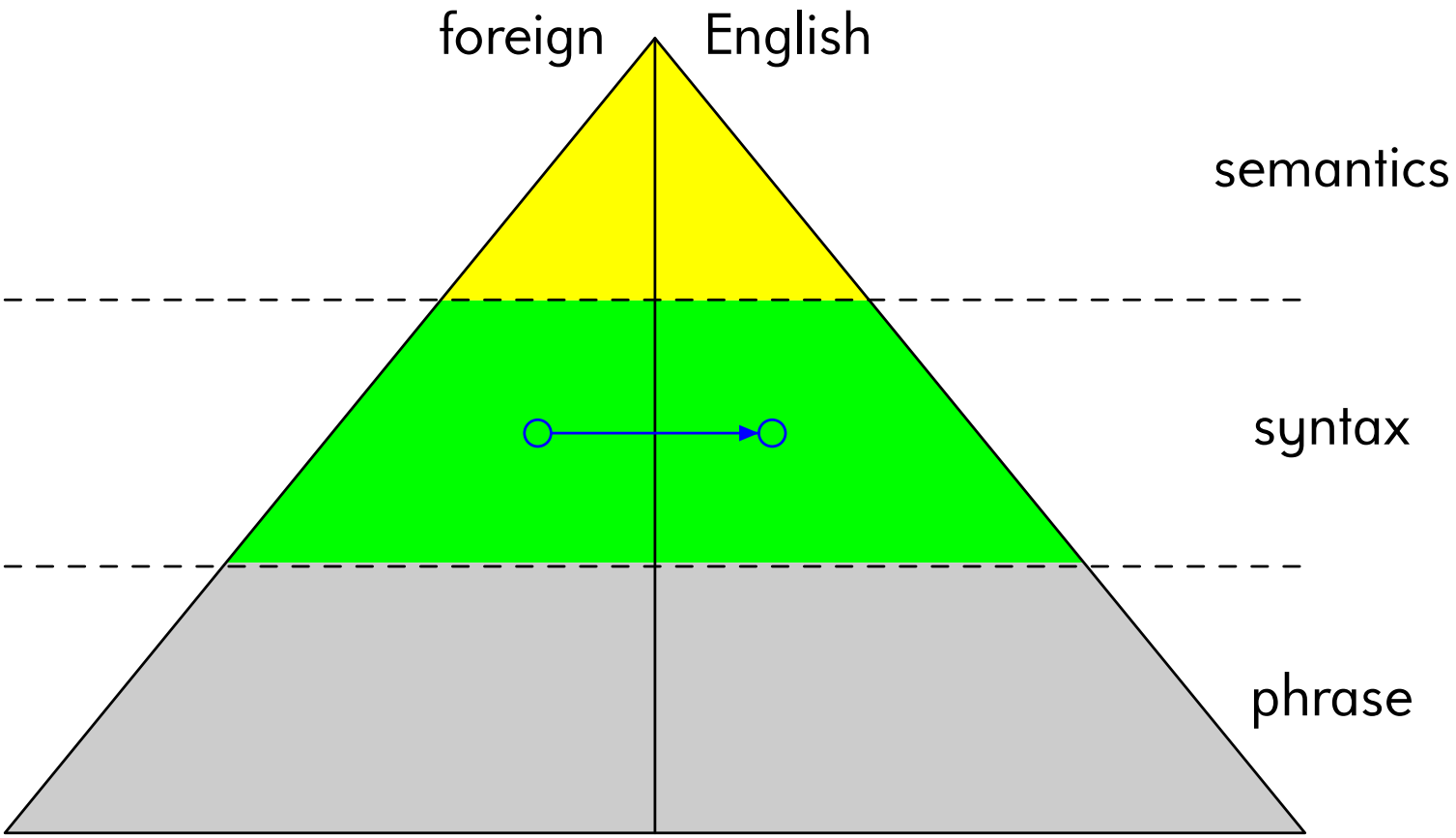
Vauquois triangle:



Translation model: string-to-tree

Machine Translation

Vauquois triangle:



Translation model: tree-to-tree

Machine Translation

Training data

- parallel corpus
- word alignments
- parse trees (for syntax-based systems)

Machine Translation

Training data

- parallel corpus
- word alignments
- parse trees (for syntax-based systems)

Parallel corpus

linguistic resource containing (sentence-by-sentence) example translations

Machine Translation

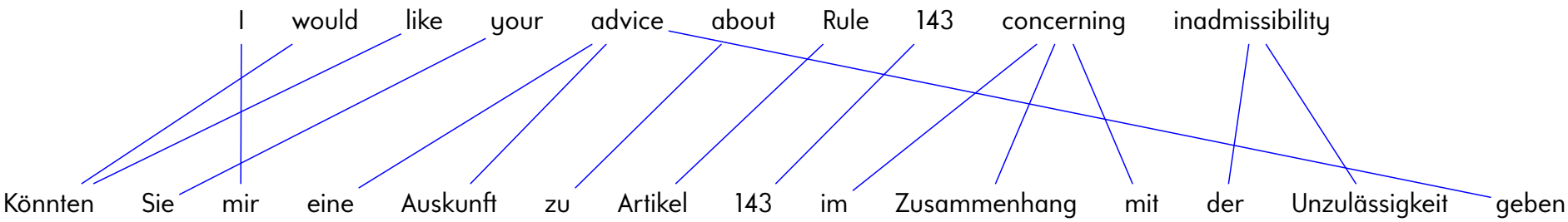
parallel corpus, word alignments, parse tree

I would like your advice about Rule 143 concerning inadmissibility

Könnten Sie mir eine Auskunft zu Artikel 143 im Zusammenhang mit der Unzulässigkeit geben

Machine Translation

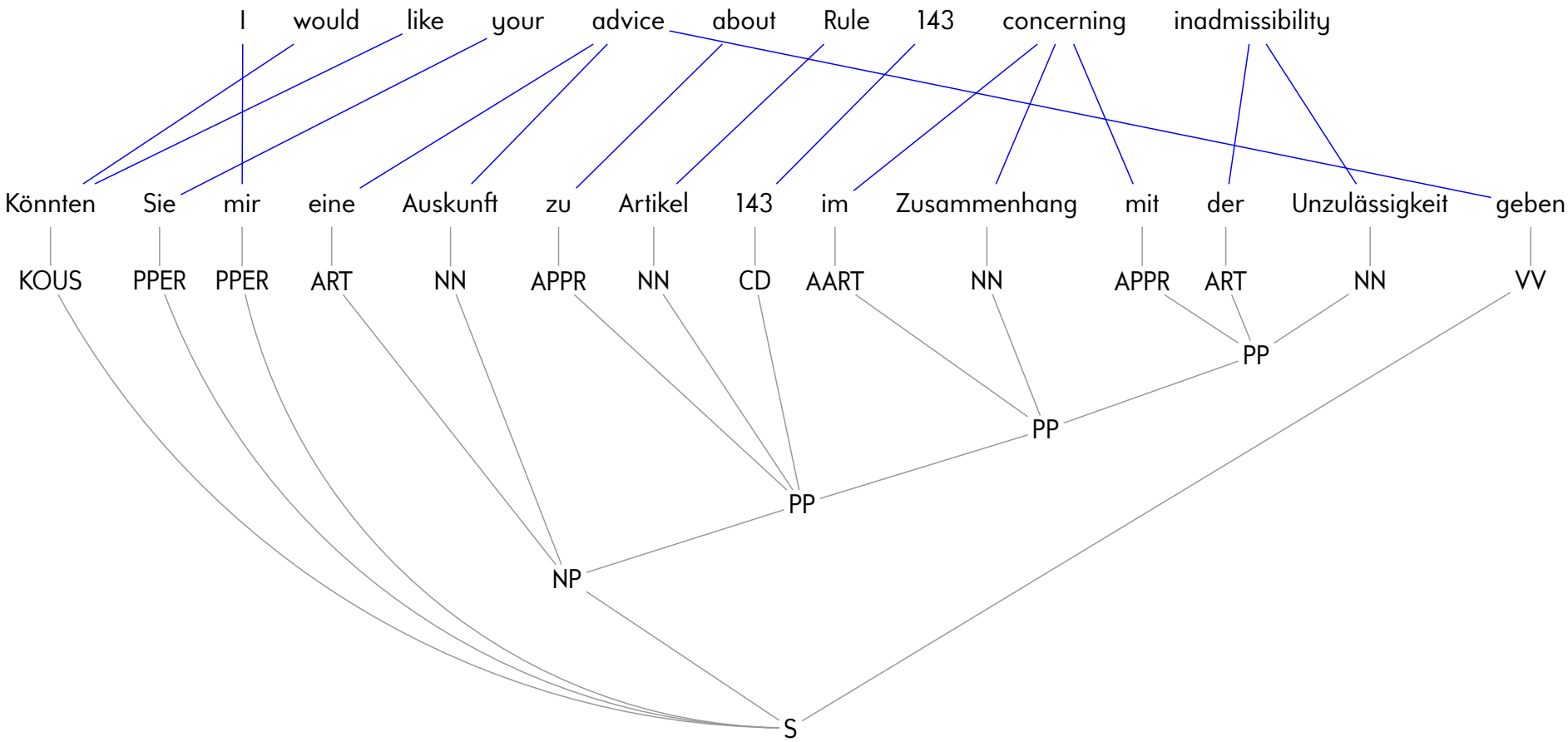
parallel corpus, word alignments, parse tree



via GIZA++ [Och, Ney: A systematic comparison of various statistical alignment models. *Computational Linguistics* 29(1), 2003]

Machine Translation

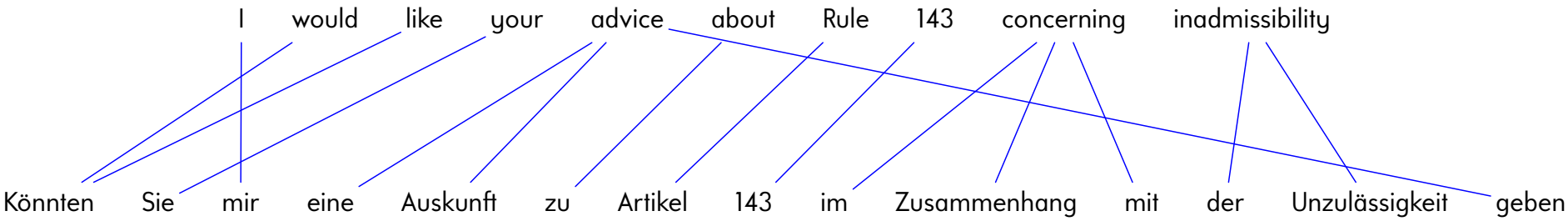
parallel corpus, word alignments, parse tree



via Berkeley parser [Petrov, Barrett, Thibaux, Klein: Learning accurate, compact, and interpretable tree annotation. *Proc. ACL*, 2006]

Phrase-based Model

Training example:



Extracted rules:

I	—	mir	would like	—	Könnten
your	—	Sie	about	—	zu
Rule	—	Artikel	143	—	143
concerning	—	im Zusammenhang mit	about Rule	—	zu Artikel
inadmissibility	—	der Unzulässigkeit			

Phrase-based Model

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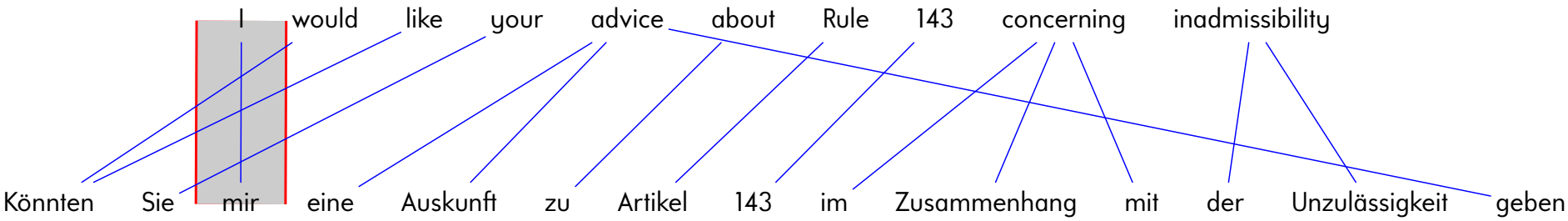

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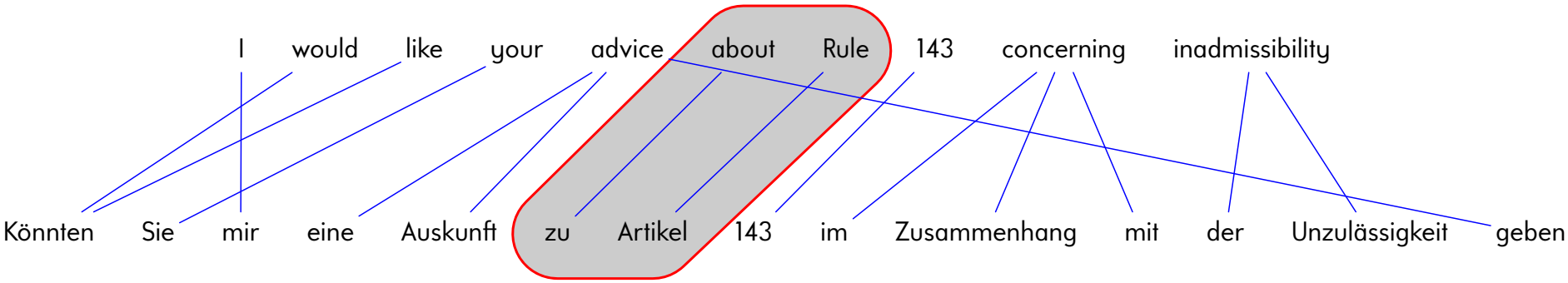

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inadmissibility	—	der Unzulässigkeit			

Phrase-based Model

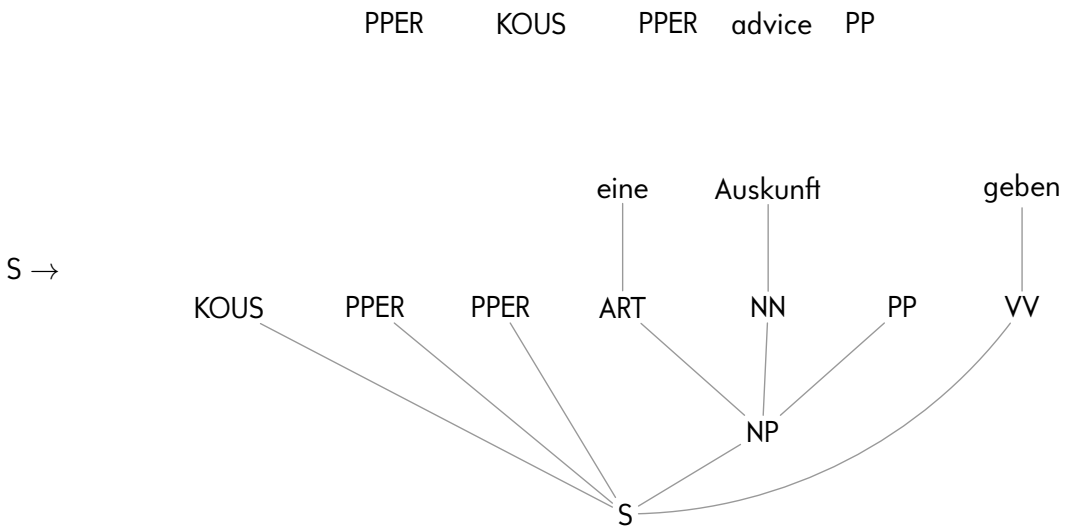
Notes

- essentially weighted finite-state transducer
- weights estimated using maximum likelihood

Weighted Synchronous Grammars

Synchronous tree substitution grammar: productions $N \to (r, r_1)$

- nonterminal N
- right-hand side r of context-free grammar production
- right-hand side r_1 of tree substitution grammar production

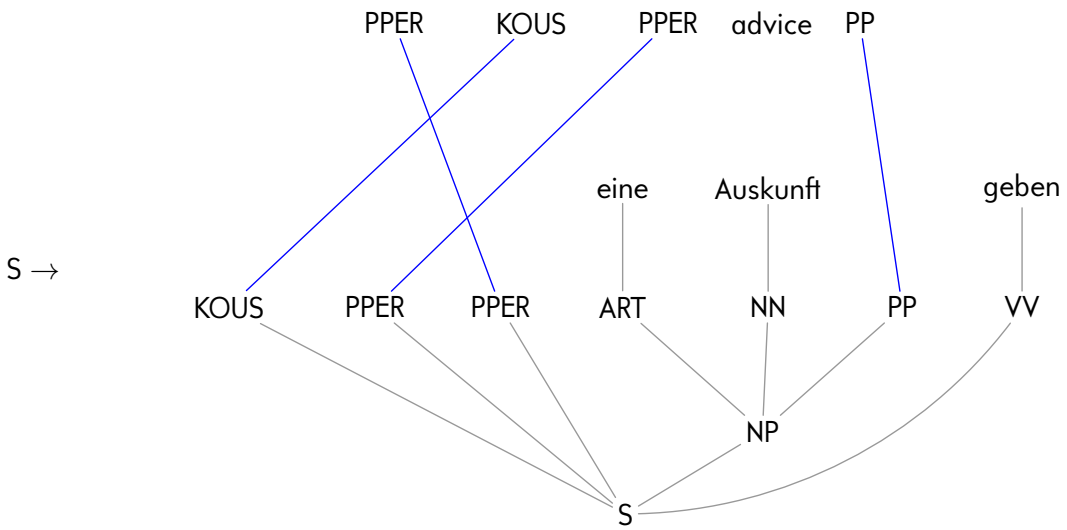


variant of [M., Graehl, Hopkins, Knight: The power of extended top-down tree transducers. *SIAM Journal on Computing* 39(2), 2009]

Weighted Synchronous Grammars

Synchronous tree substitution grammar: productions $N \to (r, r_1)$

- nonterminal N
- right-hand side r of context-free grammar production
- right-hand side r_1 of tree substitution grammar production
- (bijective) synchronization of nonterminals



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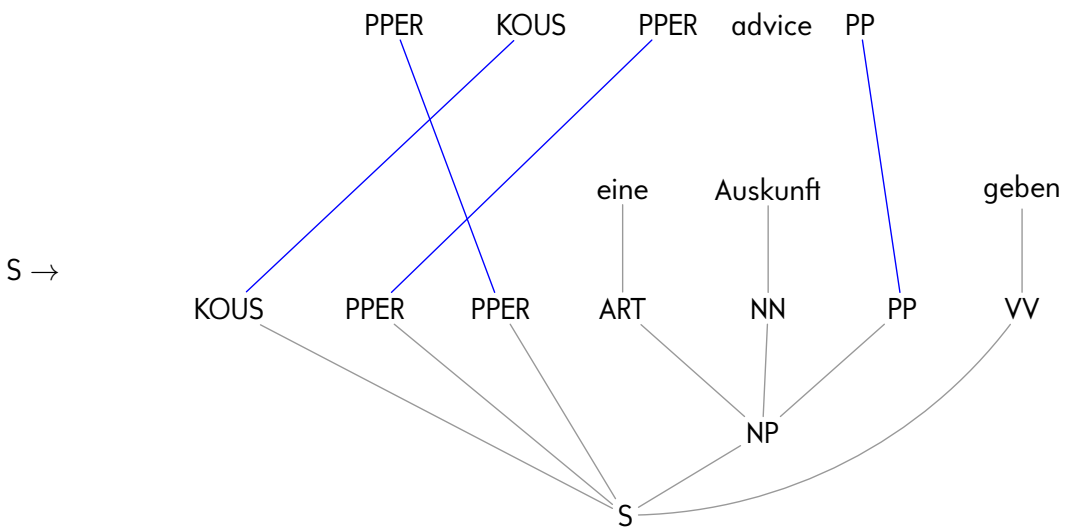
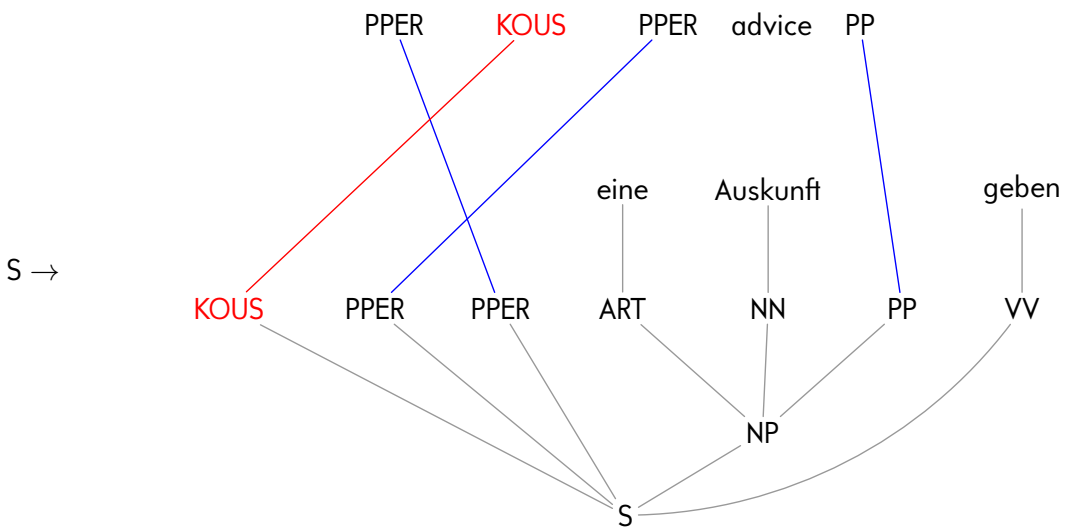
Synchronous Grammars



