Bitext parsing

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5/4/16

Context-Free Grammars

A **CFG** grammar G is denoted by

- a set of **nonterminal** symbols N
- a set of **terminal** symbols Σ with $\Sigma \cap N = \varnothing$
- a set R of **rules** of the form $X \rightarrow \alpha$ where
  - $X \in N$ and $\alpha \in (\Sigma \cup N)^*$
- $S \in N$ 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 $\mathbf{s}_1 \dots \mathbf{s}_n$
  - $\mathbf{s}_1 = S$
  - $\mathbf{s}_n \in \Sigma^*$
  - $\mathbf{s}_{i \geq 2}$ derived from $\mathbf{s}_{i-1}$ by picking the left-most nonterminal X
    - replacing it by some α such that $X \rightarrow \alpha \in R$

Example of Derivation

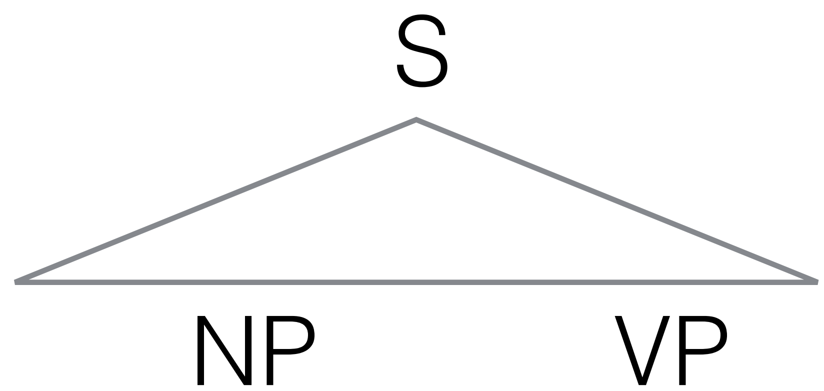
		Substitution
$\mathbf{s}_1$ =	S	S → NP VP
$\mathbf{s}_2$ =	NP VP	NP → DT NN
$\mathbf{s}_3$ =	DT NN VP	DT → the
$\mathbf{s}_4$ =	the NN VP	NN → man
$\mathbf{s}_5$ =	the man VP	VP → Vi
$\mathbf{s}_6$ =	the man Vi	Vi → sleeps
$\mathbf{s}_7$ =	the man sleeps	
$\mathbf{s}_7$ =	S $\Rightarrow^*$ the man sleeps	

Example of Generation

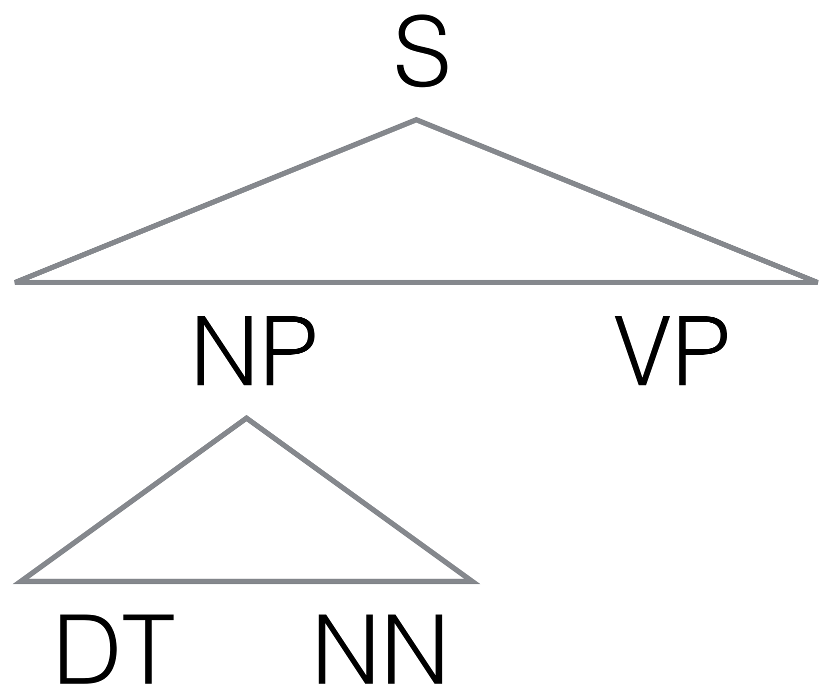
Example of Generation

S

Example of Generation



Example of Generation



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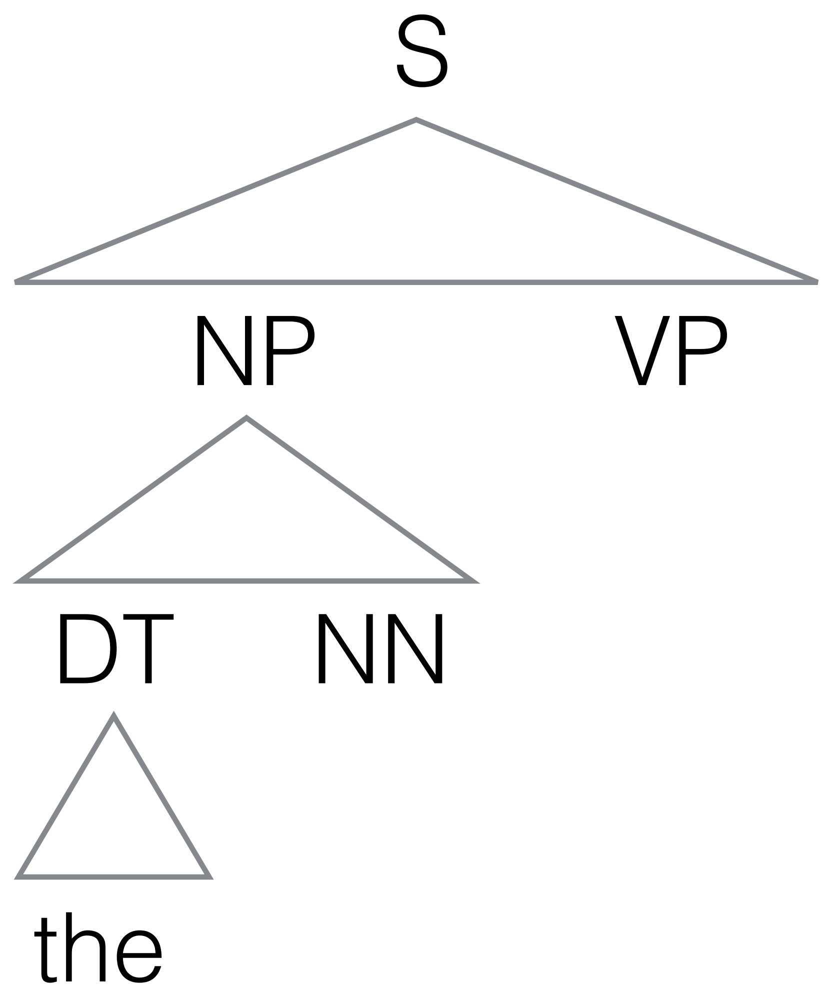

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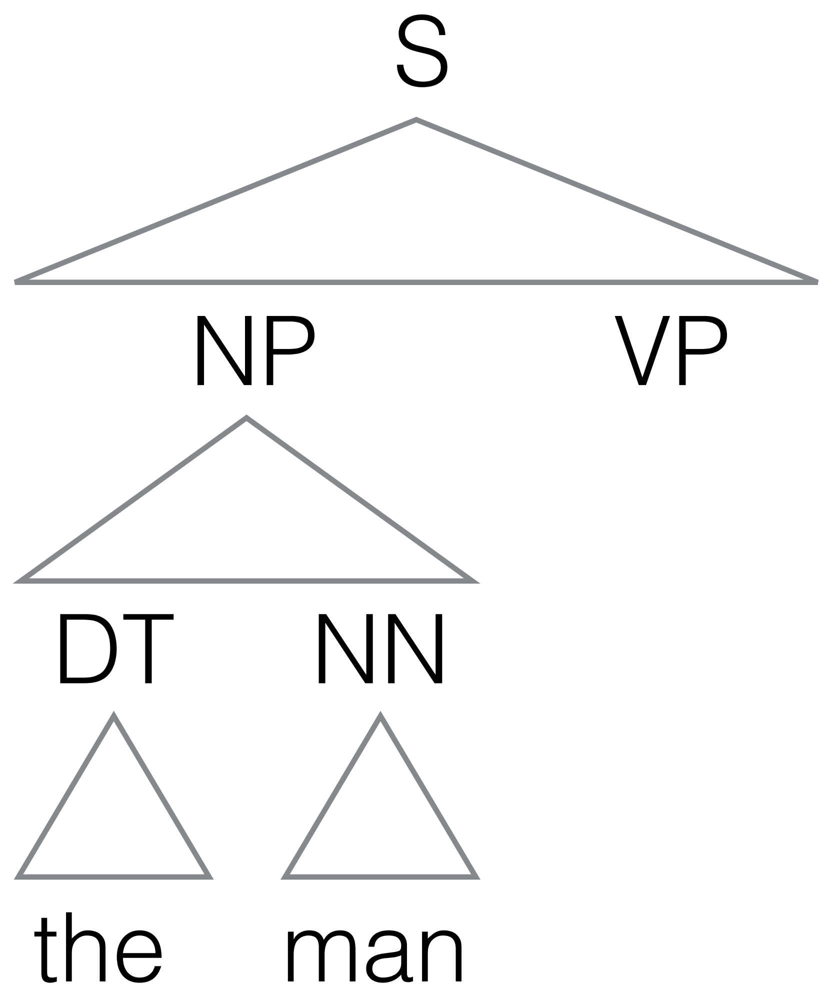

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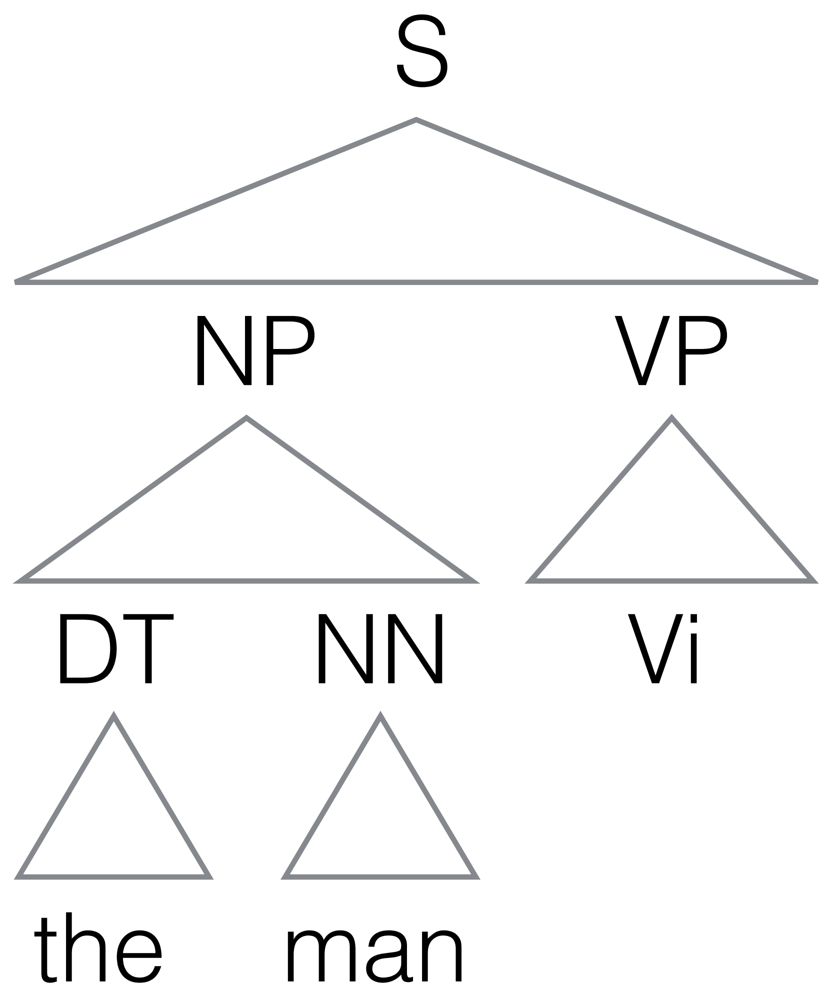

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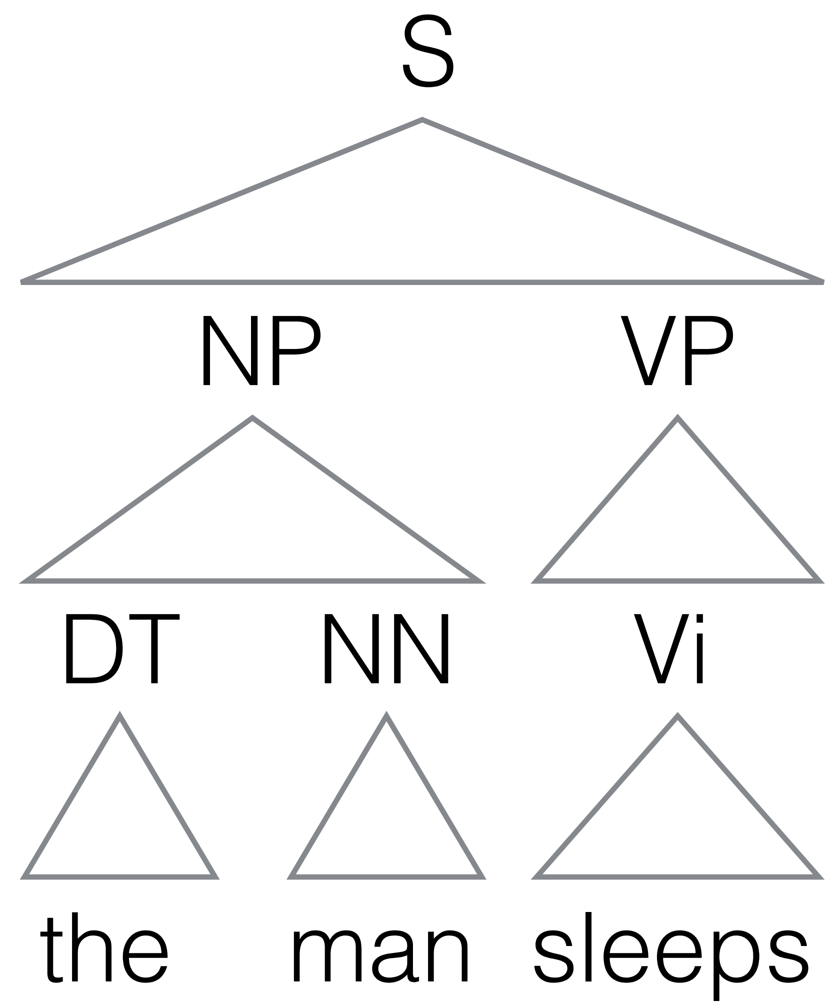


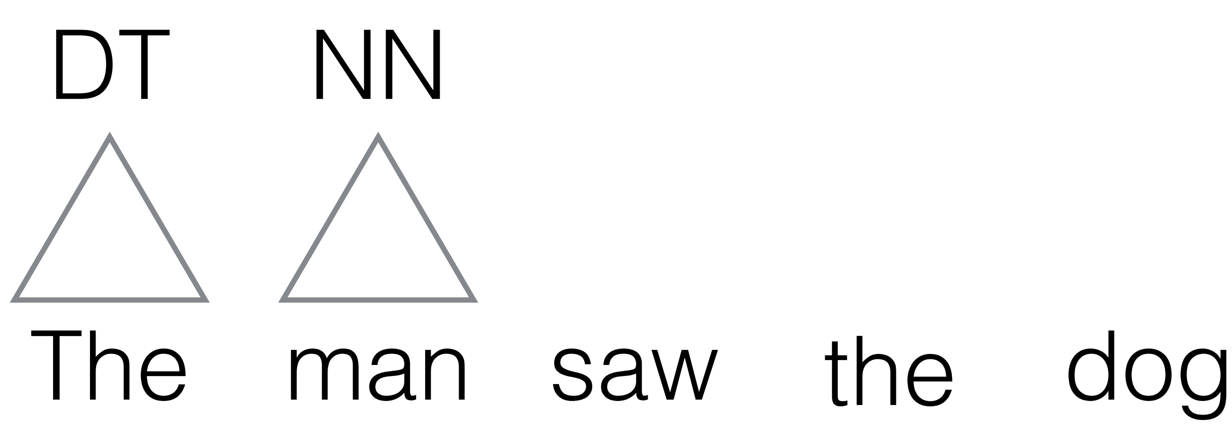
Example of Recognition

Example of Recognition

The man saw the dog

Example of Recognition

Example of Recognition



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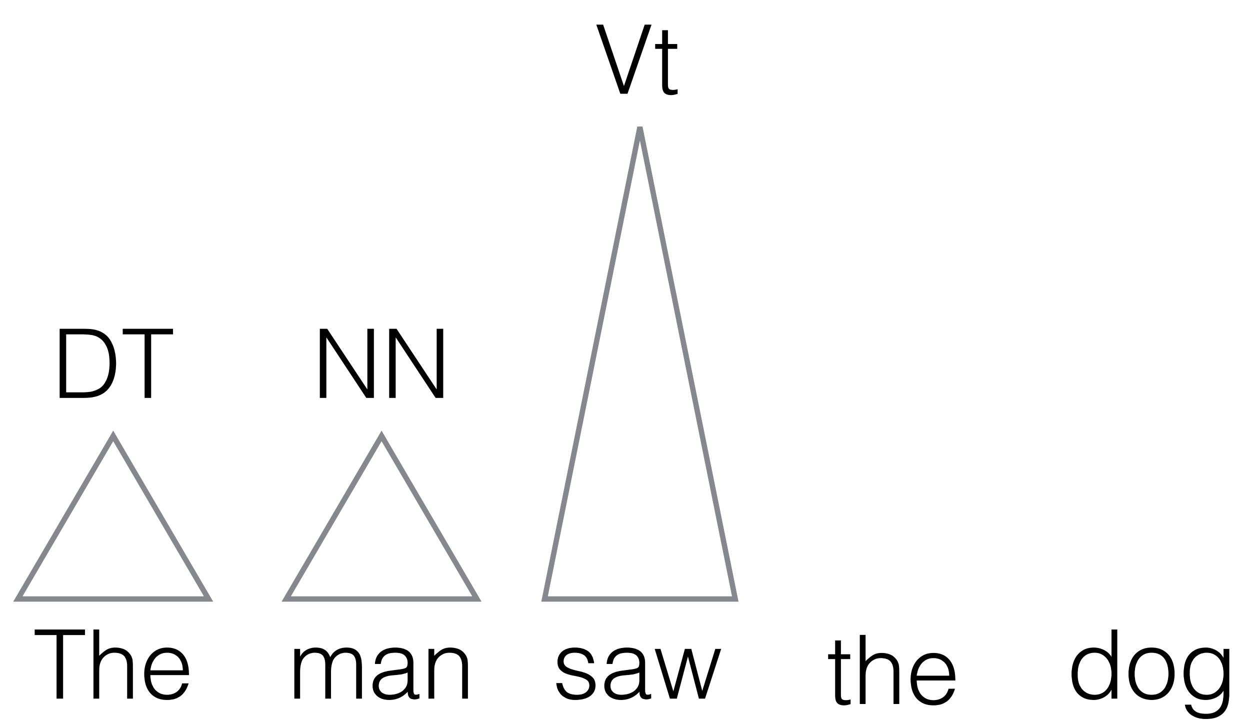

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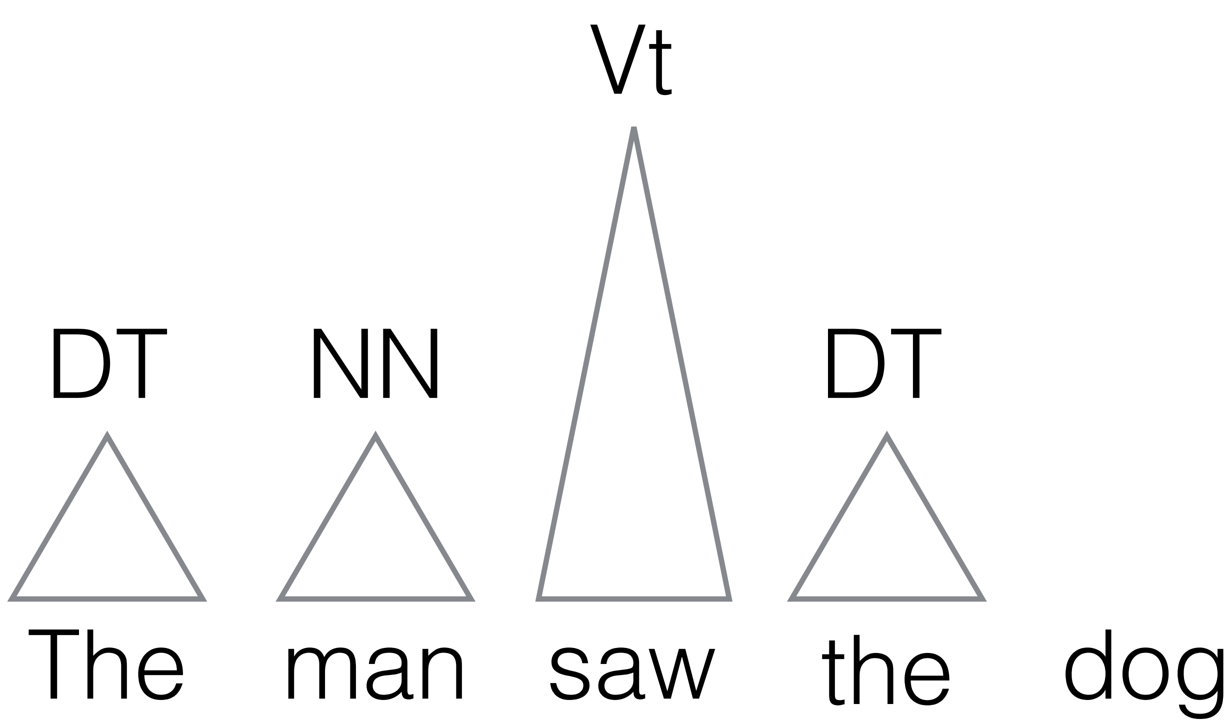

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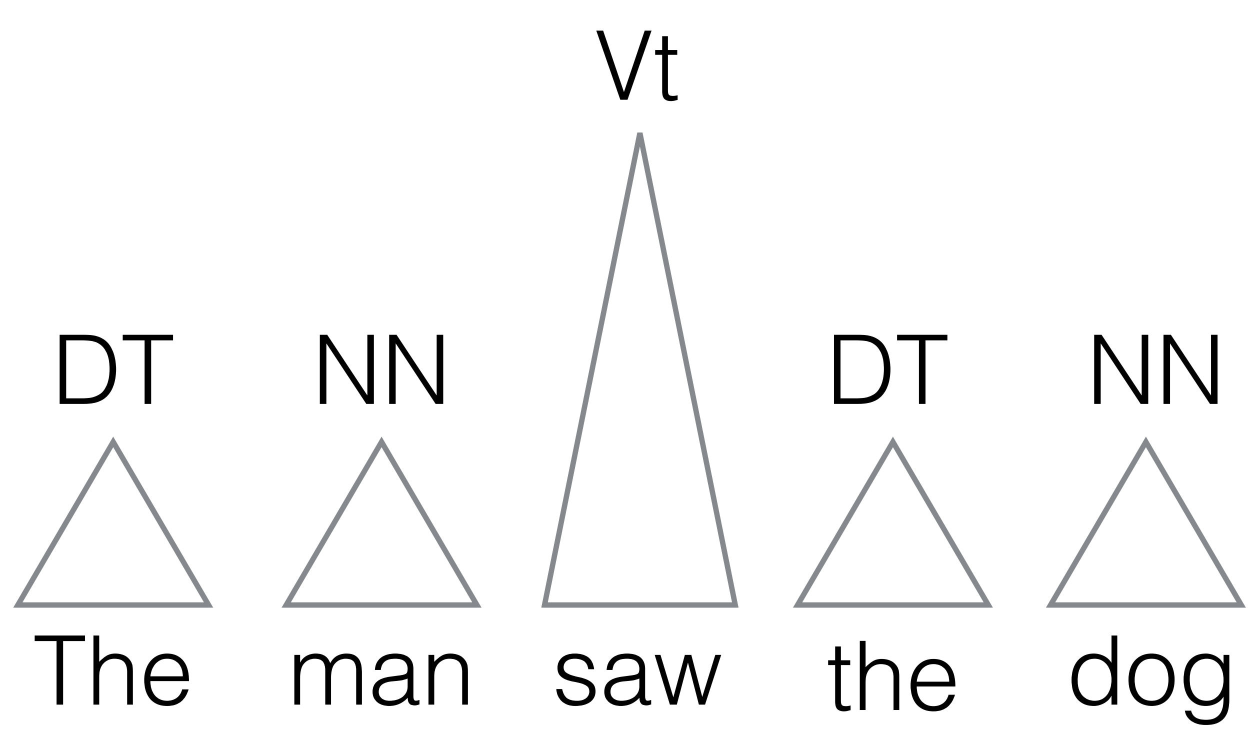

