Natural Language Models and Interfaces

BSc Artificial Intelligence

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Institute for Logic, Language, and Computation

2018, week 5, lecture b

Context-Free Grammars

A **CFG** grammar G is denoted by

- a finite set of **nonterminal** symbols $\mathscr{V}$
- a finite set of **terminal** symbols Σ with $\Sigma \cap \mathscr{V} = \varnothing$
- a finite set $\mathscr{R}$ of **rules** of the form $X \rightarrow \beta$ where
  - $X \in \mathscr{V}$ and $\beta \in (\Sigma \cup \mathscr{V})^*$
- $S \in \mathscr{V}$ a distinguished **start** symbol

Let ε denote an **empty** string

Example CFG

S → NP VP	Vi → sleeps
VP → Vi	Vt → saw
VP → Vt NP	NN → man
VP → VP PP	NN → dog
NP → DT NN	NN → telescope
NP → NP PP	DT → the
PP → IN NP	IN → with

Generative Device

Left-most derivation

- sequence of strings $\alpha_1 \ldots \alpha_n$
- $\alpha_1 = \langle S \rangle$
- $\alpha_n \in \Sigma^*$
- $\alpha_{i \geq 2}$ derived from α_{i-1} by picking the left-most nonterminal X
  - and replacing it by some α such that $X \rightarrow \beta \in \mathscr{R}$

Example of Derivation

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String	Substitution

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$\alpha_1 =$	S	S → NP VP

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	String	Substitution
α_1 =	S	S → NP VP
α_2 =	NP VP	NP → DT NN

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	String	Substitution
α_1 =	S	S → NP VP
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$\alpha_1 =$	S	S → NP VP
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$\alpha_3 =$	DT NN VP	DT → the
$\alpha_4 =$	the NN VP	NN → man

Example of Derivation

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α_1 =	S	S → NP VP
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α_5 =	the man VP	VP → Vi

Example of Derivation

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α_1 =	S	S → NP VP
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α_6 =	the man Vi	Vi → sleeps

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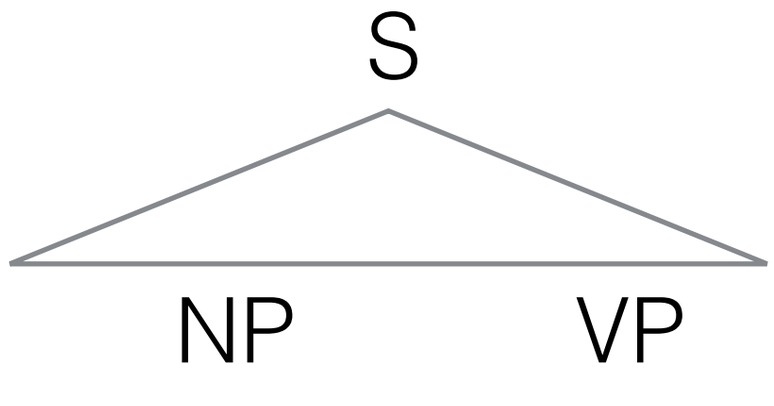
α_6 =	the man Vi	Vi → sleeps
α_7 =	the man sleeps	
α_7 =	S $\Rightarrow^*$ the man sleeps	

Example of Generation

Example of Generation

s

Example of Generation



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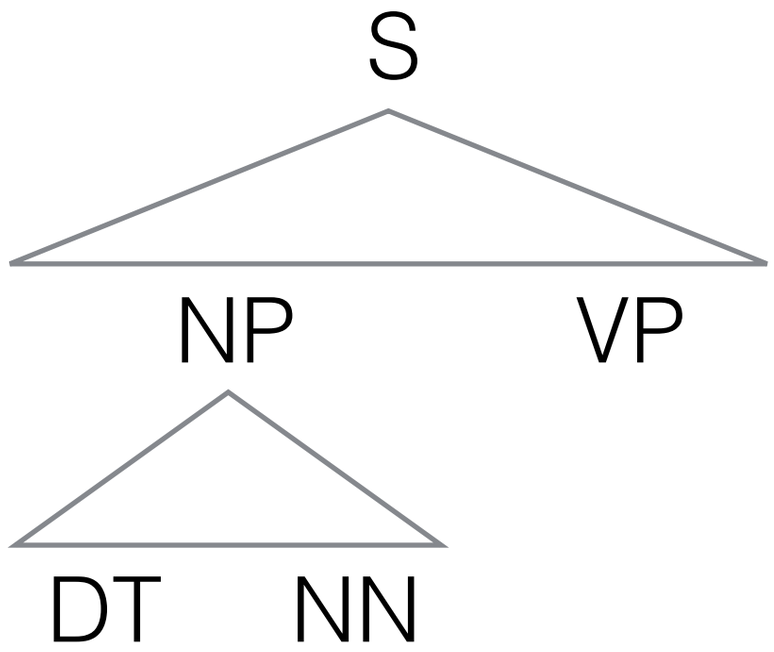

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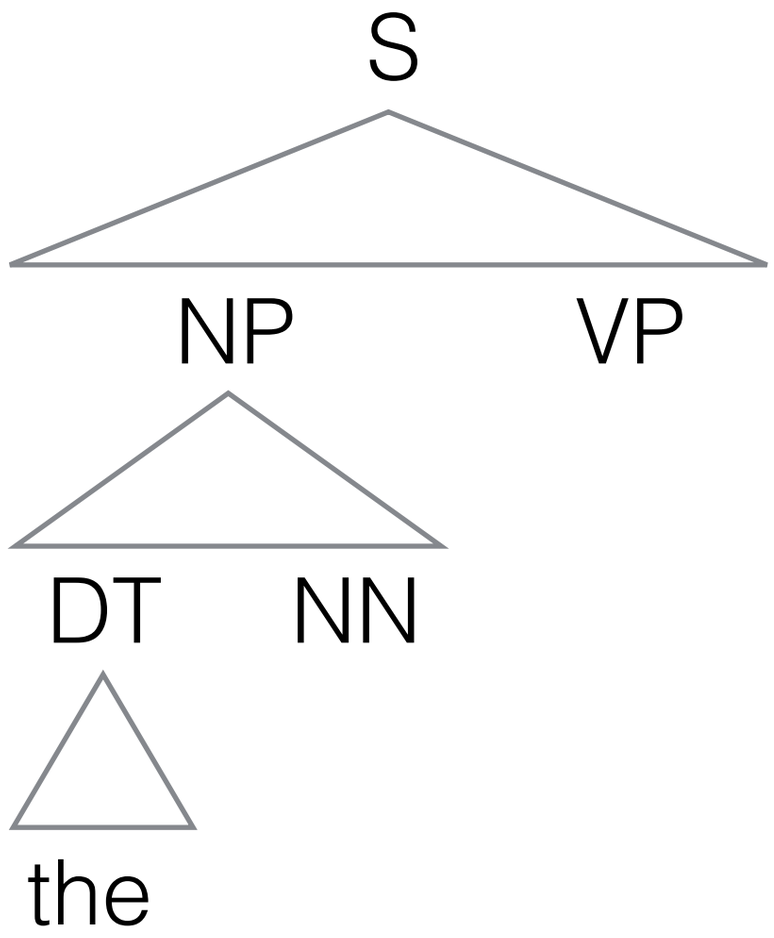

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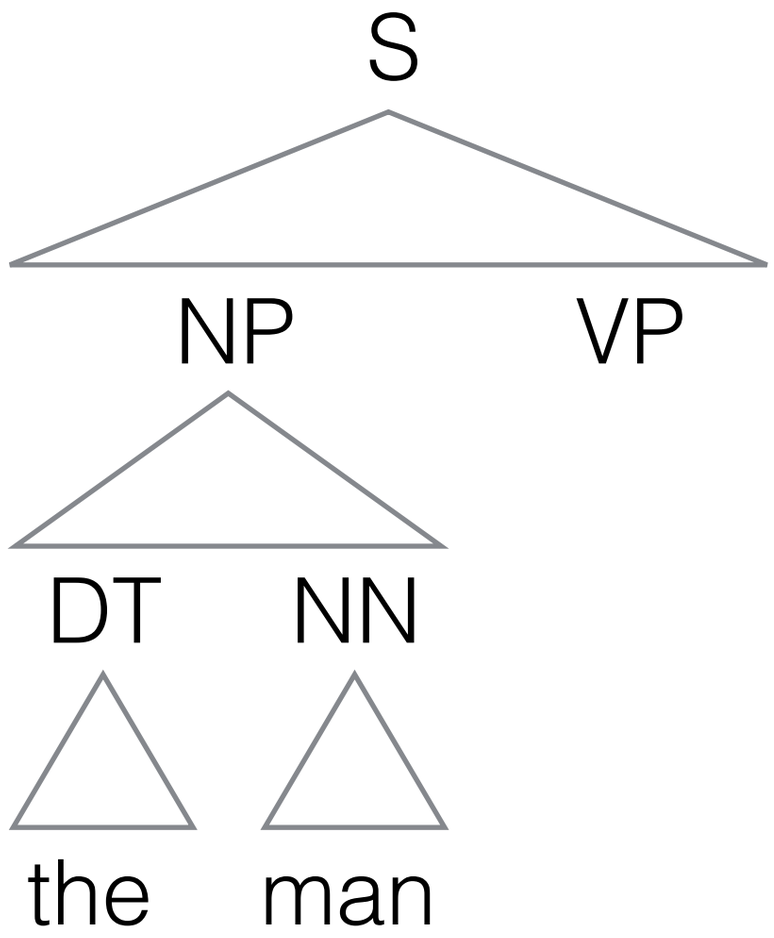

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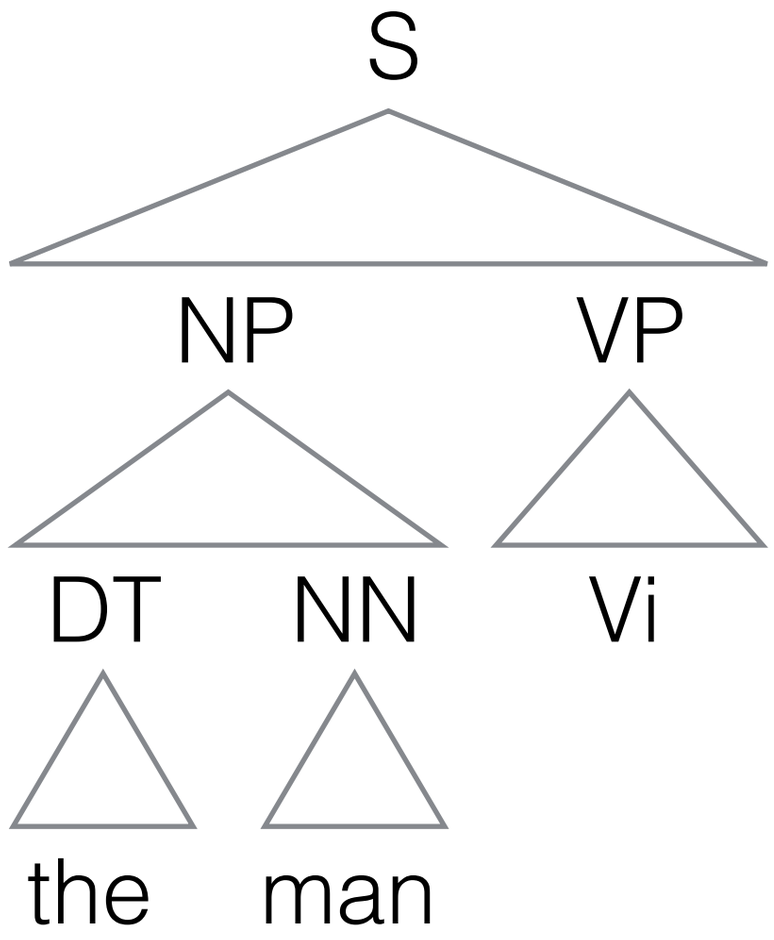

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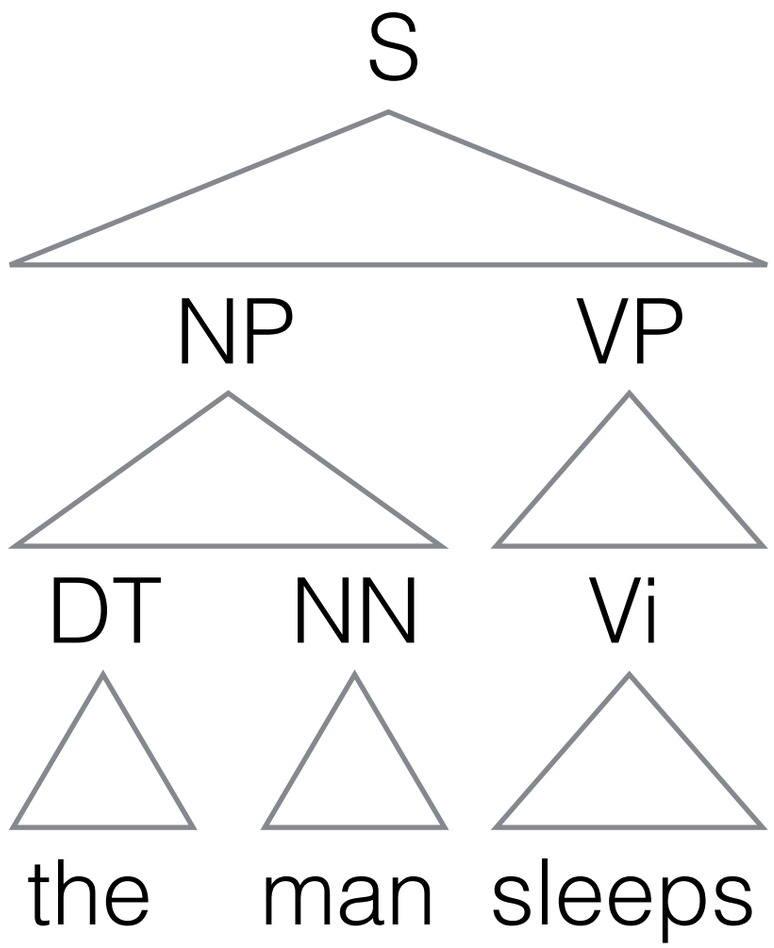

Example of Recognition

Example of Recognition

The man saw the dog

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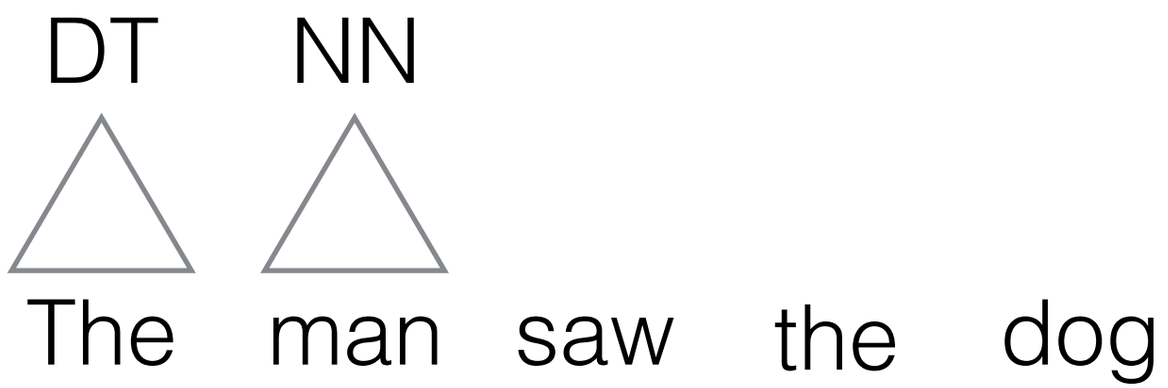

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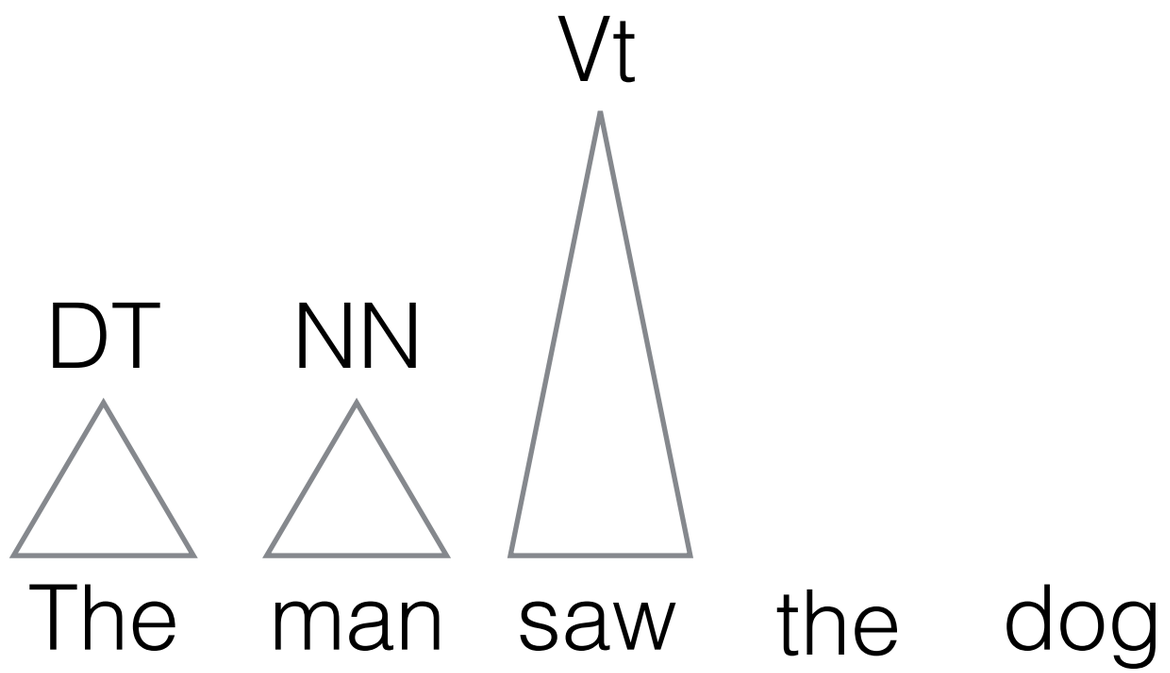

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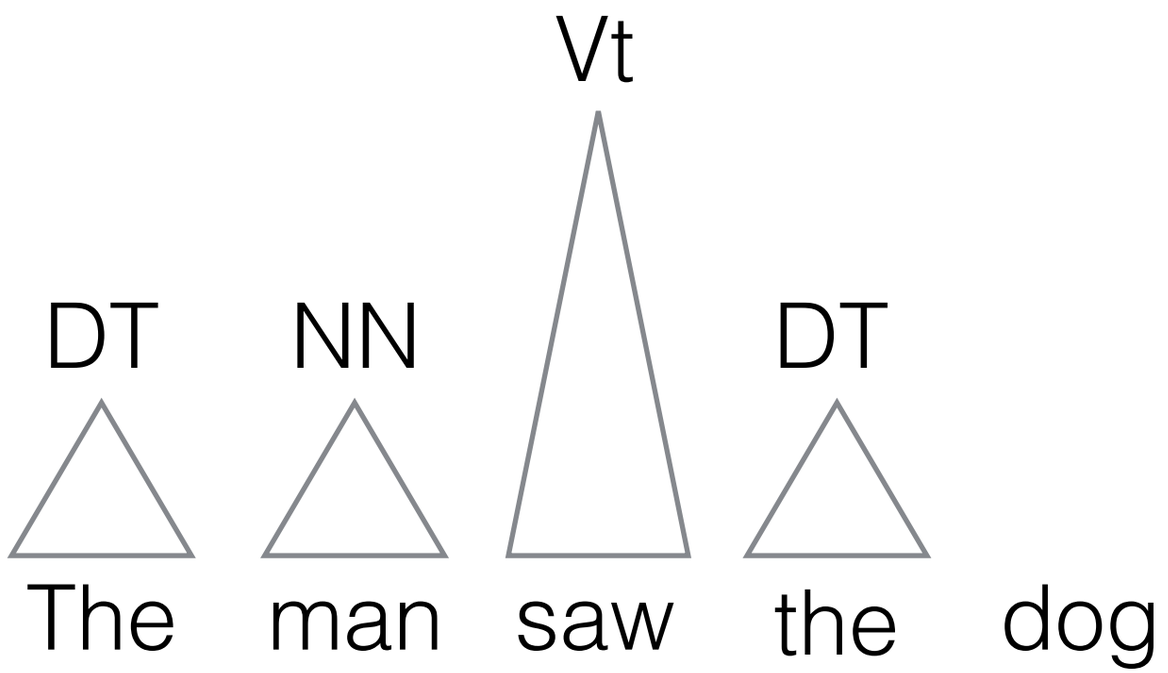

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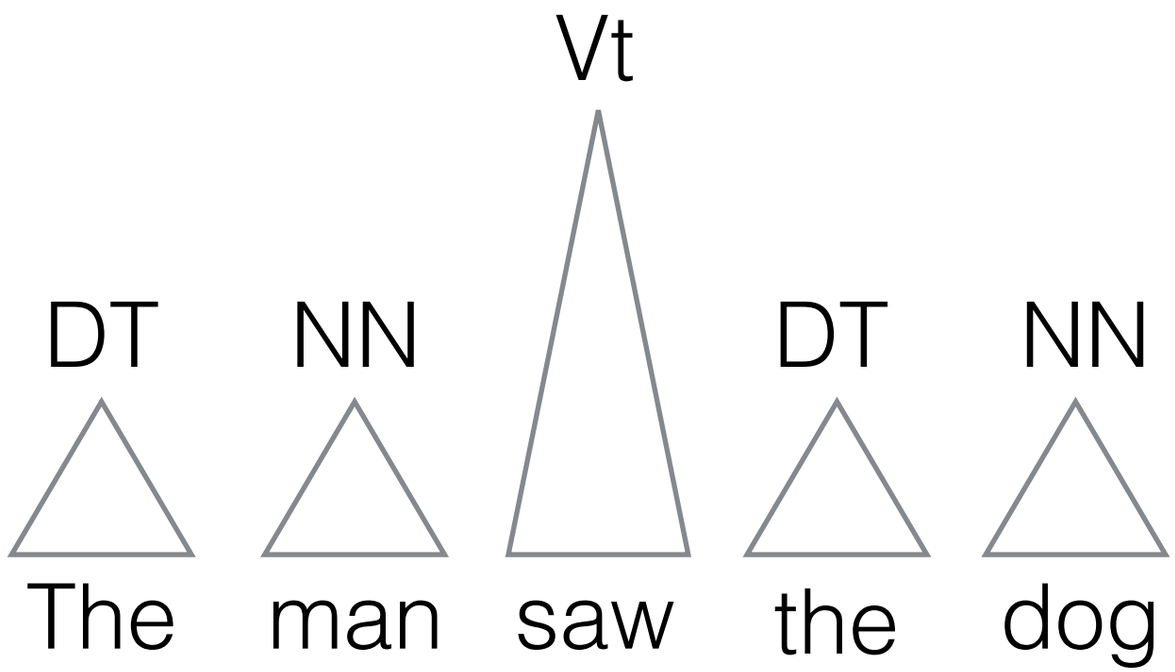

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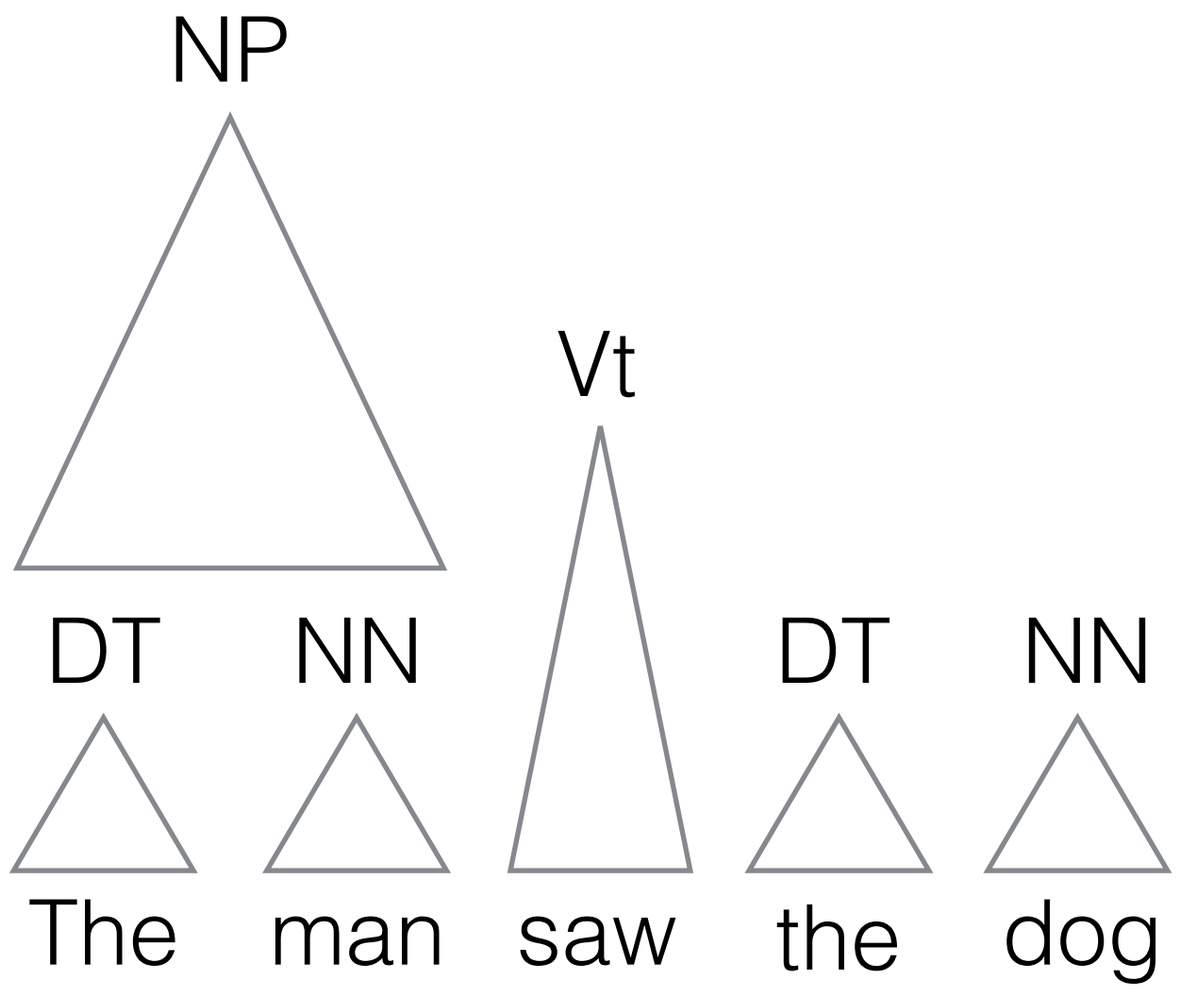

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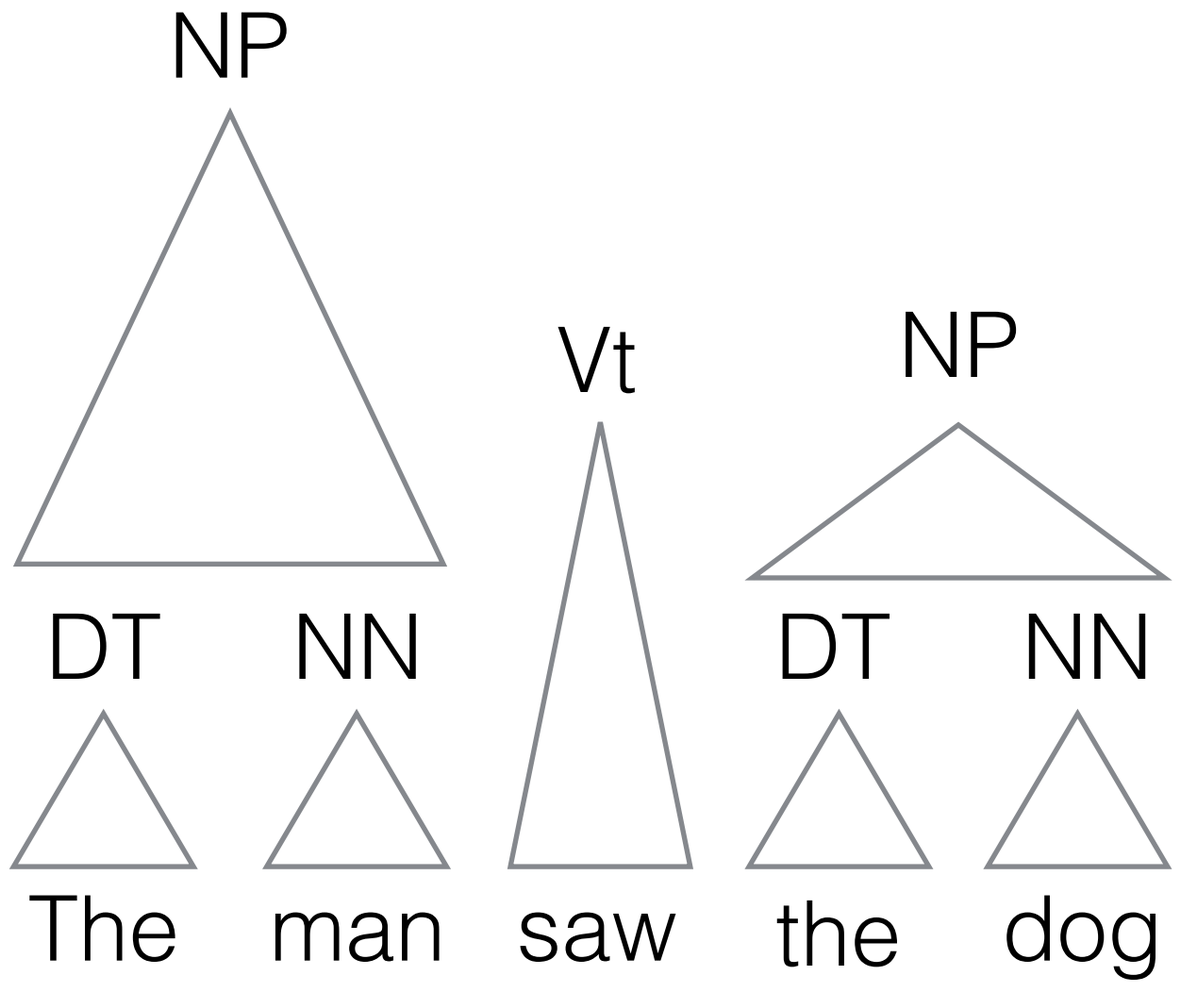

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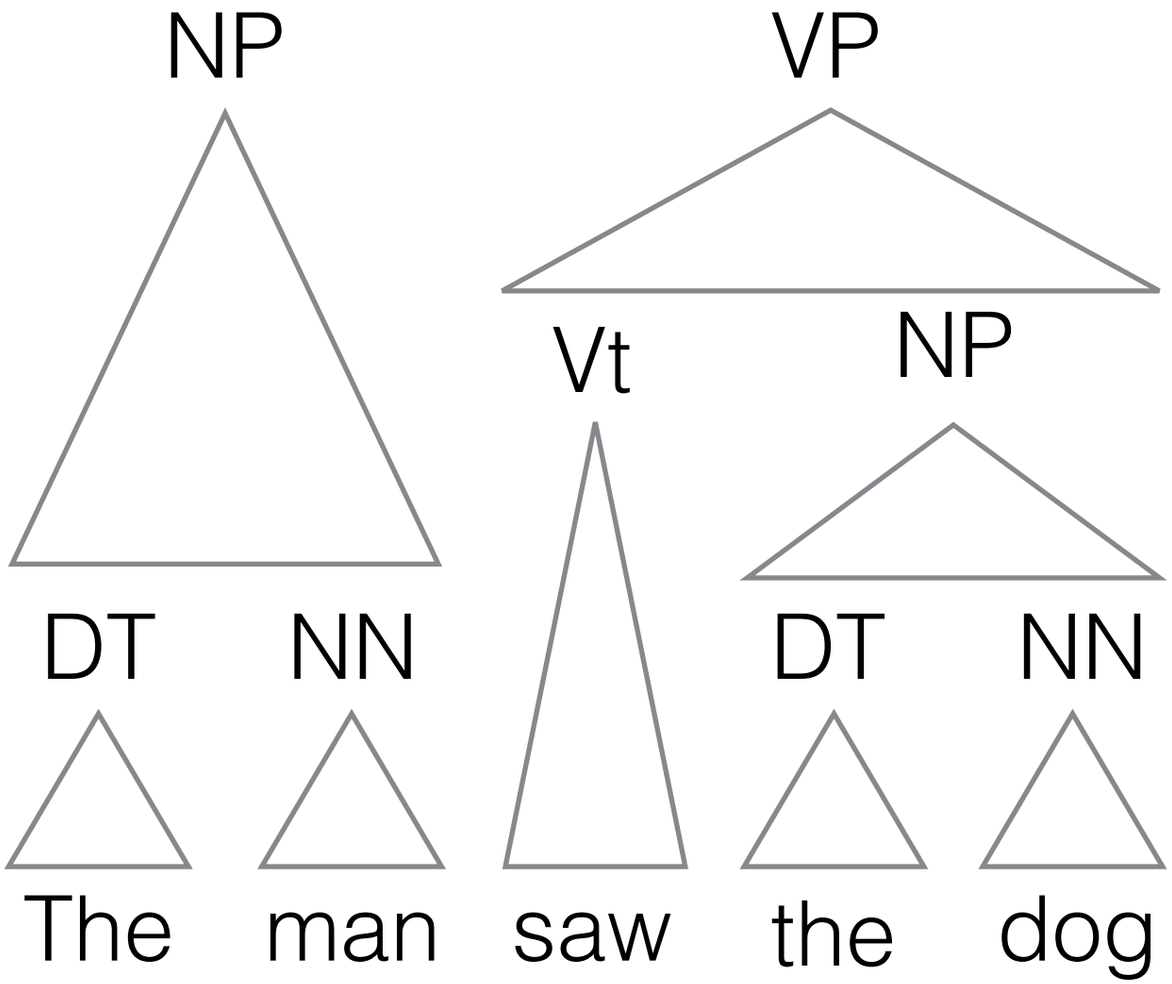

