Minimalist Grammar Transition-Based Parsing

Miloš Stanojević
m.stanojevic@uva.nl

Institute for Logic, Language and Computation
University of Amsterdam

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Motivation

Types of parsers

- Chart-based : full search space
- Transition-based : partial search space, no guarantees

Motivation

Types of parsers

- Chart-based : full search space
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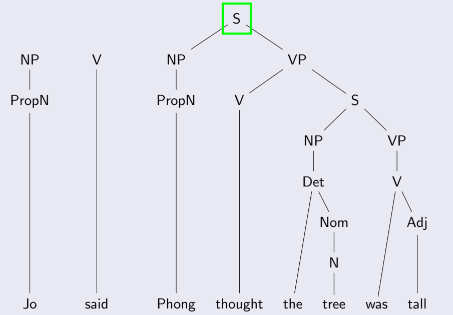
Why use Transition-Based parser instead of Chart-Based one?

- Speed: $O(n^{4m+4})$ vs $O(n^2)$
- Accuracy: local vs non-local conditioning

Accuracy – Locally vs Non-Locally Conditioned Models

Example sentence



Accuracy – Locally vs Non-Locally Conditioned Models

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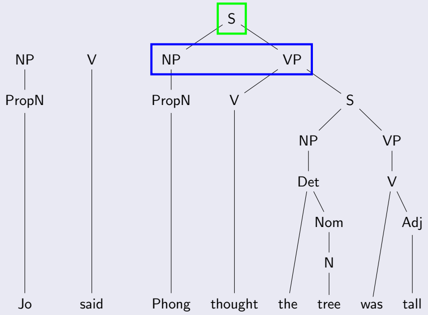
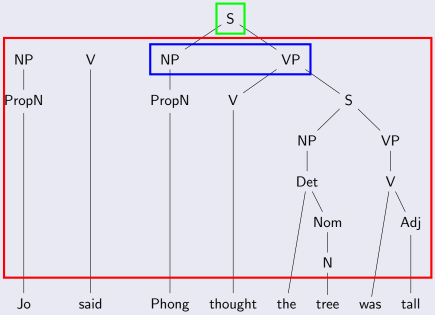


Locally conditioned model

$$P(\boxed{\text{S}} \mid \boxed{\text{NP} \quad \text{VP}})$$

Accuracy – Locally vs Non-Locally Conditioned Models

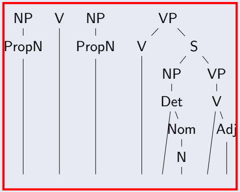
Example sentence



Locally conditioned model

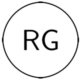
$$P(\boxed{\text{S}} \mid \boxed{\text{NP} \quad \text{VP}})$$

Non-Locally conditioned model

$P(\boxed{\text{S}} \mid$  $)$

Very successfull for CFG, CCG and dependency parsing.

Speed



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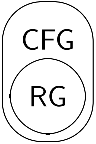

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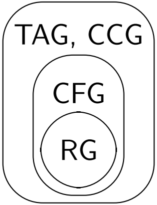

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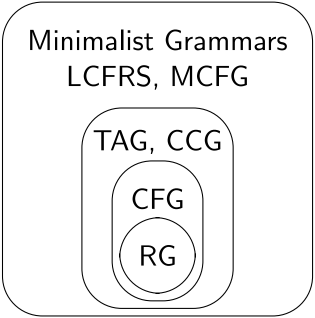

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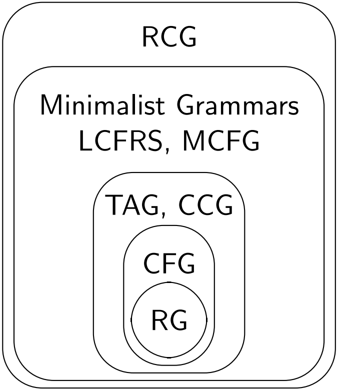

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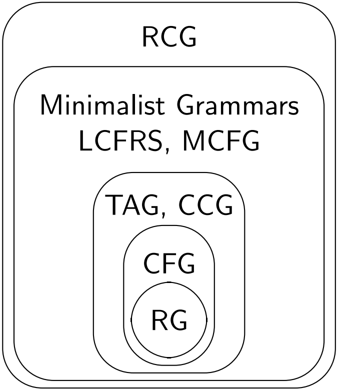


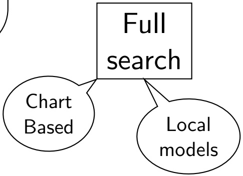
RCG

Minimalist Grammars
LCFRS, MCFG

TAG, CCG

CFG

RG

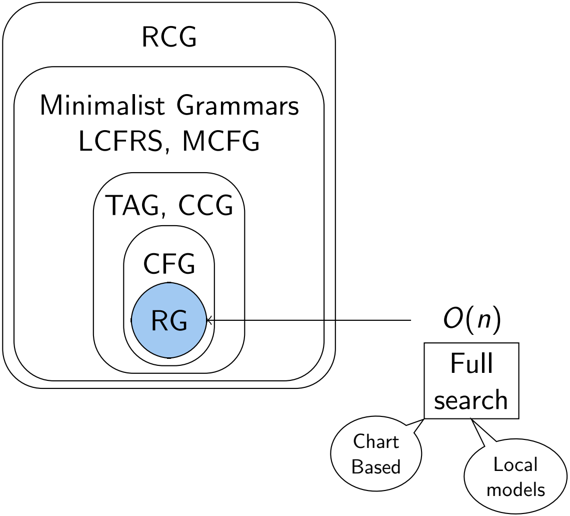


Full search

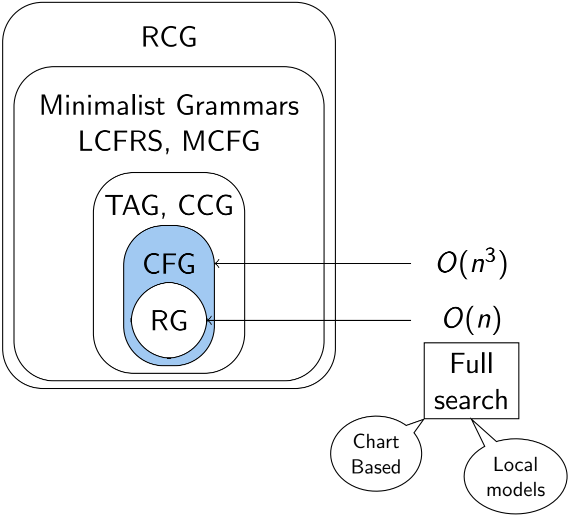
Chart Based

Local models

Speed


RCG
Minimalist Grammars
LCFRS, MCFG
TAG, CCG
CFG
RG
$O(n)$
Full search
Chart Based
Local models

Speed


RCG
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LCFRS, MCFG
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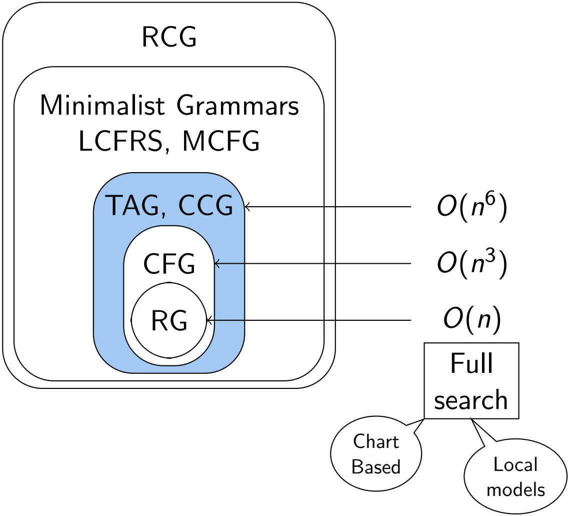
$O(n^3)$
$O(n)$
Full search
Chart Based
Local models

