Tree Automata in Parsing and Machine Translation

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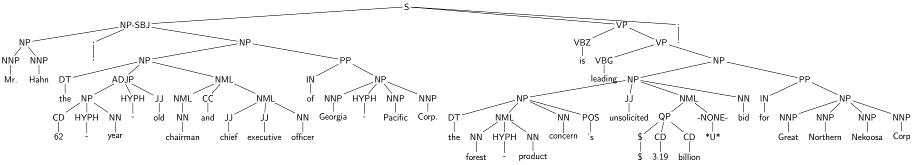
Leipzig — November 22, 2016

Parsing

- determining the syntactic structure of a sentence
- subject to a given theory of syntax (encoded in the training data)
  - constituent syntax
  - dependency syntax
  - ...



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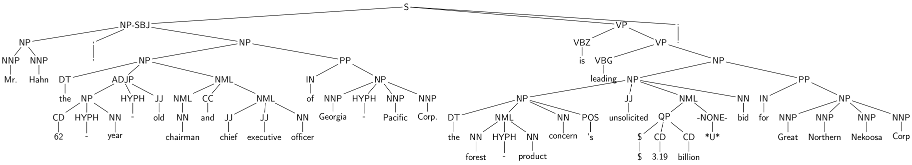
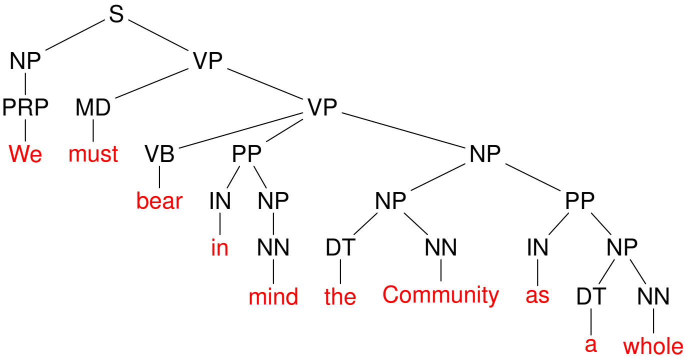


Constituent Parsing

Example: We must bear in mind the Community as a whole



Constituent Parsing

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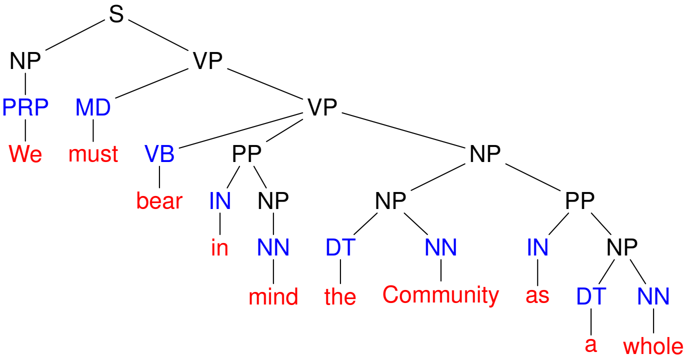

POS-tag: part-of-speech tag, “class” of a word

Constituent Parsing

today

Subcategorization

manual: Collins (1999), Stanford (2003), BLLIP (2005)

automatic, e.g. Berkeley (2007)

2000

Statistical approach (cheap, automatically trained)

Penn and WSJ tree bank (1M and 30M words)

automatically obtained weighted CFG

1990

Chomskyan approach (perfect analysis, poor coverage)

hand-crafted CFG, TAG (refined via POS tags)

corrections and selection by human annotators

Constituent Parsing

grammar	F_1-score $\lvert w \rvert \leq 40$	full
wCFG		62.7
wTSG [Post, Gildea, 2009]	82.6	
wTSG [Cohn et al., 2010]	85.4	84.7
wCFG_{sub} [Collins, 1999]	88.6	88.2
wCFG_{sub} [Petrov, Klein, 2007]	90.6	90.1
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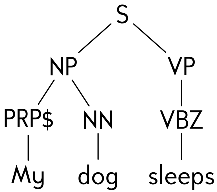
Subcategorization

Tags:

- official tags often conservative
  - English: $\approx$ 50 tags
  - German: $\gg$ 200 tags

ADJA-Sup-Dat-Sg-Fem



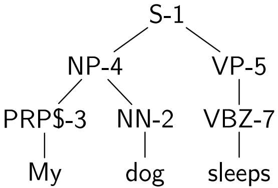
Subcategorization

Tags:

- official tags often conservative
  - English: ≈ 50 tags
  - German: $\gg 200$ tags

ADJA-Sup-Dat-Sg-Fem

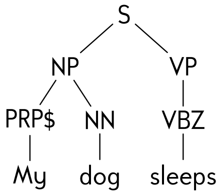
- all modern parsers use refined tags $\rightarrow$ subcategorization



Subcategorization

Tags:

- official tags often conservative
  - English: $\approx$ 50 tags
  - German: $\gg$ 200 tags ADJA-Sup-Dat-Sg-Fem
- all modern parsers use refined tags $\rightarrow$ subcategorization
- but return parse over official tags $\rightarrow$ relabeling



Definition (Tree automaton)

Tuple (Q, Σ, I, R)

- finite set Q of states (subcategorizations)
- finite set Σ of terminals
- initial states $I \subseteq Q$
- finite set R of rules of the form $q \rightarrow \sigma(q_1, \dots, q_k)$

  $(\sigma \in \Sigma,\ k \geq 0,\ q, q_1, \dots, q_k \in Q)$

Example rules

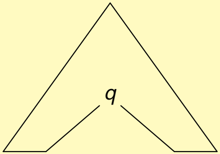
$$q_4 \rightarrow \begin{array}{c}\mathrm{VP}\\ \diagup \quad \mid \quad \diagdown\\ q_5 \quad q_2 \quad q_3\end{array} \qquad q_0 \rightarrow \begin{array}{c}\mathrm{S}\\ \diagup \quad \diagdown\\ q_1 \quad q_4\end{array} \qquad q_0 \rightarrow \begin{array}{c}\mathrm{S}\\ \diagup \quad \diagdown\\ q_6 \quad q_2\end{array}$$

Tree Automaton

Definition (Derivation semantics and recognized tree language)

Let (Q, Σ, I, R) tree automaton

- for each leaf position labeled q and rule $q \to r \in R$



- recognized tree language

$$\{t \mid \exists q \in I \colon q \Rightarrow^* t\}$$

Constituent Parsing

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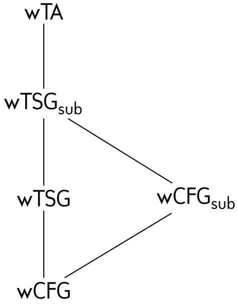

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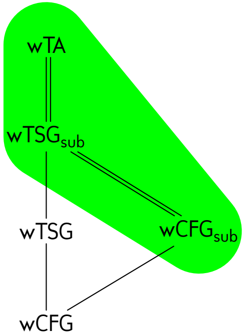

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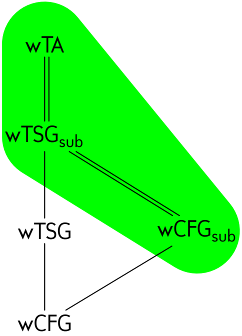

Hence:

- subcategorization = finite-state
- all modern models equivalent to tree automata in expressive power

Constituent Parsing

Comparison:

- rule of subcategorized CFG vs. corresponding rule of tree automaton

$$\text{S-1} \to \text{ADJP-2} \quad \text{S-1} \qquad\qquad \text{S-1} \to \text{S}\big(\text{ADJP-2},\ \text{S-1}\big)$$

Advances in NLP

- best learning algorithms from positive data
  (state splitting & EM)
- fastest evaluators of weighted tree automata
  (coarse-to-fine parsing)
- fastest *n*-best derivation extraction
- ...