Production application

1. Selection of synchronous nonterminals

Synchronous Grammars



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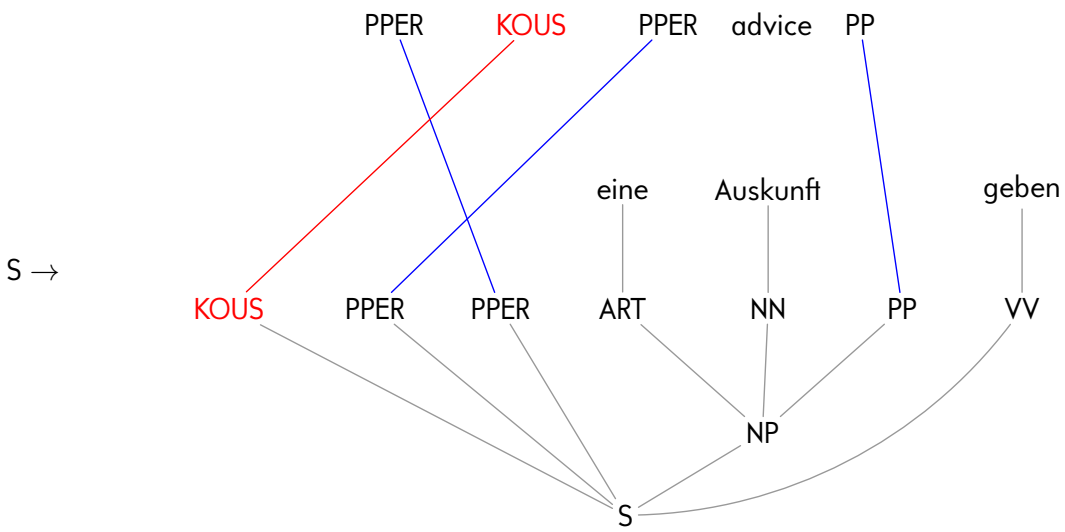


Production application

1. Selection of synchronous nonterminals
2. Selection of suitable production

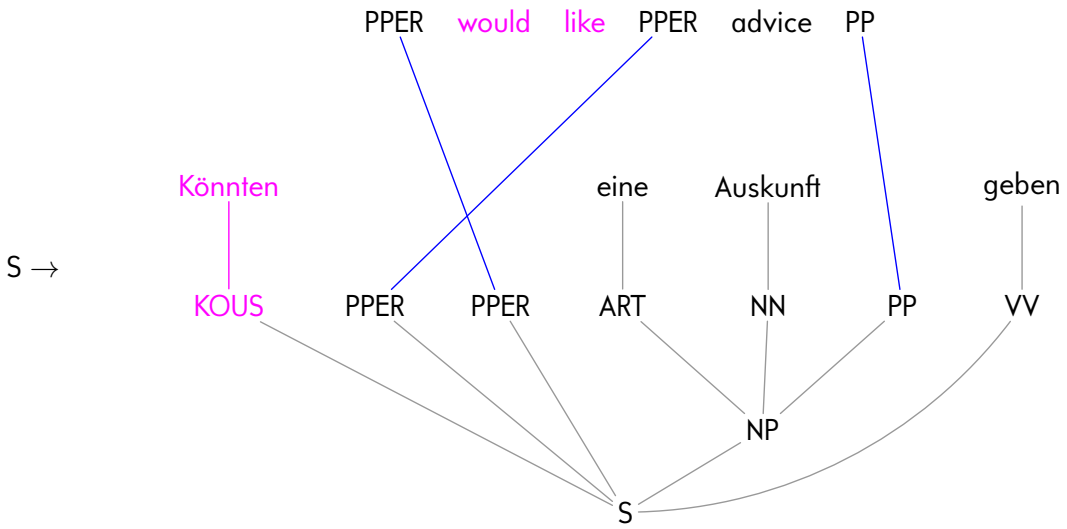
would like

KOUS →

Könnten

KOUS

Synchronous Grammars



Production application

1. Selection of synchronous nonterminals
2. Selection of suitable production
3. Replacement on both sides

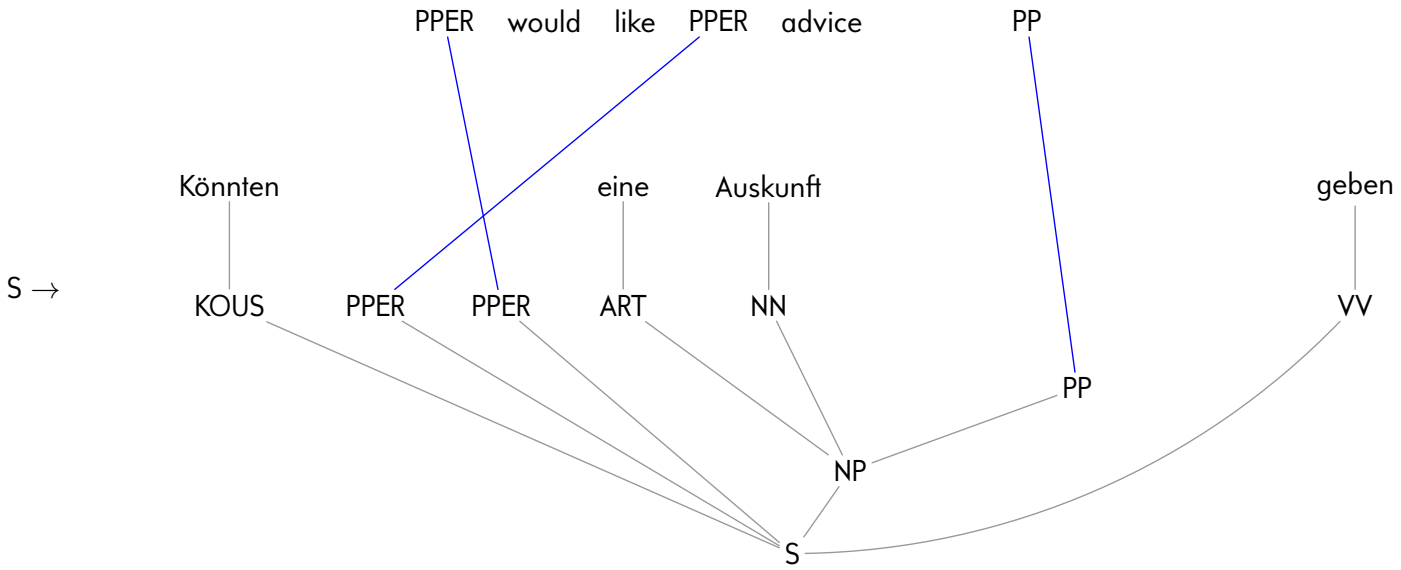
would like

KOUS →

Könnten

KOUS

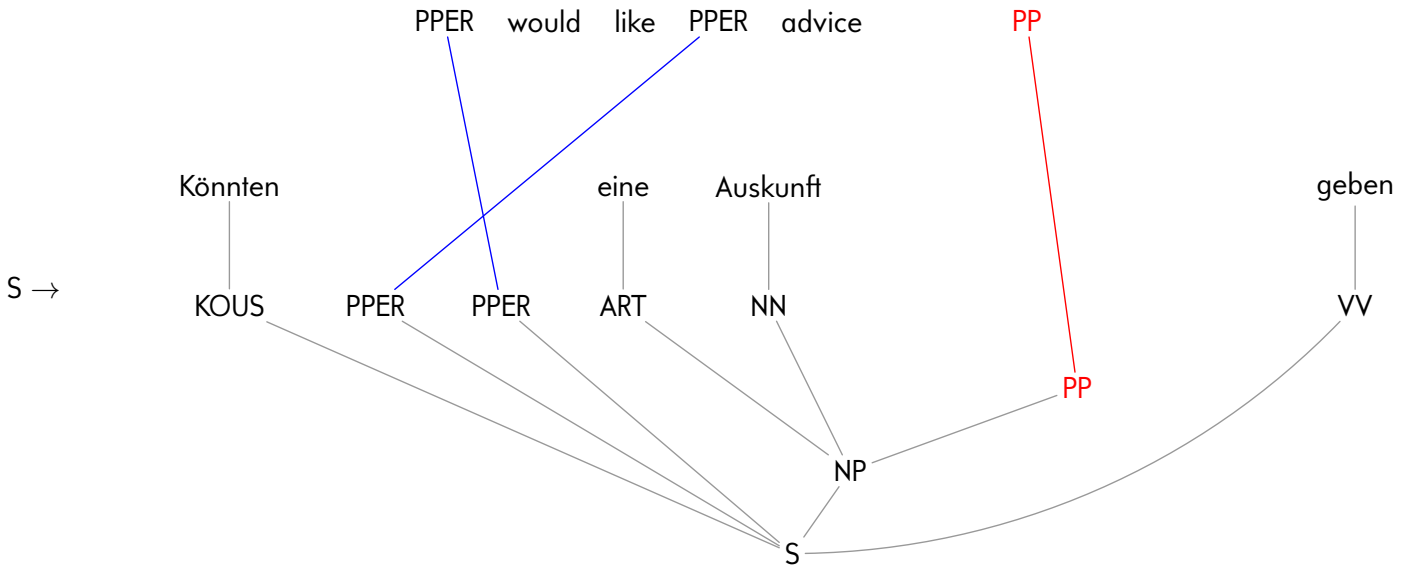
Synchronous Grammars



Production application

1. synchronous nonterminals

Synchronous Grammars



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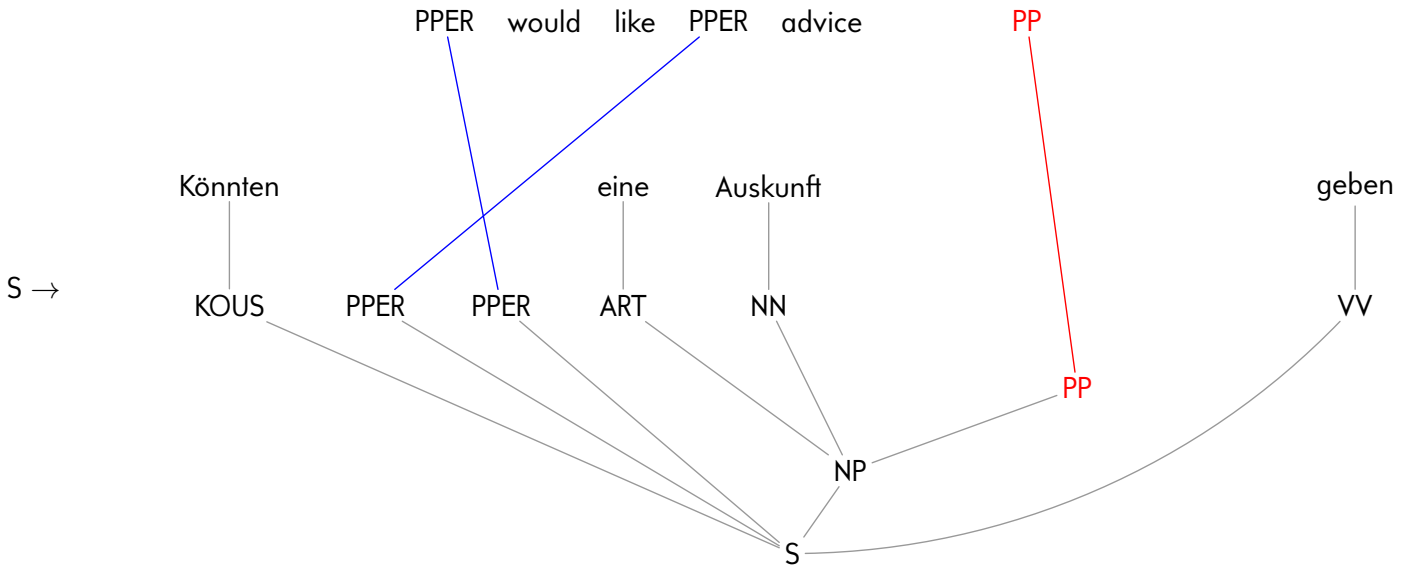
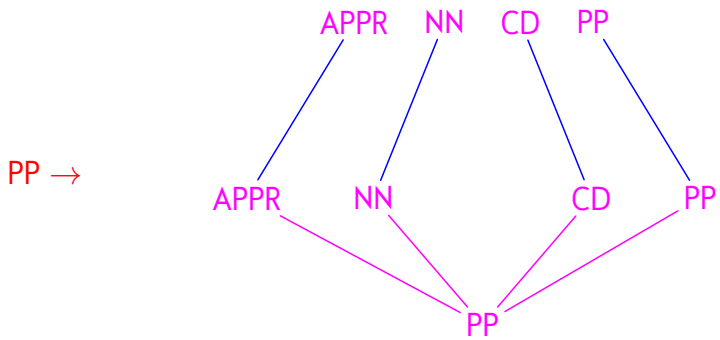
Synchronous Grammars



Production application

1. synchronous nonterminals
2. suitable production



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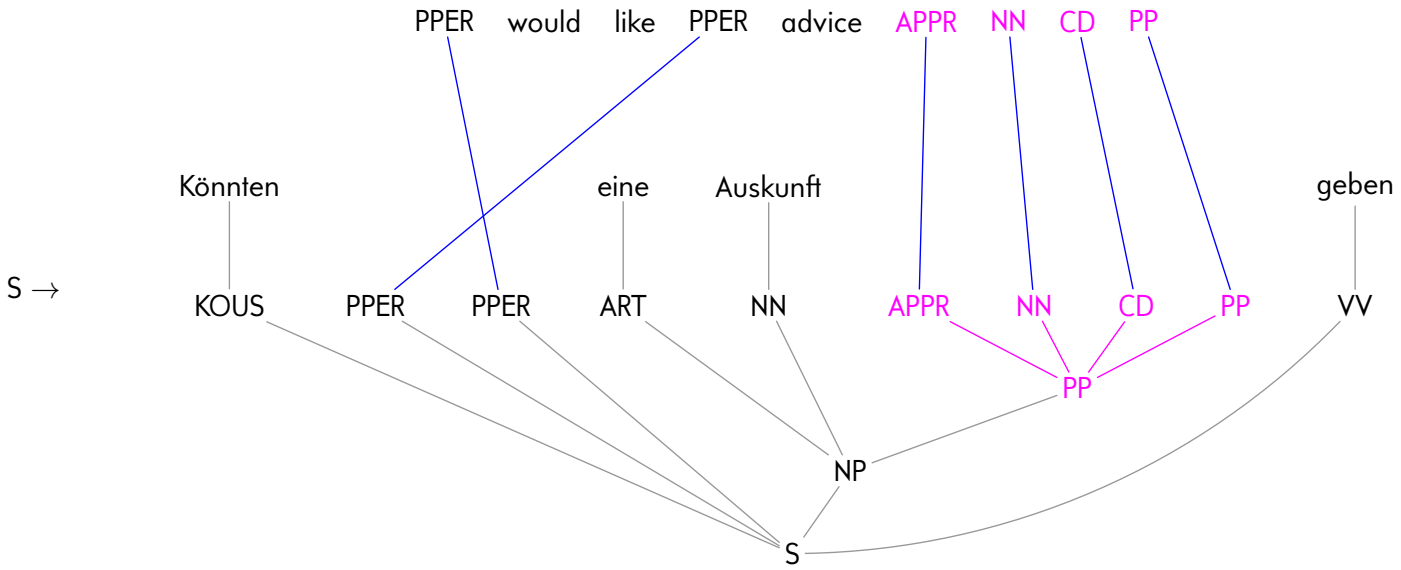
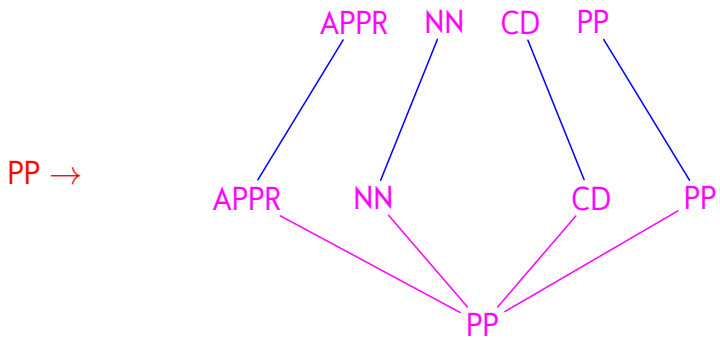
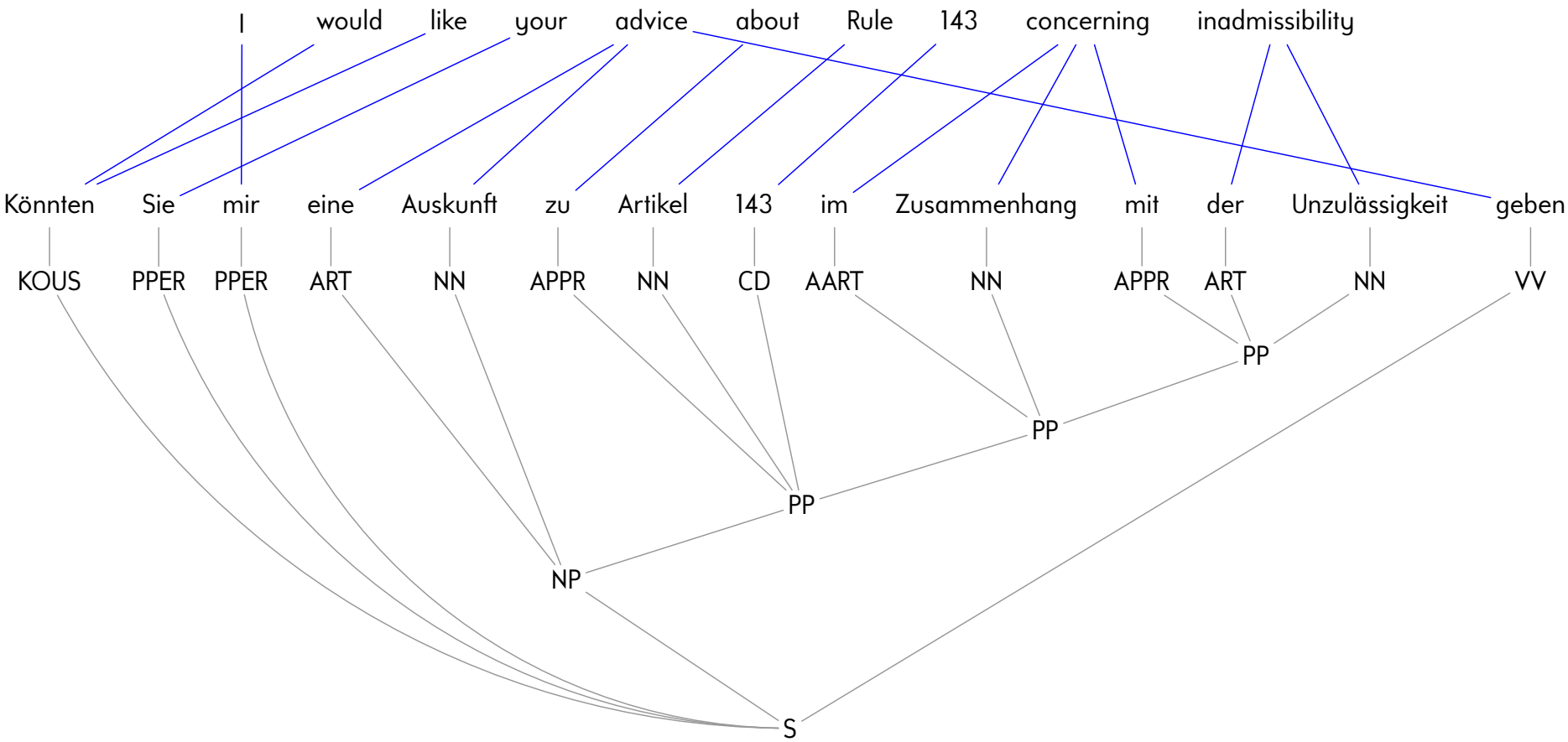


