

Parsing, (Probabilistic) Context Free Grammars

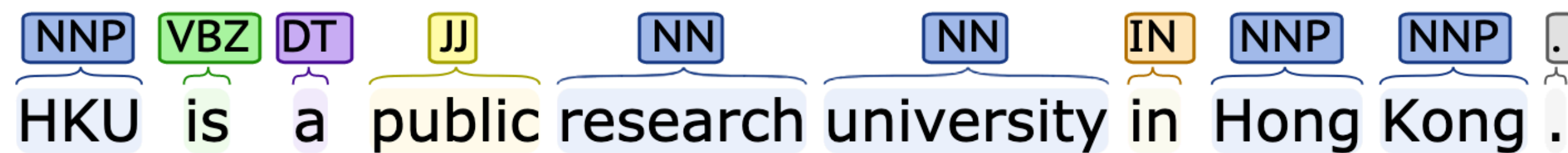
COMP7607 — Lecture 5

Lingpeng Kong

Department of Computer Science, The University of Hong Kong
Many materials from Columbia CS4705 with special thanks!

Linguistic Structures

HKU is a public research university in Hong Kong.

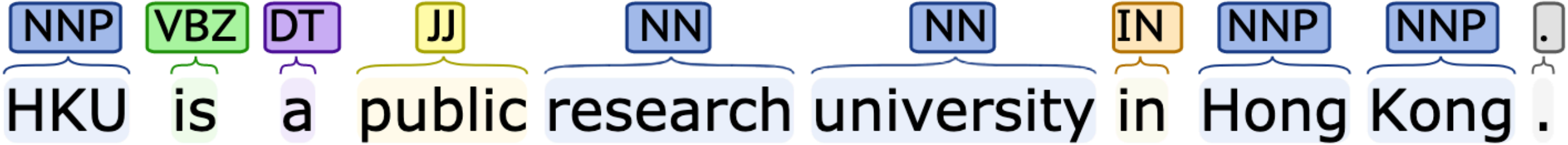


Part-of-speech tagging
(word class)

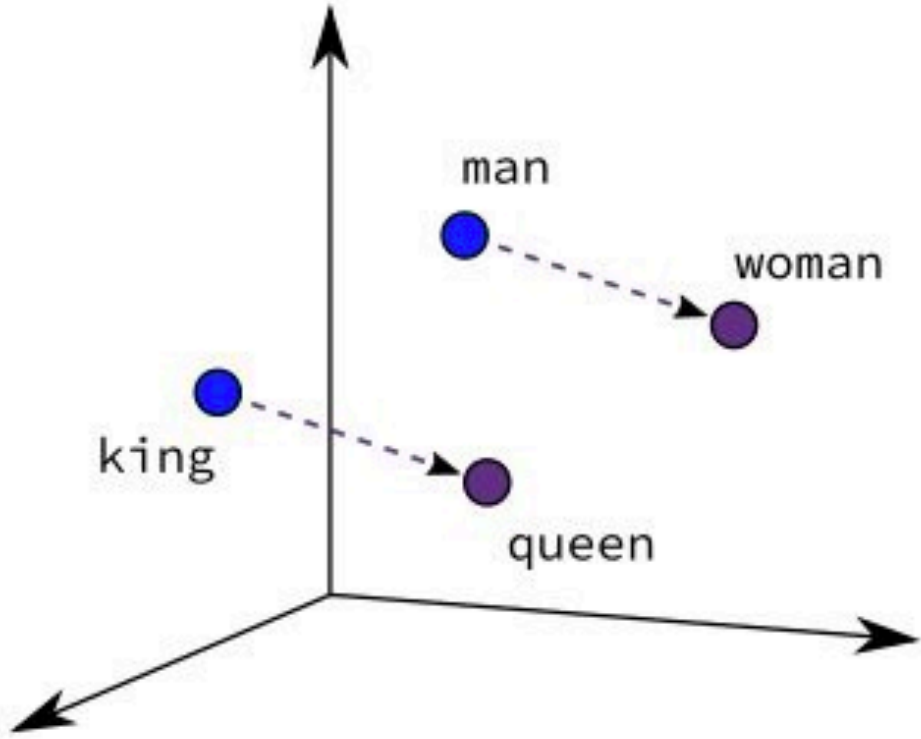


Named entity recognition

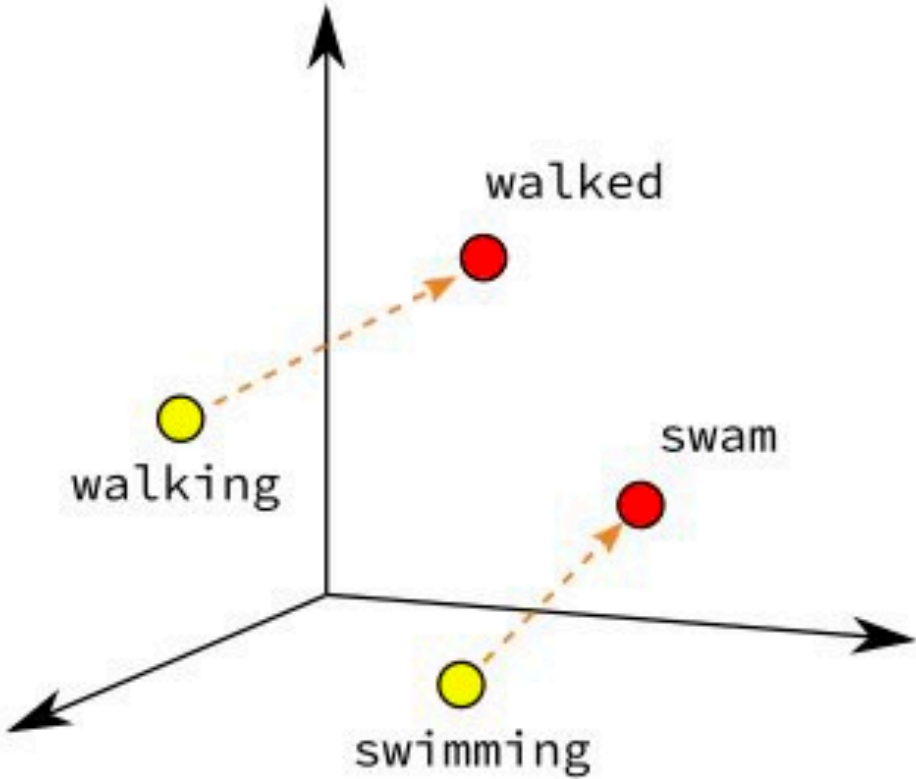
Linguistic Structures



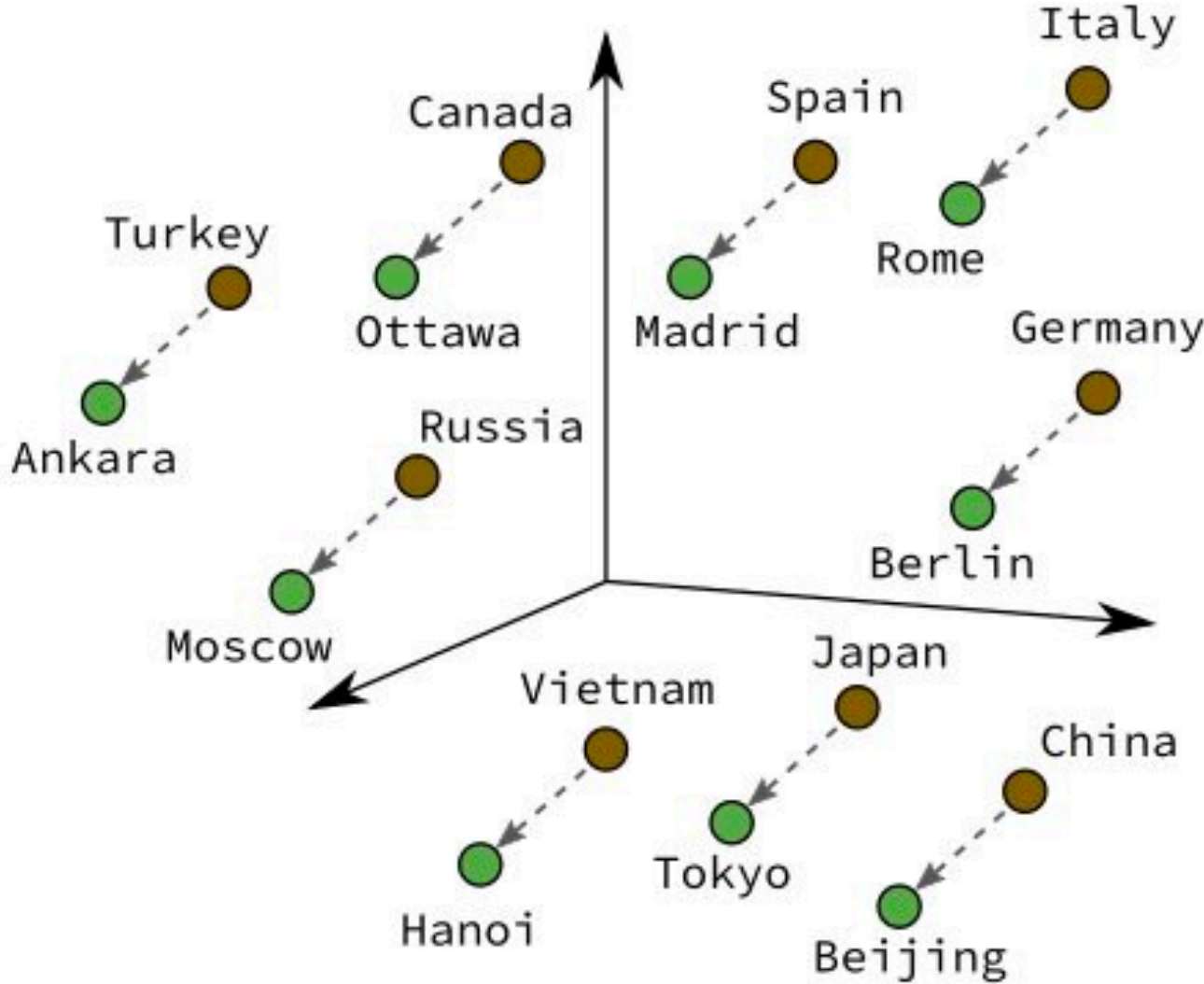
Part-of-speech tagging
(word class)