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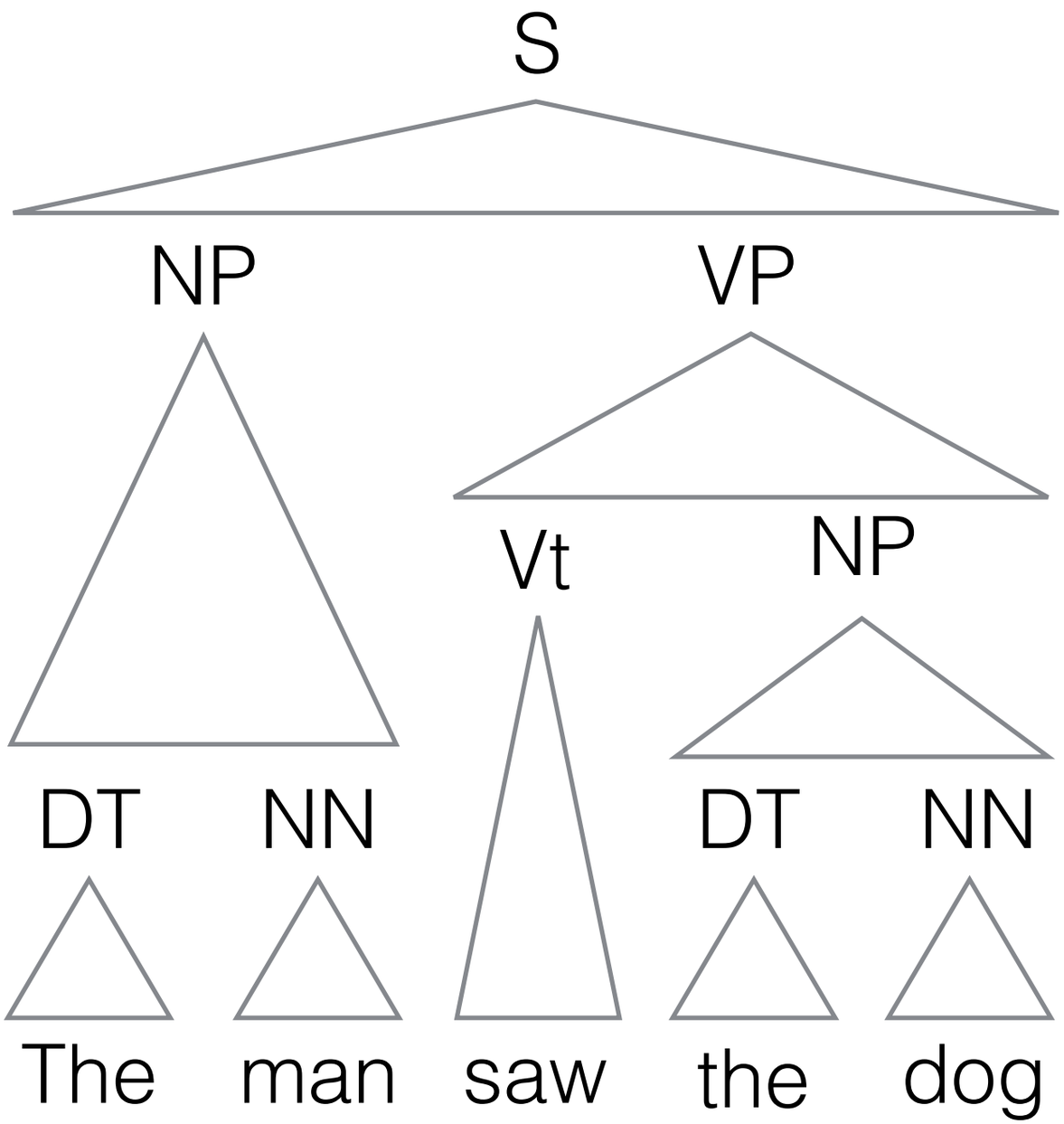

Language

A string $\omega \in \Sigma^*$ is generated/accepted by G if

$$S \Rightarrow^* \omega$$

$\Rightarrow^*$ denotes a sequence of rule applications

Language of G

$$L(G) = \{\omega: S \Rightarrow^* \omega\} \subseteq \Sigma^*$$

Chomsky Normal Form

Every CFG is weakly equivalent to another such that

- $X \rightarrow Y\ Z$ where $X, Y, Z \in \mathscr{V}$
- $X \rightarrow w$ where $w \in \Sigma$
- and possibly $S \rightarrow \varepsilon$

[Hopcroft and Ullman, 1979]

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Deductive process to prove claims about grammaticality

[Shieber et al., 1995]

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- dynamic program follows directly

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Deductive process to prove claims about grammaticality
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- focus on strategy rather than implementation
- soundness/completeness easier to prove
- complexity determined by inspection
- dynamic program follows directly
- generality

Deductive systems

Item: a statement / intermediate sound result

- formula or schemata expressed with variables

Inference rule: statement derived from existing items

- $\frac{A_1 \ldots A_m}{B}\ (\text{condition})$ where A_i and B are items
  - Ai are called antecedents
  - B is called consequent

Deductive program

Axioms: trivial items

- do not depend on previous statements

Goal: states that a proof exists

Proof:

- start from axioms
- exhaustively deduce items
  - never twice under the same premises
- accept if goal is proven

Bottom-up: Shift-Reduce

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The man saw the dog

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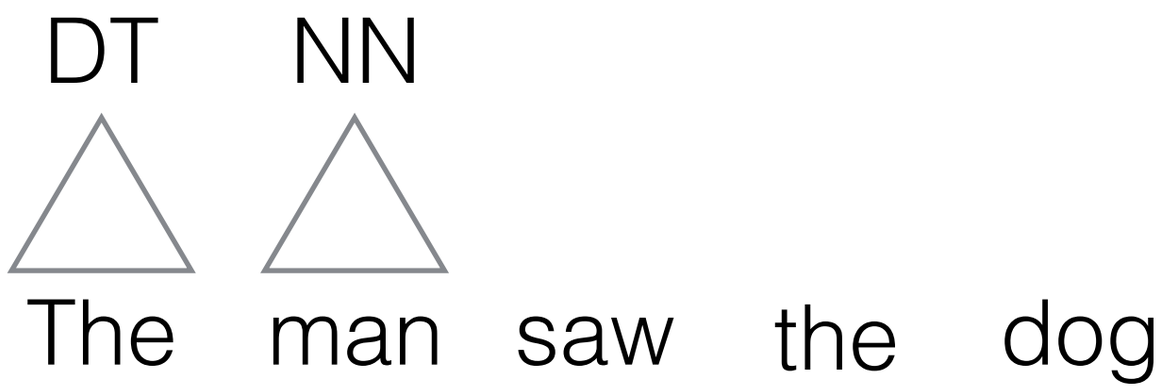

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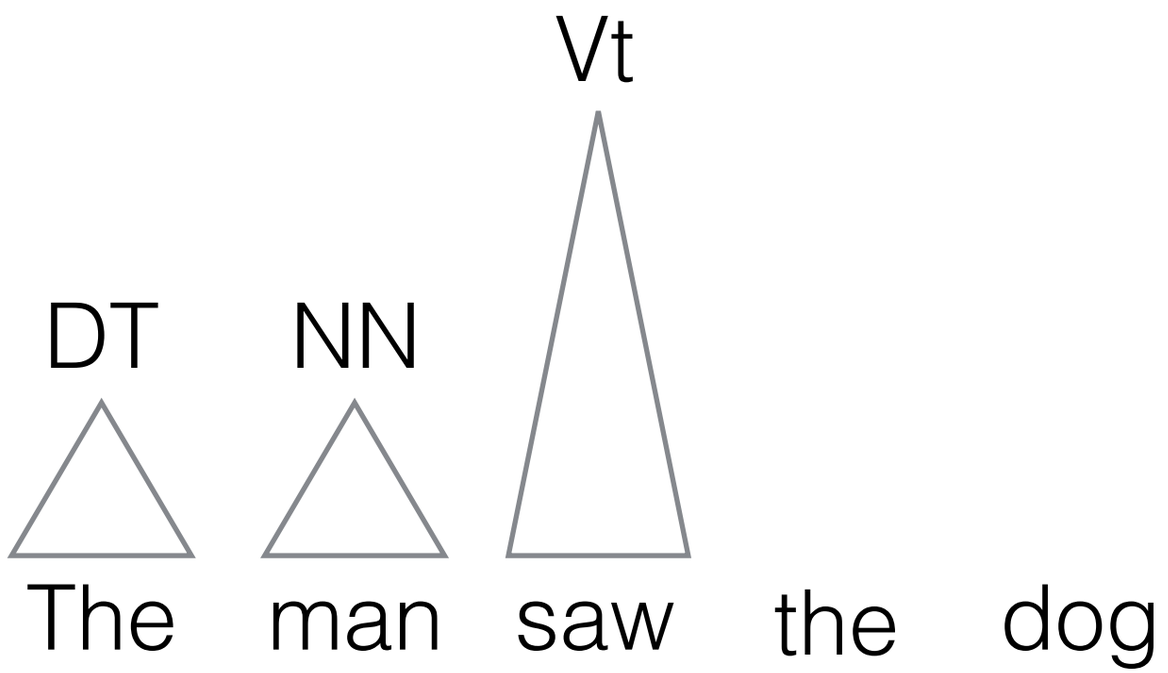

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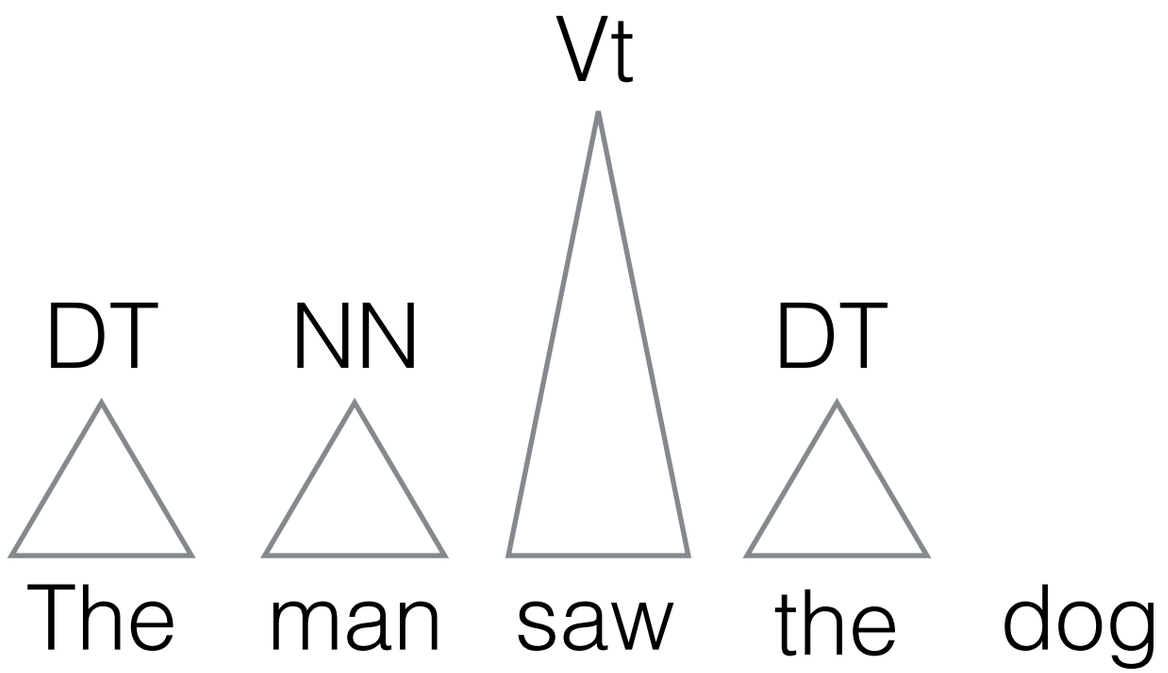

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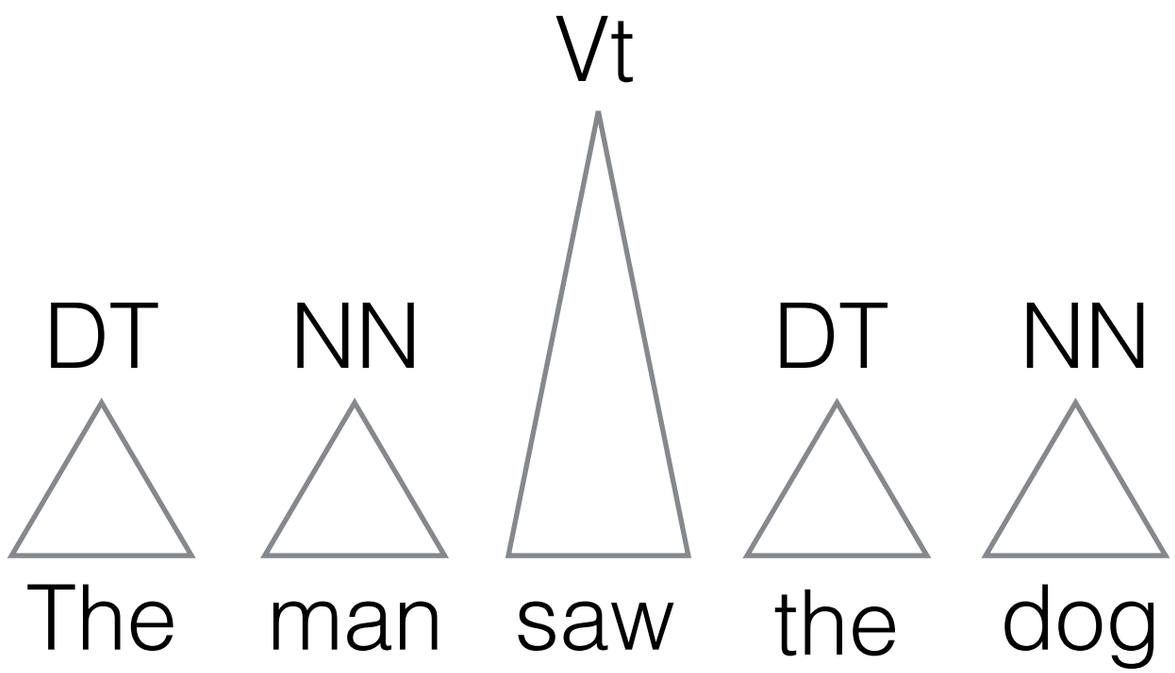

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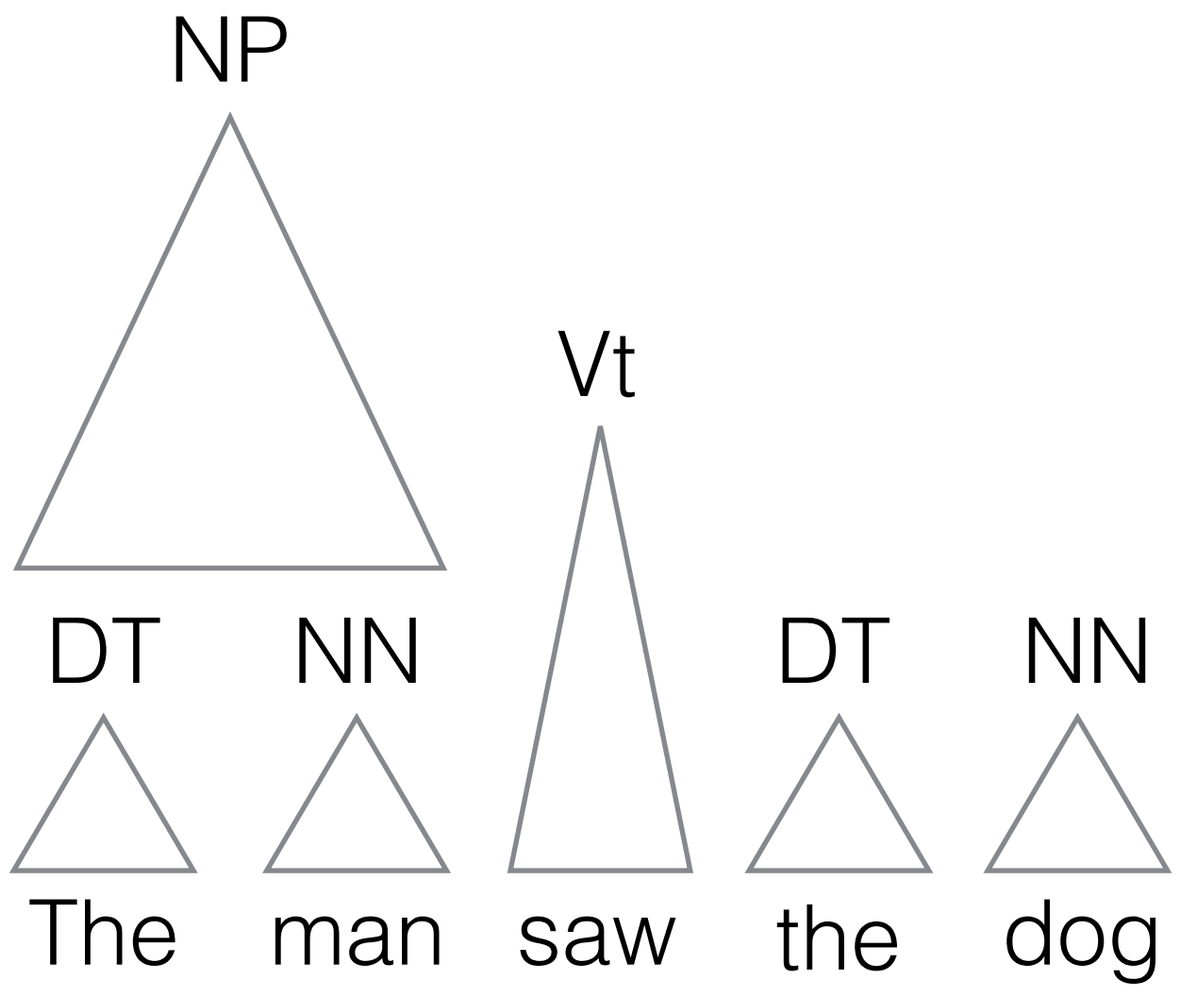

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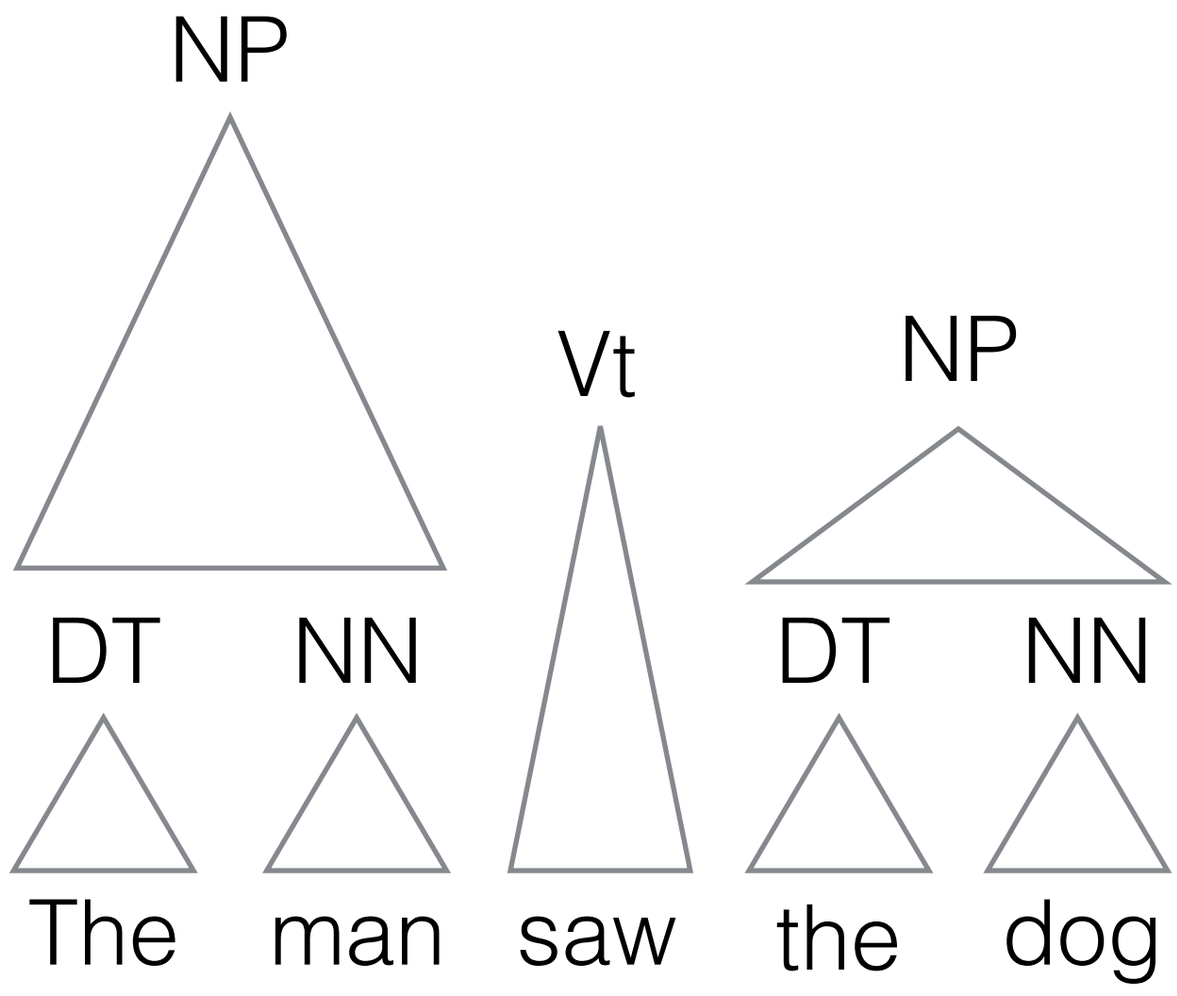

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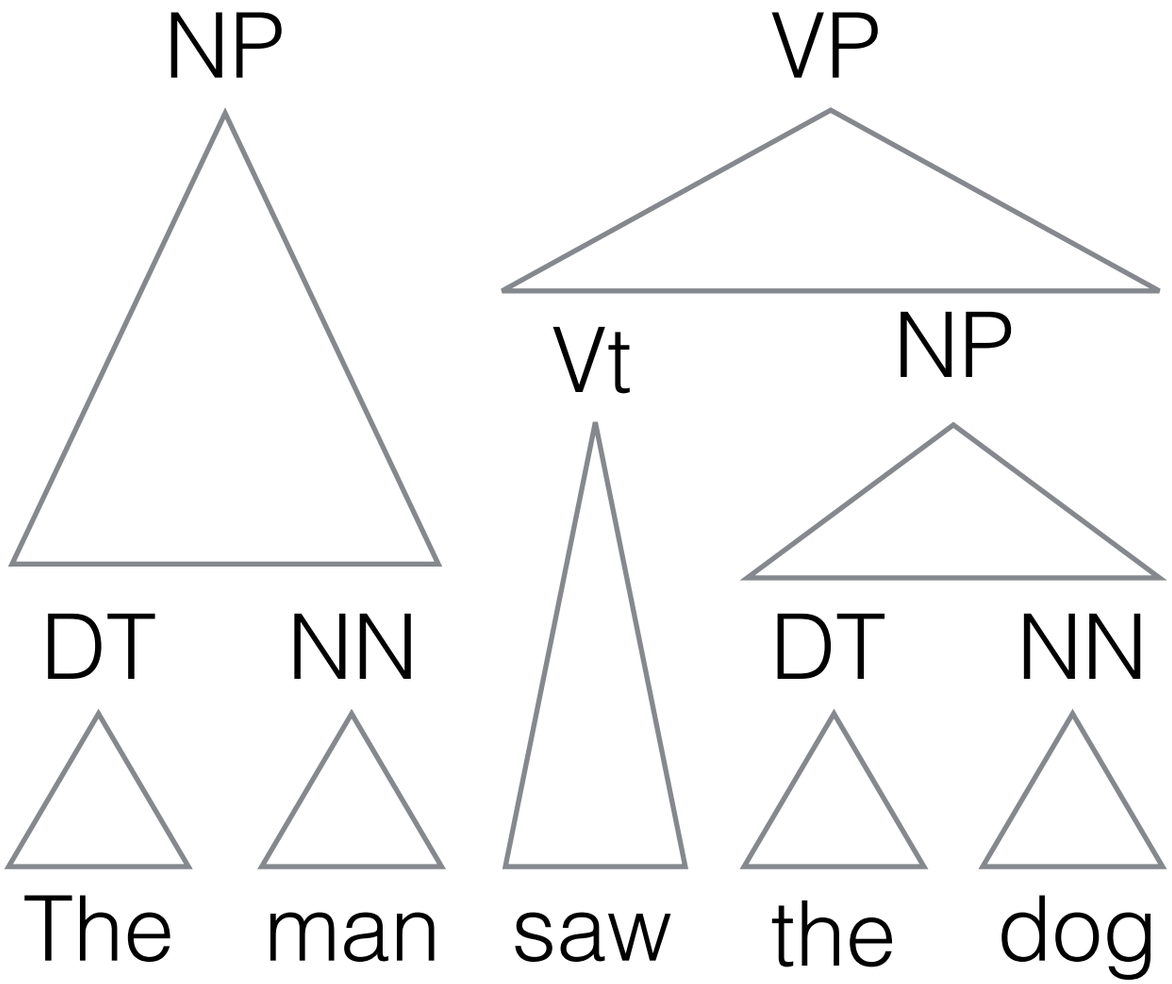

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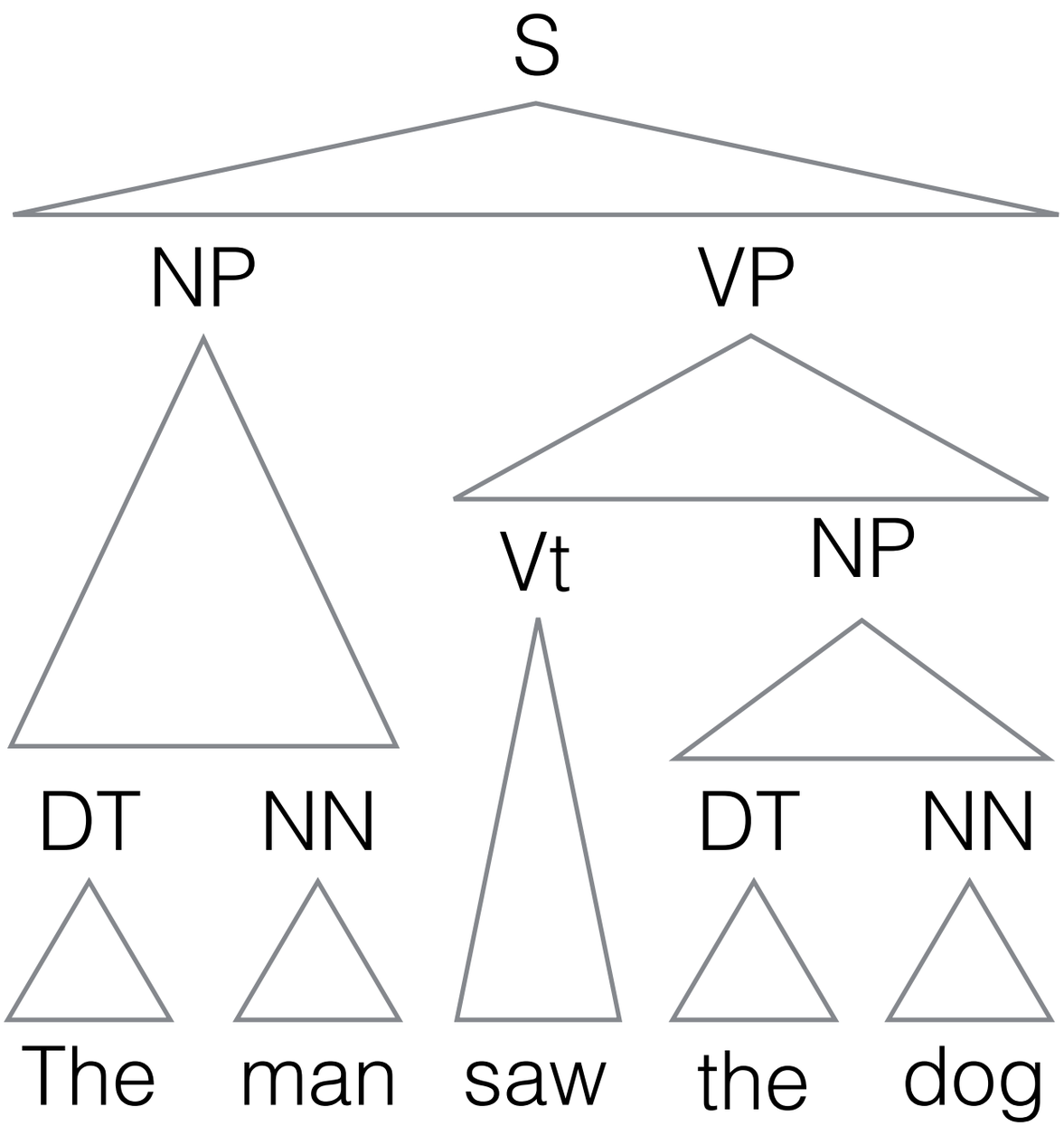

Shift-Reduce Example

Input: *the man sleeps*

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VP → Vi

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VP → VP PP

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Shift: [3]		4	[DT man •, 2]	4

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Reduce: [5]	NP → DT NN	6	[NP •, 2]	6

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Reduce: [5]	NP → DT NN	6	[NP •, 2]	6
Shift: [6]		7	[NP sleeps •, 3]	7

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Reduce: [5]	NP → DT NN	6	[NP •, 2]	6
Shift: [6]		7	[NP sleeps •, 3]	7
Reduce: [7]	Vi → sleeps	8	[NP Vi •, 3]	8

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Reduce: [2]	DT → the	3	[DT•,1]	3
Shift: [3]		4	[DT man •, 2]	4
Reduce: [4]	NN → man	5	[DT NN •, 2]	5
Reduce: [5]	NP → DT NN	6	[NP •, 2]	6
Shift: [6]		7	[NP sleeps •, 3]	7
Reduce: [7]	Vi → sleeps	8	[NP Vi •, 3]	8

S → NP VP
VP → Vi
VP → Vt NP
VP → VP PP
NP → DT NN
NP → NP PP
PP → IN NP
Vi → sleeps
Vt → saw
NN → man
NN → dog
NN → telescope
DT → the
IN → with

Shift-Reduce Example

Input: *the man sleeps*

Rule	Condition		Statement	Queue
Axiom		1	[•,0]	1
Shift: [1]		2	[the•,1]	2
Reduce: [2]	DT → the	3	[DT•,1]	3
Shift: [3]		4	[DT man •, 2]	4
Reduce: [4]	NN → man	5	[DT NN •, 2]	5
Reduce: [5]	NP → DT NN	6	[NP •, 2]	6
Shift: [6]		7	[NP sleeps •, 3]	7
Reduce: [7]	Vi → sleeps	8	[NP Vi •, 3]	8
Reduce: [8]	VP → Vi	9	[NP VP •, 3]	9

S → NP VP
VP → Vi
VP → Vt NP
VP → VP PP
NP → DT NN
NP → NP PP
PP → IN NP
Vi → sleeps
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NN → man
NN → dog
NN → telescope
DT → the
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Shift-Reduce Example

Input: *the man sleeps*

Rule	Condition		Statement	Queue
Axiom		1	[•,0]	1
Shift: [1]		2	[the•,1]	2
Reduce: [2]	DT → the	3	[DT•,1]	3
Shift: [3]		4	[DT man •, 2]	4
Reduce: [4]	NN → man	5	[DT NN •, 2]	5
Reduce: [5]	NP → DT NN	6	[NP •, 2]	6
Shift: [6]		7	[NP sleeps •, 3]	7
Reduce: [7]	Vi → sleeps	8	[NP Vi •, 3]	8
Reduce: [8]	VP → Vi	9	[NP VP •, 3]	9

S → NP VP
VP → Vi
VP → Vt NP
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NP → DT NN
NP → NP PP
PP → IN NP
Vi → sleeps
Vt → saw
NN → man
NN → dog
NN → telescope
DT → the
IN → with

Shift-Reduce Example

Input: *the man sleeps*

Rule	Condition		Statement	Queue
Axiom		1	[•,0]	1
Shift: [1]		2	[the•,1]	2
Reduce: [2]	DT → the	3	[DT•,1]	3
Shift: [3]		4	[DT man •, 2]	4
Reduce: [4]	NN → man	5	[DT NN •, 2]	5
Reduce: [5]	NP → DT NN	6	[NP •, 2]	6
Shift: [6]		7	[NP sleeps •, 3]	7
Reduce: [7]	Vi → sleeps	8	[NP Vi •, 3]	8
Reduce: [8]	VP → Vi	9	[NP VP •, 3]	9
Reduce: [9]	S → NP VP	10	[S •, 3]	10

S → NP VP
VP → Vi
VP → Vt NP
VP → VP PP
NP → DT NN
NP → NP PP
PP → IN NP
Vi → sleeps
Vt → saw
NN → man
NN → dog
NN → telescope
DT → the
IN → with

Shift-Reduce Example

Input: *the man sleeps*

Rule	Condition		Statement	Queue
Axiom		1	[•,0]	1
Shift: [1]		2	[the•,1]	2
Reduce: [2]	DT → the	3	[DT•,1]	3
Shift: [3]		4	[DT man •, 2]	4
Reduce: [4]	NN → man	5	[DT NN •, 2]	5
Reduce: [5]	NP → DT NN	6	[NP •, 2]	6
Shift: [6]		7	[NP sleeps •, 3]	7
Reduce: [7]	Vi → sleeps	8	[NP Vi •, 3]	8
Reduce: [8]	VP → Vi	9	[NP VP •, 3]	9
Reduce: [9]	S → NP VP	10	[S •, 3]	10
GOAL: [10]				∅

S → NP VP
VP → Vi
VP → Vt NP
VP → VP PP
NP → DT NN
NP → NP PP
PP → IN NP
Vi → sleeps
Vt → saw
NN → man
NN → dog
NN → telescope
DT → the
IN → with

Shift-Reduce

Input: G and $x_1 \ldots x_n$

Axiom: [•,0]

Goal: [S•,n]

Scan (shift)
asserts that $\alpha\ x_{j+1} \Rightarrow^* x_1 \ldots x_j\ x_{j+1}$

Complete (reduce)
asserts that $\alpha B \Rightarrow^* x_1 \ldots x_j$

Item form: [α•, j]
asserts that $\alpha \Rightarrow^* x_1 \ldots x_j$ or

that $\alpha\ x_{j+1} \ldots x_n \Rightarrow^* x_1 \ldots x_n$

$$\textsc{Shift}\ \frac{[\alpha\bullet, j]}{[\alpha\, x_{j+1}, j+1]}$$

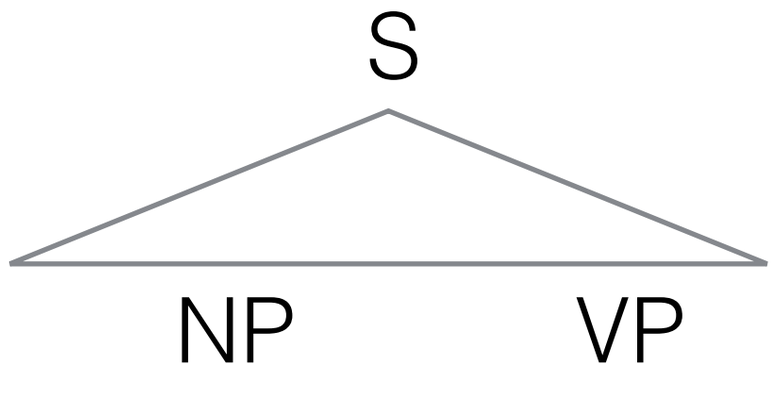
$$\textsc{Reduce}\ \frac{[\alpha\,\beta\bullet, j]}{[\alpha\, B, j]}\ B \to \beta \in \mathcal{R}$$