Speed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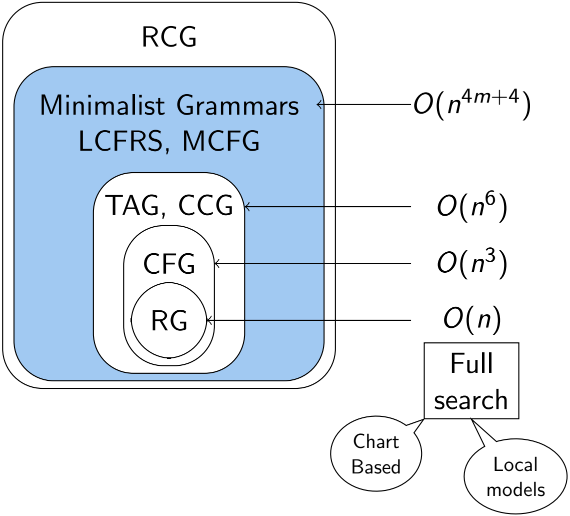
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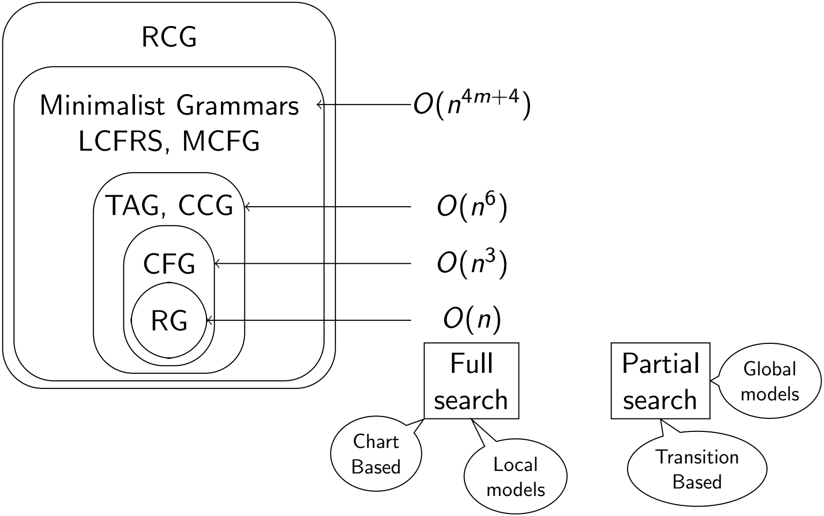
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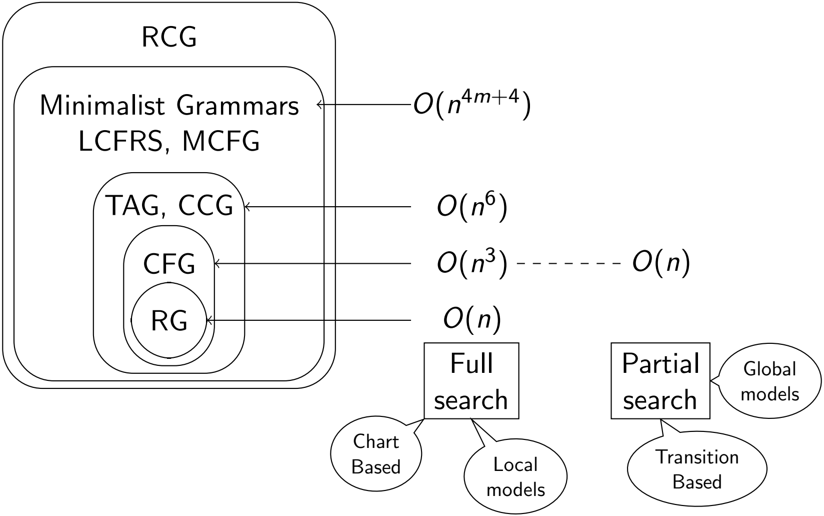
Full search
Chart Based
Local models
Partial search
Global models
Transition Based

Speed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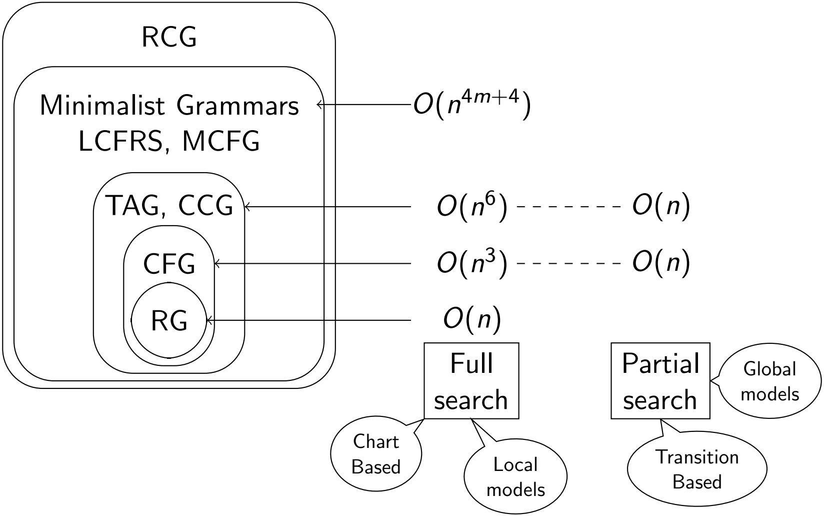
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Full search
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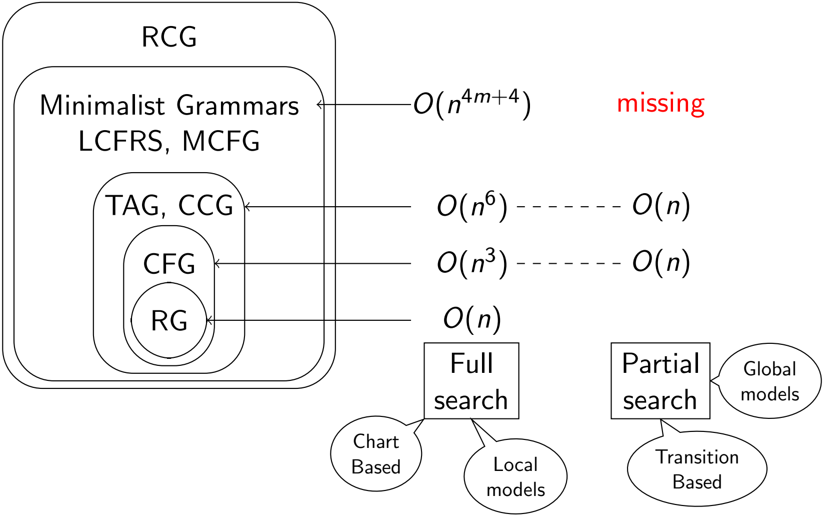
RCG
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missing
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$O(n)$
Full search
Partial search
Global models
Chart Based
Local models
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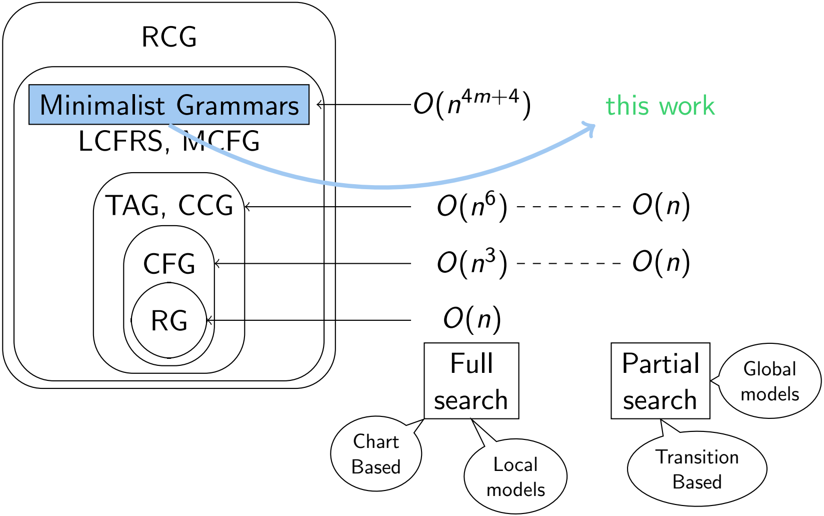
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this work
$O(n^6)$
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Full search
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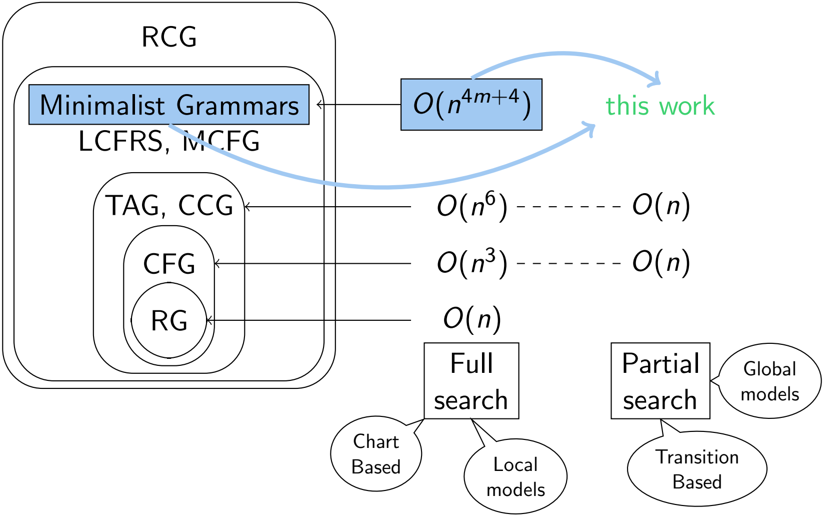
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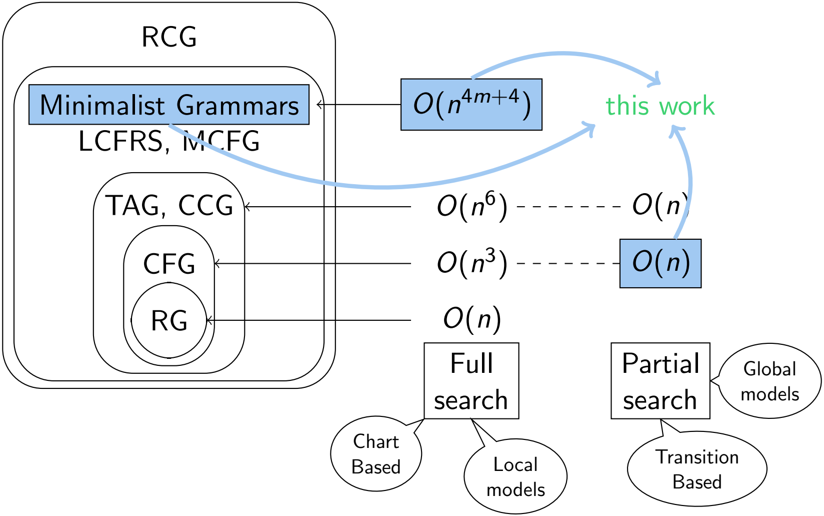
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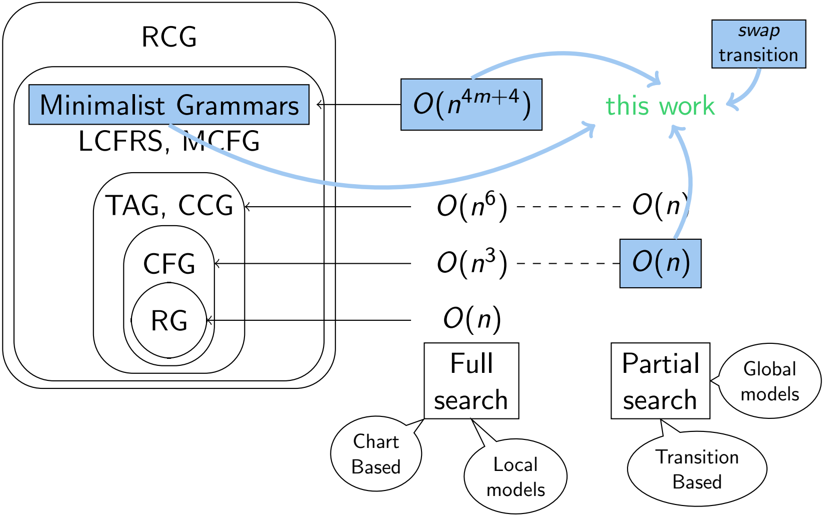
Speed