Male-Female

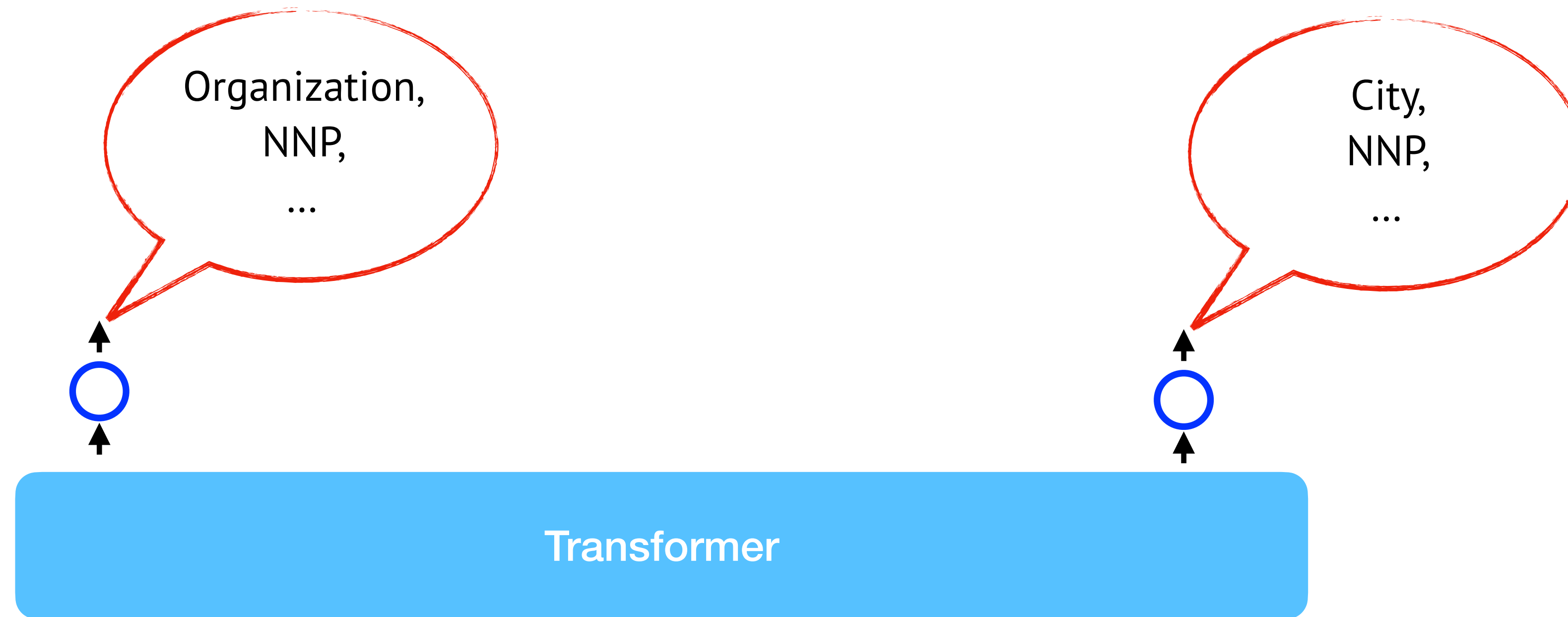


Verb Tense



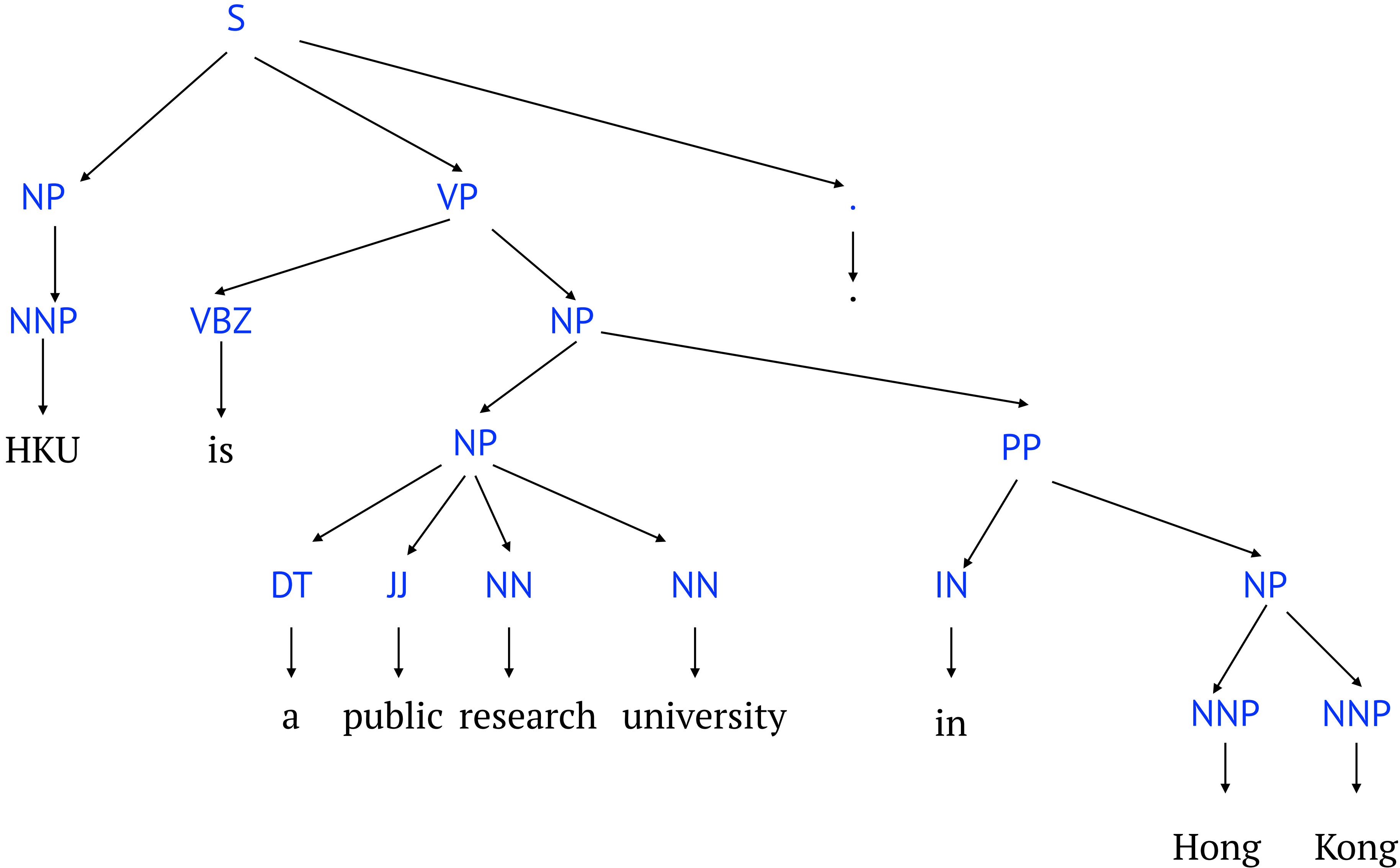
Country-Capital

Linguistic Structures



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Linguistic Structures



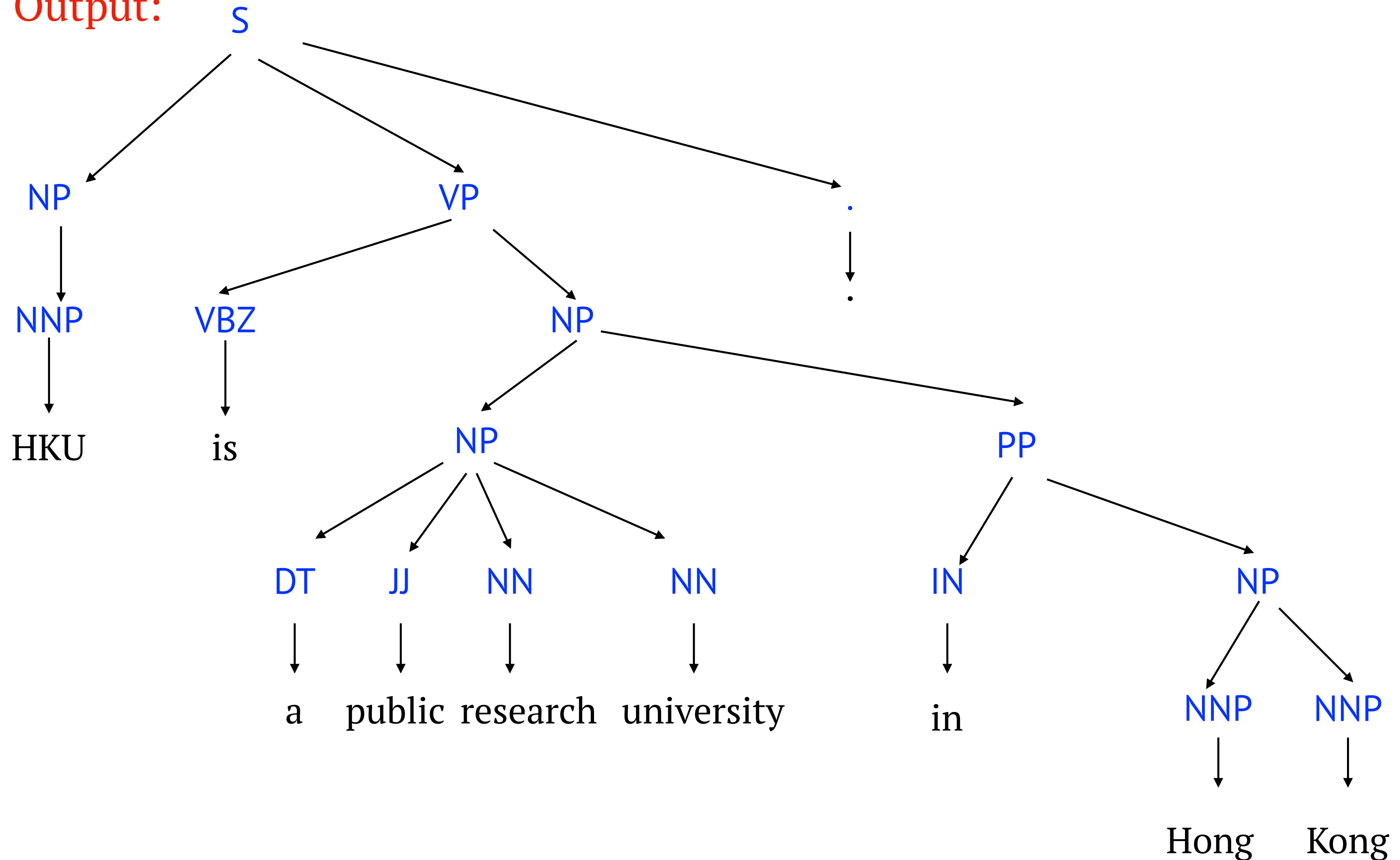
phrase-Structure tree,
constituency tree