Parsing

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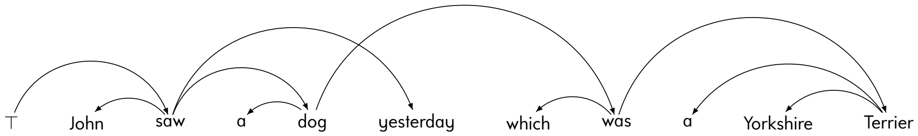
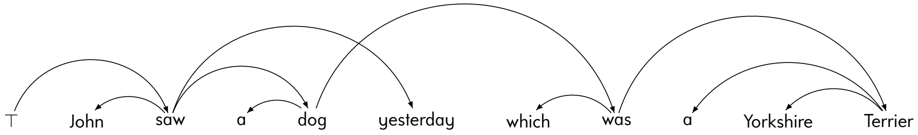


Dependency Parsing

Illustration page-number:



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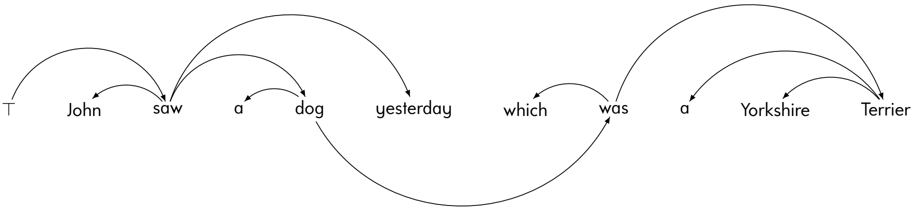

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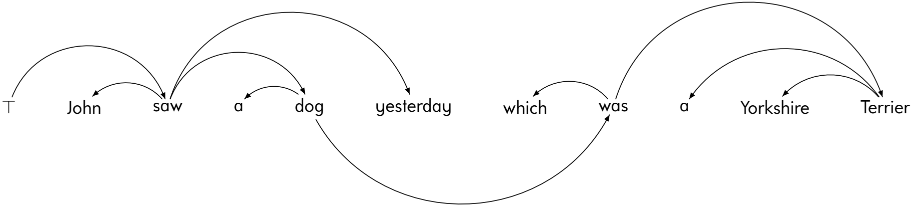


Practical results:

- linear-time statistical parsers
- Google's "Parsey McParseface" [Andor et al., 2016]
  94% F_1-score; linguists achieve 96–97%

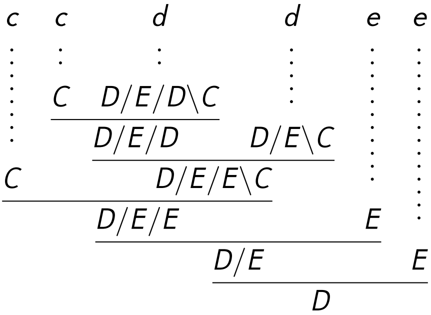
Dependency Parsing

Theoretical problems

Given edge-weighted directed graph, extract "best" edge cover

- (general) [Edmonds, 1965]
- that is a tree [Chu-Liu & Edmonds, 1965–1967]
- that is projective tree [Eisner, 1996]
- that is acyclic NP-hard [Guruswami et al., 2011]
- that is a tree with page-number 2 [Gómez-Rodríguez & Nivre, 2013]
- that has page-number $k \geq 2$ NP-hard [Kuhlmann & Jonsson, 2015]
- that is a tree with page-number $k \geq 3$ open

Combinatory Categorial Grammars



The lexicon generates string language $\mathcal{L}$ with $\mathcal{L} \cap c^+ d^+ e^+ = \{c^i d^i e^i \mid i \geq 1\}$ for goal item D

$$L(c) = \{C\}$$
$$L(d) = \{D/E\backslash C,\ D/E/D\backslash C\}$$
$$L(e) = \{E\}$$

Combinatory Categorial Grammars

Theoretical problems

Under a suitable relabeling, characterize the set of valid proof trees

- for just applications $\rightarrow$ sub-regular tree languages
- for compositions of order 1 $\rightarrow$ open (probably still regular)
- for compositions of order $k \geq 2$ $\rightarrow$ open
- for arbitrary compositions $\rightarrow$ context-free tree language

ongoing work with Marco Kuhlmann

Lexicalization

Definition (lexicalized)

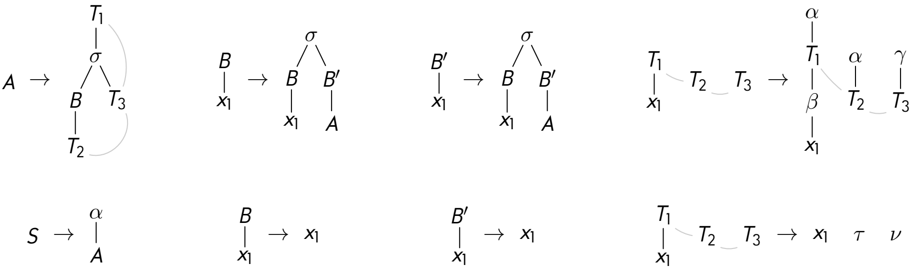
A grammar is lexicalized if each rule contains a lexical item

Existing results

- CFG weakly lexicalize themselves — Greibach normal form
- TAG weakly lexicalize themselves — [Schabes, 1990]
- TAG strongly lexicalize CFG and TSG — [Schabes, 1990]
- CFTG strongly lexicalize TAG and themselves — [M, Engelfriet, 2012]
- $(d+1)$-TAG strongly lexicalize d-TAG — [De Santo et al., 2016]

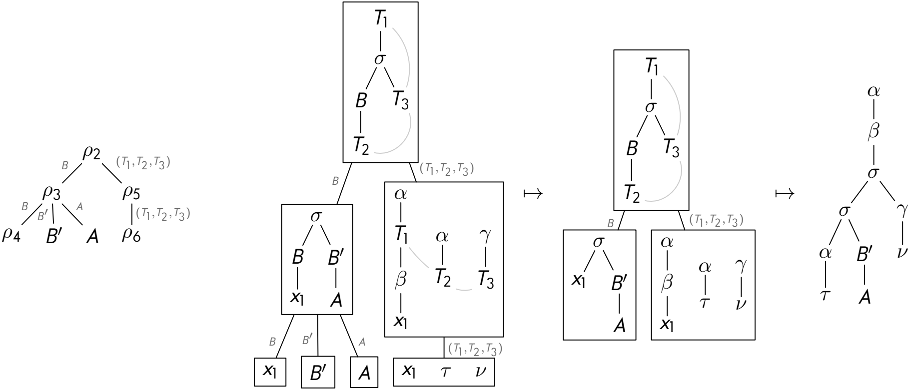
Lexicalization

Multiple context-free tree grammar:



Lexicalization

Derivation tree and evaluation:



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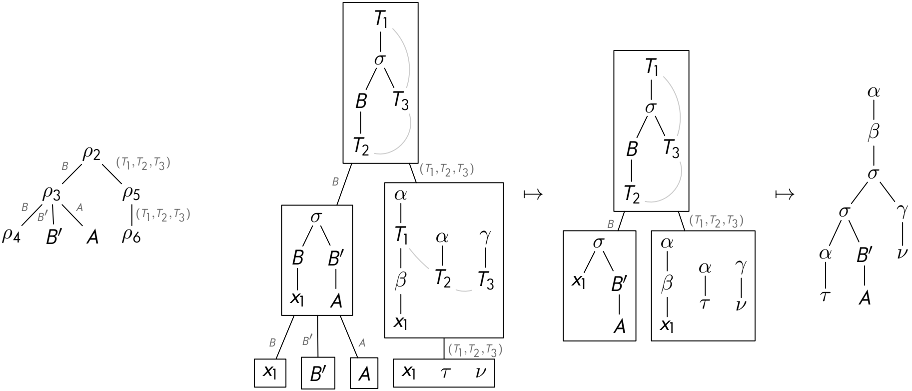

MCFTG strongly lexicalize themselves and inv. of their expressive power

ongoing work with Joost Engelfriet and Sebastian Maneth

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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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。

Machine Translation

Short History:

today

Reformation

phrase-based and syntax-based systems

statistical approach (cheap, automatically trained)