Production application

1. synchronous nonterminals
2. suitable production
3. replacement



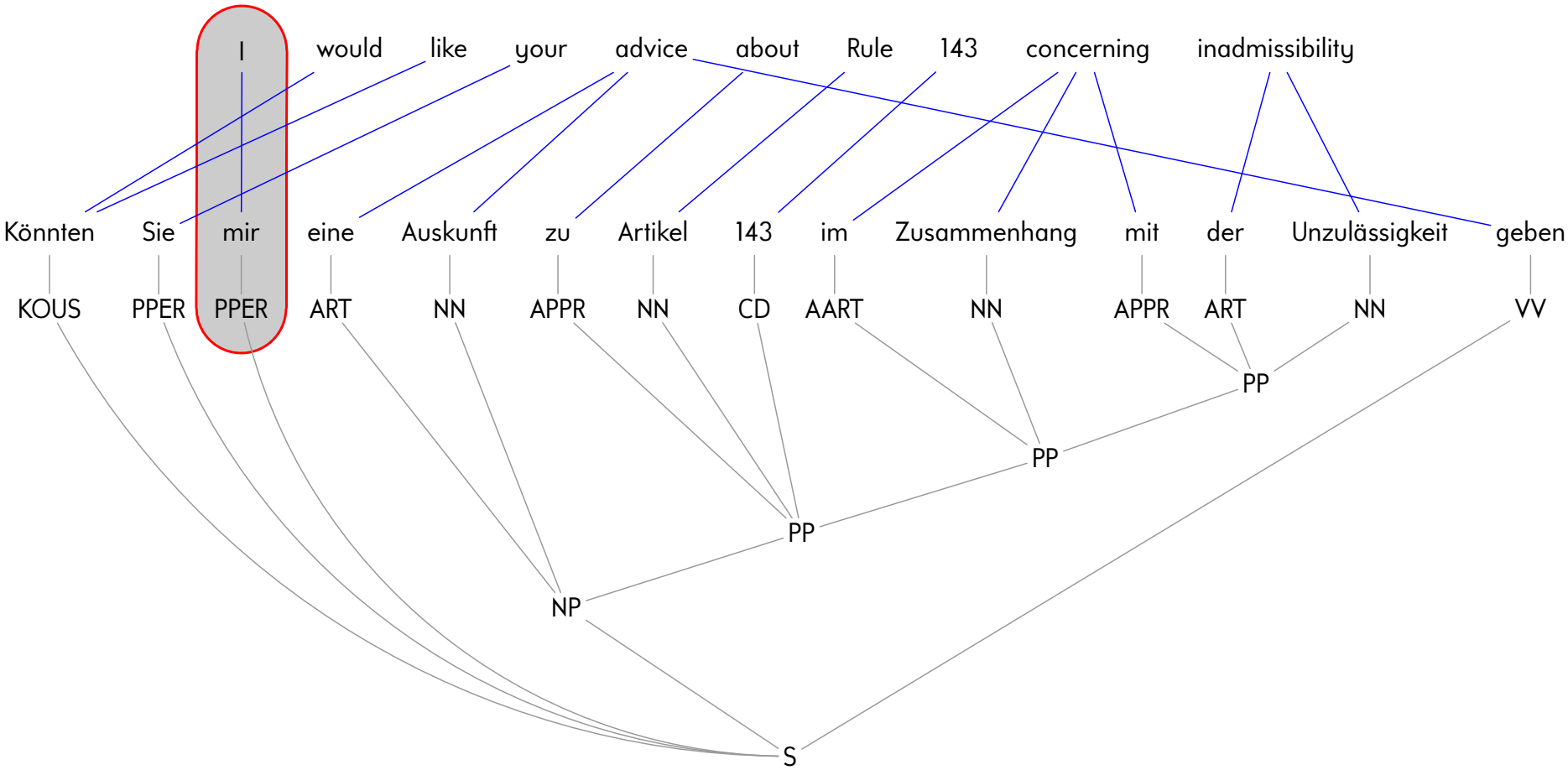
Production Extraction



following [Galley, Hopkins, Knight, Marcu: What's in a translation rule? *Proc. NAACL*, 2004]

Production Extraction

(extractable productions marked in red)



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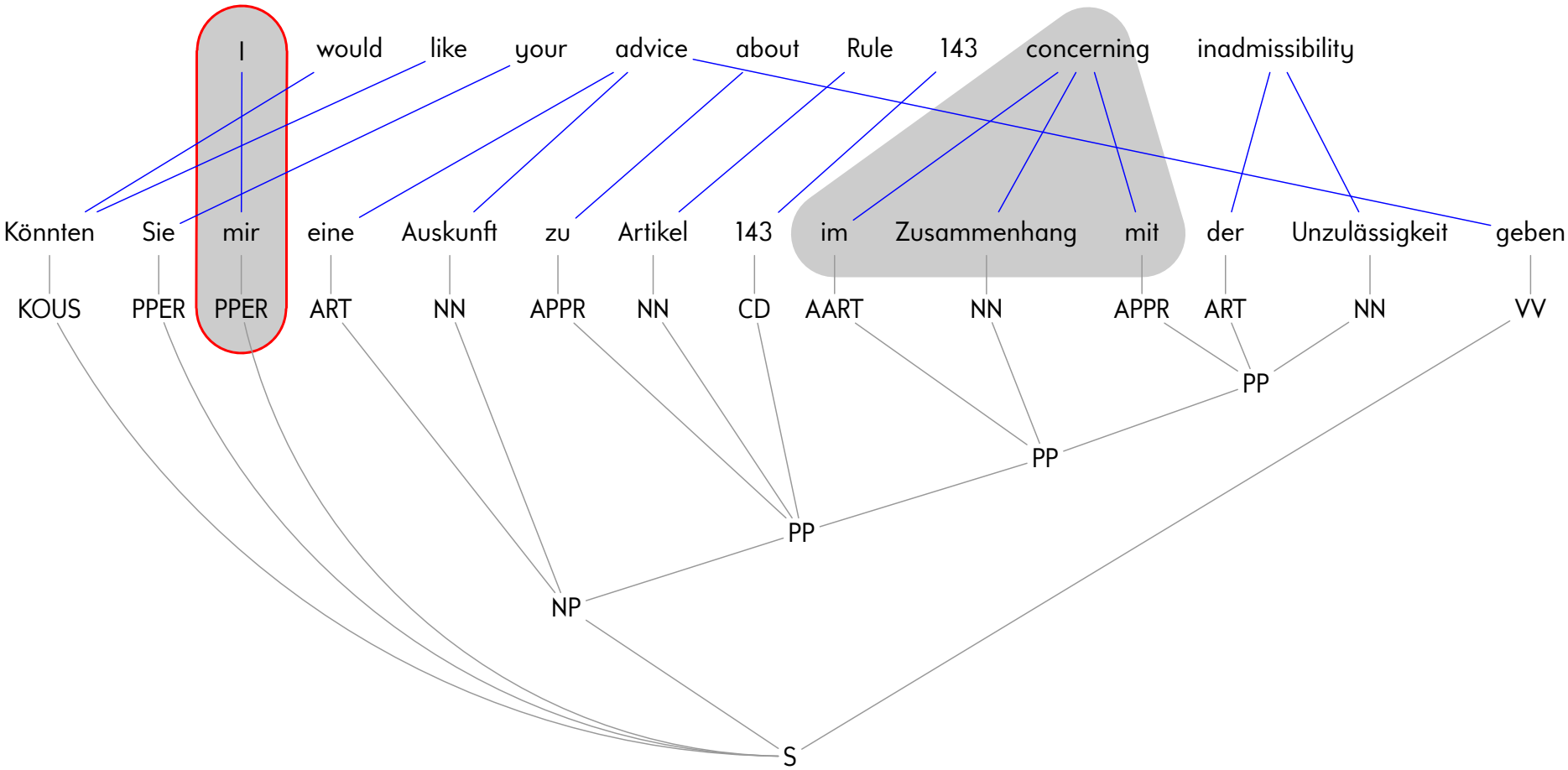

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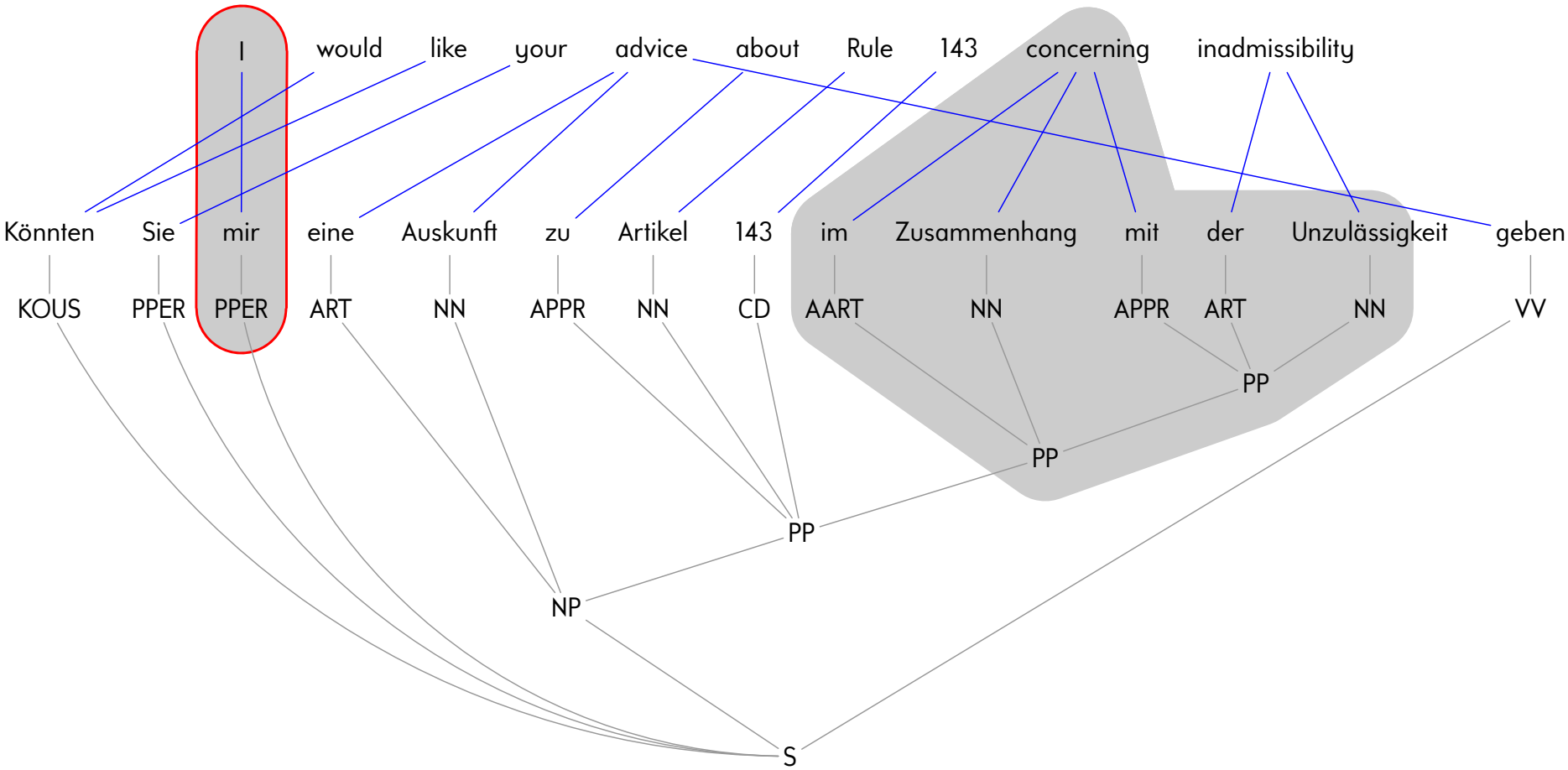

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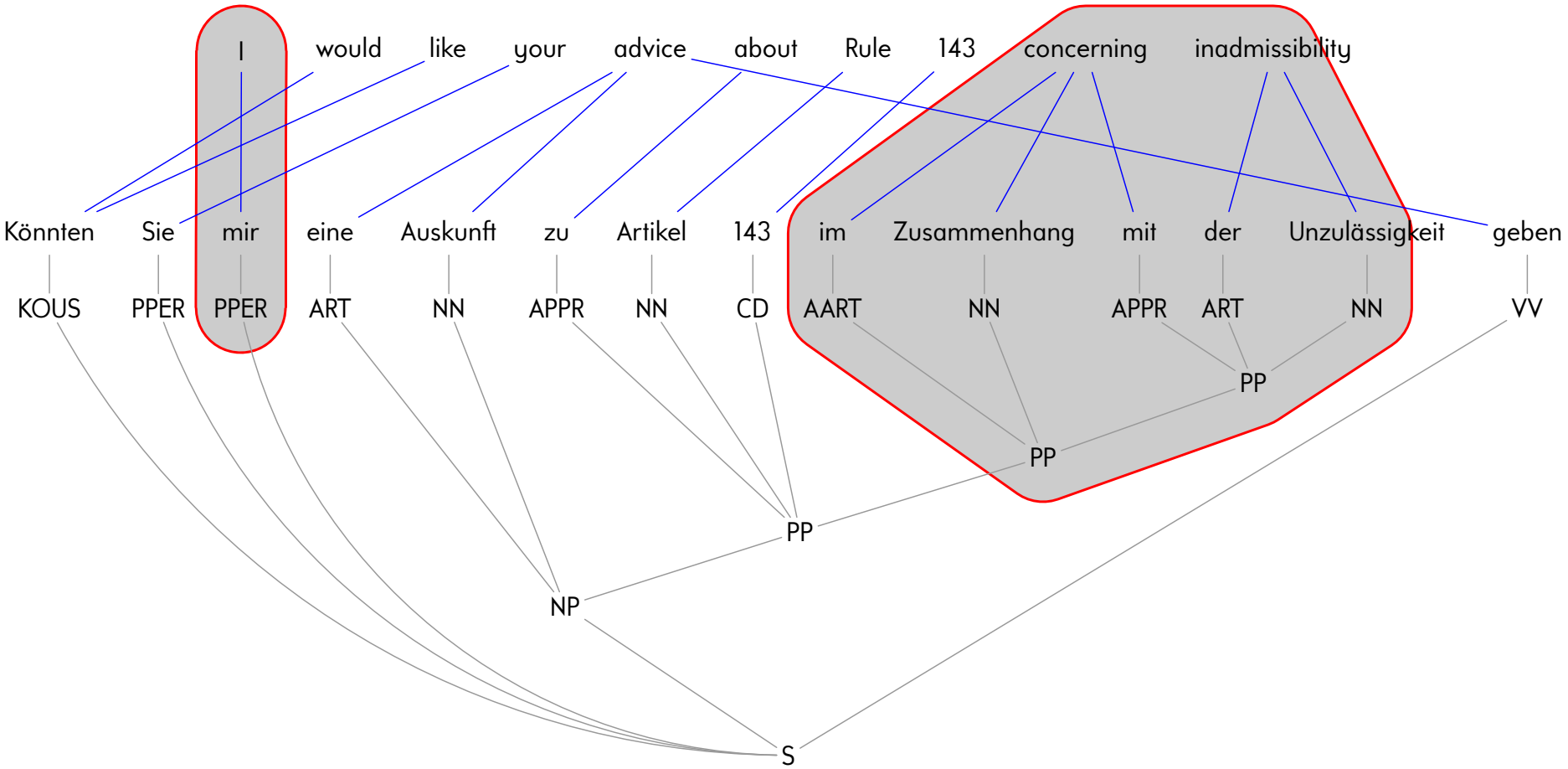

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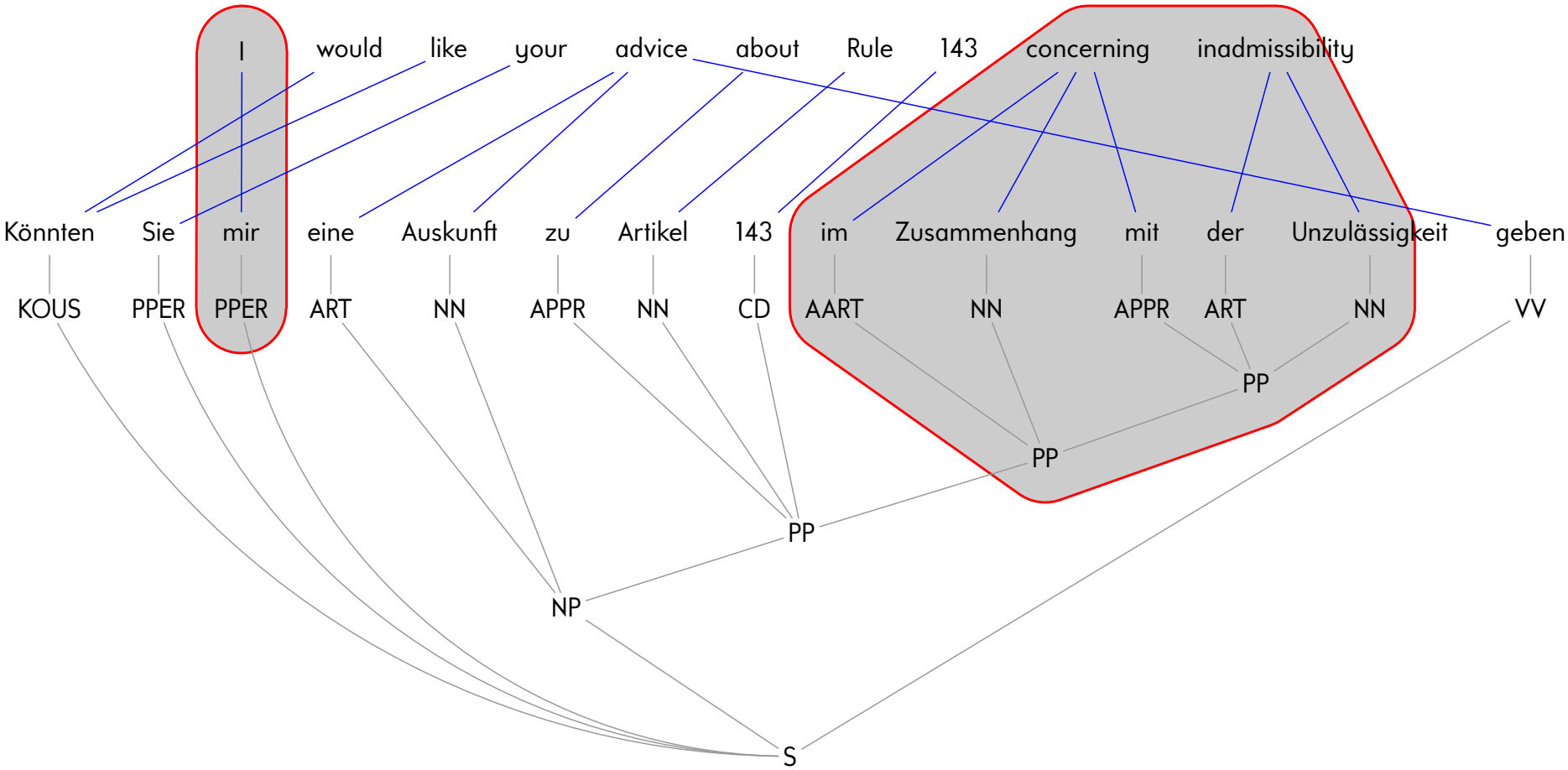
Production Extraction