Top-down: Predict-Scan

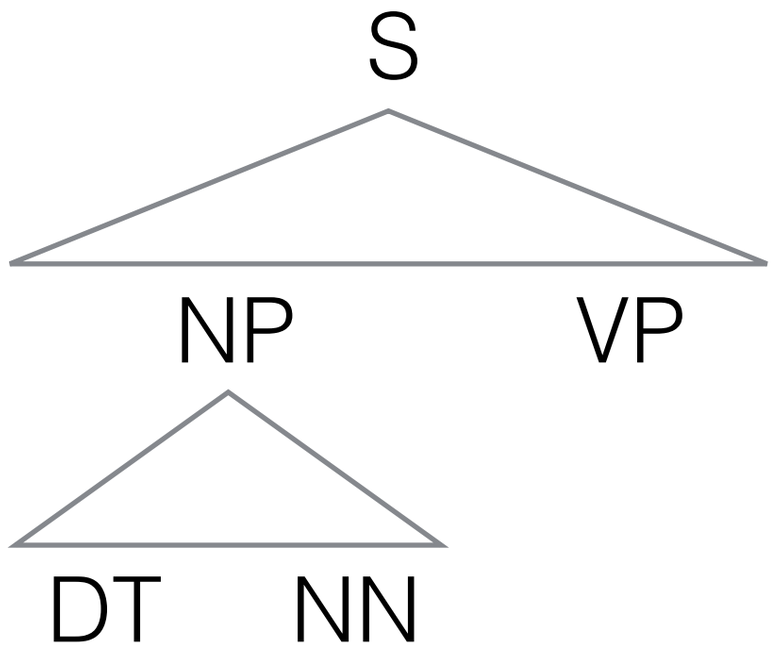
Top-down: Predict-Scan

s

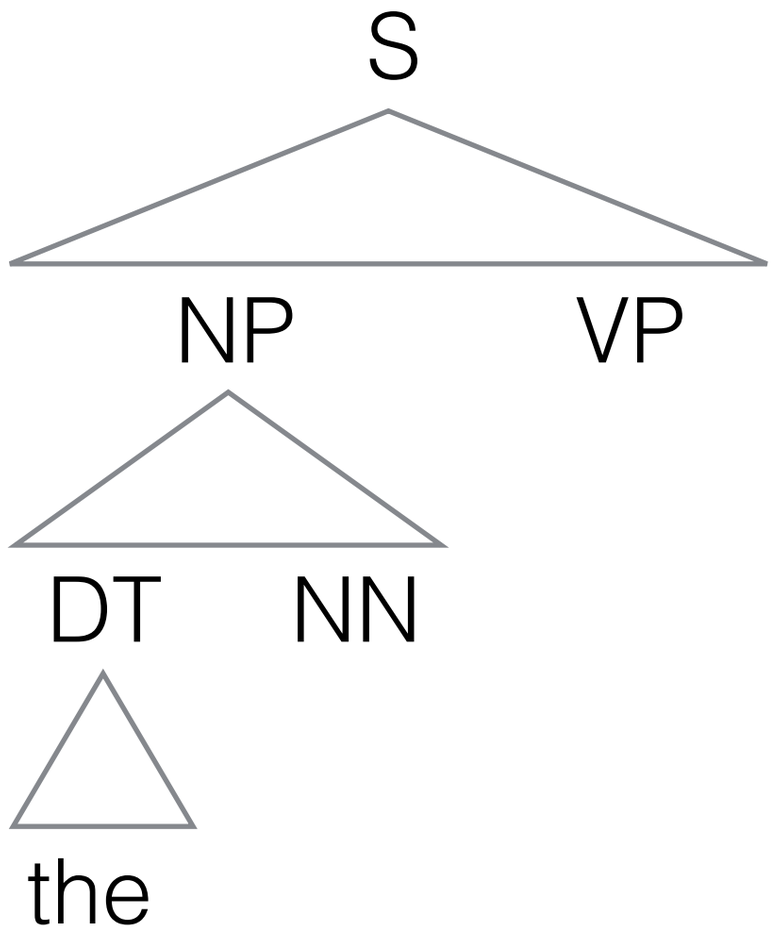
Top-down: Predict-Scan



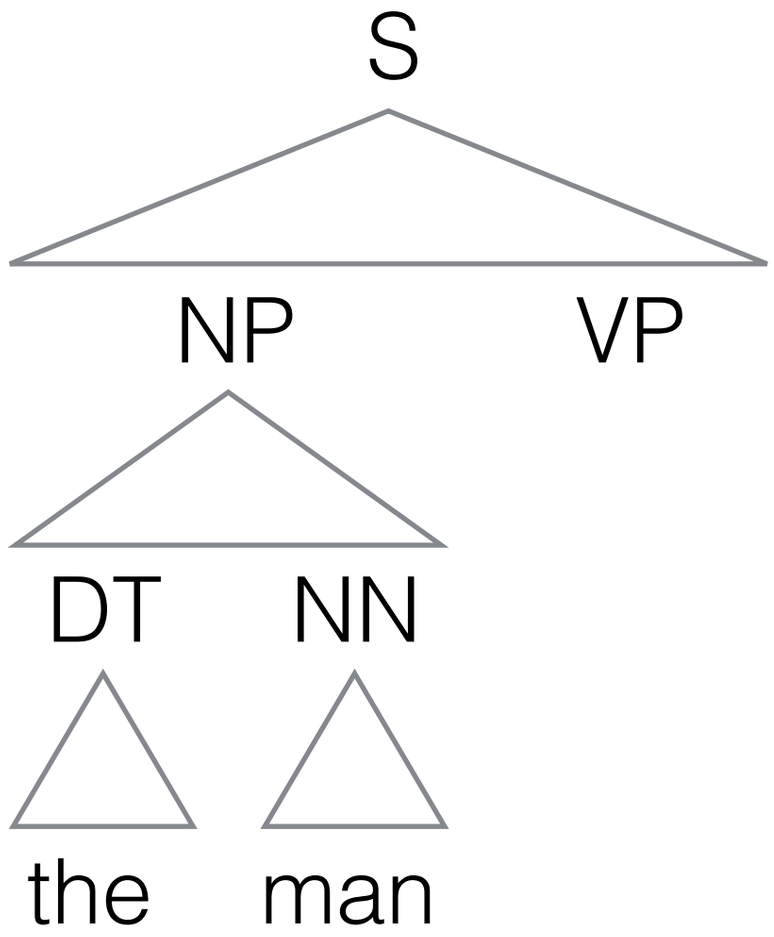
Top-down: Predict-Scan



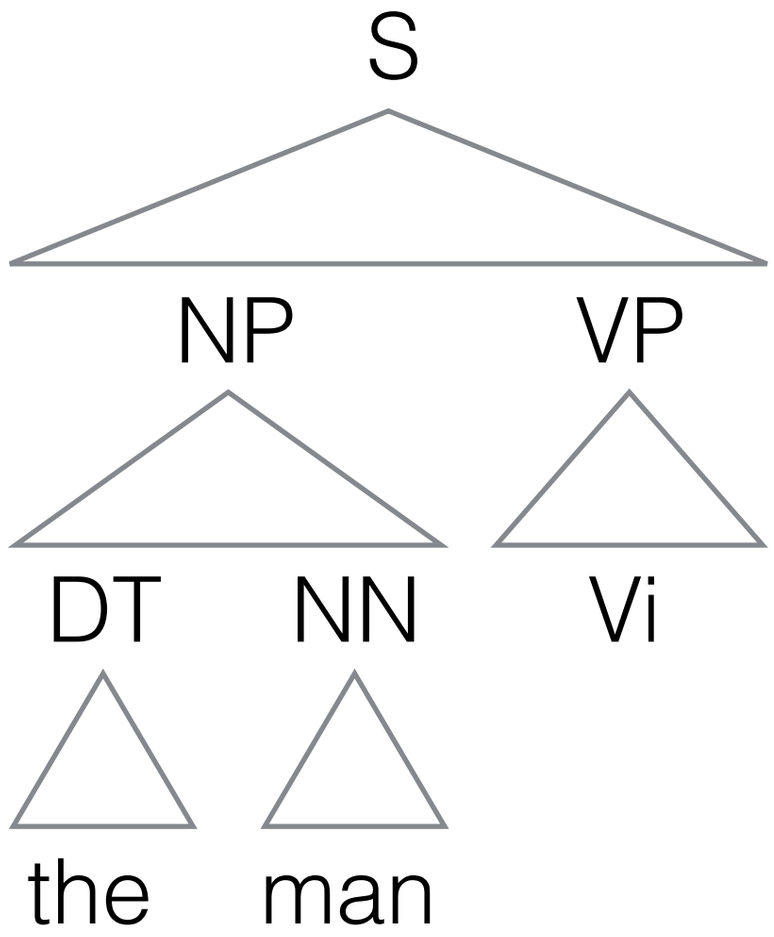
Top-down: Predict-Scan



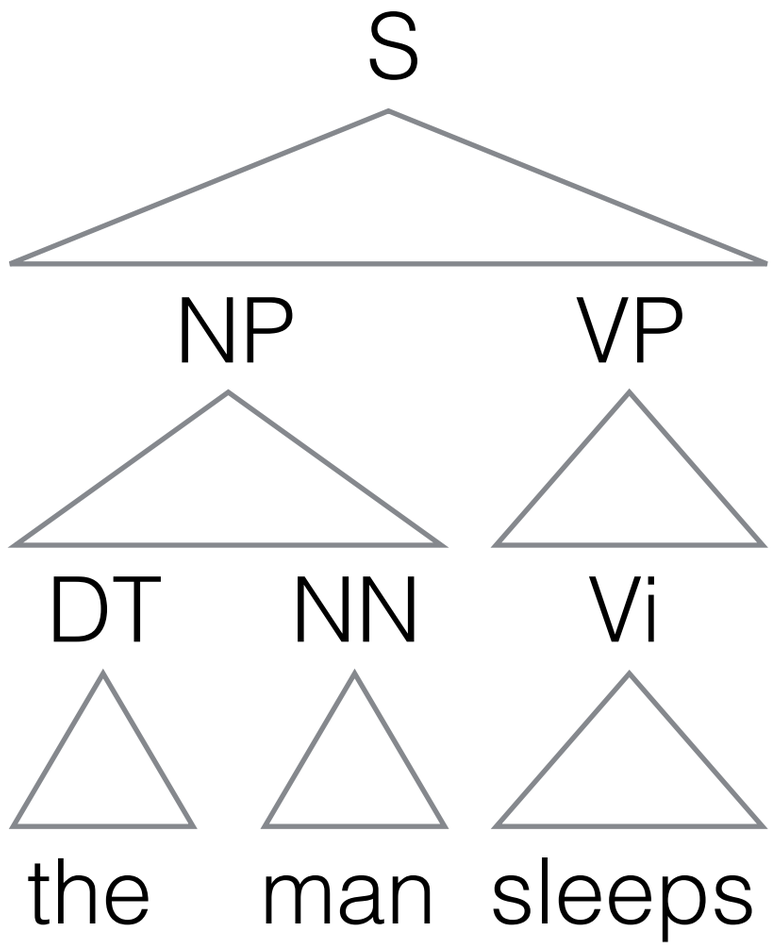
Top-down: Predict-Scan



Top-down: Predict-Scan



Top-down: Predict-Scan



Top-Down Example

Input: *the man sleeps*

S → NP VP

VP → Vi

VP → Vt NP

~~VP → VP PP~~

NP → DT NN

NP → NP PP

PP → IN NP

Vi → sleeps

Vt → saw

NN → man

NN → dog

NN → telescope

DT → the

IN → with

Top-Down Example

Input: *the man sleeps*

Rule	Condition	Statement	Queue

S → NP VP

VP → Vi

VP → Vt NP

~~VP → VP PP~~

NP → DT NN

NP → NP PP

PP → IN NP

Vi → sleeps

Vt → saw

NN → man

NN → dog

NN → telescope

DT → the

IN → with

Top-Down Example

Input: *the man sleeps*

Rule	Condition		Statement	Queue
Axiom		1	[• S, 0]	1

S → NP VP

VP → Vi

VP → Vt NP

~~VP → VP PP~~

NP → DT NN

NP → NP PP

PP → IN NP

Vi → sleeps

Vt → saw

NN → man

NN → dog

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Top-Down Example

Input: *the man sleeps*

Rule	Condition		Statement	Queue
Axiom		1	[• S, 0]	1

S → NP VP

VP → Vi

VP → Vt NP

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NP → DT NN

NP → NP PP

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Vi → sleeps

Vt → saw

NN → man

NN → dog

NN → telescope

DT → the

IN → with

Top-Down Example

Input: *the man sleeps*

Rule	Condition		Statement	Queue
Axiom		1	[• S, 0]	1
Predict: [1]	S → NP VP	2	[• NP VP, 0]	2

S → NP VP

VP → Vi

VP → Vt NP

~~VP → VP PP~~

NP → DT NN

NP → NP PP

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Vi → sleeps

Vt → saw

NN → man

NN → dog

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Top-Down Example

Input: *the man sleeps*

Rule	Condition		Statement	Queue
Axiom		1	[• S, 0]	1
Predict: [1]	S → NP VP	2	[• NP VP, 0]	2

S → NP VP

VP → Vi

VP → Vt NP

~~VP → VP PP~~

NP → DT NN

NP → NP PP

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Vt → saw

NN → man

NN → dog

NN → telescope

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IN → with

Top-Down Example

Input: *the man sleeps*

Rule	Condition		Statement	Queue
Axiom		1	[• S, 0]	1
Predict: [1]	S → NP VP	2	[• NP VP, 0]	2
Predict: [2]	NP → DT NN	3	[• DT NN VP, 0]	3

S → NP VP

VP → Vi

VP → Vt NP

~~VP → VP PP~~

NP → DT NN

NP → NP PP

PP → IN NP

Vi → sleeps

Vt → saw

NN → man

NN → dog

NN → telescope

DT → the

IN → with

Top-Down Example

Input: *the man sleeps*

Rule	Condition		Statement	Queue
Axiom		1	[• S, 0]	1
Predict: [1]	S → NP VP	2	[• NP VP, 0]	2
Predict: [2]	NP → DT NN	3	[• DT NN VP, 0]	3

S → NP VP

VP → Vi

VP → Vt NP

~~VP → VP PP~~

NP → DT NN

NP → NP PP

PP → IN NP

Vi → sleeps

Vt → saw

NN → man

NN → dog

NN → telescope

DT → the

IN → with

Top-Down Example

Input: *the man sleeps*

Rule	Condition		Statement	Queue
Axiom		1	[• S, 0]	1
Predict: [1]	S → NP VP	2	[• NP VP, 0]	2
Predict: [2]	NP → DT NN	3	[• DT NN VP, 0]	3
Predict: [3]	DT → the	4	[• the NN VP,0]	4

S → NP VP

VP → Vi

VP → Vt NP

~~VP → VP PP~~

NP → DT NN

NP → NP PP

PP → IN NP

Vi → sleeps

Vt → saw

NN → man

NN → dog

NN → telescope

DT → the

IN → with

Top-Down Example

Input: *the man sleeps*

Rule	Condition		Statement	Queue
Axiom		1	[• S, 0]	1
Predict: [1]	S → NP VP	2	[• NP VP, 0]	2
Predict: [2]	NP → DT NN	3	[• DT NN VP, 0]	3
Predict: [3]	DT → the	4	[• the NN VP,0]	4

S → NP VP

VP → Vi

VP → Vt NP

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NP → DT NN

NP → NP PP

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Vi → sleeps

Vt → saw

NN → man

NN → dog

NN → telescope

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Top-Down Example

Input: *the man sleeps*

Rule	Condition		Statement	Queue
Axiom		1	[• S, 0]	1
Predict: [1]	S → NP VP	2	[• NP VP, 0]	2
Predict: [2]	NP → DT NN	3	[• DT NN VP, 0]	3
Predict: [3]	DT → the	4	[• the NN VP,0]	4
Scan: [4]		5	[• NN VP,1]	5

S → NP VP

VP → Vi

VP → Vt NP

~~VP → VP PP~~

NP → DT NN

NP → NP PP

PP → IN NP

Vi → sleeps

Vt → saw

NN → man

NN → dog

NN → telescope

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Top-Down Example

Input: *the man sleeps*

Rule	Condition		Statement	Queue
Axiom		1	[• S, 0]	1
Predict: [1]	S → NP VP	2	[• NP VP, 0]	2
Predict: [2]	NP → DT NN	3	[• DT NN VP, 0]	3
Predict: [3]	DT → the	4	[• the NN VP,0]	4
Scan: [4]		5	[• NN VP,1]	5

S → NP VP

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VP → Vt NP

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Top-Down Example

Input: *the man sleeps*

Rule	Condition		Statement	Queue
Axiom		1	[• S, 0]	1
Predict: [1]	S → NP VP	2	[• NP VP, 0]	2
Predict: [2]	NP → DT NN	3	[• DT NN VP, 0]	3
Predict: [3]	DT → the	4	[• the NN VP,0]	4
Scan: [4]		5	[• NN VP,1]	5
Predict: [5]	NN → man	6	[• man VP, 1]	6

S → NP VP

VP → Vi

VP → Vt NP

~~VP → VP PP~~

NP → DT NN

NP → NP PP

PP → IN NP

Vi → sleeps

Vt → saw

NN → man

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NN → telescope

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Top-Down Example

Input: *the man sleeps*

Rule	Condition		Statement	Queue
Axiom		1	[• S, 0]	1
Predict: [1]	S → NP VP	2	[• NP VP, 0]	2
Predict: [2]	NP → DT NN	3	[• DT NN VP, 0]	3
Predict: [3]	DT → the	4	[• the NN VP,0]	4
Scan: [4]		5	[• NN VP,1]	5
Predict: [5]	NN → man	6	[• man VP, 1]	6

S → NP VP

VP → Vi

VP → Vt NP

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NN → dog

NN → telescope

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Top-Down Example

Input: *the man sleeps*

Rule	Condition		Statement	Queue
Axiom		1	[• S, 0]	1
Predict: [1]	S → NP VP	2	[• NP VP, 0]	2
Predict: [2]	NP → DT NN	3	[• DT NN VP, 0]	3
Predict: [3]	DT → the	4	[• the NN VP,0]	4
Scan: [4]		5	[• NN VP,1]	5
Predict: [5]	NN → man	6	[• man VP, 1]	6
Scan: [6]		7	[• VP, 2]	7

S → NP VP

VP → Vi

VP → Vt NP

~~VP → VP PP~~

NP → DT NN

NP → NP PP

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Vi → sleeps

Vt → saw

NN → man

NN → dog

NN → telescope

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Top-Down Example

Input: *the man sleeps*

Rule	Condition		Statement	Queue
Axiom		1	[• S, 0]	1
Predict: [1]	S → NP VP	2	[• NP VP, 0]	2
Predict: [2]	NP → DT NN	3	[• DT NN VP, 0]	3
Predict: [3]	DT → the	4	[• the NN VP,0]	4
Scan: [4]		5	[• NN VP,1]	5
Predict: [5]	NN → man	6	[• man VP, 1]	6
Scan: [6]		7	[• VP, 2]	7

S → NP VP

VP → Vi

VP → Vt NP

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Top-Down Example

Input: *the man sleeps*

Rule	Condition		Statement	Queue
Axiom		1	[• S, 0]	1
Predict: [1]	S → NP VP	2	[• NP VP, 0]	2
Predict: [2]	NP → DT NN	3	[• DT NN VP, 0]	3
Predict: [3]	DT → the	4	[• the NN VP,0]	4
Scan: [4]		5	[• NN VP,1]	5
Predict: [5]	NN → man	6	[• man VP, 1]	6
Scan: [6]		7	[• VP, 2]	7

S → NP VP

VP → Vi

VP → Vt NP

~~VP → VP PP~~

NP → DT NN

NP → NP PP

PP → IN NP

Vi → sleeps

Vt → saw

NN → man

NN → dog

NN → telescope

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Top-Down Example

Input: *the man sleeps*

Rule	Condition		Statement	Queue
Axiom		1	[• S, 0]	1
Predict: [1]	S → NP VP	2	[• NP VP, 0]	2
Predict: [2]	NP → DT NN	3	[• DT NN VP, 0]	3
Predict: [3]	DT → the	4	[• the NN VP,0]	4
Scan: [4]		5	[• NN VP,1]	5
Predict: [5]	NN → man	6	[• man VP, 1]	6
Scan: [6]		7	[• VP, 2]	7
Predict: [7]	VP → Vi	8	[• Vi, 2]	8, 9

S → NP VP
VP → Vi
VP → Vt NP
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NP → DT NN
NP → NP PP
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Vi → sleeps
Vt → saw
NN → man
NN → dog
NN → telescope
DT → the
IN → with

Top-Down Example

Input: *the man sleeps*

Rule	Condition		Statement	Queue
Axiom		1	[• S, 0]	1
Predict: [1]	S → NP VP	2	[• NP VP, 0]	2
Predict: [2]	NP → DT NN	3	[• DT NN VP, 0]	3
Predict: [3]	DT → the	4	[• the NN VP,0]	4
Scan: [4]		5	[• NN VP,1]	5
Predict: [5]	NN → man	6	[• man VP, 1]	6
Scan: [6]		7	[• VP, 2]	7
Predict: [7]	VP → Vi	8	[• Vi, 2]	8, 9
	VP → Vt NP	9	[• Vt NP, 2]	

S → NP VP
VP → Vi
VP → Vt NP
~~VP → VP PP~~
NP → DT NN
NP → NP PP
PP → IN NP
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Vt → saw
NN → man
NN → dog
NN → telescope
DT → the
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Top-Down Example

Input: *the man sleeps*

Rule	Condition		Statement	Queue
Axiom		1	[• S, 0]	1
Predict: [1]	S → NP VP	2	[• NP VP, 0]	2
Predict: [2]	NP → DT NN	3	[• DT NN VP, 0]	3
Predict: [3]	DT → the	4	[• the NN VP,0]	4
Scan: [4]		5	[• NN VP,1]	5
Predict: [5]	NN → man	6	[• man VP, 1]	6
Scan: [6]		7	[• VP, 2]	7
Predict: [7]	VP → Vi	8	[• Vi, 2]	8, 9
	VP → Vt NP	9	[• Vt NP, 2]	

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Top-Down Example

Input: *the man sleeps*

Rule	Condition		Statement	Queue
Axiom		1	[• S, 0]	1
Predict: [1]	S → NP VP	2	[• NP VP, 0]	2
Predict: [2]	NP → DT NN	3	[• DT NN VP, 0]	3
Predict: [3]	DT → the	4	[• the NN VP,0]	4
Scan: [4]		5	[• NN VP,1]	5
Predict: [5]	NN → man	6	[• man VP, 1]	6
Scan: [6]		7	[• VP, 2]	7
Predict: [7]	VP → Vi	8	[• Vi, 2]	8, 9
	VP → Vt NP	9	[• Vt NP, 2]	
Predict: [8]	Vi → sleeps	10	[• sleeps, 2]	9, 10

S → NP VP
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NP → DT NN
NP → NP PP
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Vi → sleeps
Vt → saw
NN → man
NN → dog
NN → telescope
DT → the
IN → with

Top-Down Example

Input: *the man sleeps*

Rule	Condition		Statement	Queue
Axiom		1	[• S, 0]	1
Predict: [1]	S → NP VP	2	[• NP VP, 0]	2
Predict: [2]	NP → DT NN	3	[• DT NN VP, 0]	3
Predict: [3]	DT → the	4	[• the NN VP,0]	4
Scan: [4]		5	[• NN VP,1]	5
Predict: [5]	NN → man	6	[• man VP, 1]	6
Scan: [6]		7	[• VP, 2]	7
Predict: [7]	VP → Vi	8	[• Vi, 2]	8, 9
	VP → Vt NP	9	[• Vt NP, 2]	
Predict: [8]	Vi → sleeps	10	[• sleeps, 2]	9, 10

S → NP VP
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VP → Vt NP
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NP → DT NN
NP → NP PP
PP → IN NP
Vi → sleeps
Vt → saw
NN → man
NN → dog
NN → telescope
DT → the
IN → with

Top-Down Example

Input: *the man sleeps*

Rule	Condition		Statement	Queue
Axiom		1	[• S, 0]	1
Predict: [1]	S → NP VP	2	[• NP VP, 0]	2
Predict: [2]	NP → DT NN	3	[• DT NN VP, 0]	3
Predict: [3]	DT → the	4	[• the NN VP,0]	4
Scan: [4]		5	[• NN VP,1]	5
Predict: [5]	NN → man	6	[• man VP, 1]	6
Scan: [6]		7	[• VP, 2]	7
Predict: [7]	VP → Vi	8	[• Vi, 2]	8, 9
	VP → Vt NP	9	[• Vt NP, 2]	
Predict: [8]	Vi → sleeps	10	[• sleeps, 2]	9, 10
[9]				10

S → NP VP
VP → Vi
VP → Vt NP
~~VP → VP PP~~
NP → DT NN
NP → NP PP
PP → IN NP
Vi → sleeps
Vt → saw
NN → man
NN → dog
NN → telescope
DT → the
IN → with

Top-Down Example

Input: *the man sleeps*

Rule	Condition		Statement	Queue
Axiom		1	[• S, 0]	1
Predict: [1]	S → NP VP	2	[• NP VP, 0]	2
Predict: [2]	NP → DT NN	3	[• DT NN VP, 0]	3
Predict: [3]	DT → the	4	[• the NN VP,0]	4
Scan: [4]		5	[• NN VP,1]	5
Predict: [5]	NN → man	6	[• man VP, 1]	6
Scan: [6]		7	[• VP, 2]	7
Predict: [7]	VP → Vi	8	[• Vi, 2]	8, 9
	VP → Vt NP	9	[• Vt NP, 2]	
Predict: [8]	Vi → sleeps	10	[• sleeps, 2]	9, 10
[9]				10

S → NP VP
VP → Vi
VP → Vt NP
~~VP → VP PP~~
NP → DT NN
NP → NP PP
PP → IN NP
Vi → sleeps
Vt → saw
NN → man
NN → dog
NN → telescope
DT → the
IN → with

Top-Down Example

Input: *the man sleeps*

Rule	Condition		Statement	Queue
Axiom		1	[• S, 0]	1
Predict: [1]	S → NP VP	2	[• NP VP, 0]	2
Predict: [2]	NP → DT NN	3	[• DT NN VP, 0]	3
Predict: [3]	DT → the	4	[• the NN VP,0]	4
Scan: [4]		5	[• NN VP,1]	5
Predict: [5]	NN → man	6	[• man VP, 1]	6
Scan: [6]		7	[• VP, 2]	7
Predict: [7]	VP → Vi	8	[• Vi, 2]	8, 9
	VP → Vt NP	9	[• Vt NP, 2]	
Predict: [8]	Vi → sleeps	10	[• sleeps, 2]	9, 10
[9]				10
Scan: [10]		11	[•, 3]	11

S → NP VP
VP → Vi
VP → Vt NP
~~VP → VP PP~~
NP → DT NN
NP → NP PP
PP → IN NP
Vi → sleeps
Vt → saw
NN → man
NN → dog
NN → telescope
DT → the
IN → with

Top-Down Example

Input: *the man sleeps*

Rule	Condition		Statement	Queue
Axiom		1	[• S, 0]	1
Predict: [1]	S → NP VP	2	[• NP VP, 0]	2
Predict: [2]	NP → DT NN	3	[• DT NN VP, 0]	3
Predict: [3]	DT → the	4	[• the NN VP,0]	4
Scan: [4]		5	[• NN VP,1]	5
Predict: [5]	NN → man	6	[• man VP, 1]	6
Scan: [6]		7	[• VP, 2]	7
Predict: [7]	VP → Vi	8	[• Vi, 2]	8, 9
	VP → Vt NP	9	[• Vt NP, 2]	
Predict: [8]	Vi → sleeps	10	[• sleeps, 2]	9, 10
[9]				10
Scan: [10]		11	[•, 3]	11
GOAL: [11]				∅

S → NP VP
VP → Vi
VP → Vt NP
~~VP → VP PP~~
NP → DT NN
NP → NP PP
PP → IN NP
Vi → sleeps
Vt → saw
NN → man
NN → dog
NN → telescope
DT → the
IN → with

Top-Down recognition

Input: G and $x_1 \ldots x_n$

Item form: [•β, j]
asserts that $S \Rightarrow^* x_1 \ldots x_j\ \beta$

Axiom: [•S,0]

Goal: [•,n]

Scan
asserts that $S \Rightarrow^* x_1 \ldots x_j\, x_{j+1}\, \beta$

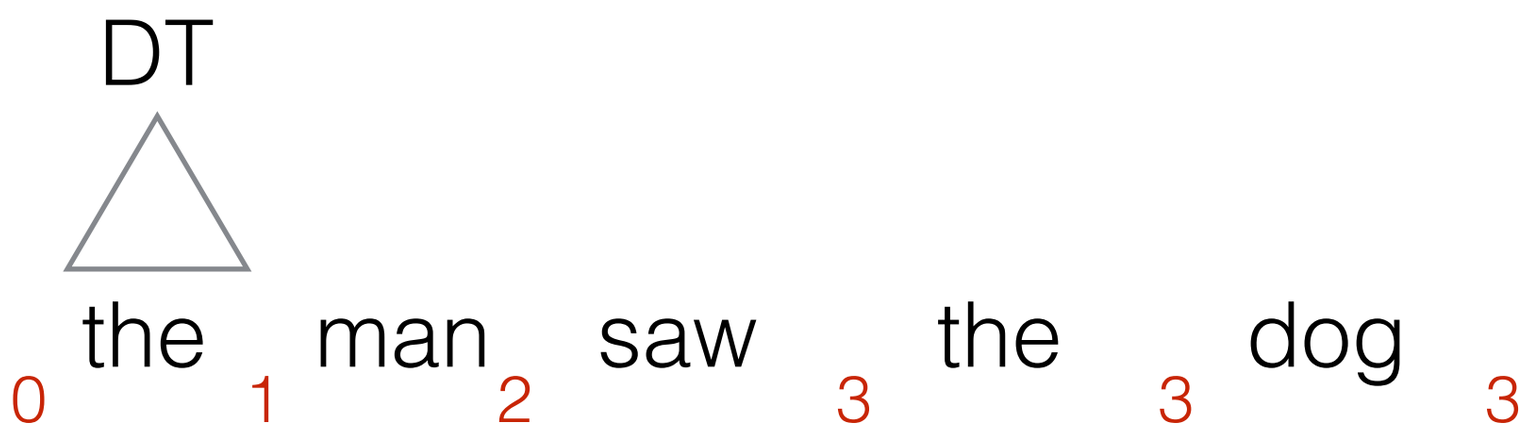
$$\textsc{Scan}\ \frac{[\bullet x_{j+1}\,\beta, j]}{[\bullet\beta, j+1]}$$

Predict
asserts that $S \Rightarrow^* x_1 \ldots x_j\, B\, \beta$

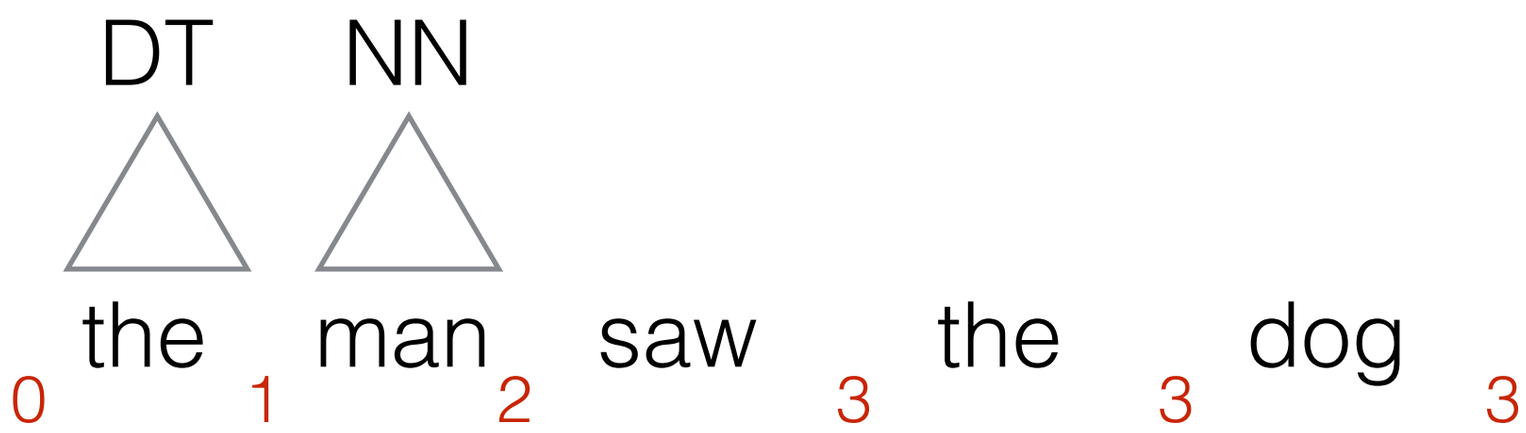
$$\textsc{Predict}\ \frac{[\bullet A\,\beta, j]}{[\bullet\alpha\,\beta, j]}\ A \to \alpha \in \mathcal{R}$$