Parsing (Phrase-structure Parsing)

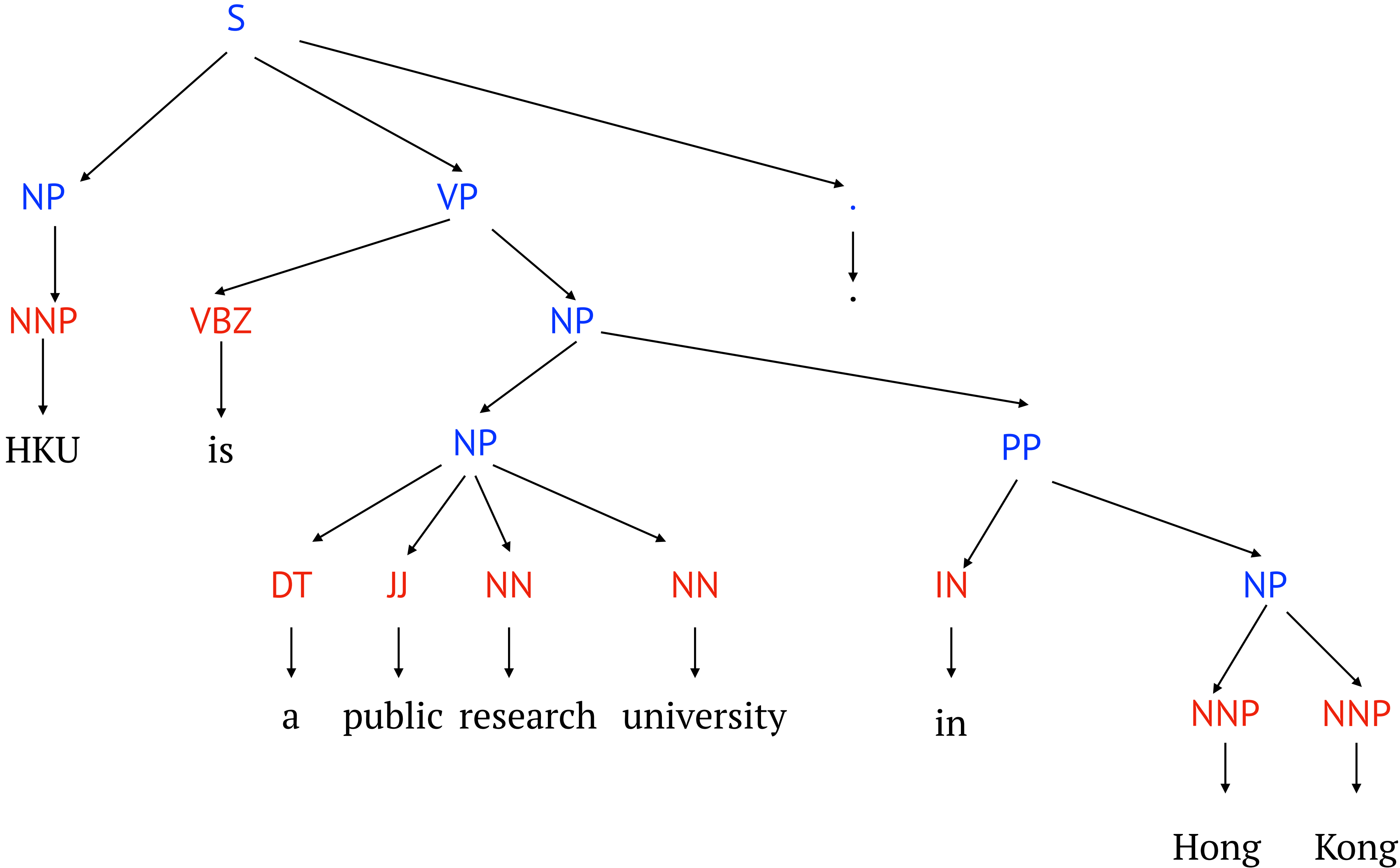
Input:

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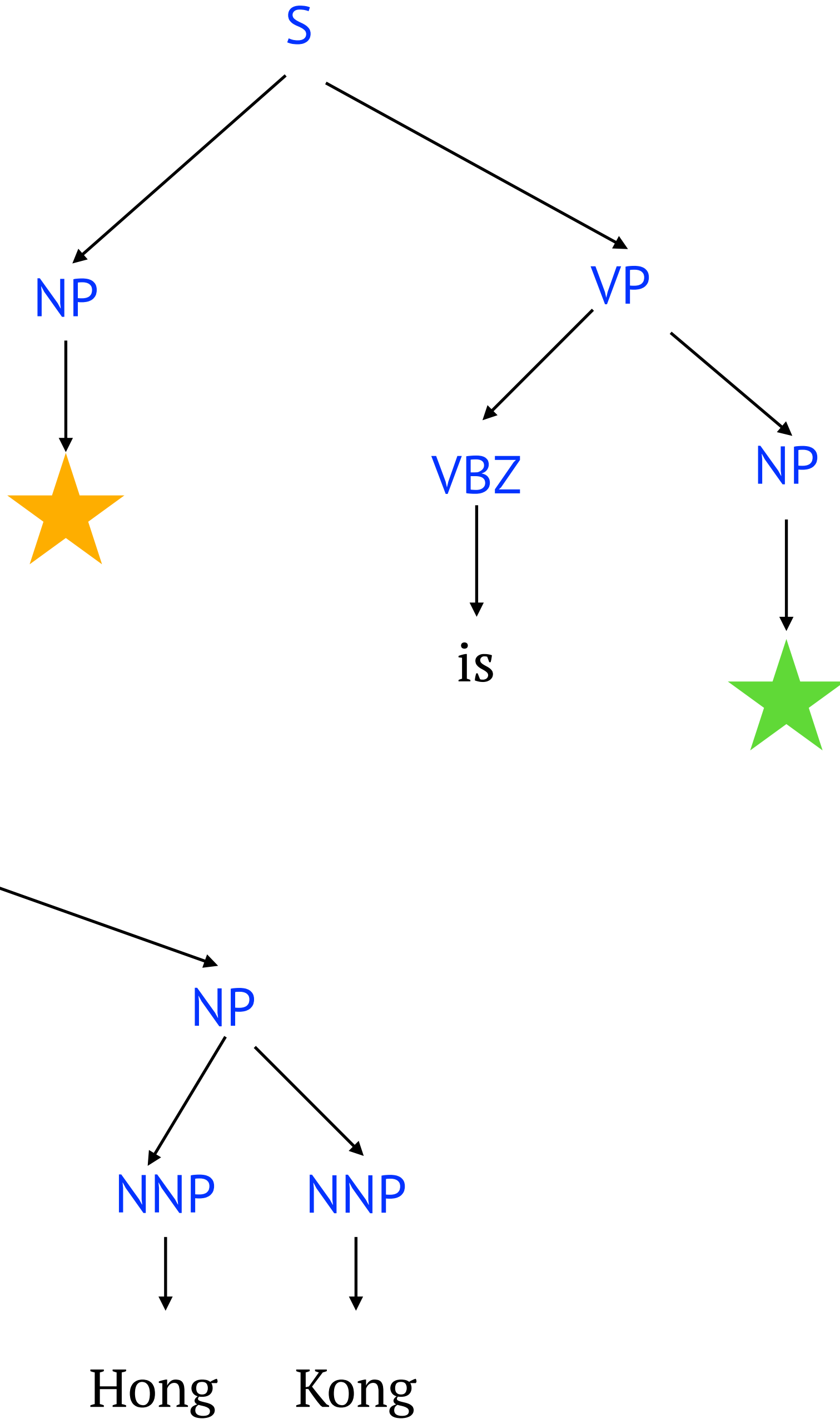
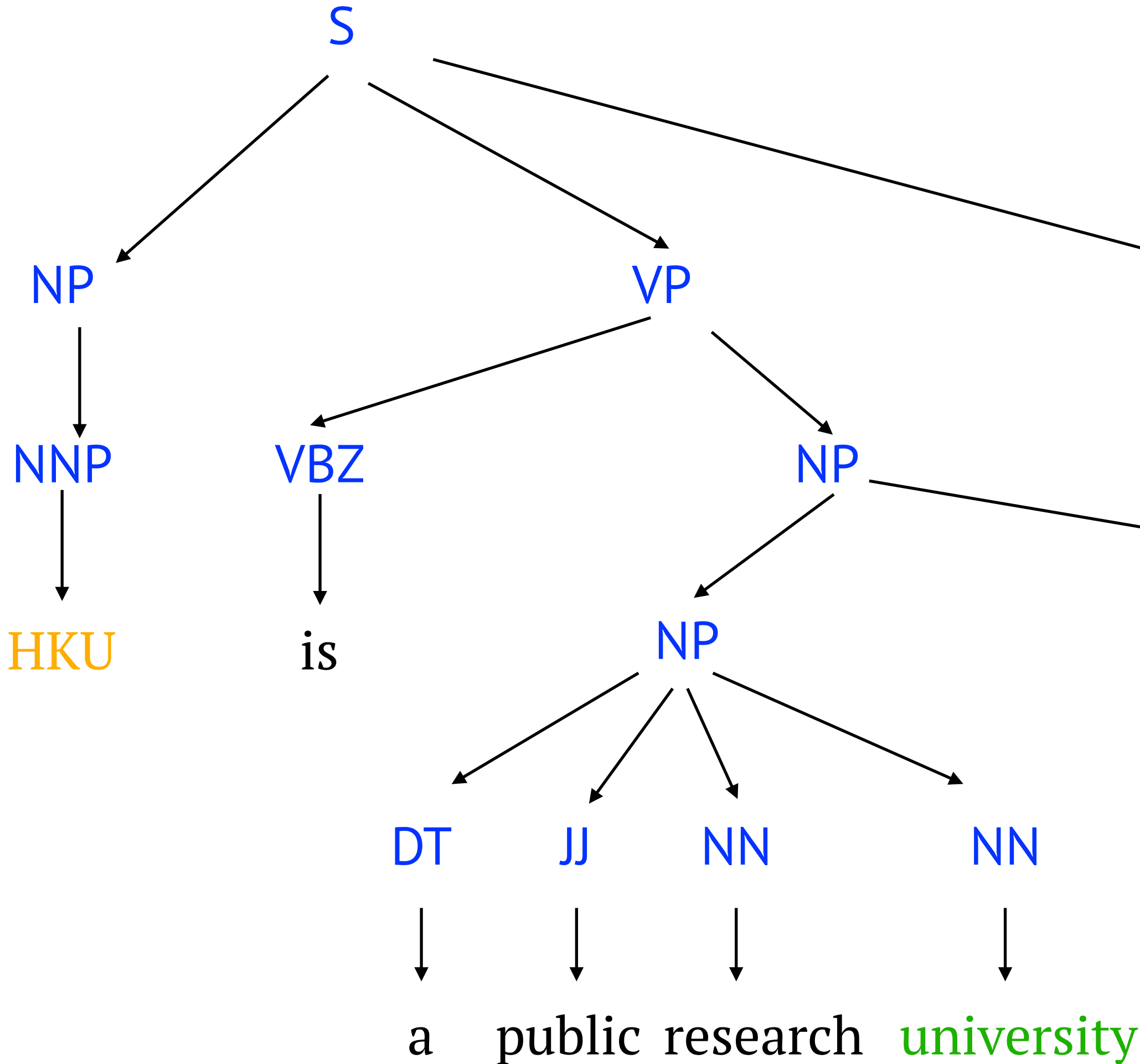
Output:



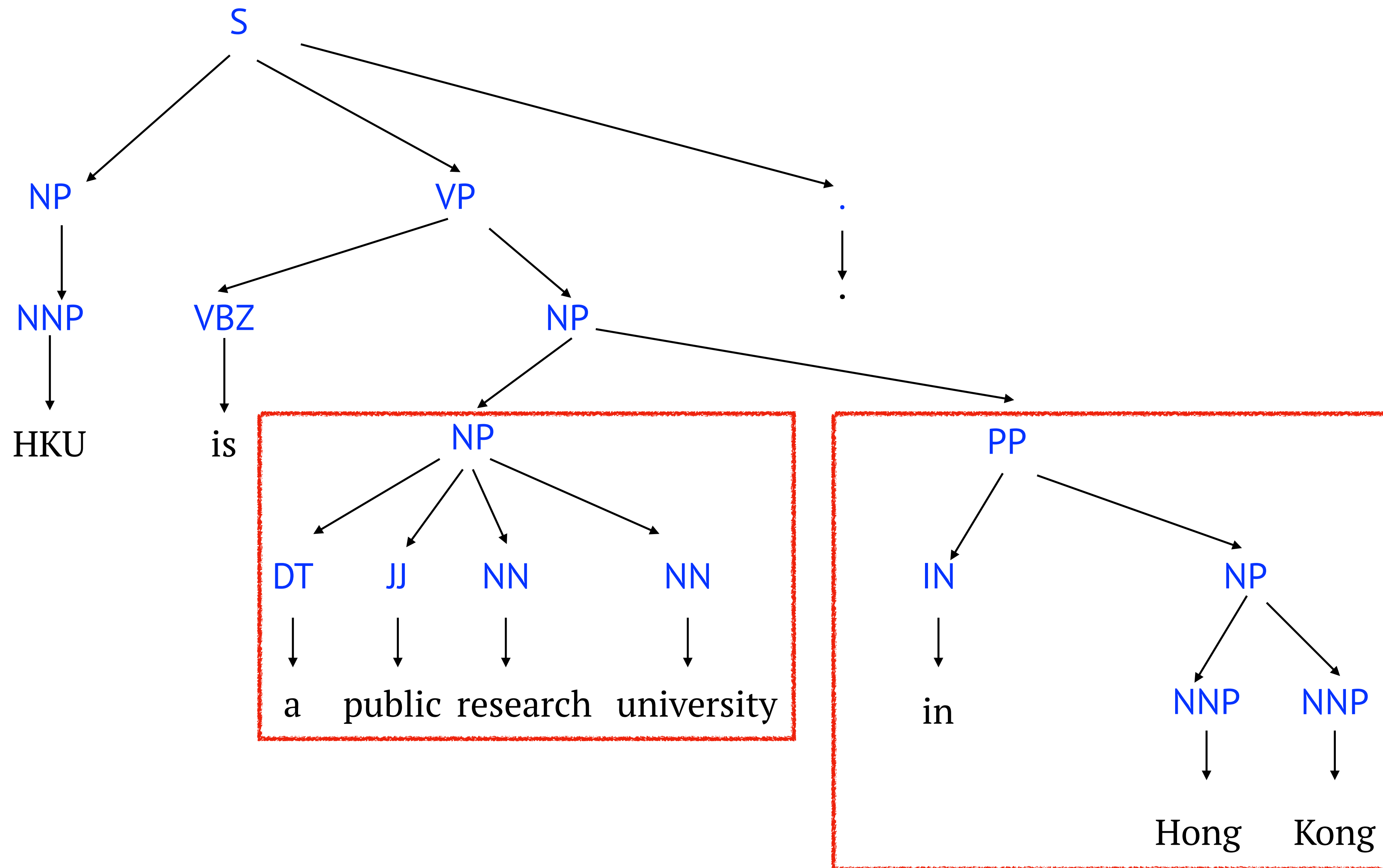
Parse Trees



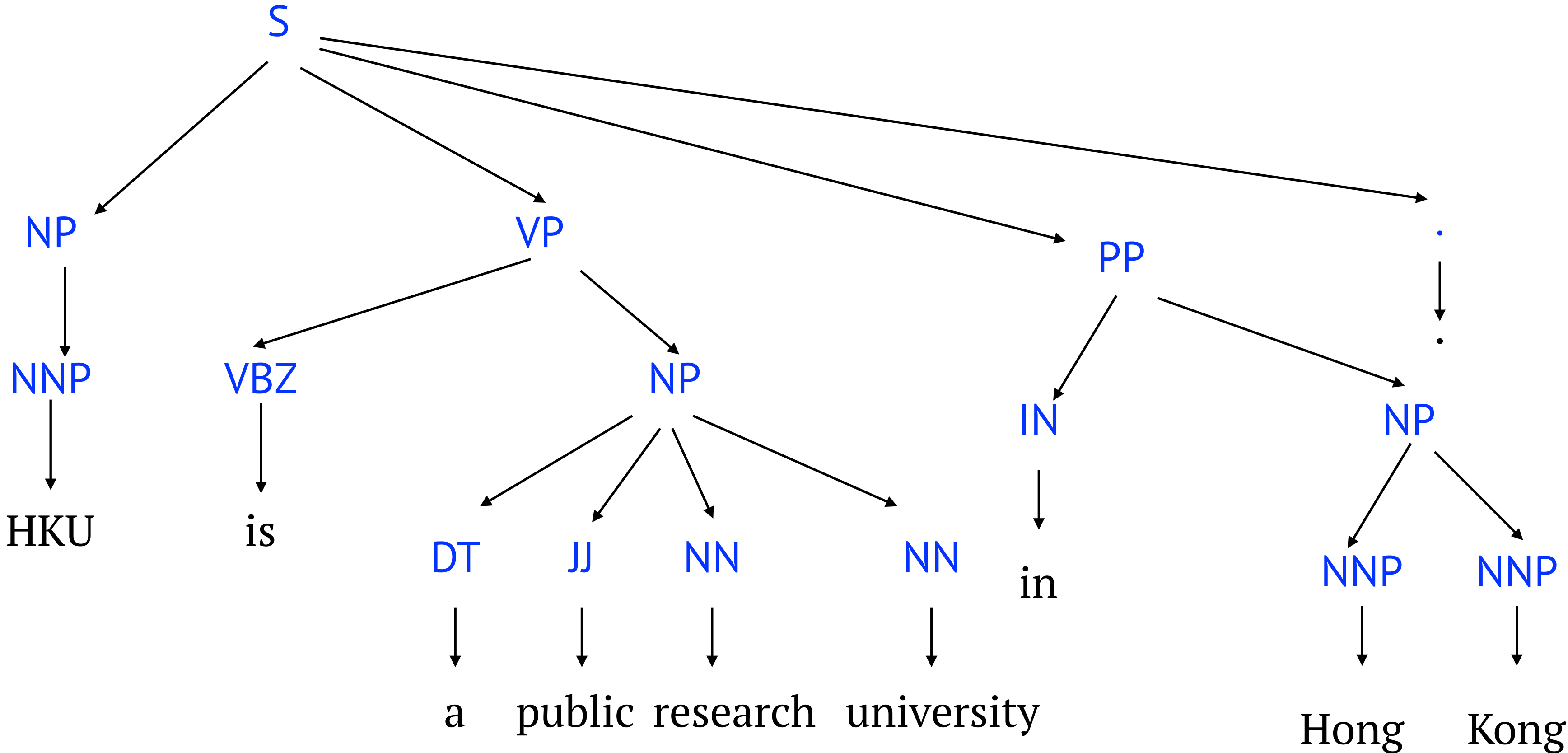
Parse Trees



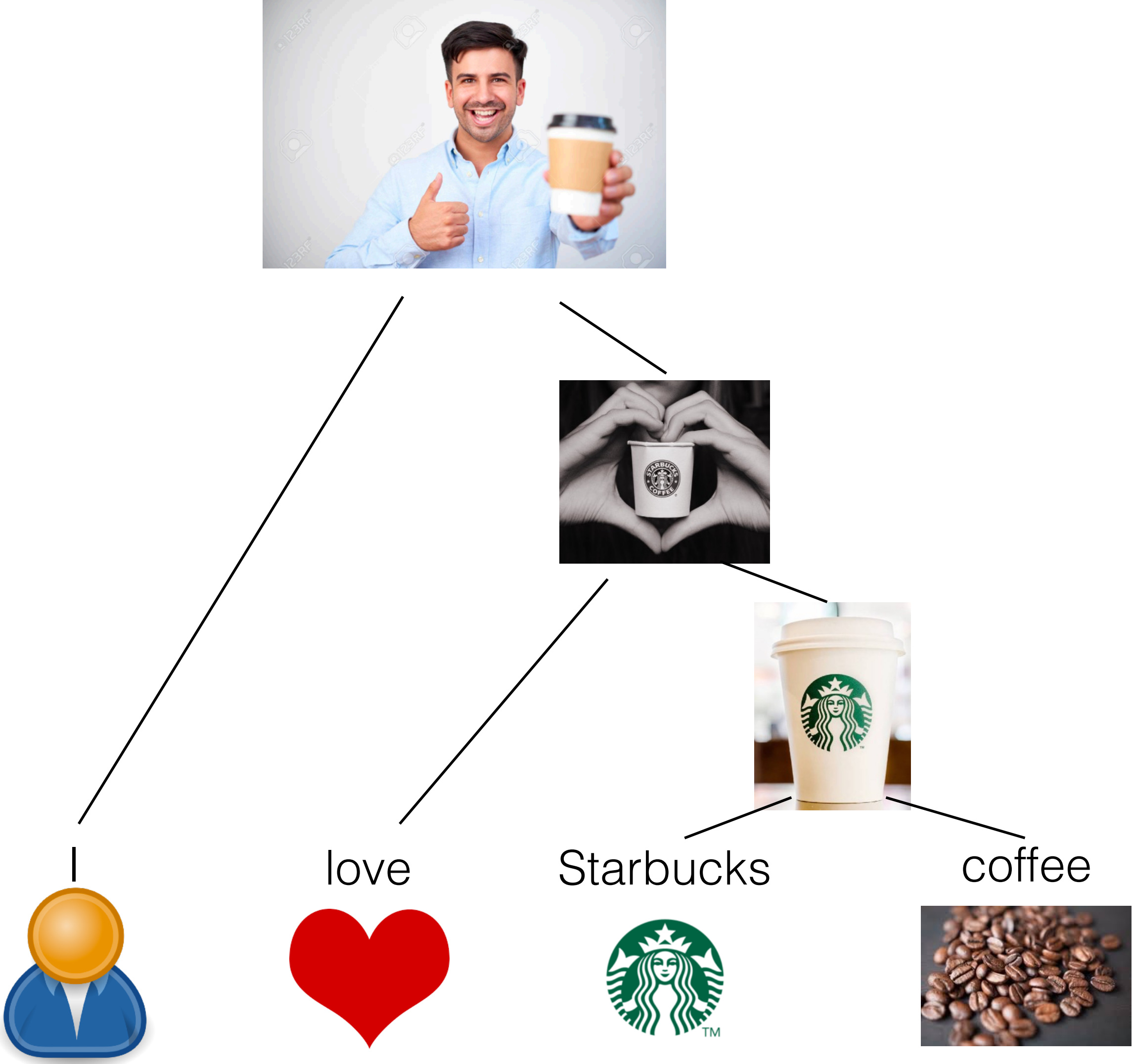
Parse Trees



Parse Trees



Linguistic Structures



Context-Free Grammars

A context free grammar $G = (N, \Sigma, R, S)$ where:

N is a set of non-terminal symbols

Σ is a set of terminal symbols

R is a set of rules of the form $X \rightarrow Y_1 Y_2 \dots Y_n$

for $n \geq 0$ $X \in N$ $Y_i \in (N \cup \Sigma)$

$S \in N$ is a distinguished start symbol

A Context-Free Grammar for English

$N = \{S, NP, VP, PP, DT, Vi, Vt, NN, IN\}$

$S = S$

$\Sigma = \{\text{sleeps, saw, man, woman, telescope, the, with, in}\}$

$R =$

$S \longrightarrow NP VP$

$Vi \longrightarrow \text{sleeps}$

$Vt \longrightarrow \text{saw}$

$VP \longrightarrow Vi$

$VP \longrightarrow Vt NP$

$NN \longrightarrow \text{man}$

$NN \longrightarrow \text{woman}$

$VP \longrightarrow VP PP$

$NN \longrightarrow \text{telescope}$

$NP \longrightarrow DT NN$

$DT \longrightarrow \text{the}$

$NP \longrightarrow NP PP$