RCG
Minimalist Grammars
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RG
$O(n^{4m+4})$
this work
swap transition
$O(n^6)$
$O(n)$
$O(n^3)$
$O(n)$
$O(n)$
Full search
Partial search
Global models
Chart Based
Local models
Transition Based

Minimalist Grammars

Composition Functions

- *merge*
- *move*

Features

- features for *merge*:
  - selectees: v, n, c, d, a
  - selectors: $=v,\ =n,\ =c,\ =d,\ =a$
- features for *move*:
  - licensees: $-wh, -case$
  - licensors: $+wh, +case$

Minimalist Grammars

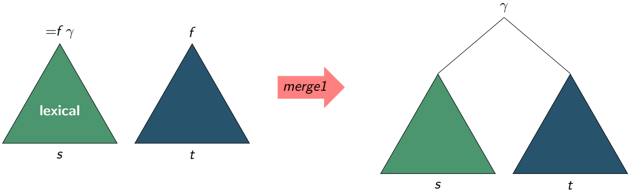
Lexicon

- likes :: $=d \;\; =d \;\; v$
- Chomsky :: d
- what :: $d \;\; -wh$
- ε :: $=v \;\; c$
- ε :: $=v \;\; +wh \; c$

Chains and Expressions

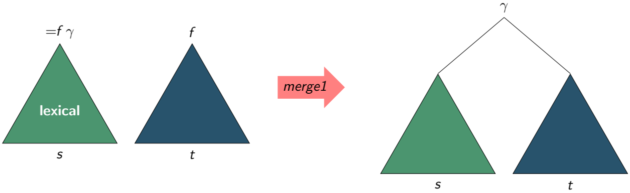
- likes Chomsky : $=d \;\; v$
- likes : $=d \;\; v$, what : $-wh$

Merge for Complements



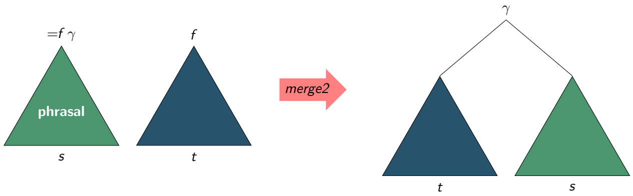
$$\textit{merge1}\ \frac{s :: =f\ \gamma \qquad\qquad t \cdot f, \alpha_1, \ldots, \alpha_k}{st : \gamma, \alpha_1, \ldots, \alpha_k}$$

Merge for Complements



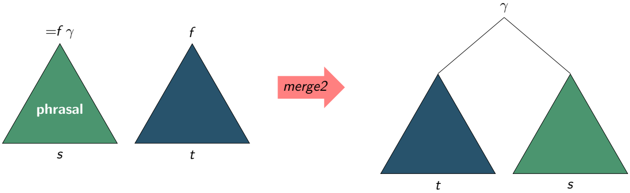
$$\textit{merge1} \quad \frac{s :: =f\gamma \qquad\qquad t \cdot f, \alpha_1, \ldots, \alpha_k}{st : \gamma, \alpha_1, \ldots, \alpha_k}$$

Merge for Specifiers



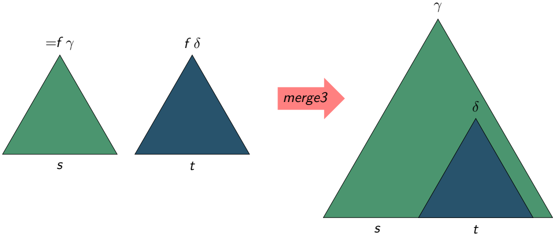
$$\textit{merge2}\ \frac{s : {=}f\ \gamma, \alpha_1, \ldots, \alpha_k \qquad\qquad t \cdot f, \iota_1, \ldots, \iota_l}{ts : \gamma, \alpha_1, \ldots, \alpha_k, \iota_1, \ldots, \iota_l}$$

Merge for Specifiers



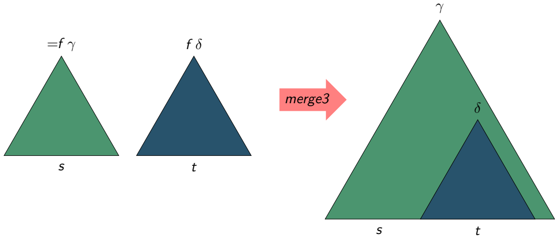
$$\textit{merge2}\ \frac{s : \boxed{=f}\boxed{\gamma, \alpha_1, \ldots, \alpha_k} \qquad\qquad t \cdot \boxed{f}, \boxed{\iota_1, \ldots, \iota_l}}{ts : \boxed{\gamma, \alpha_1, \ldots, \alpha_k}, \boxed{\iota_1, \ldots, \iota_l}}$$

Merge for Moving Constituents



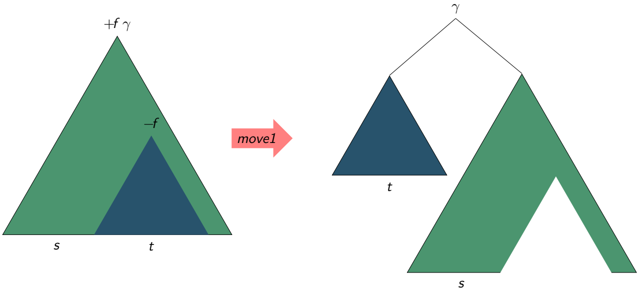
$$merge3 \quad \frac{s \cdot \;\; {=}f\,\gamma, \alpha_1, \ldots, \alpha_k \qquad\qquad t \cdot f\,\delta, \iota_1, \ldots, \iota_l}{s : \gamma, \alpha_1, \ldots, \alpha_k, t : \delta, \iota_1, \ldots, \iota_l}$$

Merge for Moving Constituents



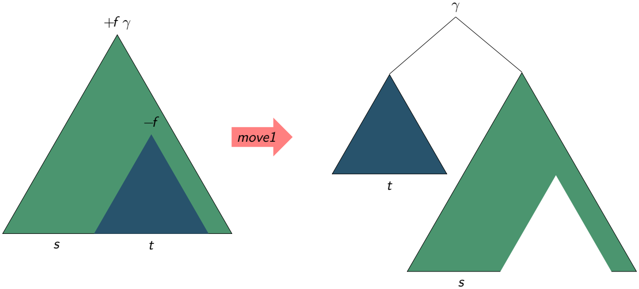
$$\textit{merge3}\quad \frac{s \cdot =f\gamma, \alpha_1, \ldots, \alpha_k \qquad t \cdot f\delta, \iota_1, \ldots, \iota_l}{s : \gamma, \alpha_1, \ldots, \alpha_k, t : \delta, \iota_1, \ldots, \iota_l}$$

Move for the Landing Constituents



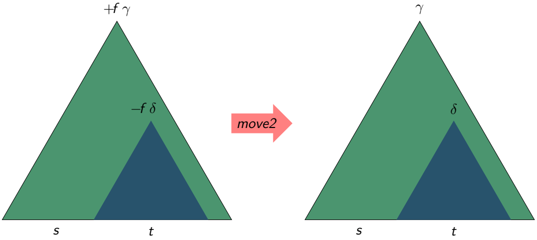
$$move1 \quad \frac{s : +f\ \gamma, \alpha_1, \ldots, \alpha_{i-1}, t : -f, \alpha_{i+1}, \ldots, \alpha_k}{ts : \gamma, \alpha_1, \ldots, \alpha_{i-1}, \alpha_{i+1}, \ldots, \alpha_k}$$

Move for the Landing Constituents



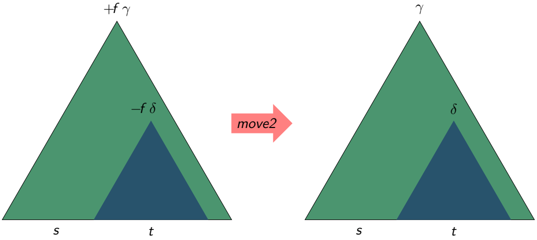
$$move1 \quad \frac{s : +f\,\gamma, \alpha_1, \ldots, \alpha_{i-1},\ t : -f, \alpha_{i+1}, \ldots, \alpha_k}{ts : \gamma, \alpha_1, \ldots, \alpha_{i-1}, \alpha_{i+1}, \ldots, \alpha_k}$$