Bottom-Up for CNF: CKY

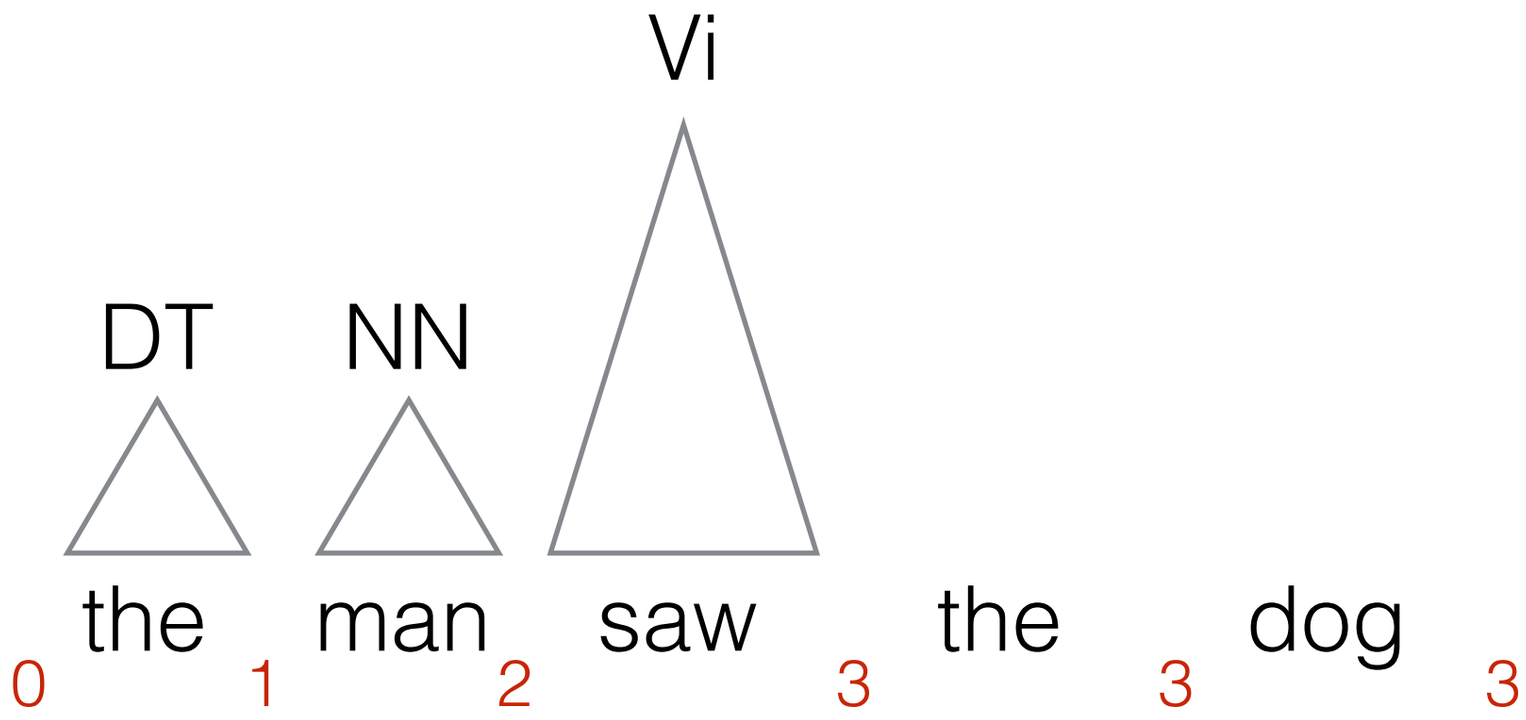
Bottom-Up for CNF: CKY



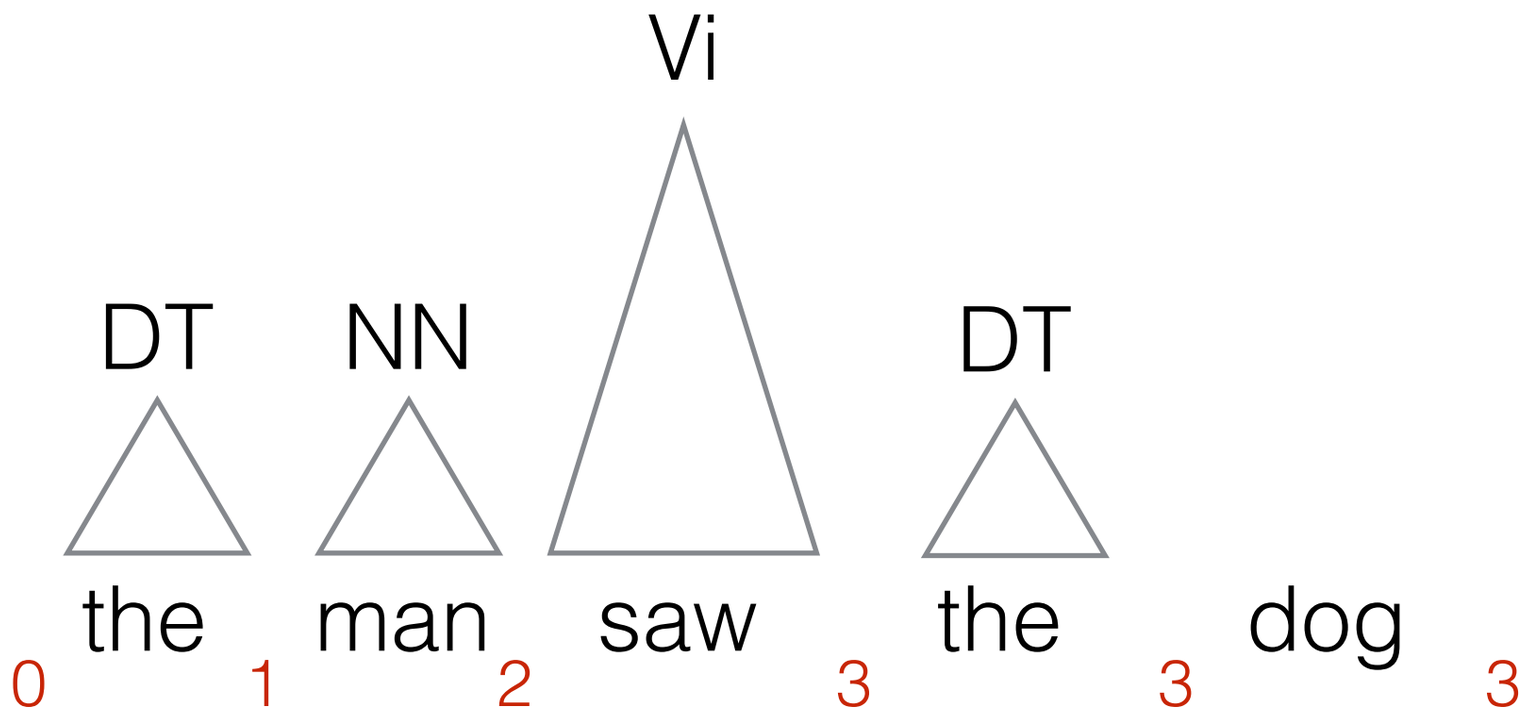
Bottom-Up for CNF: CKY



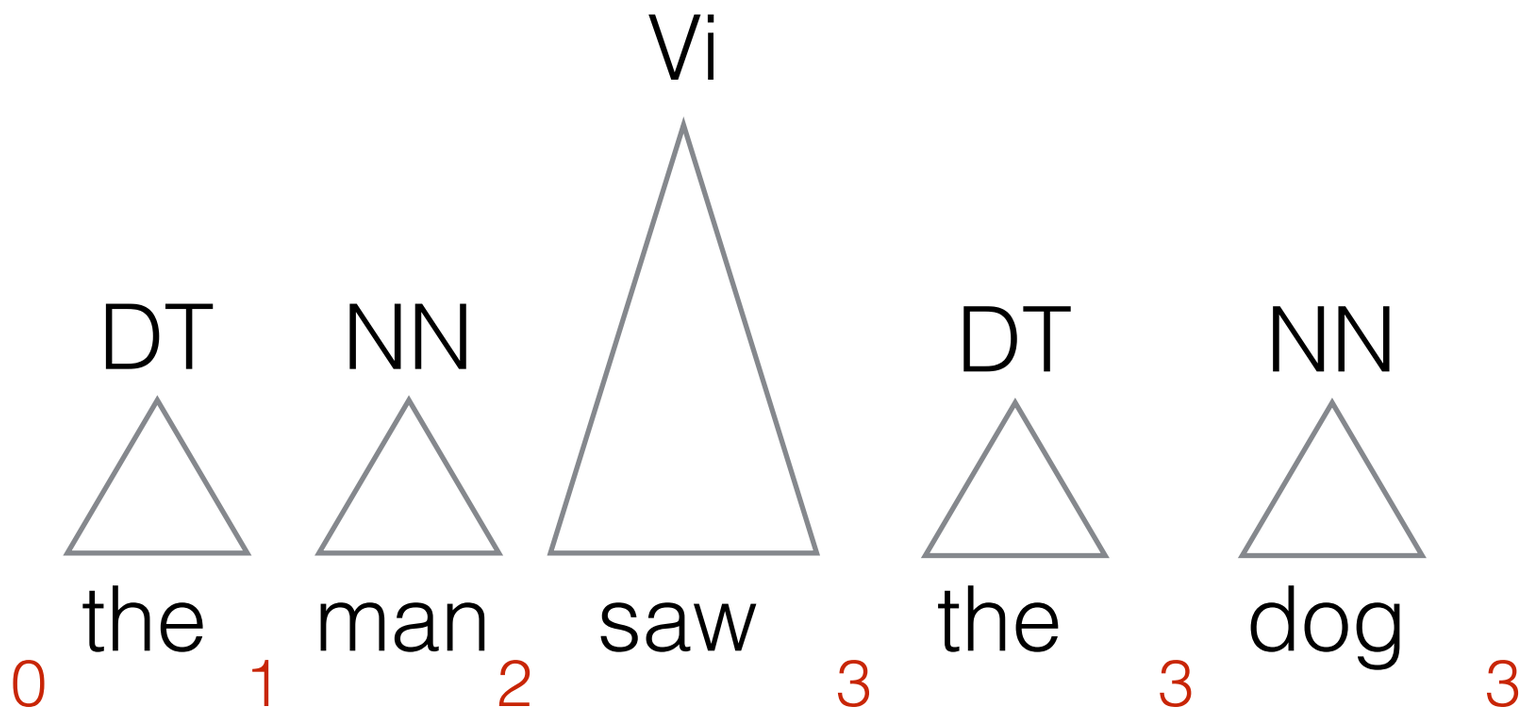
Bottom-Up for CNF: CKY



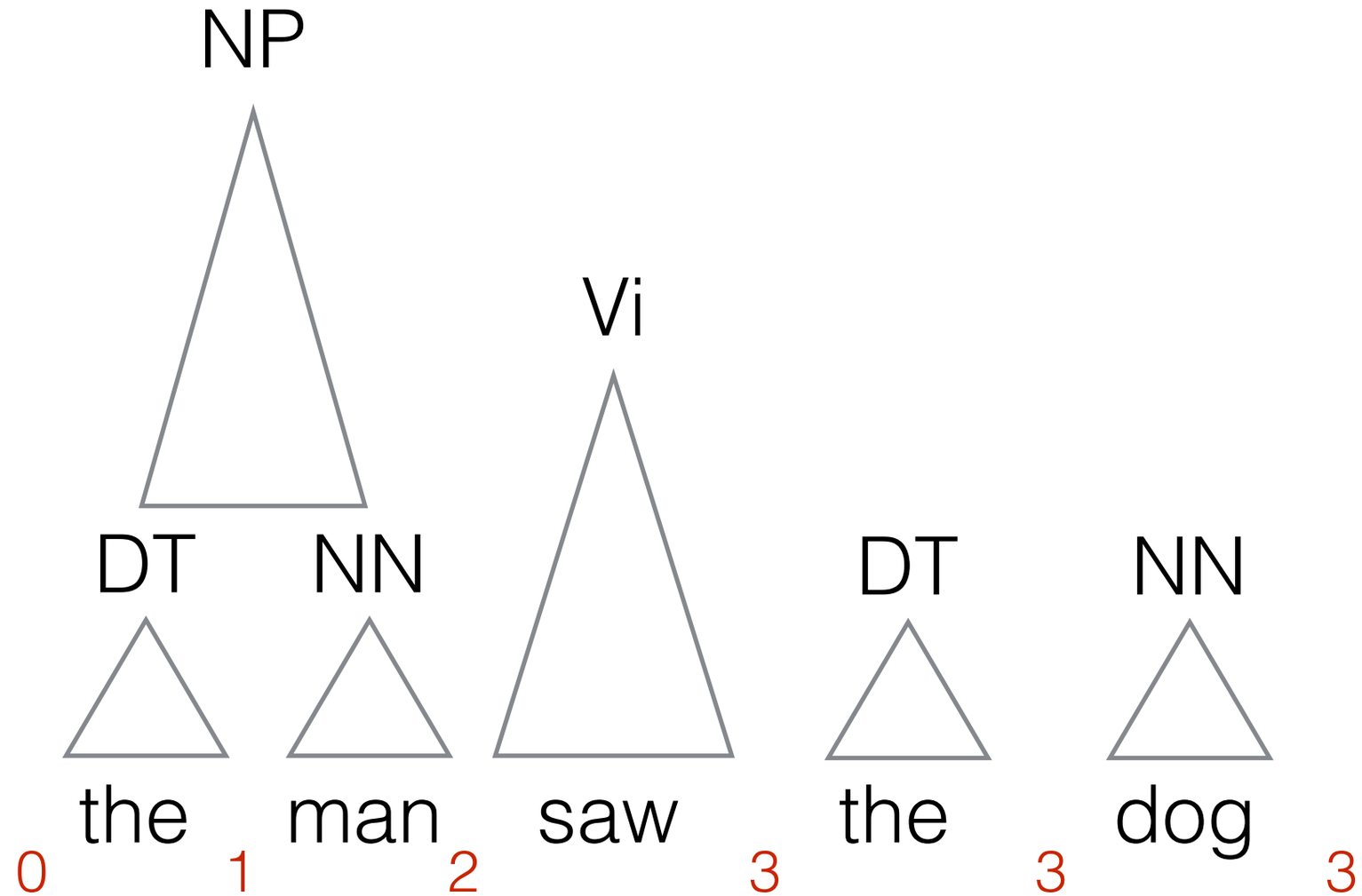
Bottom-Up for CNF: CKY



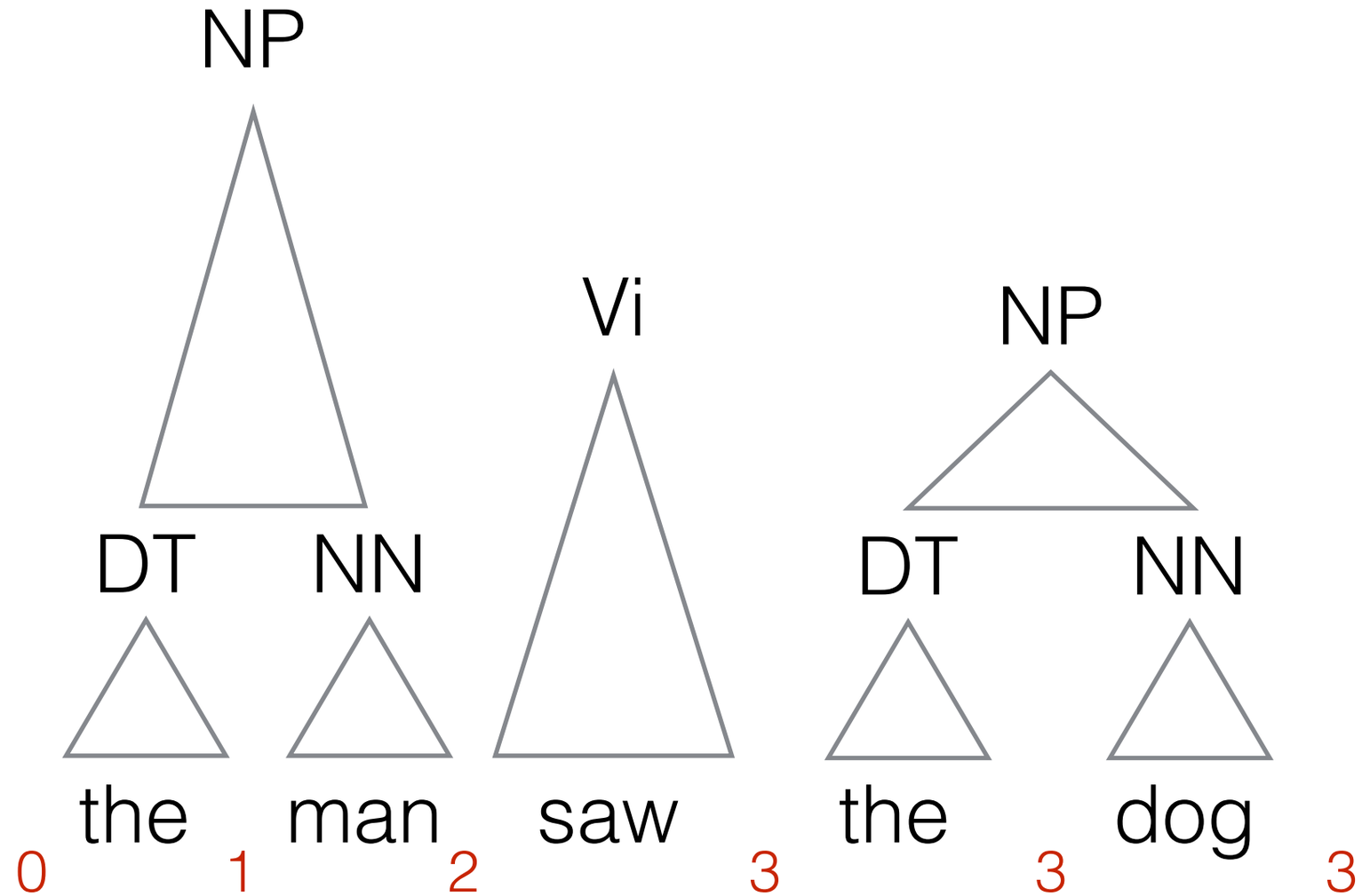
Bottom-Up for CNF: CKY



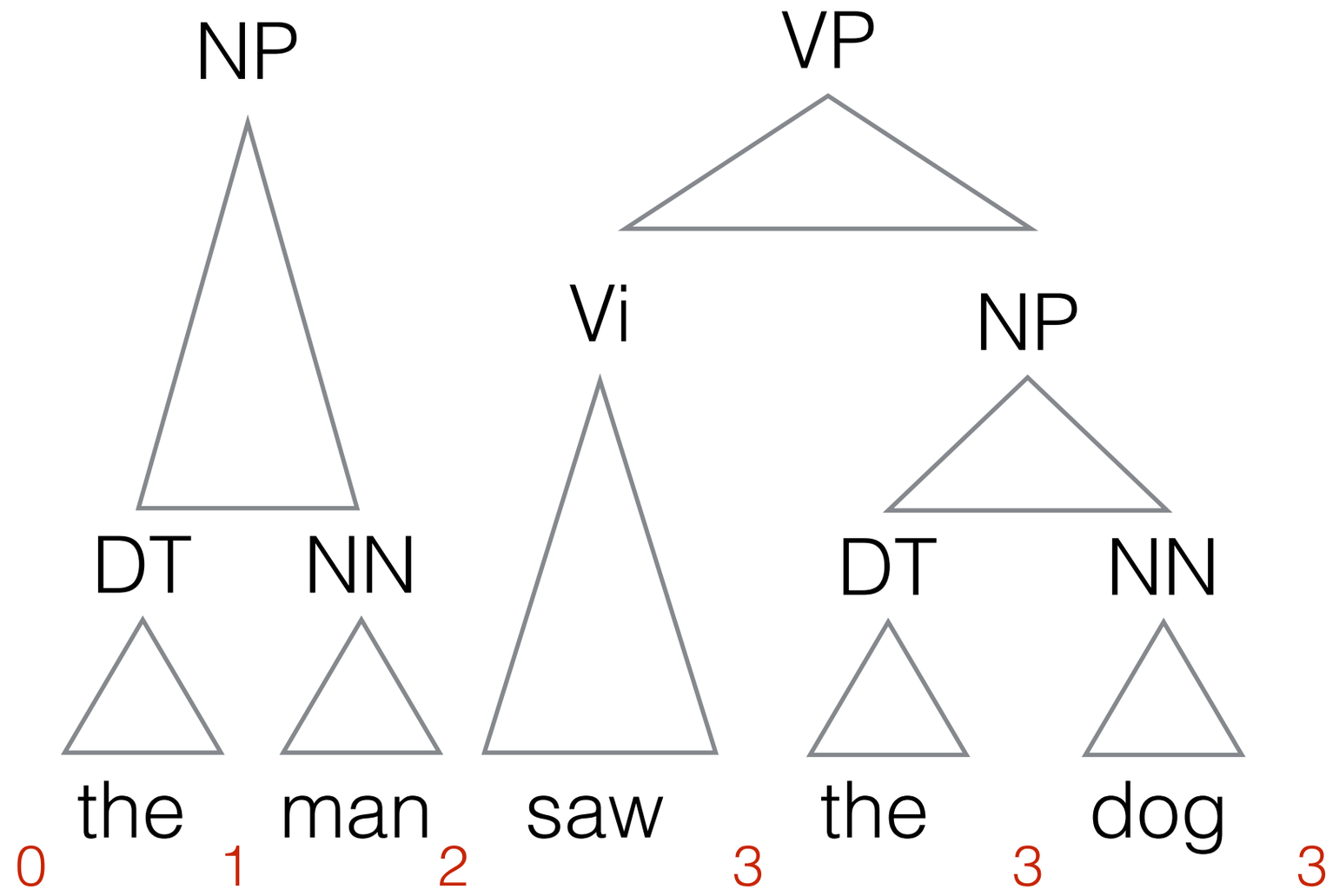
Bottom-Up for CNF: CKY



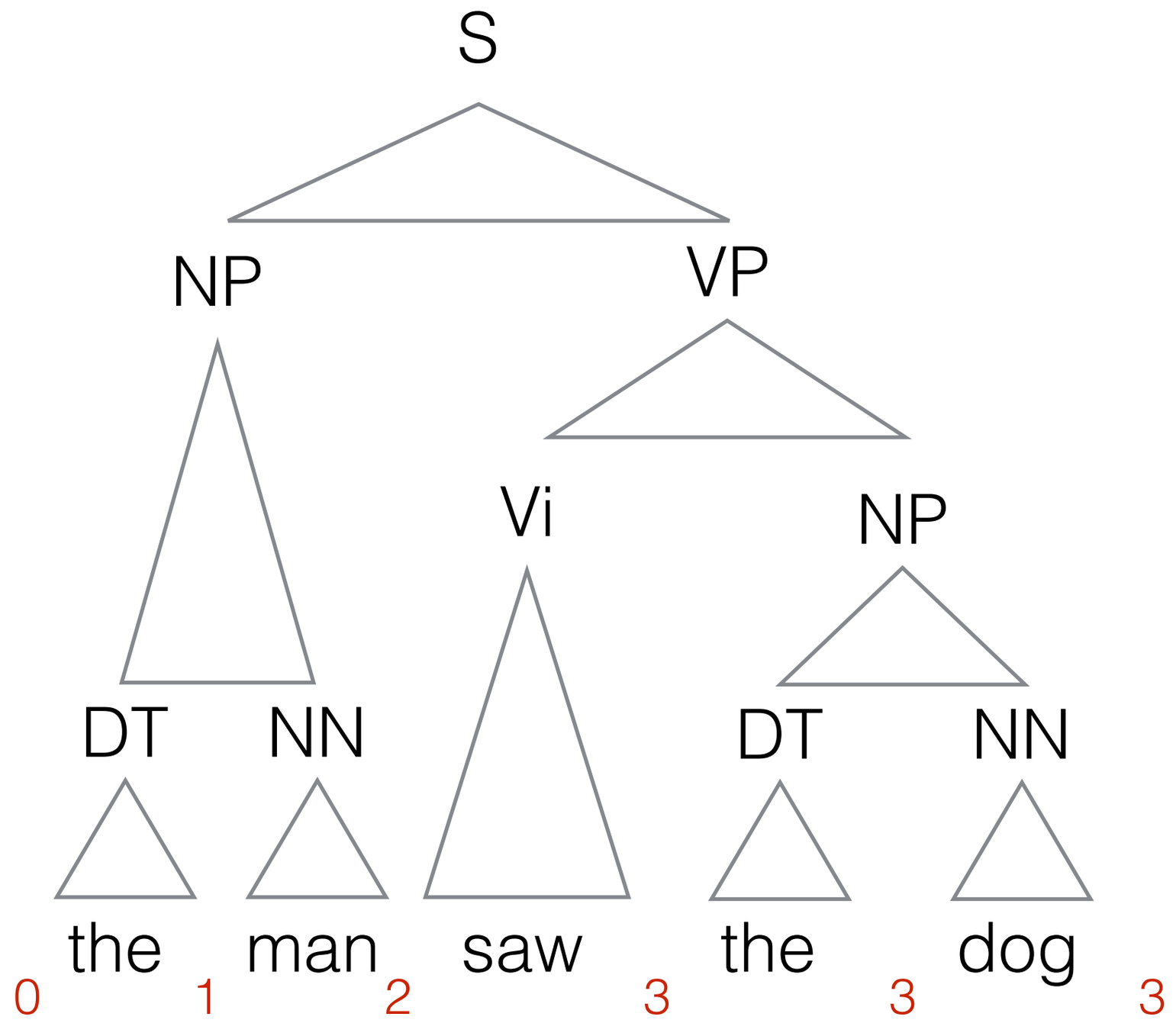
Bottom-Up for CNF: CKY



Bottom-Up for CNF: CKY



Bottom-Up for CNF: CKY



CKY - CNF only

Input: G and $s = x_1 \ldots x_n$ **Item form:** [i, X, j]
asserts that $X \Rightarrow^* x_{i+1} \ldots x_j$

Axioms: [i, X, i+1] $X \rightarrow x_i \in \mathscr{R}$

Goal: [0, S, n]

Merge:

$$\frac{[i, A, k][k, B, j]}{[i, C, j]} \; C \rightarrow A\,B \in \mathcal{R}$$

asserts that

$x_{i+1} \ldots x_k \, x_{k+1} \ldots x_j \Rightarrow^* x_{i+1} \ldots x_j$

CKY Example

Input: *the man saw the dog*

S → NP VP	Vi → sleeps
~~VP → Vi~~	Vt → saw
VP → Vt NP	NN → man
VP → VP PP	NN → dog
NP → DT NN	NN → telescope
NP → NP PP	DT → the
PP → IN NP	IN → with

CKY Example

Input: *the man saw the dog*

S → NP VP	Vi → sleeps
~~VP → Vi~~	Vt → saw
VP → Vt NP	NN → man
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NP → DT NN	NN → telescope
NP → NP PP	DT → the
PP → IN NP	IN → with

Rule	Condition	Statement	Queue	Passive

CKY Example

Input: *the man saw the dog*

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~~VP → Vi~~	Vt → saw
VP → Vt NP	NN → man
VP → VP PP	NN → dog
NP → DT NN	NN → telescope
NP → NP PP	DT → the
PP → IN NP	IN → with

Rule	Condition		Statement	Queue	Passive
Axiom	DT → the	1	[0, DT, 1]	1	

CKY Example

Input: *the man saw the dog*

S → NP VP	Vi → sleeps
~~VP → Vi~~	Vt → saw
VP → Vt NP	NN → man
VP → VP PP	NN → dog
NP → DT NN	NN → telescope
NP → NP PP	DT → the
PP → IN NP	IN → with

Rule	Condition		Statement	Queue	Passive
Axiom	DT → the	1	[0, DT, 1]	1	
	NN → man	2	[1, NN, 2]	1, 2	

CKY Example

Input: *the man saw the dog*

S → NP VP	Vi → sleeps
~~VP → Vi~~	Vt → saw
VP → Vt NP	NN → man
VP → VP PP	NN → dog
NP → DT NN	NN → telescope
NP → NP PP	DT → the
PP → IN NP	IN → with

Rule	Condition		Statement	Queue	Passive
Axiom	DT → the	1	[0, DT, 1]	1	
	NN → man	2	[1, NN, 2]	1, 2	
	Vt → saw	3	[2, Vt, 3]	1, 2, 3	

CKY Example

Input: *the man saw the dog*

S → NP VP	Vi → sleeps
~~VP → Vi~~	Vt → saw
VP → Vt NP	NN → man
VP → VP PP	NN → dog
NP → DT NN	NN → telescope
NP → NP PP	DT → the
PP → IN NP	IN → with

Rule	Condition		Statement	Queue	Passive
Axiom	DT → the	1	[0, DT, 1]	1	
	NN → man	2	[1, NN, 2]	1, 2	
	Vt → saw	3	[2, Vt, 3]	1, 2, 3	
	DT → the	4	[3, DT, 4]	1, 2, 3, 4	

CKY Example

Input: *the man saw the dog*

S → NP VP	Vi → sleeps
~~VP → Vi~~	Vt → saw
VP → Vt NP	NN → man
VP → VP PP	NN → dog
NP → DT NN	NN → telescope
NP → NP PP	DT → the
PP → IN NP	IN → with

Rule	Condition		Statement	Queue	Passive
Axiom	DT → the	1	[0, DT, 1]	1	
	NN → man	2	[1, NN, 2]	1, 2	
	Vt → saw	3	[2, Vt, 3]	1, 2, 3	
	DT → the	4	[3, DT, 4]	1, 2, 3, 4	
	NN → dog	5	[4, NN, 5]	1, 2, 3, 4, 5	

CKY Example

Input: *the man saw the dog*

S → NP VP	Vi → sleeps
~~VP → Vi~~	Vt → saw
VP → Vt NP	NN → man
VP → VP PP	NN → dog
NP → DT NN	NN → telescope
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Rule	Condition		Statement	Queue	Passive
Axiom	DT → the	1	[0, DT, 1]	1	
	NN → man	2	[1, NN, 2]	1, 2	
	Vt → saw	3	[2, Vt, 3]	1, 2, 3	
	DT → the	4	[3, DT, 4]	1, 2, 3, 4	
	NN → dog	5	[4, NN, 5]	1, 2, 3, 4, 5	
				2, 3, 4, 5	1

CKY Example

Input: *the man saw the dog*

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Rule	Condition		Statement	Queue	Passive
Axiom	DT → the	1	[0, DT, 1]	1	
	NN → man	2	[1, NN, 2]	1, 2	
	Vt → saw	3	[2, Vt, 3]	1, 2, 3	
	DT → the	4	[3, DT, 4]	1, 2, 3, 4	
	NN → dog	5	[4, NN, 5]	1, 2, 3, 4, 5	
				2, 3, 4, 5	1
Merge: [1][2]	NP → DT NN	6	[0, NP, 2]	3, 4, 5, 6	2

CKY Example

Input: *the man saw the dog*

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~~VP → Vi~~	Vt → saw
VP → Vt NP	NN → man
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Rule	Condition		Statement	Queue	Passive
Axiom	DT → the	1	[0, DT, 1]	1	
	NN → man	2	[1, NN, 2]	1, 2	
	Vt → saw	3	[2, Vt, 3]	1, 2, 3	
	DT → the	4	[3, DT, 4]	1, 2, 3, 4	
	NN → dog	5	[4, NN, 5]	1, 2, 3, 4, 5	
				2, 3, 4, 5	1
Merge: [1][2]	NP → DT NN	6	[0, NP, 2]	3, 4, 5, 6	2
				4, 5, 6	3

CKY Example

Input: *the man saw the dog*

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Rule	Condition		Statement	Queue	Passive
Axiom	DT → the	1	[0, DT, 1]	1	
	NN → man	2	[1, NN, 2]	1, 2	
	Vt → saw	3	[2, Vt, 3]	1, 2, 3	
	DT → the	4	[3, DT, 4]	1, 2, 3, 4	
	NN → dog	5	[4, NN, 5]	1, 2, 3, 4, 5	
				2, 3, 4, 5	1
Merge: [1][2]	NP → DT NN	6	[0, NP, 2]	3, 4, 5, 6	2
				4, 5, 6	3
				5, 6	4

CKY Example

Input: *the man saw the dog*

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~~VP → Vi~~	Vt → saw
VP → Vt NP	NN → man
VP → VP PP	NN → dog
NP → DT NN	NN → telescope
NP → NP PP	DT → the
PP → IN NP	IN → with

Rule	Condition		Statement	Queue	Passive
Axiom	DT → the	1	[0, DT, 1]	1	
	NN → man	2	[1, NN, 2]	1, 2	
	Vt → saw	3	[2, Vt, 3]	1, 2, 3	
	DT → the	4	[3, DT, 4]	1, 2, 3, 4	
	NN → dog	5	[4, NN, 5]	1, 2, 3, 4, 5	
				2, 3, 4, 5	1
Merge: [1][2]	NP → DT NN	6	[0, NP, 2]	3, 4, 5, 6	2
				4, 5, 6	3
				5, 6	4
Merge: [4][5]	NP → DT NN	7	[3, NP, 5]	6, 7	5

CKY Example

Input: *the man saw the dog*

S → NP VP	Vi → sleeps
~~VP → Vi~~	Vt → saw
VP → Vt NP	NN → man
VP → VP PP	NN → dog
NP → DT NN	NN → telescope
NP → NP PP	DT → the
PP → IN NP	IN → with

Rule	Condition		Statement	Queue	Passive
Axiom	DT → the	1	[0, DT, 1]	1	
	NN → man	2	[1, NN, 2]	1, 2	
	Vt → saw	3	[2, Vt, 3]	1, 2, 3	
	DT → the	4	[3, DT, 4]	1, 2, 3, 4	
	NN → dog	5	[4, NN, 5]	1, 2, 3, 4, 5	
				2, 3, 4, 5	1
Merge: [1][2]	NP → DT NN	6	[0, NP, 2]	3, 4, 5, 6	2
				4, 5, 6	3
				5, 6	4
Merge: [4][5]	NP → DT NN	7	[3, NP, 5]	6, 7	5
				7	6

CKY Example

Input: *the man saw the dog*

S → NP VP	Vi → sleeps
~~VP → Vi~~	Vt → saw
VP → Vt NP	NN → man
VP → VP PP	NN → dog
NP → DT NN	NN → telescope
NP → NP PP	DT → the
PP → IN NP	IN → with

Rule	Condition		Statement	Queue	Passive
Axiom	DT → the	1	[0, DT, 1]	1	
	NN → man	2	[1, NN, 2]	1, 2	
	Vt → saw	3	[2, Vt, 3]	1, 2, 3	
	DT → the	4	[3, DT, 4]	1, 2, 3, 4	
	NN → dog	5	[4, NN, 5]	1, 2, 3, 4, 5	
				2, 3, 4, 5	1
Merge: [1][2]	NP → DT NN	6	[0, NP, 2]	3, 4, 5, 6	2
				4, 5, 6	3
				5, 6	4
Merge: [4][5]	NP → DT NN	7	[3, NP, 5]	6, 7	5
				7	6
Merge: [3] [7]	VP → Vt NP	8	[2, VP, 5]	8	7

CKY Example

Input: *the man saw the dog*

S → NP VP	Vi → sleeps
~~VP → Vi~~	Vt → saw
VP → Vt NP	NN → man
VP → VP PP	NN → dog
NP → DT NN	NN → telescope
NP → NP PP	DT → the
PP → IN NP	IN → with

Rule	Condition		Statement	Queue	Passive
Axiom	DT → the	1	[0, DT, 1]	1	
	NN → man	2	[1, NN, 2]	1, 2	
	Vt → saw	3	[2, Vt, 3]	1, 2, 3	
	DT → the	4	[3, DT, 4]	1, 2, 3, 4	
	NN → dog	5	[4, NN, 5]	1, 2, 3, 4, 5	
				2, 3, 4, 5	1
Merge: [1][2]	NP → DT NN	6	[0, NP, 2]	3, 4, 5, 6	2
				4, 5, 6	3
				5, 6	4
Merge: [4][5]	NP → DT NN	7	[3, NP, 5]	6, 7	5
				7	6
Merge: [3] [7]	VP → Vt NP	8	[2, VP, 5]	8	7
Merge: [6] [8]	S → NP VP	9	[0, S, 5]	9	8

CKY Example

Input: *the man saw the dog*

S → NP VP	Vi → sleeps
~~VP → Vi~~	Vt → saw
VP → Vt NP	NN → man
VP → VP PP	NN → dog
NP → DT NN	NN → telescope
NP → NP PP	DT → the
PP → IN NP	IN → with

Rule	Condition		Statement	Queue	Passive
Axiom	DT → the	1	[0, DT, 1]	1	
	NN → man	2	[1, NN, 2]	1, 2	
	Vt → saw	3	[2, Vt, 3]	1, 2, 3	
	DT → the	4	[3, DT, 4]	1, 2, 3, 4	
	NN → dog	5	[4, NN, 5]	1, 2, 3, 4, 5	
				2, 3, 4, 5	1
Merge: [1][2]	NP → DT NN	6	[0, NP, 2]	3, 4, 5, 6	2
				4, 5, 6	3
				5, 6	4
Merge: [4][5]	NP → DT NN	7	[3, NP, 5]	6, 7	5
				7	6
Merge: [3] [7]	VP → Vt NP	8	[2, VP, 5]	8	7
Merge: [6] [8]	S → NP VP	9	[0, S, 5]	9	8
GOAL: [9]				∅	9

Rule Segmentation: "Split Points"

$_0S_3 \rightarrow {}_0NP_2\ {}_2VP_3$

$_0NP_2 \rightarrow {}_0DT_1\ {}_1NN_2$

$_2VP_3 \rightarrow {}_2Vi_3$

$_0DT_1 \rightarrow$ the

$_1NN_2 \rightarrow$ man

$_2Vi_3 \rightarrow$ sleeps

0 1 2 3

Rule Segmentation: "Split Points"

$_0$the $_1$man $_2$sleeps $_3$

$_0S_3 \rightarrow {}_0NP_2\ {}_2VP_3$

$_0NP_2 \rightarrow {}_0DT_1\ {}_1NN_2$

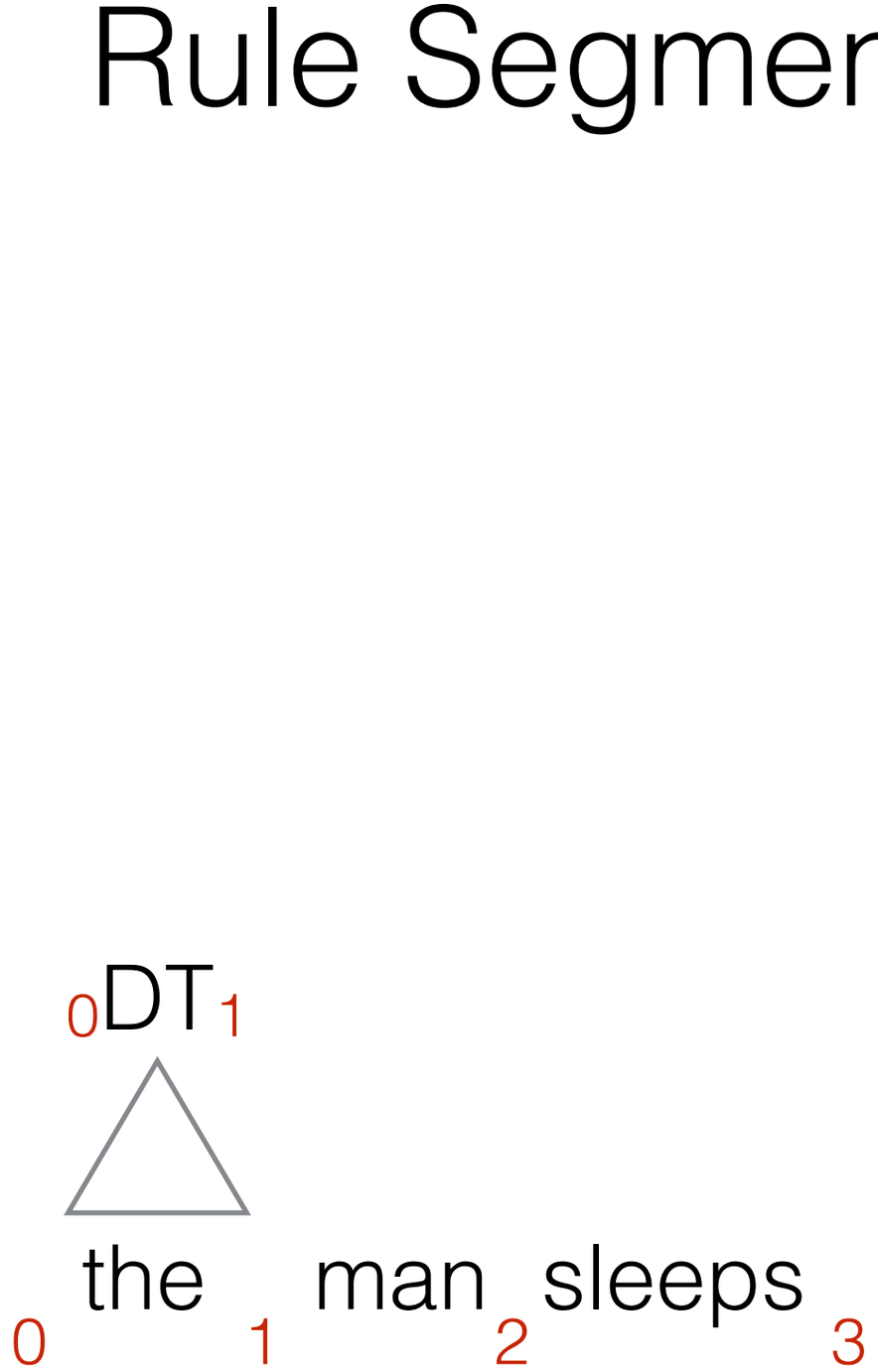
$_2VP_3 \rightarrow {}_2Vi_3$

$_0DT_1 \rightarrow$ the

$_1NN_2 \rightarrow$ man

$_2Vi_3 \rightarrow$ sleeps

Rule Segmentation: "Split Points"