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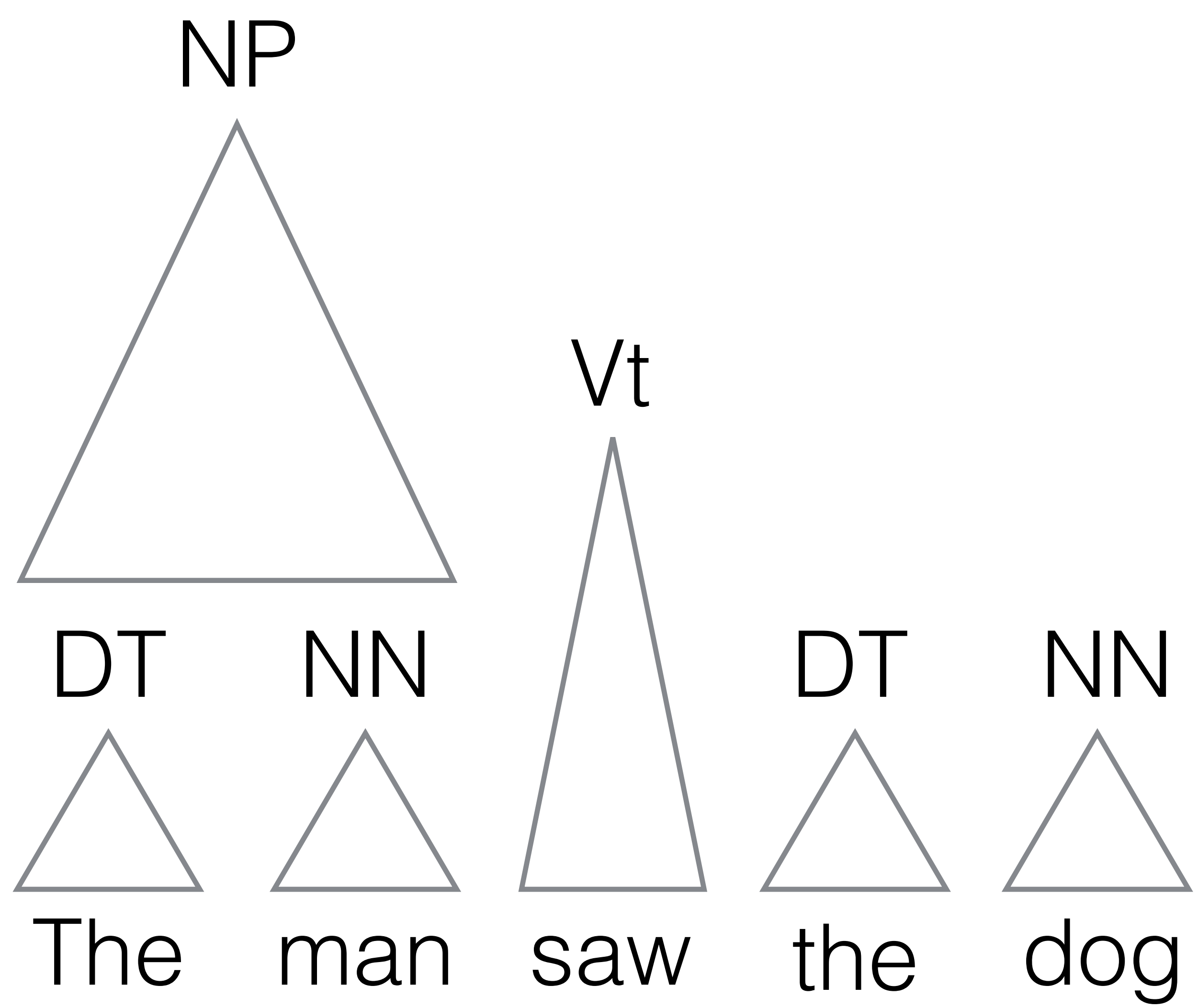

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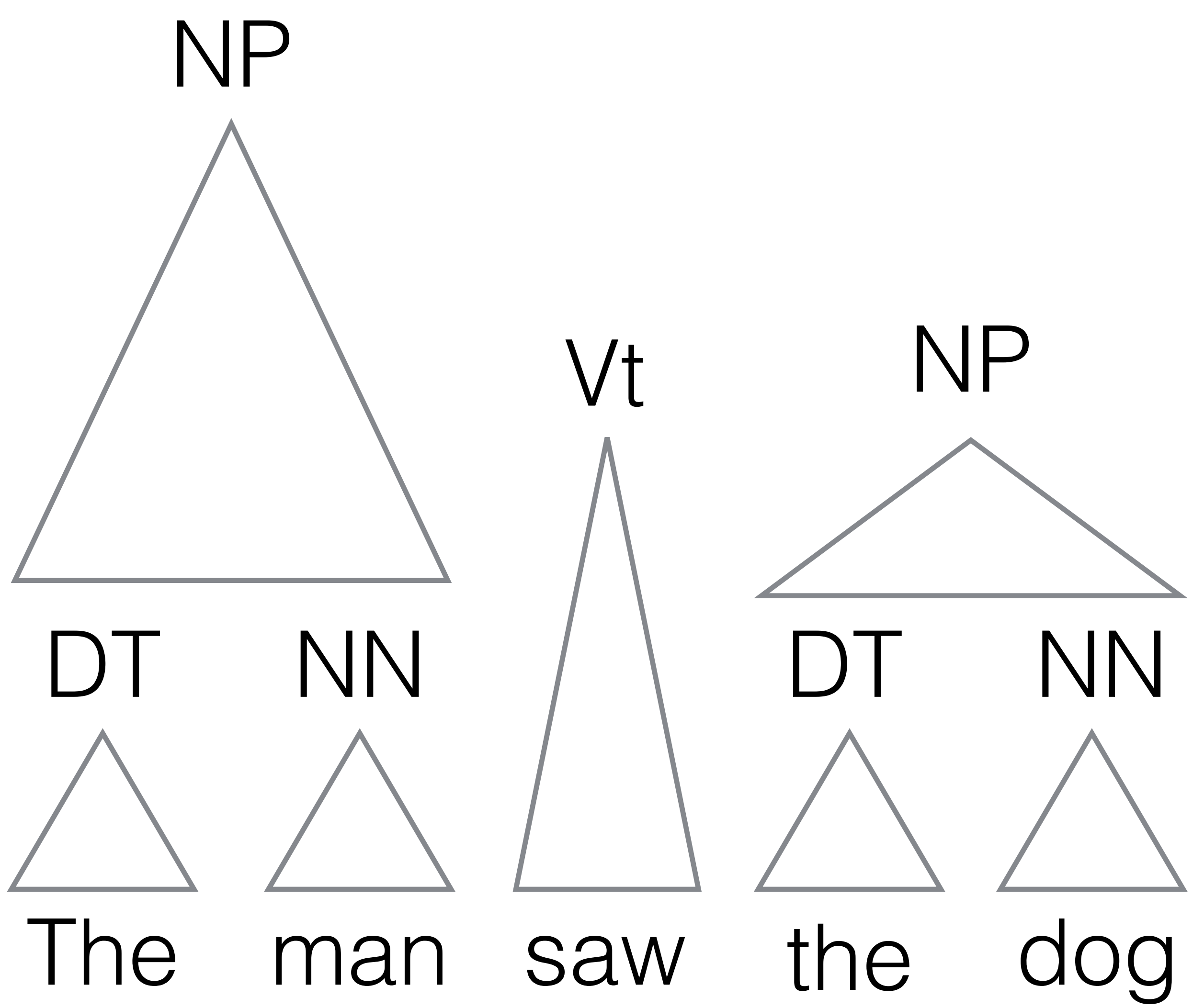

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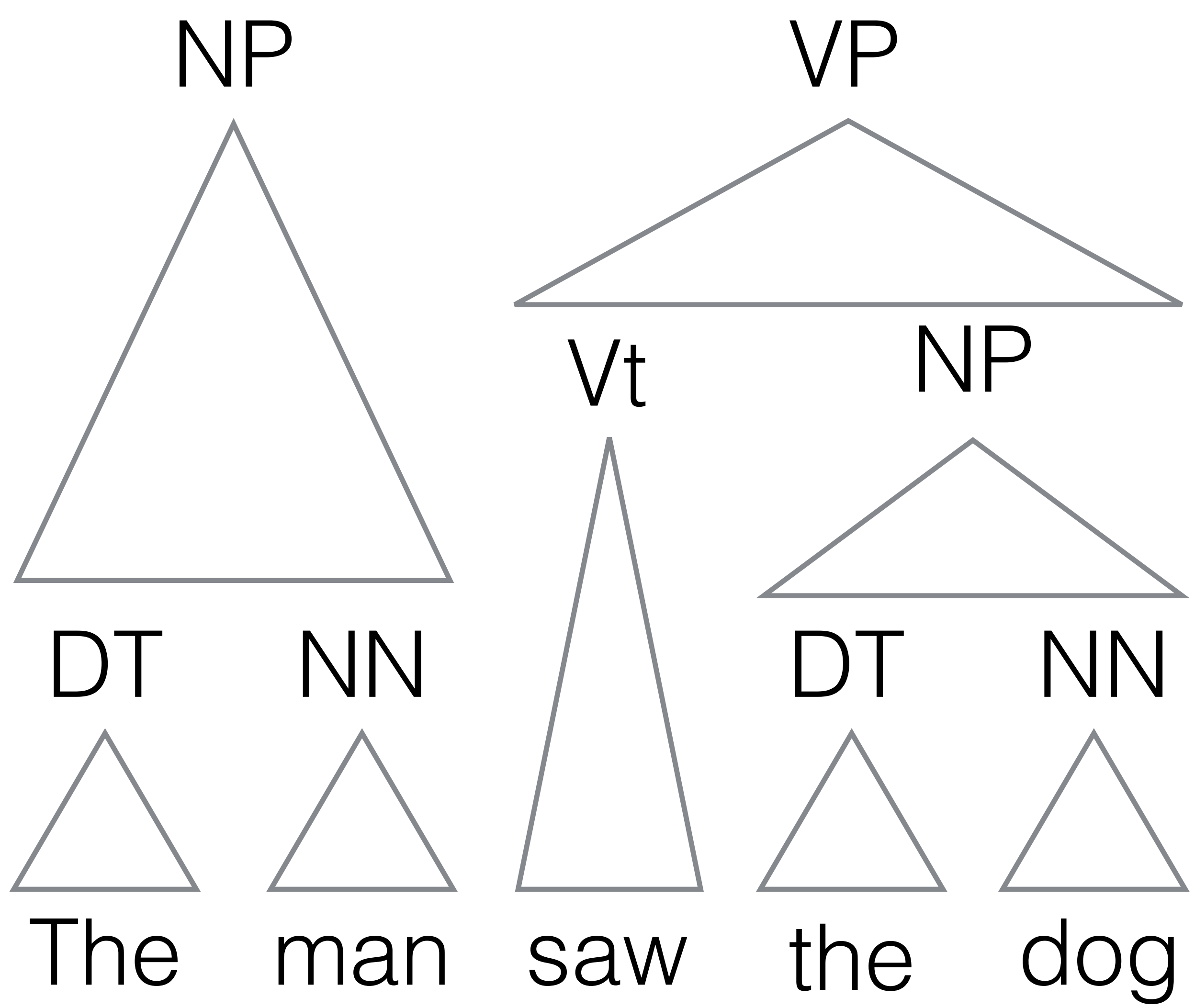

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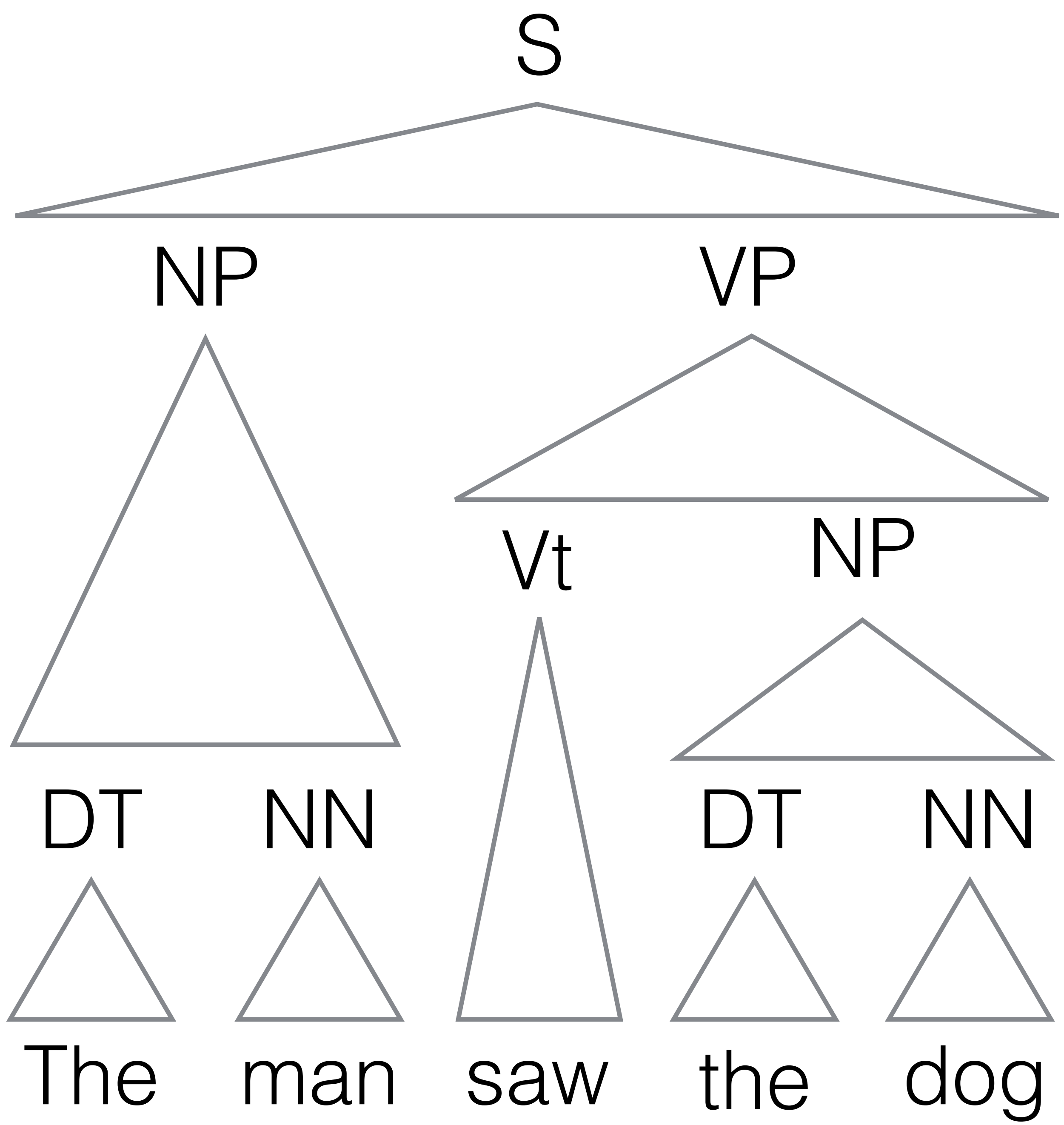

Language

A string $\mathbf{s} = s_1 \ldots s_n$ is generated/accepted by G if

$$S \Rightarrow^* \mathbf{s}$$

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

Language of G

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

Chomsky Normal Form

Every CFG is weakly equivalent to another such that

- $X \rightarrow Y\ Z$ where $X, Y, Z \in N$
- $X \rightarrow w$ where $w \in \Sigma$
- and possibly $S \rightarrow \varepsilon$

[Hopcroft and Ullman, 1979]

Parsing as Deduction

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Deductive process to prove claims about grammaticality

[Shieber et al., 1995]

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- focus on strategy rather than implementation

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- dynamic program follows directly

Parsing as Deduction

Deductive process to prove claims about grammaticality
[Shieber et al., 1995]

- 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

- $\dfrac{A_1 \ldots A_m}{B}$ (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

Shift-Reduce 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

Shift-Reduce Example

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Rule	Condition	Statement	Queue

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Shift-Reduce Example

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

S → NP VP
VP → Vi
VP → Vt NP
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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

S → NP VP
VP → Vi
VP → Vt NP
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NP → DT NN
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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

S → NP VP
VP → Vi
VP → Vt NP
VP → VP PP
NP → DT NN
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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

S → NP VP
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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

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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

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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

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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

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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

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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

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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]				∅

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Shift-Reduce

Input: G and $w_1 \ldots w_n$

Item form: $[\alpha\bullet, j]$
asserts that $\alpha \Rightarrow^* w_1 \ldots w_j$ or

that $\alpha\, w_{j+1} \ldots w_n \Rightarrow^* w_1 \ldots w_j$

Axiom: $[\bullet, 0]$

Goal: $[S\bullet, n]$

Scan (shift)
asserts that $\alpha \Rightarrow^* w_1 \ldots w_j\, w_{j+1}$

Complete (reduce)
asserts that $\alpha B \Rightarrow^* w_1 \ldots w_j$

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

$$\textsc{Reduce}\quad \frac{[\alpha\,\gamma\bullet, j]}{[\alpha\, B\bullet, j]}\quad B \rightarrow \gamma \in R$$

Top-Down recognition

Input: G and $w_1 \dots w_n$

Item form: $[\bullet\beta, j]$
asserts that $S \Rightarrow^* w_1 \dots w_j \; \beta$

Axiom: $[\bullet S, 0]$

Goal: $[\bullet, n]$

Scan
asserts that $S \Rightarrow^* w_1 \dots w_j \, w_{j+1} \, \beta$

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

Predict
asserts that $S \Rightarrow^* w_1 \dots w_j \, B \, \beta$

$$\textsc{Predict} \quad \frac{\bullet B \;\, \beta, j}{[\bullet\gamma \;\, \beta, j]} \quad B \to \gamma \in R$$

Top-Down Example

Input: *the man sleeps*

S → NP VP
VP → Vi
VP → Vt NP
VP → VP PP
NP → DT NN
NP → NP PP
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Top-Down Example

Input: *the man sleeps*

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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
VP → VP PP
NP → DT NN
NP → NP PP
PP → IN NP
Vi → sleeps
Vt → saw
NN → man
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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
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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

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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

S → NP VP
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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

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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

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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

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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, 10

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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, 10
	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, 10
	VP → Vt NP	9	[• Vt NP, 2]	
	VP → VP PP	10	[• VP PP, 2]	

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, 10
	VP → Vt NP	9	[• Vt NP, 2]	
	VP → VP PP	10	[• VP PP, 2]	
Predict: [8]	Vi → sleeps	11	[• sleeps, 2]	9, 10, 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, 10
	VP → Vt NP	9	[• Vt NP, 2]	
	VP → VP PP	10	[• VP PP, 2]	
Predict: [8]	Vi → sleeps	11	[• sleeps, 2]	9, 10, 11
		12		10, 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, 10
	VP → Vt NP	9	[• Vt NP, 2]	
	VP → VP PP	10	[• VP PP, 2]	
Predict: [8]	Vi → sleeps	11	[• sleeps, 2]	9, 10, 11
		12		10, 11
		13		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, 10
	VP → Vt NP	9	[• Vt NP, 2]	
	VP → VP PP	10	[• VP PP, 2]	
Predict: [8]	Vi → sleeps	11	[• sleeps, 2]	9, 10, 11
		12		10, 11
		13		11
Scan: [11]		14	[•, 3]	14

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, 10
	VP → Vt NP	9	[• Vt NP, 2]	
	VP → VP PP	10	[• VP PP, 2]	
Predict: [8]	Vi → sleeps	11	[• sleeps, 2]	9, 10, 11
		12		10, 11
		13		11
Scan: [11]		14	[•, 3]	14
GOAL: [14]				∅

- 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

CKY - CNF only

Input: G and $s = w_1 \ldots w_n$

Item form: $[i, X, j]$
asserts that $X \Rightarrow^* w_{i+1} \ldots w_j$

Axioms: $[i, X, i+1]$ $\quad X \rightarrow w_i \in R$

Goal: $[0, S, n]$

Merge:
asserts that
$w_{i+1} \ldots w_k \, w_{k+1} \ldots w_j \Rightarrow^* w_{i+1} \ldots w_j$

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

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
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

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	

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

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

Input: *the man saw the dog*

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
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

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

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

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

CKY Example

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

Input: *the man saw the dog*

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

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

Input: *the man saw the dog*

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

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

Input: *the man saw the dog*

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"

${}_0S_3 \rightarrow {}_0NP_2\ {}_2VP_3$
${}_0NP_2 \rightarrow {}_0DT_1\ {}_1NN_2$
${}_2VP_3 \rightarrow {}_2Vi_3$
${}_0DT_1 \rightarrow \text{the}$
${}_1NN_2 \rightarrow \text{man}$
${}_2Vi_3 \rightarrow \text{sleeps}$

0 1 2 3

Rule Segmentation: "Split Points"

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

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

$_2VP_3 \rightarrow {_2Vi_3}$

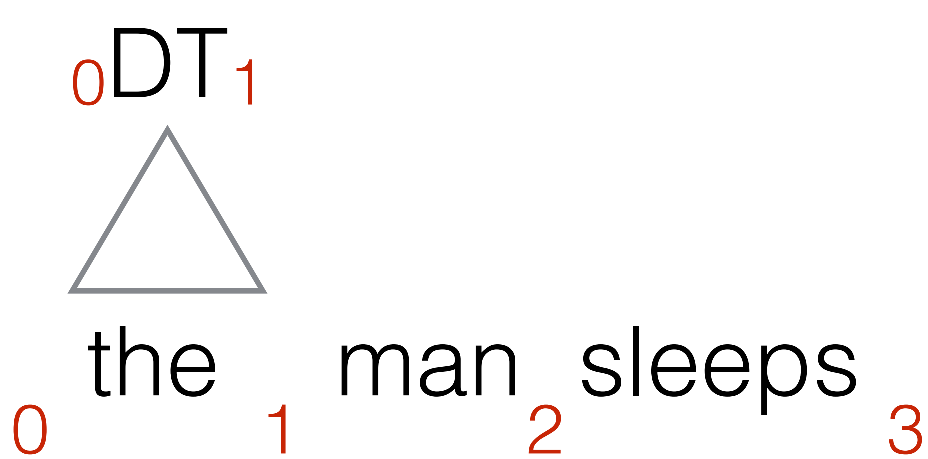
$_0DT_1 \rightarrow$ the

$_1NN_2 \rightarrow$ man

$_2Vi_3 \rightarrow$ sleeps

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

Rule Segmentation: "Split Points"



$${}_0\mathrm{S}_3 \rightarrow {}_0\mathrm{NP}_2\ {}_2\mathrm{VP}_3$$

$${}_0\mathrm{NP}_2 \rightarrow {}_0\mathrm{DT}_1\ {}_1\mathrm{NN}_2$$

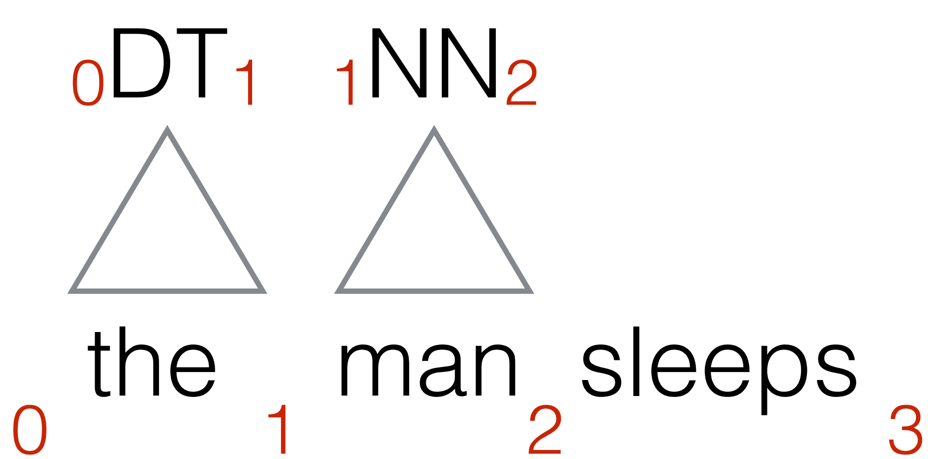
$${}_2\mathrm{VP}_3 \rightarrow {}_2\mathrm{Vi}_3$$

$${}_0\mathrm{DT}_1 \rightarrow \text{the}$$

$${}_1\mathrm{NN}_2 \rightarrow \text{man}$$

$${}_2\mathrm{Vi}_3 \rightarrow \text{sleeps}$$

Rule Segmentation: "Split Points"



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

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

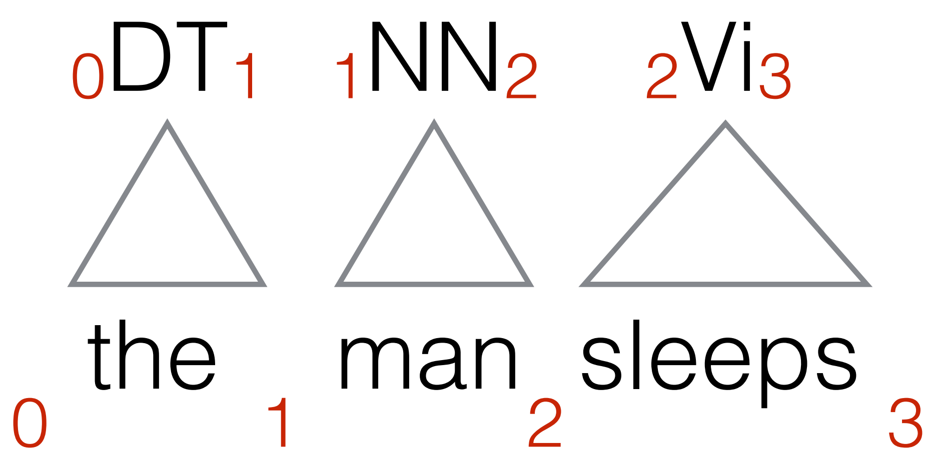
$${}_2VP_3 \rightarrow {}_2Vi_3$$

$${}_0DT_1 \rightarrow \text{the}$$

$${}_1NN_2 \rightarrow \text{man}$$

$${}_2Vi_3 \rightarrow \text{sleeps}$$

Rule Segmentation: "Split Points"



$${}_0\mathrm{S}_3 \rightarrow {}_0\mathrm{NP}_2\ {}_2\mathrm{VP}_3$$

$${}_0\mathrm{NP}_2 \rightarrow {}_0\mathrm{DT}_1\ {}_1\mathrm{NN}_2$$

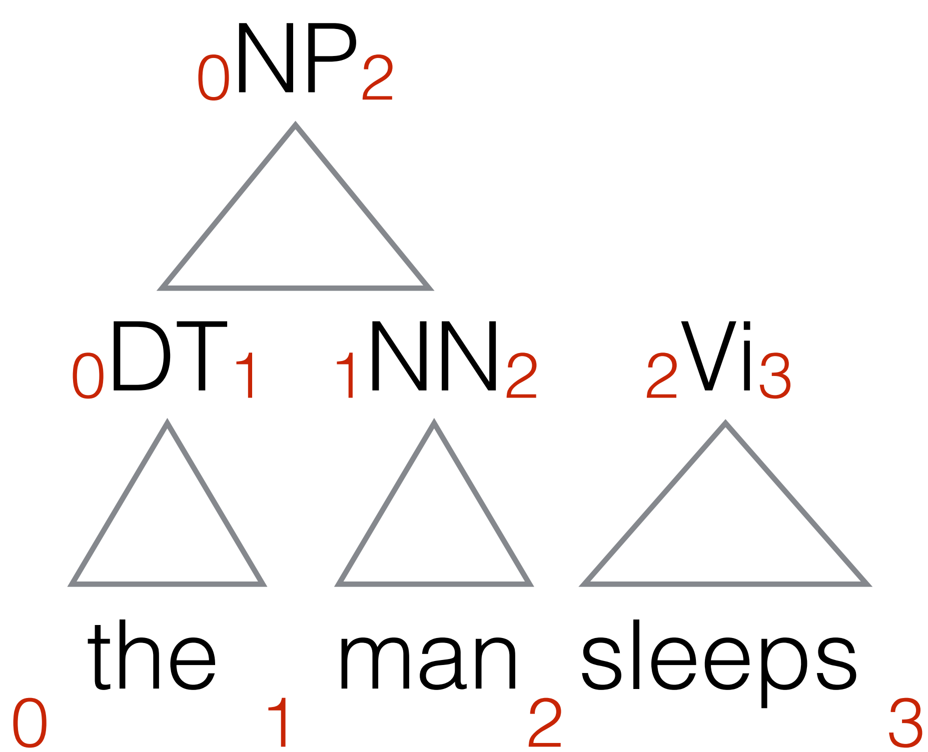
$${}_2\mathrm{VP}_3 \rightarrow {}_2\mathrm{Vi}_3$$

$${}_0\mathrm{DT}_1 \rightarrow \text{the}$$

$${}_1\mathrm{NN}_2 \rightarrow \text{man}$$

$${}_2\mathrm{Vi}_3 \rightarrow \text{sleeps}$$

Rule Segmentation: "Split Points"