1991

Dark age

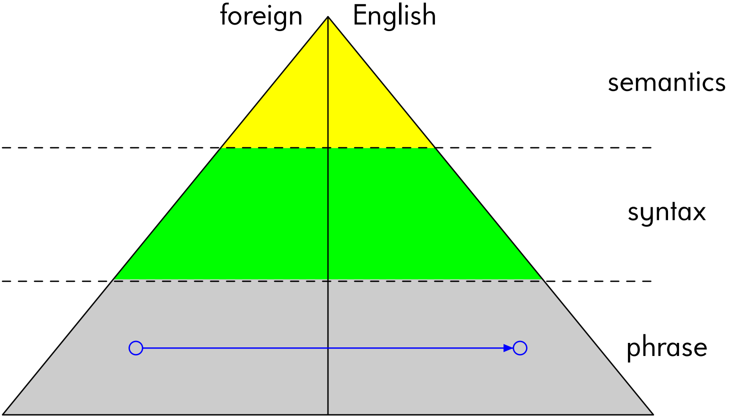
rule-based systems (e.g., SYSTRAN)

Chomskyan approach (perfect translation, poor coverage)

1960

Machine Translation

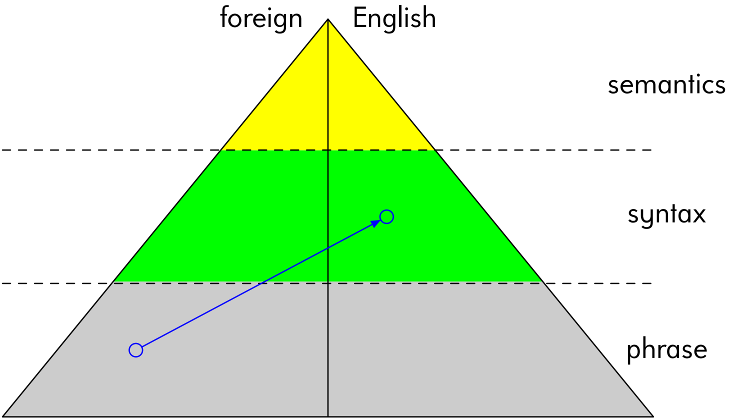
Vauquois triangle:



Translation model: string-to-string

Machine Translation

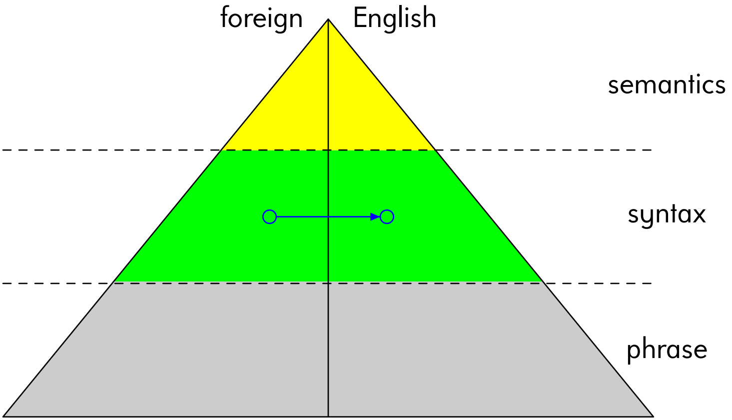
Vauquois triangle:



Translation model: string-to-tree

Machine Translation

Vauquois triangle:



Translation model: tree-to-tree

Machine Translation

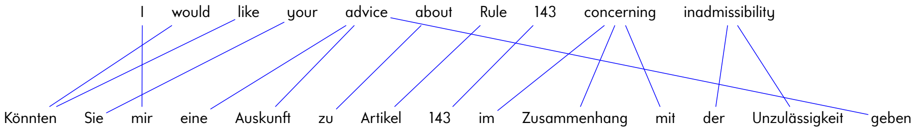
parallel corpus, word alignments, parse tree

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

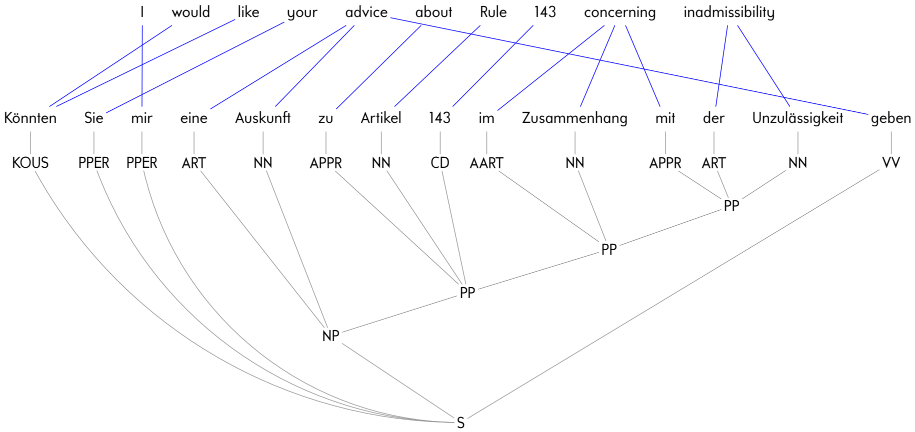
parallel corpus, word alignments, parse tree



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

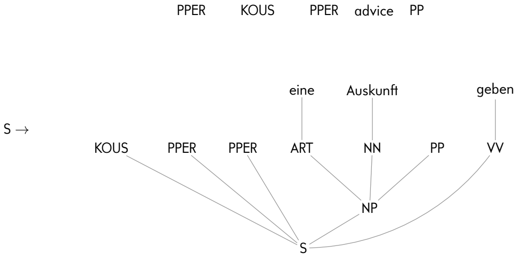


via Berkeley parser [Petrov, Barrett, Thibaux, Klein: Learning accurate, compact, and interpretable tree annotation. *Proc. ACL*, 2006]

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

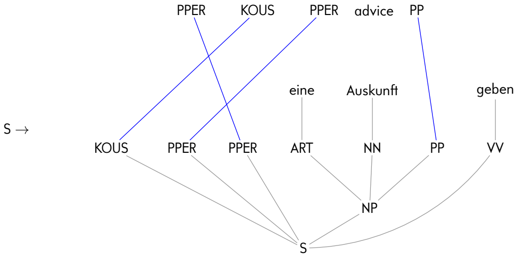


variant of [M., Graehl, Hopkins, Knight: The power of extended top-down tree transducers. *SIAM Journal on Computing* 39(2), 2009]

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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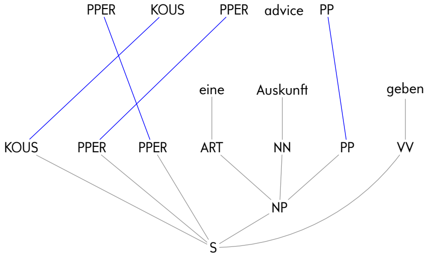
Synchronous Grammars

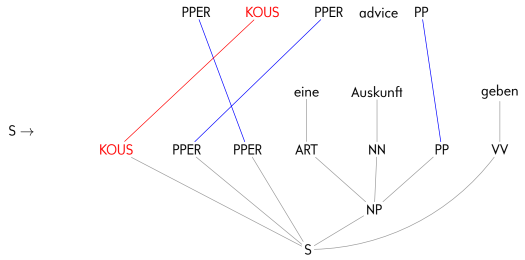
S →



Production application:

1. Selection of synchronous nonterminals

Synchronous Grammars



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Synchronous Grammars

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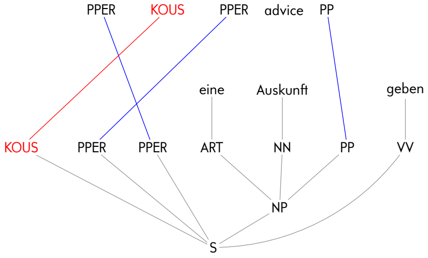
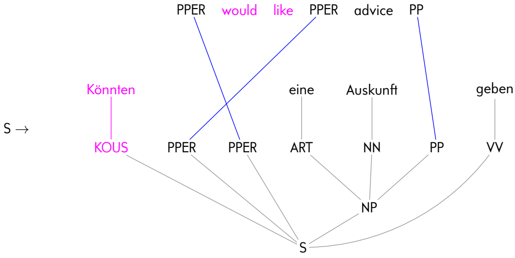


Production application:

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

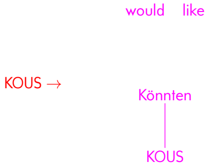
KOUS →

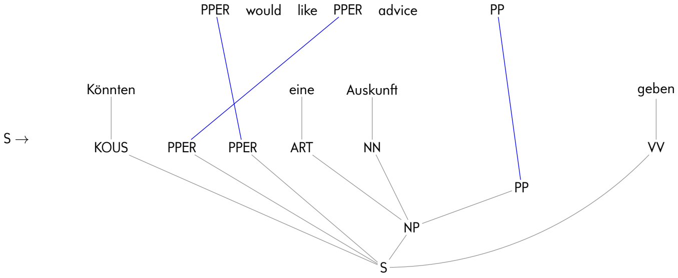
Synchronous Grammars



Production application:

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





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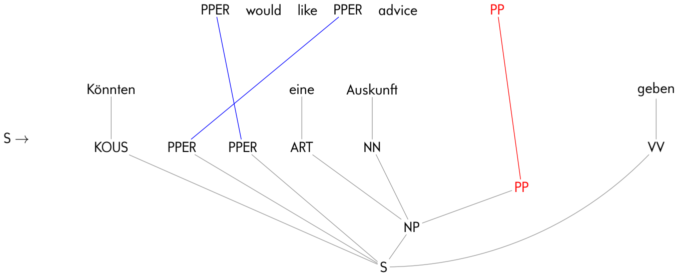

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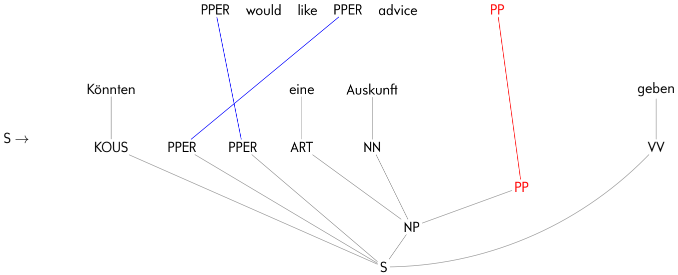
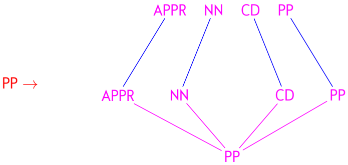


Production application:

1. synchronous nonterminals
2. suitable production



Synchronous Grammars

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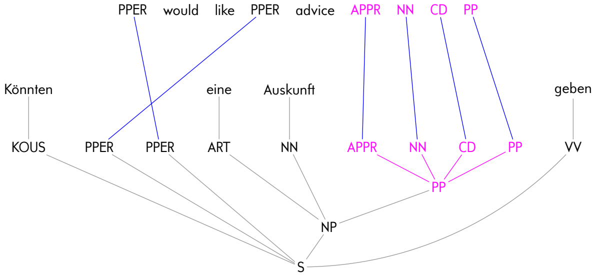
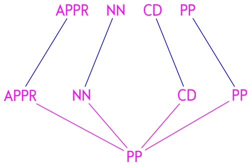


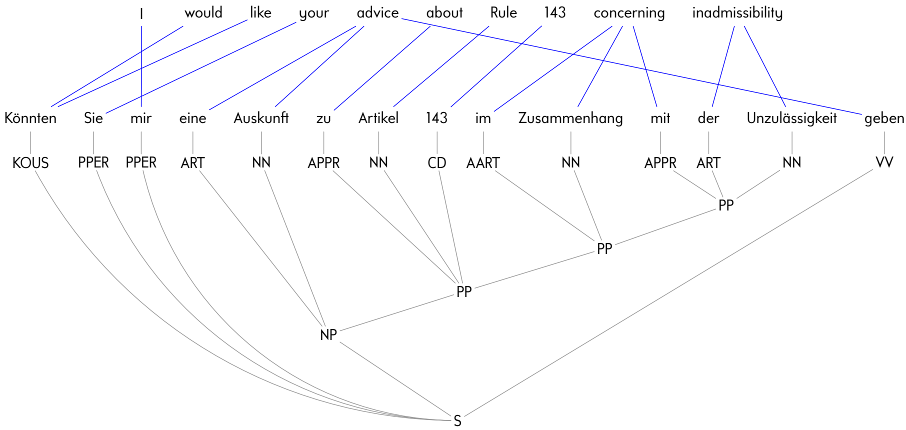
Production application:

1. synchronous nonterminals
2. suitable production
3. replacement

PP →



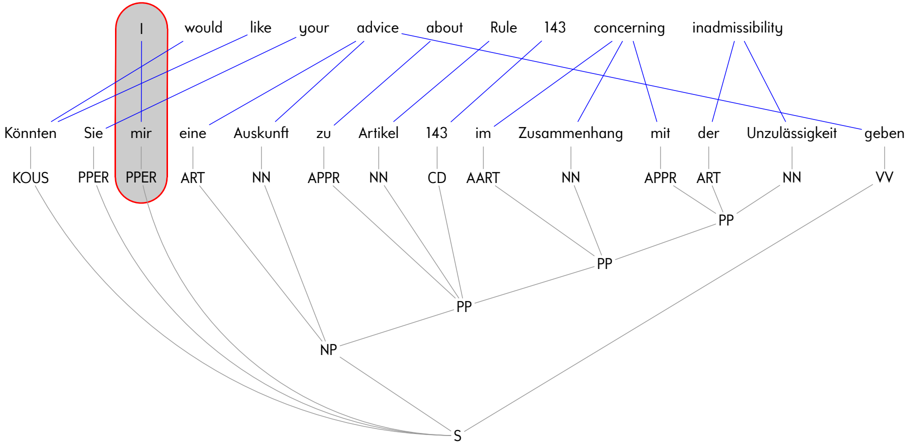
Production Extraction



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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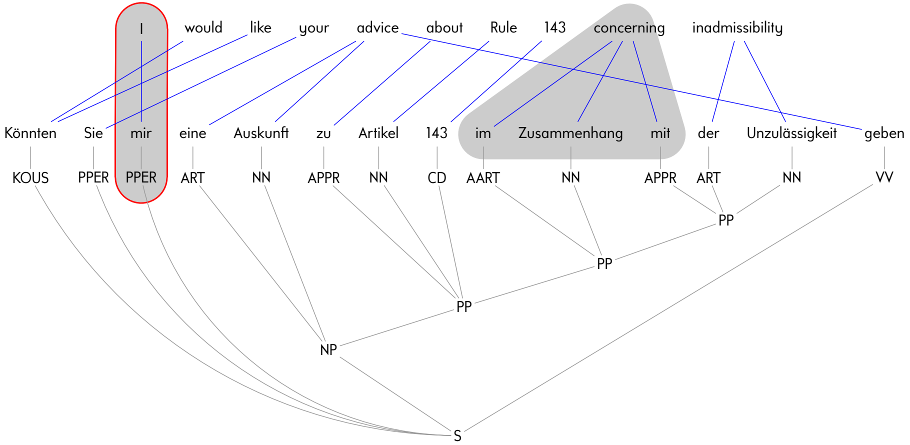

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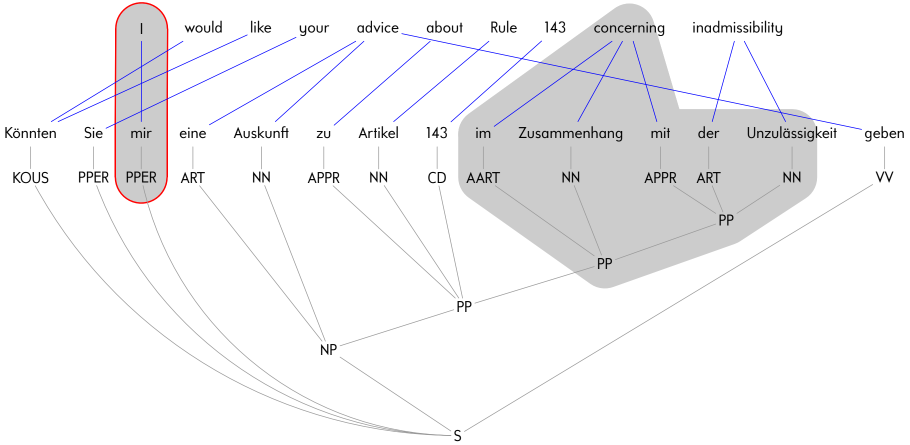