Move for the Moving Constituents



$$\textit{move2}\quad \frac{s : +f\ \gamma, \alpha_1, \ldots, \alpha_{i-1}, t : -f\ \delta, \alpha_{i+1}, \ldots, \alpha_k}{s : \gamma, \alpha_1, \ldots, \alpha_{i-1}, t : \delta, \alpha_{i+1}, \ldots, \alpha_k}$$

Move for the Moving Constituents



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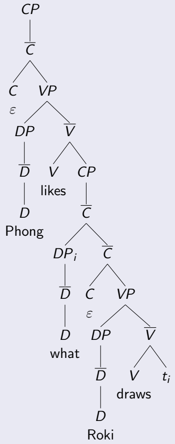
Derived and Derivation Trees

X-bar Structure



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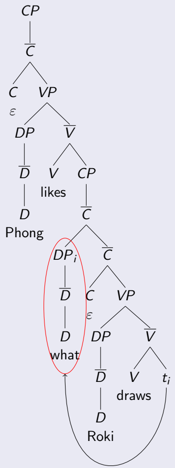

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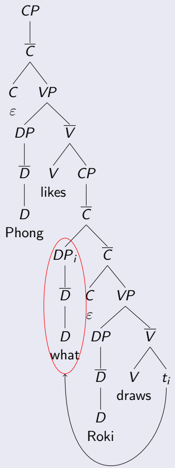
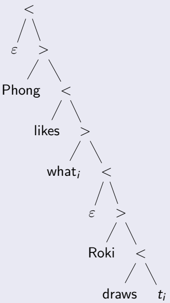


Bare Phrase Structure



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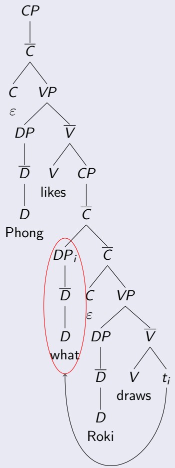

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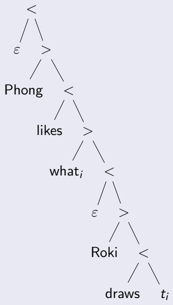
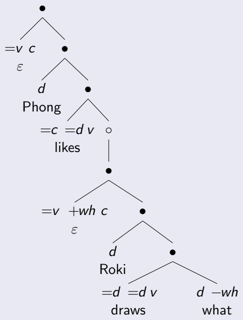


Derivation Tree



Example MG derivation

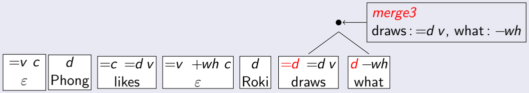
Derivation Tree

$=v\ c$	d	$=c\ =d\ v$	$=v\ +wh\ c$	d	$=d\ =d\ v$	$d\ -wh$
ε	Phong	likes	ε	Roki	draws	what

Derived Tree

Example MG derivation

Derivation Tree



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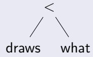
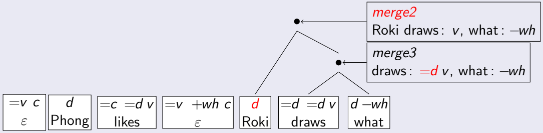


Example MG derivation

Derivation Tree



merge2
Roki draws : v, what : $-wh$

merge3
draws : $=d$ v, what : $-wh$

$=v$ c
ε

d
Phong

$=c$ $=d$ v
likes

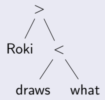
$=v$ $+wh$ c
ε

d
Roki

$=d$ $=d$ v
draws

d $-wh$
what

Derived Tree



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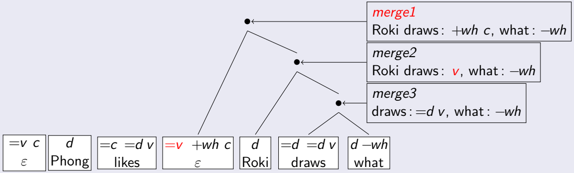


merge1
Roki draws : $+wh\ c$, what : $-wh$

merge2
Roki draws : v, what : $-wh$

merge3
draws : $=d\ v$, what : $-wh$

$=v\ c$
ε

d
Phong

$=c\ \ =d\ v$
likes

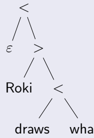
$=v\ \ +wh\ c$
ε

d
Roki

$=d\ \ =d\ v$
draws

$d\ -wh$
what

Derived Tree



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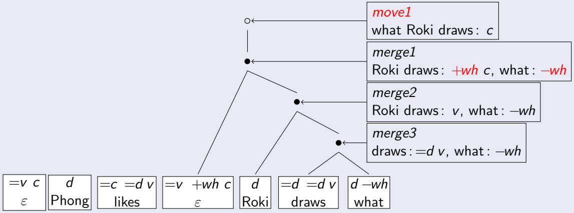


move1
what Roki draws : c

merge1
Roki draws : $+wh$ c, what : $-wh$

merge2
Roki draws : v, what : $-wh$

merge3
draws : $=d$ v, what : $-wh$

$=v$ c
ε

d
Phong

$=c$ $=d$ v
likes

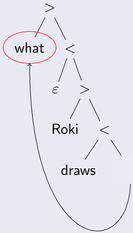
$=v$ $+wh$ c
ε

d
Roki

$=d$ $=d$ v
draws

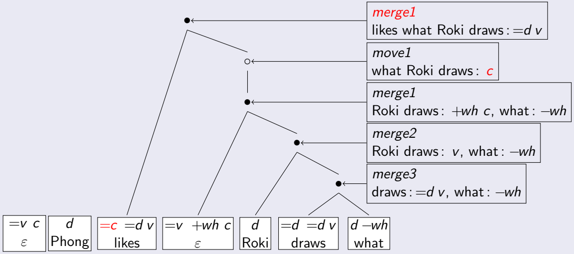
d $-wh$
what

Derived Tree

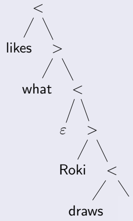


Example MG derivation

Derivation Tree

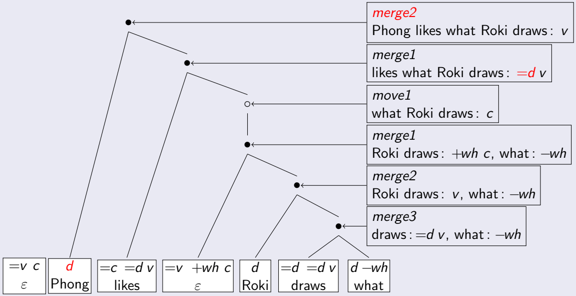


Derived Tree



Example MG derivation

Derivation Tree



merge2
Phong likes what Roki draws : v

merge1
likes what Roki draws : $=d\ v$

move1
what Roki draws : c

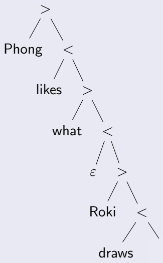
merge1
Roki draws : $+wh\ c$, what : $-wh$

merge2
Roki draws : v, what : $-wh$

merge3
draws : $=d\ v$, what : $-wh$

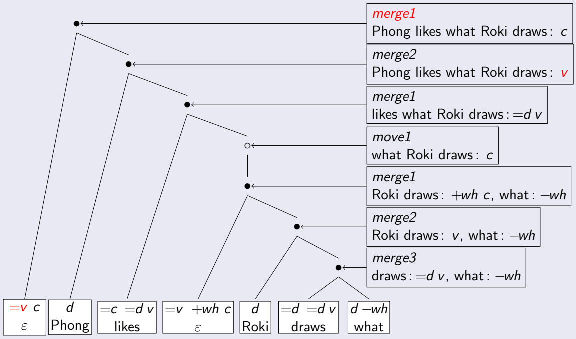
$=v\ c$	d	$=c\ =d\ v$	$=v\ +wh\ c$	d	$=d\ =d\ v$	$d\ -wh$
ε	Phong	likes	ε	Roki	draws	what

Derived Tree



Example MG derivation

Derivation Tree



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$=v\ c$	d	$=c\ =d\ v$	$=v\ +wh\ c$	d	$=d\ =d\ v$	$d\ -wh$
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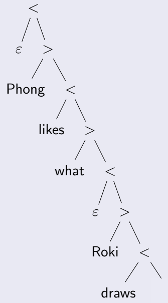
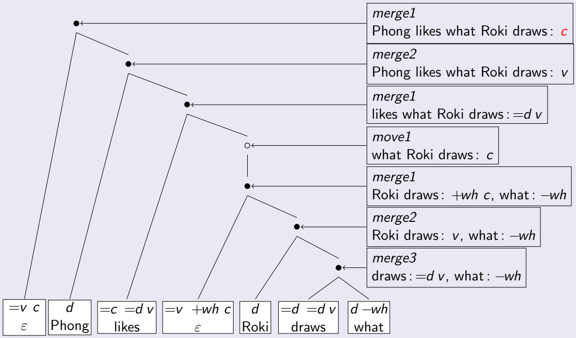
Derived Tree



Example MG derivation

Derivation Tree



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Roki draws : v, what : $-wh$