Removal of extractable production:



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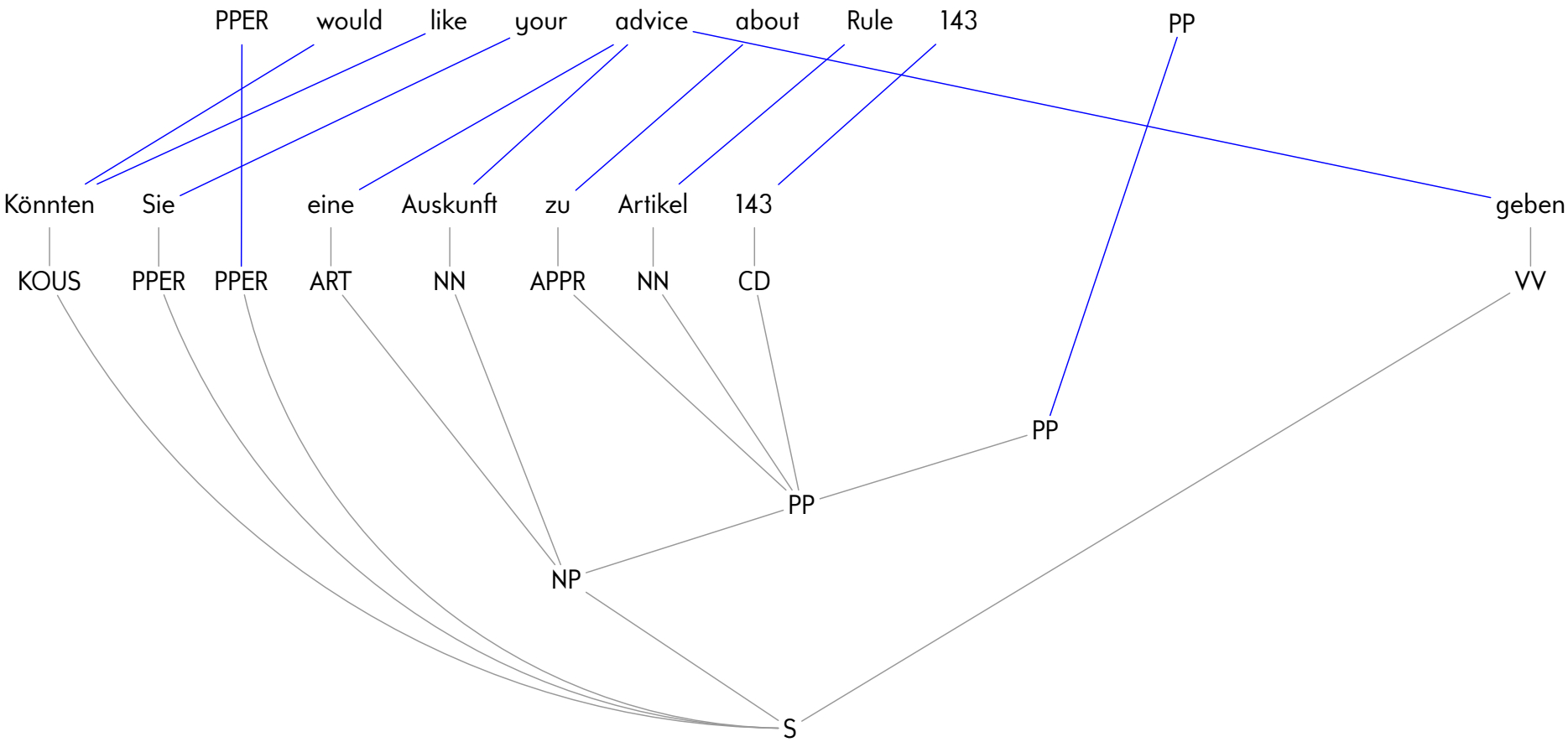
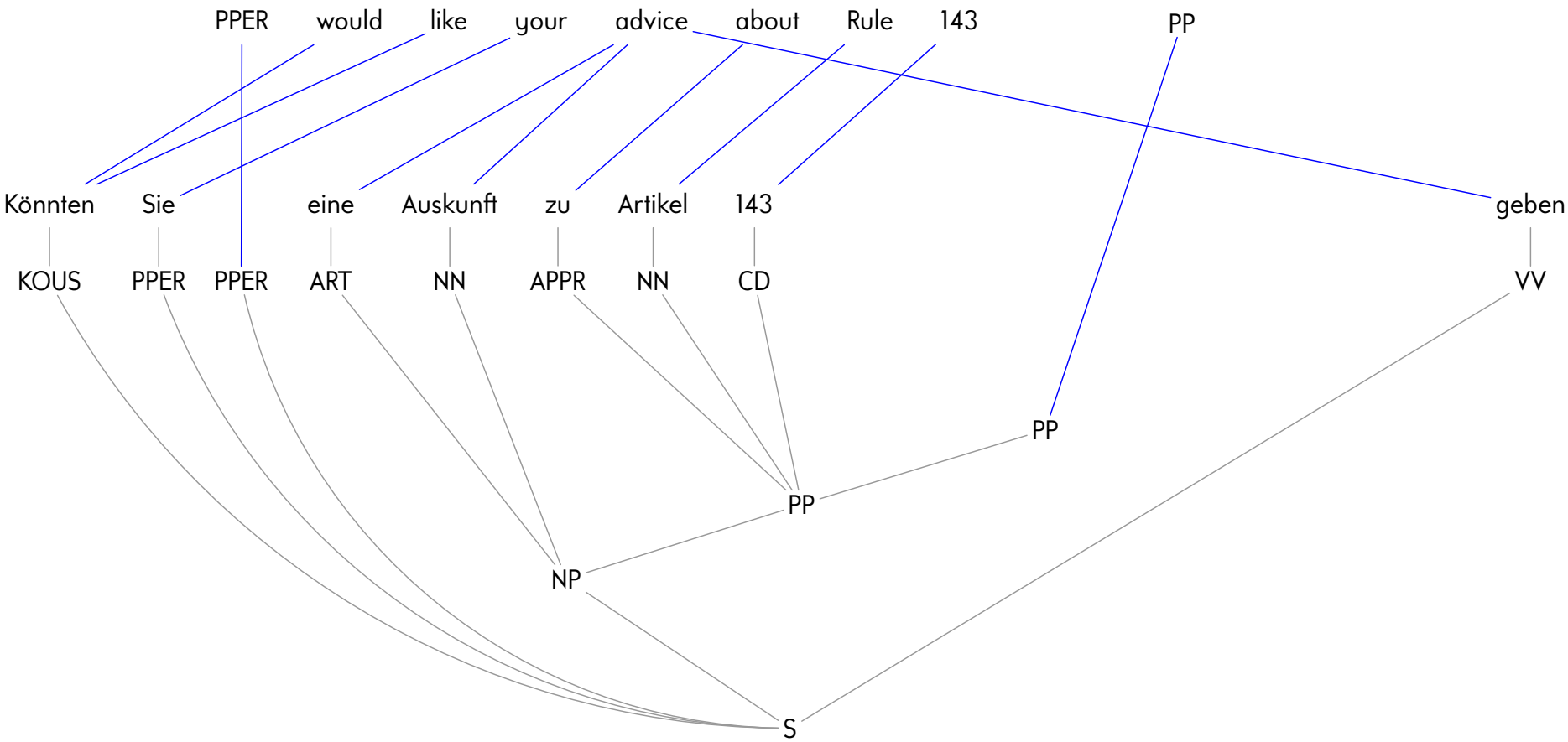


Production Extraction

Repeated production extraction:



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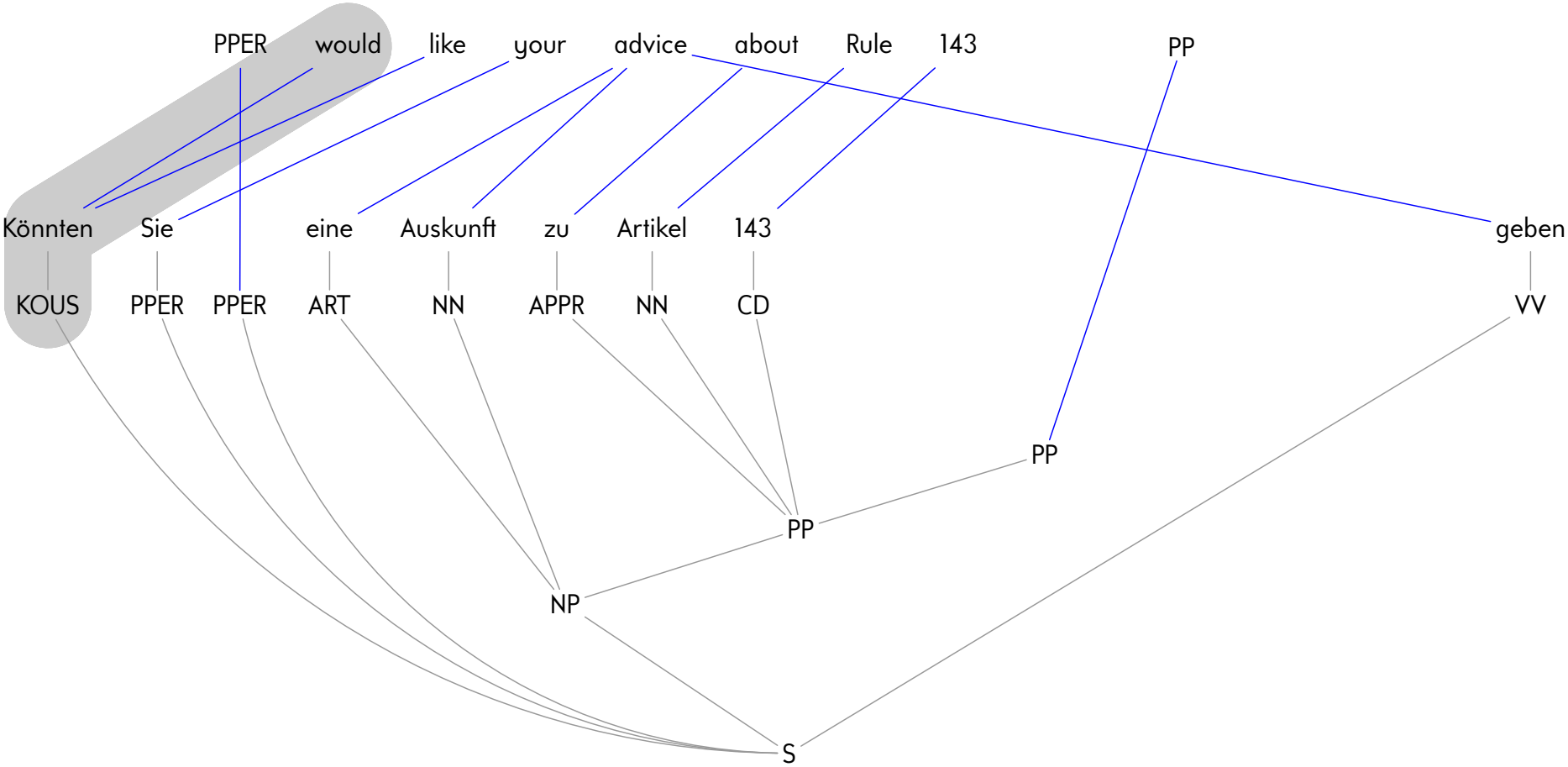

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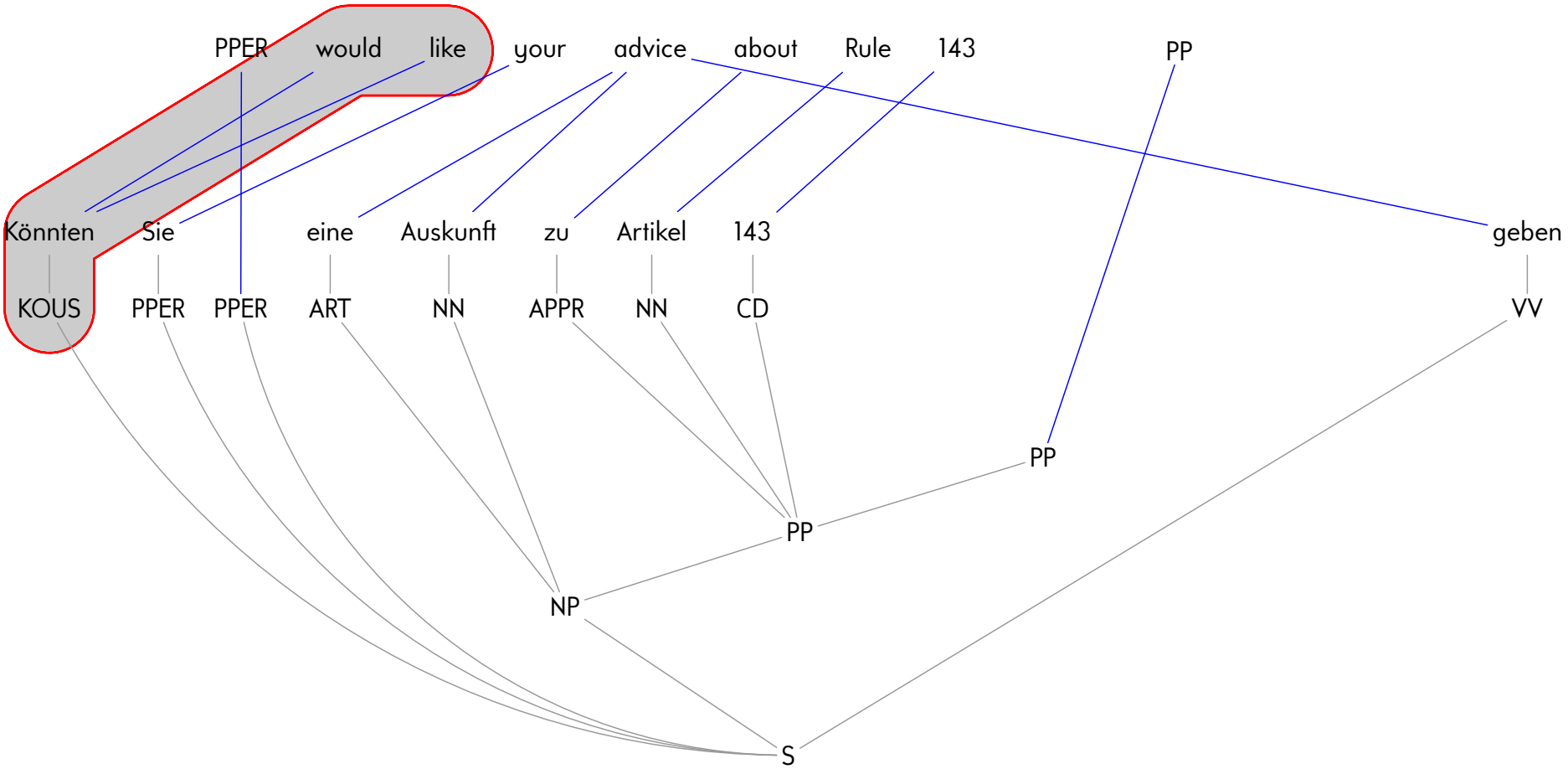

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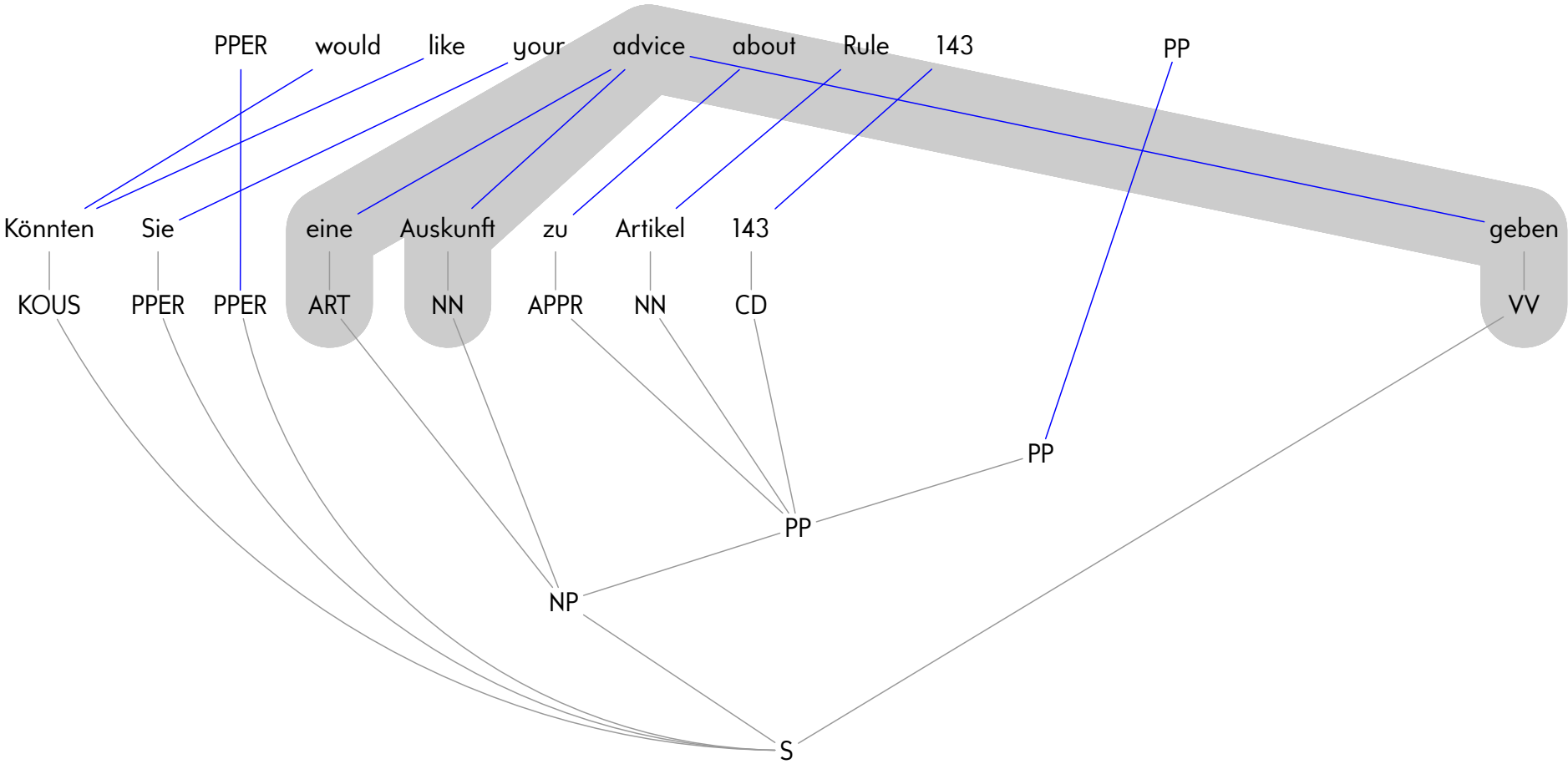