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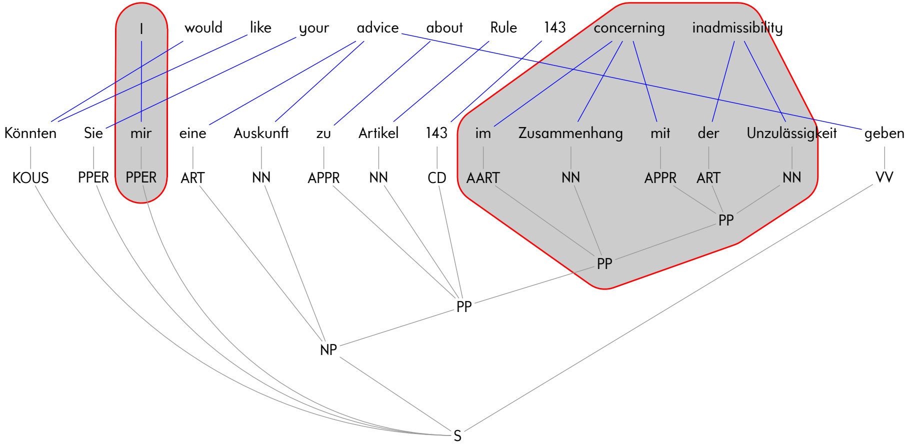
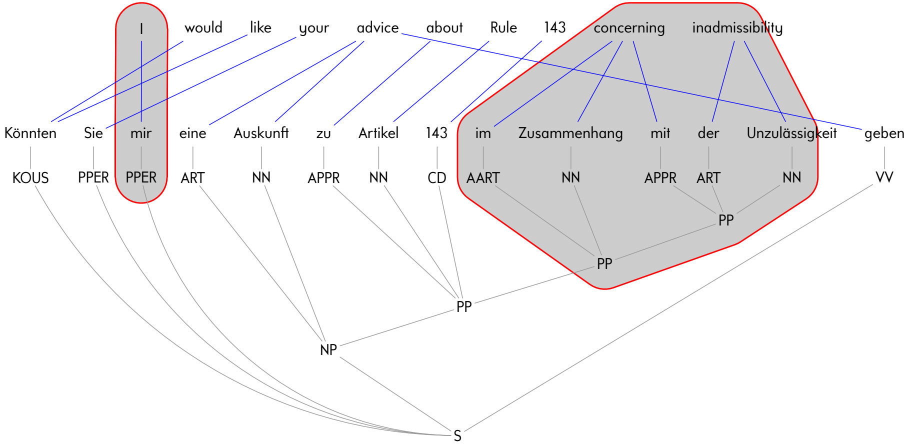


following [Galley, Hopkins, Knight, Marcu: What's in a translation rule? *Proc. NAACL,* 2004]

Production Extraction

Removal of extractable production:



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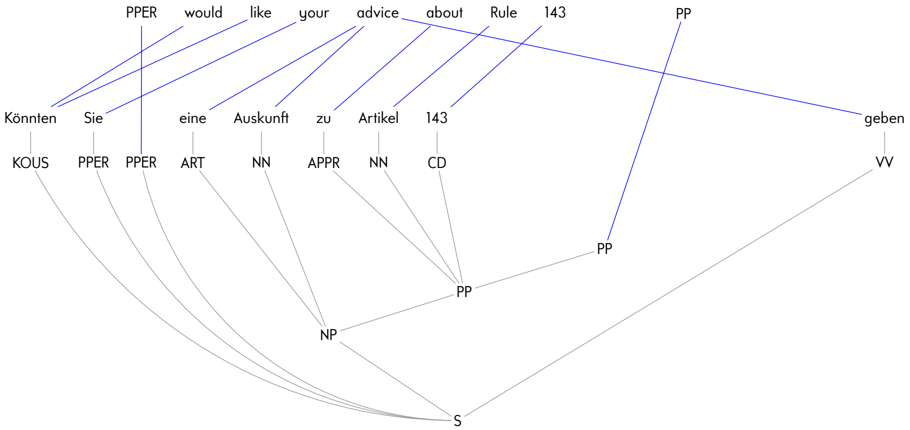
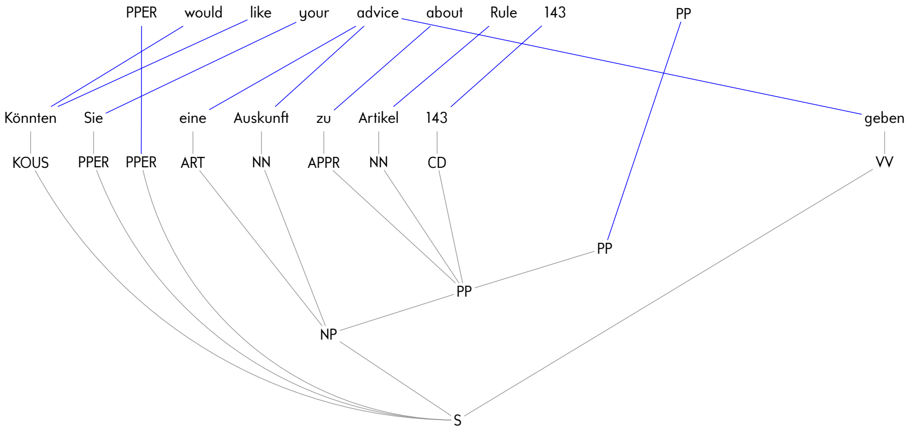


Production Extraction

Repeated production extraction:



Production Extraction

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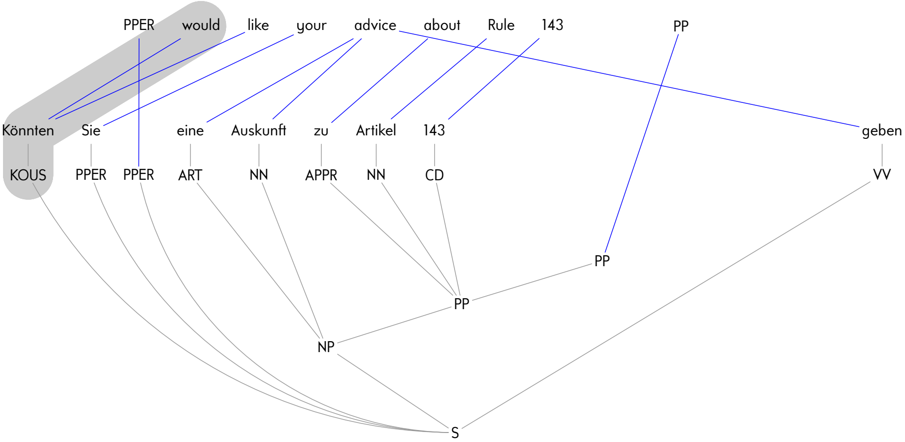
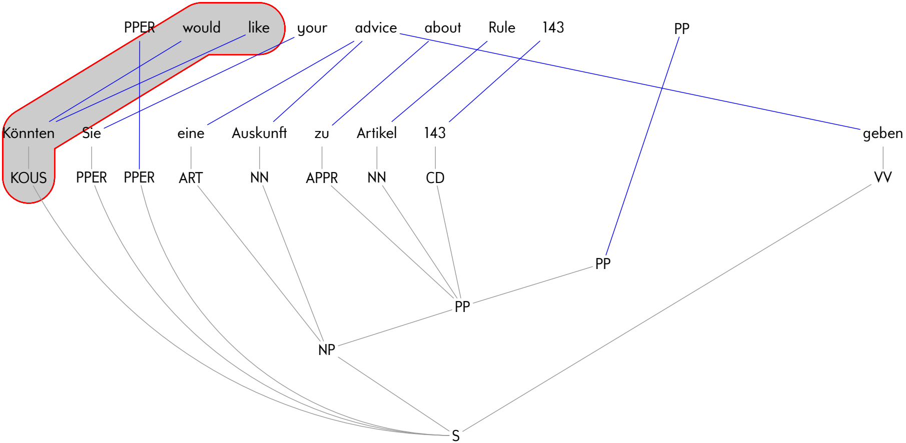