$_0S_3 \rightarrow {}_0NP_2\ {}_2VP_3$

$_0NP_2 \rightarrow {}_0DT_1\ {}_1NN_2$

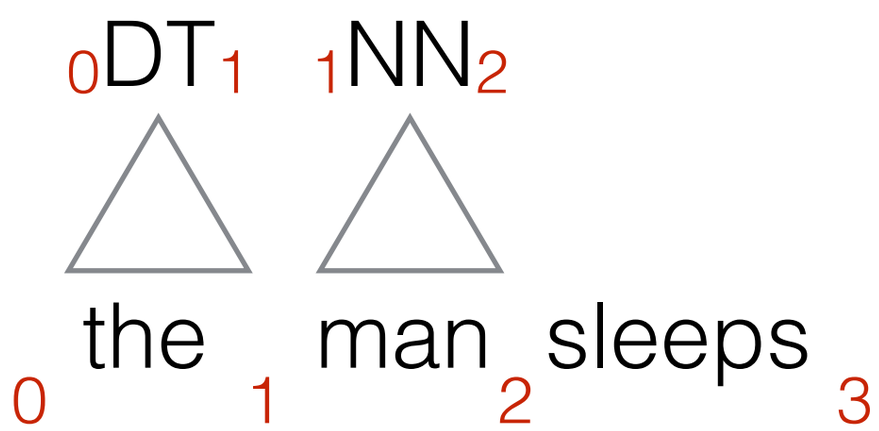
$_2VP_3 \rightarrow {}_2Vi_3$

$_0DT_1 \rightarrow$ the

$_1NN_2 \rightarrow$ man

$_2Vi_3 \rightarrow$ sleeps

Rule Segmentation: "Split Points"



$_0S_3 \rightarrow {}_0NP_2\ {}_2VP_3$

$_0NP_2 \rightarrow {}_0DT_1\ {}_1NN_2$

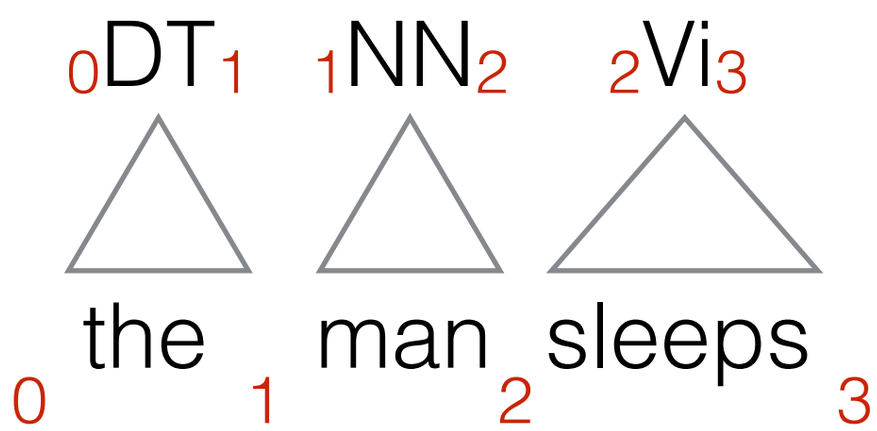
$_2VP_3 \rightarrow {}_2Vi_3$

$_0DT_1 \rightarrow$ the

$_1NN_2 \rightarrow$ man

$_2Vi_3 \rightarrow$ sleeps

Rule Segmentation: "Split Points"



$_0S_3 \rightarrow {}_0NP_2\ {}_2VP_3$

$_0NP_2 \rightarrow {}_0DT_1\ {}_1NN_2$

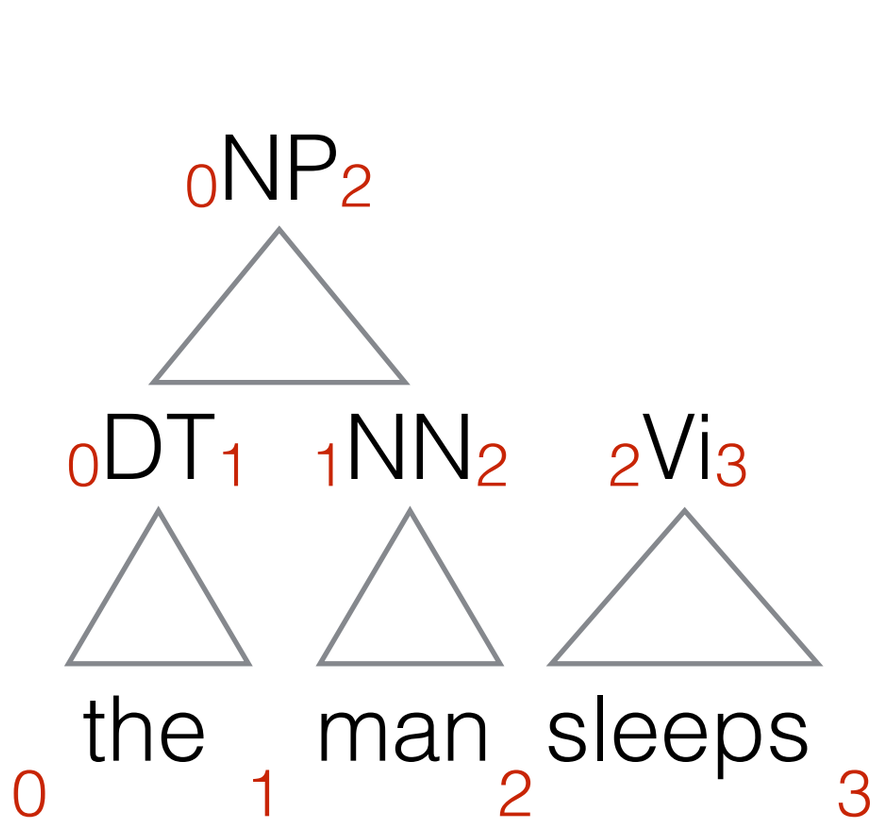
$_2VP_3 \rightarrow {}_2Vi_3$

$_0DT_1 \rightarrow$ the

$_1NN_2 \rightarrow$ man

$_2Vi_3 \rightarrow$ sleeps

Rule Segmentation: "Split Points"



$_0S_3 \rightarrow {}_0NP_2\ {}_2VP_3$

$_0NP_2 \rightarrow {}_0DT_1\ {}_1NN_2$

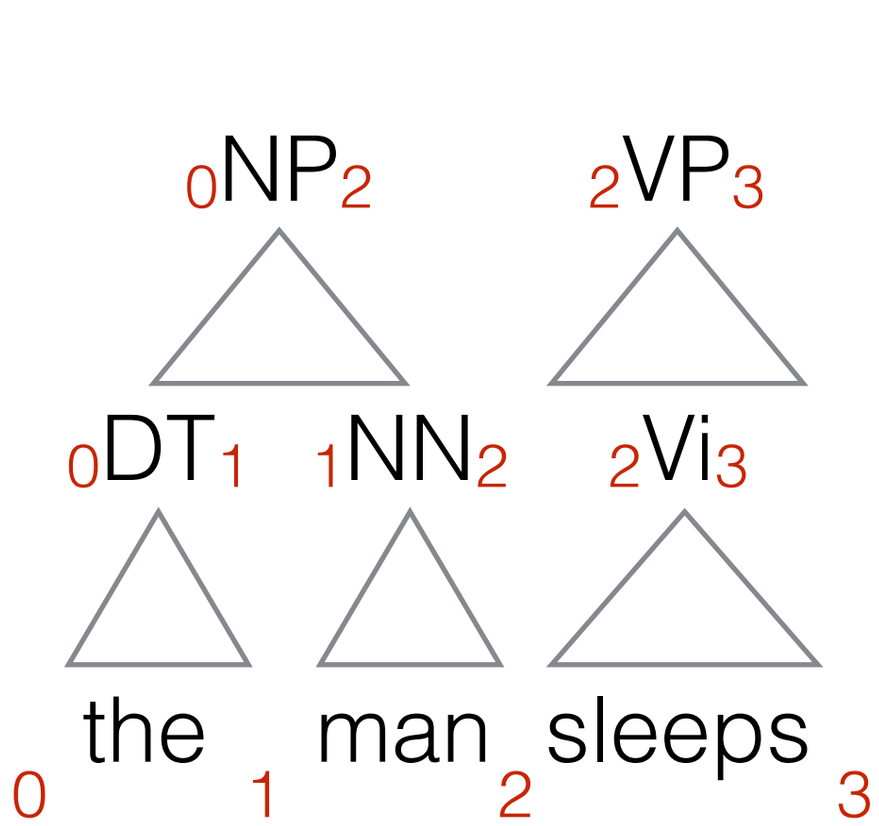
$_2VP_3 \rightarrow {}_2Vi_3$

$_0DT_1 \rightarrow$ the

$_1NN_2 \rightarrow$ man

$_2Vi_3 \rightarrow$ sleeps

Rule Segmentation: "Split Points"



$_0S_3 \rightarrow {}_0NP_2\ {}_2VP_3$

$_0NP_2 \rightarrow {}_0DT_1\ {}_1NN_2$

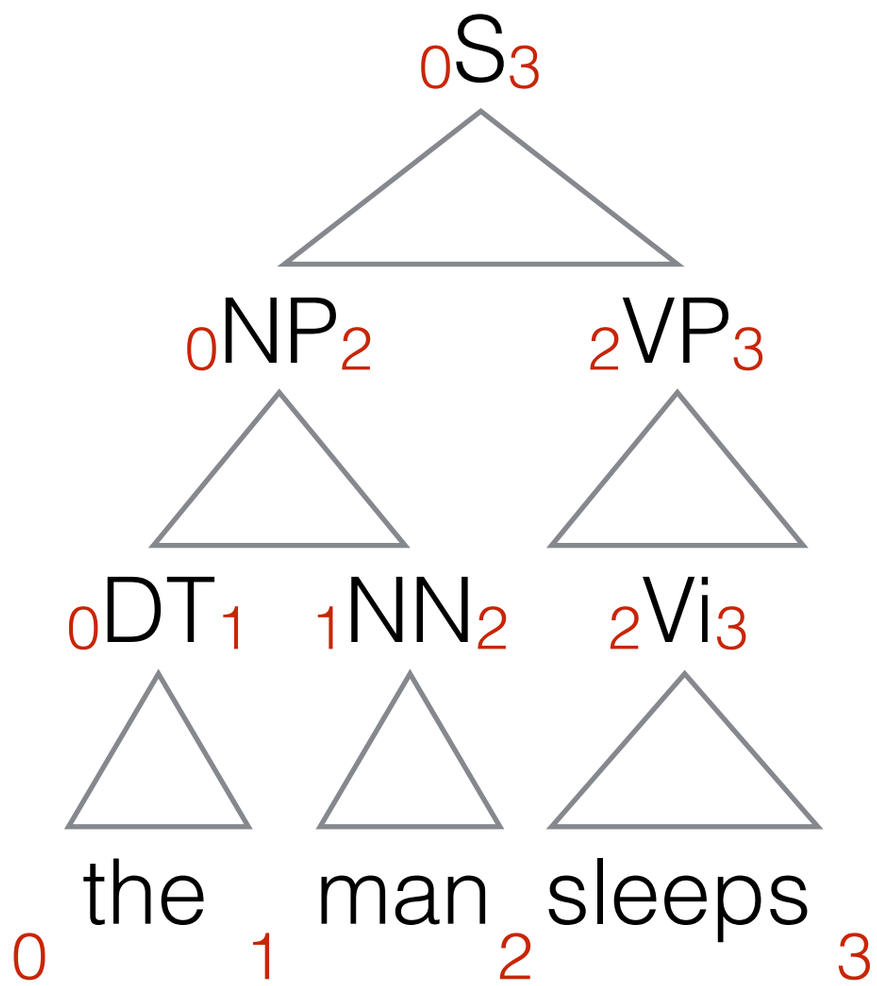
$_2VP_3 \rightarrow {}_2Vi_3$

$_0DT_1 \rightarrow$ the

$_1NN_2 \rightarrow$ man

$_2Vi_3 \rightarrow$ sleeps

Rule Segmentation: "Split Points"



$_0S_3 \rightarrow {}_0NP_2\ {}_2VP_3$

$_0NP_2 \rightarrow {}_0DT_1\ {}_1NN_2$

$_2VP_3 \rightarrow {}_2Vi_3$

$_0DT_1 \rightarrow$ the

$_1NN_2 \rightarrow$ man

$_2Vi_3 \rightarrow$ sleeps

"Dotted items"

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Parsing a CNF grammar is easy because we know the shape of rules

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- In general, we segment rules with respect to the input x_1 ... x_n
- The dot represents progress through the rule's right-hand side (RHS)
- The prefix α has already been parsed and we are waiting for β
- The filled box represents a segmentation of [0 .. j] into |α| adjacent parts
- The empty box has no actual role, it's just a reminder that the segmentation beyond j is unknown

Earley Parser

Input: G and $s = x_1 \ldots x_n$

Item form: $[i, X \rightarrow \alpha\blacksquare\bullet\beta\square, j]$
asserts that $X \Rightarrow^* x_{i+1} \ldots x_j \beta$

Axioms: $[0, S \rightarrow \bullet\, \alpha\square, 0]$ $S \rightarrow \alpha \in \mathscr{R}$

Goal: $[0, S \rightarrow \alpha\blacksquare\, \bullet, n]$

Scan

$$\frac{[i, X \rightarrow \alpha_{\blacksquare}\, \bullet\, x_{j+1}\, \beta_{\square}, j]}{[i, X \rightarrow \alpha_{\blacksquare}\, x_{j+1}\, \bullet\, \beta_{\square}, j+1]}$$

Predict

$$\frac{[i, X \rightarrow \alpha_{\blacksquare}\, \bullet\, Y\, \beta]}{[i, Y \rightarrow \bullet\, \gamma, i]}\ Y \rightarrow \gamma \in \mathcal{R}$$

Complete

$$\frac{[i, X \rightarrow \alpha_{\blacksquare}\, \bullet\, Y\, \beta_{\square}, k][k, Y \rightarrow \gamma_{\blacksquare}\, \bullet, j]}{[i, X \rightarrow \alpha_{\blacksquare}\, Y_{k,j}\, \bullet\, \beta_{\square}, j]}$$

Earley Example

Input: *the man sleeps*

S → NP VP	Vi → sleeps
VP → Vi	Vt → saw
VP → Vt NP	NN → man
~~VP → VP PP~~	NN → dog
NP → DT NN	NN → telescope
NP → NP PP	DT → the
PP → IN NP	IN → with

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Rule	Condition	Item	Active	Passive

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Rule	Condition		Item	Active	Passive
Axiom	S → NP VP	1	[0, S → •NP VP, 0]	1	

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Axiom	S → NP VP	1	[0, S → •NP VP, 0]	1	
Predict: [1]	NP → DT NN	2	[0, NP → • DT NN, 0]	2	1

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Rule	Condition		Item	Active	Passive
Axiom	S → NP VP	1	[0, S → •NP VP, 0]	1	
Predict: [1]	NP → DT NN	2	[0, NP → • DT NN, 0]	2	1
Predict: [2]	DT → the	3	[0, DT → • the, 0]	3	2

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Axiom	S → NP VP	1	[0, S → •NP VP, 0]	1	
Predict: [1]	NP → DT NN	2	[0, NP → • DT NN, 0]	2	1
Predict: [2]	DT → the	3	[0, DT → • the, 0]	3	2
Scan: [3]		4	[0, DT→ the •, 1]	4	3

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Axiom	S → NP VP	1	[0, S → •NP VP, 0]	1	
Predict: [1]	NP → DT NN	2	[0, NP → • DT NN, 0]	2	1
Predict: [2]	DT → the	3	[0, DT → • the, 0]	3	2
Scan: [3]		4	[0, DT→ the •, 1]	4	3
Complete: [4] [2]		5	[0, NP → $DT_{0,1}$ • NN, 1]	5	4

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Rule	Condition		Item	Active	Passive
Axiom	S → NP VP	1	[0, S → •NP VP, 0]	1	
Predict: [1]	NP → DT NN	2	[0, NP → • DT NN, 0]	2	1
Predict: [2]	DT → the	3	[0, DT → • the, 0]	3	2
Scan: [3]		4	[0, DT→ the •, 1]	4	3
Complete: [4] [2]		5	[0, NP → $DT_{0,1}$ • NN, 1]	5	4
Predict: [5]	NN → man	6	[1, NN → • man, 1]	6	5

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Rule	Condition		Item	Active	Passive
Axiom	S → NP VP	1	[0, S → •NP VP, 0]	1	
Predict: [1]	NP → DT NN	2	[0, NP → • DT NN, 0]	2	1
Predict: [2]	DT → the	3	[0, DT → • the, 0]	3	2
Scan: [3]		4	[0, DT→ the •, 1]	4	3
Complete: [4] [2]		5	[0, NP → $DT_{0,1}$ • NN, 1]	5	4
Predict: [5]	NN → man	6	[1, NN → • man, 1]	6	5
Scan: [6]		7	[1, NN → man •, 2]	7	6

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Axiom	S → NP VP	1	[0, S → •NP VP, 0]	1	
Predict: [1]	NP → DT NN	2	[0, NP → • DT NN, 0]	2	1
Predict: [2]	DT → the	3	[0, DT → • the, 0]	3	2
Scan: [3]		4	[0, DT→ the •, 1]	4	3
Complete: [4] [2]		5	[0, NP → $DT_{0,1}$ • NN, 1]	5	4
Predict: [5]	NN → man	6	[1, NN → • man, 1]	6	5
Scan: [6]		7	[1, NN → man •, 2]	7	6
Complete: [7] [5]		8	[0, NP → $DT_{0,1}$ $NN_{1,2}$ •, 2]	8	7

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Axiom	S → NP VP	1	[0, S → •NP VP, 0]	1	
Predict: [1]	NP → DT NN	2	[0, NP → • DT NN, 0]	2	1
Predict: [2]	DT → the	3	[0, DT → • the, 0]	3	2
Scan: [3]		4	[0, DT→ the •, 1]	4	3
Complete: [4] [2]		5	[0, NP → $DT_{0,1}$ • NN, 1]	5	4
Predict: [5]	NN → man	6	[1, NN → • man, 1]	6	5
Scan: [6]		7	[1, NN → man •, 2]	7	6
Complete: [7] [5]		8	[0, NP → $DT_{0,1}$ $NN_{1,2}$ •, 2]	8	7
Complete: [8] [1]		9	[0, S → $NP_{0,2}$ • VP, 2]	9	8

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Axiom	S → NP VP	1	[0, S → •NP VP, 0]	1	
Predict: [1]	NP → DT NN	2	[0, NP → • DT NN, 0]	2	1
Predict: [2]	DT → the	3	[0, DT → • the, 0]	3	2
Scan: [3]		4	[0, DT→ the •, 1]	4	3
Complete: [4] [2]		5	[0, NP → $DT_{0,1}$ • NN, 1]	5	4
Predict: [5]	NN → man	6	[1, NN → • man, 1]	6	5
Scan: [6]		7	[1, NN → man •, 2]	7	6
Complete: [7] [5]		8	[0, NP → $DT_{0,1}$ $NN_{1,2}$ •, 2]	8	7
Complete: [8] [1]		9	[0, S → $NP_{0,2}$ • VP, 2]	9	8
Predict: [9]	VP → Vi	10	[2, VP → • Vi, 2]	10	9

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Rule	Condition		Item	Active	Passive
Axiom	S → NP VP	1	[0, S → •NP VP, 0]	1	
Predict: [1]	NP → DT NN	2	[0, NP → • DT NN, 0]	2	1
Predict: [2]	DT → the	3	[0, DT → • the, 0]	3	2
Scan: [3]		4	[0, DT→ the •, 1]	4	3
Complete: [4] [2]		5	[0, NP → $DT_{0,1}$ • NN, 1]	5	4
Predict: [5]	NN → man	6	[1, NN → • man, 1]	6	5
Scan: [6]		7	[1, NN → man •, 2]	7	6
Complete: [7] [5]		8	[0, NP → $DT_{0,1}$ $NN_{1,2}$ •, 2]	8	7
Complete: [8] [1]		9	[0, S → $NP_{0,2}$ • VP, 2]	9	8
Predict: [9]	VP → Vi	10	[2, VP → • Vi, 2]	10	9
	VP → Vt NP	11	[2, VP → • Vt NP, 2]	10, 11	

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Axiom	S → NP VP	1	[0, S → •NP VP, 0]	1	
Predict: [1]	NP → DT NN	2	[0, NP → • DT NN, 0]	2	1
Predict: [2]	DT → the	3	[0, DT → • the, 0]	3	2
Scan: [3]		4	[0, DT→ the •, 1]	4	3
Complete: [4] [2]		5	[0, NP → $DT_{0,1}$ • NN, 1]	5	4
Predict: [5]	NN → man	6	[1, NN → • man, 1]	6	5
Scan: [6]		7	[1, NN → man •, 2]	7	6
Complete: [7] [5]		8	[0, NP → $DT_{0,1}$ $NN_{1,2}$ •, 2]	8	7
Complete: [8] [1]		9	[0, S → $NP_{0,2}$ • VP, 2]	9	8
Predict: [9]	VP → Vi	10	[2, VP → • Vi, 2]	10	9
	VP → Vt NP	11	[2, VP → • Vt NP, 2]	10, 11	
Predict: [10]	Vi → sleeps	12	[2, Vi → • sleeps, 2]	11, 12	10

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Rule	Condition		Item	Active	Passive
Axiom	S → NP VP	1	[0, S → •NP VP, 0]	1	
Predict: [1]	NP → DT NN	2	[0, NP → • DT NN, 0]	2	1
Predict: [2]	DT → the	3	[0, DT → • the, 0]	3	2
Scan: [3]		4	[0, DT→ the •, 1]	4	3
Complete: [4] [2]		5	[0, NP → $DT_{0,1}$ • NN, 1]	5	4
Predict: [5]	NN → man	6	[1, NN → • man, 1]	6	5
Scan: [6]		7	[1, NN → man •, 2]	7	6
Complete: [7] [5]		8	[0, NP → $DT_{0,1}$ $NN_{1,2}$ •, 2]	8	7
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Predict: [10]	Vi → sleeps	12	[2, Vi → • sleeps, 2]	11, 12	10
Predict: [11]	Vt → saw	13	[2, Vt → • saw, 2]	12, 13	11

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Rule	Condition		Item	Active	Passive
Axiom	S → NP VP	1	[0, S → •NP VP, 0]	1	
Predict: [1]	NP → DT NN	2	[0, NP → • DT NN, 0]	2	1
Predict: [2]	DT → the	3	[0, DT → • the, 0]	3	2
Scan: [3]		4	[0, DT→ the •, 1]	4	3
Complete: [4] [2]		5	[0, NP → $DT_{0,1}$ • NN, 1]	5	4
Predict: [5]	NN → man	6	[1, NN → • man, 1]	6	5
Scan: [6]		7	[1, NN → man •, 2]	7	6
Complete: [7] [5]		8	[0, NP → $DT_{0,1}$ $NN_{1,2}$ •, 2]	8	7
Complete: [8] [1]		9	[0, S → $NP_{0,2}$ • VP, 2]	9	8
Predict: [9]	VP → Vi	10	[2, VP → • Vi, 2]	10	9
	VP → Vt NP	11	[2, VP → • Vt NP, 2]	10, 11	
Predict: [10]	Vi → sleeps	12	[2, Vi → • sleeps, 2]	11, 12	10
Predict: [11]	Vt → saw	13	[2, Vt → • saw, 2]	12, 13	11
Scan: [12]		14	[2, Vi → sleeps •, 3]	13, 14	12

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Rule	Condition		Item	Active	Passive
Axiom	S → NP VP	1	[0, S → •NP VP, 0]	1	
Predict: [1]	NP → DT NN	2	[0, NP → • DT NN, 0]	2	1
Predict: [2]	DT → the	3	[0, DT → • the, 0]	3	2
Scan: [3]		4	[0, DT→ the •, 1]	4	3
Complete: [4] [2]		5	[0, NP → $DT_{0,1}$ • NN, 1]	5	4
Predict: [5]	NN → man	6	[1, NN → • man, 1]	6	5
Scan: [6]		7	[1, NN → man •, 2]	7	6
Complete: [7] [5]		8	[0, NP → $DT_{0,1}$ $NN_{1,2}$ •, 2]	8	7
Complete: [8] [1]		9	[0, S → $NP_{0,2}$ • VP, 2]	9	8
Predict: [9]	VP → Vi	10	[2, VP → • Vi, 2]	10	9
	VP → Vt NP	11	[2, VP → • Vt NP, 2]	10, 11	
Predict: [10]	Vi → sleeps	12	[2, Vi → • sleeps, 2]	11, 12	10
Predict: [11]	Vt → saw	13	[2, Vt → • saw, 2]	12, 13	11
Scan: [12]		14	[2, Vi → sleeps •, 3]	13, 14	12
Dead end for [13]				14	13

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Rule	Condition		Item	Active	Passive
Axiom	S → NP VP	1	[0, S → •NP VP, 0]	1	
Predict: [1]	NP → DT NN	2	[0, NP → • DT NN, 0]	2	1
Predict: [2]	DT → the	3	[0, DT → • the, 0]	3	2
Scan: [3]		4	[0, DT→ the •, 1]	4	3
Complete: [4] [2]		5	[0, NP → $DT_{0,1}$ • NN, 1]	5	4
Predict: [5]	NN → man	6	[1, NN → • man, 1]	6	5
Scan: [6]		7	[1, NN → man •, 2]	7	6
Complete: [7] [5]		8	[0, NP → $DT_{0,1}$ $NN_{1,2}$ •, 2]	8	7
Complete: [8] [1]		9	[0, S → $NP_{0,2}$ • VP, 2]	9	8
Predict: [9]	VP → Vi	10	[2, VP → • Vi, 2]	10	9
	VP → Vt NP	11	[2, VP → • Vt NP, 2]	10, 11	
Predict: [10]	Vi → sleeps	12	[2, Vi → • sleeps, 2]	11, 12	10
Predict: [11]	Vt → saw	13	[2, Vt → • saw, 2]	12, 13	11
Scan: [12]		14	[2, Vi → sleeps •, 3]	13, 14	12
Dead end for [13]				14	13
Complete: [14] [10]		15	[2, VP → Vi •, 3]	15	14

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Rule	Condition		Item	Active	Passive
Axiom	S → NP VP	1	[0, S → •NP VP, 0]	1	
Predict: [1]	NP → DT NN	2	[0, NP → • DT NN, 0]	2	1
Predict: [2]	DT → the	3	[0, DT → • the, 0]	3	2
Scan: [3]		4	[0, DT→ the •, 1]	4	3
Complete: [4] [2]		5	[0, NP → $DT_{0,1}$ • NN, 1]	5	4
Predict: [5]	NN → man	6	[1, NN → • man, 1]	6	5
Scan: [6]		7	[1, NN → man •, 2]	7	6
Complete: [7] [5]		8	[0, NP → $DT_{0,1}$ $NN_{1,2}$ •, 2]	8	7
Complete: [8] [1]		9	[0, S → $NP_{0,2}$ • VP, 2]	9	8
Predict: [9]	VP → Vi	10	[2, VP → • Vi, 2]	10	9
	VP → Vt NP	11	[2, VP → • Vt NP, 2]	10, 11	
Predict: [10]	Vi → sleeps	12	[2, Vi → • sleeps, 2]	11, 12	10
Predict: [11]	Vt → saw	13	[2, Vt → • saw, 2]	12, 13	11
Scan: [12]		14	[2, Vi → sleeps •, 3]	13, 14	12
Dead end for [13]				14	13
Complete: [14] [10]		15	[2, VP → Vi •, 3]	15	14
Complete: [15] [9]		16	[0, S → $NP_{0,2}$ $VP_{2,3}$ •, 3]	16	15

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Rule	Condition		Item	Active	Passive
Axiom	S → NP VP	1	[0, S → •NP VP, 0]	1	
Predict: [1]	NP → DT NN	2	[0, NP → • DT NN, 0]	2	1
Predict: [2]	DT → the	3	[0, DT → • the, 0]	3	2
Scan: [3]		4	[0, DT→ the •, 1]	4	3
Complete: [4] [2]		5	[0, NP → $DT_{0,1}$ • NN, 1]	5	4
Predict: [5]	NN → man	6	[1, NN → • man, 1]	6	5
Scan: [6]		7	[1, NN → man •, 2]	7	6
Complete: [7] [5]		8	[0, NP → $DT_{0,1}$ $NN_{1,2}$ •, 2]	8	7
Complete: [8] [1]		9	[0, S → $NP_{0,2}$ • VP, 2]	9	8
Predict: [9]	VP → Vi	10	[2, VP → • Vi, 2]	10	9
	VP → Vt NP	11	[2, VP → • Vt NP, 2]	10, 11	
Predict: [10]	Vi → sleeps	12	[2, Vi → • sleeps, 2]	11, 12	10
Predict: [11]	Vt → saw	13	[2, Vt → • saw, 2]	12, 13	11
Scan: [12]		14	[2, Vi → sleeps •, 3]	13, 14	12
Dead end for [13]				14	13
Complete: [14] [10]		15	[2, VP → Vi •, 3]	15	14
Complete: [15] [9]		16	[0, S → $NP_{0,2}$ $VP_{2,3}$ •, 3]	16	15
Goal: [16]					

Correctness of Parsing Strategy

Soundness: if a goal item is proven for α

- then $\omega \in L(G)$

Completeness: if $\alpha \in L(G)$

- then a goal item can be proven for α

Parse Forest

Efficient representation of the whole space $T_G(\omega)$

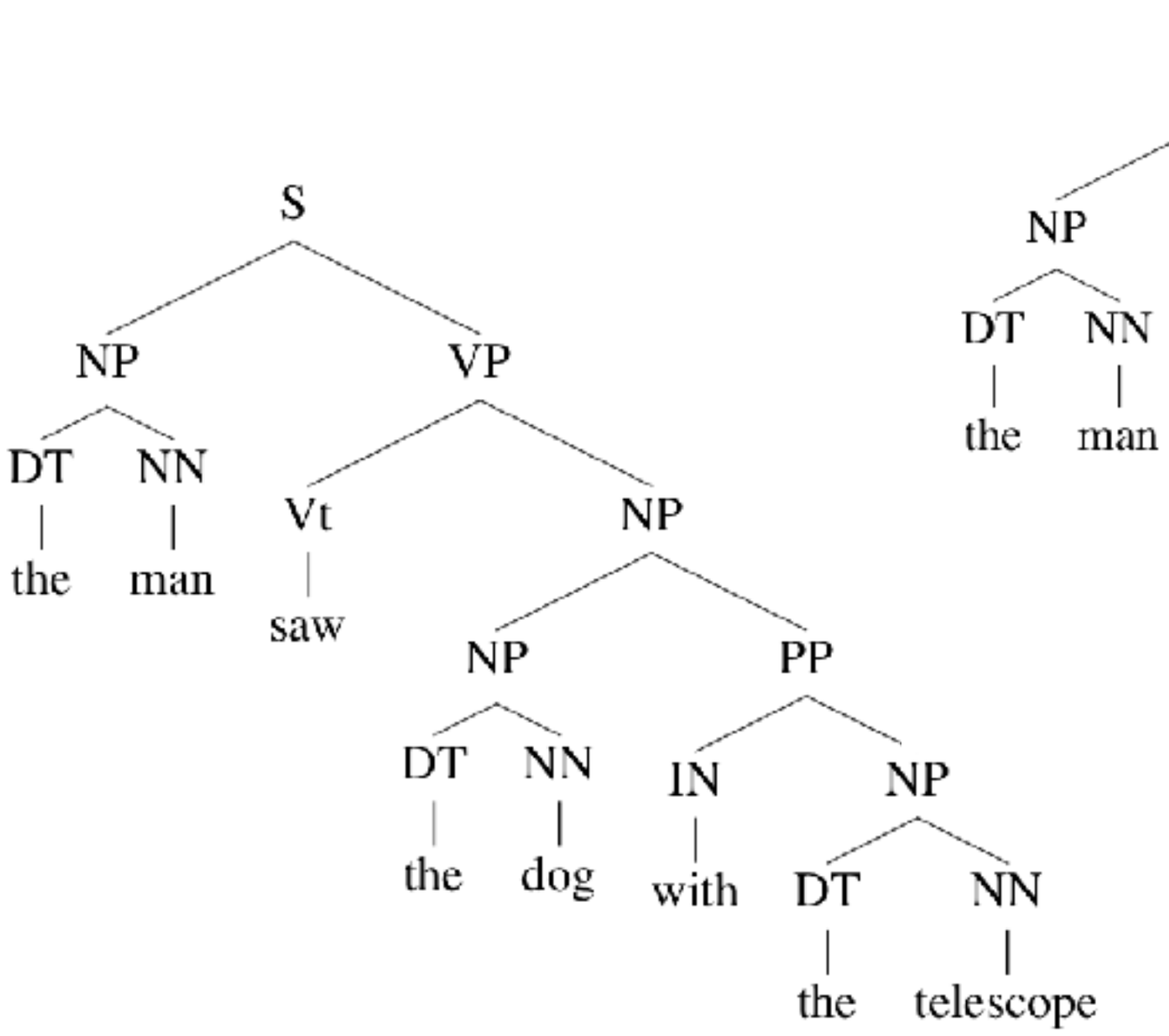
- each and every possible tree yielding ω