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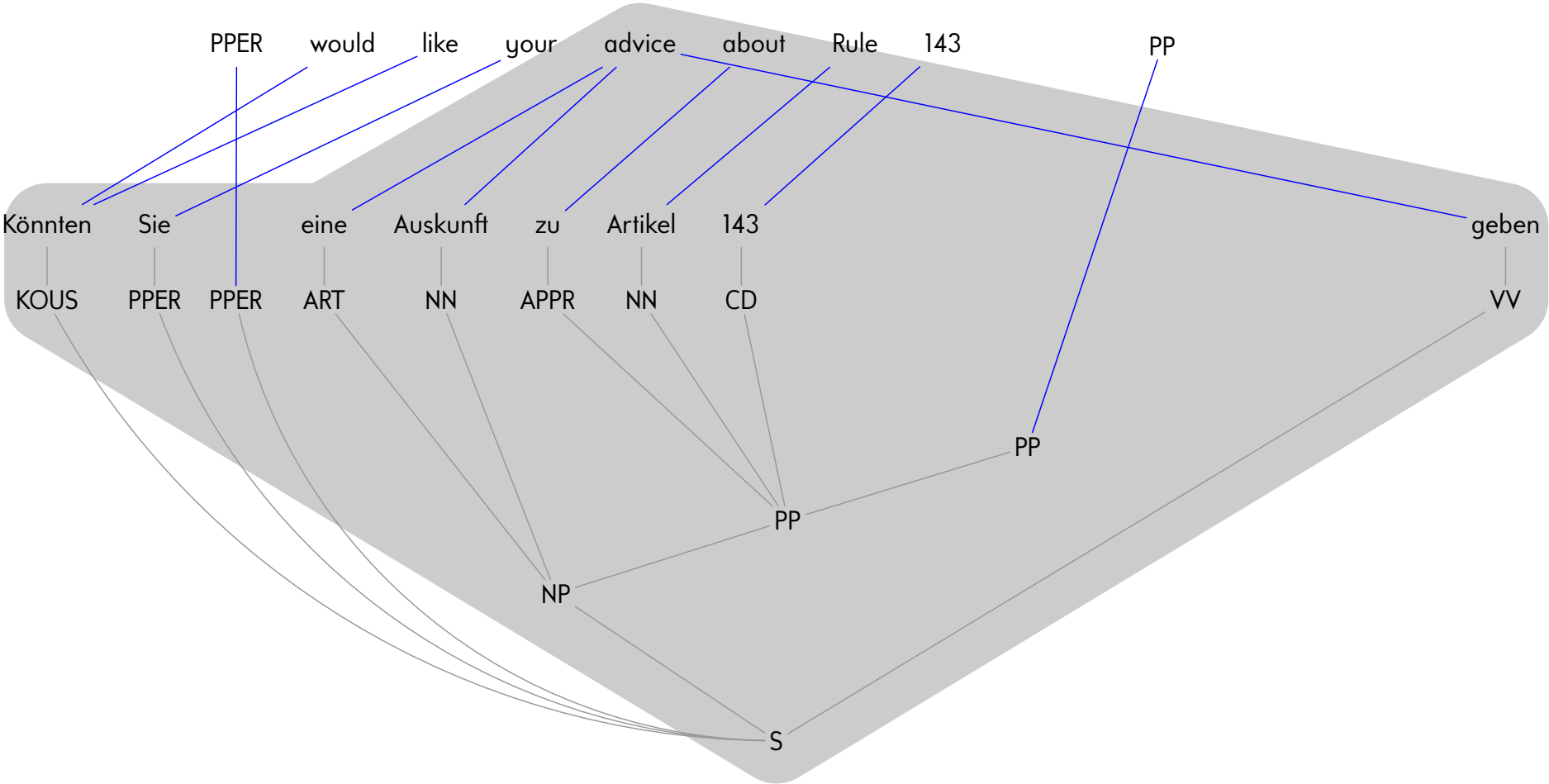

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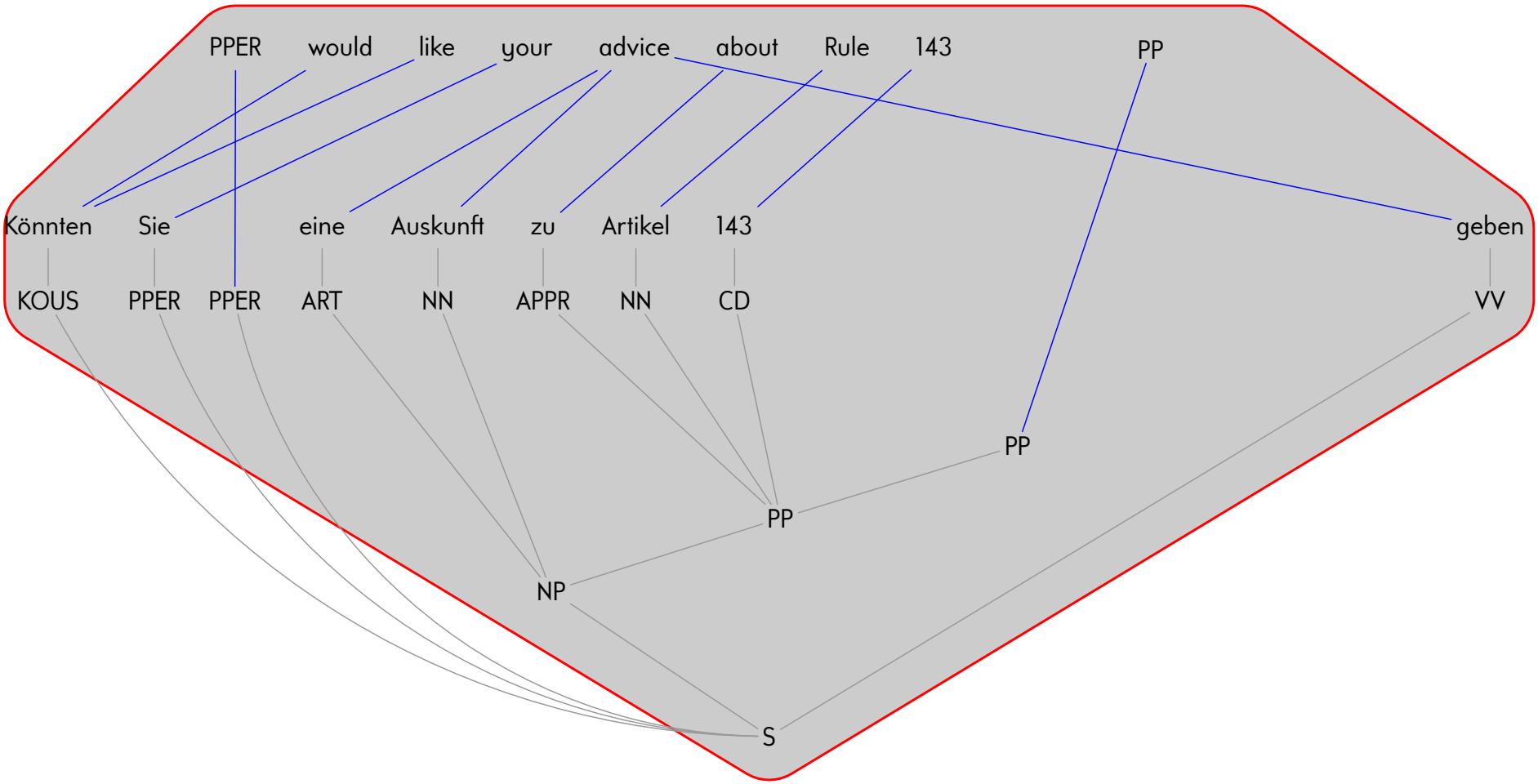

Synchronous Tree Substitution Grammars

Advantages

- very simple
- implemented in framework ‘Moses’
  [Koehn et al.: Moses — Open source toolkit for statistical machine translation. *Proc. ACL*, 2007]
- “context-free”

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Disadvantages

- problems with discontinuities
- composition and binarization not possible
  [M., Graehl, Hopkins, Knight: The power of extended top-down tree transducers. *SIAM Journal on Computing* 39(2), 2009]
  [Zhang, Huang, Gildea, Knight: Synchronous Binarization for Machine Translation. *Proc. NAACL*, 2006]
- “context-free”

Evaluation

English → German translation task: (higher BLEU is better)

Type	System	BLEU		
		vanilla	WMT 2013	WMT 2015
string-to-string	phrase-based	16.7	20.3	23.3
	hierarchical	17.0	—	—
string-to-tree	STSG	15.2	19.4	24.5
tree-to-tree	STSG	14.5	—	15.3

from [Seemann, Braune, M.: A systematic evaluation of MBOT in statistical machine translation. *Proc. MT-Summit,* 2015]
and [Bojar et al.: Findings of the 2013 workshop on statistical machine translation. *Proc. WMT,* 2013]
and [Bojar et al.: Findings of the 2015 workshop on statistical machine translation. *Proc. WMT,* 2015]

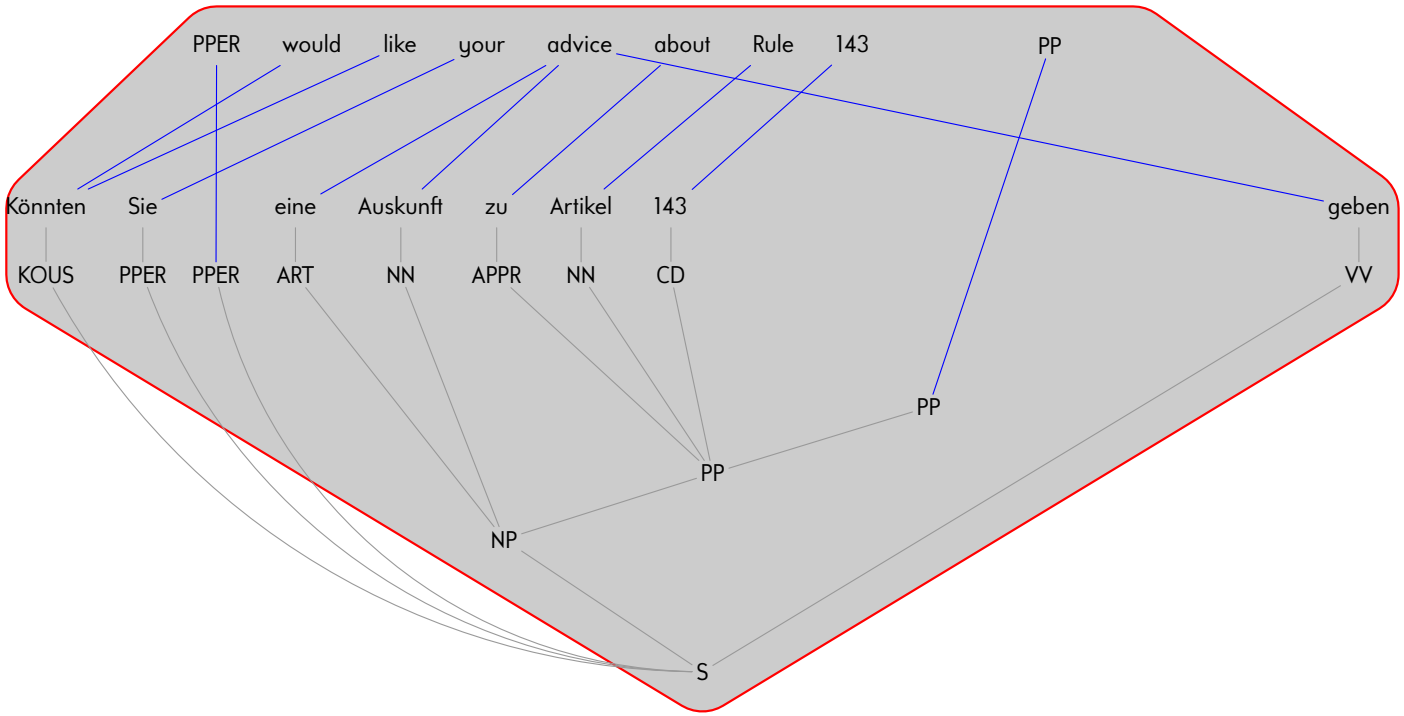
Conclusion

Observation

- syntax-based systems competitive with manual adjustments
- much less so for vanilla systems
- very unfortunate situation [more supervision yields lower scores]

Overview

Production Extraction



- very specific production
- every production for ‘advice’ contains sentence structure

(syntax “in the way”)

Synchronous Grammars

Synchronous multi tree substitution grammar: $N \rightarrow \left(r, \langle r_1, \ldots, r_n \rangle\right)$

variant of [M.: Why synchronous tree substitution grammars?. *Proc. NAACL*, 2010]

- nonterminal N
- right-hand side r of context-free grammar production
- right-hand sides $r_1, \ldots, r_n$ of regular tree grammar production

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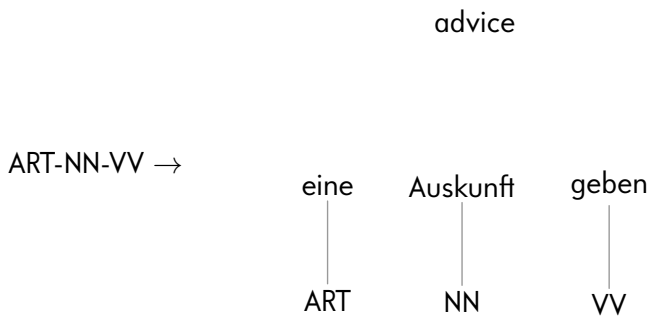

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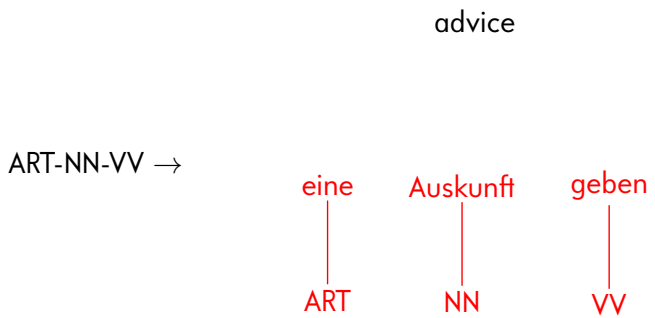

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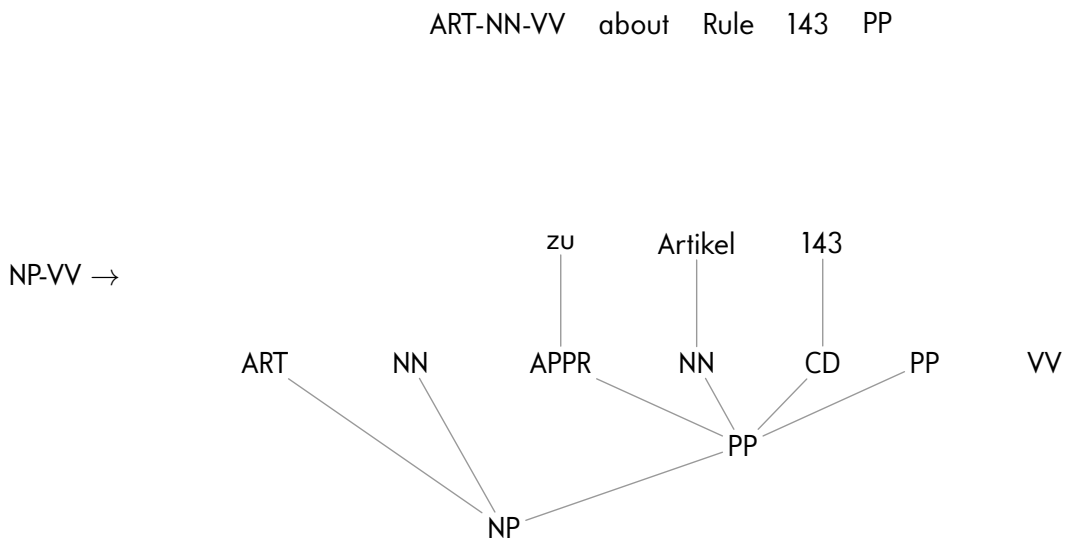

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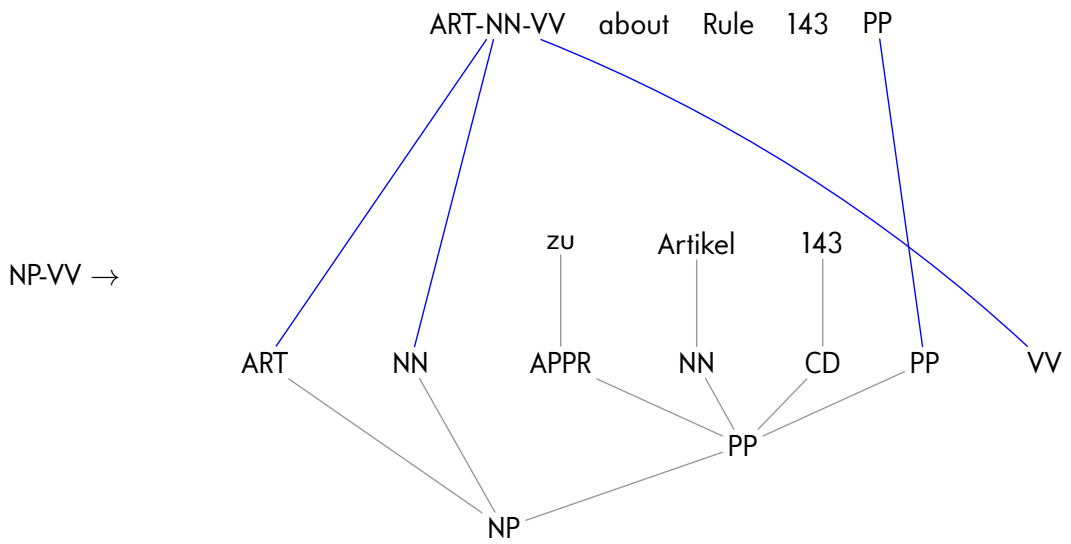
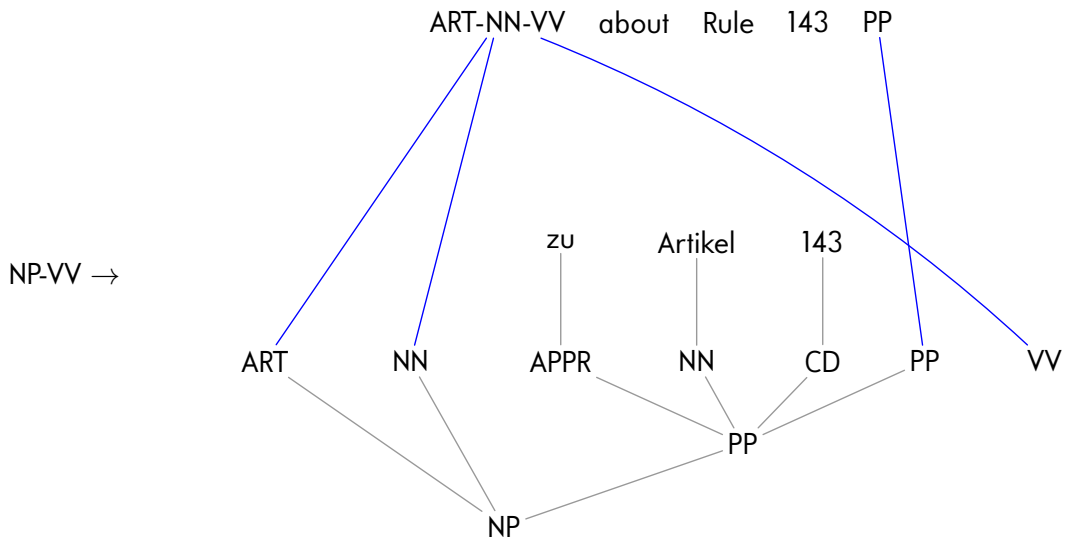
- nonterminal N
- right-hand side r of context-free grammar production
- right-hand sides $r_1, \ldots, r_n$ of regular tree grammar production
- synchronization via map NT $r_1, \ldots, r_n$ to NT r