Production Extraction

Repeated production extraction: (extractable productions marked in red)



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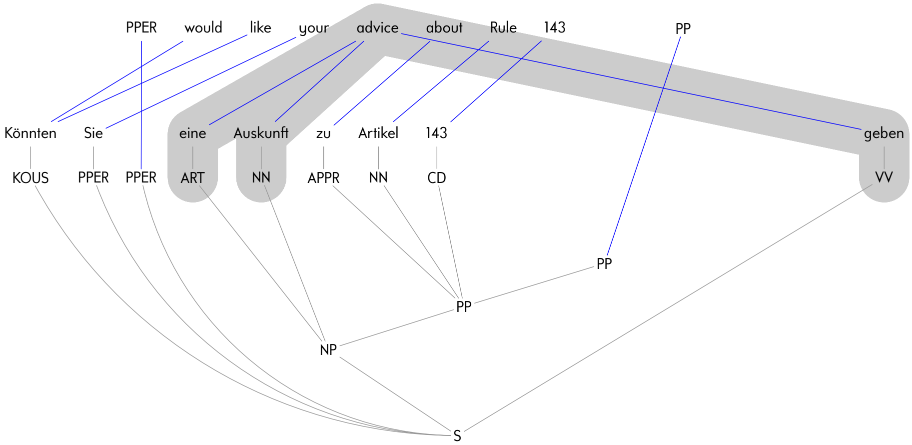

Production Extraction

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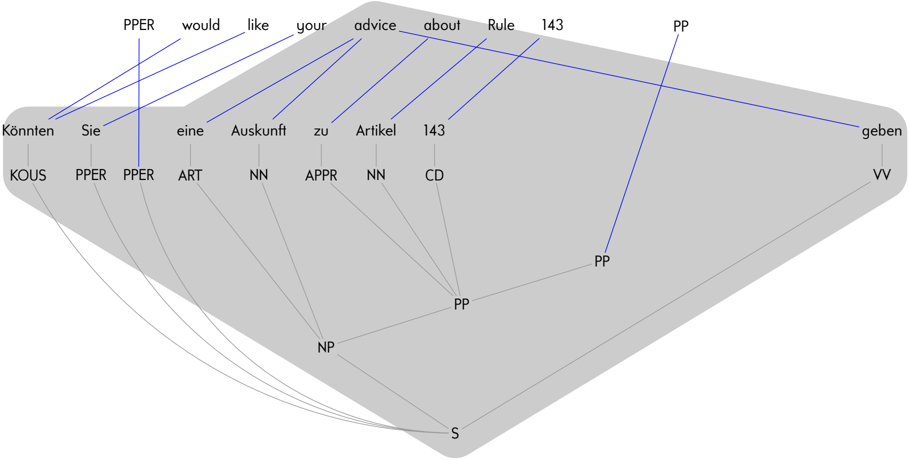

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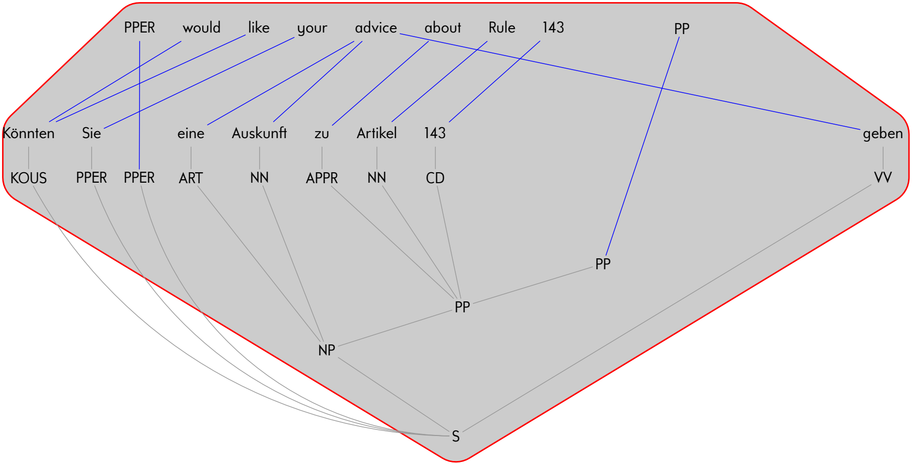
Repeated production extraction: (extractable productions marked in red)



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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  [Koehn et al.: Moses — Open source toolkit for statistical machine translation. *Proc. ACL*, 2007]
- "context-free"

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-tree	STSG	15.2	19.4	24.5
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STSG = synchronous tree substitution grammar

from [Seemann, Braune, M.: A systematic evaluation of MBOT in statistical machine translation. *Proc. MT-Summit*, 2015]
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string-to-tree	STSG	15.2	19.4	24.5
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STSG = synchronous tree substitution grammar

Observations:

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

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]
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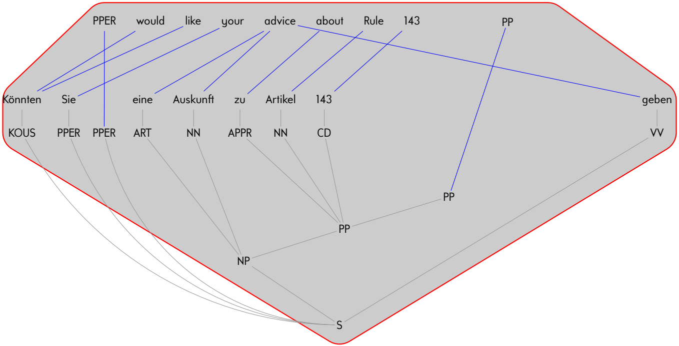
Production Extraction



- very specific production
- every production for 'advice' contains sentence structure

(syntax "in the way")

Synchronous Grammars

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

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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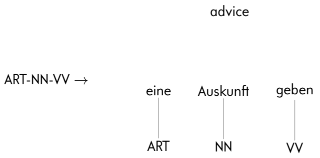

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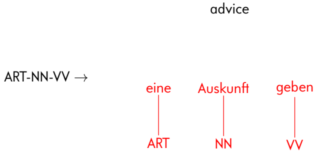

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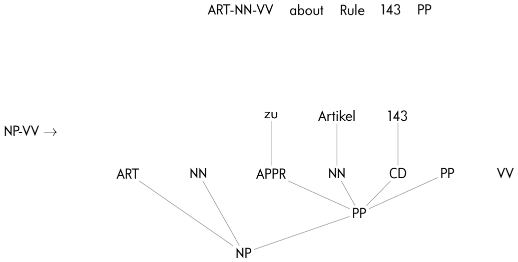

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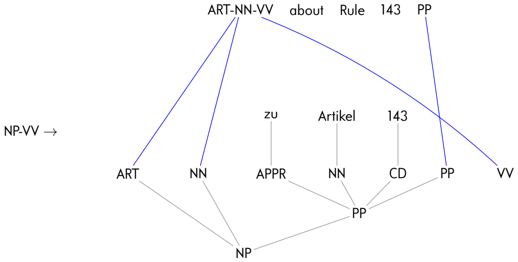
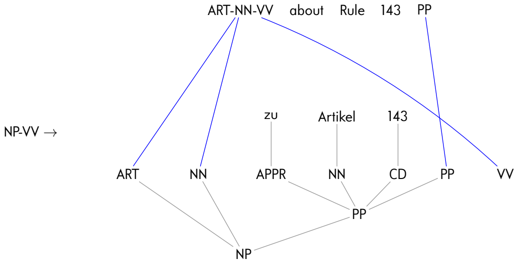
- nonterminal N
- right-hand side r of context-free grammar production
- right-hand sides $r_1, \ldots, r_n$ of regular tree grammar production
- synchronization via map NT $r_1, \ldots, r_n$ to NT r



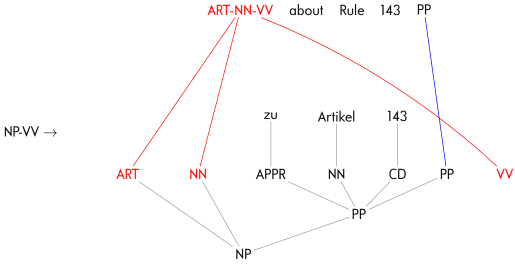
Synchronous Grammars



Production application:

1. synchronous nonterminals

Synchronous Grammars



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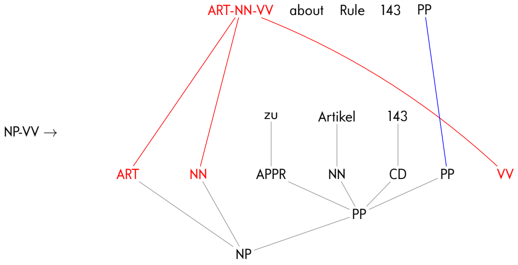

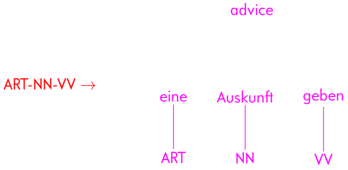

Production application:

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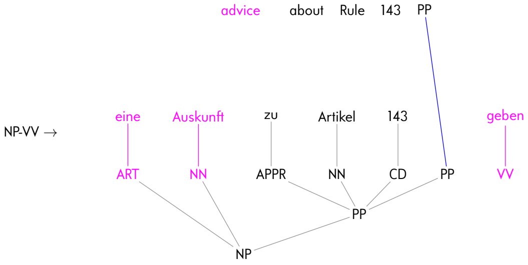
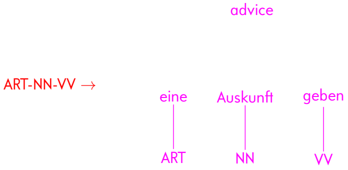
2. suitable production

Synchronous Grammars

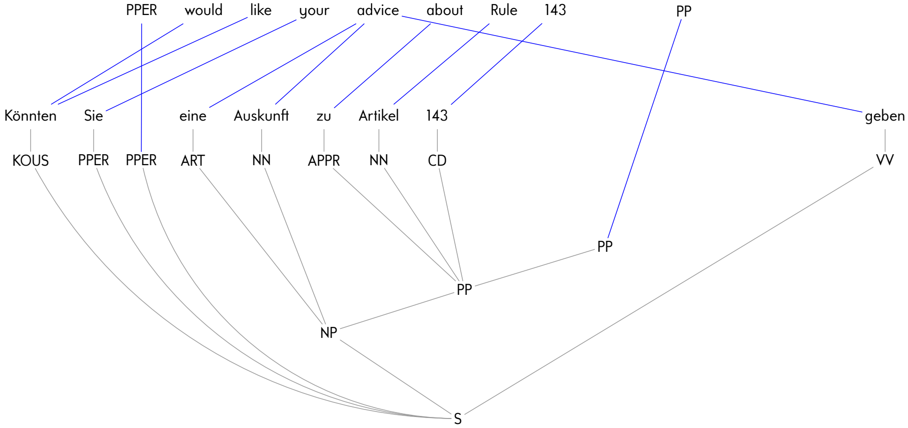


Production application:

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]

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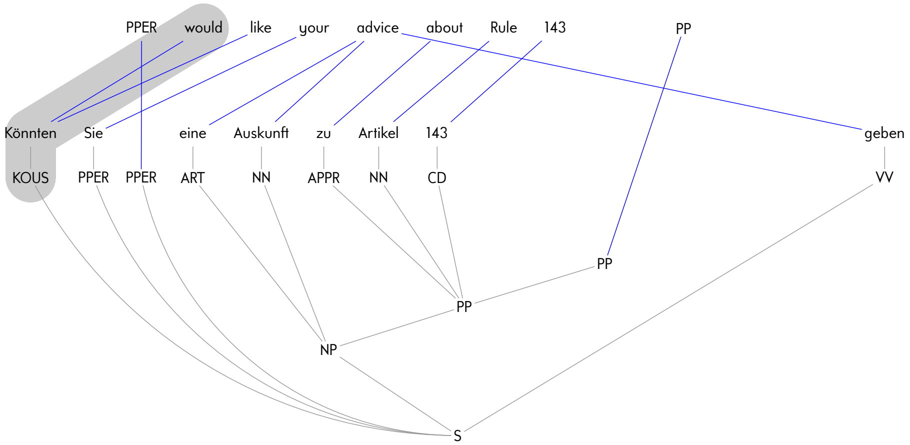

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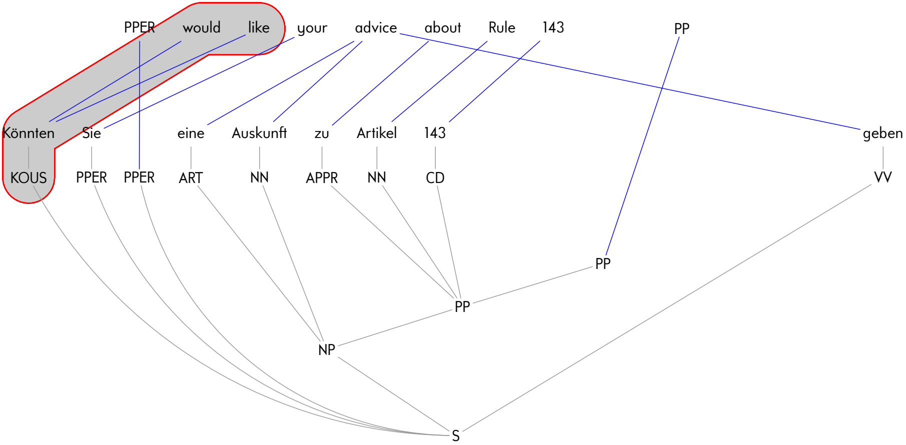
Production Extraction

(extractable productions marked in red)



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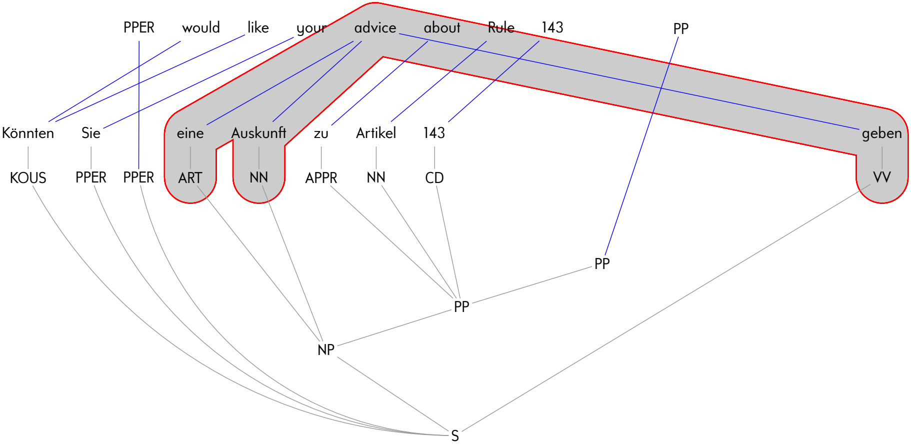

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Synchronous Multi Tree Substitution Grammars

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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Disadvantages:

- output non-regular (tree-level) or non-context-free (string-level)
  (in fact output is captured by MRTG = MCFTG without variables)
- not symmetric (input context-free; output not)

Evaluation

Task	BLEU	
	STSG	SMTSG
English → German	15.0	*15.5
English → Arabic	48.2	*49.1
English → Chinese	17.7	*18.4
English → Polish	21.3	*23.4
English → Russian	24.7	*26.1

STSG = synchronous tree substitution grammar
SMTSG = synchronous multi tree substitution grammar

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

Task	BLEU		Productions	
	STSG	SMTSG	STSG	SMTSG
English → German	15.0	*15.5	14M	144M
English → Arabic	48.2	*49.1	55M	491M
English → Chinese	17.7	*18.4	17M	162M
English → Polish	21.3	*23.4	—	—
English → Russian	24.7	*26.1	—	—

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English $\to$ Polish	21.3	*23.4	—	—
English $\to$ Russian	24.7	*26.1	—	—