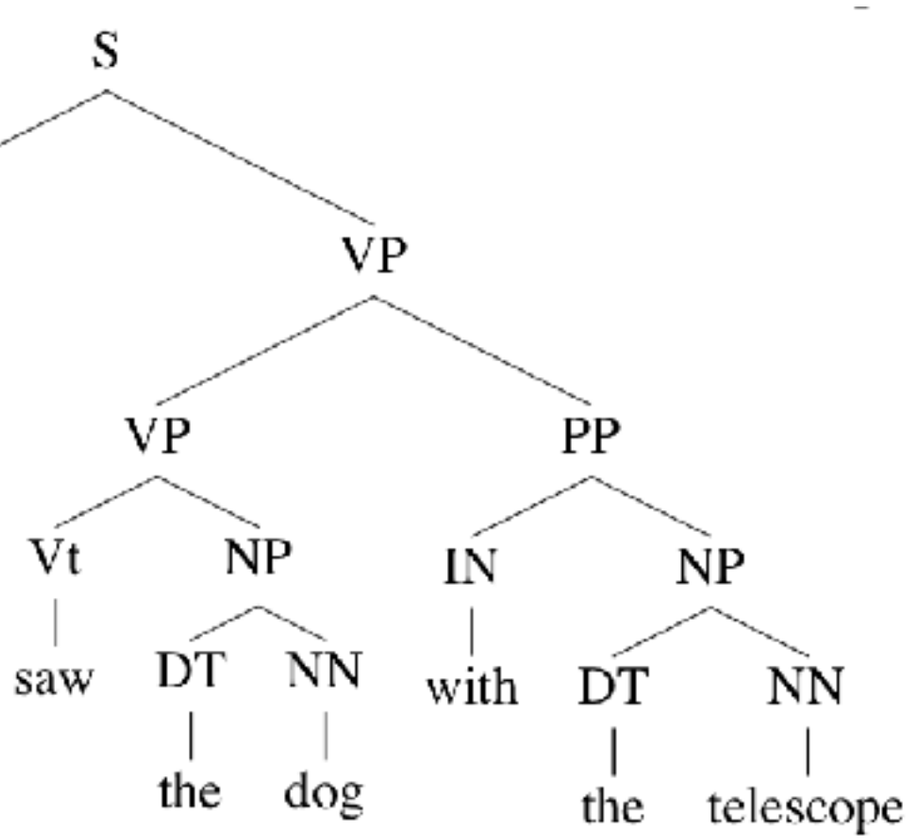
We must be able to represent partial derivations

- including alternative ones

Ambiguity

Some strings may have more than one derivation in G





Dealing with Ambiguity

Statistical model: weight steps in a derivation

- induces a partial ordering over derivations
- can be used to make a decision
  - e.g. best tree under the model

Probabilistic CFG

CFG extended with parameters $0 \leq \theta_r \leq 1$

- where $r \in \mathscr{R}$ and

$$\sum_{\alpha : X \to \alpha \in R} \theta_{X \to \alpha} = 1$$

Probabilistic CFG

Distribution over trees and their yields

$$P_{DS|NM}(R_1^m = r_1^m, X_1^n = \text{yield}(r_1^m)|n, m)$$

$$= \prod_{i=1}^{m} \theta_{r_i} = \prod_{i=1}^{m} \theta_{v_i \to \beta_i}$$

where r_i corresponds to $v_i \to \beta_i$

Joint Distribution

$_0S_3 \rightarrow {}_0NP_2\ {}_2VP_3$

$_0NP_2 \rightarrow {}_0DT_1\ {}_1NN_2$

$_2VP_3 \rightarrow {}_2Vi_3$

$_0DT_1 \rightarrow$ the

$_1NN_2 \rightarrow$ man

$_2Vi_3 \rightarrow$ sleeps

Joint Distribution

$_0S_3 \rightarrow {}_0NP_2\ {}_2VP_3$

$_0NP_2 \rightarrow {}_0DT_1\ {}_1NN_2$

$_2VP_3 \rightarrow {}_2Vi_3$

$_0DT_1 \rightarrow$ the

$_1NN_2 \rightarrow$ man

$_2Vi_3 \rightarrow$ sleeps

the man sleeps

Joint Distribution

$_0S_3 \rightarrow {}_0NP_2\ {}_2VP_3$

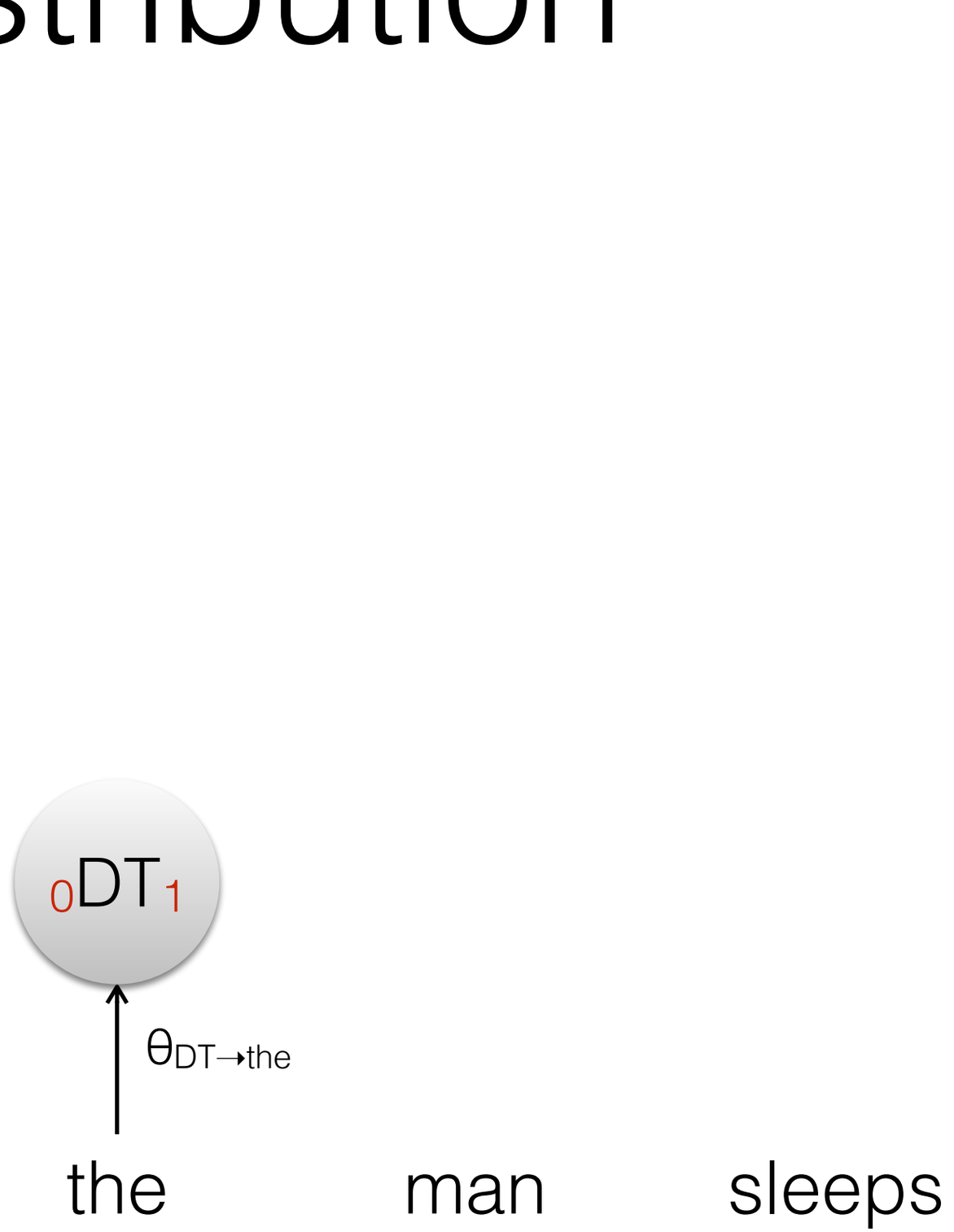
$_0NP_2 \rightarrow {}_0DT_1\ {}_1NN_2$

$_2VP_3 \rightarrow {}_2Vi_3$

$_0DT_1 \rightarrow$ the

$_1NN_2 \rightarrow$ man

$_2Vi_3 \rightarrow$ sleeps



Joint Distribution

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$_0NP_2 \rightarrow {}_0DT_1\ {}_1NN_2$

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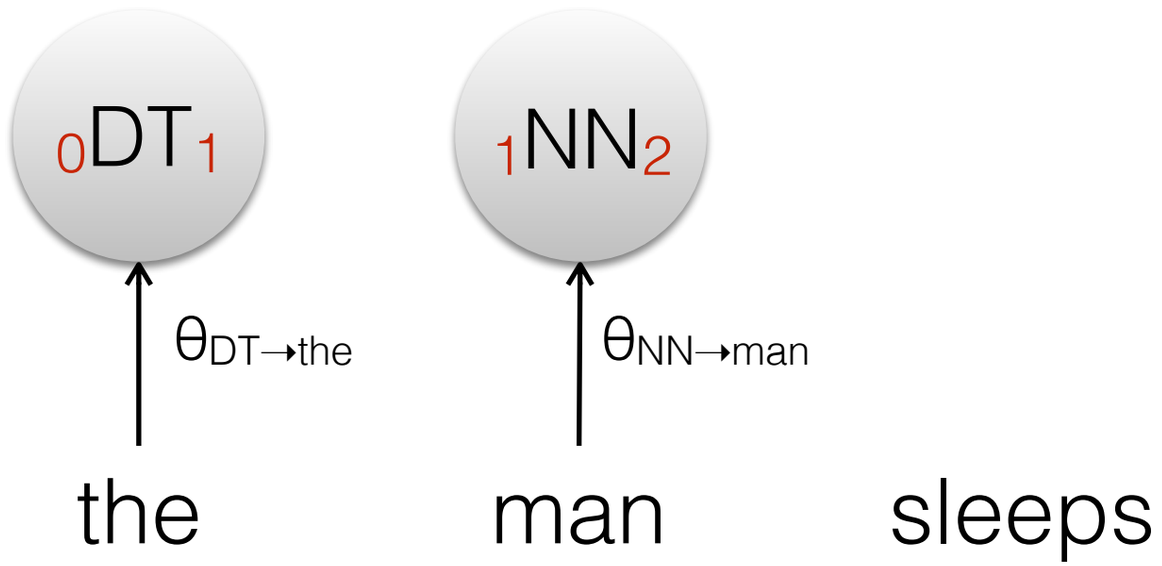
$_0DT_1 \rightarrow$ the

$_1NN_2 \rightarrow$ man

$_2Vi_3 \rightarrow$ sleeps



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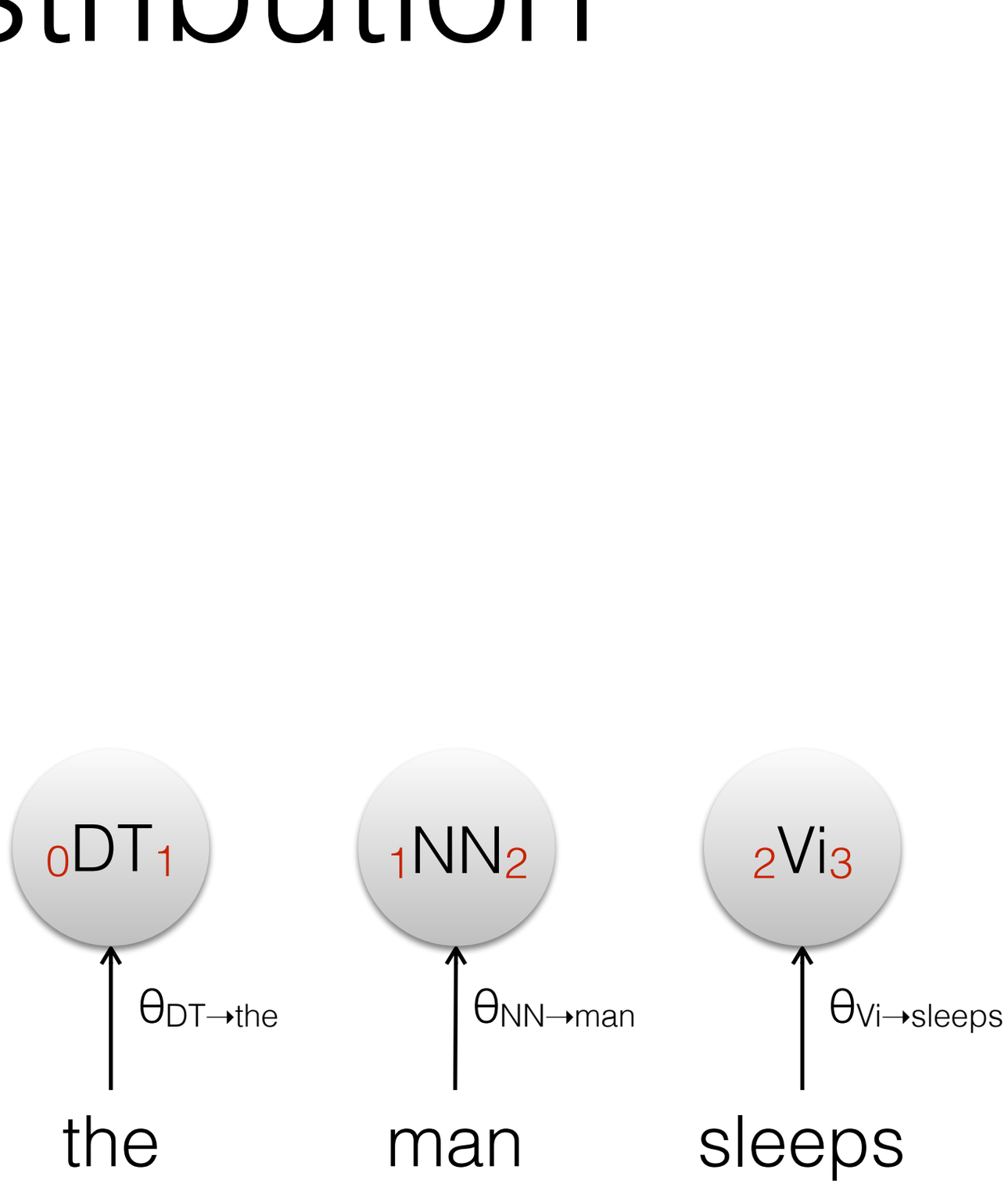
$_0DT_1 \rightarrow$ the

$_1NN_2 \rightarrow$ man

$_2Vi_3 \rightarrow$ sleeps



Joint Distribution

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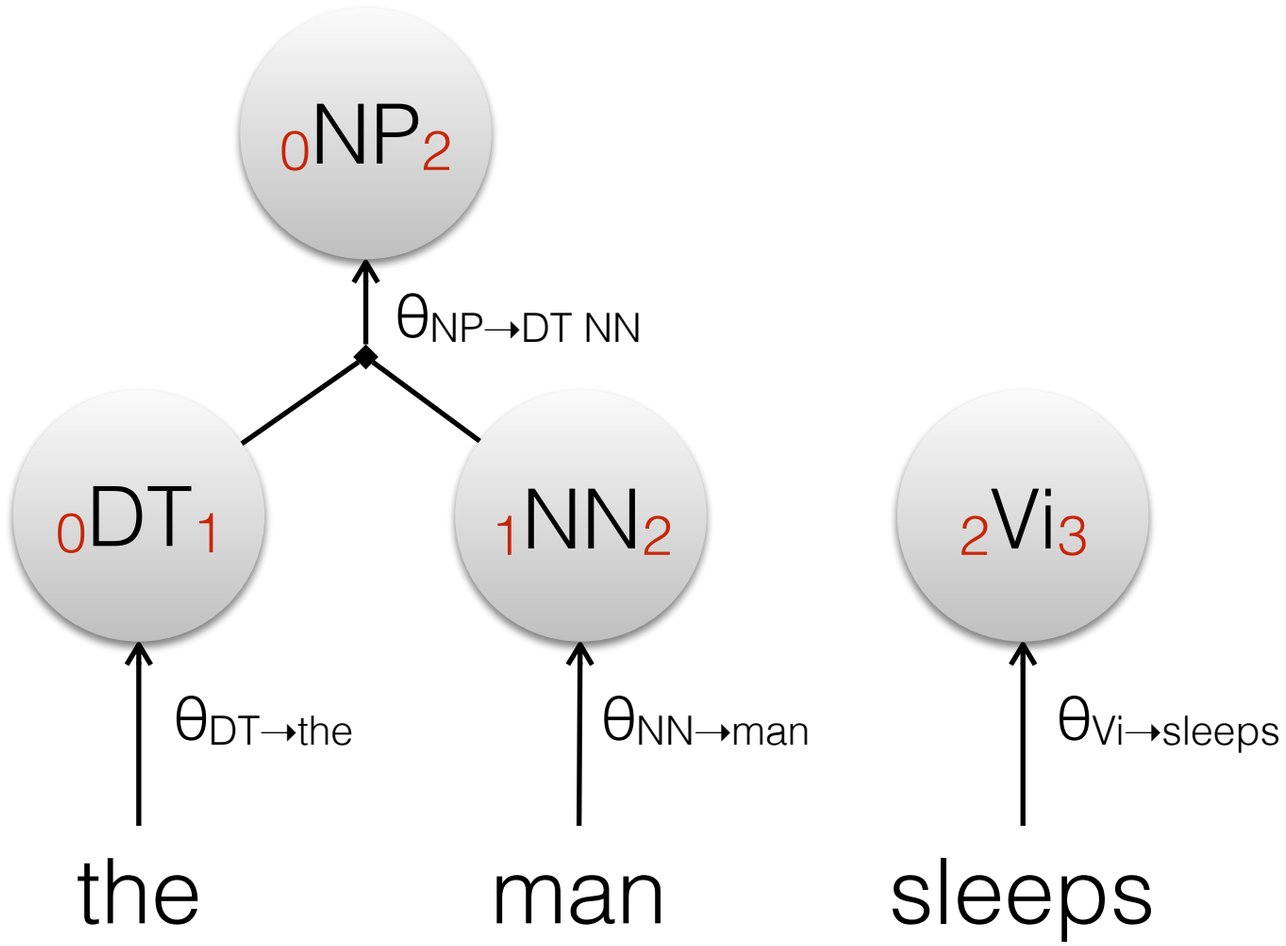
$_0NP_2 \rightarrow {}_0DT_1\ {}_1NN_2$

$_2VP_3 \rightarrow {}_2Vi_3$

$_0DT_1 \rightarrow$ the

$_1NN_2 \rightarrow$ man

$_2Vi_3 \rightarrow$ sleeps



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$_1NN_2 \rightarrow$ man

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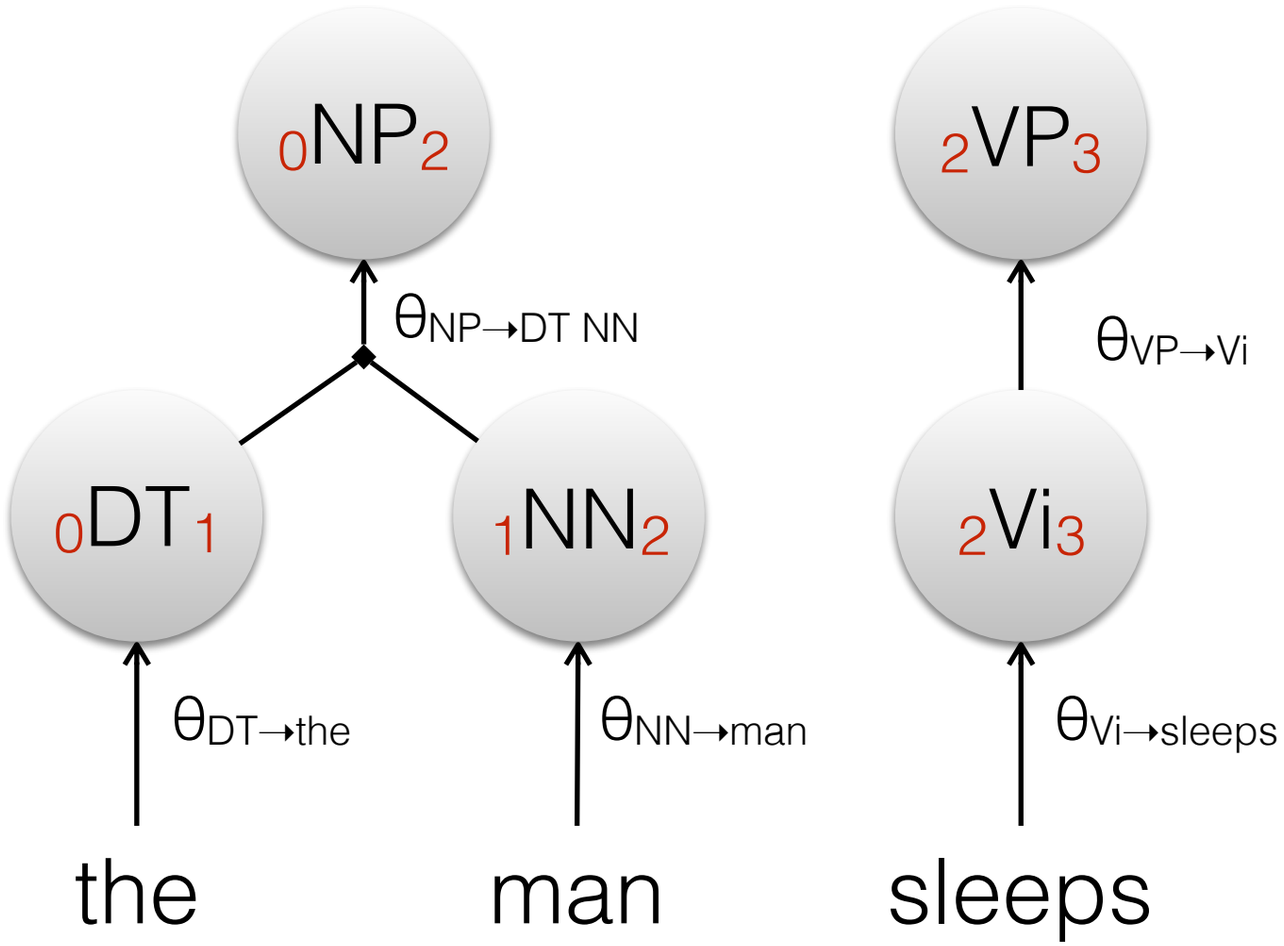

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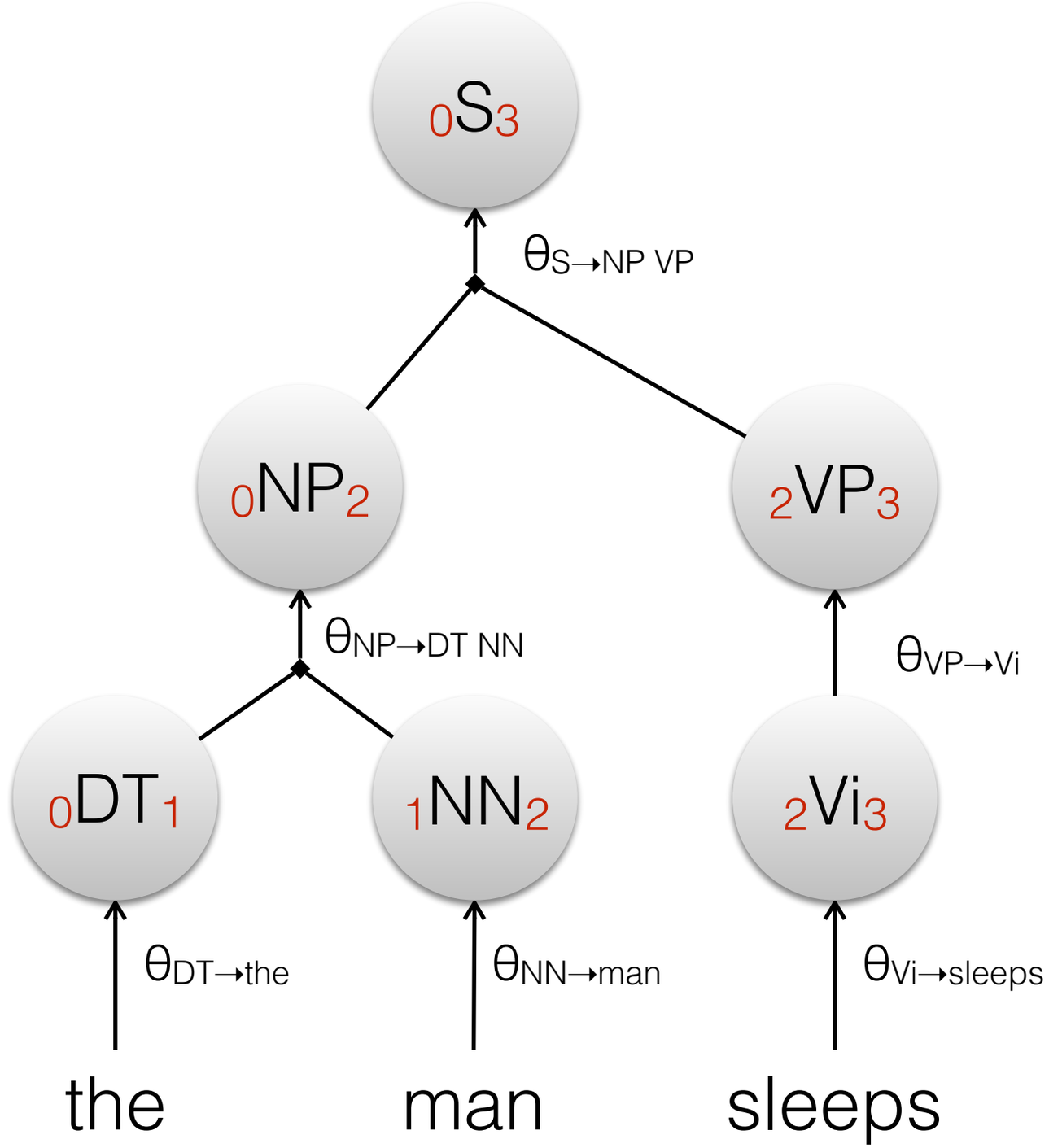
$_0DT_1 \rightarrow$ the