${}_0\mathrm{S}_3 \rightarrow {}_0\mathrm{NP}_2\ {}_2\mathrm{VP}_3$

${}_0\mathrm{NP}_2 \rightarrow {}_0\mathrm{DT}_1\ {}_1\mathrm{NN}_2$

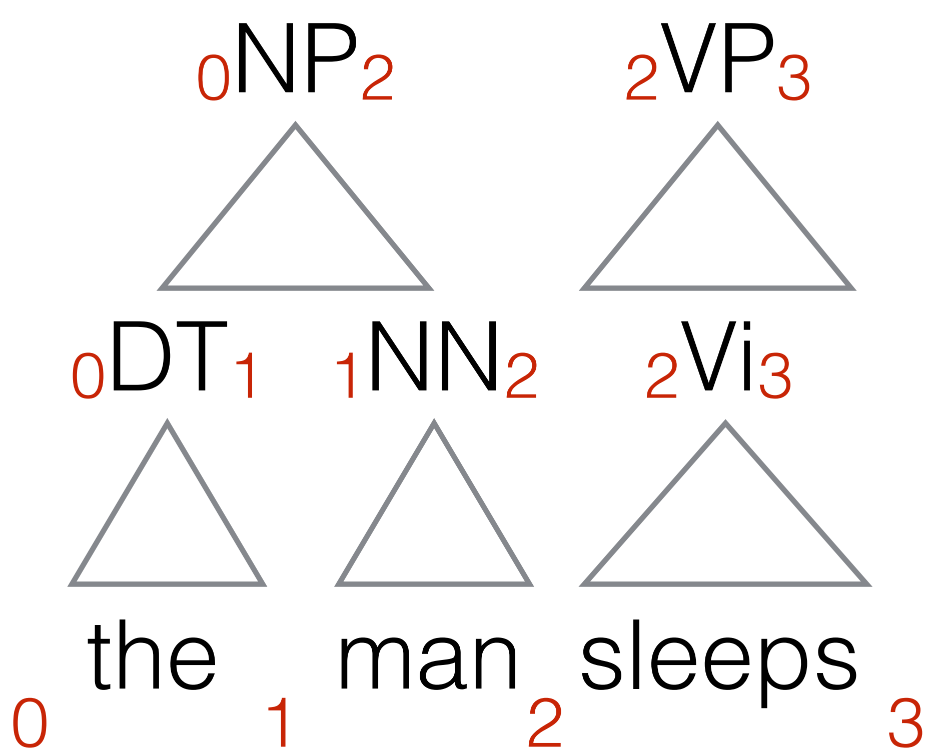
${}_2\mathrm{VP}_3 \rightarrow {}_2\mathrm{Vi}_3$

${}_0\mathrm{DT}_1 \rightarrow$ the

${}_1\mathrm{NN}_2 \rightarrow$ man

${}_2\mathrm{Vi}_3 \rightarrow$ sleeps

Rule Segmentation: "Split Points"



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

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

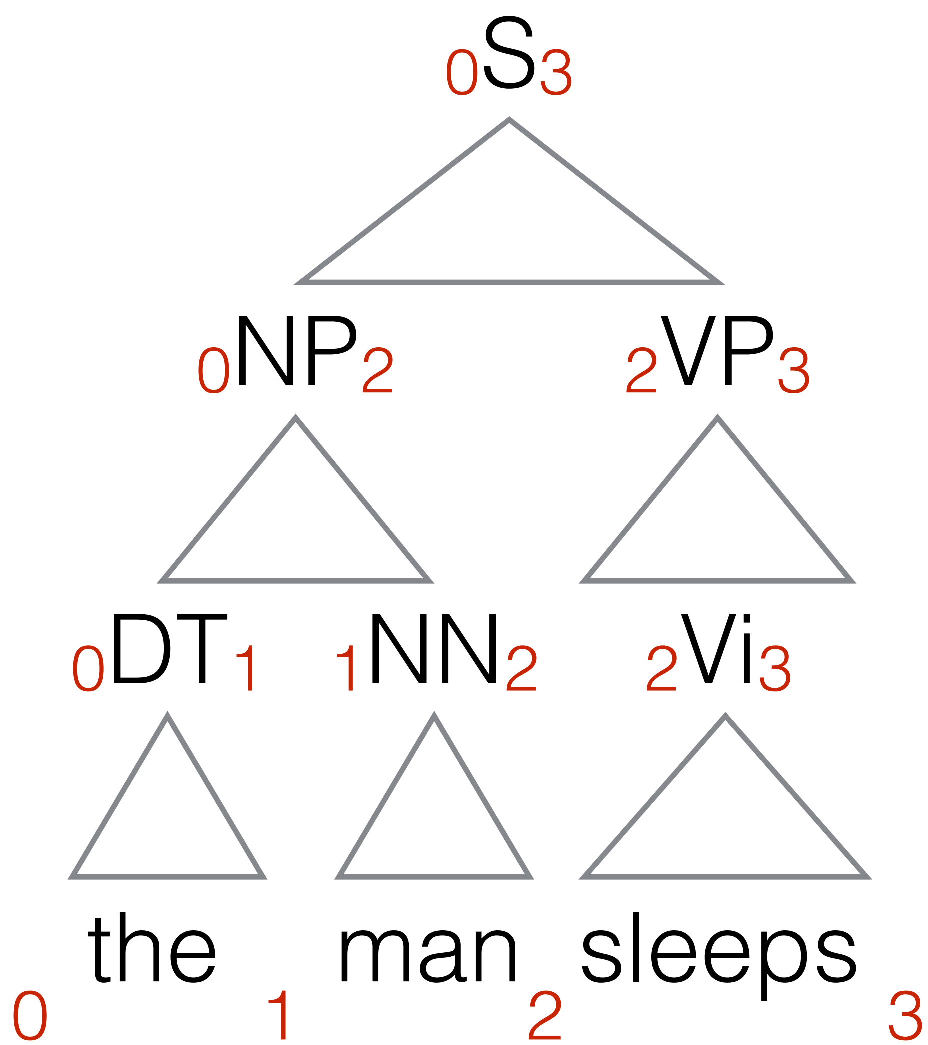
$${}_2VP_3 \rightarrow {}_2Vi_3$$

$${}_0DT_1 \rightarrow \text{the}$$

$${}_1NN_2 \rightarrow \text{man}$$

$${}_2Vi_3 \rightarrow \text{sleeps}$$

Rule Segmentation: "Split Points"



${}_0\mathrm{S}_3 \rightarrow {}_0\mathrm{NP}_2\ {}_2\mathrm{VP}_3$

${}_0\mathrm{NP}_2 \rightarrow {}_0\mathrm{DT}_1\ {}_1\mathrm{NN}_2$

${}_2\mathrm{VP}_3 \rightarrow {}_2\mathrm{Vi}_3$

${}_0\mathrm{DT}_1 \rightarrow$ the

${}_1\mathrm{NN}_2 \rightarrow$ man

${}_2\mathrm{Vi}_3 \rightarrow$ sleeps

"Dotted items"

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

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When that's not the case, we have to **scan rules symbol by symbol** using a general mechanism:

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

When that's not the case, we have to **scan rules symbol by symbol** using a general mechanism:

Item form: $[i, X \rightarrow \alpha_{\blacksquare} \bullet \beta_{\square}, j]$ where $X \rightarrow \alpha\ \beta \in R$ is a rule

"Dotted items"

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- The filled box represents a segmentation of $[0 .. j]$ into $|\alpha|$ adjacent parts

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- In general, we segment rules with respect to the input $w_1 \ldots w_n$
- 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 $|\alpha|$ adjacent parts
- The empty box has no actual role, it's just a reminder that the segmentation beyond j is unknown

CKY+

Input: G and $s = w_1 \ldots w_n$

Item form: $[i, X \rightarrow \alpha_\blacksquare \bullet \beta_\square, j]$
asserts that $X \Rightarrow^* w_{i+1} \ldots w_j \beta$

Axioms: $[i, X \rightarrow w_i \bullet \alpha_\square, i+1]$ $\quad X \rightarrow w_i \alpha \in R$
$[i, X \rightarrow \varepsilon \bullet, i]$ $\quad X \rightarrow \varepsilon \in R$

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

Scan

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

Prefix

$$\frac{[i, Y \rightarrow \alpha_\blacksquare \bullet, j]}{[i, X \rightarrow Y_{i,j} \bullet \beta_\square, j]} \quad X \rightarrow Y \beta \in R$$

Complete

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

CKY+ Example

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

Input: *the man sleeps*

CKY+ Example

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
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Input: *the man sleeps*

Rule	Condition	Item	Active	Passive

CKY+ 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

Rule	Condition		Item	Active	Passive
Axiom	DT → the	1	[0, DT → the •,1]	1	

CKY+ Example

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

Input: *the man sleeps*

Rule	Condition		Item	Active	Passive
Axiom	DT → the	1	[0, DT → the •,1]	1	
	NN → man	2	[1, NN → man •, 2]	1, 2	

CKY+ Example

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

Input: *the man sleeps*

Rule	Condition		Item	Active	Passive
Axiom	DT → the	1	[0, DT → the •,1]	1	
	NN → man	2	[1, NN → man •, 2]	1, 2	
	Vi → sleeps	3	[2, Vi → sleeps •, 3]	1, 2, 3	

CKY+ Example

S → NP VP	Vi → sleeps
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VP → Vt NP	NN → man
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NP → DT NN	NN → telescope
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Input: *the man sleeps*

Rule	Condition		Item	Active	Passive
Axiom	DT → the	1	[0, DT → the •,1]	1	
	NN → man	2	[1, NN → man •, 2]	1, 2	
	Vi → sleeps	3	[2, Vi → sleeps •, 3]	1, 2, 3	
Prefix: [1]	NP → DT NN	4	[0, NP → $DT_{0,1}$ • NN, 2]	2, 3, 4	1

CKY+ Example

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

Input: *the man sleeps*

Rule	Condition		Item	Active	Passive
Axiom	DT → the	1	[0, DT → the •,1]	1	
	NN → man	2	[1, NN → man •, 2]	1, 2	
	Vi → sleeps	3	[2, Vi → sleeps •, 3]	1, 2, 3	
Prefix: [1]	NP → DT NN	4	[0, NP → $DT_{0,1}$ • NN, 2]	2, 3, 4	1
				3, 4	2

CKY+ Example

Input: *the man sleeps*

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Rule	Condition		Item	Active	Passive
Axiom	DT → the	1	[0, DT → the •,1]	1	
	NN → man	2	[1, NN → man •, 2]	1, 2	
	Vi → sleeps	3	[2, Vi → sleeps •, 3]	1, 2, 3	
Prefix: [1]	NP → DT NN	4	[0, NP → $DT_{0,1}$ • NN, 2]	2, 3, 4	1
				3, 4	2
Prefix: [3]	VP → Vi	5	[2, VP → $Vi_{2,3}$ •, 3]	4, 5	3

CKY+ Example

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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Input: *the man sleeps*

Rule	Condition		Item	Active	Passive
Axiom	DT → the	1	[0, DT → the •, 1]	1	
	NN → man	2	[1, NN → man •, 2]	1, 2	
	Vi → sleeps	3	[2, Vi → sleeps •, 3]	1, 2, 3	
Prefix: [1]	NP → DT NN	4	[0, NP → $DT_{0,1}$ • NN, 2]	2, 3, 4	1
				3, 4	2
Prefix: [3]	VP → Vi	5	[2, VP → $Vi_{2,3}$ •, 3]	4, 5	3
Complete: [4] [2]		6	[0, NP → $DT_{0,1}$ $NN_{1,2}$ •, 2]	5, 6	4

CKY+ Example

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VP → Vt NP	NN → man
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Input: *the man sleeps*

Rule	Condition		Item	Active	Passive
Axiom	DT → the	1	[0, DT → the •, 1]	1	
	NN → man	2	[1, NN → man •, 2]	1, 2	
	Vi → sleeps	3	[2, Vi → sleeps •, 3]	1, 2, 3	
Prefix: [1]	NP → DT NN	4	[0, NP → $\text{DT}_{0,1}$ • NN, 2]	2, 3, 4	1
				3, 4	2
Prefix: [3]	VP → Vi	5	[2, VP → $\text{Vi}_{2,3}$ •, 3]	4, 5	3
Complete: [4] [2]		6	[0, NP → $\text{DT}_{0,1}$ $\text{NN}_{1,2}$ •, 2]	5, 6	4
				6	5

CKY+ Example

Input: *the man sleeps*

S → NP VP	Vi → sleeps
VP → Vi	Vt → saw
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Rule	Condition		Item	Active	Passive
Axiom	DT → the	1	[0, DT → the •,1]	1	
	NN → man	2	[1, NN → man •, 2]	1, 2	
	Vi → sleeps	3	[2, Vi → sleeps •, 3]	1, 2, 3	
Prefix: [1]	NP → DT NN	4	[0, NP → $DT_{0,1}$ • NN, 2]	2, 3, 4	1
				3, 4	2
Prefix: [3]	VP → Vi	5	[2, VP → $Vi_{2,3}$ •, 3]	4, 5	3
Complete: [4] [2]		6	[0, NP → $DT_{0,1}$ $NN_{1,2}$ •, 2]	5, 6	4
				6	5
Prefix: [6]	S → NP VP	7	[0, S → $NP_{0,2}$ • VP, 2]	7	6

CKY+ Example

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

Input: *the man sleeps*

Rule	Condition		Item	Active	Passive
Axiom	DT → the	1	[0, DT → the •,1]	1	
	NN → man	2	[1, NN → man •, 2]	1, 2	
	Vi → sleeps	3	[2, Vi → sleeps •, 3]	1, 2, 3	
Prefix: [1]	NP → DT NN	4	[0, NP → $DT_{0,1}$ • NN, 2]	2, 3, 4	1
				3, 4	2
Prefix: [3]	VP → Vi	5	[2, VP → $Vi_{2,3}$ •, 3]	4, 5	3
Complete: [4] [2]		6	[0, NP → $DT_{0,1}$ $NN_{1,2}$ •, 2]	5, 6	4
				6	5
Prefix: [6]	S → NP VP	7	[0, S → $NP_{0,2}$ • VP, 2]	7	6
Complete: [7] [5]		8	[0, S → $NP_{0,2}$ $VP_{2,3}$ •, 3]	8	7

CKY+ 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

Rule	Condition		Item	Active	Passive
Axiom	DT → the	1	[0, DT → the •,1]	1	
	NN → man	2	[1, NN → man •, 2]	1, 2	
	Vi → sleeps	3	[2, Vi → sleeps •, 3]	1, 2, 3	
Prefix: [1]	NP → DT NN	4	[0, NP → $DT_{0,1}$ • NN, 2]	2, 3, 4	1
				3, 4	2
Prefix: [3]	VP → Vi	5	[2, VP → $Vi_{2,3}$ •, 3]	4, 5	3
Complete: [4] [2]		6	[0, NP → $DT_{0,1}$ $NN_{1,2}$ •, 2]	5, 6	4
				6	5
Prefix: [6]	S → NP VP	7	[0, S → $NP_{0,2}$ • VP, 2]	7	6
Complete: [7] [5]		8	[0, S → $NP_{0,2}$ $VP_{2,3}$ •, 3]	8	7
GOAL: [8]				∅	

Correctness of Parsing Strategy

Soundness: if a goal item is proven for **s**

- then **s** ∈ L(G)

Completeness: if **s** ∈ L(G)

- then a goal item can be proven for **s**

Parse Forest

Efficient representation of the whole space $T_G(\boldsymbol{s})$

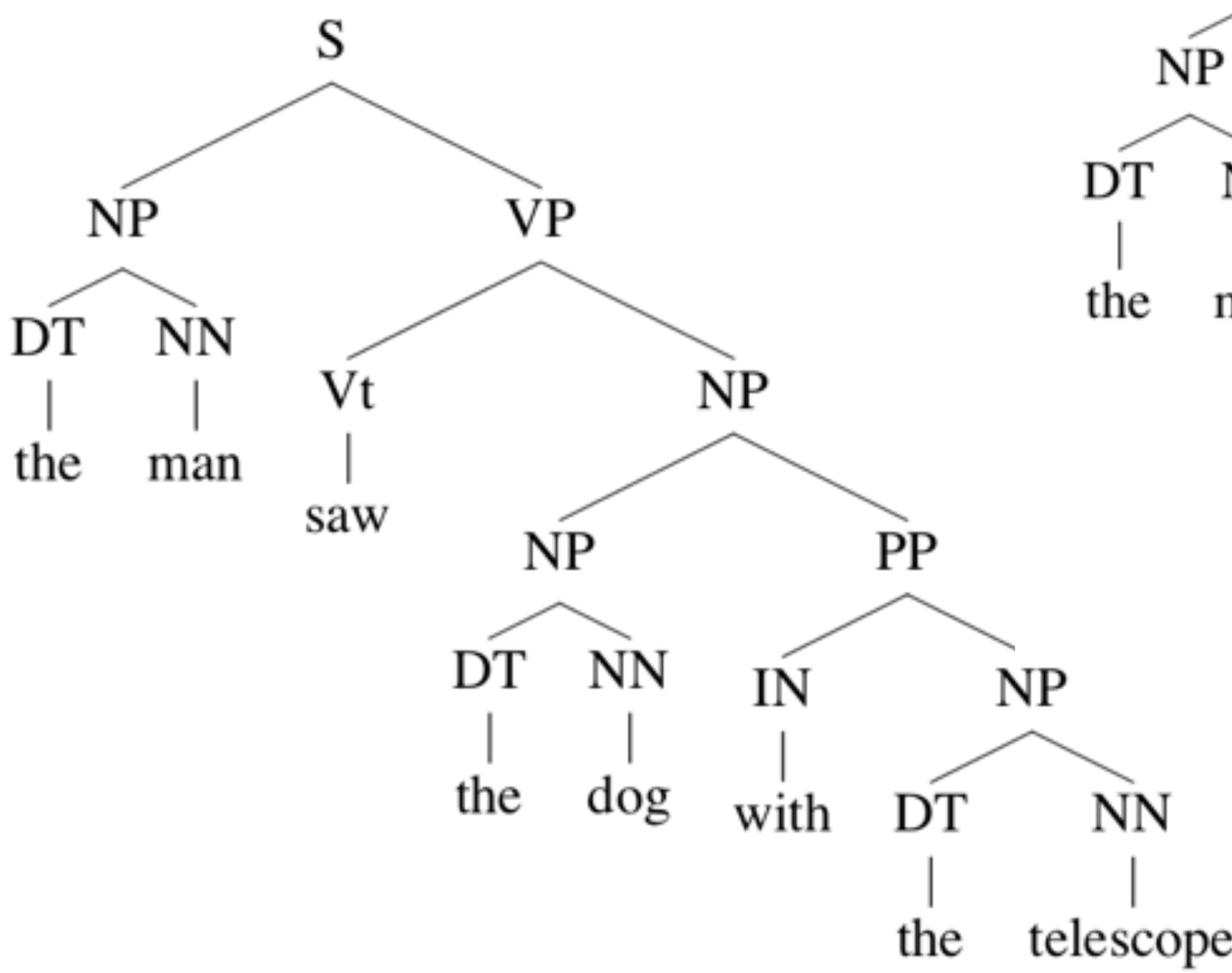
- each and every possible tree yielding **s**

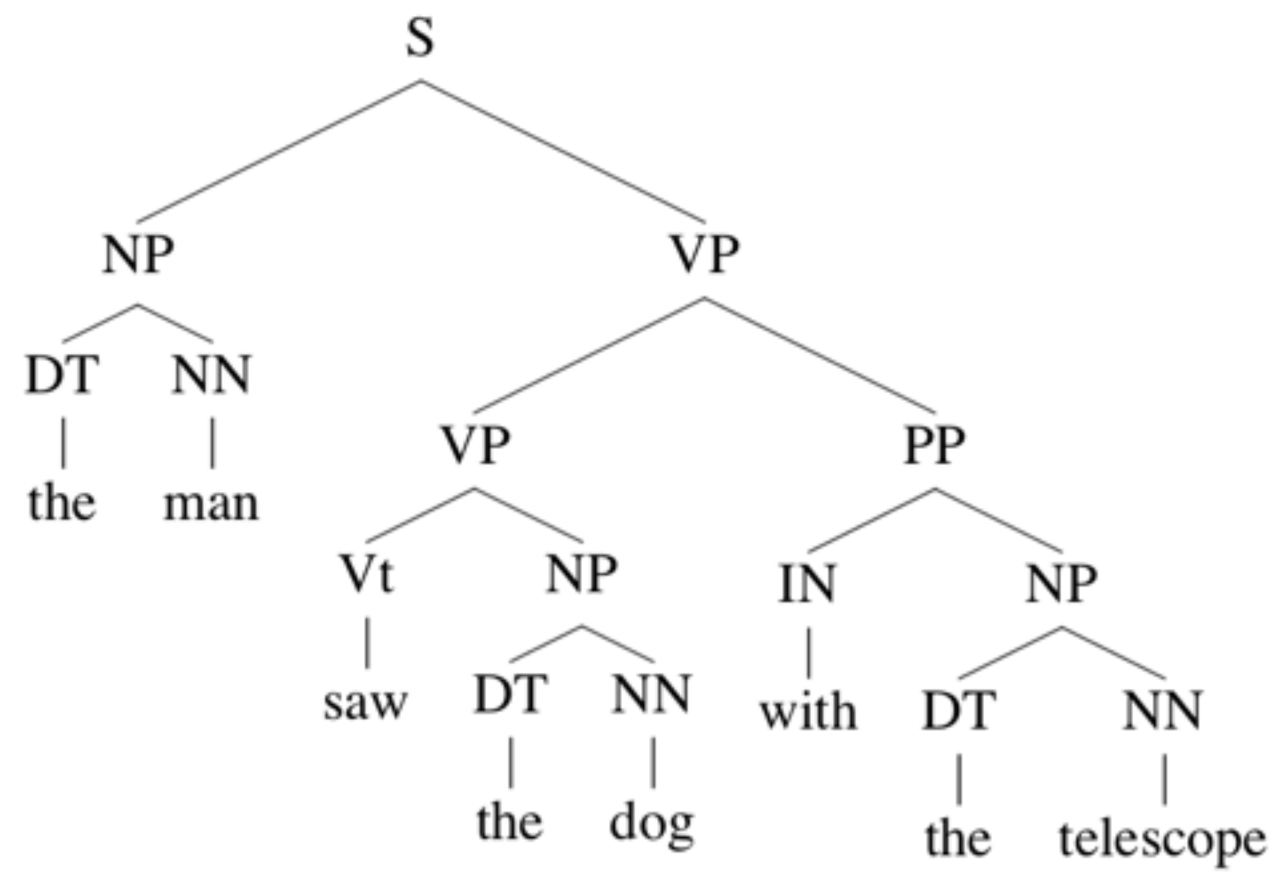
We must be able to represent partial derivations

- 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 $r \in R$ and

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

Probabilistic CFG

Distribution over trees

$$P(T = t, S = \text{yield}(t)) = P(T = \langle r_1 \ldots r_n \rangle, S = s)$$
$$= \prod_{i=1}^{n} \theta_{r_i} = \prod_{i=1}^{n} \theta_{X_i \rightarrow \alpha_i} = \prod_{r \in t}^{n} \theta_r{}^{n(r,t)}$$

and strings

$$P(S = s) = \sum_{t \in T_G(s)} P(T = t, S = s)$$

Estimation

Let us assume the parametric form of θ is a multinomial

- one categorical distribution per X ∈ N

Suppose we can observe a *treebank*, then by MLE

$$\theta_{X \to \alpha} = \frac{n(X \to \alpha)}{n(X)}$$
$$= \frac{n(X \to \alpha)}{\sum_{\alpha'} n(X \to \alpha')}$$

Weighted CKY+

Input: G and $s = w_1 \ldots w_n$

Item form: $[i, X \rightarrow \alpha_{\blacksquare} \bullet \beta_{\square}, j]$
asserts that $X \Rightarrow^* w_{i+1} \ldots w_j \beta$

Axioms: $[i, X \rightarrow w_i \bullet \alpha_{\square}, i+1]:\theta_r$ $\quad r = X \rightarrow w_i\, \alpha \in R$
$[i, X \rightarrow \varepsilon \bullet, i]:\theta_r$ $\quad r = X \rightarrow \varepsilon \in R$