STSG = synchronous tree substitution grammar

SMTSG = synchronous multi tree substitution grammar

Observations:

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

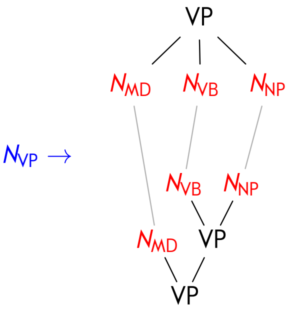
from [Seemann, Braune, M.: A systematic evaluation of MBOT in statistical machine translation. *Proc. MT-Summit*, 2015]
and [Seemann, M.: Discontinuous statistical machine translation with target-side dependency syntax. *Proc. WMT*, 2015]

Synchronous Grammars

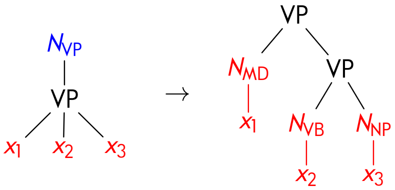
Notes:

- 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:

input sides	**synchronization**	
	bijective	injective (o. $\to$ i.)
shallow	nondeleting top-down …	top-down …
general	nondeleting extended …	extended …

Further distinction:

- allow productions on disconnected input nonterminals
  $\to$ regular look-ahead
- allow arbitrary trees for disconnected input nonterminals
  $\to$ no look-ahead

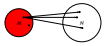
Synchronous Grammars

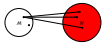
Evaluation properties:

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

$$\sigma(\sigma(t_1, t_2), t_3) \mapsto \sigma(t_1, \sigma(t_2, t_3))$$

 symmetric?

 domain regular?

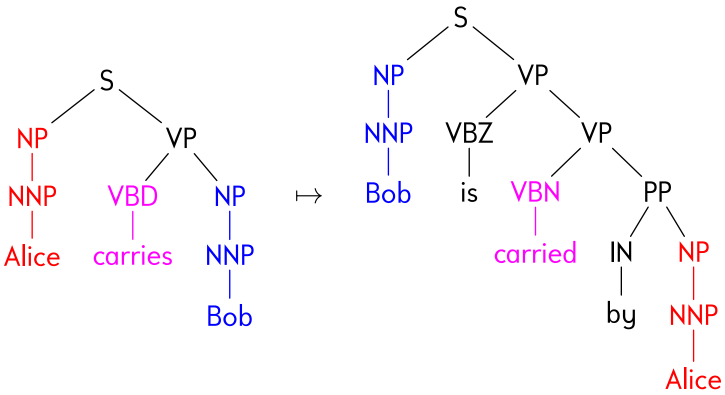
 range regular?

 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]

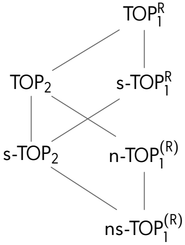
Icons by interactivemania (`http://www.interactivemania.com/`) and UN Office for the Coordination of Humanitarian Affairs

Illustration of rotation:

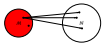
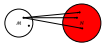


Top-down Tree Transducer

Hasse diagram:

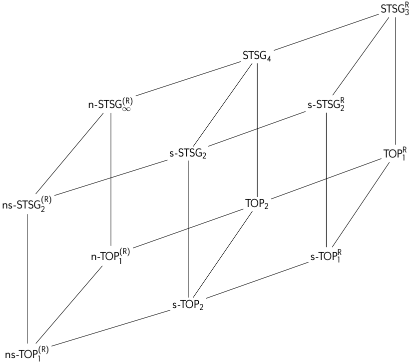


(composition closure in subscript)

Model	**Property**				
					
ns-TOP	✗	✗	✓	✓	✓
n-TOP	✗	✗	✓	✓	✓
s-TOP	✗	✗	✓	✓	✗$_2$
s-TOP^R	✗	✗	✓	✓	✓
TOP	✗	✗	✓	✓	✗$_2$
TOP^R	✗	✗	✓	✓	✓

Synchronous Tree Substitution Grammars

Hasse diagram:



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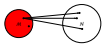	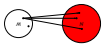	
n-TOP	✗	✗	✓	✓	✓
TOP	✗	✗	✓	✓	$✗_2$
$\mathrm{TOP}^{\mathrm{R}}$	✗	✗	✓	✓	✓
ns-STSG	✓	✓	✓	✓	$✗_2$
n-STSG	✓	✗	✓	✓	$✗_\infty$
$\text{s-STSG}^{(\mathrm{R})}$	✓	✗	✓	✓	$✗_2$
STSG	✓	✗	✓	✓	$✗_4$
$\mathrm{STSG}^{\mathrm{R}}$	✓	✗	✓	✓	$✗_3$

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

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]

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

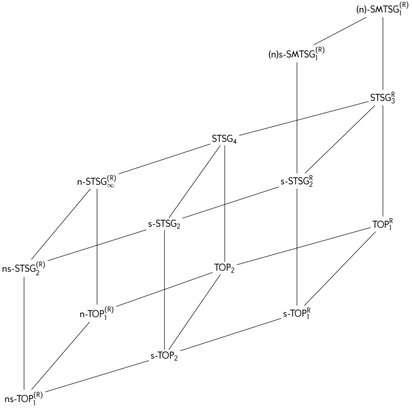
Disadvantages of SMTSG:

- non-regular range (theoretically interesting?)

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

Synchronous Multi Tree Substitution Grammars

Hasse diagram:



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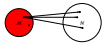
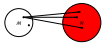
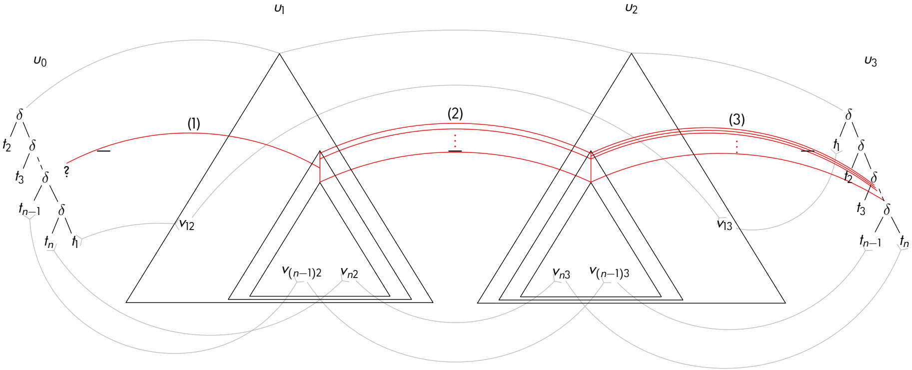
Model	Property				
					
n-TOP	✗	✗	✓	✓	✓
TOP	✗	✗	✓	✓	✗$_2$
TOP^R	✗	✗	✓	✓	✓
ns-STSG	✓	✓	✓	✓	✗$_2$
n-STSG	✓	✗	✓	✓	✗$_\infty$
s-STSG$^{(R)}$	✓	✗	✓	✓	✗$_2$
STSG	✓	✗	✓	✓	✗$_4$
STSG^R	✓	✗	✓	✓	✗$_3$
SMTSG	✓	✗	✓	✗	✓
reg. range	✓	✗	✓	✓	✓
symmetric	✓	✓	✓	✓	✓

(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

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



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

Summary

Parsing:

- tree automata = CFG with subcategorization
  (which are the state-of-the-art models for many languages)
- wealth of open problems for non-constituent parsing
  (alternative theories seem to be on the rise; "Parsey McParseface")

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  (alternative theories seem to be on the rise; “Parsey McParseface”)

Machine translation:

- all major translation models in use are grammar-based
  (and their expressive power is often ill-understood)
- combination of parser and translation model challenging
  (although that is typically just a regular domain restriction)
- evaluation of theoretically well-behaved models (in practice)

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- wealth of open problems for non-constituent parsing
  (alternative theories seem to be on the rise; “Parsey McParseface”)

Machine translation:

- all major translation models in use are grammar-based
  (and their expressive power is often ill-understood)
- combination of parser and translation model challenging
  (although that is typically just a regular domain restriction)
- evaluation of theoretically well-behaved models (in practice)

Thank you for the attention.