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$=v\ c$ ε

d Phong

$=c\ =d\ v$ likes

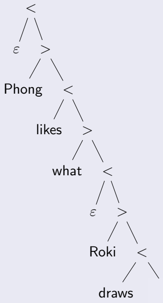
$=v\ +wh\ c$ ε

d Roki

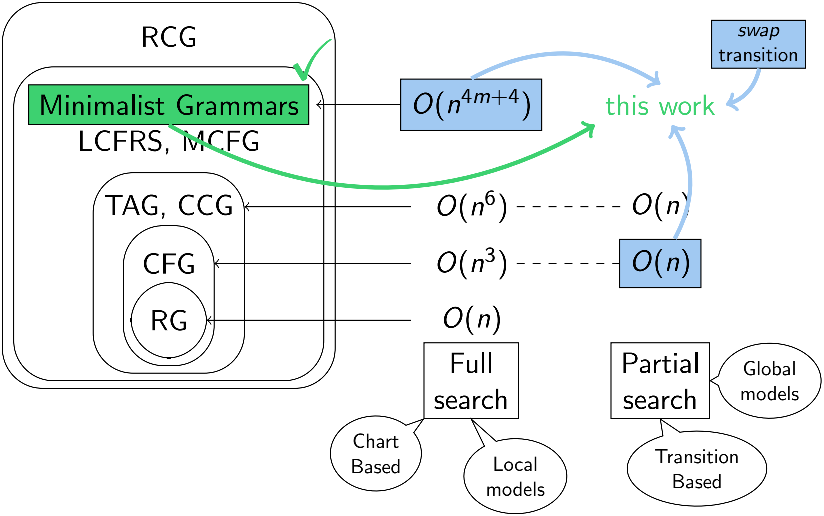
$=d\ =d\ v$ draws

$d\ -wh$ what

Derived Tree



Big Picture



RCG

Minimalist Grammars

LCFRS, MCFG

TAG, CCG

CFG

RG

$O(n^{4m+4})$

this work

swap transition

$O(n^6)$ - - - - - - - $O(n)$

$O(n^3)$ - - - - - - - $O(n)$

$O(n)$

Full search

Partial search

Chart Based

Local models

Transition Based

Global models

Chart-Based MG Parser

Harkema/Stabler MG Chart Parser

- Items $\sim$ MG expressions
- Inference rules $\sim$ MG composition functions
- axioms $\sim$ supertags
- goal $(0, n) \cdot c$
- Computational Complexity $O(n^{4m+4})$

Chart-Based MG Parser

merge1 DEFINITION

$$\frac{s :: =f\ \gamma \qquad t\ \cdot f, \alpha_1, \ldots, \alpha_k}{st : \gamma, \alpha_1, \ldots, \alpha_k}$$

merge1 INFERENCE RULE

$$\frac{(a, b) :: =f\ \gamma \qquad (b, c) \cdot f, \alpha_1, \ldots, \alpha_k}{(a, c) : \gamma, \alpha_1, \ldots, \alpha_k}$$

Chart-Based MG Parser

merge2 definition

$$\frac{s : {=}f\ \gamma, \alpha_1, \ldots, \alpha_k \qquad t \cdot f, \iota_1, \ldots, \iota_l}{ts : \gamma, \alpha_1, \ldots, \alpha_k, \iota_1, \ldots, \iota_l}$$

merge2 inference rule

$$\frac{(b, c) : {=}f\ \gamma, \alpha_1, \ldots, \alpha_k \qquad (a, b) \cdot f, \iota_1, \ldots, \iota_l}{(a, c) : \gamma, \alpha_1, \ldots, \alpha_k, \iota_1, \ldots, \iota_l}$$

Chart-Based MG Parser

merge3 Definition

$$\frac{s \quad \cdot{=}f\ \gamma, \alpha_1, \ldots, \alpha_k \qquad\qquad t \ \cdot f\ \delta, \iota_1, \ldots, \iota_l}{s : \gamma, \alpha_1, \ldots, \alpha_k, t : \delta, \iota_1, \ldots, \iota_l}$$

merge3 Inference Rule

$$\frac{(a, b) \cdot {=}f\ \gamma, \alpha_1, \ldots, \alpha_k \qquad\qquad (c, d) \cdot f\,\delta, \iota_1, \ldots, \iota_l}{(a, b) : \gamma, \alpha_1, \ldots, \alpha_k, (c, d) : \delta, \iota_1, \ldots, \iota_l}$$

Chart-Based MG Parser

move1 DEFINITION

$$\frac{s : +f\,\gamma, \alpha_1, \ldots, \alpha_{i-1}, \; t : -f, \alpha_{i+1}, \ldots, \alpha_k}{ts : \gamma, \alpha_1, \ldots, \alpha_{i-1}, \alpha_{i+1}, \ldots, \alpha_k}$$

move1 INFERENCE RULE

$$\frac{(b, c) : +f\,\gamma, \alpha_1, \ldots, \alpha_{i-1}, \; (a, b) : -f, \alpha_{i+1}, \ldots, \alpha_k}{(a, c) : \gamma, \alpha_1, \ldots, \alpha_{i-1}, \alpha_{i+1}, \ldots, \alpha_k}$$

Chart-Based MG Parser

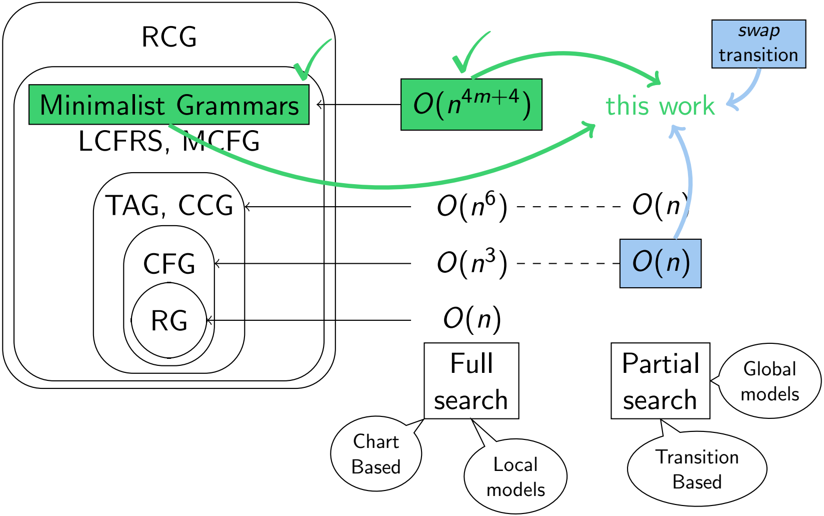
move2 DEFINITION

$$\frac{s : +f\ \gamma, \alpha_1, \ldots, \alpha_{i-1}, t : -f\ \delta, \alpha_{i+1}, \ldots, \alpha_k}{s : \gamma, \alpha_1, \ldots, \alpha_{i-1}, t : \delta, \alpha_{i+1}, \ldots, \alpha_k}$$

move2 INFERENCE RULE

$$\frac{(a, b) : +f\ \gamma, \alpha_1, \ldots, \alpha_{i-1}, (c, d) : -f\ \delta, \alpha_{i+1}, \ldots, \alpha_k}{(a, b) : \gamma, \alpha_1, \ldots, \alpha_{i-1}, (c, d) : \delta, \alpha_{i+1}, \ldots, \alpha_k}$$

Big Picture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Full search
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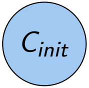
Transition Based

What is a Transition-Based Parser?



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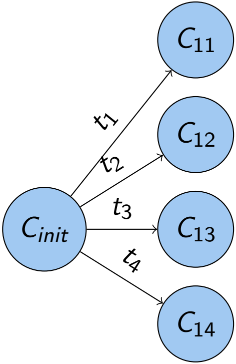

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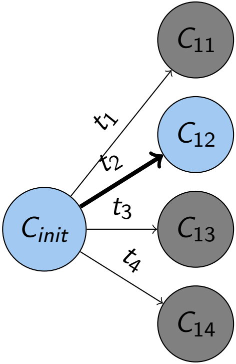

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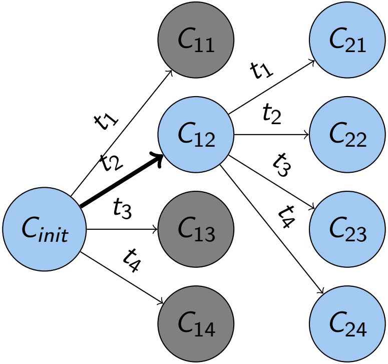

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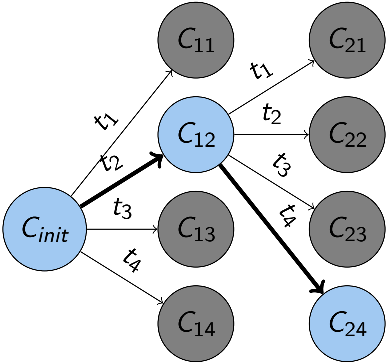

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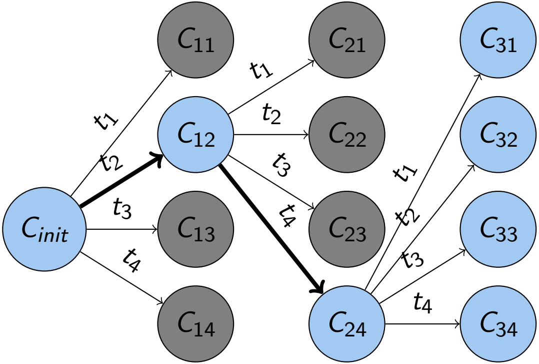