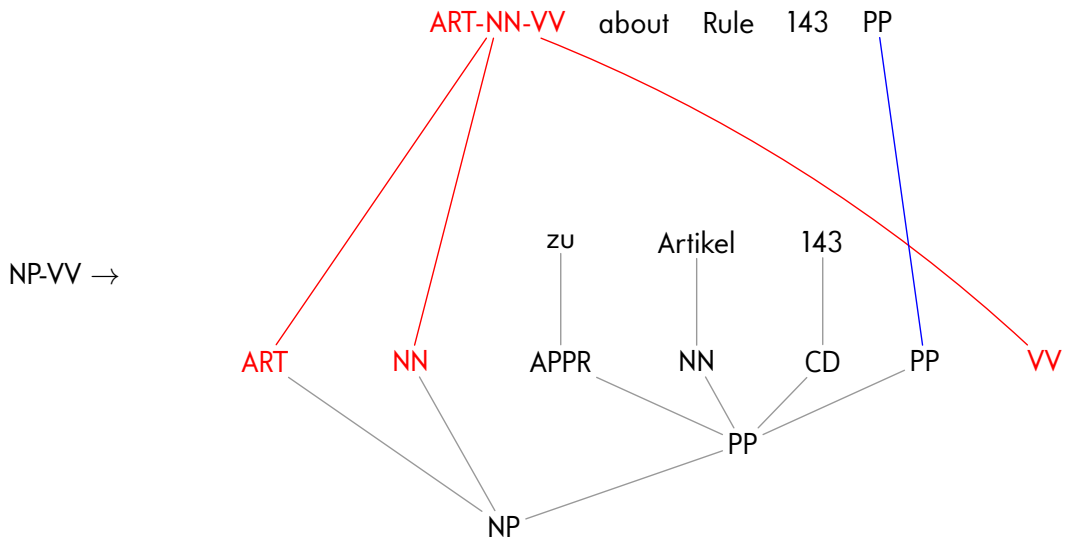
Synchronous Grammars



Production application

1. synchronous nonterminals

Synchronous Grammars



Production application

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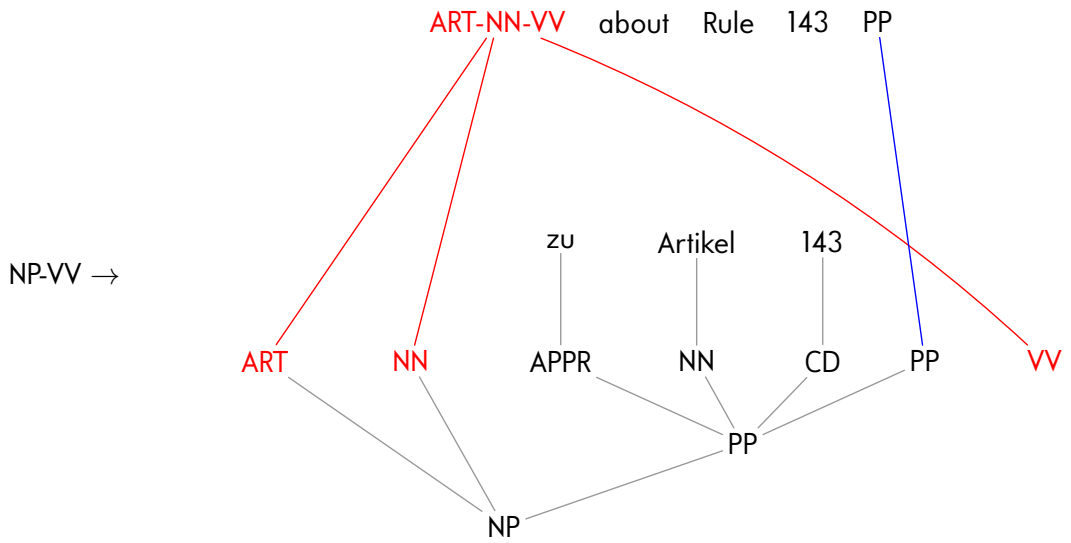
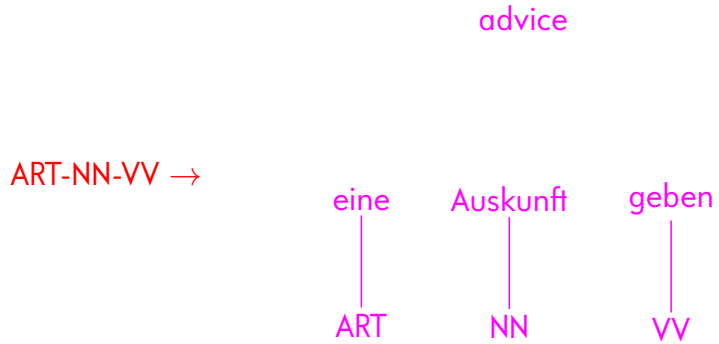
Synchronous Grammars

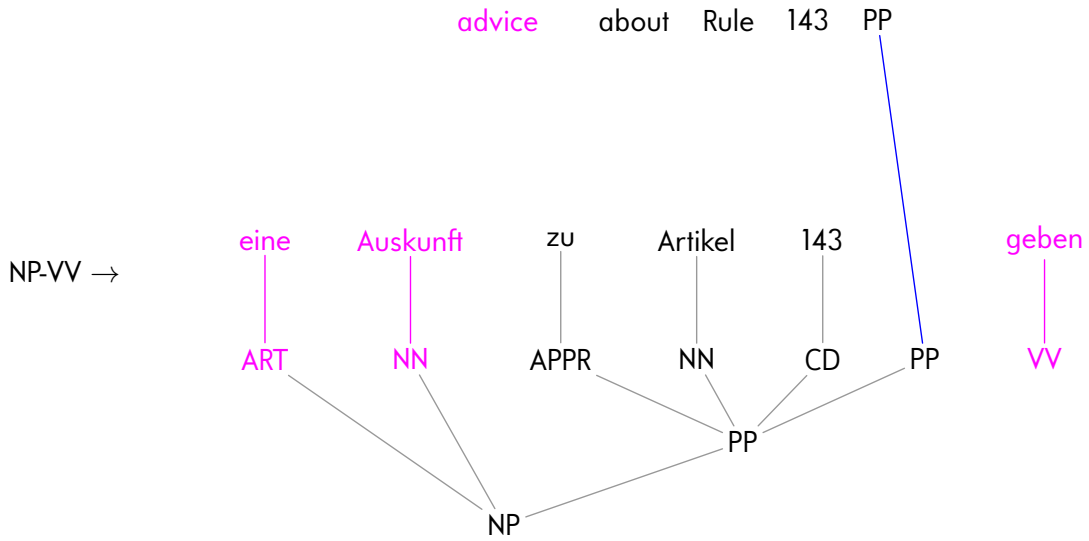


Production application

1. synchronous nonterminals
2. suitable production

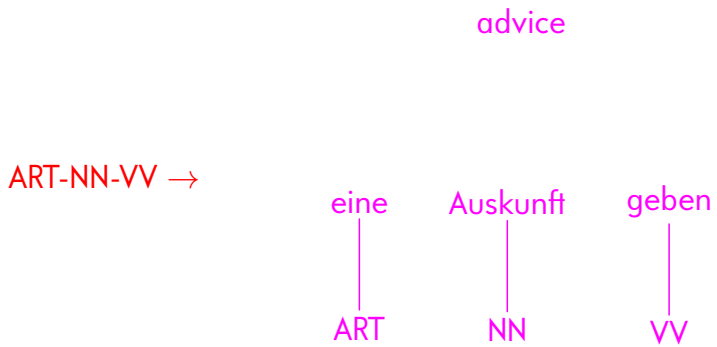


Synchronous Grammars

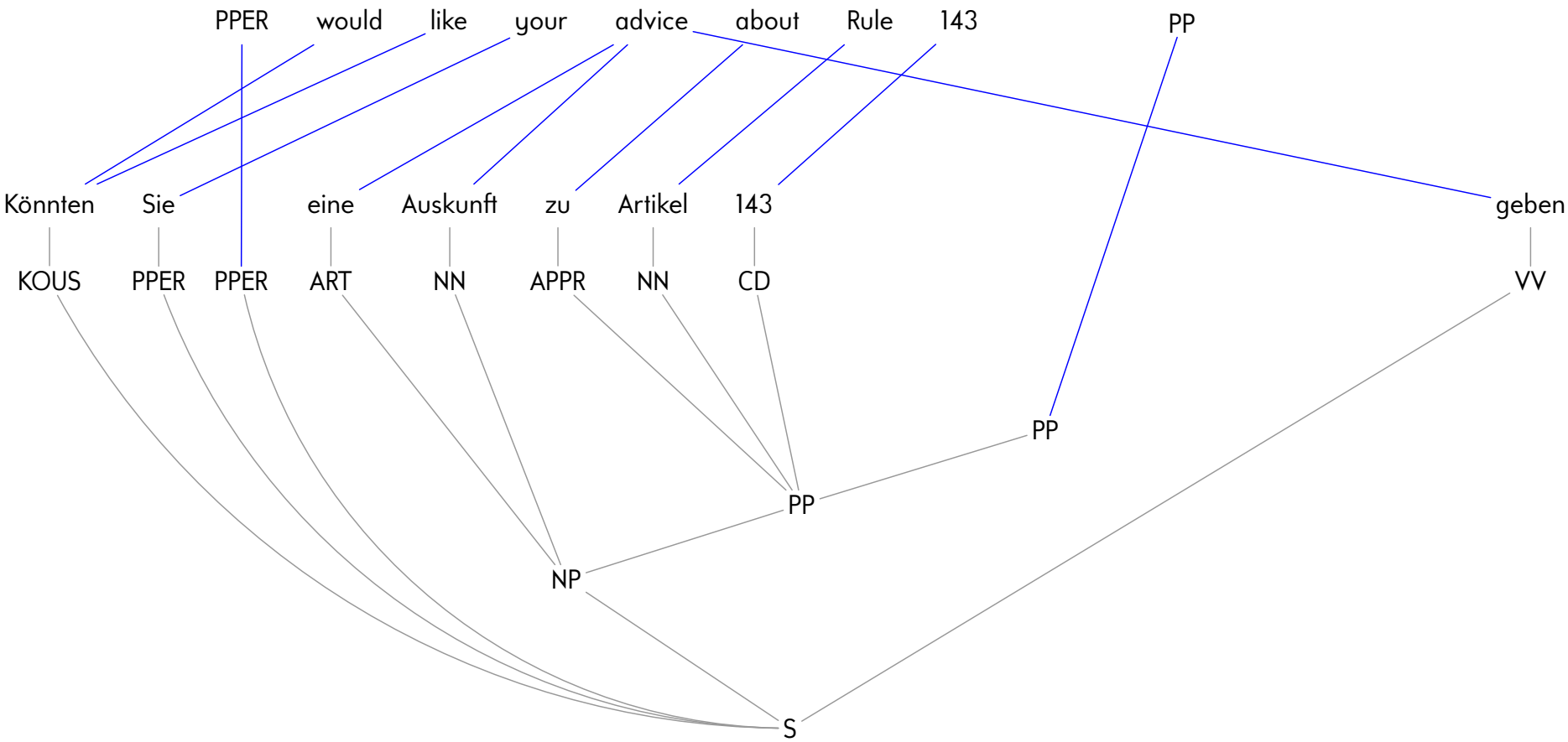


Production application

1. synchronous nonterminals
2. suitable production
3. replacement

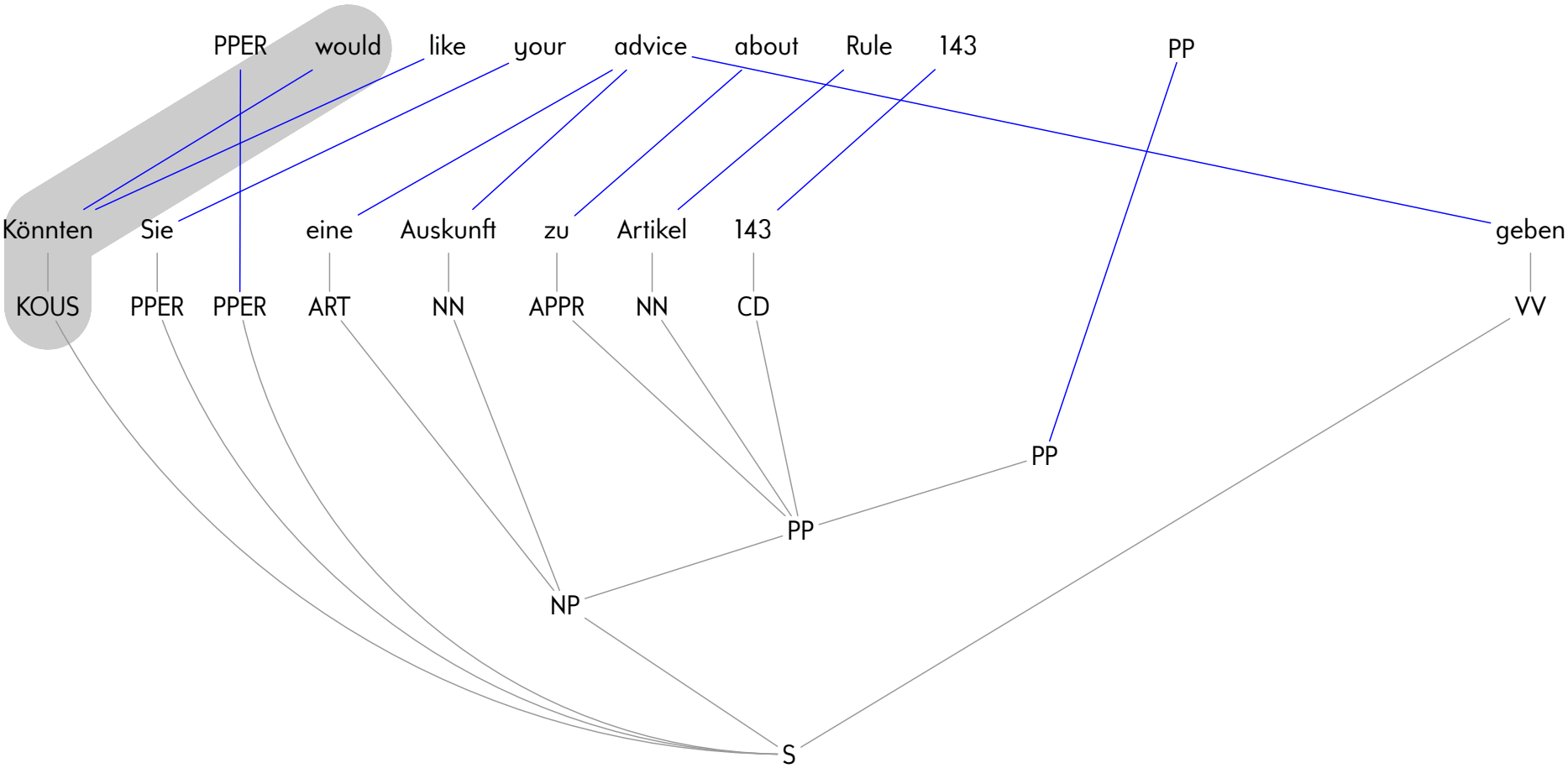


Production Extraction



variant of [M.: How to train your multi bottom-up tree transducer. *Proc. ACL*, 2011]

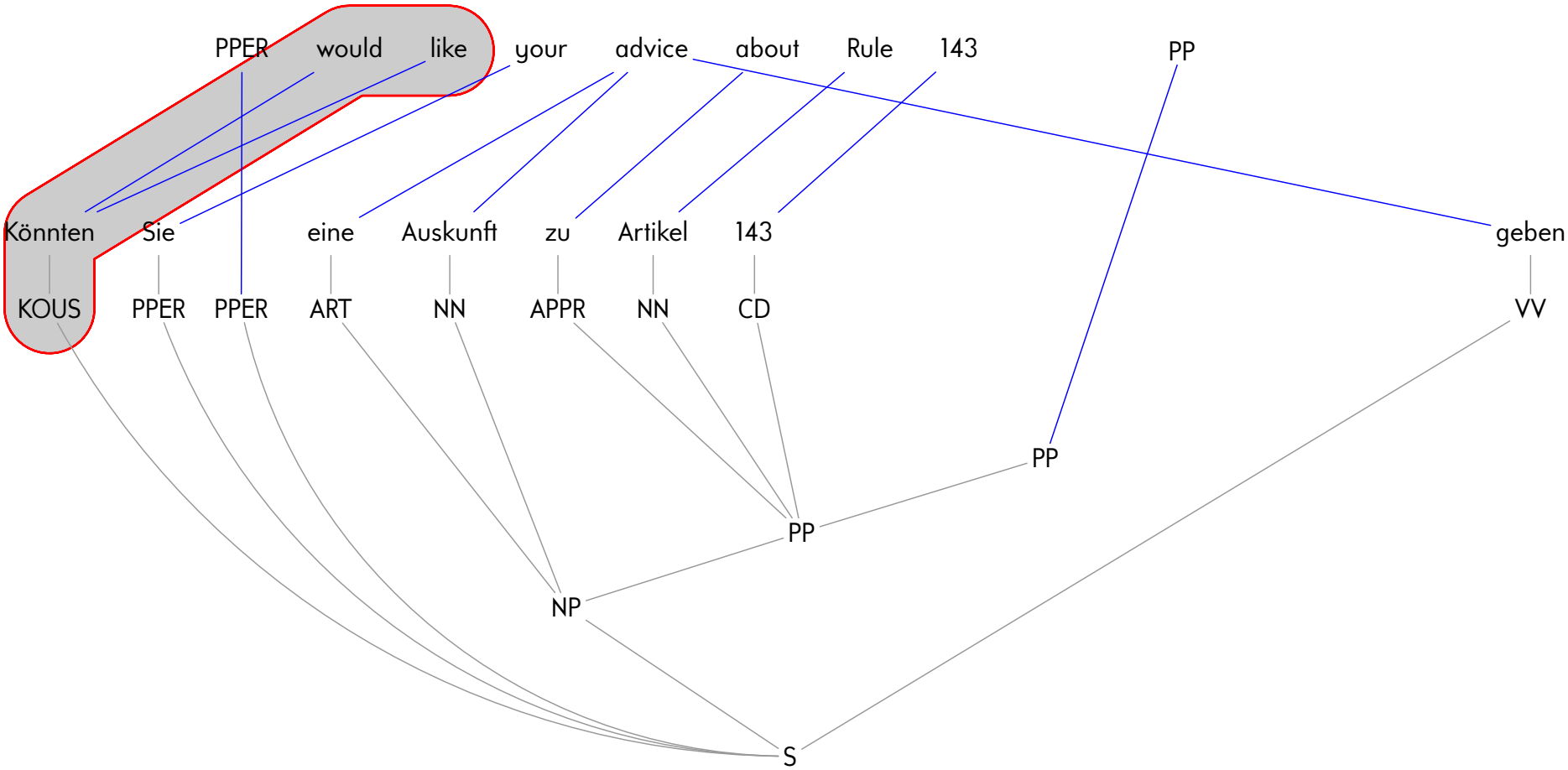
Production Extraction



variant of [M.: How to train your multi bottom-up tree transducer. *Proc. ACL*, 2011]