$IN \longrightarrow \text{with}$

$PP \longrightarrow IN NP$

$IN \longrightarrow \text{in}$

Left-Most Derivations

$R =$

$S \longrightarrow NP VP$

$VP \longrightarrow Vi$

$VP \longrightarrow Vt NP$

$VP \longrightarrow VP PP$

$NP \longrightarrow DT NN$

$NP \longrightarrow NP PP$

$PP \longrightarrow IN NP$

$Vi \longrightarrow \text{sleeps}$

$Vt \longrightarrow \text{saw}$

$NN \longrightarrow \text{man}$

$NN \longrightarrow \text{woman}$

$NN \longrightarrow \text{telescope}$

$DT \longrightarrow \text{the}$

$IN \longrightarrow \text{with}$

$IN \longrightarrow \text{in}$

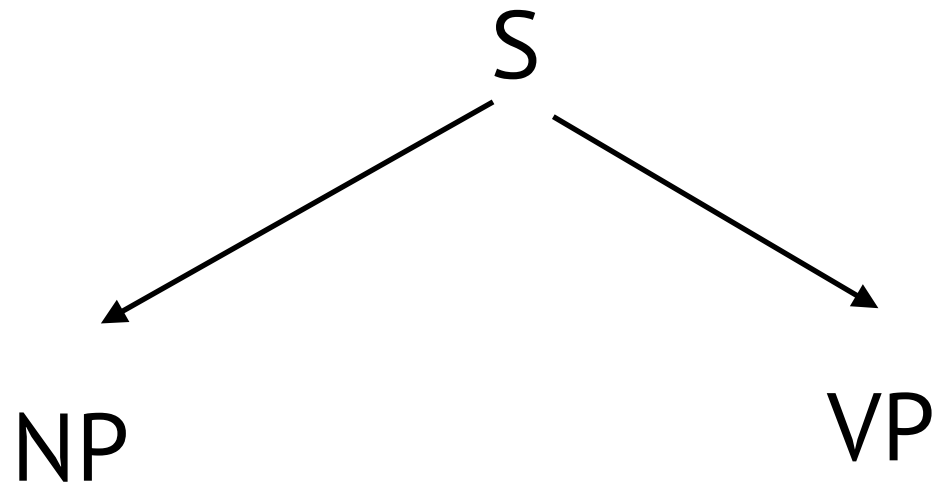
S

(S)

Left-Most Derivations

$R =$

$S \longrightarrow NP VP$	$Vi \longrightarrow$ sleeps
$VP \longrightarrow Vi$	$Vt \longrightarrow$ saw
$VP \longrightarrow Vt NP$	$NN \longrightarrow$ man
$VP \longrightarrow VP PP$	$NN \longrightarrow$ woman
$NP \longrightarrow DT NN$	$NN \longrightarrow$ telescope
$NP \longrightarrow NP PP$	$DT \longrightarrow$ the
$PP \longrightarrow IN NP$	$IN \longrightarrow$ with
	$IN \longrightarrow$ in