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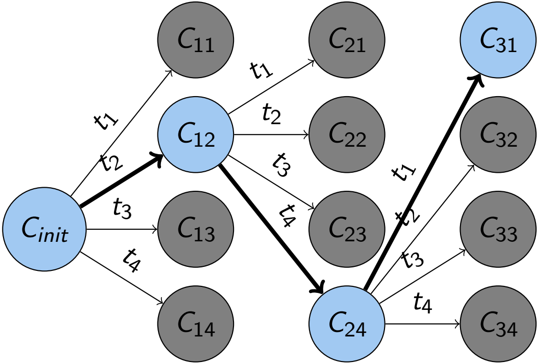

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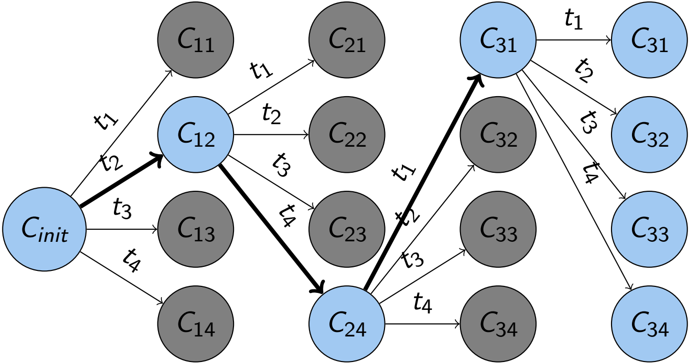

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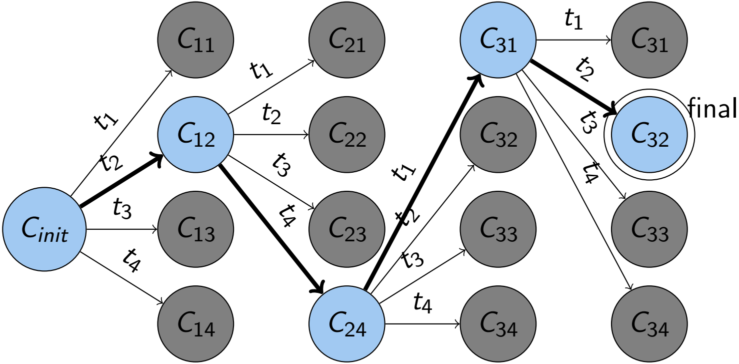


Transition-Based CFG Parsing

Components

- Configurations
  - buffer β
    words remaining to process
  - stack σ
    constituents built so far
- Transitions
  - Shift
  - Reduce

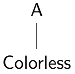
Deduction System

$$\begin{array}{rl}
\textit{axiom} & \langle [], [w_1, \ldots, w_n] \rangle \\
\textit{goal} & \langle [S], [] \rangle \\
\textit{shift}\{X\} & \dfrac{\langle \sigma, w|\beta \rangle}{\langle \sigma|X, \beta \rangle} \quad X \rightarrow w \in G \\
\textit{reduce}\{Z\} & \dfrac{\langle \sigma|X|Y, \beta \rangle}{\langle \sigma|Z, \beta \rangle} \quad Z \rightarrow XY \in G
\end{array}$$

CFG Transition-Based Parsing Example

	σ	β	transition
1		Colorless , green , ideas , sleep ,furiously	*shift*$\{A\}$

CFG Transition-Based Parsing Example

	σ	β	transition
1		Colorless , green , ideas , sleep ,furiously	*shift*$\{A\}$
2	 A Colorless	green , ideas , sleep ,furiously	*shift*$\{A\}$

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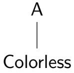
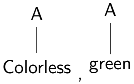
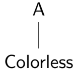
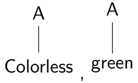
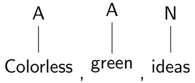
2	 A Colorless	green , ideas , sleep ,furiously	*shift*$\{A\}$
3	 A Colorless , A green	ideas, sleep ,furiously	*shift*$\{N\}$

CFG Transition-Based Parsing Example

	σ	β	transition
1		Colorless , green , ideas , sleep ,furiously	*shift*$\{A\}$
2		green , ideas , sleep ,furiously	*shift*$\{A\}$
3		ideas, sleep ,furiously	*shift*$\{N\}$
4		sleep ,furiously	*reduce*$\{NP\}$

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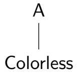
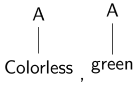
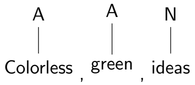
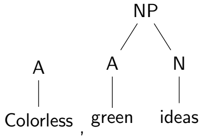
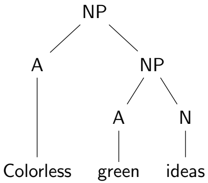
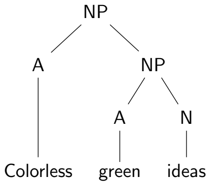
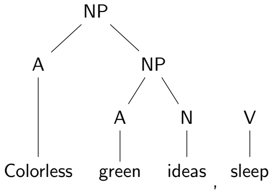
2		green , ideas , sleep ,furiously	*shift*$\{A\}$
3		ideas, sleep ,furiously	*shift*$\{N\}$
4		sleep ,furiously	*reduce*$\{NP\}$
5		sleep ,furiously	*reduce*$\{NP\}$

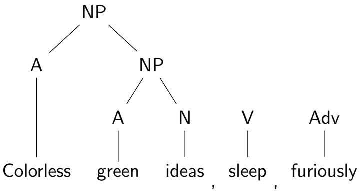
CFG Transition-Based Parsing Example

	σ	β	transition
6		sleep ,furiously	*shift*$\{V\}$

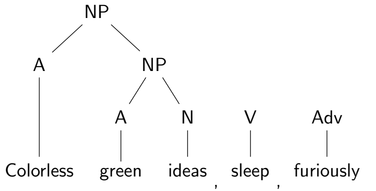
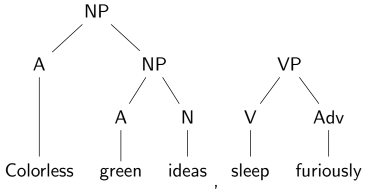
CFG Transition-Based Parsing Example

	σ	β	transition
6		sleep ,furiously	$\mathit{shift}\{V\}$
7	 NP A NP A N V Colorless green ideas , sleep	furiously	$\mathit{shift}\{Adv\}$

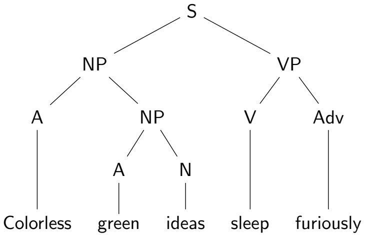
CFG Transition-Based Parsing Example

	σ	β	transition
8	 NP A NP A N V Adv Colorless green ideas , sleep , furiously		*reduce*$\{VP\}$

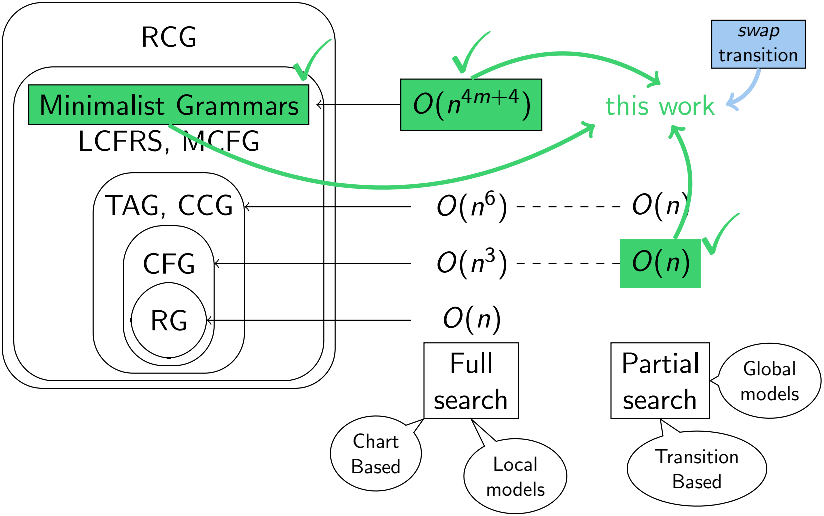
CFG Transition-Based Parsing Example

	σ	β	transition
8	 NP A NP A N V Adv Colorless green ideas , sleep , furiously		$\mathit{reduce}\{VP\}$
9	 NP A NP VP A N V Adv Colorless green ideas , sleep furiously		$\mathit{reduce}\{S\}$

CFG Transition-Based Parsing Example

	σ	β	transition
10			*goal*

Big Picture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Minimalist Transition-Based Parser

Convert CFG Parser to MG Parser

- keep shift-reduce structure

Minimalist Transition-Based Parser

Convert CFG Parser to MG Parser

- keep shift-reduce structure
- *mini-items* instead of constituents on the stack

Minimalist Transition-Based Parser

Convert CFG Parser to MG Parser

- keep shift-reduce structure
- *mini-items* instead of constituents on the stack
- add a stack to the configuration

Minimalist Transition-Based Parser

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- keep shift-reduce structure
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- add new transitions

Minimalist Transition-Based Parser

Convert CFG Parser to MG Parser

- keep shift-reduce structure
- *mini-items* instead of constituents on the stack
- add a stack to the configuration
- add new transitions