Goal: $[0, S \rightarrow \alpha_{\blacksquare} \bullet, n]$

Scan

$$\frac{[i, X \rightarrow \alpha_{\blacksquare} \bullet w_{j+1}\, \beta_{\square}, j] : \theta_1}{[i, X \rightarrow \alpha_{\blacksquare} w_{j+1} \bullet \beta_{\square}, j+1] : \theta_1}$$

Prefix

$$\frac{[i, Y \rightarrow \alpha_{\blacksquare} \bullet, j] : \theta_1}{[i, X \rightarrow Y_{i,j} \bullet \beta_{\square}, j] : \theta_r} \quad r = X \rightarrow Y \beta \in R$$

Complete

$$\frac{[i, X \rightarrow \alpha_{\blacksquare} \bullet Y \beta_{\square}, k] : \theta_1 \; [k, Y \rightarrow \gamma_{\blacksquare} \bullet, j] : \theta_2}{[i, X \rightarrow \alpha_{\blacksquare} Y_{k,j} \bullet \beta_{\square}, j] : \theta_1}$$

Joint Distribution

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

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

${}_2VP_3 \rightarrow {}_2Vi_3$

${}_0DT_1 \rightarrow \text{the}$

${}_1NN_2 \rightarrow \text{man}$

${}_2Vi_3 \rightarrow \text{sleeps}$

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

${}_0\mathrm{S}_3 \rightarrow {}_0\mathrm{NP}_2\ {}_2\mathrm{VP}_3$

${}_0\mathrm{NP}_2 \rightarrow {}_0\mathrm{DT}_1\ {}_1\mathrm{NN}_2$

${}_2\mathrm{VP}_3 \rightarrow {}_2\mathrm{Vi}_3$

${}_0\mathrm{DT}_1 \rightarrow \text{the}$

${}_1\mathrm{NN}_2 \rightarrow \text{man}$

${}_2\mathrm{Vi}_3 \rightarrow \text{sleeps}$

Joint Distribution

${}_0\mathrm{S}_3 \rightarrow {}_0\mathrm{NP}_2 \ {}_2\mathrm{VP}_3$

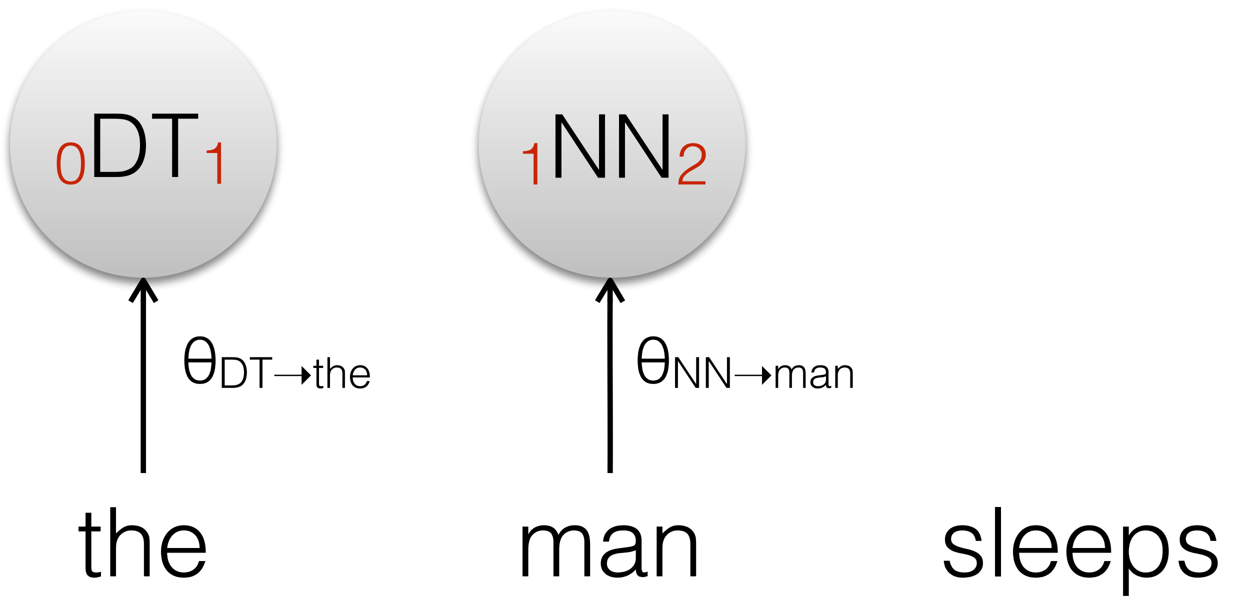
${}_0\mathrm{NP}_2 \rightarrow {}_0\mathrm{DT}_1 \ {}_1\mathrm{NN}_2$

${}_2\mathrm{VP}_3 \rightarrow {}_2\mathrm{Vi}_3$

${}_0\mathrm{DT}_1 \rightarrow \mathrm{the}$

${}_1\mathrm{NN}_2 \rightarrow \mathrm{man}$

${}_2\mathrm{Vi}_3 \rightarrow \mathrm{sleeps}$



Joint Distribution

${}_0\mathrm{S}_3 \rightarrow {}_0\mathrm{NP}_2\ {}_2\mathrm{VP}_3$

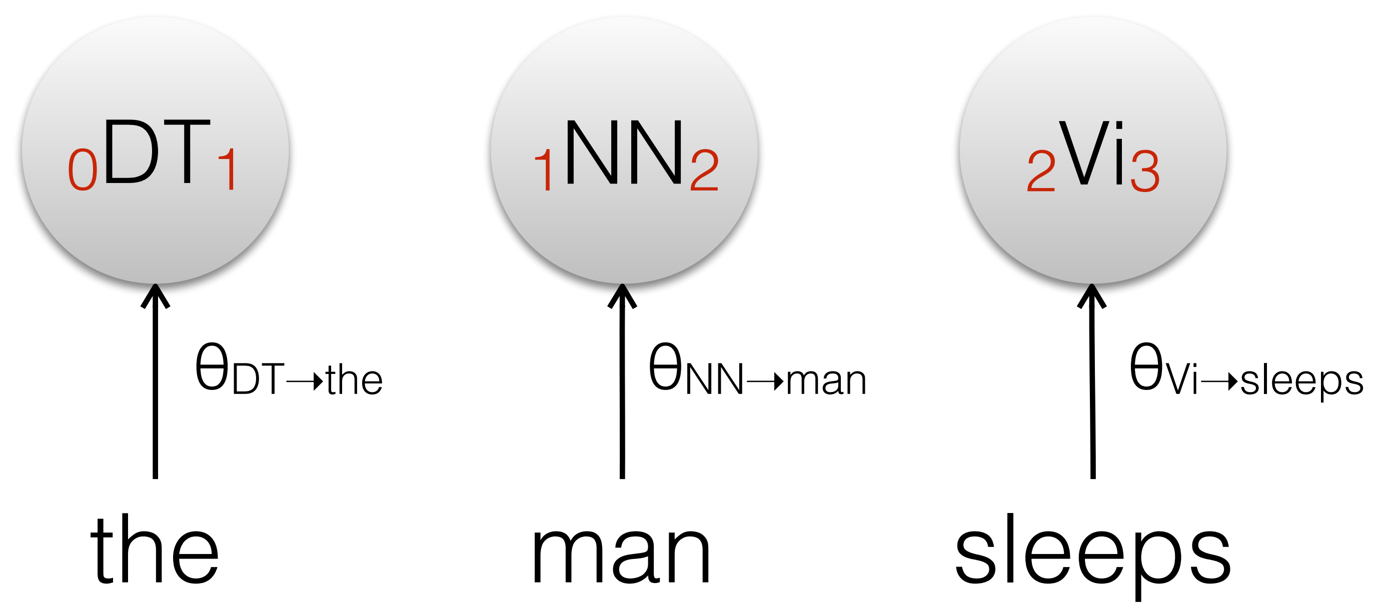
${}_0\mathrm{NP}_2 \rightarrow {}_0\mathrm{DT}_1\ {}_1\mathrm{NN}_2$

${}_2\mathrm{VP}_3 \rightarrow {}_2\mathrm{Vi}_3$

${}_0\mathrm{DT}_1 \rightarrow \text{the}$

${}_1\mathrm{NN}_2 \rightarrow \text{man}$

${}_2\mathrm{Vi}_3 \rightarrow \text{sleeps}$



Joint Distribution

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

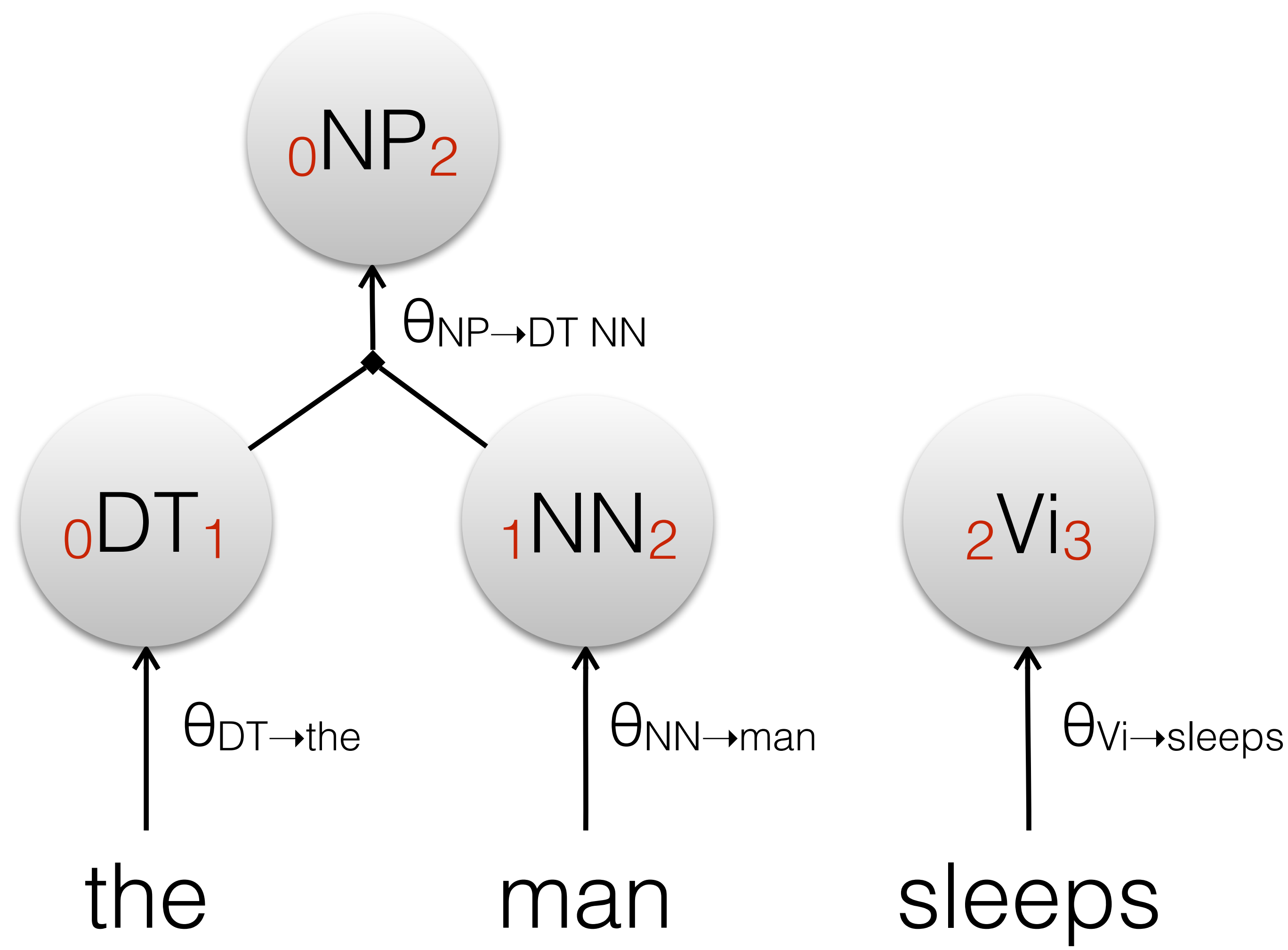
${}_0NP_2 \rightarrow {}_0DT_1 \; {}_1NN_2$

${}_2VP_3 \rightarrow {}_2Vi_3$

${}_0DT_1 \rightarrow \text{the}$

${}_1NN_2 \rightarrow \text{man}$

${}_2Vi_3 \rightarrow \text{sleeps}$



Joint Distribution

${}_0\mathrm{S}_3 \rightarrow {}_0\mathrm{NP}_2\ {}_2\mathrm{VP}_3$

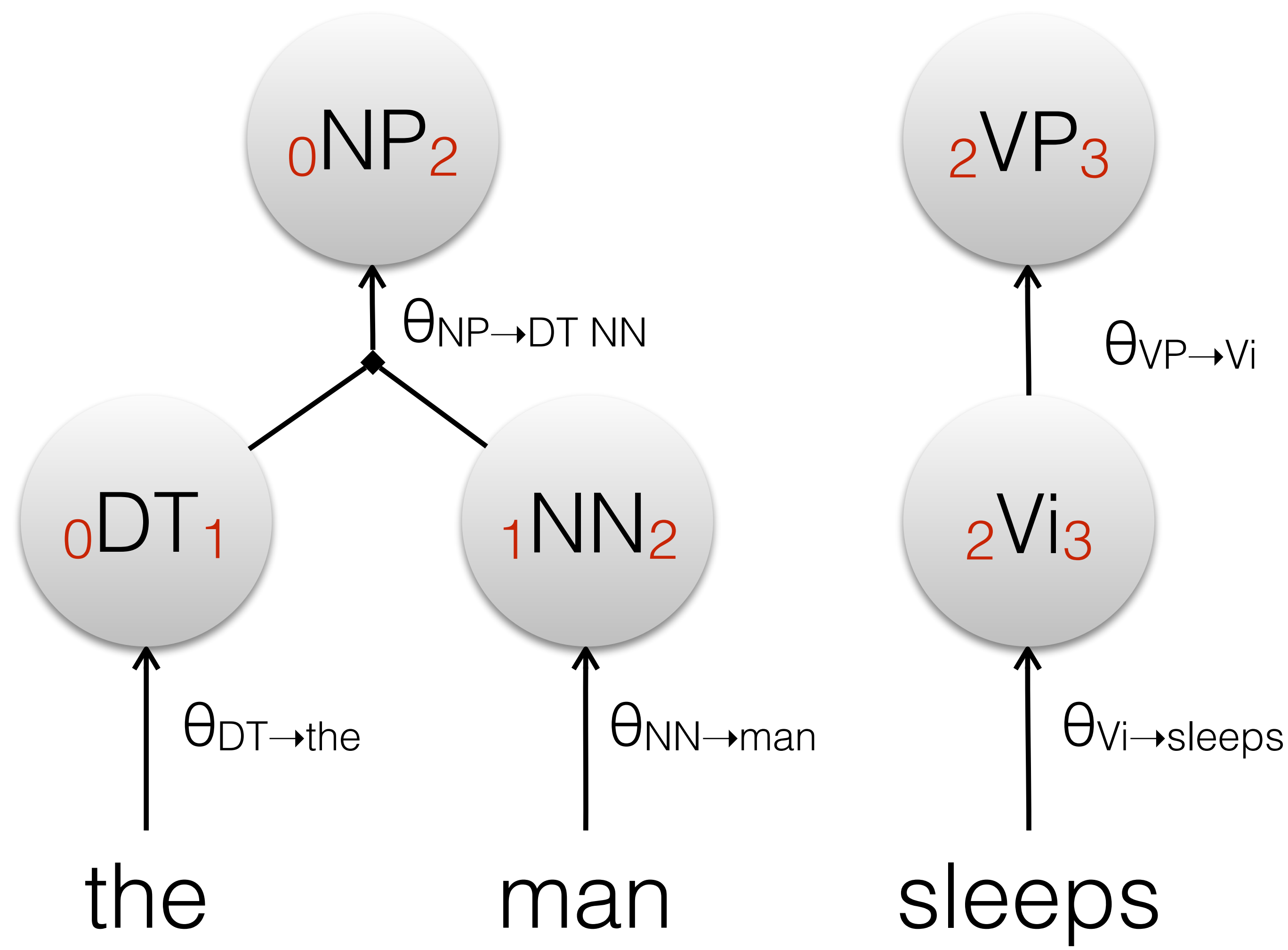
${}_0\mathrm{NP}_2 \rightarrow {}_0\mathrm{DT}_1\ {}_1\mathrm{NN}_2$