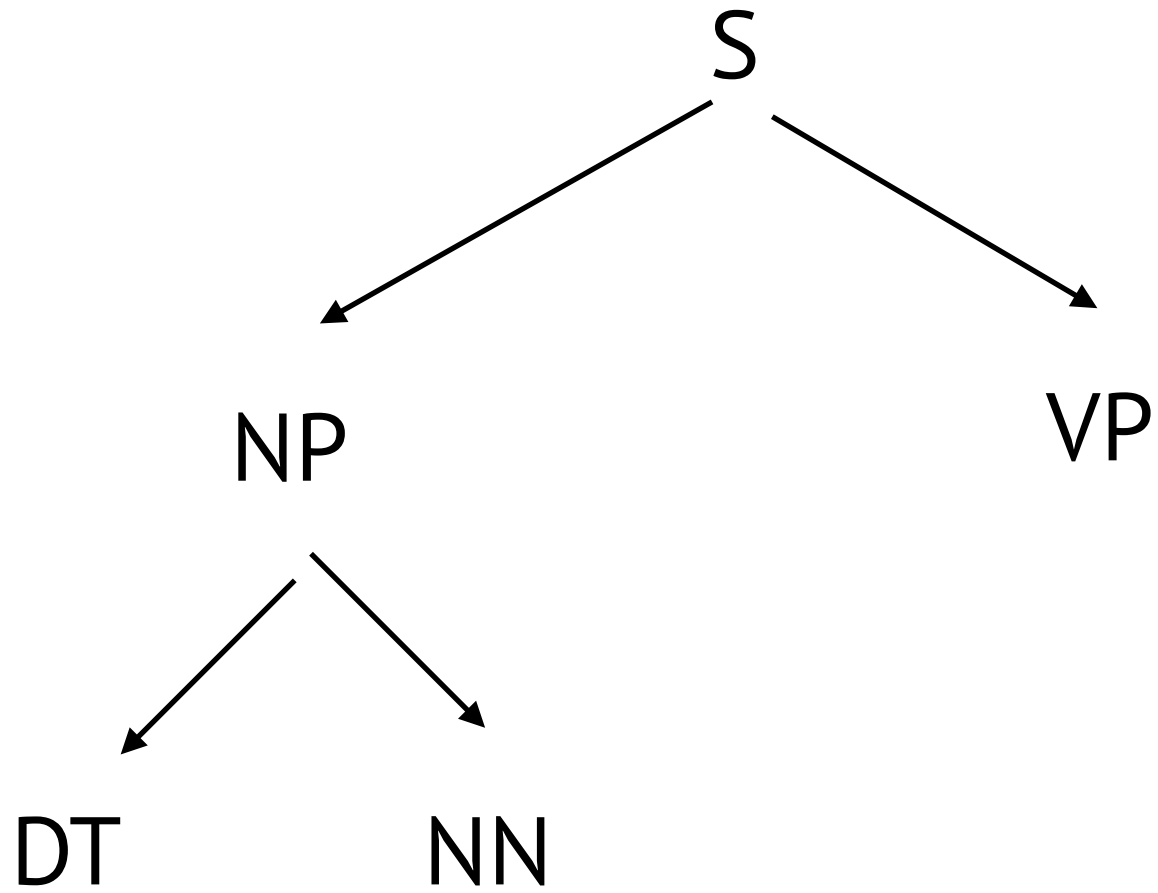


(NP VP)

Left-Most Derivations

$R =$

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

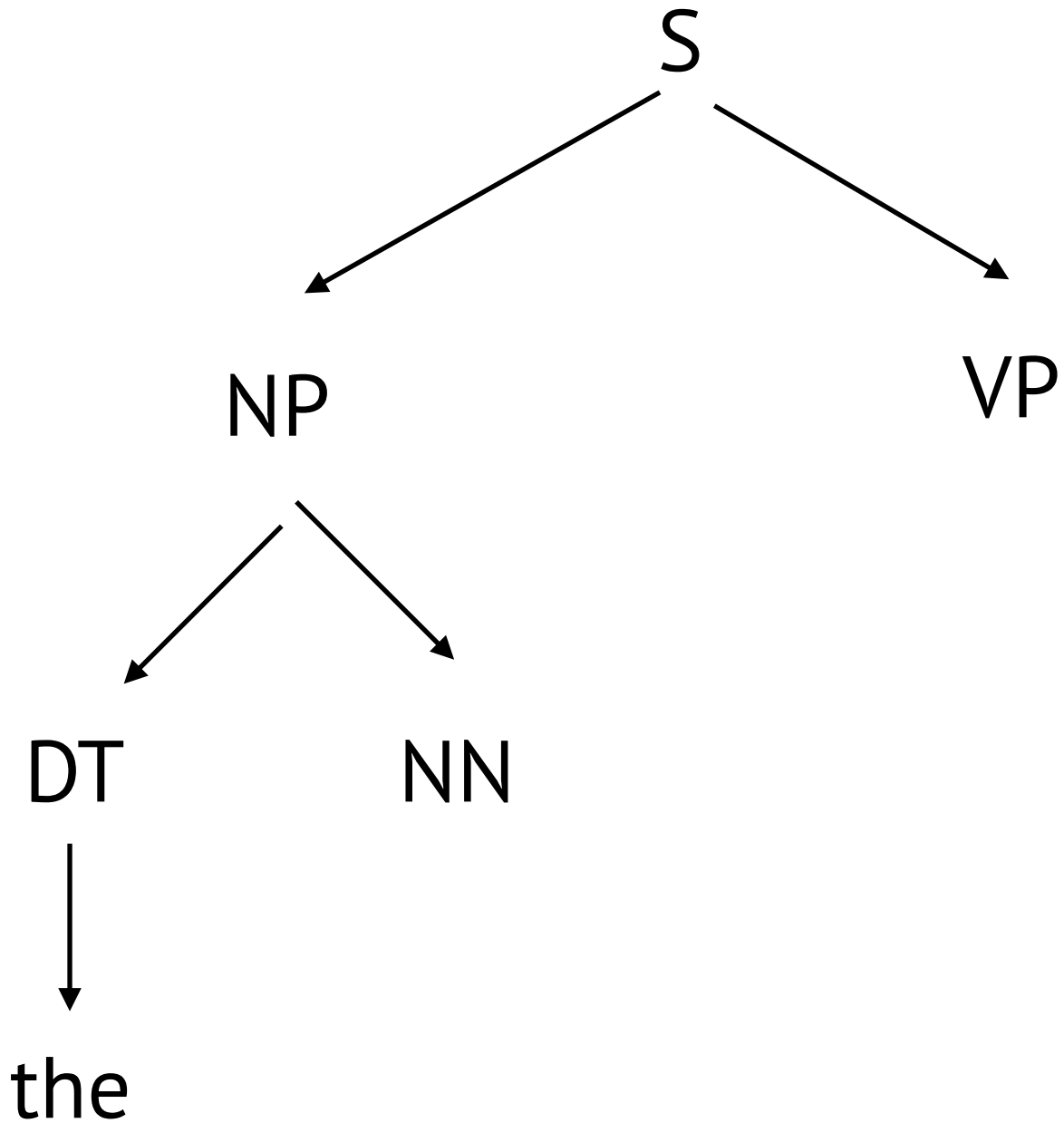


(DT NN VP)

Left-Most Derivations

$R =$

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

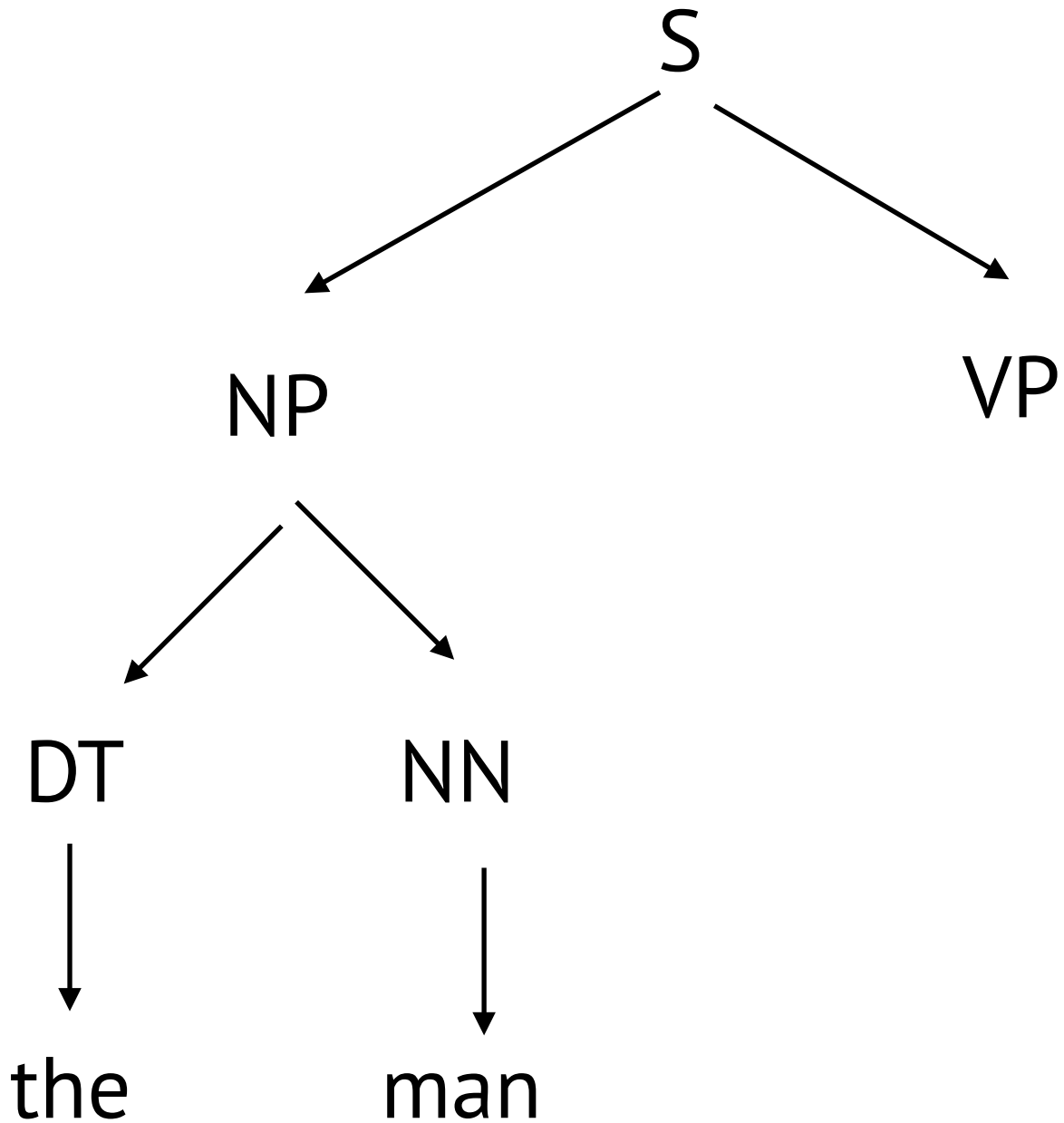


(the NN VP)