Configuration Structure

$$\langle \ \sigma_1, \quad \sigma_2, \quad \beta, \quad k \ \rangle$$

σ_1 Main stack – contains *mini-items* same as chart *items*

σ_2 Auxiliary stack

β Buffer

k Number of inserted empty strings

Transforming Transition-Based CFG to MG

CFG reuse

- axiom

Minimalist Grammar Transitions

$$\textit{axiom} \ \langle \ [\,], \quad [\,], \quad [0, \ldots, n-1], \quad 0 \ \rangle$$

Transforming Transition-Based CFG to MG

CFG reuse

- axiom
- goal

Minimalist Grammar Transitions

$$\begin{array}{rlllll} \textit{axiom} & \langle\ [\,], & [\,], & [0, \ldots, n-1], & 0 & \rangle \\ \textit{goal} & \langle\ [\{(0,n) \cdot c\}], & [\,], & [\,], & k & \rangle \end{array}$$

Transforming Transition-Based CFG to MG

CFG reuse

- axiom
- goal
- shift

Minimalist Grammar Transitions

$$\textit{axiom} \quad \langle \; [\,], \quad [\,], \quad [0, \ldots, n-1], \quad 0 \; \rangle$$

$$\textit{goal} \quad \langle \; [\{(0,n) \cdot c\}], \quad [\,], \quad [\,], \quad k \; \rangle$$

$$\textit{select}\{\gamma\} \quad \frac{\langle \; \sigma_1, \quad \sigma_2, \quad i|\beta, \quad k \; \rangle}{\langle \; \sigma_1|\{(i, i+1) :: \gamma\}, \quad \sigma_2, \quad \beta, \quad k \; \rangle} \quad w_i{::}\gamma \in \textit{Lex}$$

Transforming Transition-Based CFG to MG

CFG reuse

- axiom
- goal
- shift
- reduce

Minimalist Grammar Transitions

$$
\begin{array}{rll}
\textit{axiom} & \langle\ [\,],\quad [\,],\quad [0,\ldots,n-1],\quad 0\ \rangle & \\
\textit{goal} & \langle\ [\{(0,n)\cdot c\}],\quad [\,],\quad [\,],\quad k\ \rangle & \\
\textit{select}\{\gamma\} & \dfrac{\langle\ \sigma_1,\quad \sigma_2,\quad i|\beta,\quad k\ \rangle}{\langle\ \sigma_1|\{(i,i+1)::\gamma\},\quad \sigma_2,\quad \beta,\quad k\ \rangle} & w_i{::}\gamma \in \textit{Lex} \\
\textit{tmerge} & \dfrac{\langle\ \sigma_1|x|y,\quad \sigma_2,\quad \beta,\quad k\ \rangle}{\langle\ \sigma_1|\textit{merge}(x,y),\quad \sigma_2,\quad \beta,\quad k\ \rangle} & (x,y) \in \textit{Dom}(\textit{merge}) \\
\textit{tmove} & \dfrac{\langle\ \sigma_1|x,\quad \sigma_2,\quad \beta,\quad k\ \rangle}{\langle\ \sigma_1|\textit{move}(x),\quad \sigma_2,\quad \beta,\quad k\ \rangle} & x \in \textit{Dom}(\textit{move})
\end{array}
$$

Transforming Transition-Based CFG to MG

The Extensions Needed

- Empty strings
- Discontinuous structures

Transforming Transition-Based CFG to MG

The Extensions Needed

- Empty strings
- Discontinuous structures

Empty Strings Solution

$$\mathit{selectEpsilon}\{\gamma\}\ \frac{\langle\ \sigma_1,\quad \sigma_2,\quad \beta,\quad k\ \rangle}{\langle\ \sigma_1|\{(*,*) :: \gamma\},\quad \sigma_2,\quad \beta,\quad k+1\ \rangle}\ k < e \wedge \varepsilon{::}\gamma \in \mathit{Lex}$$

e is any linear function of sentence length *n*

Transforming Transition-Based CFG to MG

Discontinuity Solution: SWAP transition

- Reorders elements on the stack (*stupid sort*)
- Derives any permutation of words/phrases
- Minimum 0
- Maximally $O(n^2)$

Transitions

$$\textit{swap}\ \frac{\langle\ \sigma_1|x|y,\quad \sigma_2,\quad \beta,\quad k\ \rangle}{\langle\ \sigma_1|y,\quad x|\sigma_2,\quad \beta,\quad k\ \rangle}\ \textit{spanStart}(x) < \textit{spanStart}(y)$$

$$\textit{takeBack}\ \frac{\langle\ \sigma_1,\quad x|\sigma_2,\quad \beta,\quad k\ \rangle}{\langle\ \sigma_1|x,\quad \sigma_2,\quad \beta,\quad k\ \rangle}$$

MG Transition-Based Parsing Example

	σ_1	σ_2	β	k	transition
1			0 , 1 , 2 , 3 , 4 Phong likes what Roki draws	0	*select*{***d***}

MG Transition-Based Parsing Example

	σ_1	σ_2	β	k	transition
1			0 , 1 , 2 , 3 , 4 Phong likes what Roki draws	0	*select*$\{$***d***$\}$
2	$\{(0,1) :: d\}$ Phong		1 , 2 , 3 , 4 likes what Roki draws	0	*select*$\{$***=c =d v***$\}$

MG Transition-Based Parsing Example

	σ_1	σ_2	β	k	transition
1			0 , 1 , 2 , 3 , 4 Phong likes what Roki draws	0	*select*{***d***}
2	$\{(0,1) :: d\}$ Phong		1 , 2 , 3 , 4 likes what Roki draws	0	*select*{***=c =d v***}
3	$\{(0,1) :: d\}$, $\{(1,2) :: =c\ \ =d\ \ v\}$ Phong likes		2 , 3 , 4 what Roki draws	0	*select*{***d −wh***}

MG Transition-Based Parsing Example

	σ_1	σ_2	β	k	transition
1			$\underset{\text{Phong}}{0}, \underset{\text{likes}}{1}, \underset{\text{what}}{2}, \underset{\text{Roki}}{3}, \underset{\text{draws}}{4}$	0	*select*{***d***}
2	$\left\{\underset{\text{Phong}}{(0,1) :: d}\right\}$		$\underset{\text{likes}}{1}, \underset{\text{what}}{2}, \underset{\text{Roki}}{3}, \underset{\text{draws}}{4}$	0	*select*{***=c =d v***}
3	$\left\{\underset{\text{Phong}}{(0,1) :: d}\right\}, \left\{\underset{\text{likes}}{(1,2) :: {=c}\ \ {=d}\ v}\right\}$		$\underset{\text{what}}{2}, \underset{\text{Roki}}{3}, \underset{\text{draws}}{4}$	0	*select*{***d −wh***}
4	$\left\{\underset{\text{Phong}}{(0,1) :: d}\right\}, \left\{\underset{\text{likes}}{(1,2) :: {=c}\ \ {=d}\ v}\right\}, \left\{\underset{\text{what}}{(2,3) :: d\ \ {-wh}}\right\}$		$\underset{\text{Roki}}{3}, \underset{\text{draws}}{4}$	0	*select*{***d***}

MG Transition-Based Parsing Example

	σ_1	σ_2	β	k	transition
5	$\underset{\text{Phong}}{\{(0,1) :: d\}}, \underset{\text{likes}}{\{(1,2) :: =c \ \ =d \ \ v\}}, \underset{\text{what}}{\{(2,3) :: d \ \ -wh\}}, \underset{\text{Roki}}{\{(3,4) :: d\}}$		$\underset{\text{draws}}{4}$	0	*swap*

MG Transition-Based Parsing Example

	σ_1	σ_2	β	k	transition
5	$\{(0,1) :: d\}$, $\{(1,2) :: =c\ \ =d\ \ v\}$, $\{(2,3) :: d\ \ -wh\}$, $\{(3,4) :: d\}$ Phong likes what Roki		4 draws	0	*swap*
6	$\{(0,1) :: d\}$, $\{(1,2) :: =c\ \ =d\ \ v\}$, $\{(3,4) :: d\}$ Phong likes Roki	$\{(2,3) :: d\ \ -wh\}$ what	4 draws	0	*takeBack*

MG Transition-Based Parsing Example

	σ_1	σ_2	β	k	transition
5	$\{(0,1) :: d\}, \{(1,2) :: {=c}\ \ {=d}\ \ v\}, \{(2,3) :: d\ \ {-wh}\}, \{(3,4) :: d\}$ Phong likes what Roki		4 draws	0	*swap*
6	$\{(0,1) :: d\}, \{(1,2) :: {=c}\ \ {=d}\ \ v\}, \{(3,4) :: d\}$ Phong likes Roki	$\{(2,3) :: d\ \ {-wh}\}$ what	4 draws	0	*takeBack*
7	$\{(0,1) :: d\}, \{(1,2) :: {=c}\ \ {=d}\ \ v\}, \{(3,4) :: d\},\{(2,3) :: d\ \ {-wh}\}$ Phong likes Roki what		4 draws	0	$\mathit{select}\{\boldsymbol{{=d}\ \ {=d}\ \ v}\}$

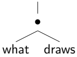
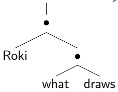
MG Transition-Based Parsing Example

	σ_1	σ_2	β	k	transition
8	$\underset{\text{Phong}}{\{(0,1) :: d\}}, \underset{\text{likes}}{\{(1,2) :: {=}c\ \ {=}d\ v\}}, \underset{\text{Roki}}{\{(3,4) :: d\}}, \underset{\text{what}}{\{(2,3) :: \mathbf{d}\ \ {-}wh\}}, \underset{\text{draws}}{\{(4,5) :: \mathbf{{=}d}\ \ {=}d\ v\}}$			0	*tmerge*