$_1NN_2 \rightarrow$ man

$_2Vi_3 \rightarrow$ sleeps

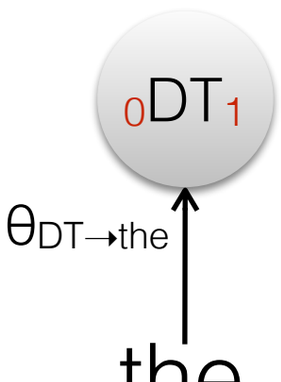


Ambiguity

Ambiguity

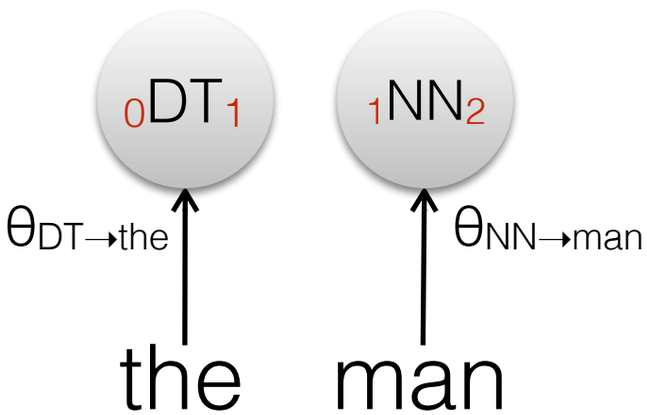
the man saw the dog with the telescope

Ambiguity



the man saw the dog with the telescope

Ambiguity

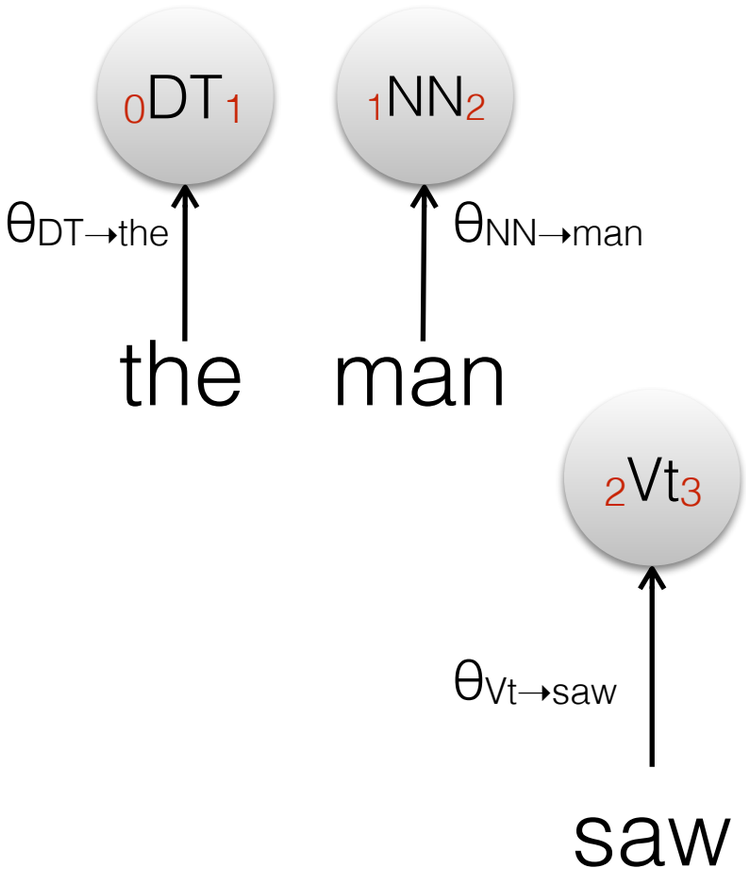


saw

the dog

with the telescope

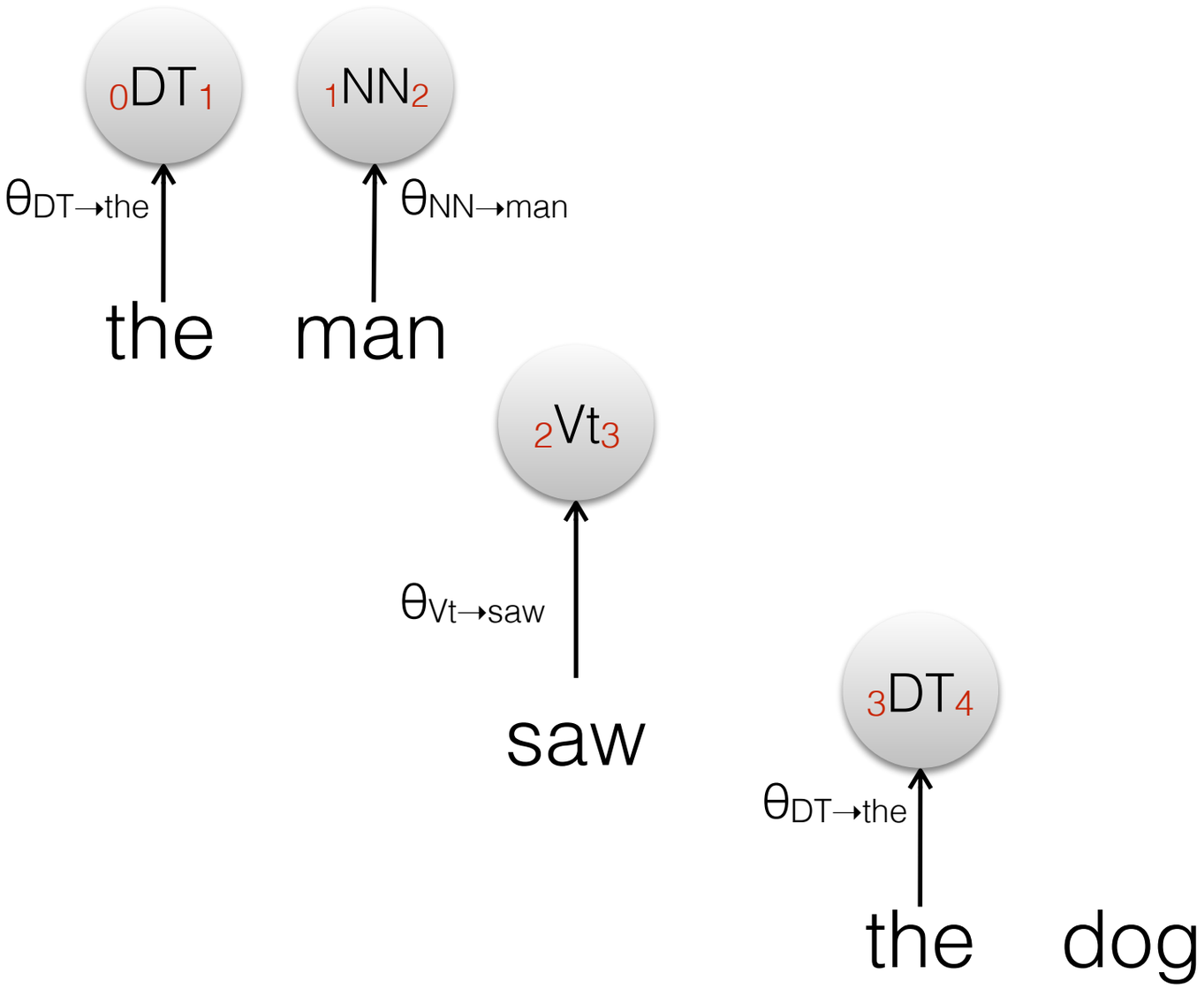
Ambiguity



the dog

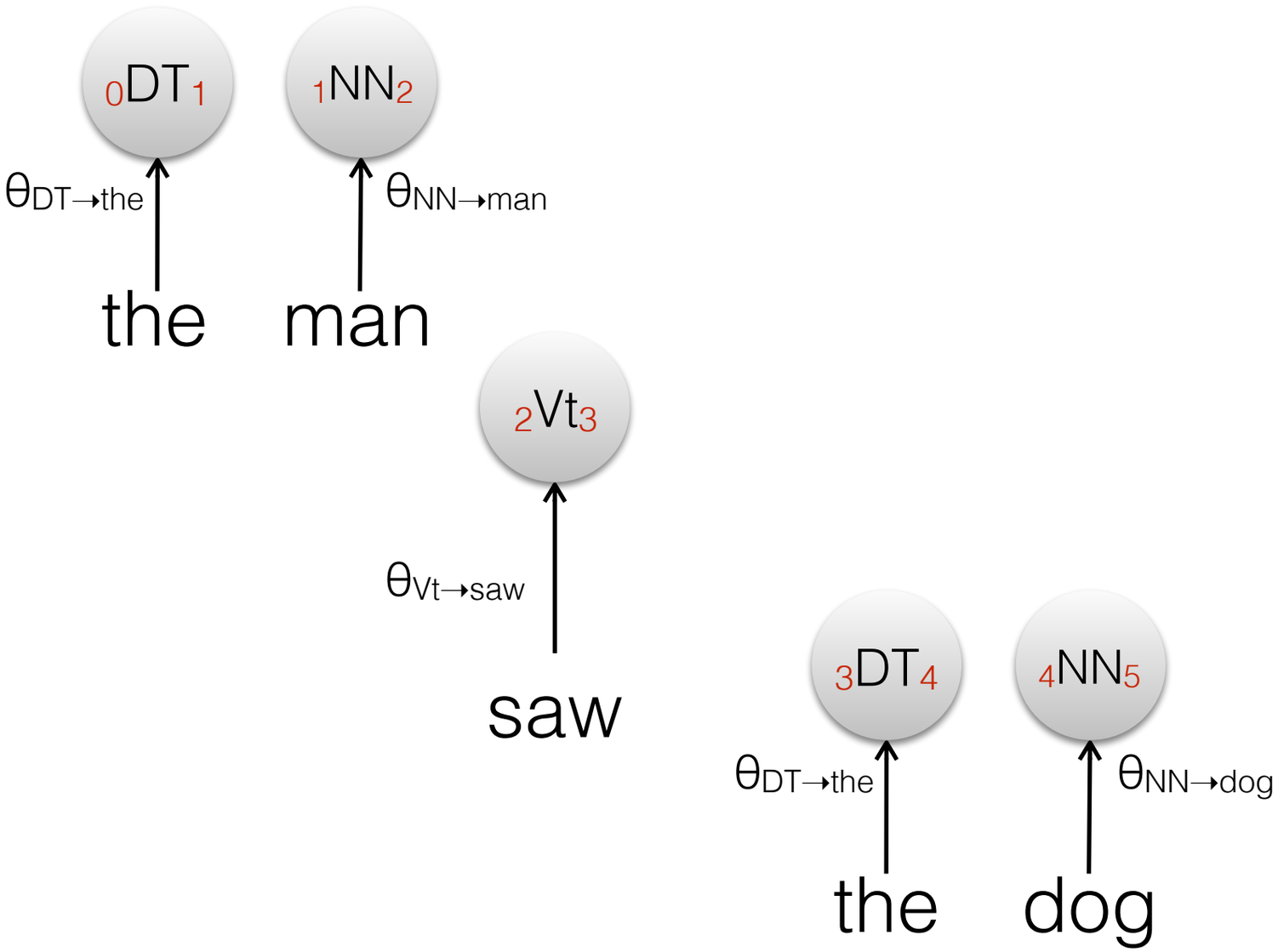
with the telescope

Ambiguity



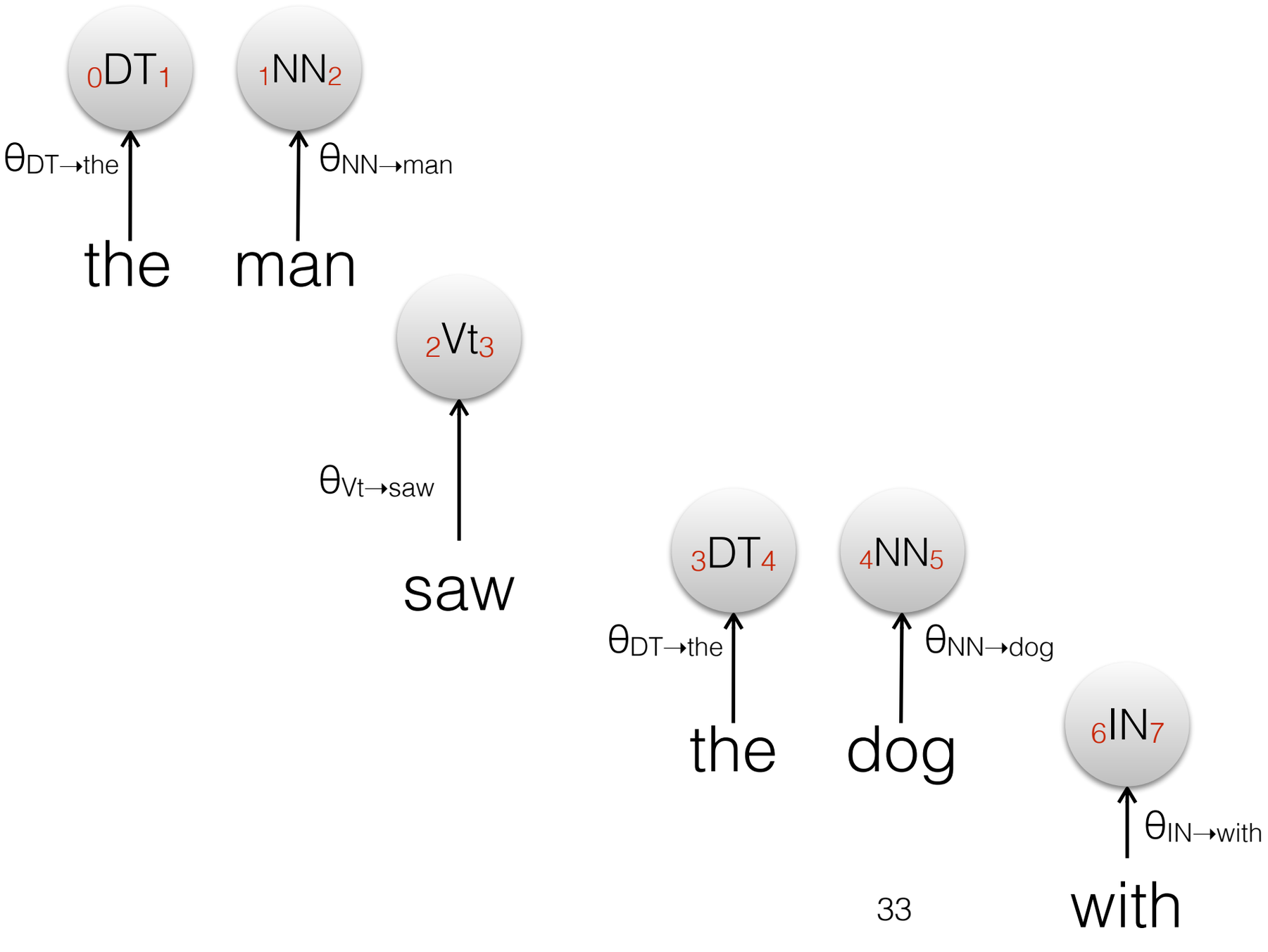
with the telescope

Ambiguity

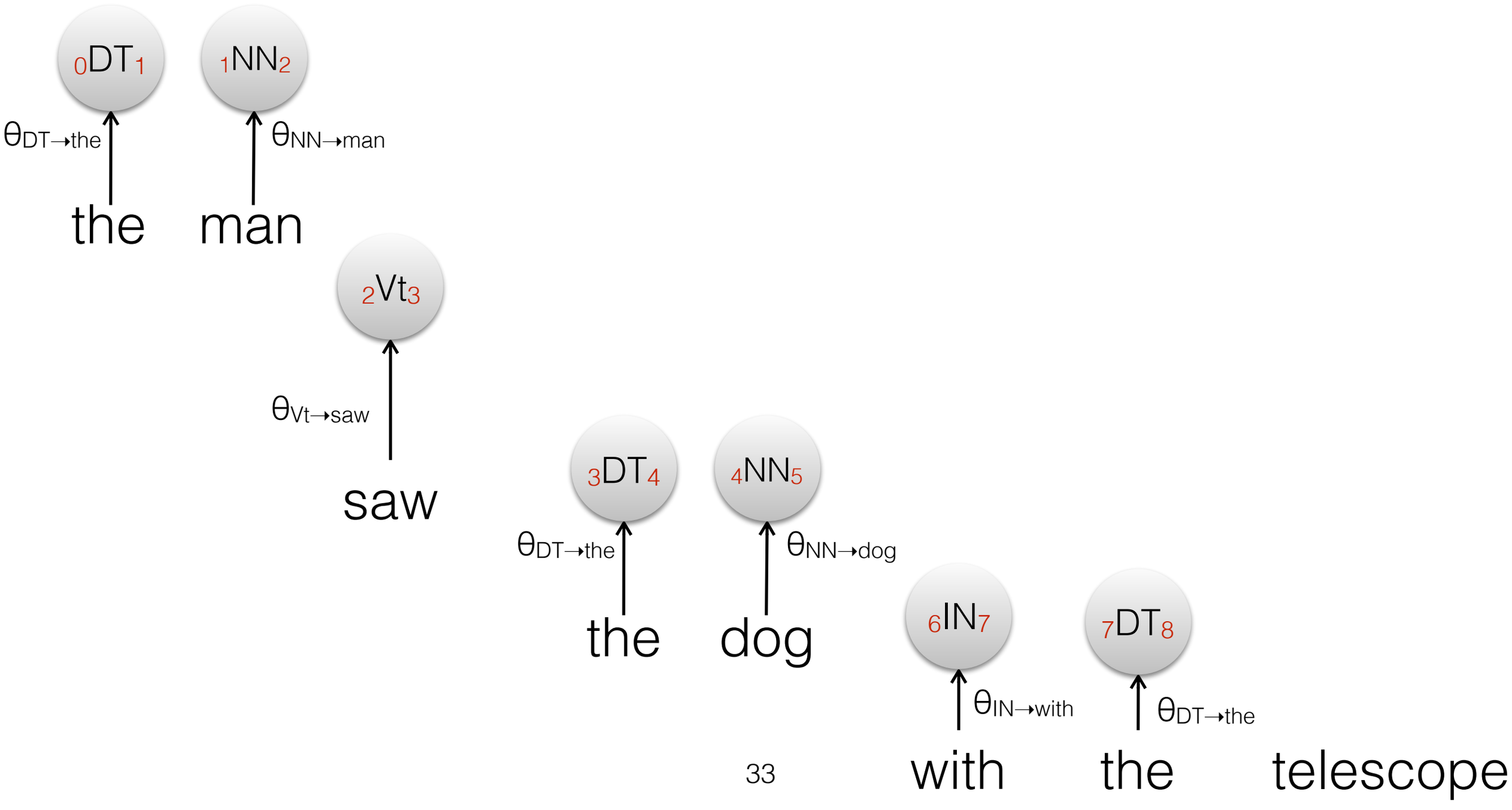


with the telescope

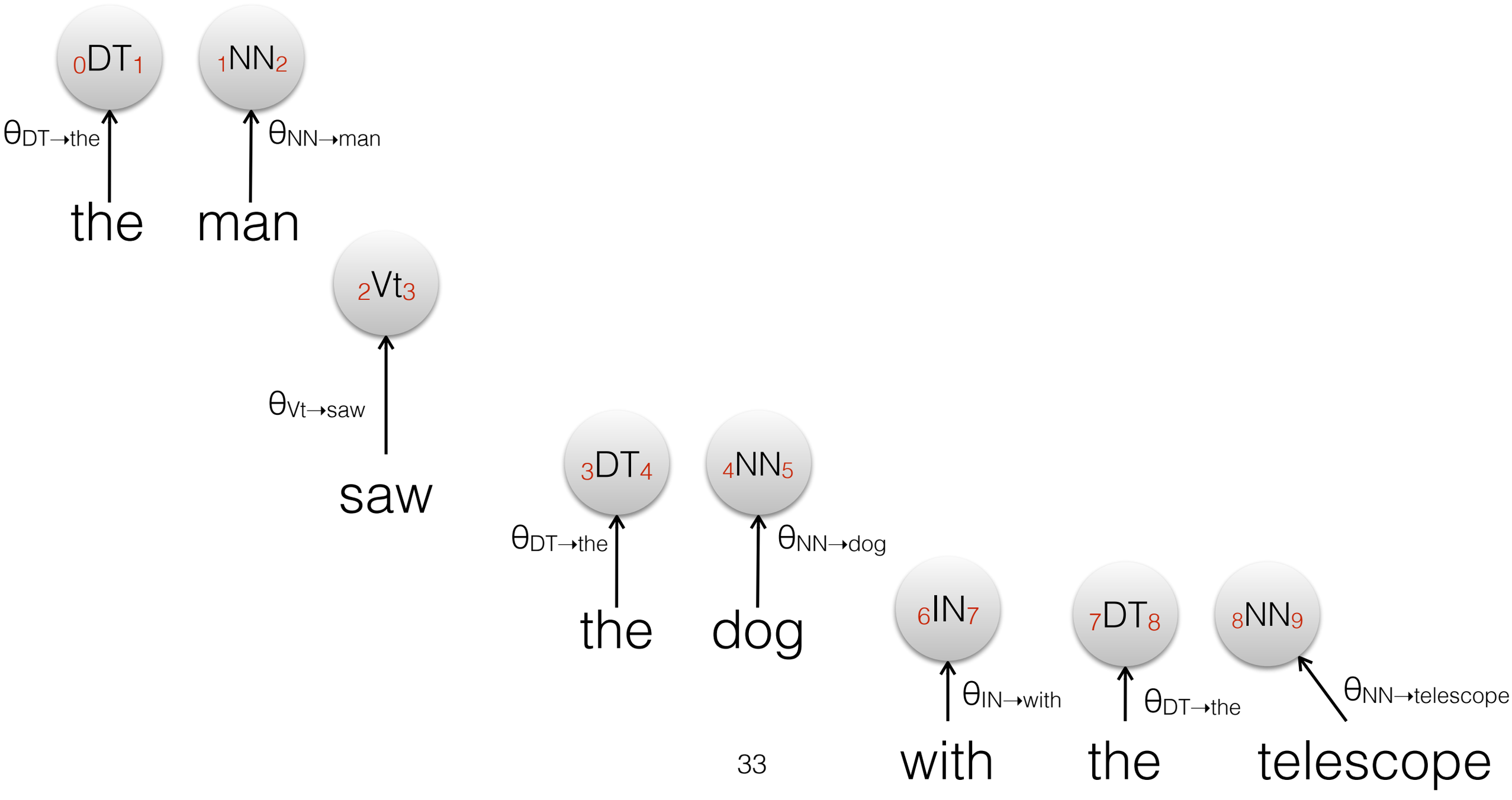
Ambiguity


$_0DT_1$
$_1NN_2$
$\theta_{DT \rightarrow the}$
$\theta_{NN \rightarrow man}$
the
man
$_2Vt_3$
$\theta_{Vt \rightarrow saw}$
saw
$_3DT_4$
$_4NN_5$
$\theta_{DT \rightarrow the}$
$\theta_{NN \rightarrow dog}$
the
dog
$_6IN_7$
$\theta_{IN \rightarrow with}$
with
the
telescope

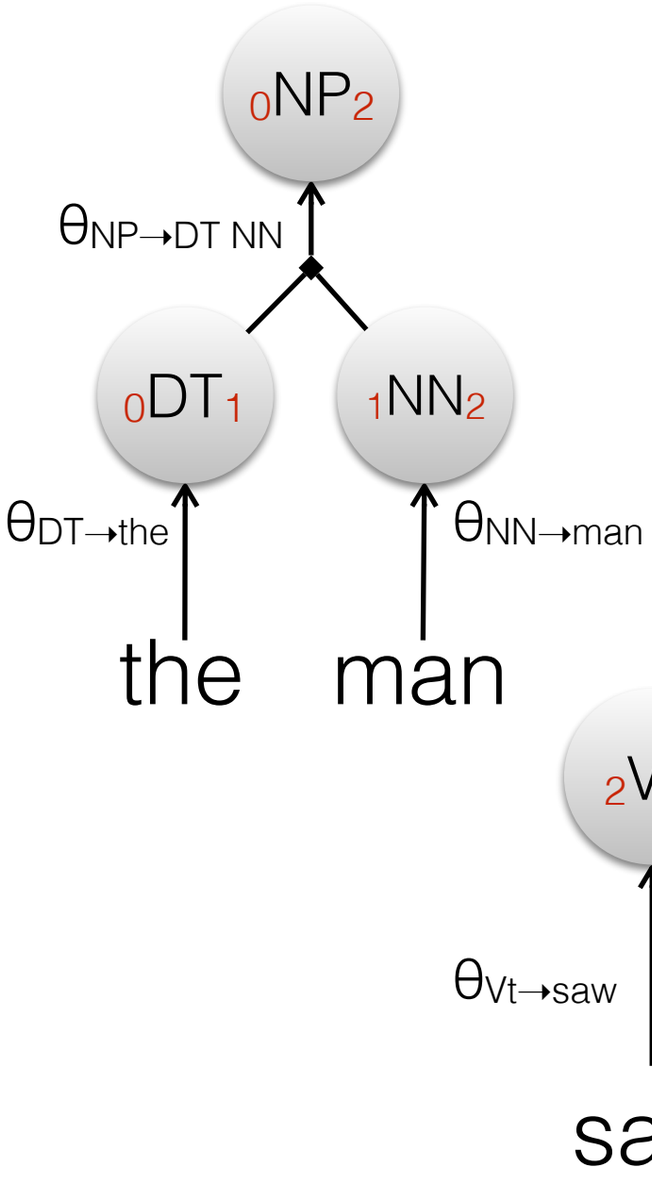
Ambiguity

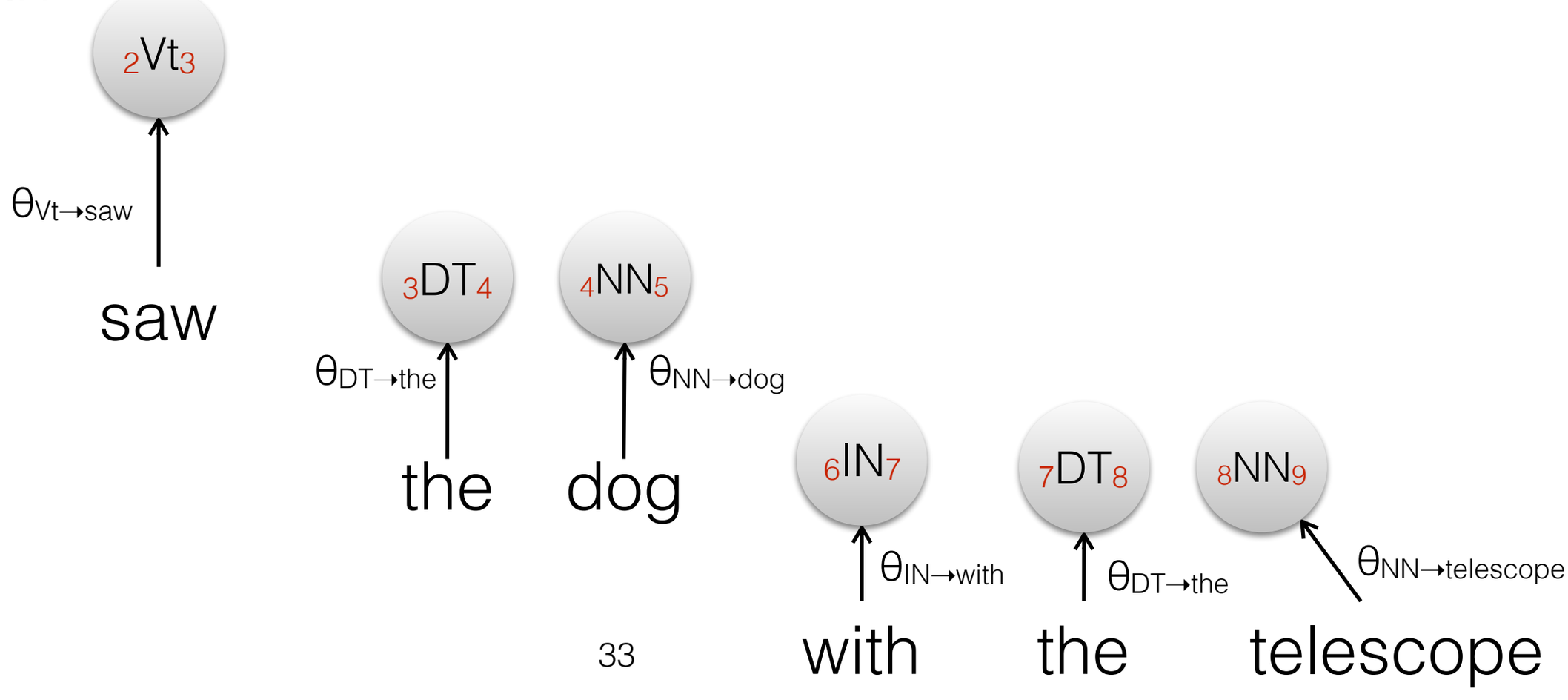

0DT1
1NN2
θDT→the
θNN→man
the
man
2Vt3
θVt→saw
saw
3DT4
4NN5
θDT→the
θNN→dog
the
dog
6IN7
7DT8
θIN→with
θDT→the
with
the
telescope

Ambiguity

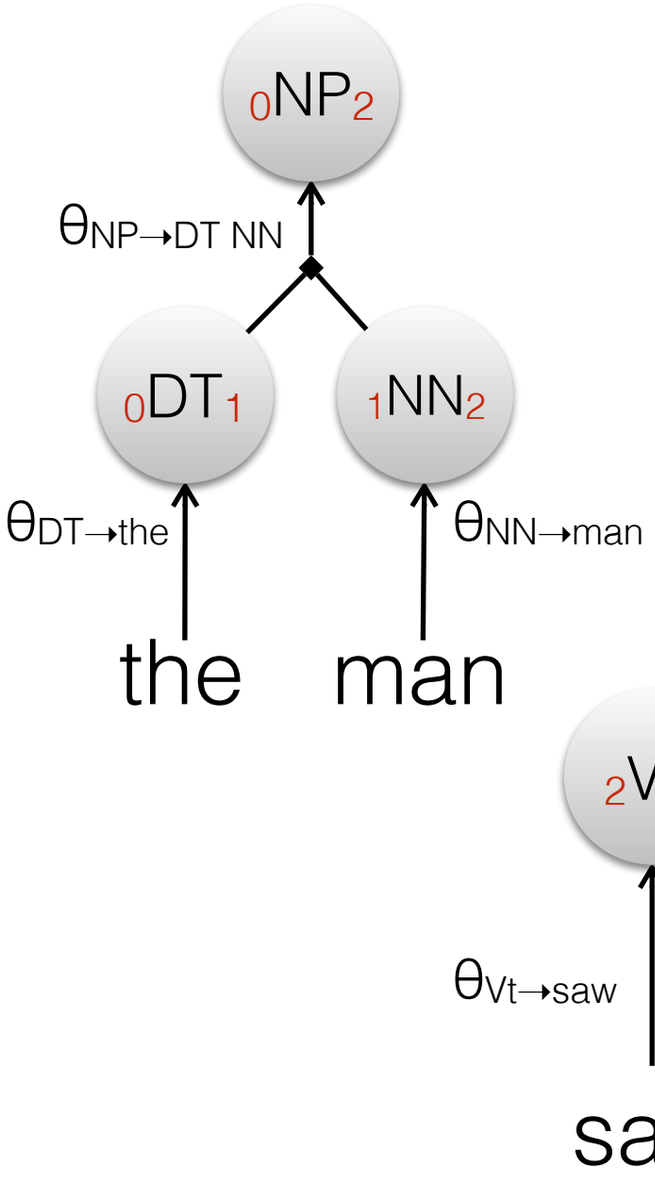

0DT1
1NN2
θDT→the
θNN→man
the
man
2Vt3
θVt→saw
saw
3DT4
4NN5
θDT→the
θNN→dog
the
dog
6IN7
7DT8
8NN9
θIN→with
θDT→the
θNN→telescope
with
the
telescope

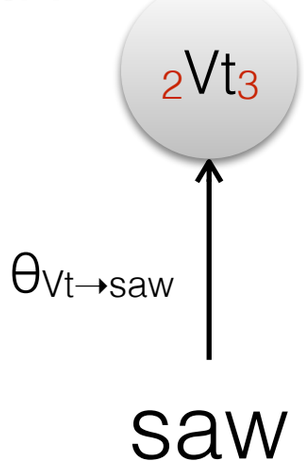
Ambiguity

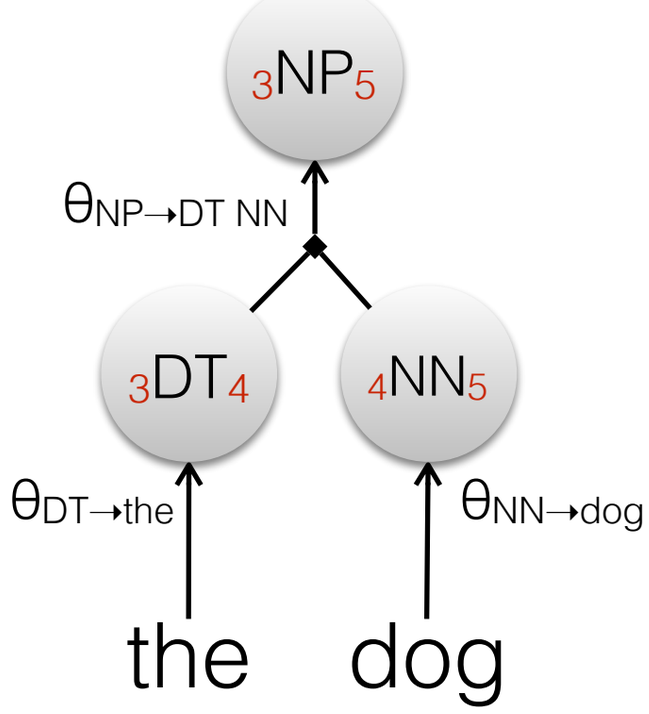

0NP2
θNP→DT NN
0DT1
1NN2
θDT→the
θNN→man
the
man

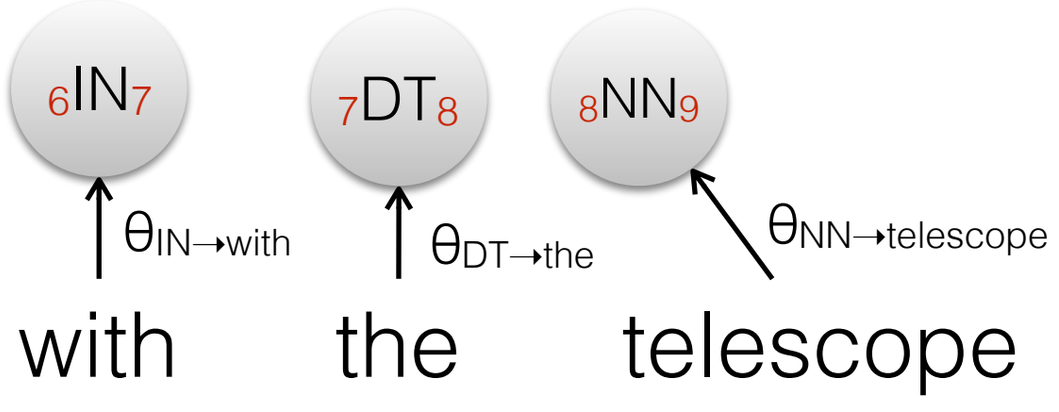

2Vt3
θVt→saw
saw
3DT4
4NN5
θDT→the
θNN→dog
the
dog
6IN7
7DT8
8NN9
θIN→with
θDT→the
θNN→telescope
with
the
telescope