${}_2\mathrm{VP}_3 \rightarrow {}_2\mathrm{Vi}_3$

${}_0\mathrm{DT}_1 \rightarrow \text{the}$

${}_1\mathrm{NN}_2 \rightarrow \text{man}$

${}_2\mathrm{Vi}_3 \rightarrow \text{sleeps}$



Joint Distribution

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

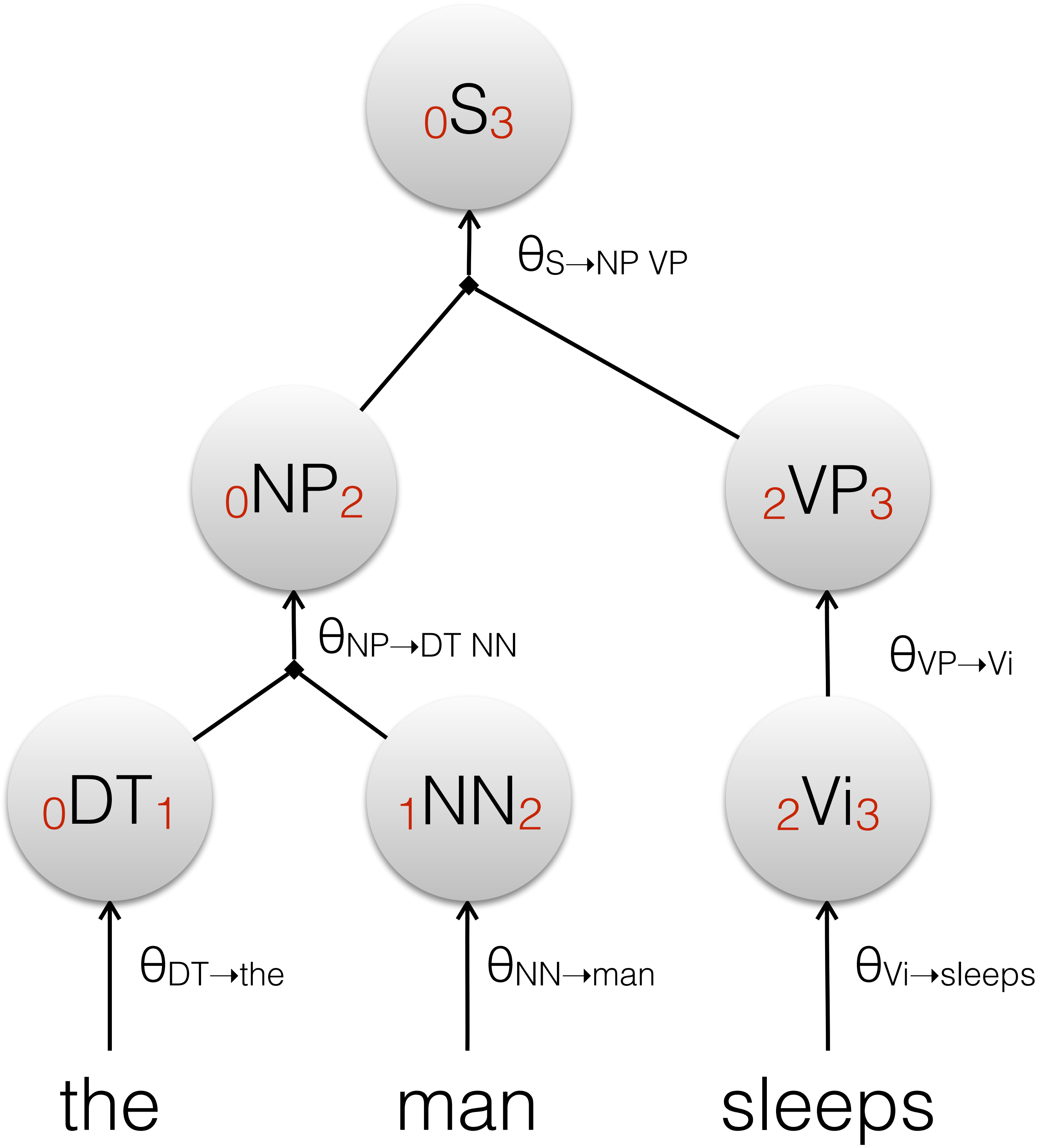
$_0NP_2 \rightarrow {_0DT_1}\ {_1NN_2}$

$_2VP_3 \rightarrow {_2Vi_3}$

$_0DT_1 \rightarrow$ the

$_1NN_2 \rightarrow$ man

$_2Vi_3 \rightarrow$ sleeps



Ambiguity

Ambiguity

the man

saw

the dog

with the telescope

Ambiguity

${}_0\mathrm{DT}_1$

$\theta_{\mathrm{DT}\rightarrow\mathrm{the}}$

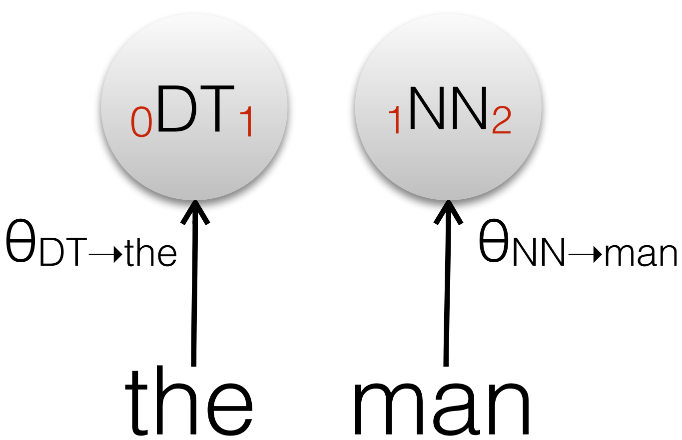
the man

saw

the dog

with the telescope

Ambiguity

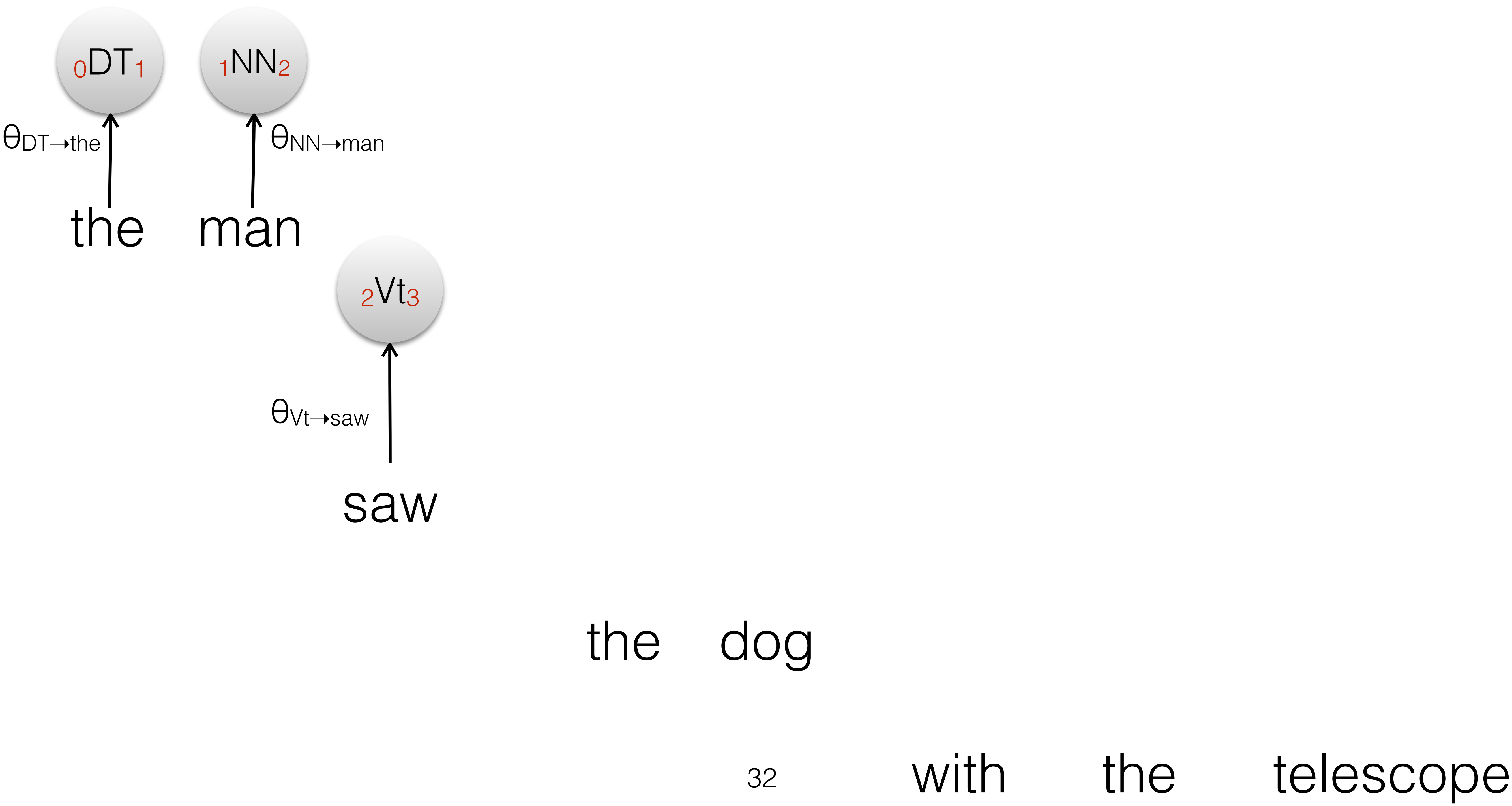


saw

the dog

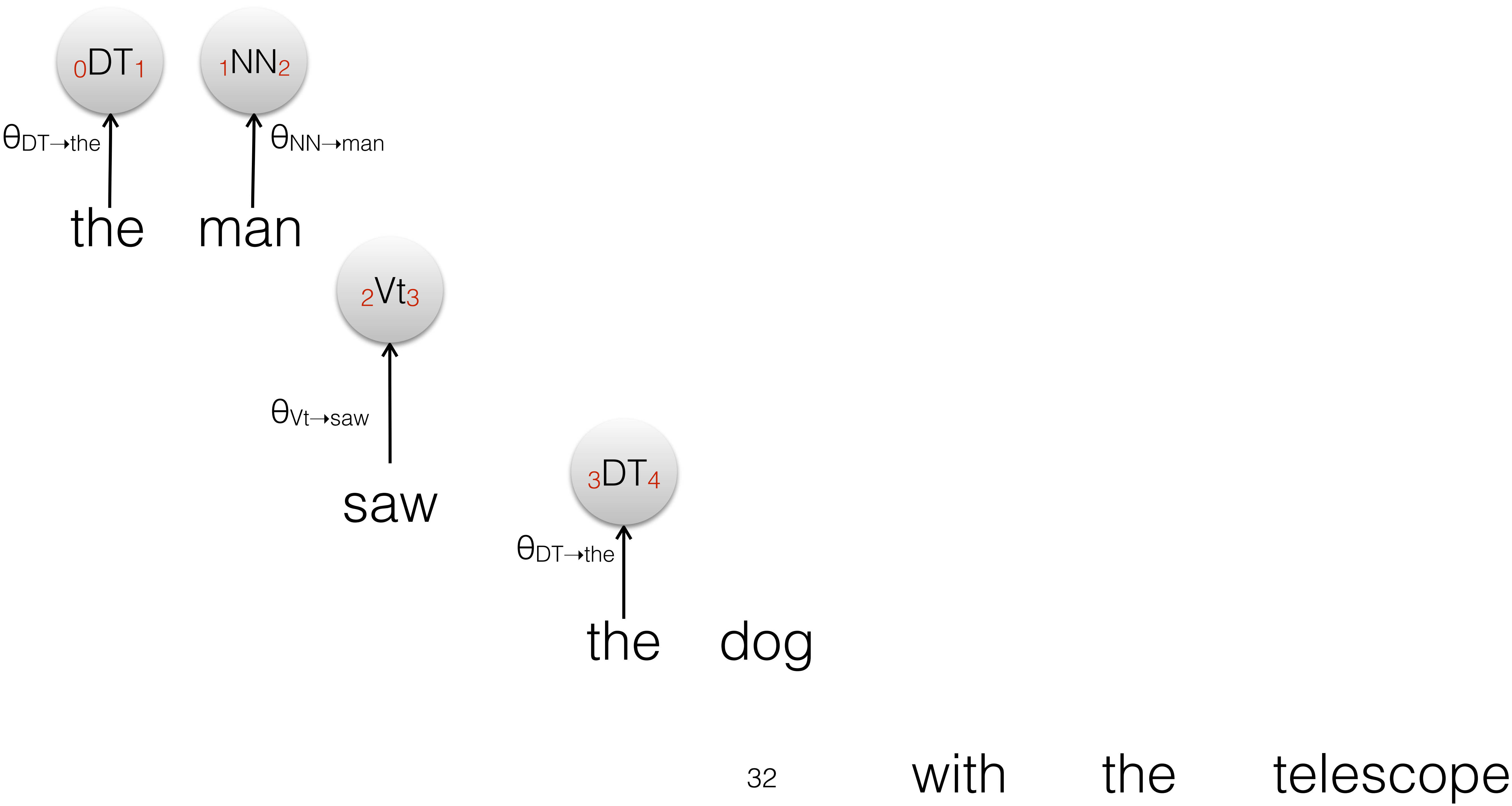
with the telescope

Ambiguity



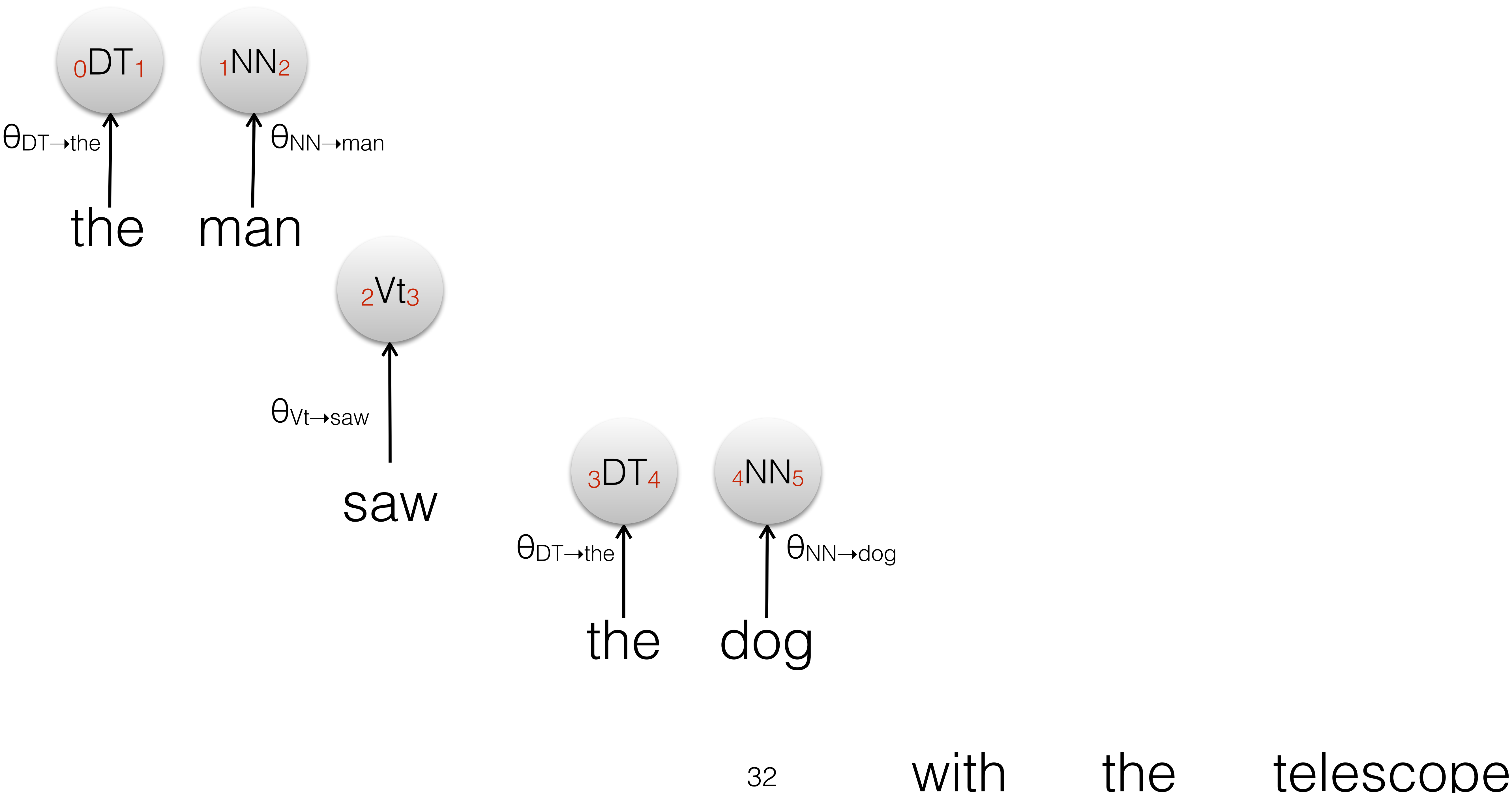
0DT1
1NN2
θDT→the
θNN→man
the
man
2Vt3
θVt→saw
saw
the
dog
with
the
telescope

Ambiguity



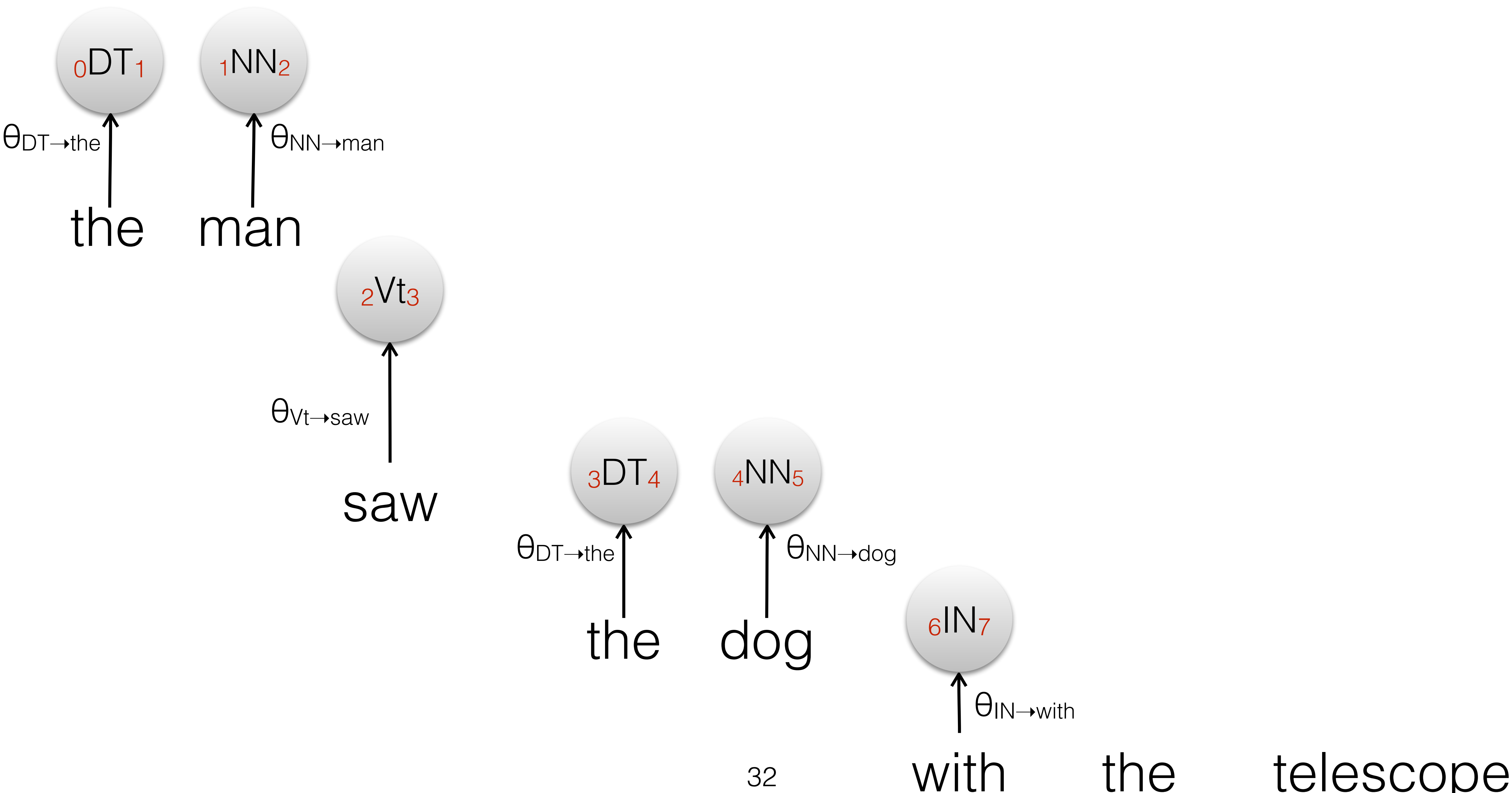
0DT1
1NN2
θDT→the
θNN→man
the
man
2Vt3
θVt→saw
saw
3DT4
θDT→the
the
dog
with
the
telescope

Ambiguity



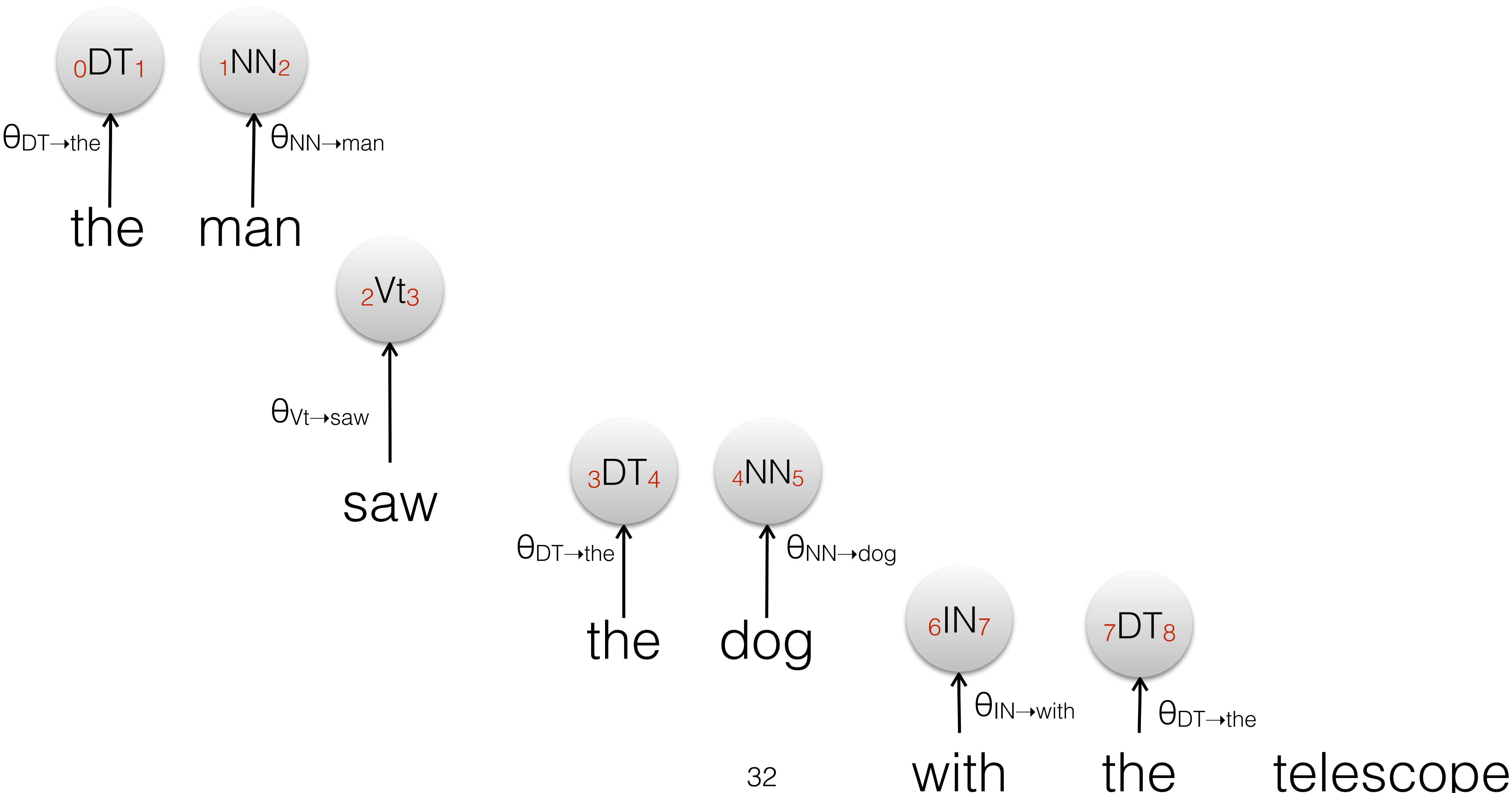
$_0DT_1$
$_1NN_2$
$\theta_{DT\to the}$
$\theta_{NN\to man}$
the
man
$_2Vt_3$
$\theta_{Vt\to saw}$
saw
$_3DT_4$
$_4NN_5$
$\theta_{DT\to the}$
$\theta_{NN\to dog}$
the
dog
with
the
telescope

Ambiguity



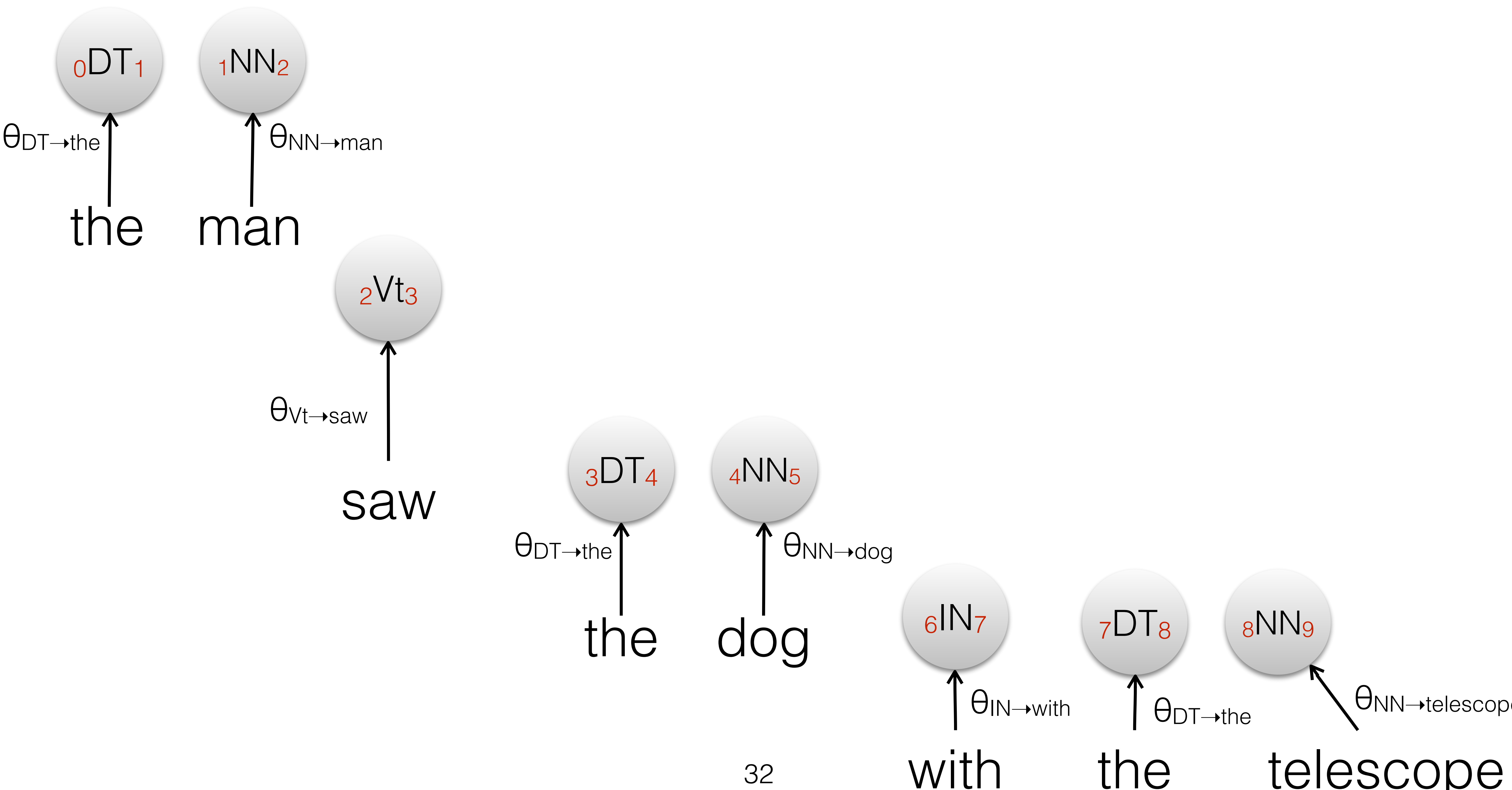
0DT1
1NN2
θDT→the
θNN→man
the
man
2Vt3
θVt→saw
saw
3DT4
4NN5
θDT→the
θNN→dog
the
dog
6IN7
θIN→with
with
the
telescope

Ambiguity

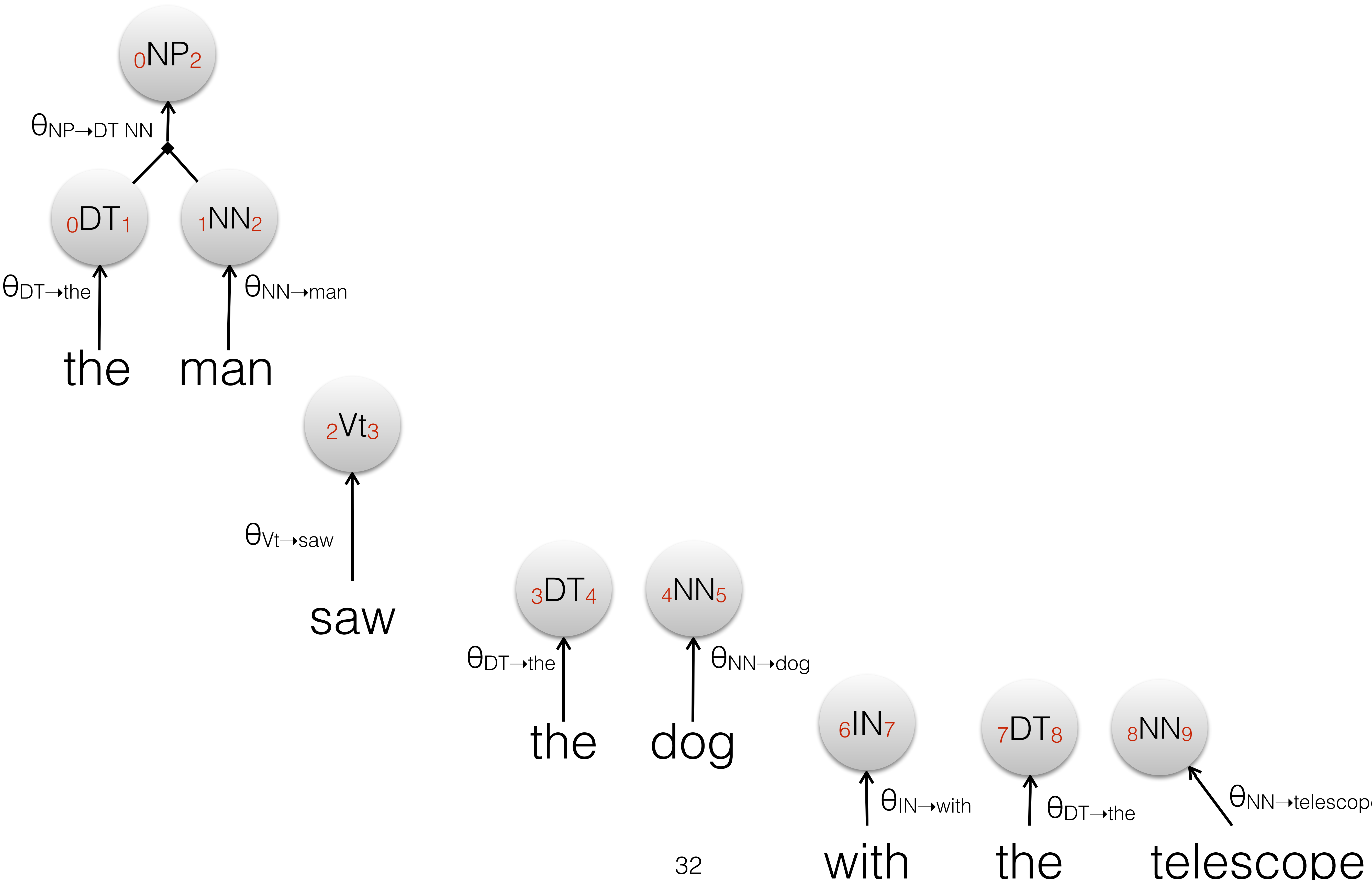


0DT1
1NN2
θDT→the
θNN→man
the
man
2Vt3
θVt→saw
saw
3DT4
4NN5
θDT→the
θNN→dog
the
dog
6IN7
7DT8
θIN→with
θDT→the
with
the
telescope

Ambiguity

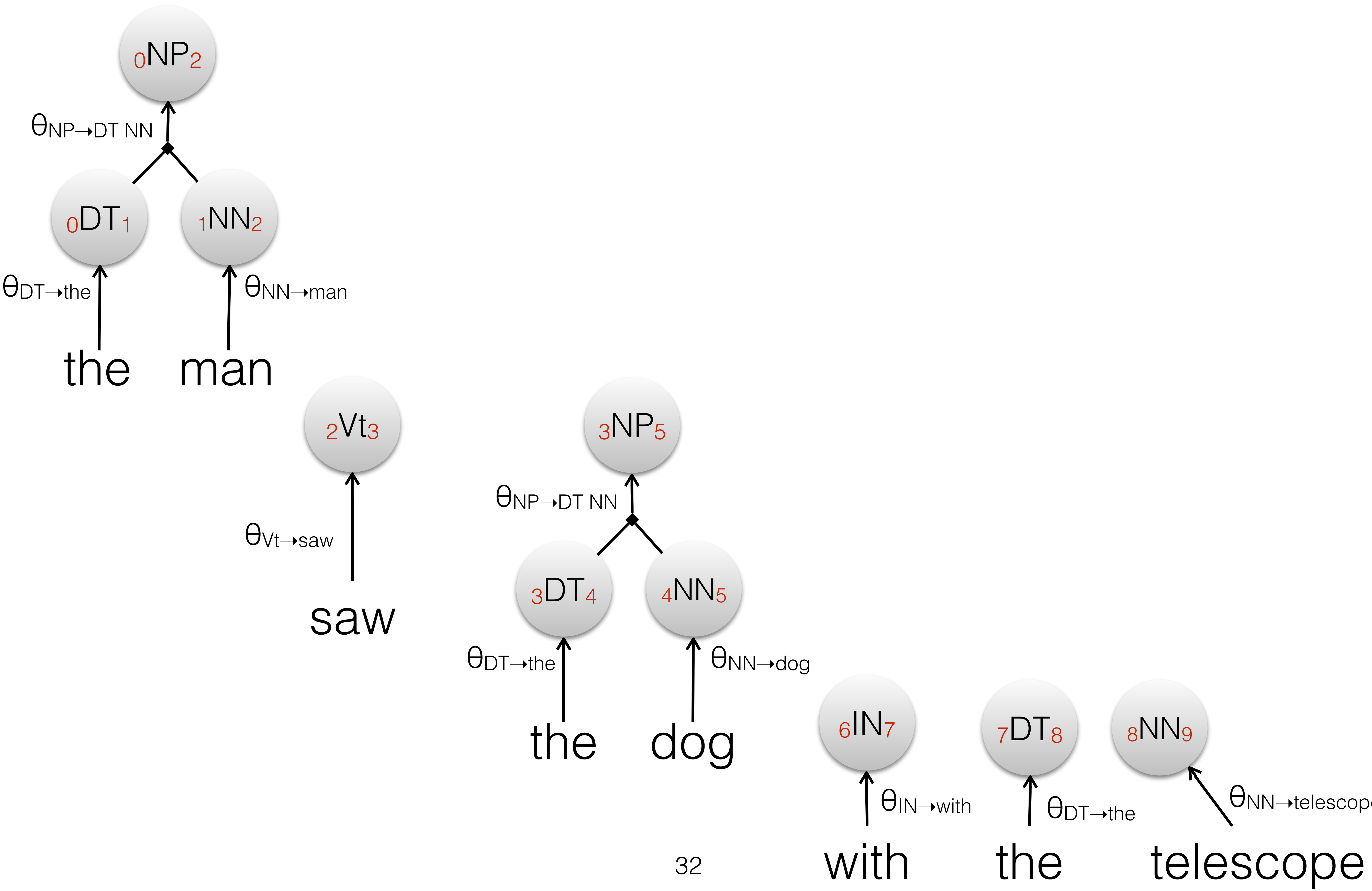

0DT1
1NN2
θDT→the
θNN→man
the
man
2Vt3
θVt→saw
saw
3DT4
4NN5
θDT→the
θNN→dog
the
dog
6IN7
7DT8
8NN9
θIN→with
θDT→the
θNN→telescope
with
the
telescope