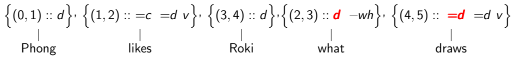
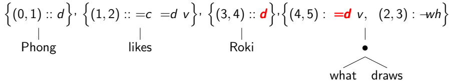
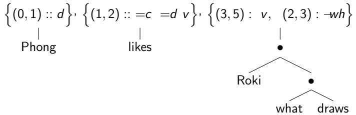
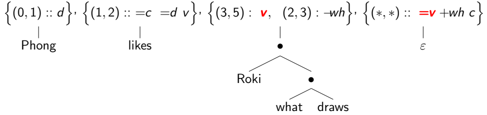
MG Transition-Based Parsing Example

	σ_1	σ_2	β	k	transition
8	$\{(0,1) :: d\}$, $\{(1,2) :: =c\ \ =d\ \ v\}$, $\{(3,4) :: d\}$, $\{(2,3) :: d\ \ -wh\}$, $\{(4,5) :: =d\ \ =d\ \ v\}$ Phong likes Roki what draws			0	*tmerge*
9	$\{(0,1) :: d\}$, $\{(1,2) :: =c\ \ =d\ \ v\}$, $\{(3,4) :: d\}$, $\{(4,5) :\ =d\ \ v,\ \ (2,3) : -wh\}$ Phong likes Roki • what draws			0	*tmerge*

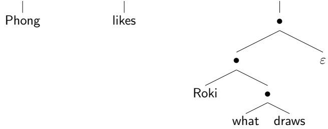
MG Transition-Based Parsing Example

	σ_1	σ_2	β	k	transition
8	$\{(0,1) :: d\}$, $\{(1,2) :: =c\ \ =d\ \ v\}$, $\{(3,4) :: d\}$,$\{(2,3) :: d\ \ -wh\}$, $\{(4,5) :: =d\ \ =d\ \ v\}$ Phong likes Roki what draws			0	*tmerge*
9	$\{(0,1) :: d\}$, $\{(1,2) :: =c\ \ =d\ \ v\}$, $\{(3,4) :: d\}$,$\{(4,5) : =d\ \ v,\ \ (2,3) : -wh\}$ Phong likes Roki 			0	*tmerge*
10	$\{(0,1) :: d\}$, $\{(1,2) :: =c\ \ =d\ \ v\}$, $\{(3,5) : v,\ \ (2,3) : -wh\}$ Phong likes 			0	*selectEpsilon* $\{=v\ \ +wh\ \ c\}$

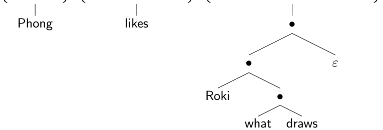
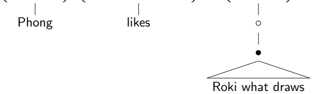
MG Transition-Based Parsing Example

	σ_1	σ_2	β	k	transition
8	 $\{(0,1) :: d\}, \{(1,2) :: {=c}\ {=d}\ v\}, \{(3,4) :: d\}, \{(2,3) :: \mathbf{d}\ {-wh}\}, \{(4,5) :: \mathbf{=d}\ {=d}\ v\}$ Phong likes Roki what draws			0	*tmerge*
9	 $\{(0,1) :: d\}, \{(1,2) :: {=c}\ {=d}\ v\}, \{(3,4) :: \mathbf{d}\}, \{(4,5) : \mathbf{=d}\ v,\ (2,3) : {-wh}\}$ Phong likes Roki what draws			0	*tmerge*
10	 $\{(0,1) :: d\}, \{(1,2) :: {=c}\ {=d}\ v\}, \{(3,5) : v,\ (2,3) : {-wh}\}$ Phong likes Roki what draws			0	*selectEpsilon* $\{\mathbf{=v}\ \ \mathbf{+wh}\ \mathbf{c}\}$
11	 $\{(0,1) :: d\}, \{(1,2) :: {=c}\ {=d}\ v\}, \{(3,5) : \mathbf{v},\ (2,3) : {-wh}\}, \{(*,*) :: \mathbf{=v}\ {+wh}\ c\}$ Phong likes Roki what draws ε			1	*tmerge*

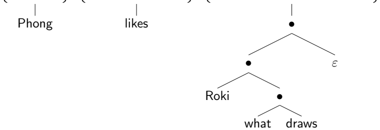
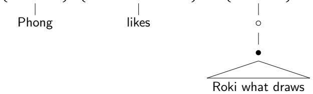
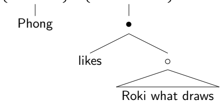
MG Transition-Based Parsing Example

	σ_1	σ_2	β	k	transition
12	$\{(0,1) :: d\}$, $\{(1,2) :: =c\ \ =d\ \ v\}$, $\{(3,5) : +wh\ \ c,\quad (2,3) : -wh\}$  			1	*tmove*

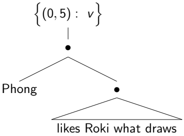
MG Transition-Based Parsing Example

	σ_1	σ_2	β	k	transition
12	$\{(0,1) :: d\}, \{(1,2) :: =c\ \ =d\ v\}, \{(3,5) : +wh\ c,\ \ (2,3) : -wh\}$  			1	*tmove*
13	$\{(0,1) :: d\}, \{(1,2) :: =c\ \ =d\ v\}, \{(2,5) : c\}$  			1	*tmerge*

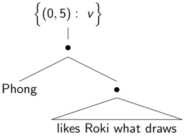
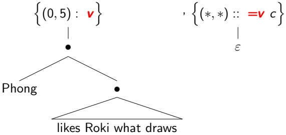
MG Transition-Based Parsing Example

	σ_1	σ_2	β	k	transition
12	$\{(0,1) :: d\}, \{(1,2) :: =c\ \ =d\ \ v\}, \{(3,5) : +wh\ \ c,\ \ (2,3) : -wh\}$  			1	*tmove*
13	$\{(0,1) :: d\}, \{(1,2) :: =c\ \ =d\ \ v\}, \{(2,5) : c\}$  			1	*tmerge*
14	$\{(0,1) :: d\}, \{(1,5) : =d\ \ v\}$  			1	*tmerge*

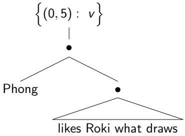
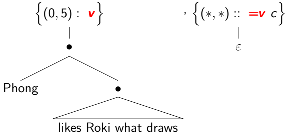
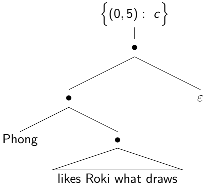
MG Transition-Based Parsing Example

	σ_1	σ_2	β	k	transition
15				1	*selectEpsilon*{***=v c***}

MG Transition-Based Parsing Example

	σ_1	σ_2	β	k	transition
15				1	*selectEpsilon*{**=v c**}
16	 {(0, 5) : **v**} Phong likes Roki what draws , {(∗, ∗) :: =v c} ε			2	*tmerge*

MG Transition-Based Parsing Example

	σ_1	σ_2	β	k	transition
15				1	*selectEpsilon*{**=v c**}
16	 $\{(0,5):\ \mathbf{v}\}$ Phong likes Roki what draws , $\{(*,*) :: \mathbf{=v}\ c\}$ ε			2	*tmerge*
17	 $\{(0,5):\ c\}$ ε Phong likes Roki what draws			2	goal

Computational Complexity

operation	best case	worst case
$select\{\cdot\}$	$O(n)$	$O(n)$

Computational Complexity

operation	best case	worst case
$select\{\cdot\}$	$O(n)$	$O(n)$
$selectEpsilon\{\cdot\}$	0	$O(n)$

Computational Complexity

operation	best case	worst case
$\mathit{select}\{\cdot\}$	$O(n)$	$O(n)$
$\mathit{selectEpsilon}\{\cdot\}$	0	$O(n)$
tmerge	$O(n)$	$O(n)$

Computational Complexity

operation	best case	worst case
$select\{\cdot\}$	$O(n)$	$O(n)$
$selectEpsilon\{\cdot\}$	0	$O(n)$
$tmerge$	$O(n)$	$O(n)$
$tmove$	0	$O(n)$

Computational Complexity

operation	best case	worst case
$select\{\cdot\}$	$O(n)$	$O(n)$
$selectEpsilon\{\cdot\}$	0	$O(n)$
$tmerge$	$O(n)$	$O(n)$
$tmove$	0	$O(n)$
$swap$	0	$O(n^2)$

Computational Complexity

operation	best case	worst case
select$\{\cdot\}$	$O(n)$	$O(n)$
selectEpsilon$\{\cdot\}$	0	$O(n)$
tmerge	$O(n)$	$O(n)$
tmove	0	$O(n)$
swap	0	$O(n^2)$
takeBack	0	$O(n^2)$

Computational Complexity

operation	best case	worst case
select$\{\cdot\}$	$O(n)$	$O(n)$
selectEpsilon$\{\cdot\}$	0	$O(n)$
tmerge	$O(n)$	$O(n)$
tmove	0	$O(n)$
swap	0	$O(n^2)$
takeBack	0	$O(n^2)$
asympt. max	$O(n)$	$O(n^2)$

Conclusion

- Efficient parser: worst case $O(n^2)$ and best case $O(n)$
- Transition Parser+Learning Model+Treebank = Minimalism in NLP applications
- Technique applicable to other formalisms

Bibliography I