Left-Most Derivations

$R =$

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

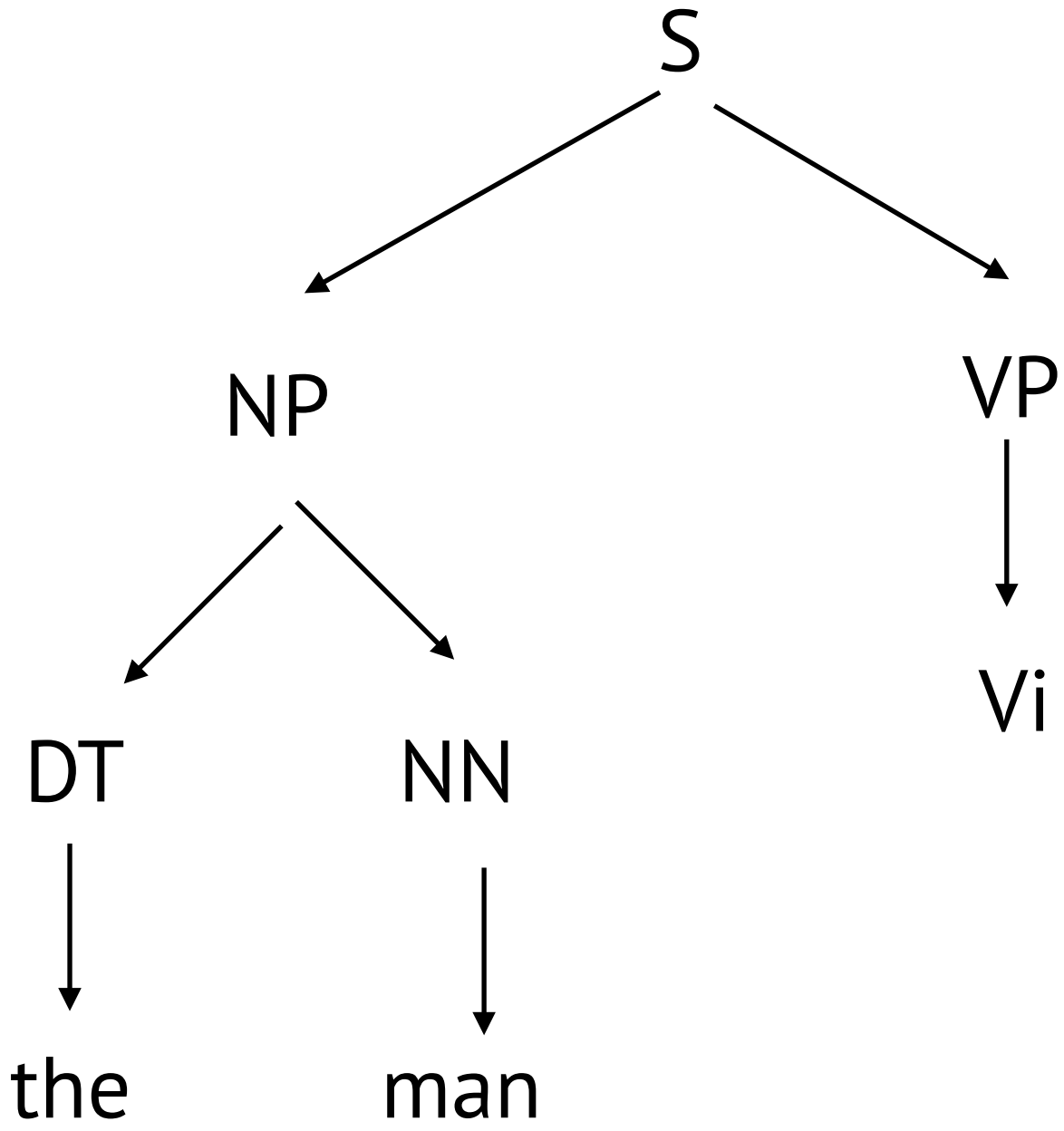


(the man VP)

Left-Most Derivations

$R =$

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

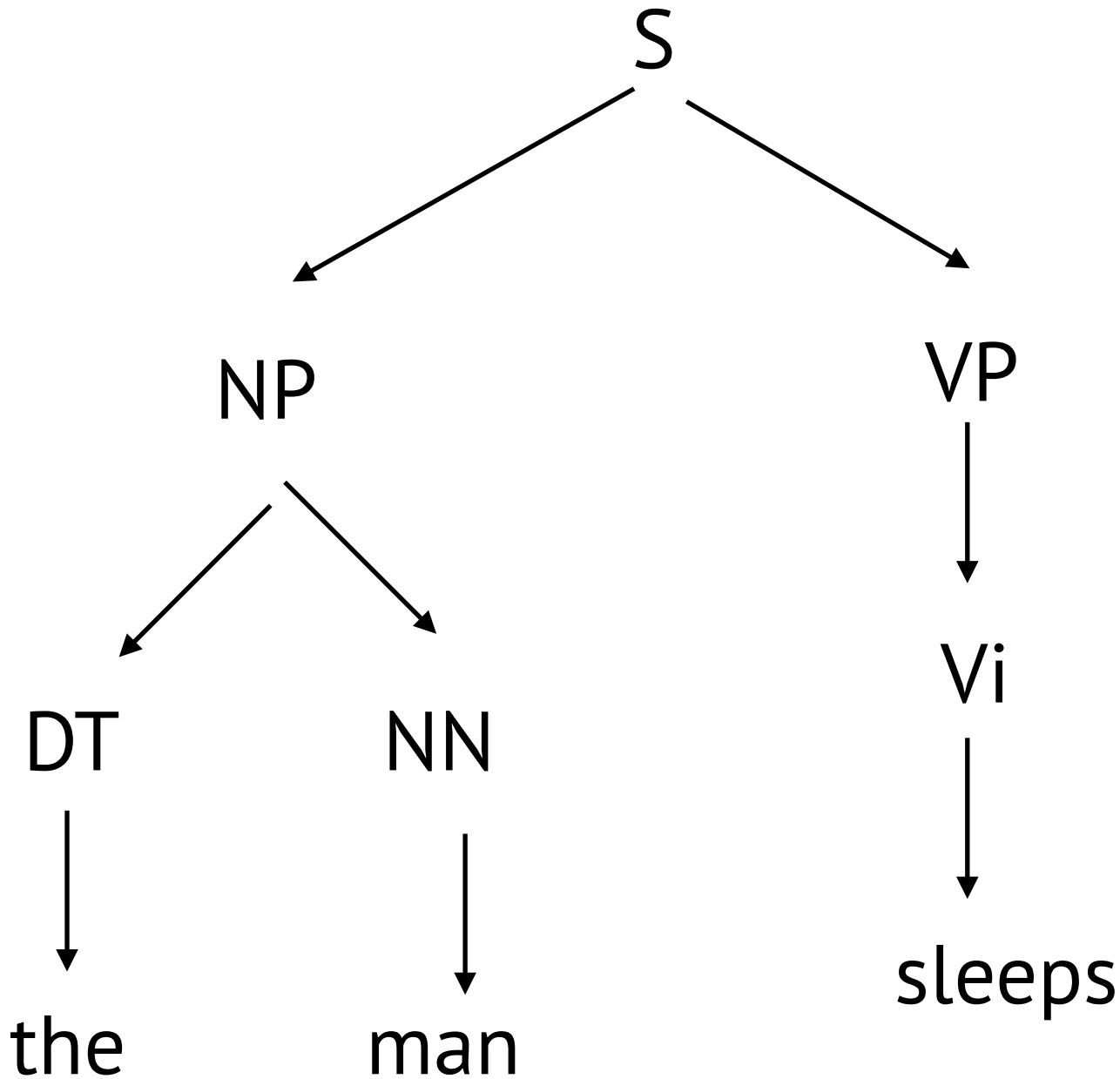


(the man Vi)