Ambiguity



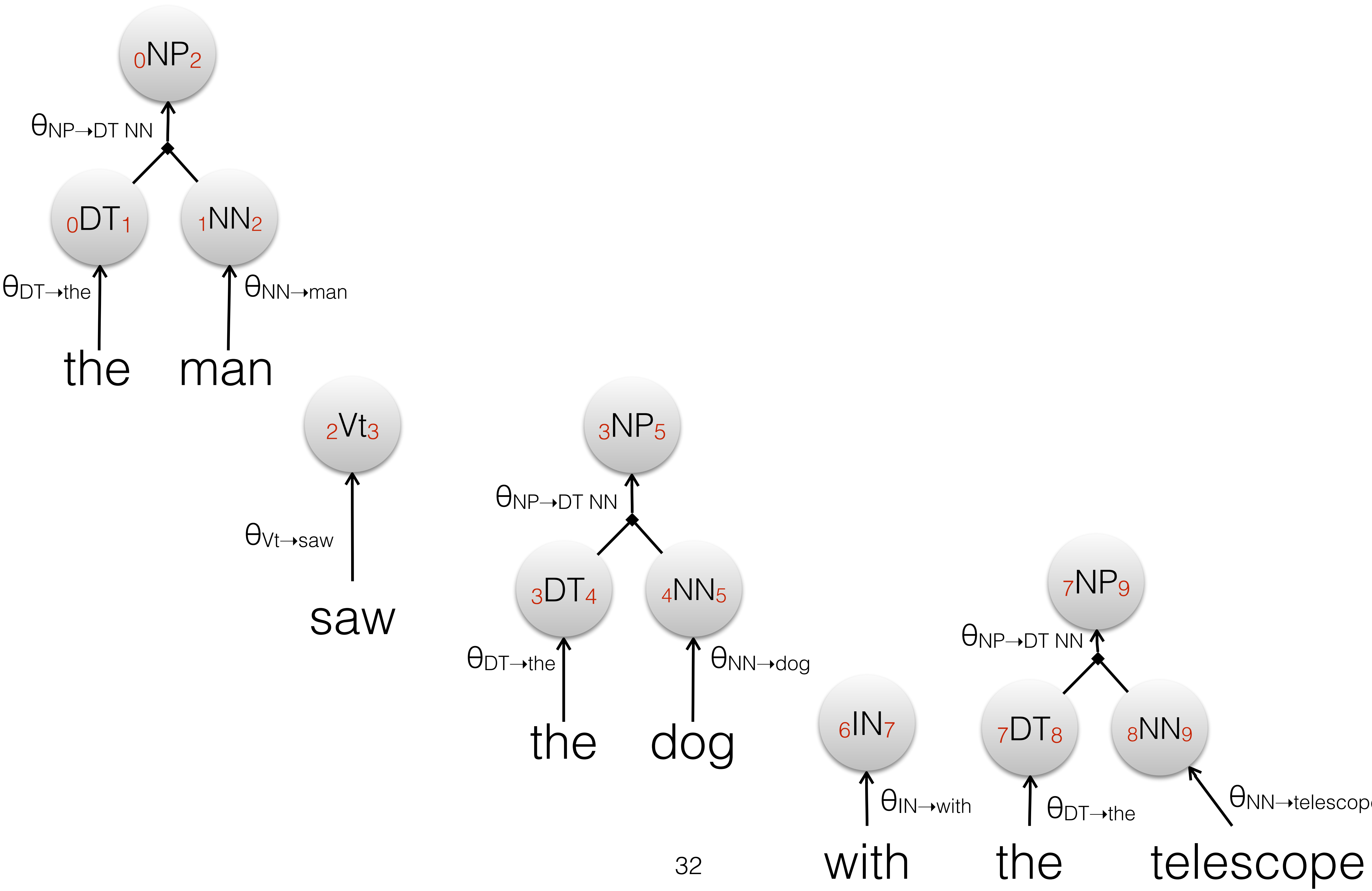
0NP2
θNP→DT NN
0DT1
1NN2
θDT→the
θNN→man
the
man
2Vt3
θVt→saw
saw
3DT4
4NN5
θDT→the
θNN→dog
the
dog
6IN7
7DT8
8NN9
θIN→with
θDT→the
θNN→telescope
with
the
telescope

Ambiguity



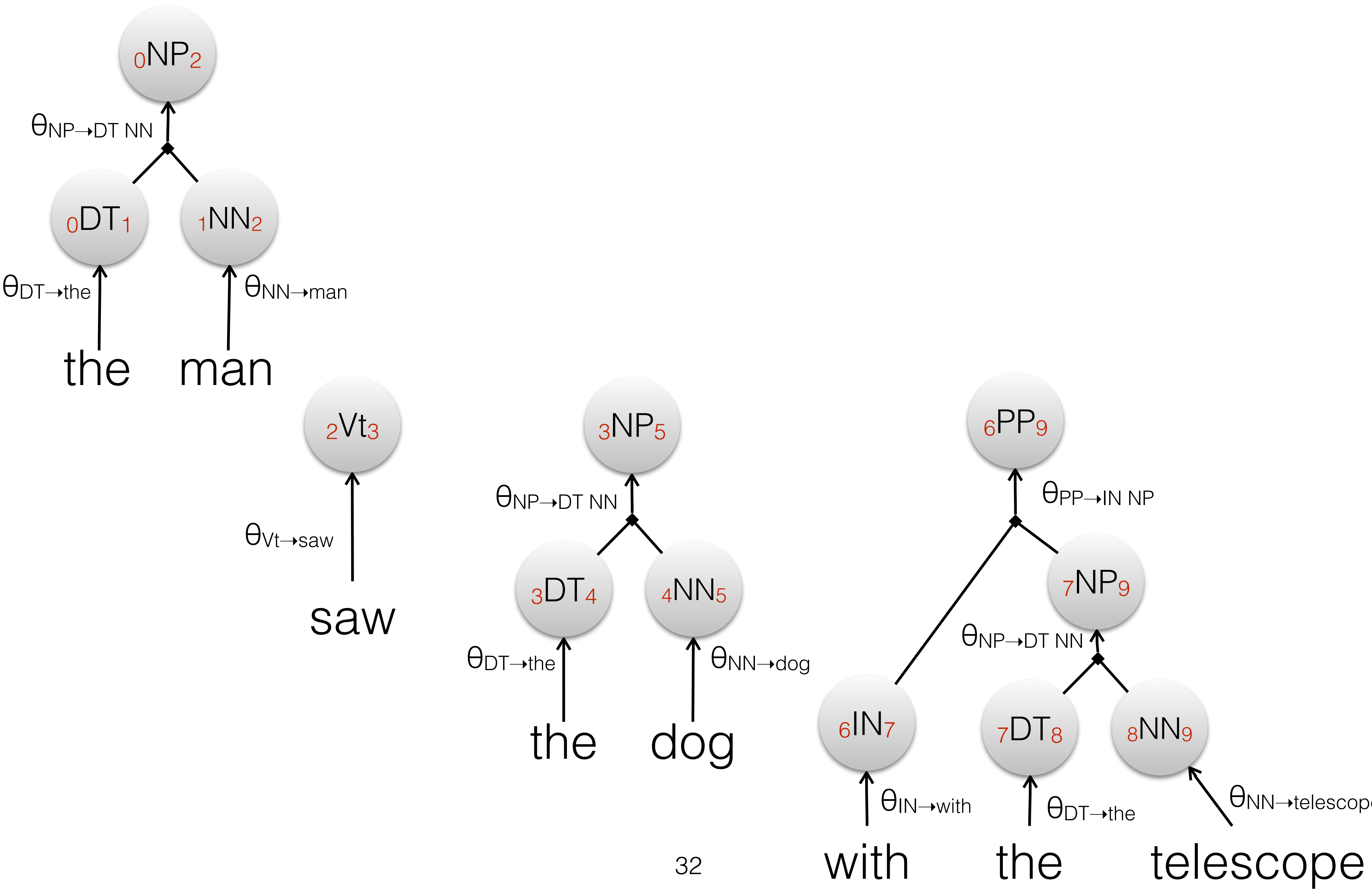
0NP2
θNP→DT NN
0DT1
1NN2
θDT→the
θNN→man
the
man
2Vt3
θVt→saw
saw
3NP5
θNP→DT NN
3DT4
4NN5
θDT→the
θNN→dog
the
dog
6IN7
7DT8
8NN9
θIN→with
θDT→the
θNN→telescope
with
the
telescope

Ambiguity

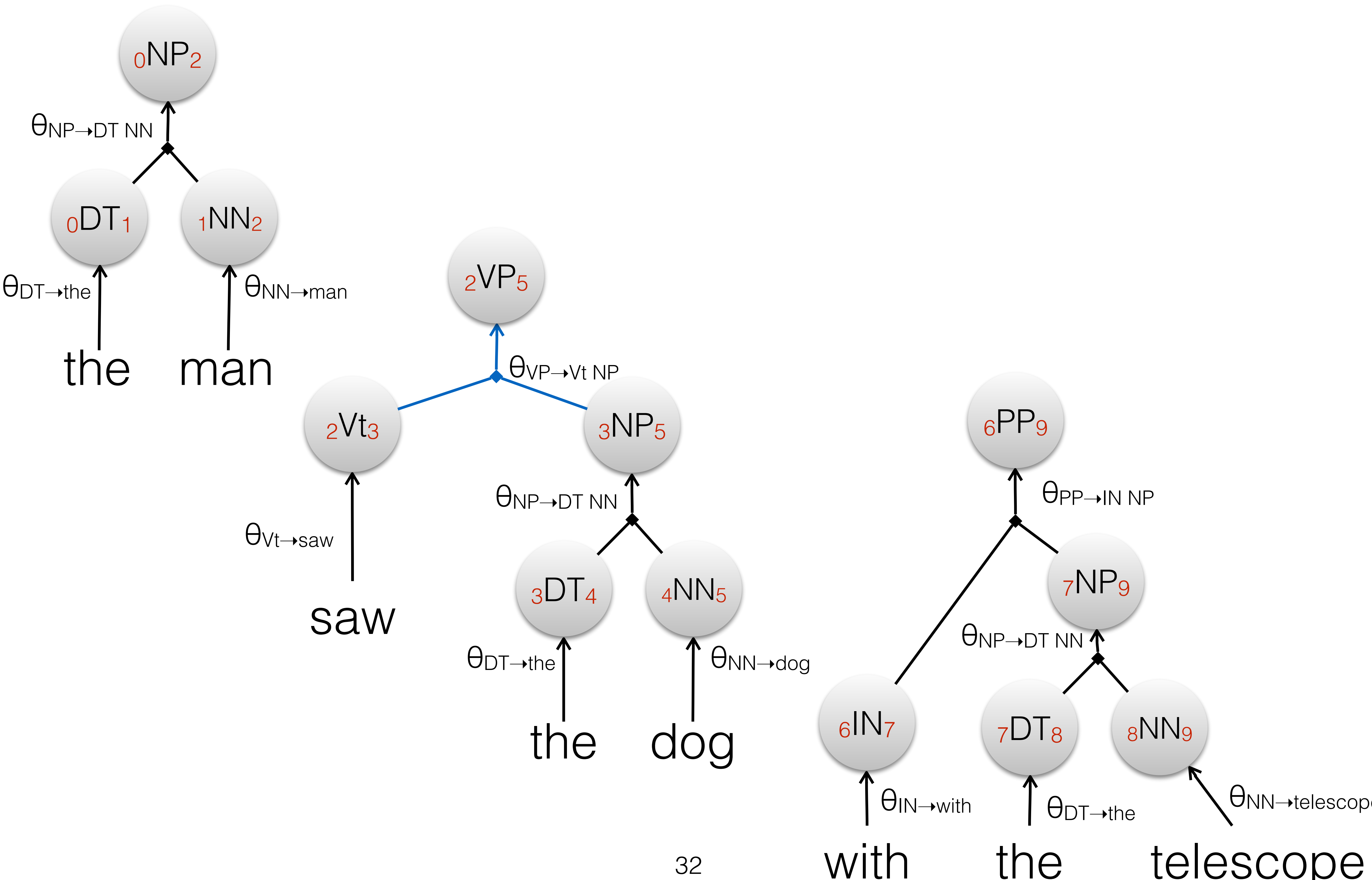


0NP2
θNP→DT NN
0DT1
1NN2
θDT→the
θNN→man
the
man
2Vt3
θVt→saw
saw
3NP5
θNP→DT NN
3DT4
4NN5
θDT→the
θNN→dog
the
dog
7NP9
θNP→DT NN
6IN7
7DT8
8NN9
θIN→with
θDT→the
θNN→telescope
with
the
telescope

Ambiguity

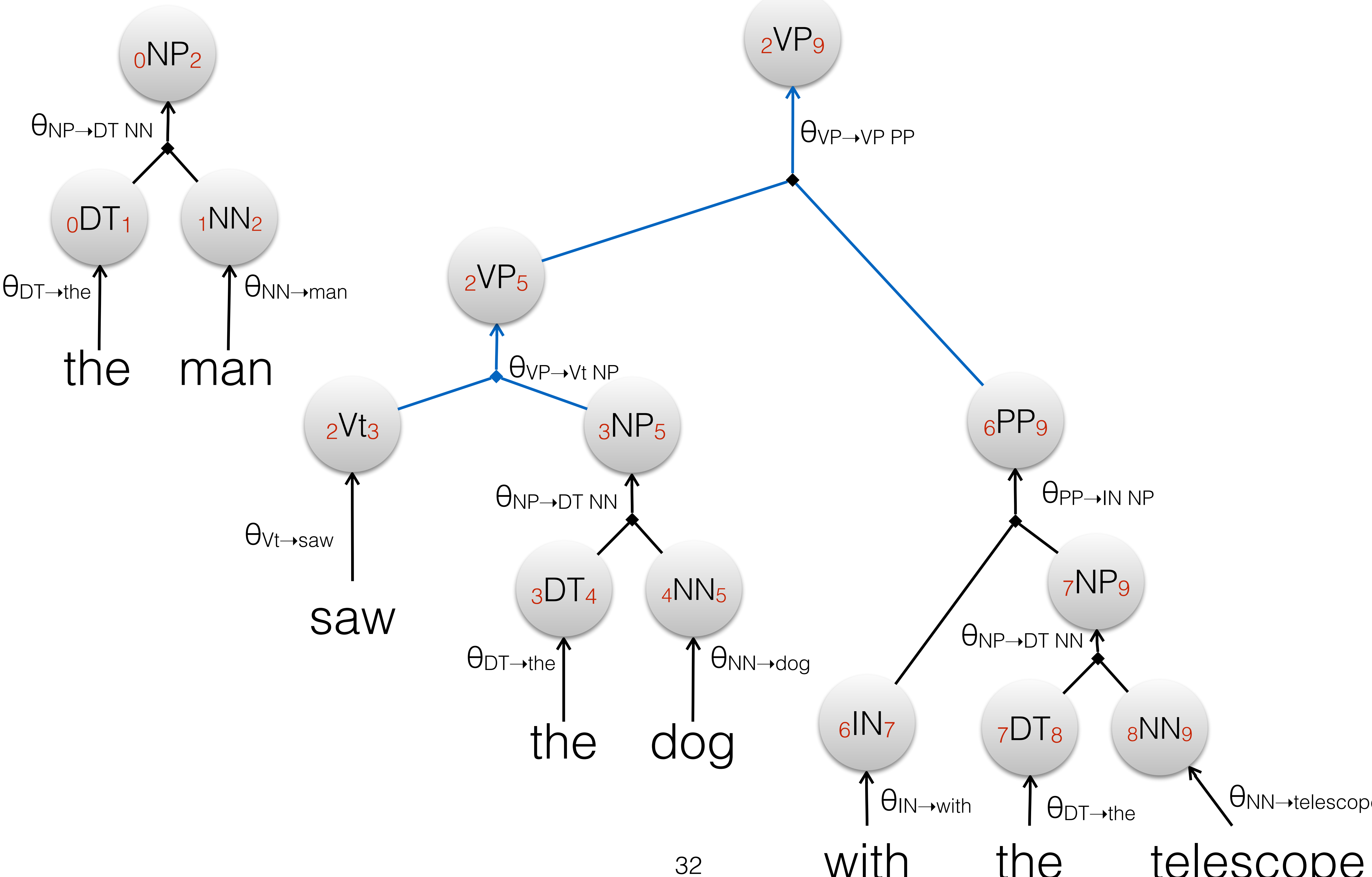

0NP2
θNP→DT NN
0DT1
1NN2
θDT→the
θNN→man
the
man
2Vt3
θVt→saw
saw
3NP5
θNP→DT NN
3DT4
4NN5
θDT→the
θNN→dog
the
dog
6PP9
θPP→IN NP
7NP9
θNP→DT NN
6IN7
7DT8
8NN9
θIN→with
θDT→the
θNN→telescope
with
the
telescope

Ambiguity



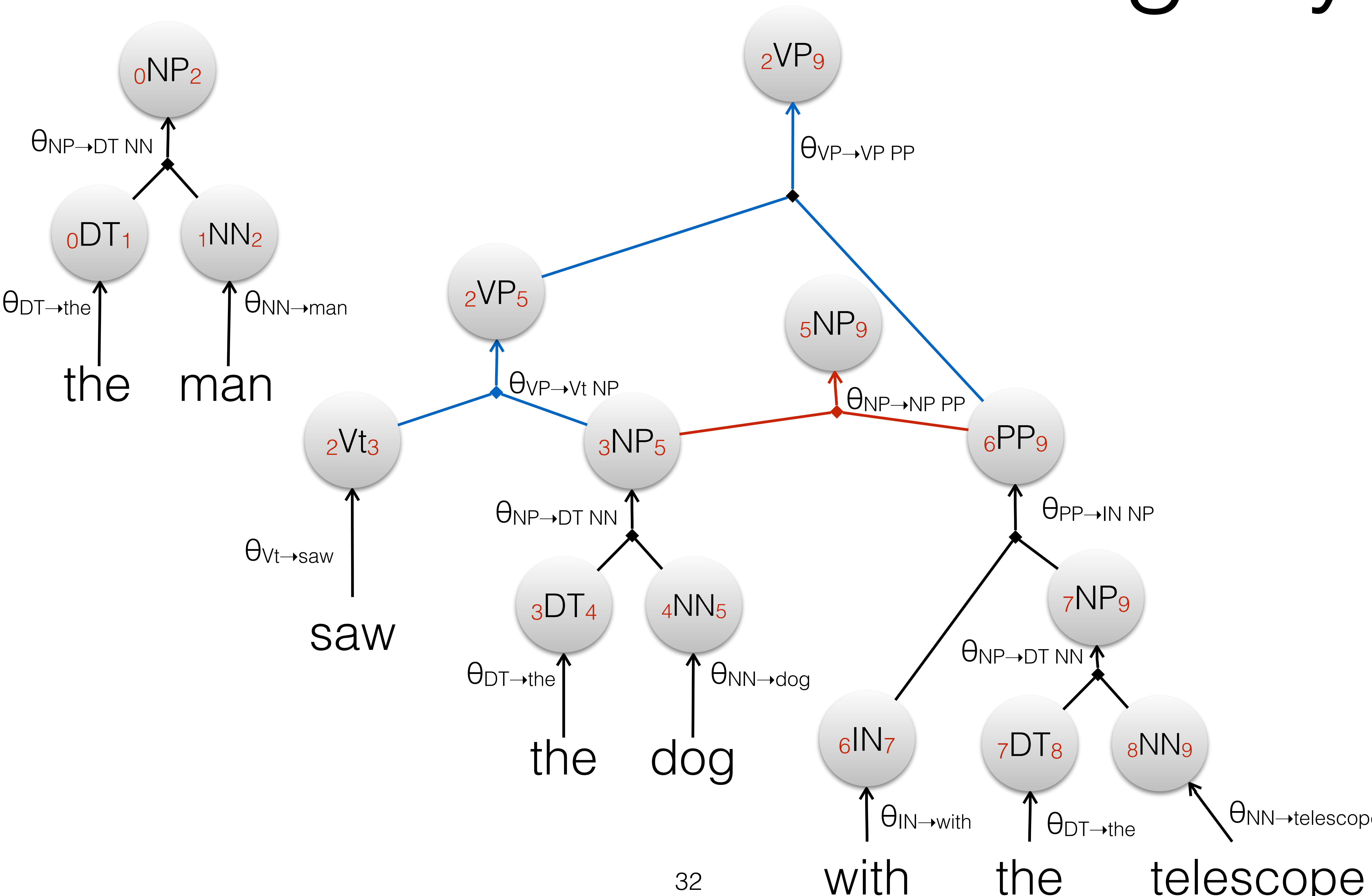
0NP2
θNP→DT NN
0DT1
1NN2
θDT→the
θNN→man
the
man
2VP5
θVP→Vt NP
2Vt3
3NP5
θVt→saw
saw
θNP→DT NN
3DT4
4NN5
θDT→the
θNN→dog
the
dog
6PP9
θPP→IN NP
7NP9
θNP→DT NN
6IN7
7DT8
8NN9
θIN→with
θDT→the
θNN→telescope
with
the
telescope

Ambiguity

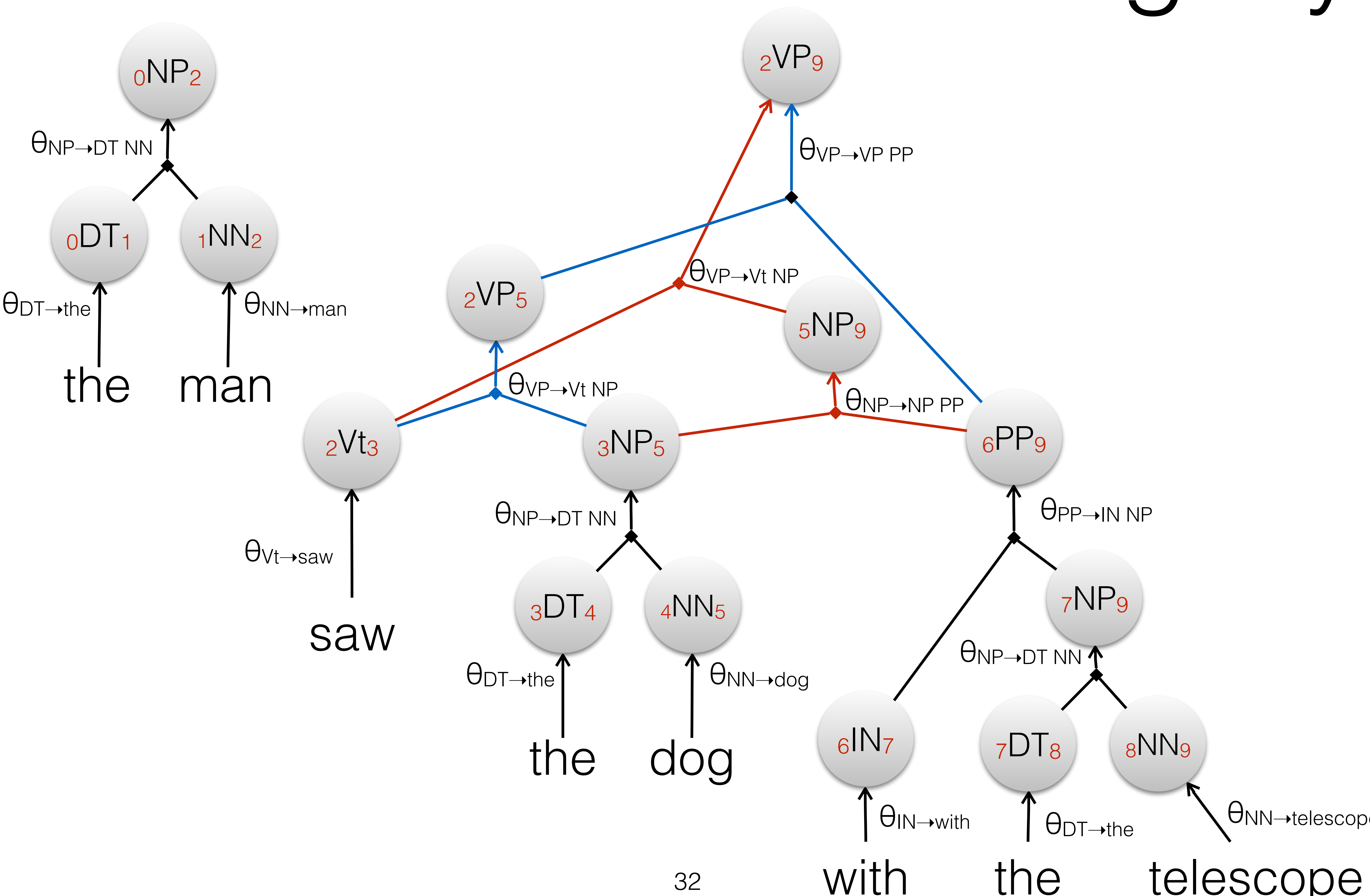


$_0NP_2$
$\theta_{NP \to DT\ NN}$
$_0DT_1$
$_1NN_2$
$\theta_{DT \to the}$
$\theta_{NN \to man}$
the
man
$_2VP_9$
$\theta_{VP \to VP\ PP}$
$_2VP_5$
$\theta_{VP \to Vt\ NP}$
$_2Vt_3$
$_3NP_5$
$\theta_{Vt \to saw}$
saw
$\theta_{NP \to DT\ NN}$
$_3DT_4$
$_4NN_5$
$\theta_{DT \to the}$
$\theta_{NN \to dog}$
the
dog
$_6PP_9$
$\theta_{PP \to IN\ NP}$
$_7NP_9$
$\theta_{NP \to DT\ NN}$
$_6IN_7$
$_7DT_8$
$_8NN_9$
$\theta_{IN \to with}$
$\theta_{DT \to the}$
$\theta_{NN \to telescope}$
with
the
telescope