Production Extraction

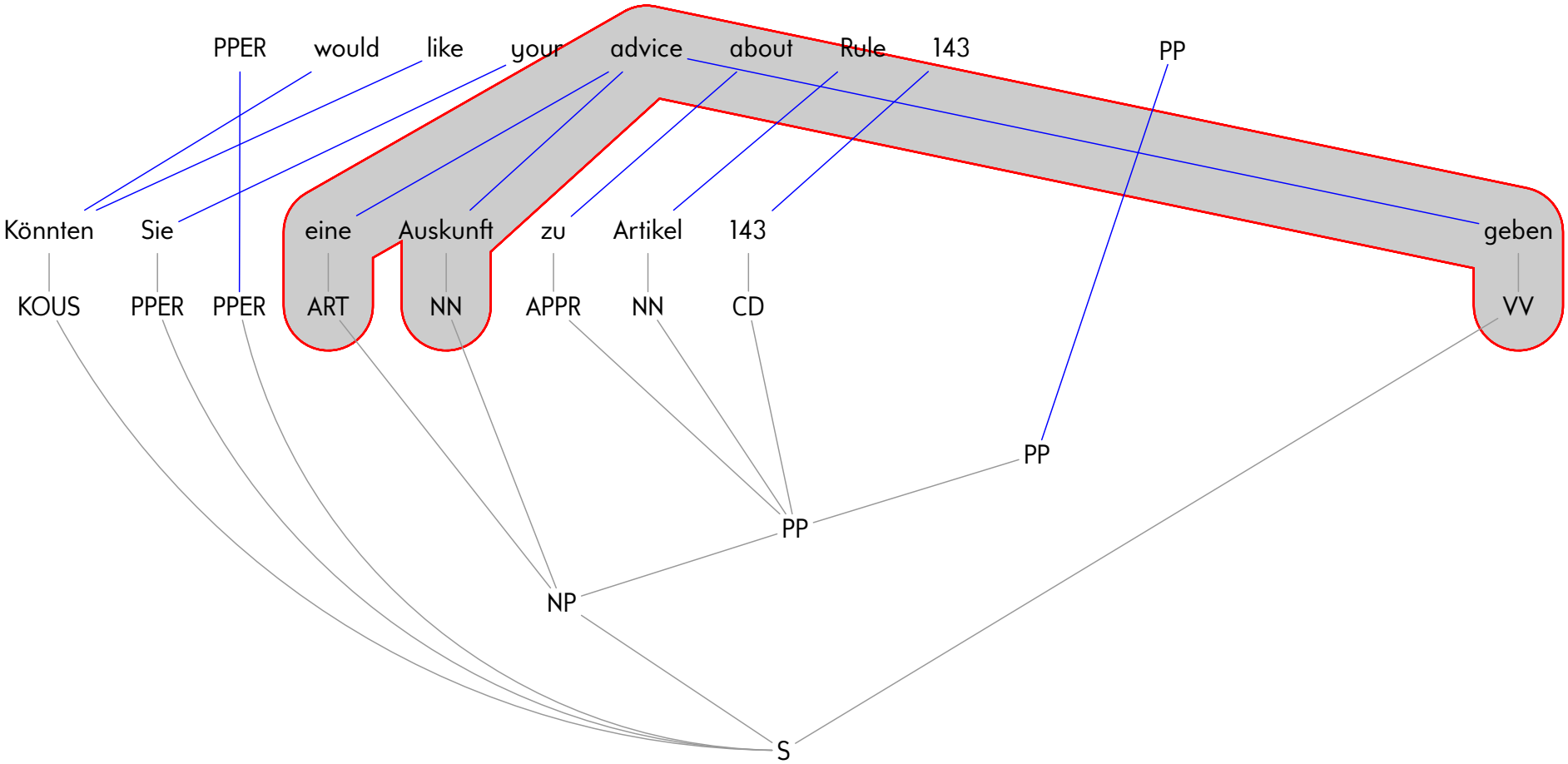
(extractable productions marked in red)



variant of [M.: How to train your multi bottom-up tree transducer. *Proc. ACL*, 2011]

Production Extraction

(extractable productions marked in red)



variant of [M.: How to train your multi bottom-up tree transducer. *Proc. ACL*, 2011]

Synchronous Multi Tree Substitution Grammars

Advantages

- complicated discontinuities
- implemented in framework ‘Moses’
  [Braune, Seemann, Quernheim, M.: Shallow local multi bottom-up tree transducers in SMT. *Proc. ACL*, 2013]
- binarizable, composable

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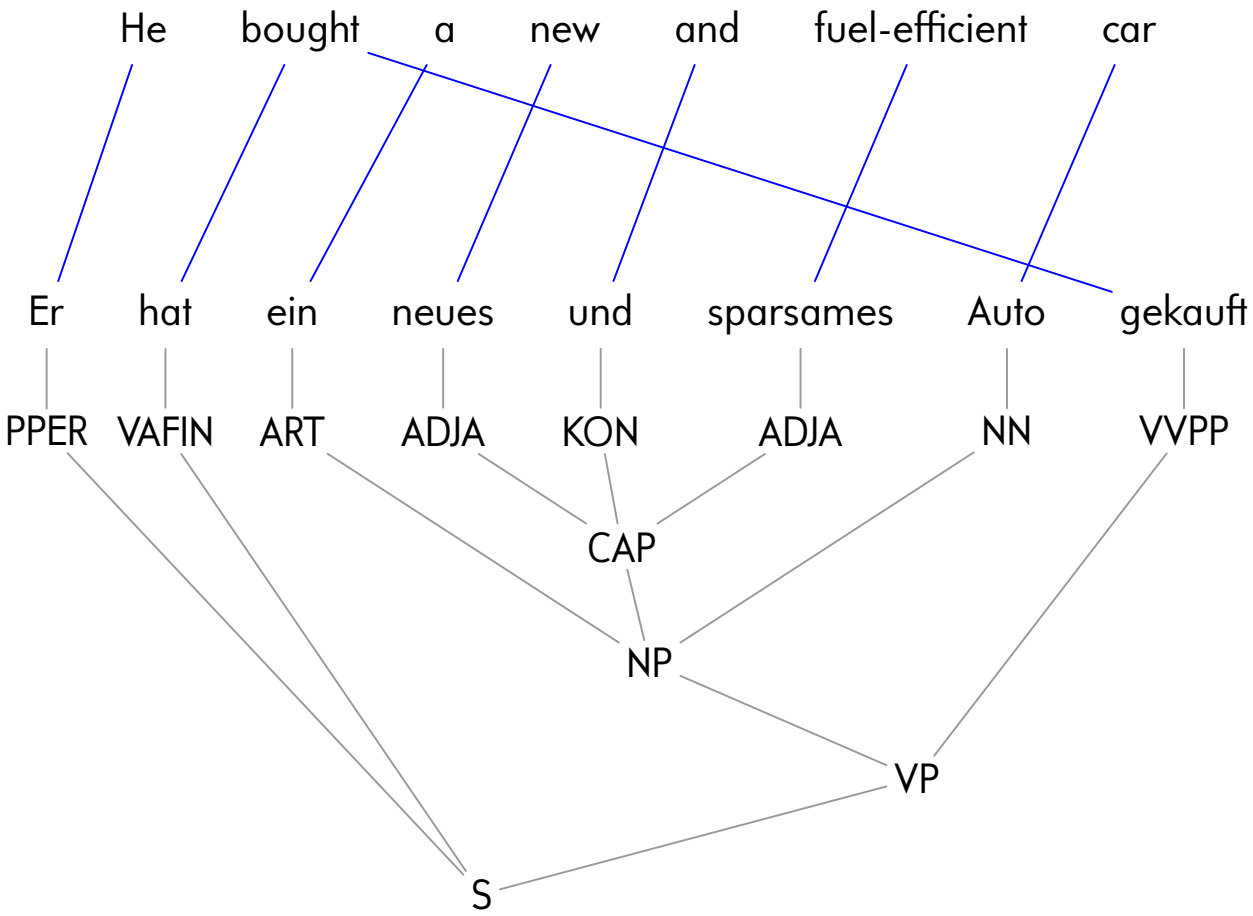
- binarizable, composable

Disadvantages

- output non-regular (trees) or non-context-free (strings)
- not symmetric (input context-free; output not)

Discontinuity



Evaluation

System	Number of productions		
	E.-to-German	E.-to-Arabic	E.-to-Chinese
t-to-t STSG	7M	24M	8M
t-to-t SMTSG	41M	151M	84M
s-to-t STSG	14M	55M	17M
s-to-t SMTSG	144M	491M	162M
phrase-based	406M	842M	209M
s-to-s SMTSG	1,084M	2,208M	683M

from [Seemann, Braune, M.: A systematic evaluation of MBOT in statistical machine translation. *Proc. MT-Summit,* 2015]

Evaluation

String-to-tree systems vs. phrase-based:

Task	BLEU		
	STSG	SMTSG	phrase-based
English → German	15.0	*15.5	16.8
English → Arabic	48.2	*49.1	51.9
English → Chinese	17.7	*18.4	18.1
English → Polish	21.3	*23.4	24.4
English → Russian	24.7	*26.1	27.9

from [Seemann, Braune, M.: A systematic evaluation of MBOT in statistical machine translation. *Proc. MT-Summit*, 2015] and [Seemann, M.: Discontinuous statistical machine translation with target-side dependency syntax. *Proc. WMT*, 2015]

Evaluation

Conclusions

- consistent improvements
- 1 magnitude more productions
- SMTSG alleviate some of the problems of syntax-based systems

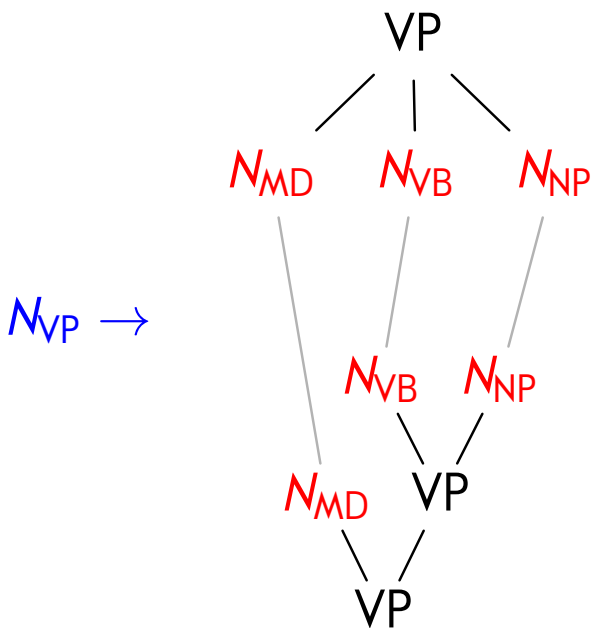
Overview

Synchronous Grammars

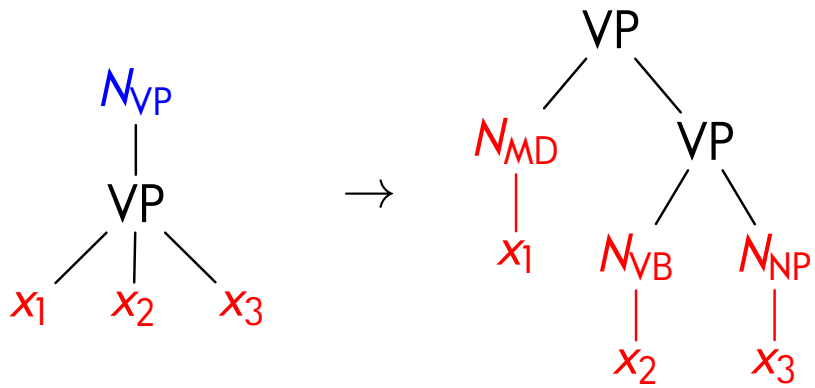
Notes

- tree-to-tree models easier for theoretical investigation
- strongly related to tree transducers
- we disallow trivial input sides of just a nonterminal (ε-free)

Synchronous grammar:



Tree transducer:



Synchronous Grammars

Major linear tree transducers:

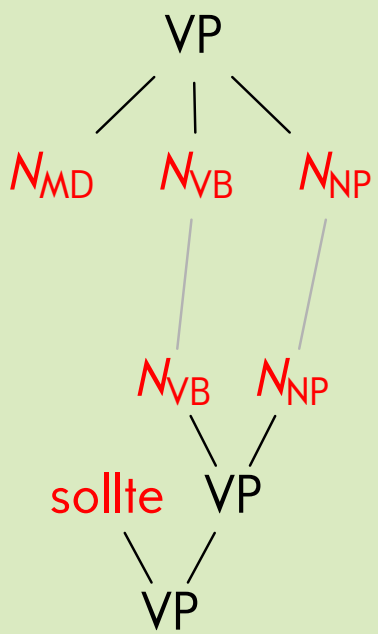
synchronization / input sides	**bijective**	**injective** (output → input)
shallow	nondeleting top-down ...	top-down ...
general	nondeleting extended ...	extended ...

Further distinction

- allow productions on disconnected input nonterminals
  → regular look-ahead
- allow arbitrary trees for disconnected input nonterminals
  → no look-ahead

Synchronous Grammars

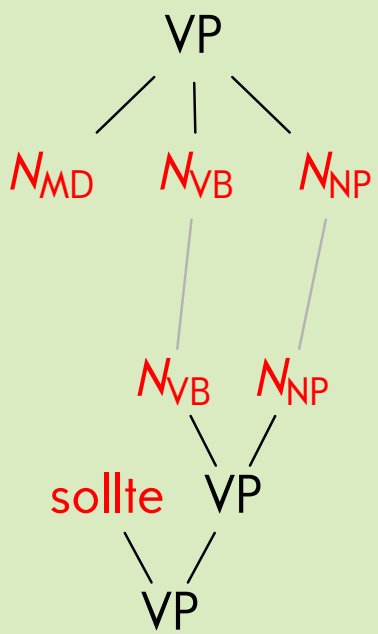
Illustration



- no look-ahead: can plug any (terminal) tree for N_{MD}
  [e.g., NP(DT(the), NN(tower))]

Synchronous Grammars

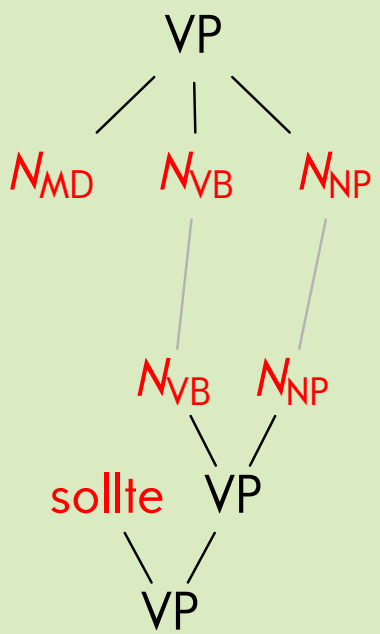
Illustration



- no look-ahead: can plug any (terminal) tree for N_{MD}
  [e.g., $\mathrm{NP}(\mathrm{DT}(\mathrm{the}), \mathrm{NN}(\mathrm{tower}))$]
- regular look-ahead: use special "no-output"-productions $N \to (r)$
  [e.g., $N_{MD} \to (\mathrm{MD}(\mathrm{should}))$]

Synchronous Grammars

Illustration

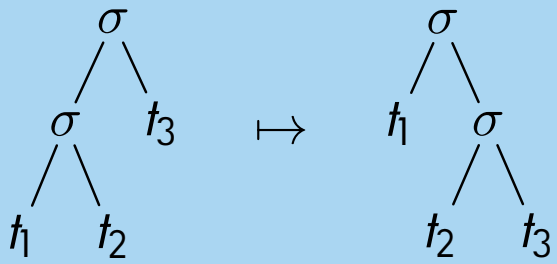


- no look-ahead: can plug any (terminal) tree for N_{MD}
  [e.g., NP(DT(the), NN(tower))]
- regular look-ahead: use special "no-output"-productions $N \to (r)$
  [e.g., $N_{MD} \to$ (MD(should))]
- SMTSG always have regular look-ahead
  (any number of components includes 0)

Synchronous Grammars

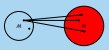
Evaluation criteria


rotations implementable? (for arbitrary t_1, t_2, t_3)




symmetric?


domain regular?

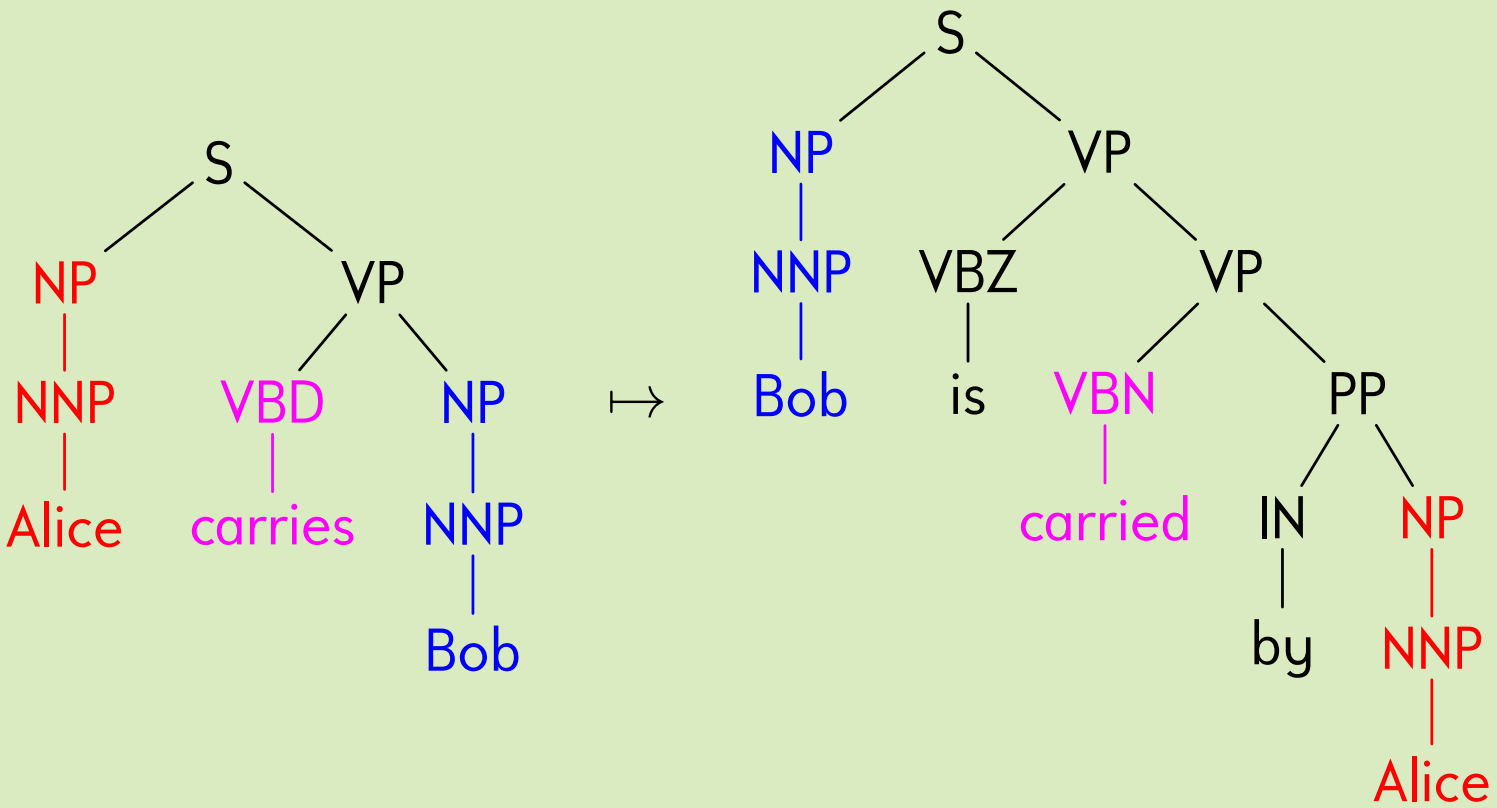

range regular?


closed under composition?

following [Knight: Capturing practical natural language transformations. *Machine Translation* 21(2), 2007]
and [May, Knight, Vogler: Efficient inference through cascades of weighted tree transducers. *Proc. ACL*, 2010]

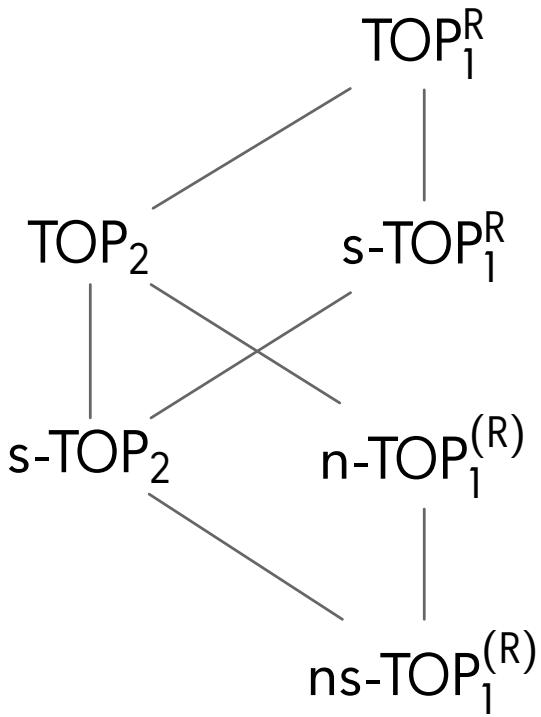
Icons by interactivemania (`http://www.interactivemania.com/`) and UN Office for the Coordination of Humanitarian Affairs

Illustration of rotations

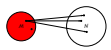
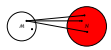


Top-down Tree Transducer

Hasse diagram with composition closure indicated in subscript:

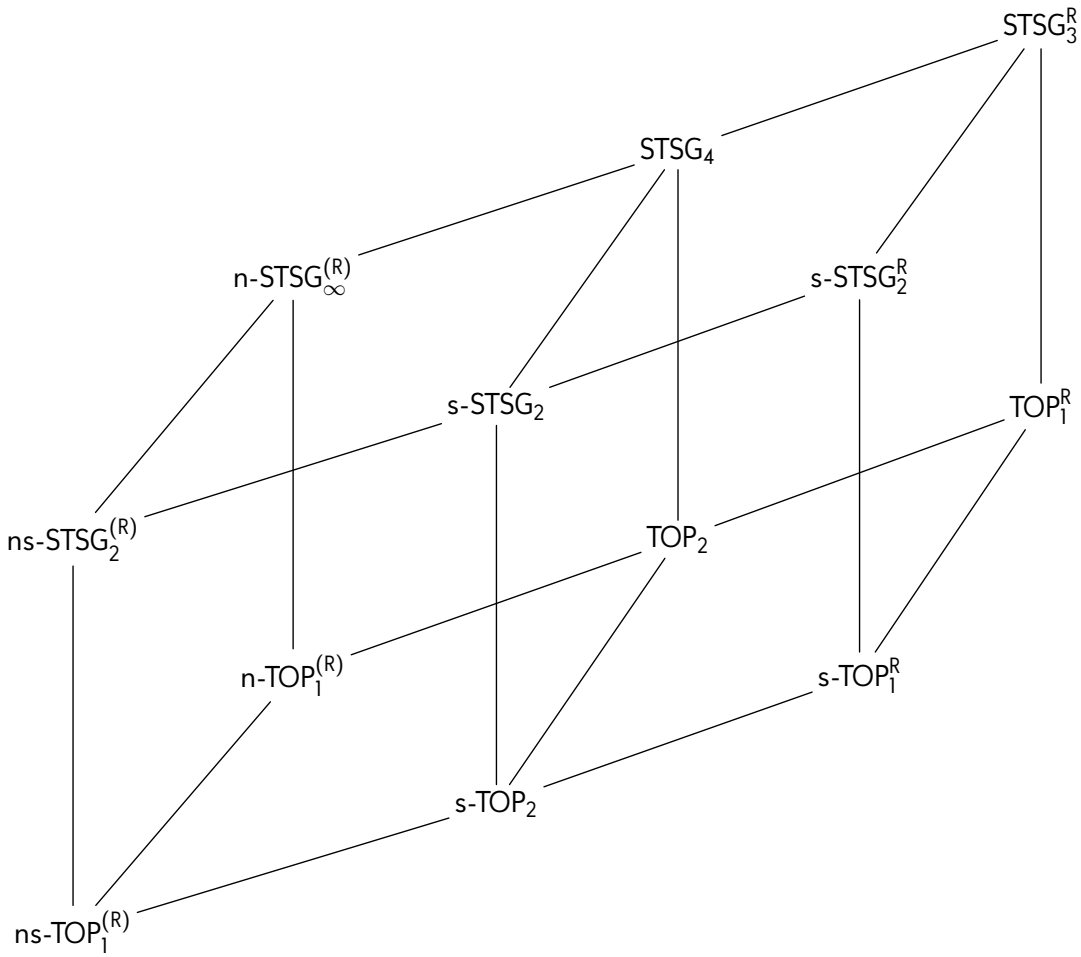


Top-down Tree Transducer

Model \ Criterion				
ns-TOP	✗	✗	✓	✓	✓
n-TOP	✗	✗	✓	✓	✓
s-TOP	✗	✗	✓	✓	✗$_2$
s-TOP^R	✗	✗	✓	✓	✓
TOP	✗	✗	✓	✓	✗$_2$
TOP^R	✗	✗	✓	✓	✓

Synchronous Tree Substitution Grammars

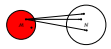
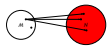
Hasse diagram with the composition closure indicated in subscript:



composition closures by

[Engelfriet, Fülöp, M.: Composition closure of linear extended top-down tree transducers. *Theory of Computing Systems*, to appear 2016]

Synchronous Tree Substitution Grammars

Model \ Criterion					
n-TOP	✗	✗	✓	✓	✓
TOP	✗	✗	✓	✓	$✗_2$
TOP^R	✗	✗	✓	✓	✓
ns-STSG	✓	✓	✓	✓	$✗_2$
n-STSG	✓	✗	✓	✓	$✗_\infty$
$s\text{-}STSG^{(R)}$	✓	✗	✓	✓	$✗_2$
STSG	✓	✗	✓	✓	$✗_4$
$STSG^R$	✓	✗	✓	✓	$✗_3$

Synchronous Multi Tree Substitution Grammars

Advantages of SMTSG

- always have regular look-ahead
- can always be made nondeleting & shallow
- closed under composition

[Engelfriet, Lilin, M.: Extended multi bottom-up tree transducers — composition and decomposition. *Acta Informatica* 46(8), 2009]

Synchronous Multi Tree Substitution Grammars

Advantages of SMTSG

- always have regular look-ahead
- can always be made nondeleting & shallow
- closed under composition

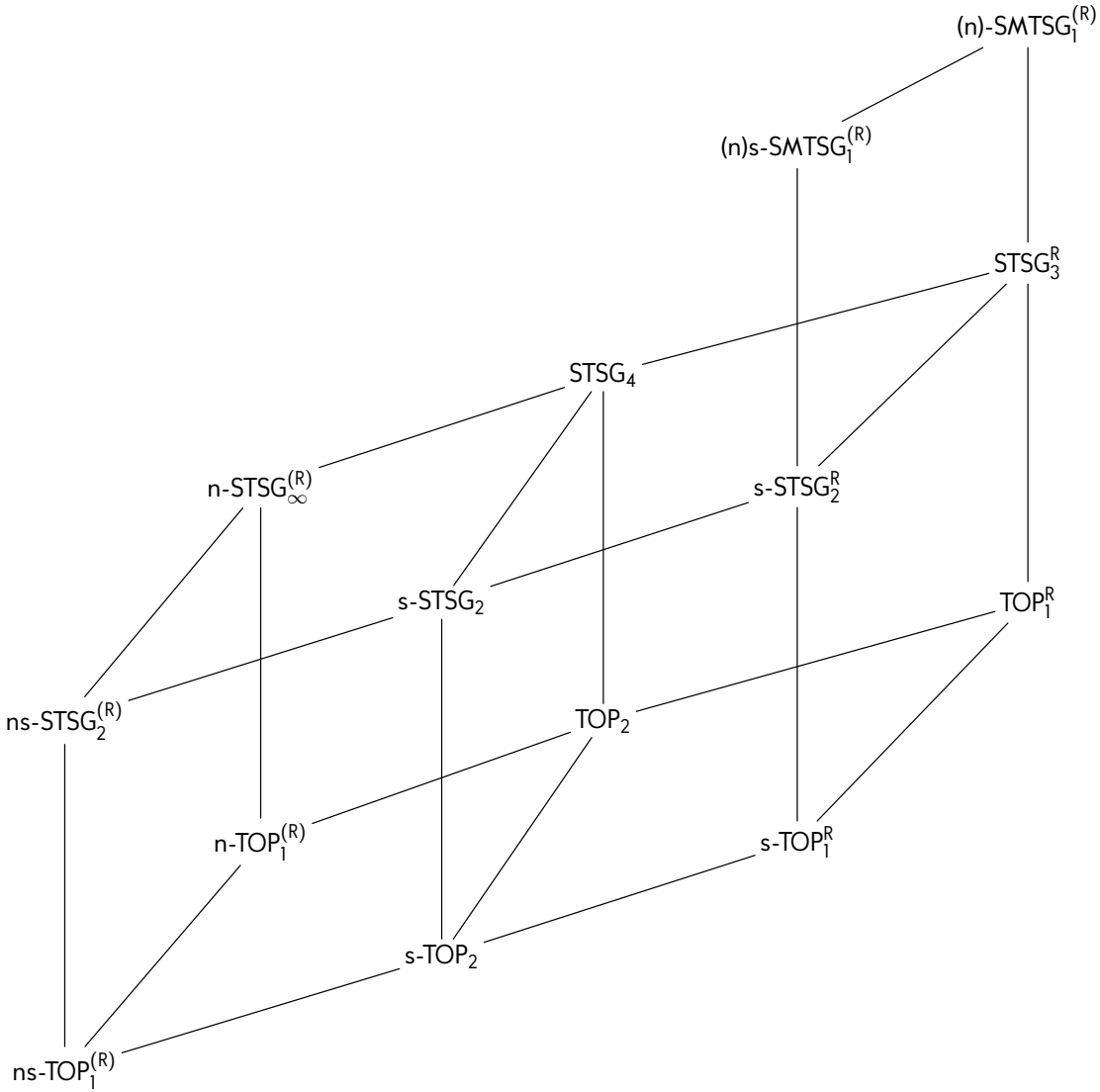
Disadvantages of SMTSG

- non-regular range

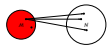
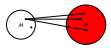
[Engelfriet, Lilin, M.: Extended multi bottom-up tree transducers — composition and decomposition. *Acta Informatica* 46(8), 2009]

Synchronous Multi Tree Substitution Grammars

Hasse diagram with the composition closure indicated in subscript:



Synchronous Multi Tree Substitution Grammars

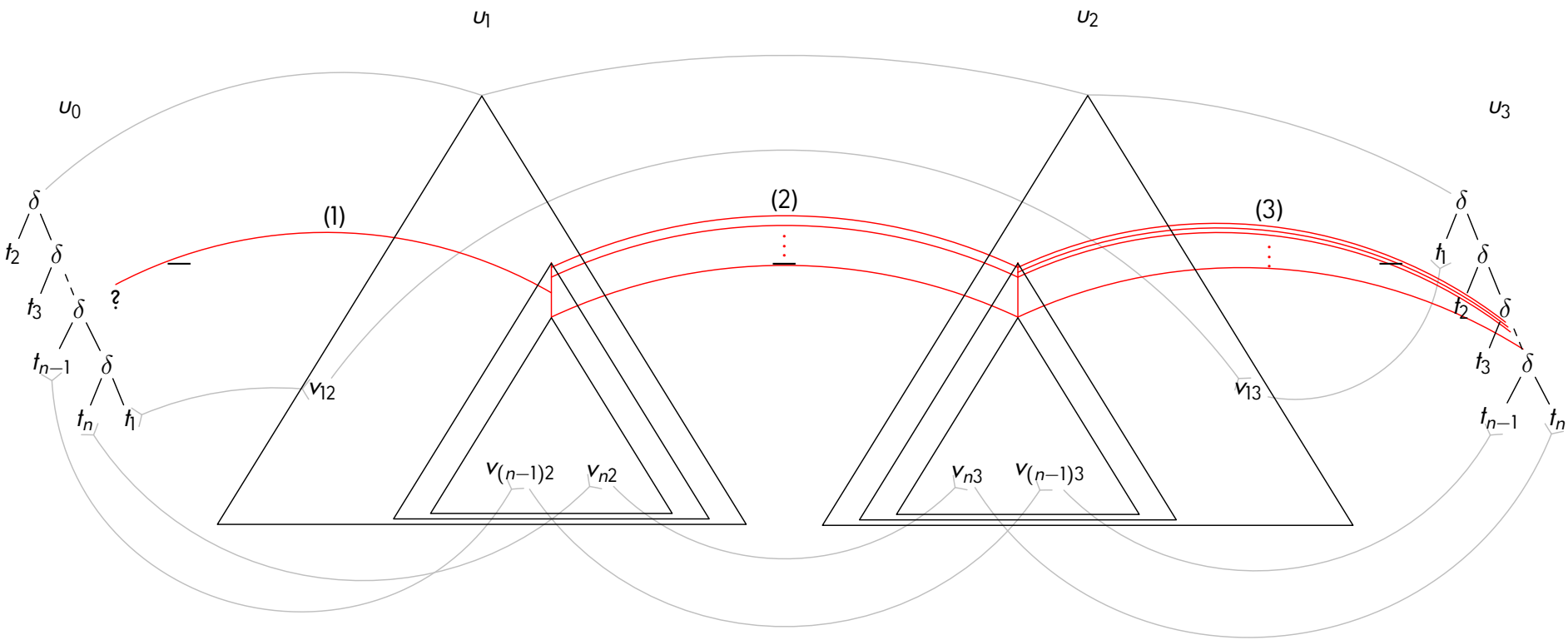
Model \ Criterion					
n-TOP	✗	✗	✓	✓	✓
TOP	✗	✗	✓	✓	$\times_2$
TOP^R	✗	✗	✓	✓	✓
ns-STSG	✓	✓	✓	✓	$\times_2$
n-STSG	✓	✗	✓	✓	$\times_\infty$
$\text{s-STSG}^{(R)}$	✓	✗	✓	✓	$\times_2$
STSG	✓	✗	✓	✓	$\times_4$
STSG^R	✓	✗	✓	✓	$\times_3$
$\text{(n)s-SMTSG}^{(R)}$	✓	✗	✓	✗	✓
$\text{(n)-SMTSG}^{(R)}$	✓	✗	✓	✗	✓
reg.-range SMTSG	✓	✗	✓	✓	✓
symmetric SMTSG	✓	✓	✓	✓	✓

(string-level) range characterization by
[Gildea: On the string translations produced by multi bottom-up tree transducers. *Computational Linguistics* 38(3), 2012]

Synchronous Multi Tree Substitution Grammars

Theorem

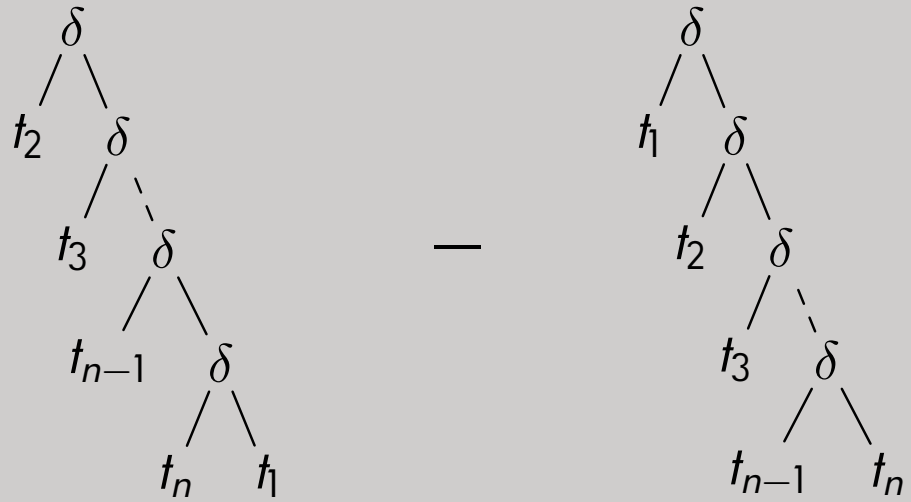
$$\left(\mathrm{STSG}^{\mathrm{R}}\right)^3 \subsetneq \text{reg.-range SMTSG}$$



[M.: The power of weighted regularity-preserving multi bottom-up tree transducers. *Int. J. Found. Comput. Sci.* 26(7), 2015]

Synchronous Multi Tree Substitution Grammars

Counterexample relation



- abstracts a well-known linguistic transformation called topicalization
- implementable by SMTSG, but not by any composition of STSG

Synchronous Multi Tree Substitution Grammars

Illustration of topicalization

- It rained yesterday night.

  Topicalized: Yesterday night, it rained.

Synchronous Multi Tree Substitution Grammars

Illustration of topicalization

- It rained yesterday night.

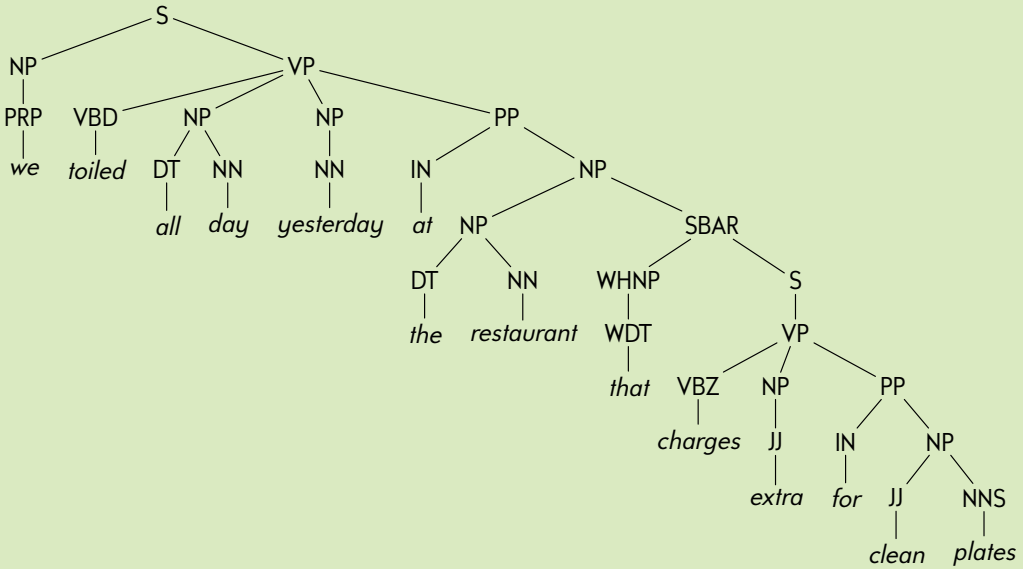
  Topicalized: Yesterday night, it rained.

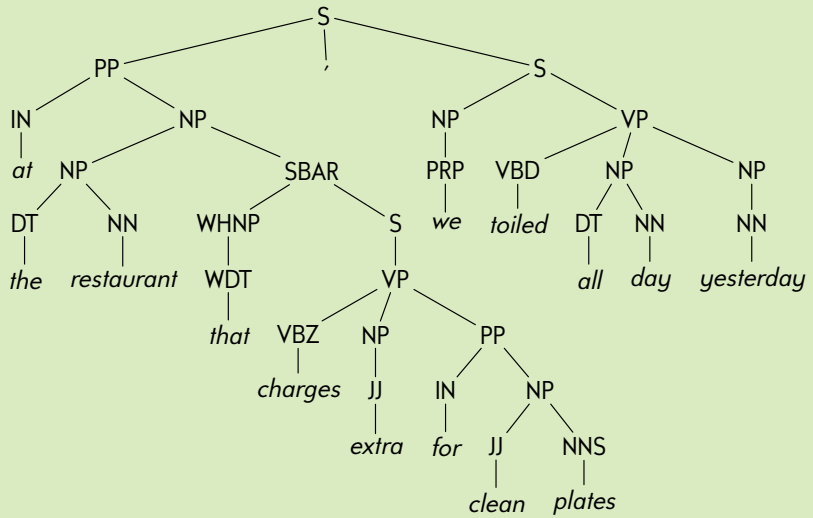
- We toiled all day yesterday
  at the restaurant that charges extra for clean plates.

  Topicalized: At the restaurant that charges extra for clean plates,
  we toiled all day yesterday.

Synchronous Multi Tree Substitution Grammars

On the tree level





Summary

Contributions

- SMTSG implementation and evaluation
  [Braune, Seemann, Quernheim, M.: Shallow local multi bottom-up tree transducers in SMT. *Proc. ACL*, 2013]
  [Seemann, Braune, M.: String-to-tree multi bottom-up tree transducers. *Proc. ACL*, 2015]
  [Seemann, Braune, M.: A systematic evaluation of MBOT in statistical machine translation. *Proc. MT-Summit*, 2015]
- characterization of expressive power of STSG and SMTSG
  [Engelfriet, Lilin, M.: Extended multi bottom-up tree transducers — composition and decomposition. *Acta Informatica* 46(8), 2009]
  [Engelfriet, Fülöp, M.: Composition closure of linear extended top-down tree transducers. *Theory of Computing Systems*, 2015]
  [M.: The power of weighted regularity-preserving multi bottom-up tree transducers. *Int. J. Found. Comput. Sci.*, 2015]
- new proof technique (based on synchronization links)
  [Fülöp, M.: Linking theorems for tree transducers. Manuscript, 2014]
  similar ideas used in
  [Bojanczyk: Transducers with origin information. *Proc. ICALP*, 2014]
  [Filiot, Maneth, Reynier, Talbot: Decision problems of tree transducers with origin. *Proc. ICALP*, 2015]

Summary

Open Questions

- better production extraction? [better algorithms]
- additional expressive power necessary? [new models]
- further improvements possible? [tweaks]

Summary

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Thank you for the attention.