Ambiguity

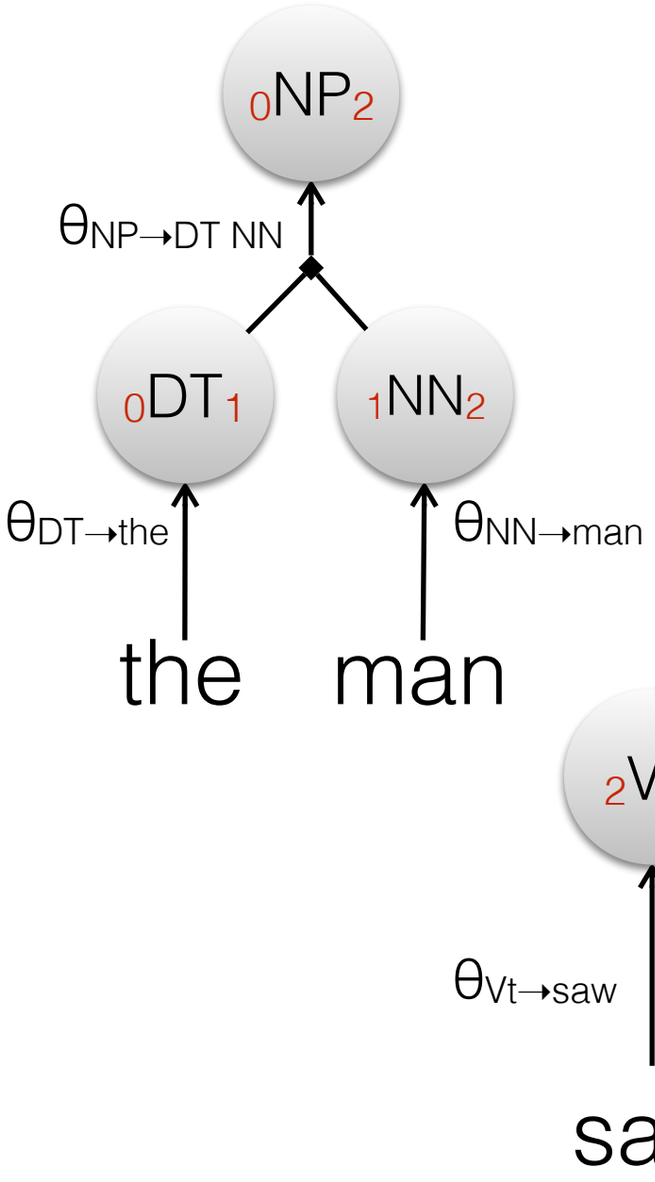

0NP2
θNP→DT NN
0DT1
1NN2
θDT→the
θNN→man
the
man

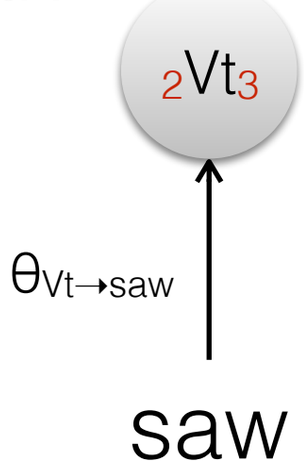

2Vt3
θVt→saw
saw

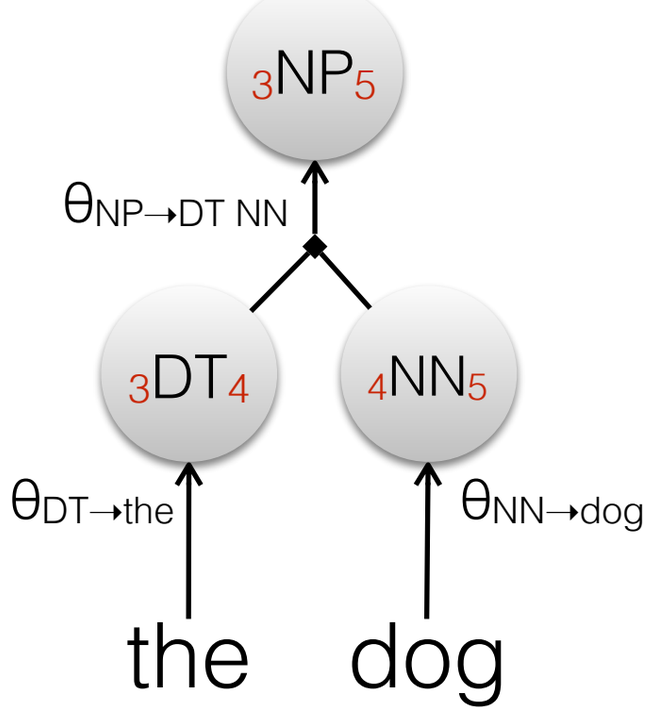

3NP5
θNP→DT NN
3DT4
4NN5
θDT→the
θNN→dog
the
dog

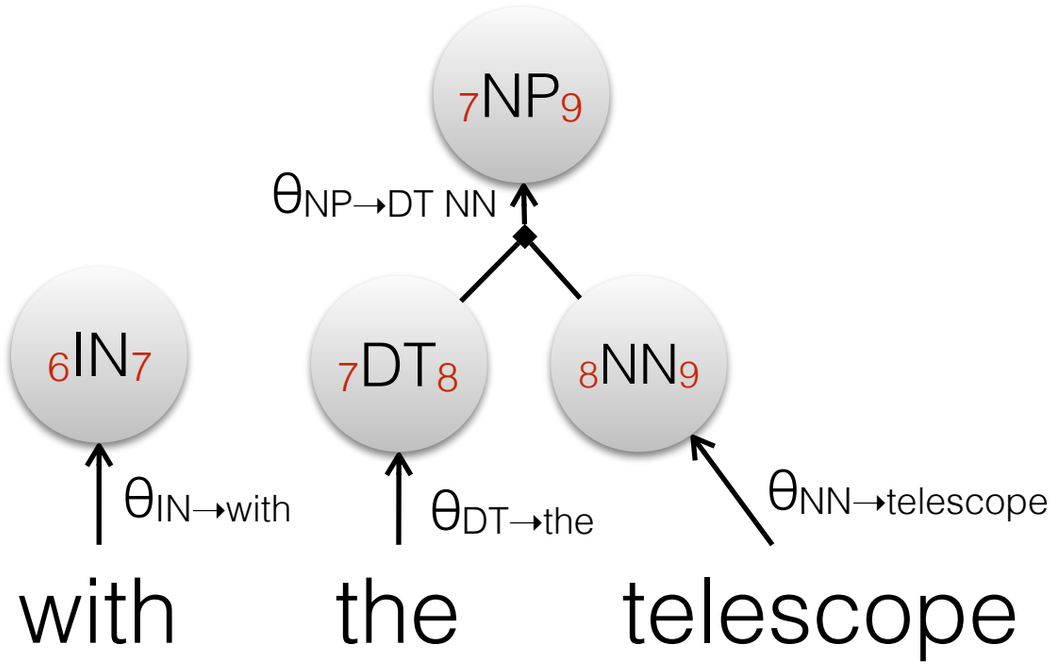

6IN7
7DT8
8NN9
θIN→with
θDT→the
θNN→telescope
with
the
telescope

Ambiguity

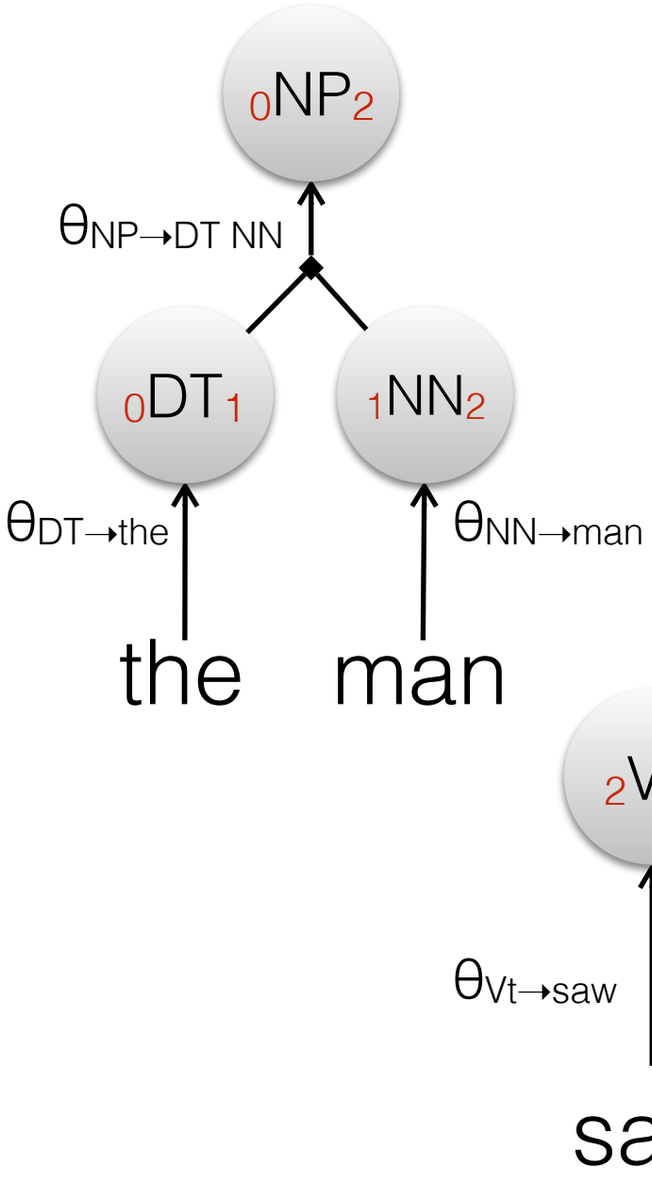

0NP2
θNP→DT NN
0DT1
1NN2
θDT→the
θNN→man
the
man

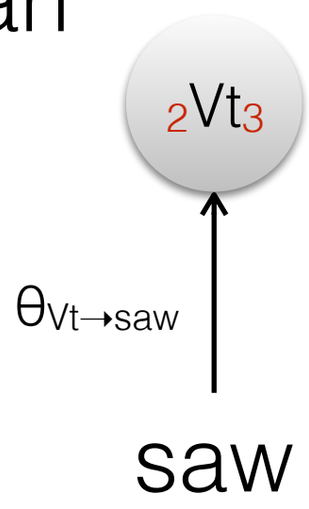

2Vt3
θVt→saw
saw

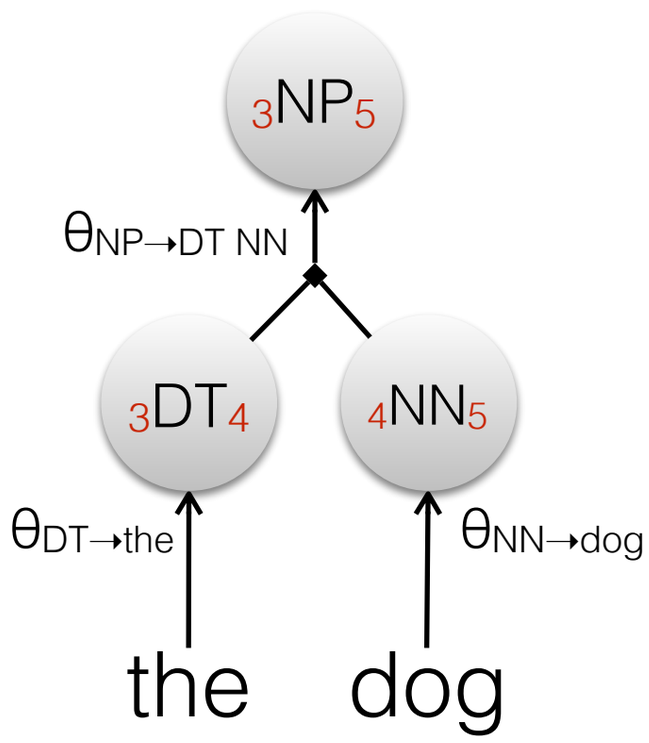

3NP5
θNP→DT NN
3DT4
4NN5
θDT→the
θNN→dog
the
dog


7NP9
θNP→DT NN
6IN7
7DT8
8NN9
θIN→with
θDT→the
θNN→telescope
with
the
telescope

Ambiguity


0NP2
θNP→DT NN
0DT1
1NN2
θDT→the
θNN→man
the
man


2Vt3
θVt→saw
saw


3NP5
θNP→DT NN
3DT4
4NN5
θDT→the
θNN→dog
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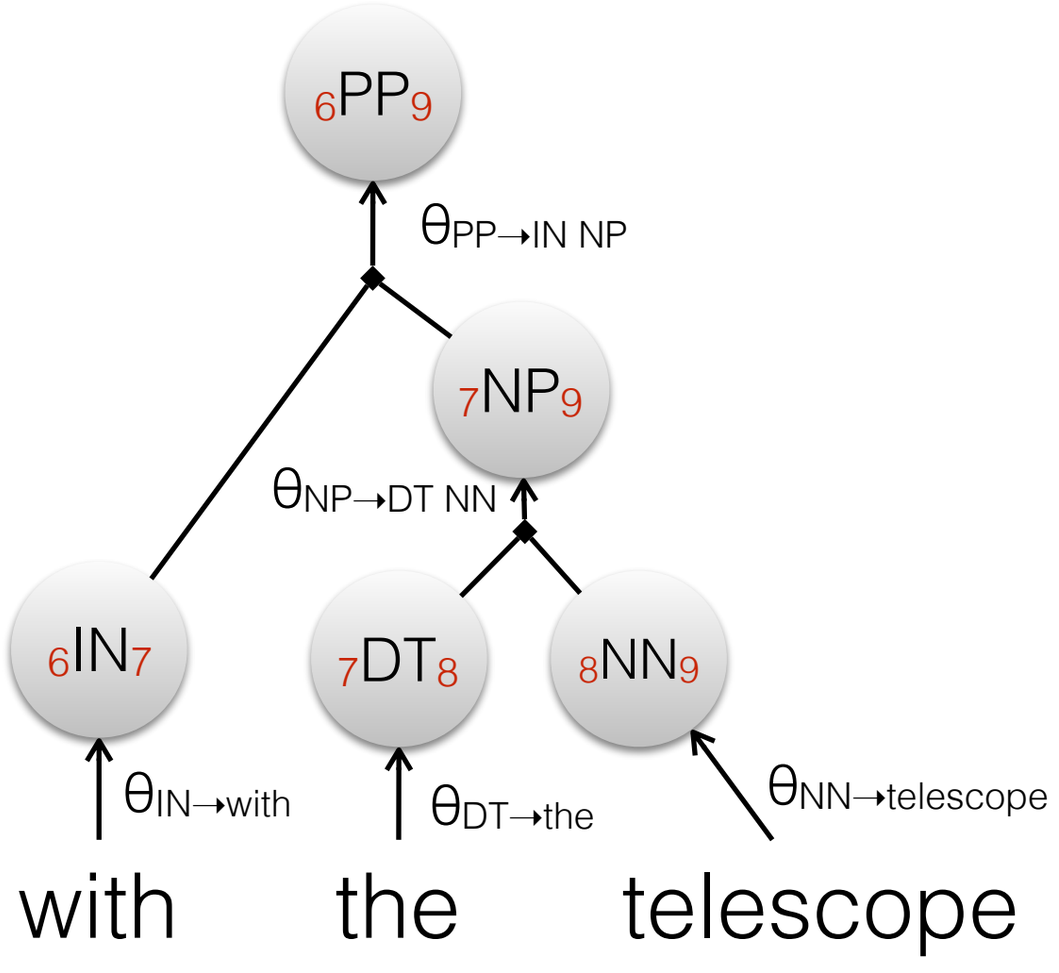
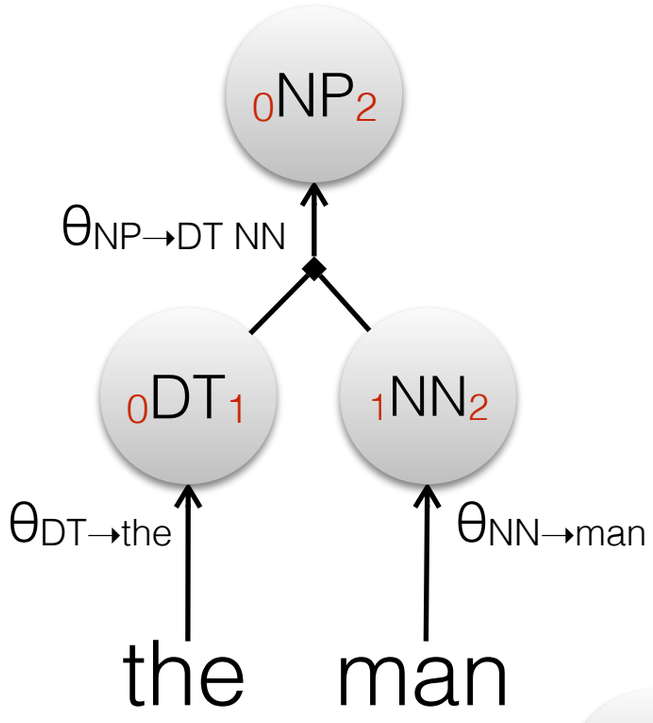
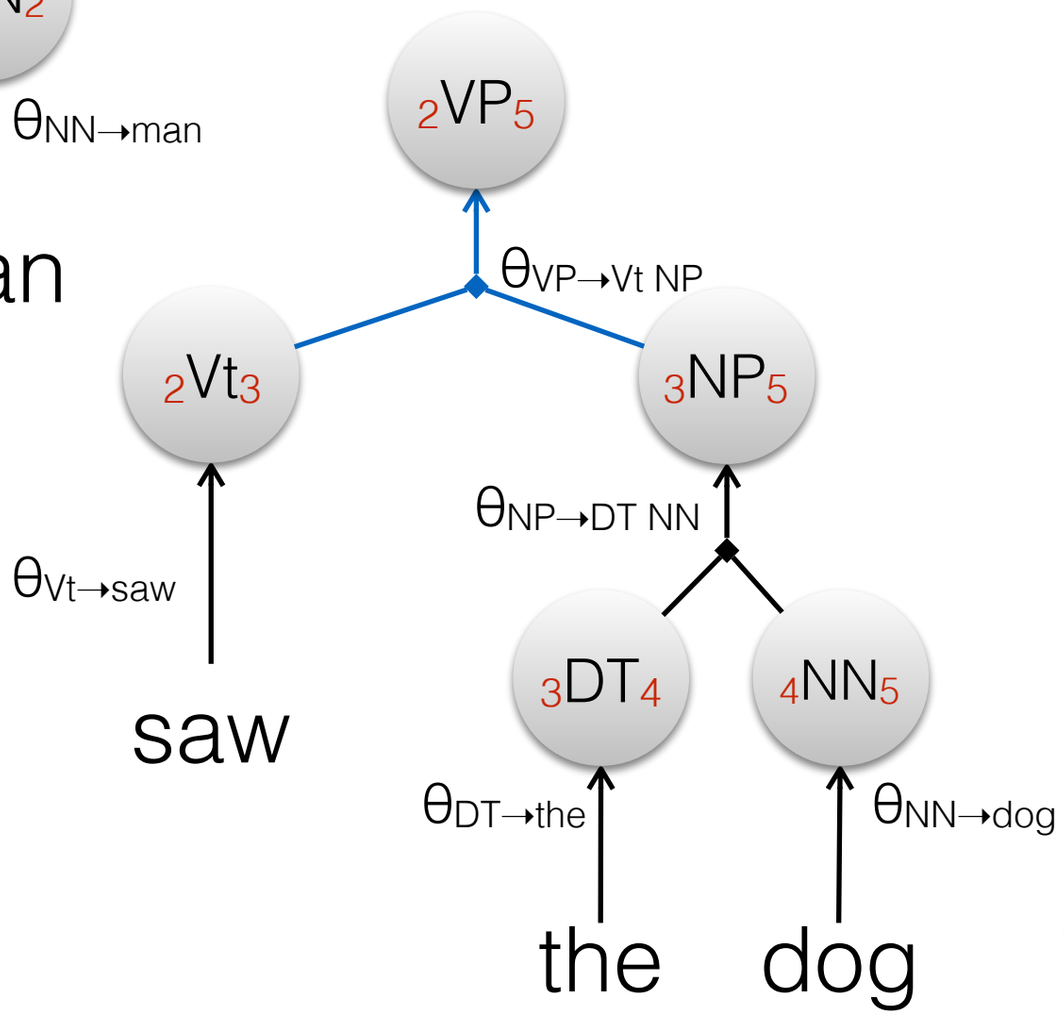
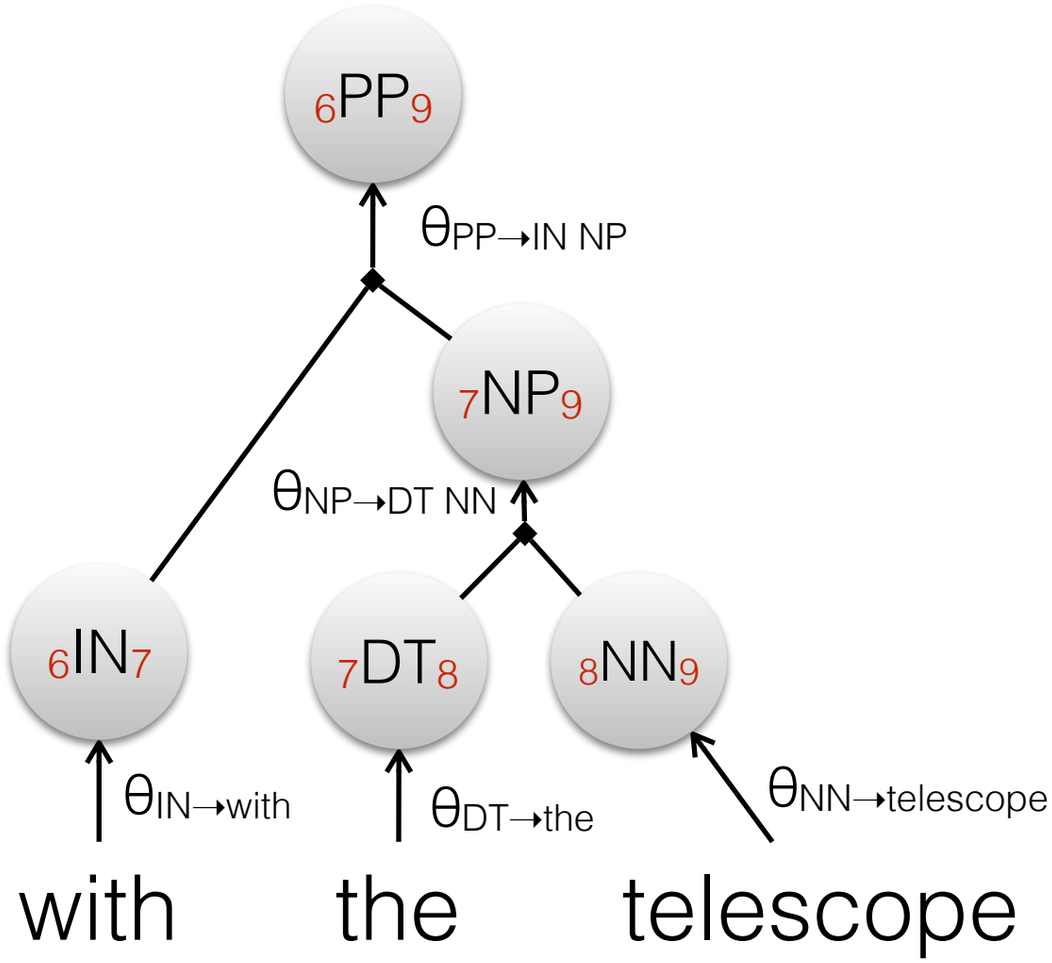

6PP9
θPP→IN NP
7NP9
θNP→DT NN
6IN7
7DT8
8NN9
θIN→with
θDT→the
θNN→telescope
with
the
telescope

Ambiguity


0NP2
θNP→DT NN
0DT1
1NN2
θDT→the
θNN→man
the
man


2VP5
θVP→Vt NP
2Vt3
3NP5
θVt→saw
θNP→DT NN
saw
3DT4
4NN5
θDT→the
θNN→dog
the
dog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θPP→IN NP
7NP9
θNP→DT NN
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7DT8
8NN9
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θDT→the
θNN→telescope
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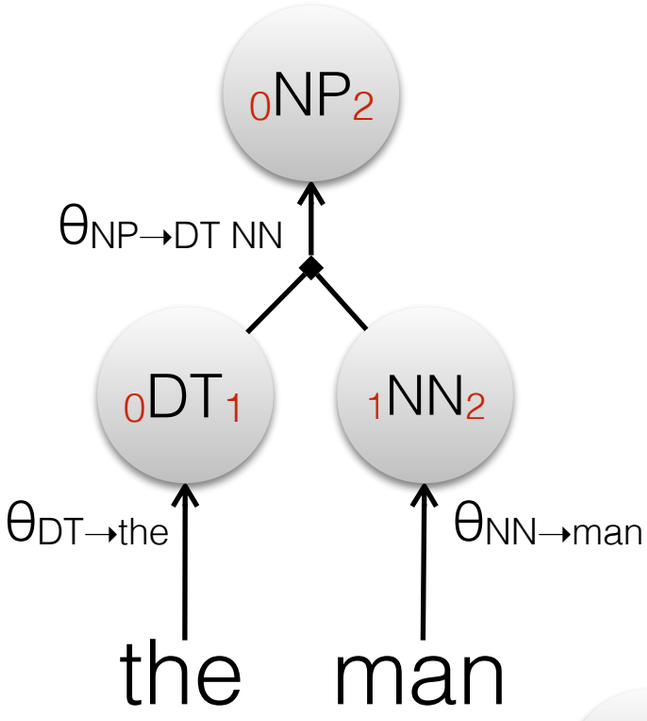
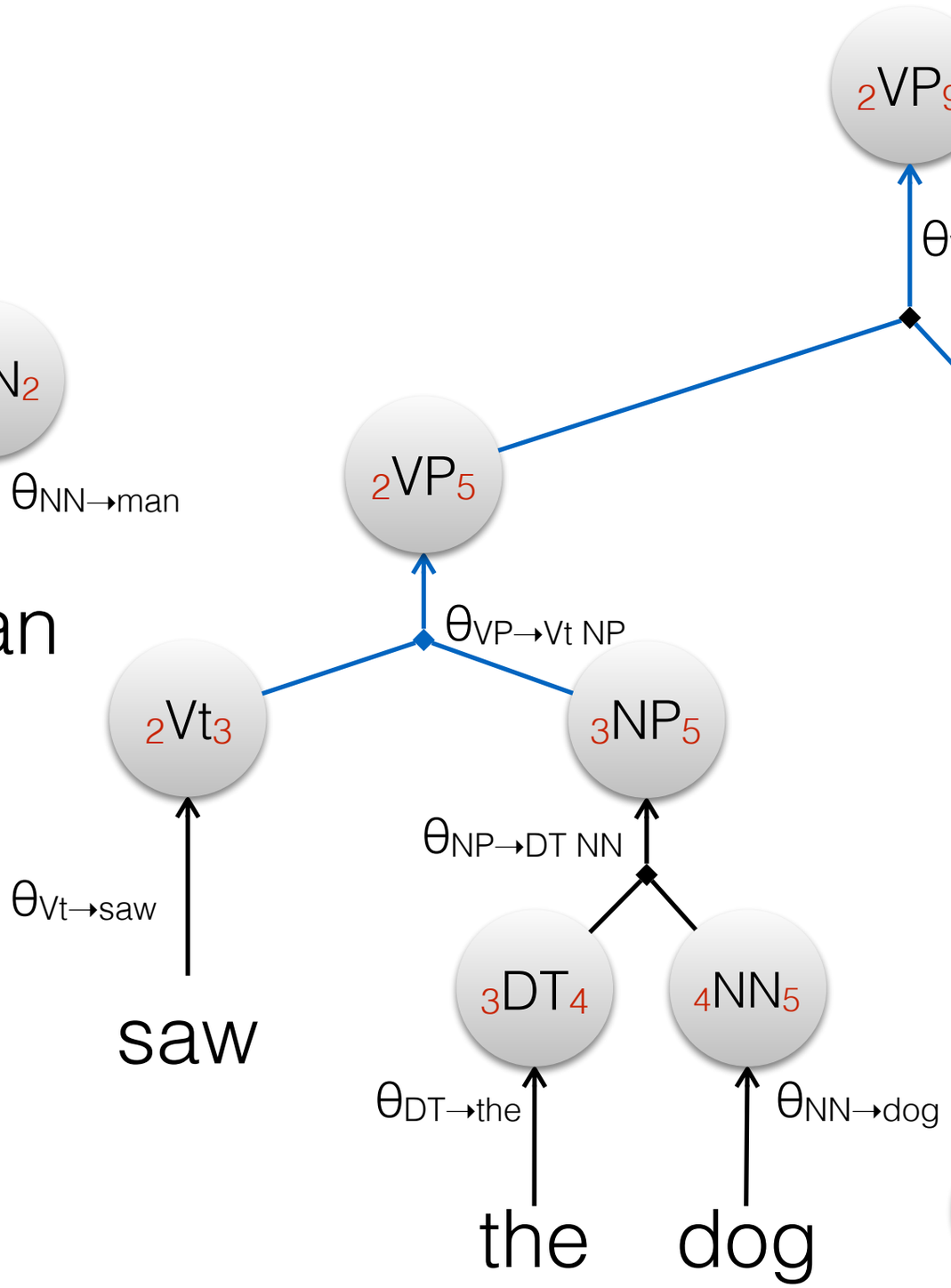
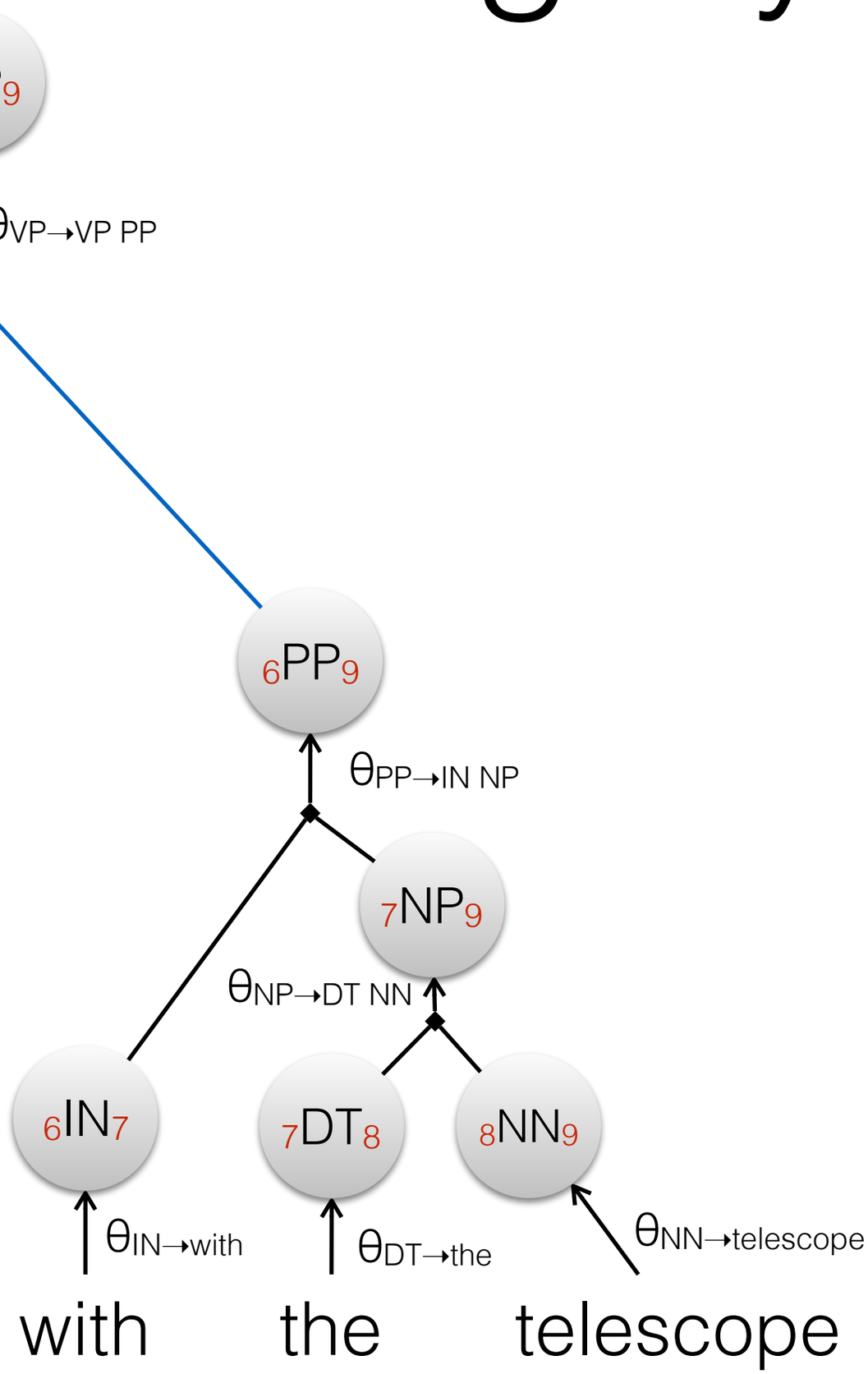

0NP2
θNP→DT NN
0DT1
1NN2
θDT→the
θNN→man
the
man


2VP5
θVP→Vt NP
2Vt3
3NP5
θVt→saw
saw
θNP→DT NN
3DT4
4NN5
θDT→the
θNN→dog
the
dog


2VP9
θVP→VP PP
6PP9
θPP→IN NP
6IN7
7NP9
θNP→DT NN
7DT8
8NN9
θIN→with
θDT→the
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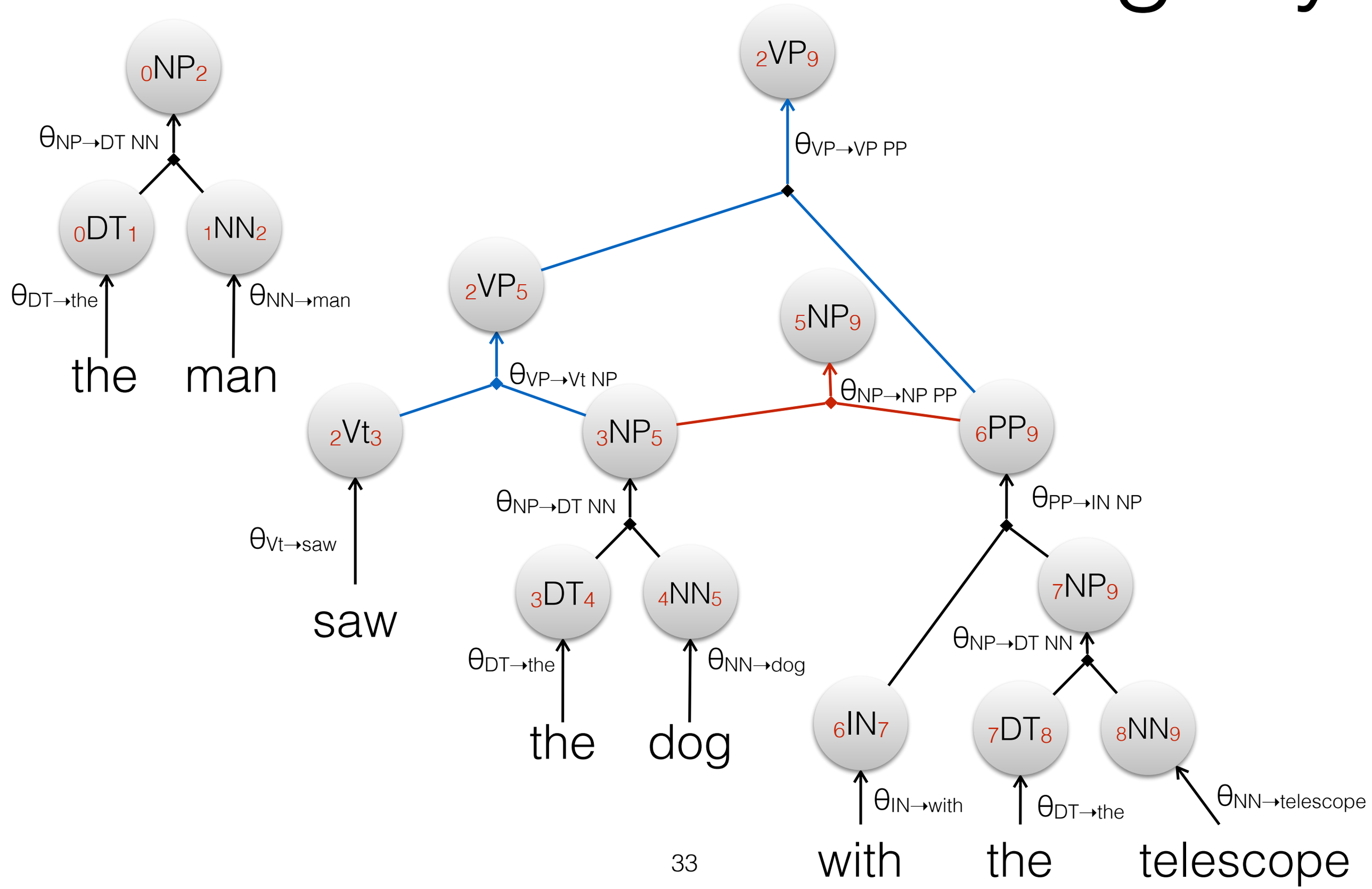
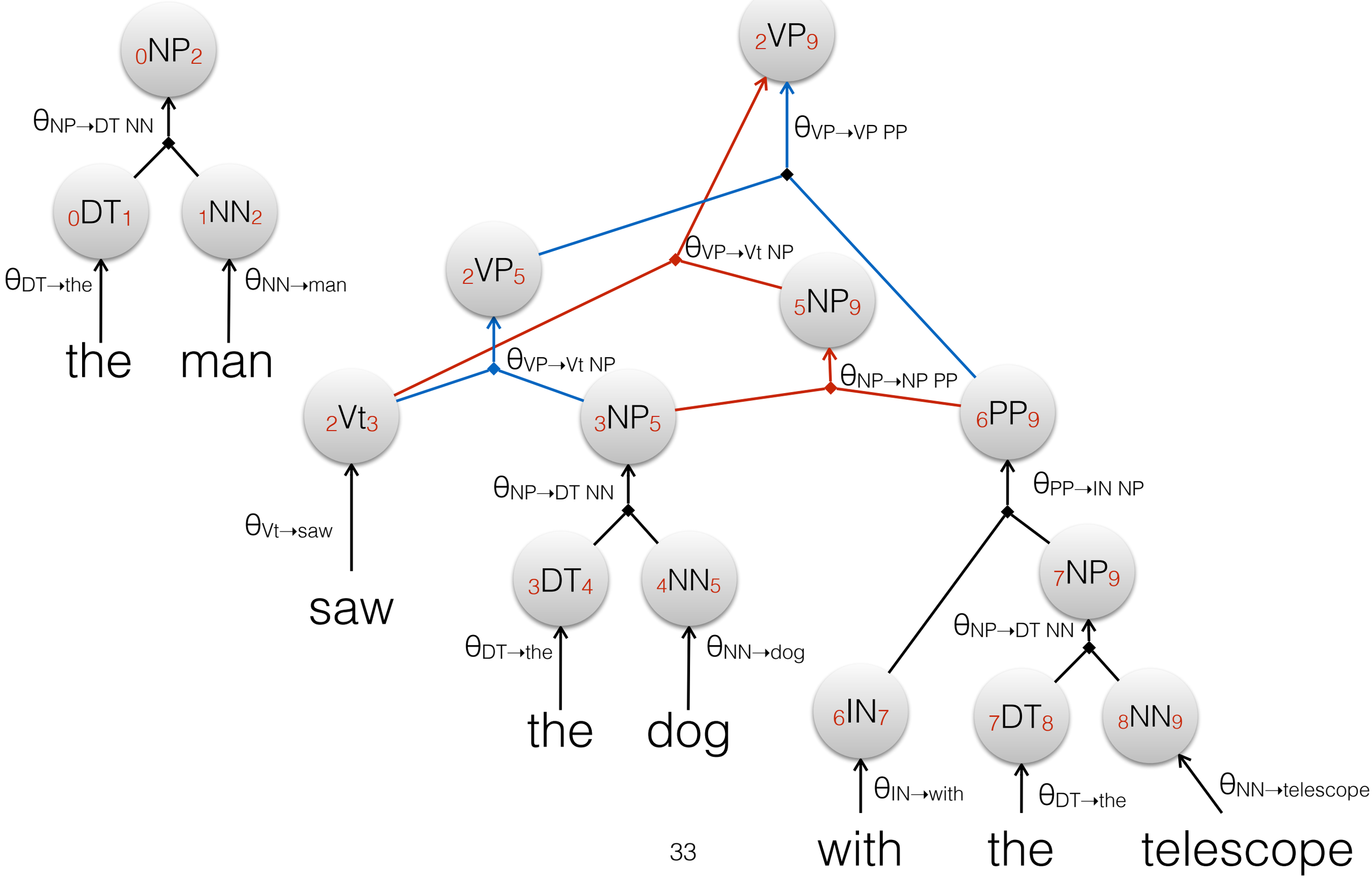
telescope

Ambiguity


0NP2
θNP→DT NN
0DT1
1NN2
θDT→the
θNN→man
the
man
2VP9
θVP→VP PP
2VP5
5NP9
θVP→Vt NP
θNP→NP PP
2Vt3
3NP5
6PP9
θPP→IN NP
θNP→DT NN
θVt→saw
saw
3DT4
4NN5
7NP9
θNP→DT NN
θDT→the
θNN→dog
6IN7
7DT8
8NN9
the
dog
θIN→with
θDT→the
θNN→telescope
with
the
telescope

Ambiguity


0NP2
θNP→DT NN
0DT1
1NN2
θDT→the
θNN→man
the
man
2VP9
θVP→VP PP
2VP5
θVP→Vt NP
5NP9
θNP→NP PP
2Vt3
3NP5
6PP9
θVt→saw
θNP→DT NN
θPP→IN NP
saw
3DT4
4NN5
7NP9
θNP→DT NN
θDT→the
θNN→dog
6IN7
7DT8
8NN9
the
dog
θIN→with
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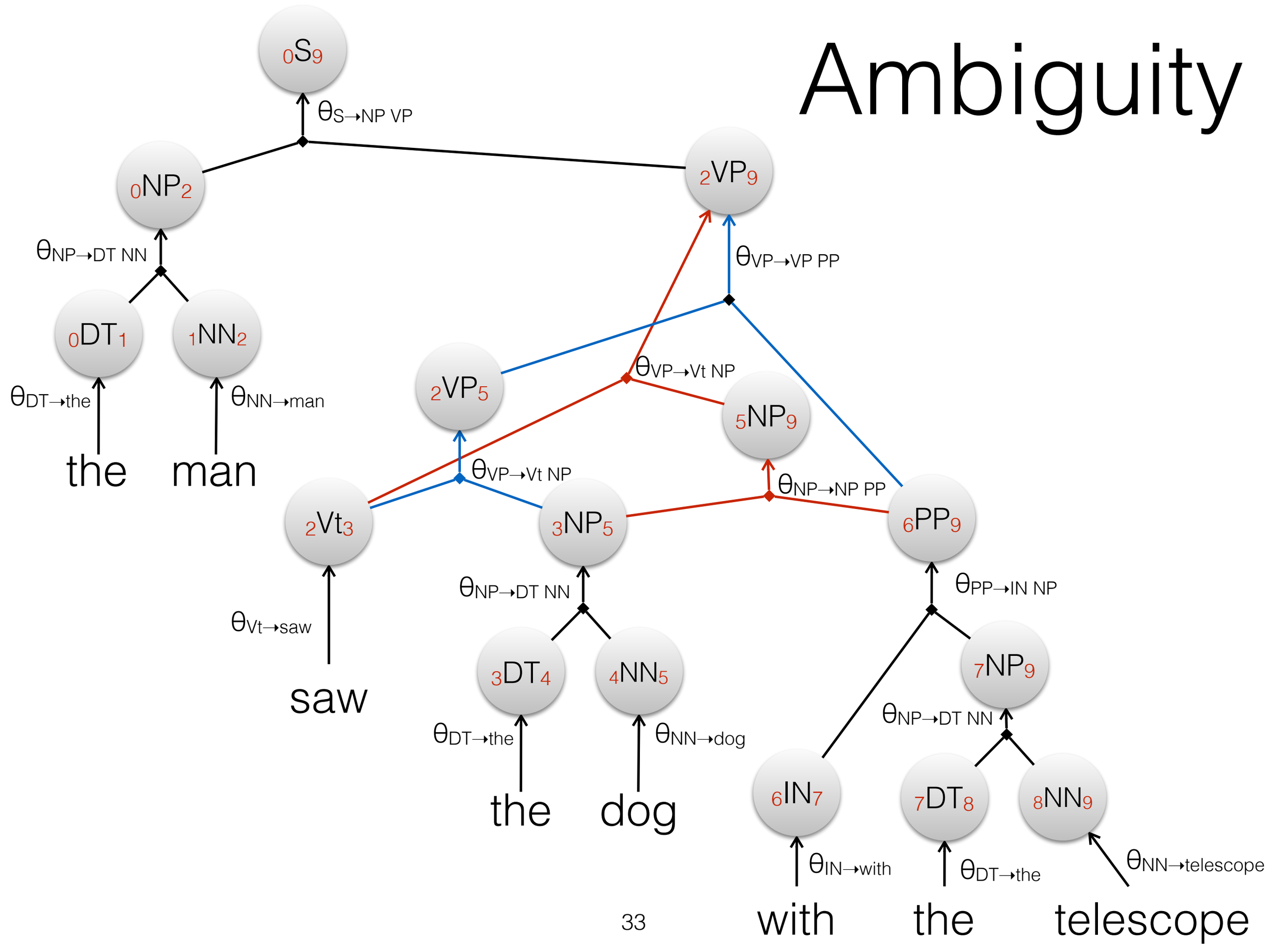
Ambiguity


0S9
θS→NP VP
0NP2
2VP9
θNP→DT NN
θVP→VP PP
0DT1
1NN2
2VP5
θVP→Vt NP
5NP9
θDT→the
θNN→man
θVP→Vt NP
θNP→NP PP
the
man
2Vt3
3NP5
6PP9
θNP→DT NN
θPP→IN NP
θVt→saw
3DT4
4NN5
7NP9
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saw
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Complexity

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Item form: [i, X → α■•β□, j]

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