Ambiguity

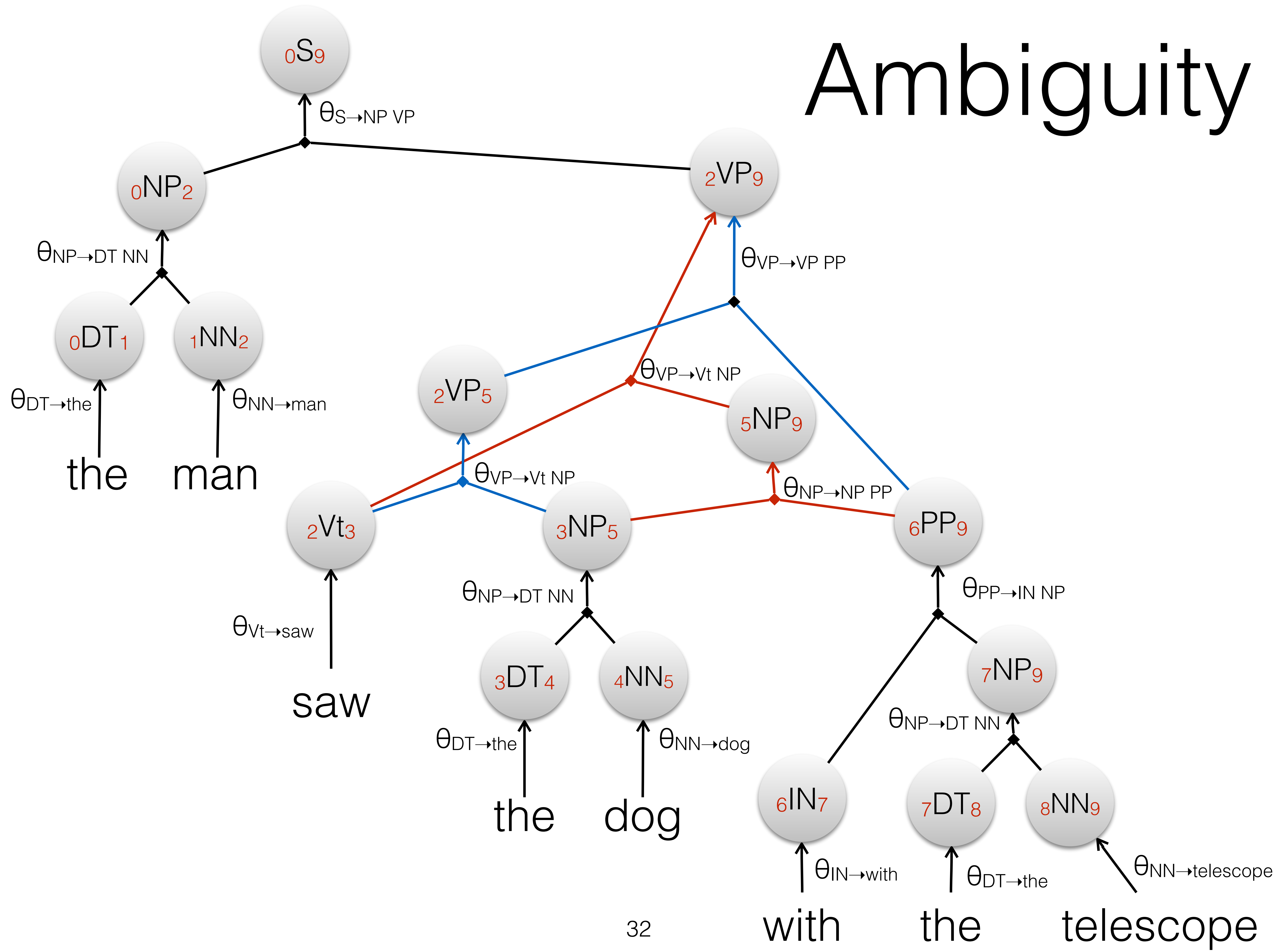

0NP2
θNP→DT NN
0DT1
1NN2
θDT→the
θNN→man
the
man
2VP9
θVP→VP PP
2VP5
5NP9
θVP→Vt NP
θNP→NP PP
2Vt3
3NP5
6PP9
θVt→saw
θNP→DT NN
θPP→IN NP
saw
3DT4
4NN5
7NP9
θDT→the
θNN→dog
θNP→DT NN
the
dog
6IN7
7DT8
8NN9
θIN→with
θDT→the
θNN→telescope
with
the
telescope

Ambiguity



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

Ambiguity



0S9
θS→NP VP
0NP2
2VP9
θNP→DT NN
0DT1
1NN2
θDT→the
θNN→man
the
man
θVP→VP PP
2VP5
θVP→Vt NP
5NP9
θVP→Vt NP
θNP→NP PP
2Vt3
3NP5
6PP9
θVt→saw
saw
θNP→DT NN
3DT4
4NN5
θDT→the
θNN→dog
the
dog
θPP→IN NP
7NP9
θNP→DT NN
6IN7
7DT8
8NN9
θIN→with
θDT→the
θNN→telescope
with
the
telescope

Complexity

Complexity

Item form: [i, X → α■•β□, j]

Complexity

Item form: $[i, X \rightarrow \alpha \blacksquare \bullet \beta \square, j]$

- Each rule segments the input $w_1 \ldots w_n$

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Every CFG can be written in CNF (max arity = 2)

Complexity

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- Each rule segments the input $w_1 .. w_n$

Every CFG can be written in CNF (max arity = 2)

- In total we get up to 3 indices ranging from 0 .. n

Complexity

Item form: $[i, X \rightarrow \alpha\blacksquare\bullet\beta\square, j]$

- Each rule segments the input w_1 .. w_n

Every CFG can be written in CNF (max arity = 2)

- In total we get up to 3 indices ranging from 0 .. n
- $O(n^3)$ annotated rules

Bitext Parsing

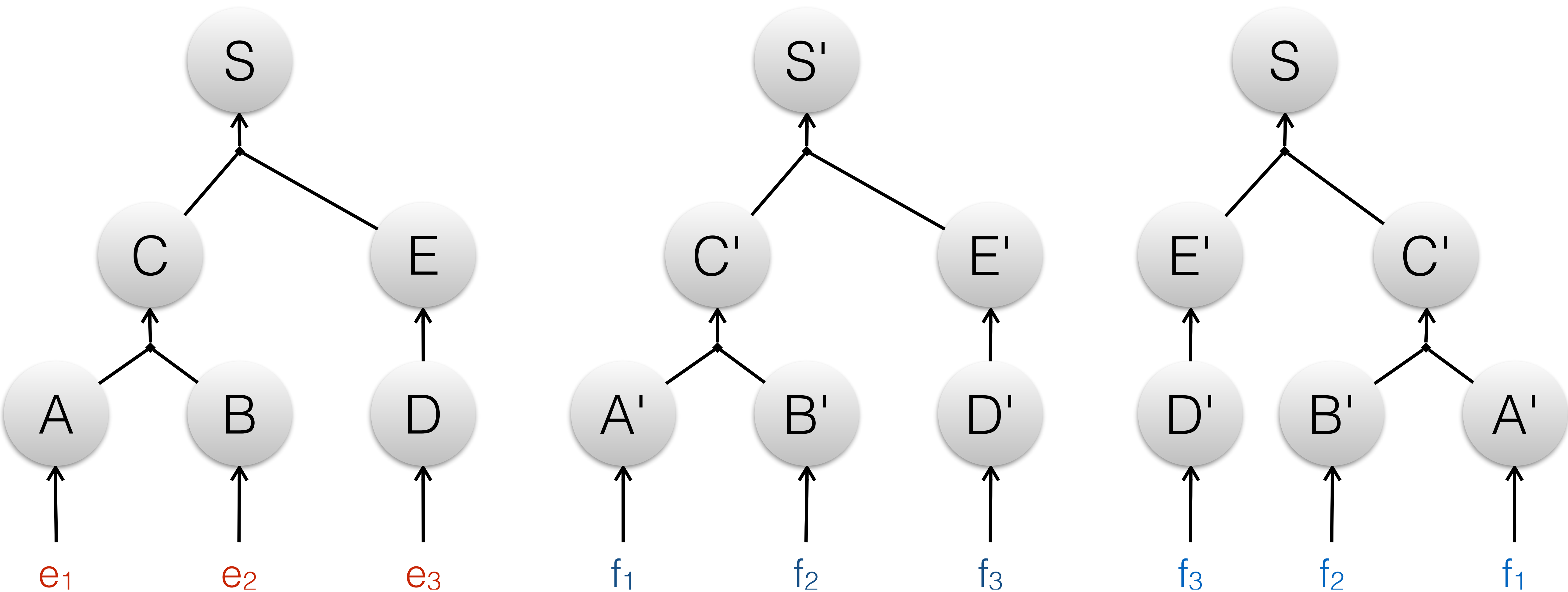
Imagine we have **two** streams of text

the man sleeps ⇔ dort l' homme

We want to parse both strings **simultaneously** such that their trees are **isomorphic**

- same structure up to
- relabelling and permutation of siblings

Isomorphic trees



Synchronous Grammar

A CFG **paired** with another

- RHS symbols map **one-to-one**

Synchronous Grammar

A CFG **paired** with another

- RHS symbols map **one-to-one**

English	French

Synchronous Grammar

A CFG **paired** with another

- RHS symbols map **one-to-one**

	English	French	
X →	A	A	copy

Synchronous Grammar

A CFG **paired** with another

- RHS symbols map **one-to-one**

	English	French	
$X \rightarrow$	A	A	copy
$X \rightarrow$	B C	B C	copy

Synchronous Grammar

A CFG **paired** with another

- RHS symbols map **one-to-one**

	English	French	
X →	A	A	copy
X →	B C	B C	copy
		C B	invert

Synchronous Grammar

A CFG **paired** with another

- RHS symbols map **one-to-one**

	English	French	
$X \rightarrow$	A	A	copy
$X \rightarrow$	B C	B C	copy
		C B	invert
$X \rightarrow$	e	f	transduce

Parse E

Parse with the English side of the grammar

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

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

$_2VP_3 \rightarrow {}_2Vi_3$

$_0DT_1 \rightarrow$ the

$_1NN_2 \rightarrow$ man

$_2Vi_3 \rightarrow$ sleeps

Projection

Projection

English	French

Projection

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

Projection

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

Projection

	English	French
${}_0S_3 \rightarrow$	${}_0NP_2\ {}_2VP_3$	${}_0NP_2\ {}_2VP_3$
		${}_2VP_3\ {}_0NP_2$
${}_0NP_2 \rightarrow$	${}_0DT_1\ {}_1NN_2$	${}_0DT_1\ {}_1NN_2$

Projection

	English	French
${}_0S_3 \rightarrow$	${}_0NP_2\ {}_2VP_3$	${}_0NP_2\ {}_2VP_3$
		${}_2VP_3\ {}_0NP_2$
${}_0NP_2 \rightarrow$	${}_0DT_1\ {}_1NN_2$	${}_0DT_1\ {}_1NN_2$
		${}_1NN_2\ {}_0DT_1$

Projection

	English	French
${}_0S_3 \rightarrow$	${}_0NP_2\ {}_2VP_3$	${}_0NP_2\ {}_2VP_3$
		${}_2VP_3\ {}_0NP_2$
${}_0NP_2 \rightarrow$	${}_0DT_1\ {}_1NN_2$	${}_0DT_1\ {}_1NN_2$
		${}_1NN_2\ {}_0DT_1$
${}_2VP_3 \rightarrow$	${}_2Vi_3$	${}_2Vi_3$

Projection

	English	French
${}_0S_3 \rightarrow$	${}_0NP_2\ {}_2VP_3$	${}_0NP_2\ {}_2VP_3$
		${}_2VP_3\ {}_0NP_2$
${}_0NP_2 \rightarrow$	${}_0DT_1\ {}_1NN_2$	${}_0DT_1\ {}_1NN_2$
		${}_1NN_2\ {}_0DT_1$
${}_2VP_3 \rightarrow$	${}_2Vi_3$	${}_2Vi_3$
${}_0DT_1 \rightarrow$	the	le

Projection

	English	French
${}_0S_3 \rightarrow$	${}_0NP_2\ {}_2VP_3$	${}_0NP_2\ {}_2VP_3$
		${}_2VP_3\ {}_0NP_2$
${}_0NP_2 \rightarrow$	${}_0DT_1\ {}_1NN_2$	${}_0DT_1\ {}_1NN_2$
		${}_1NN_2\ {}_0DT_1$
${}_2VP_3 \rightarrow$	${}_2Vi_3$	${}_2Vi_3$
${}_0DT_1 \rightarrow$	the	le
		la

Projection

	English	French
${}_0S_3 \rightarrow$	${}_0NP_2\ {}_2VP_3$	${}_0NP_2\ {}_2VP_3$
		${}_2VP_3\ {}_0NP_2$
${}_0NP_2 \rightarrow$	${}_0DT_1\ {}_1NN_2$	${}_0DT_1\ {}_1NN_2$
		${}_1NN_2\ {}_0DT_1$
${}_2VP_3 \rightarrow$	${}_2Vi_3$	${}_2Vi_3$
${}_0DT_1 \rightarrow$	the	le
		la
		l'

Projection

	English	French
${}_{0}S_{3} \rightarrow$	${}_{0}NP_{2}\ {}_{2}VP_{3}$	${}_{0}NP_{2}\ {}_{2}VP_{3}$
		${}_{2}VP_{3}\ {}_{0}NP_{2}$
${}_{0}NP_{2} \rightarrow$	${}_{0}DT_{1}\ {}_{1}NN_{2}$	${}_{0}DT_{1}\ {}_{1}NN_{2}$
		${}_{1}NN_{2}\ {}_{0}DT_{1}$
${}_{2}VP_{3} \rightarrow$	${}_{2}Vi_{3}$	${}_{2}Vi_{3}$
${}_{0}DT_{1} \rightarrow$	the	le
		la
		l'
${}_{1}NN_{2} \rightarrow$	man	homme

Projection

	English	French
${}_0S_3 \rightarrow$	${}_0NP_2\ {}_2VP_3$	${}_0NP_2\ {}_2VP_3$
		${}_2VP_3\ {}_0NP_2$
${}_0NP_2 \rightarrow$	${}_0DT_1\ {}_1NN_2$	${}_0DT_1\ {}_1NN_2$
		${}_1NN_2\ {}_0DT_1$
${}_2VP_3 \rightarrow$	${}_2Vi_3$	${}_2Vi_3$
${}_0DT_1 \rightarrow$	the	le
		la
		l'
${}_1NN_2 \rightarrow$	man	homme
${}_2Vi_3 \rightarrow$	sleeps	dort

French Grammar

	French
${}_0S_3 \rightarrow$	${}_0NP_2\ {}_2VP_3$
	${}_2VP_3\ {}_0NP_2$
${}_0NP_2 \rightarrow$	${}_0DT_1\ {}_1NN_2$
	${}_1NN_2\ {}_0DT_1$
${}_2VP_3 \rightarrow$	${}_2Vi_3$
${}_0DT_1 \rightarrow$	le
	la
	l'
${}_1NN_2 \rightarrow$	homme
${}_2Vi_3 \rightarrow$	dort

Parse F

	French
${}_0S_3 \rightarrow$	${}_0NP_2\ {}_2VP_3$
	${}_2VP_3\ {}_0NP_2$
${}_0NP_2 \rightarrow$	${}_0DT_1\ {}_1NN_2$
	${}_1NN_2\ {}_0DT_1$
${}_2VP_3 \rightarrow$	${}_2Vi_3$
${}_0DT_1 \rightarrow$	le
	la
	l'
${}_1NN_2 \rightarrow$	homme
${}_2Vi_3 \rightarrow$	dort

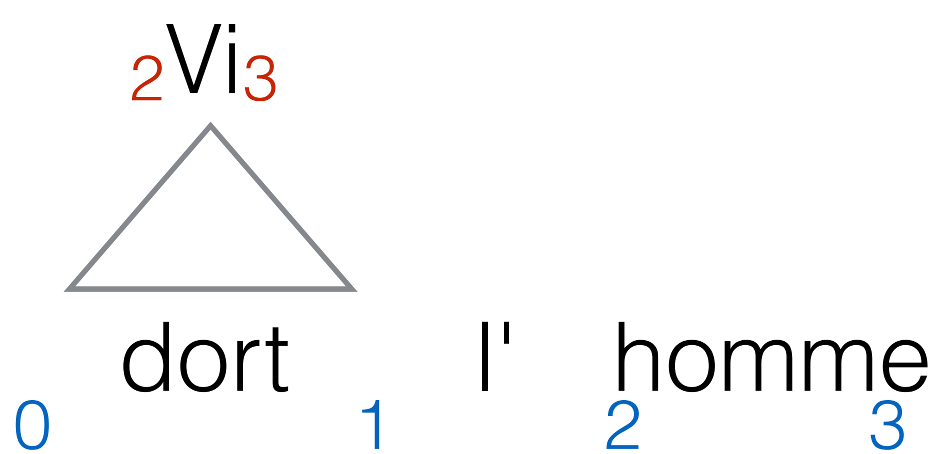
Parse F

	French
${}_0S_3 \rightarrow$	${}_0NP_2\ {}_2VP_3$
	${}_2VP_3\ {}_0NP_2$
${}_0NP_2 \rightarrow$	${}_0DT_1\ {}_1NN_2$
	${}_1NN_2\ {}_0DT_1$
${}_2VP_3 \rightarrow$	${}_2Vi_3$
${}_0DT_1 \rightarrow$	le
	la
	l'
${}_1NN_2 \rightarrow$	homme
${}_2Vi_3 \rightarrow$	dort

$_0$ dort $_1$ l' $_2$ homme $_3$

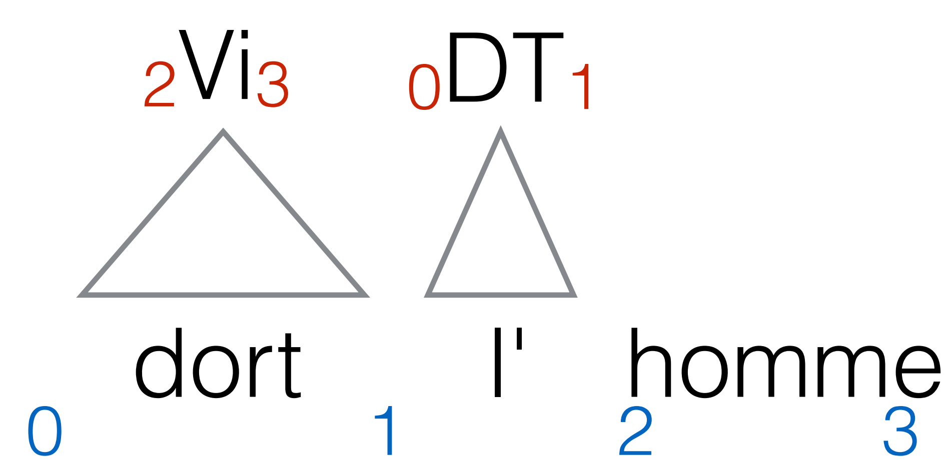
Parse F

	French
${}_0S_3 \rightarrow$	${}_0NP_2\ {}_2VP_3$
	${}_2VP_3\ {}_0NP_2$
${}_0NP_2 \rightarrow$	${}_0DT_1\ {}_1NN_2$
	${}_1NN_2\ {}_0DT_1$
${}_2VP_3 \rightarrow$	${}_2Vi_3$
${}_0DT_1 \rightarrow$	le
	la
	l'
${}_1NN_2 \rightarrow$	homme
${}_2Vi_3 \rightarrow$	dort



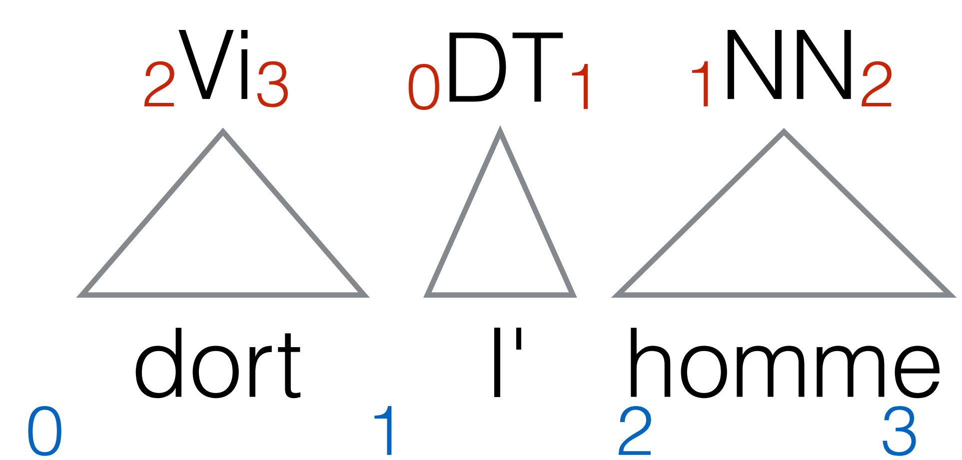
Parse F

	French
${}_0S_3 \rightarrow$	${}_0NP_2\ {}_2VP_3$
	${}_2VP_3\ {}_0NP_2$
${}_0NP_2 \rightarrow$	${}_0DT_1\ {}_1NN_2$
	${}_1NN_2\ {}_0DT_1$
${}_2VP_3 \rightarrow$	${}_2Vi_3$
${}_0DT_1 \rightarrow$	le
	la
	l'
${}_1NN_2 \rightarrow$	homme
${}_2Vi_3 \rightarrow$	dort



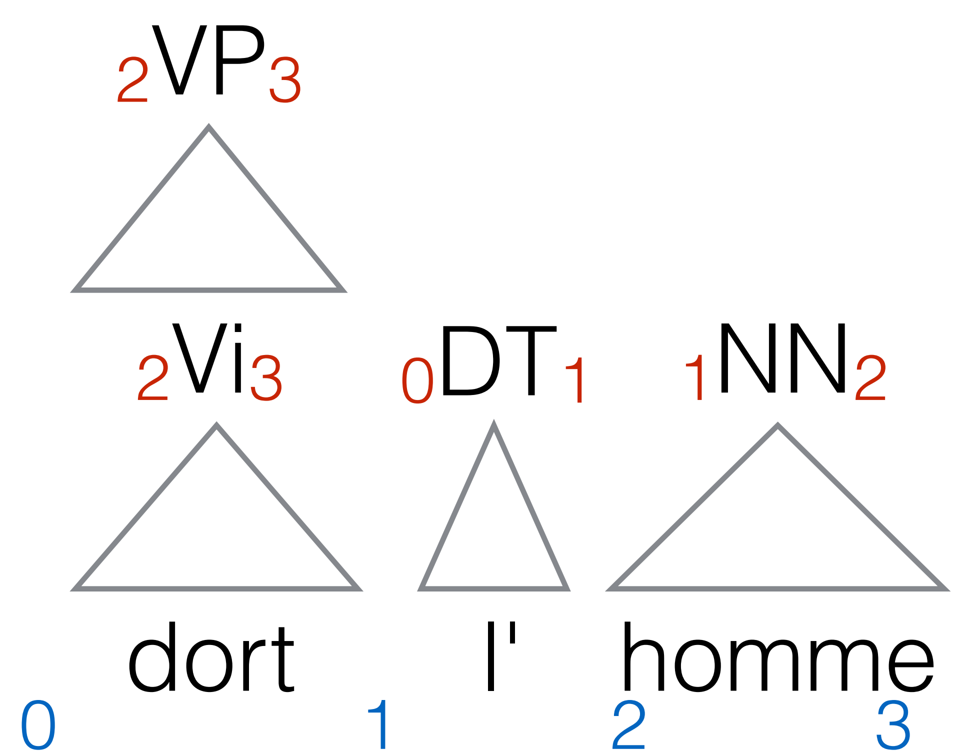
Parse F

	French
${}_0\mathrm{S}_3 \rightarrow$	${}_0\mathrm{NP}_2\ {}_2\mathrm{VP}_3$
	${}_2\mathrm{VP}_3\ {}_0\mathrm{NP}_2$
${}_0\mathrm{NP}_2 \rightarrow$	${}_0\mathrm{DT}_1\ {}_1\mathrm{NN}_2$
	${}_1\mathrm{NN}_2\ {}_0\mathrm{DT}_1$
${}_2\mathrm{VP}_3 \rightarrow$	${}_2\mathrm{Vi}_3$
${}_0\mathrm{DT}_1 \rightarrow$	le
	la
	l'
${}_1\mathrm{NN}_2 \rightarrow$	homme
${}_2\mathrm{Vi}_3 \rightarrow$	dort



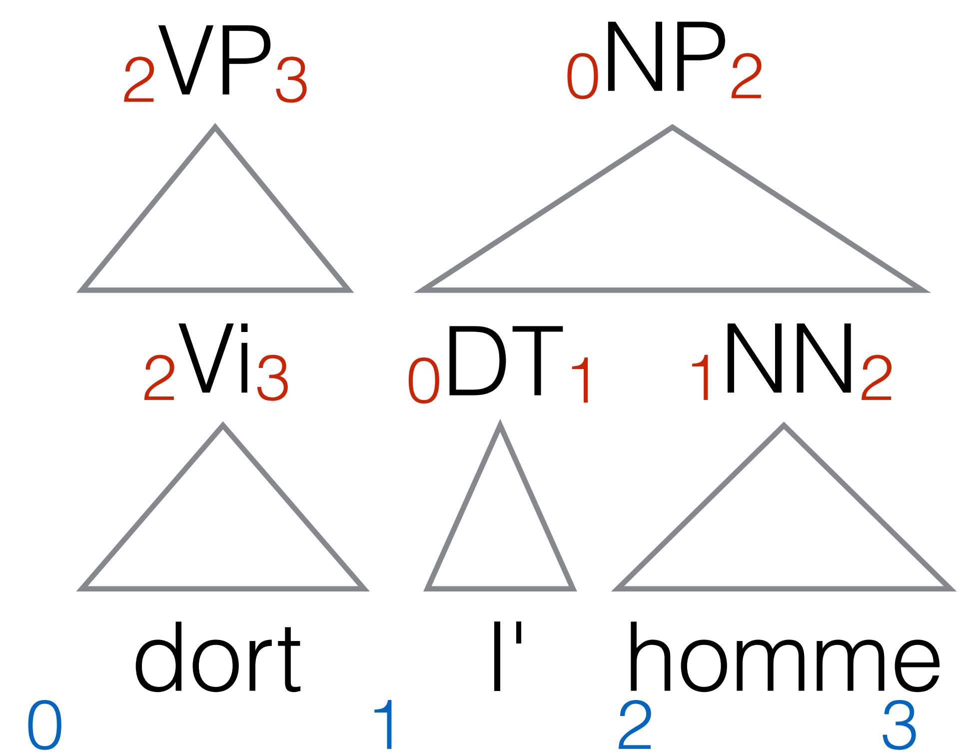
Parse F

	French
${}_0S_3 \rightarrow$	${}_0NP_2\ {}_2VP_3$
	${}_2VP_3\ {}_0NP_2$
${}_0NP_2 \rightarrow$	${}_0DT_1\ {}_1NN_2$
	${}_1NN_2\ {}_0DT_1$
${}_2VP_3 \rightarrow$	${}_2Vi_3$
${}_0DT_1 \rightarrow$	le
	la
	l'
${}_1NN_2 \rightarrow$	homme
${}_2Vi_3 \rightarrow$	dort



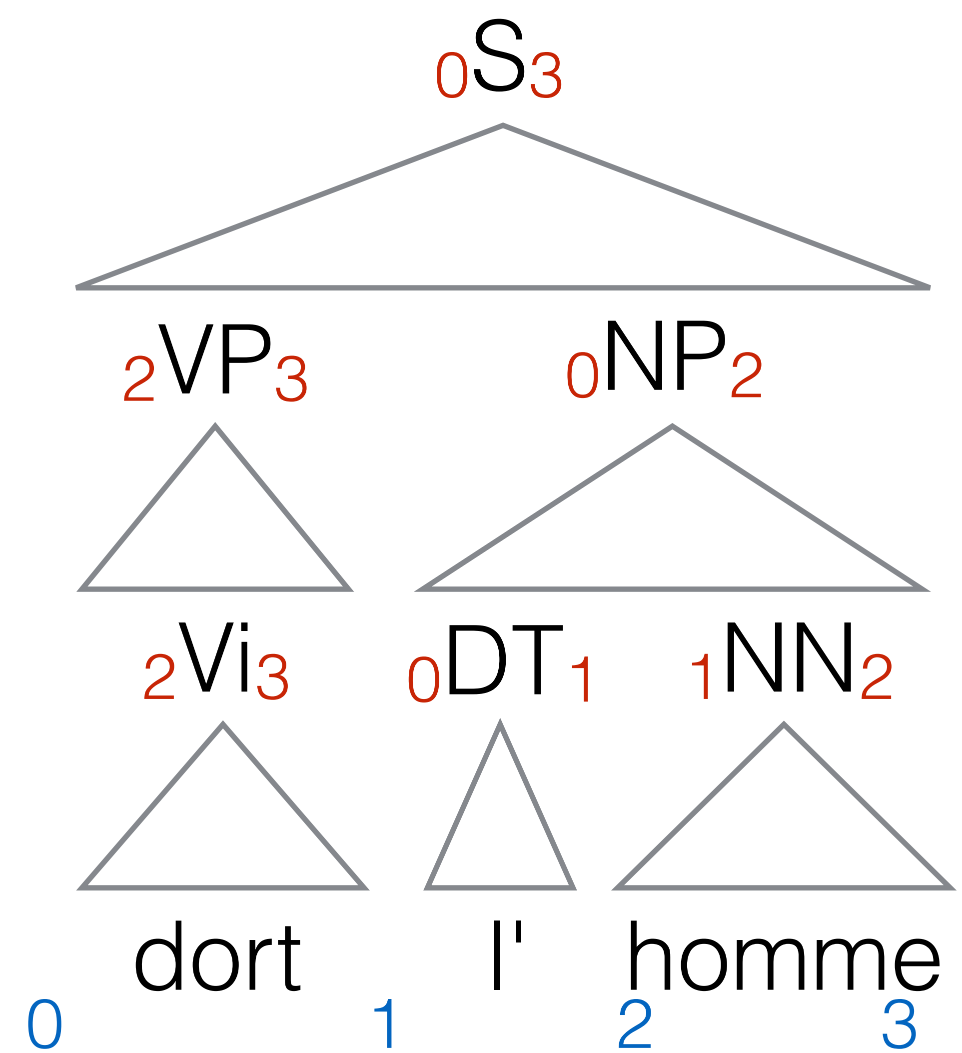
Parse F

	French
${}_0S_3 \rightarrow$	${}_0NP_2\ {}_2VP_3$
	${}_2VP_3\ {}_0NP_2$
${}_0NP_2 \rightarrow$	${}_0DT_1\ {}_1NN_2$
	${}_1NN_2\ {}_0DT_1$
${}_2VP_3 \rightarrow$	${}_2Vi_3$
${}_0DT_1 \rightarrow$	le
	la
	l'
${}_1NN_2 \rightarrow$	homme
${}_2Vi_3 \rightarrow$	dort



Parse F

	French
${}_0S_3 \rightarrow$	${}_0NP_2\ {}_2VP_3$
	${}_2VP_3\ {}_0NP_2$
${}_0NP_2 \rightarrow$	${}_0DT_1\ {}_1NN_2$
	${}_1NN_2\ {}_0DT_1$
${}_2VP_3 \rightarrow$	${}_2Vi_3$
${}_0DT_1 \rightarrow$	le
	la
	l'
${}_1NN_2 \rightarrow$	homme
${}_2Vi_3 \rightarrow$	dort



Cascade of Monolingual Parsers

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CFG parsing can be seen as intersecting a CFG and an FSA [Bar-Hillel, 1961; Billot and Lang, 1989]

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- L(CFG) ∩ L(FSA) is a context-free language

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This neat property makes cascading intersection operations (parsers) appealing [Dyer, 2010]

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- e.g. bitext parsing

Biproduct: alignments

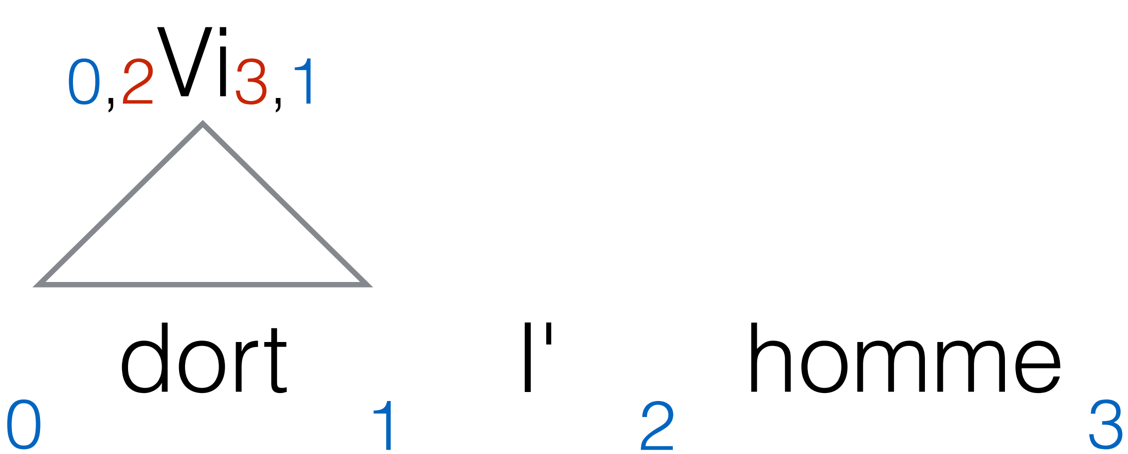
	French
${}_0S_3 \rightarrow$	${}_0NP_2\ {}_2VP_3$
	${}_2VP_3\ {}_0NP_2$
${}_0NP_2 \rightarrow$	${}_0DT_1\ {}_1NN_2$
	${}_1NN_2\ {}_0DT_1$
${}_2VP_3 \rightarrow$	${}_2Vi_3$
${}_0DT_1 \rightarrow$	le
	la
	l'
${}_1NN_2 \rightarrow$	${}_1NN_2 \rightarrow$ homme
${}_2Vi_3 \rightarrow$	${}_2Vi_3 \rightarrow$ dort

Biproduct: alignments

$_0$ dort $_1$ l' $_2$ homme $_3$

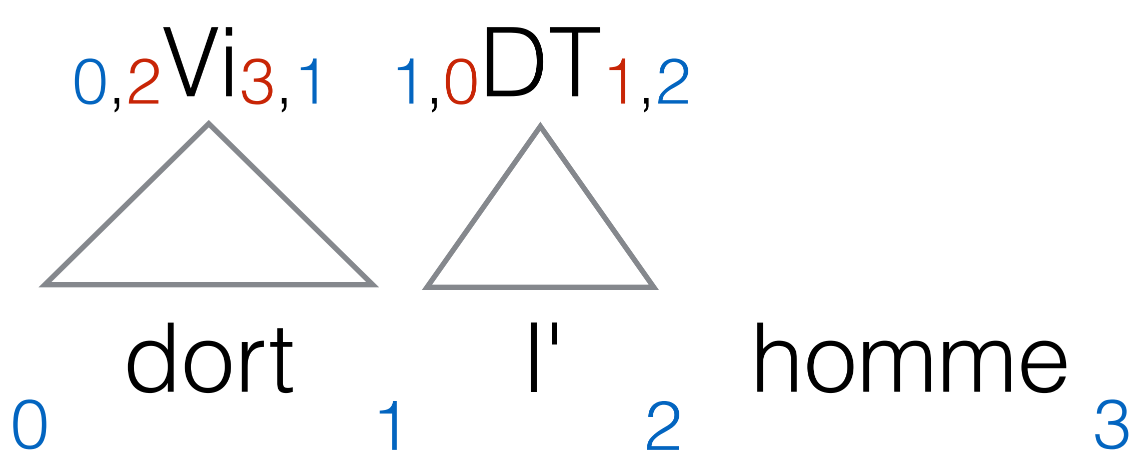
	French
$_0S_3 \rightarrow$	$_0NP_2\ _2VP_3$
	$_2VP_3\ _0NP_2$
$_0NP_2 \rightarrow$	$_0DT_1\ _1NN_2$
	$_1NN_2\ _0DT_1$
$_2VP_3 \rightarrow$	$_2Vi_3$
$_0DT_1 \rightarrow$	le
	la
	l'
$_1NN_2 \rightarrow$	$_1NN_2 \rightarrow$ homme
$_2Vi_3 \rightarrow$	$_2Vi_3 \rightarrow$ dort

Biproduct: alignments



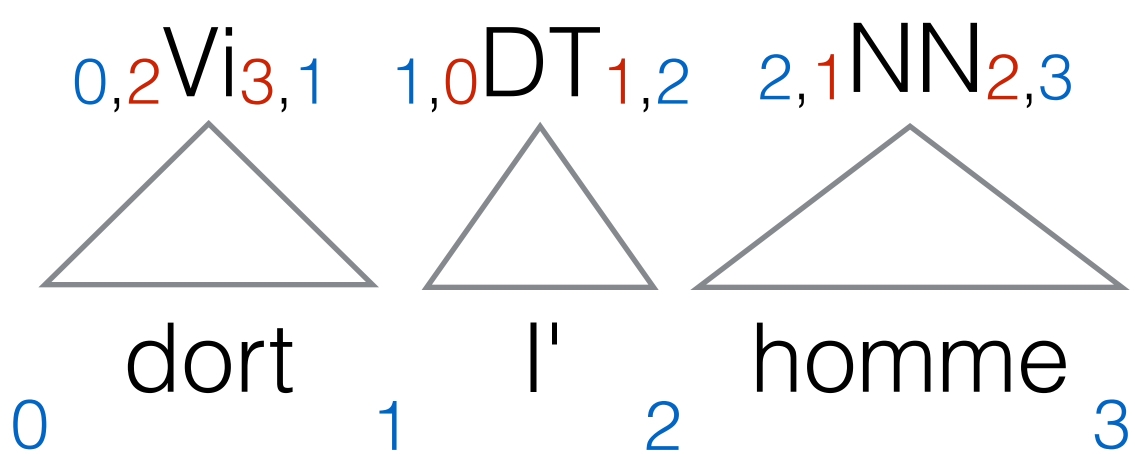
	French
${}_0S_3 \rightarrow$	${}_0NP_2\ {}_2VP_3$
	${}_2VP_3\ {}_0NP_2$
${}_0NP_2 \rightarrow$	${}_0DT_1\ {}_1NN_2$
	${}_1NN_2\ {}_0DT_1$
${}_2VP_3 \rightarrow$	${}_2Vi_3$
${}_0DT_1 \rightarrow$	le
	la
	l'
${}_1NN_2 \rightarrow$	${}_1NN_2 \rightarrow$ homme
${}_2Vi_3 \rightarrow$	${}_2Vi_3 \rightarrow$ dort

Biproduct: alignments



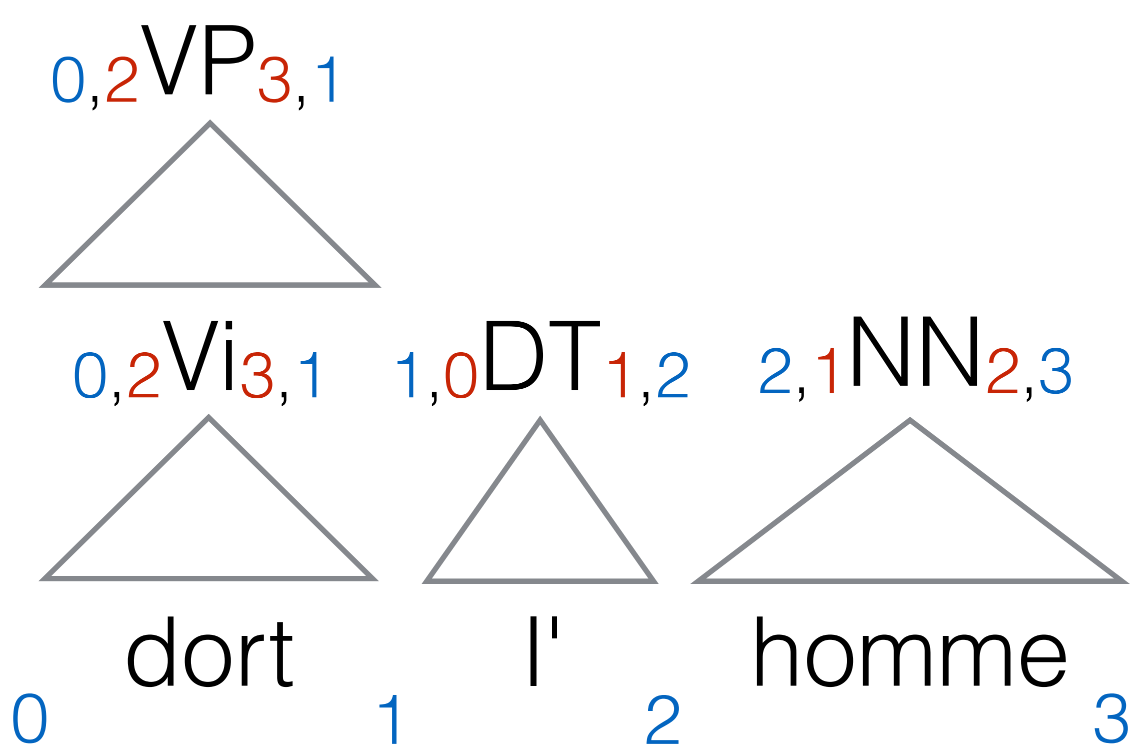
	French
$_0S_3 \rightarrow$	$_0NP_2\ _2VP_3$
	$_2VP_3\ _0NP_2$
$_0NP_2 \rightarrow$	$_0DT_1\ _1NN_2$
	$_1NN_2\ _0DT_1$
$_2VP_3 \rightarrow$	$_2Vi_3$
$_0DT_1 \rightarrow$	le
	la
	l'
$_1NN_2 \rightarrow$	$_1NN_2 \rightarrow$ homme
$_2Vi_3 \rightarrow$	$_2Vi_3 \rightarrow$ dort

Biproduct: alignments



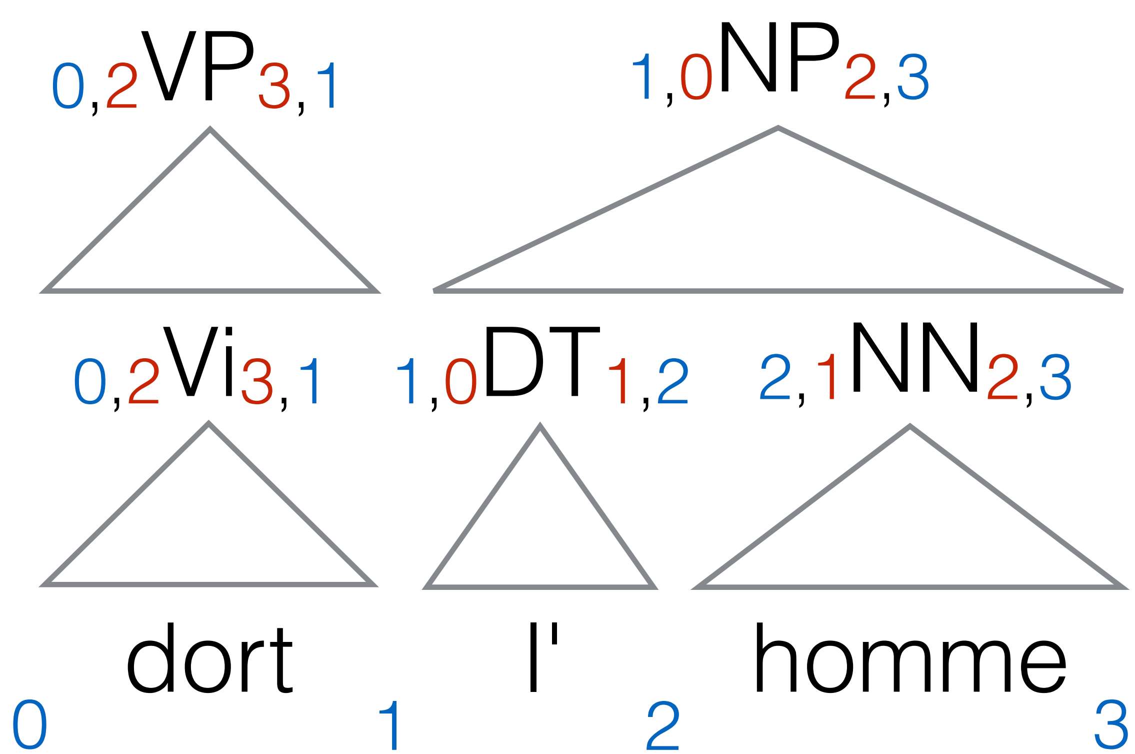
	French
$_0\mathrm{S}_3 \rightarrow$	$_0\mathrm{NP}_2\ {}_2\mathrm{VP}_3$
	$_2\mathrm{VP}_3\ {}_0\mathrm{NP}_2$
$_0\mathrm{NP}_2 \rightarrow$	$_0\mathrm{DT}_1\ {}_1\mathrm{NN}_2$
	$_1\mathrm{NN}_2\ {}_0\mathrm{DT}_1$
$_2\mathrm{VP}_3 \rightarrow$	$_2\mathrm{Vi}_3$
$_0\mathrm{DT}_1 \rightarrow$	le
	la
	l'
$_1\mathrm{NN}_2 \rightarrow$	$_1\mathrm{NN}_2 \rightarrow$ homme
$_2\mathrm{Vi}_3 \rightarrow$	$_2\mathrm{Vi}_3 \rightarrow$ dort

Biproduct: alignments



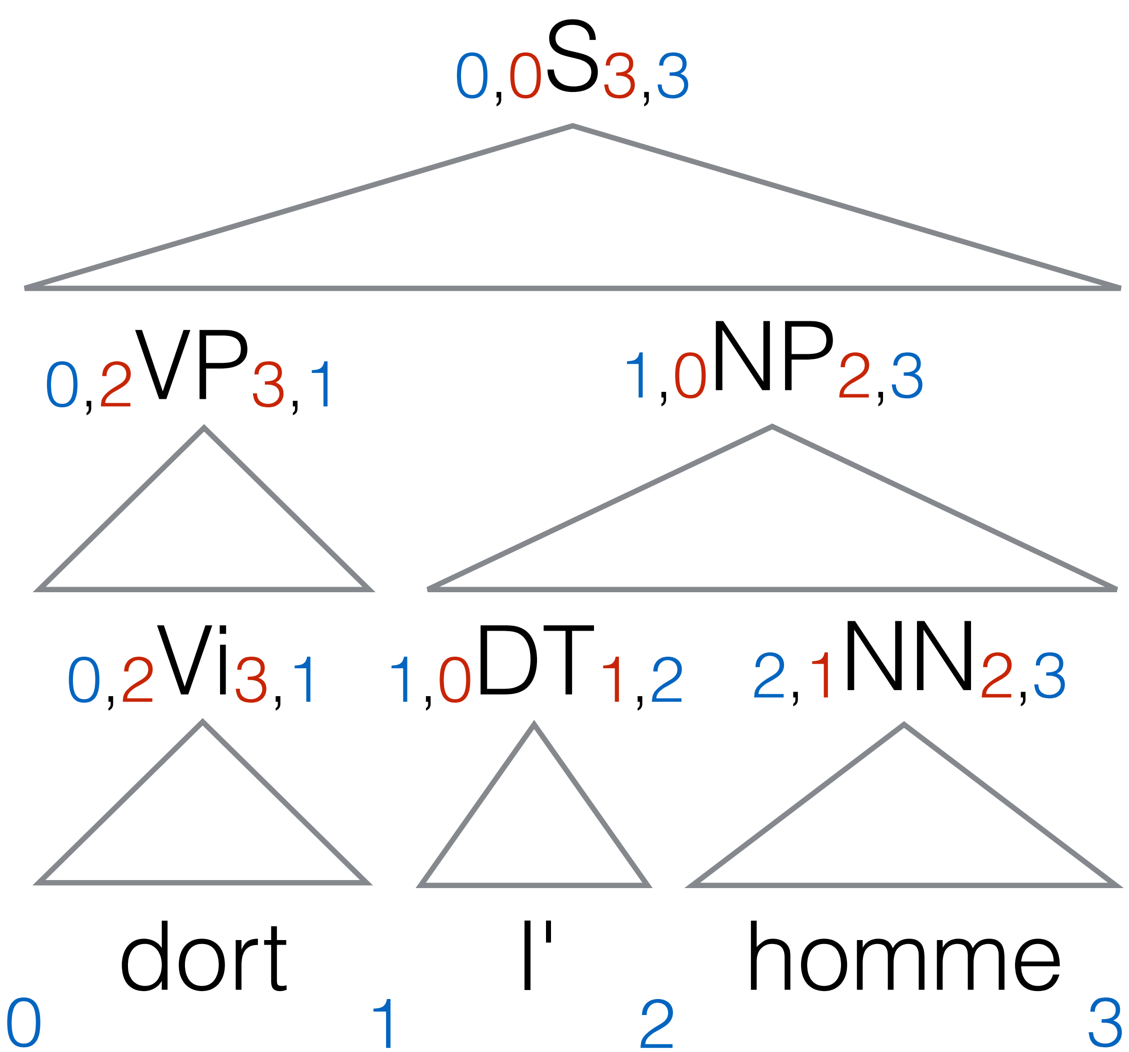
	French
${}_0S_3 \rightarrow$	${}_0NP_2\ {}_2VP_3$
	${}_2VP_3\ {}_0NP_2$
${}_0NP_2 \rightarrow$	${}_0DT_1\ {}_1NN_2$
	${}_1NN_2\ {}_0DT_1$
${}_2VP_3 \rightarrow$	${}_2Vi_3$
${}_0DT_1 \rightarrow$	le
	la
	l'
${}_1NN_2 \rightarrow$	${}_1NN_2 \rightarrow$ homme
${}_2Vi_3 \rightarrow$	${}_2Vi_3 \rightarrow$ dort

Biproduct: alignments



	French
$_0S_3 \rightarrow$	$_0NP_2\ _2VP_3$
	$_2VP_3\ _0NP_2$
$_0NP_2 \rightarrow$	$_0DT_1\ _1NN_2$
	$_1NN_2\ _0DT_1$
$_2VP_3 \rightarrow$	$_2Vi_3$
$_0DT_1 \rightarrow$	le
	la
	l'
$_1NN_2 \rightarrow$	$_1NN_2 \rightarrow$ homme
$_2Vi_3 \rightarrow$	$_2Vi_3 \rightarrow$ dort

Biproduct: alignments



	French
$_0S_3 \rightarrow$	$_0NP_2\ _2VP_3$
	$_2VP_3\ _0NP_2$
$_0NP_2 \rightarrow$	$_0DT_1\ _1NN_2$
	$_1NN_2\ _0DT_1$
$_2VP_3 \rightarrow$	$_2Vi_3$
$_0DT_1 \rightarrow$	le
	la
	l'
$_1NN_2 \rightarrow$	$_1NN_2 \rightarrow$ homme
$_2Vi_3 \rightarrow$	$_2Vi_3 \rightarrow$ dort

Complexity

- $O(l^3 \times m^3)$
    - where l is the length of the English string
    - and m is the length of the French string
- Joint parsing or cascade of parsers has the same theoretical complexity
    - Can cascading be more efficient on average? Why?

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