Left-Most Derivations

$R =$

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

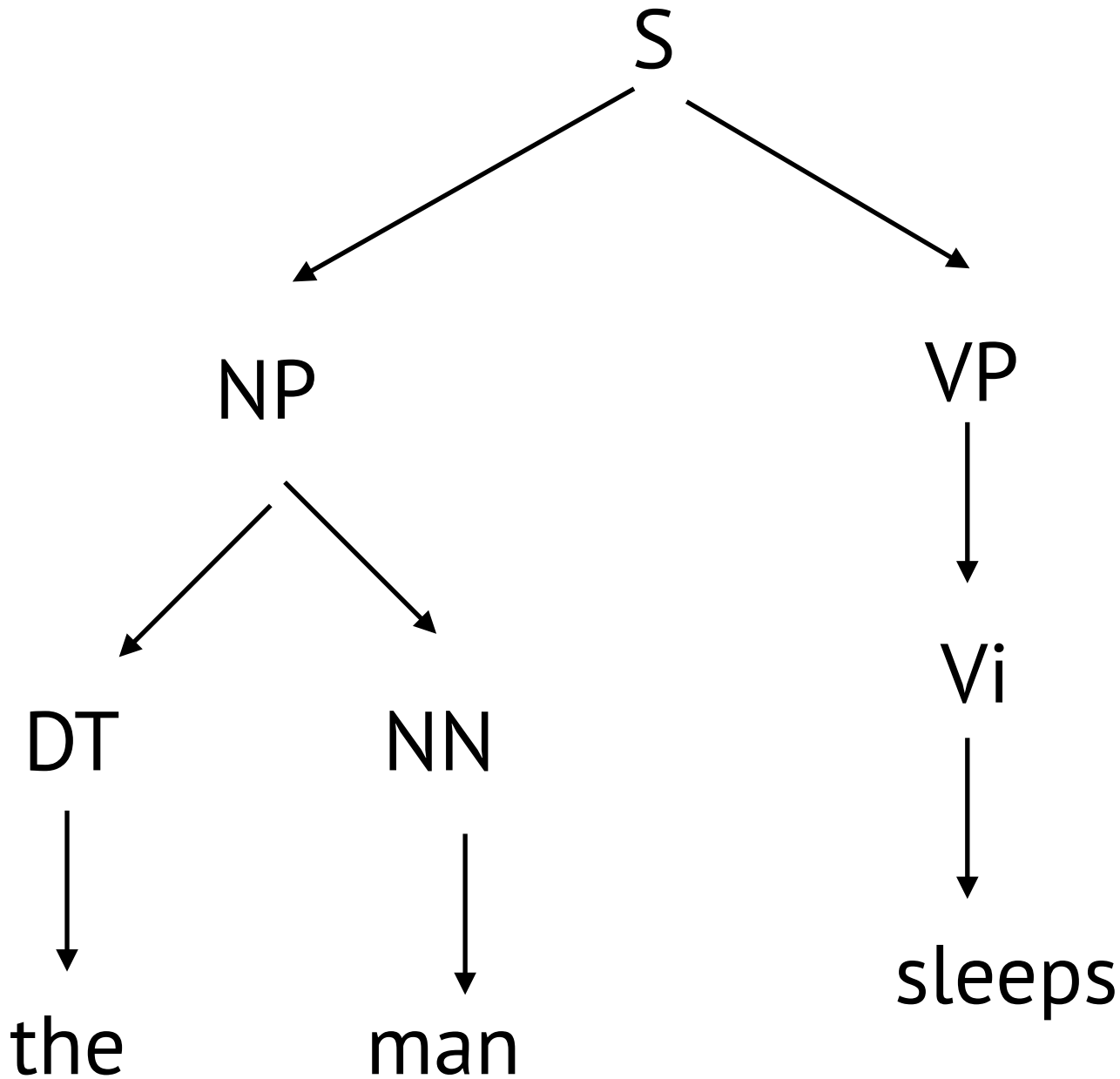


(the man sleeps)

Left-Most Derivations

$R =$

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

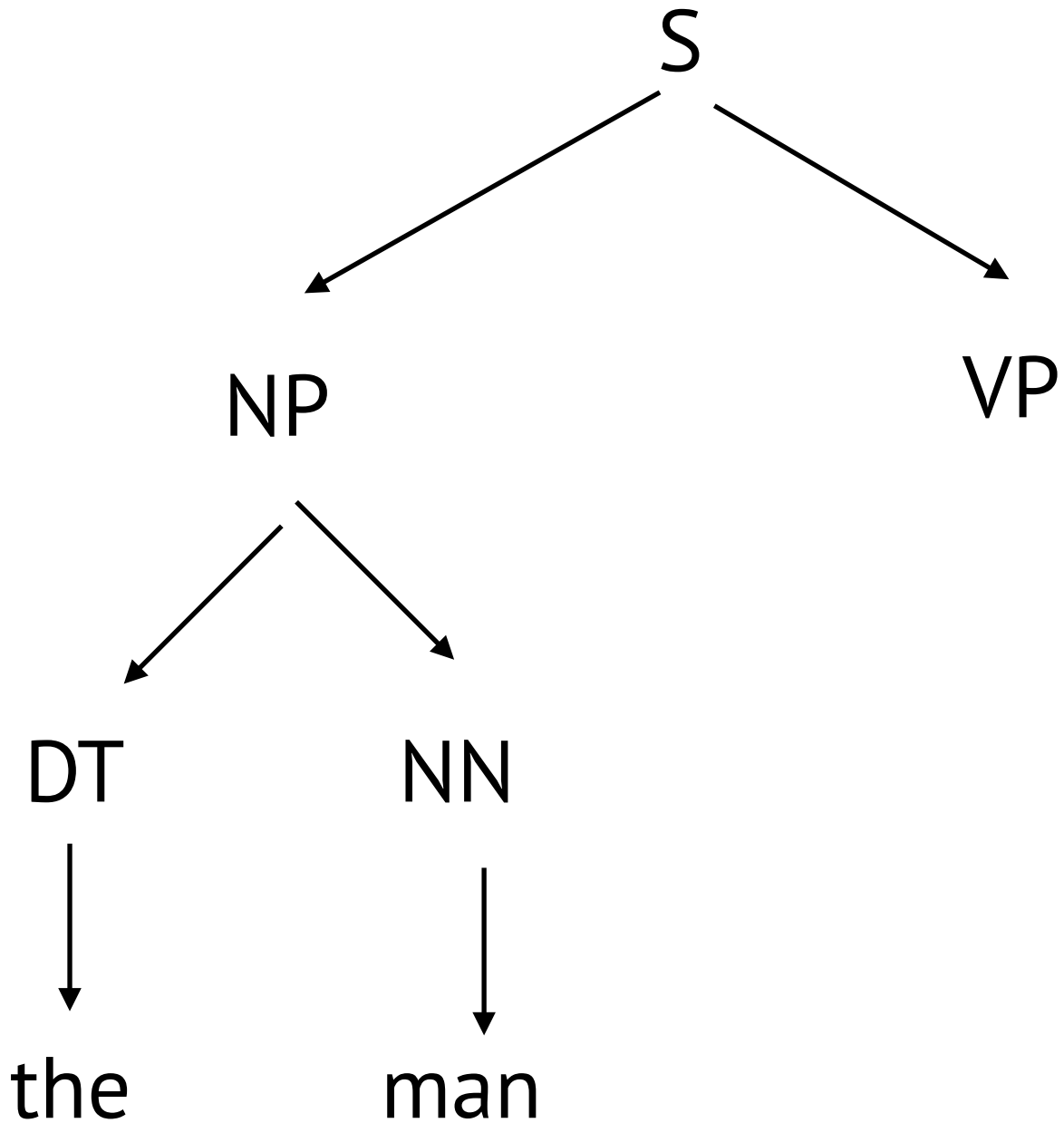


(the man sleeps)

Left-Most Derivations

$R =$

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

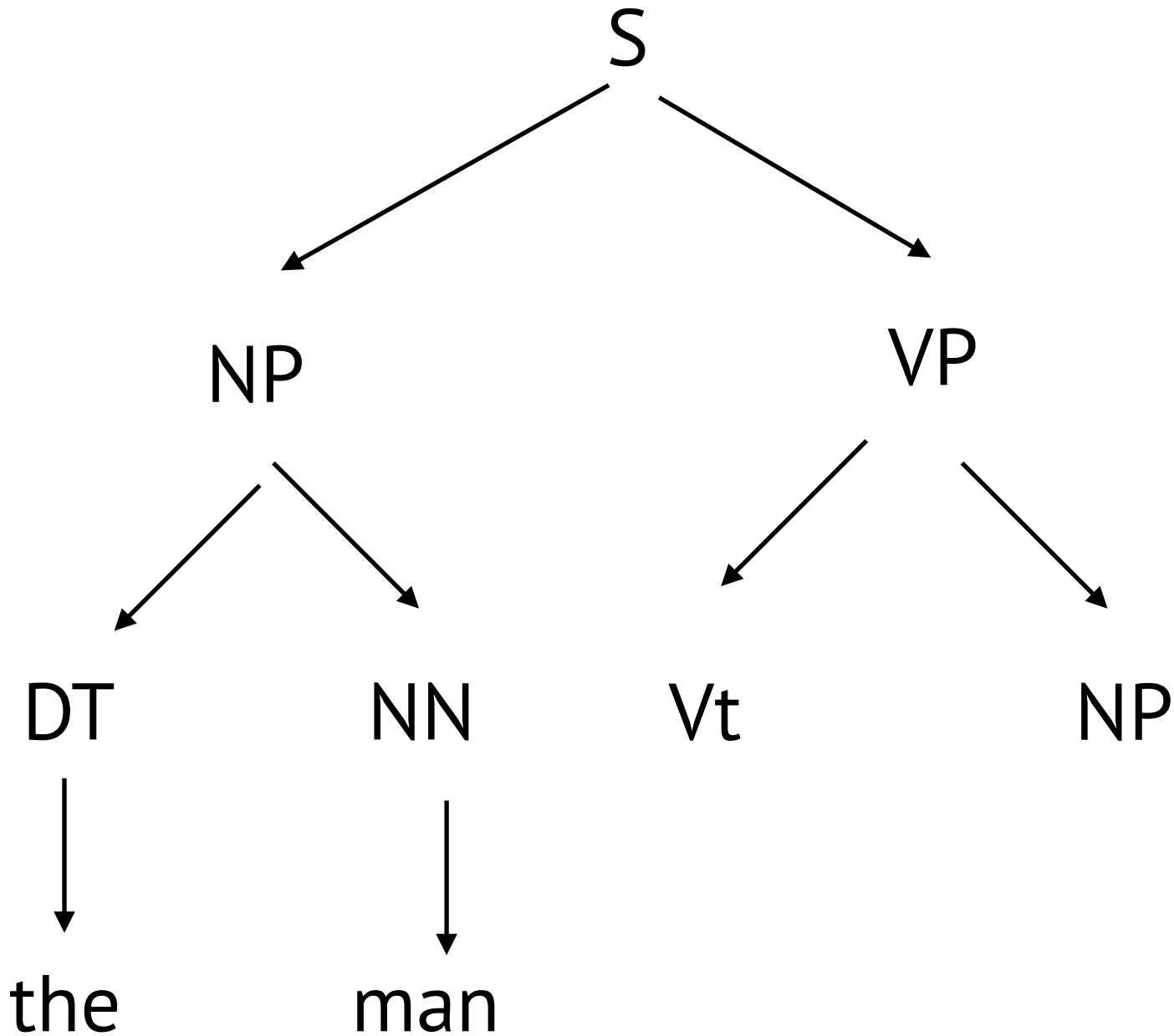


(the man VP)

Left-Most Derivations

$R =$

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

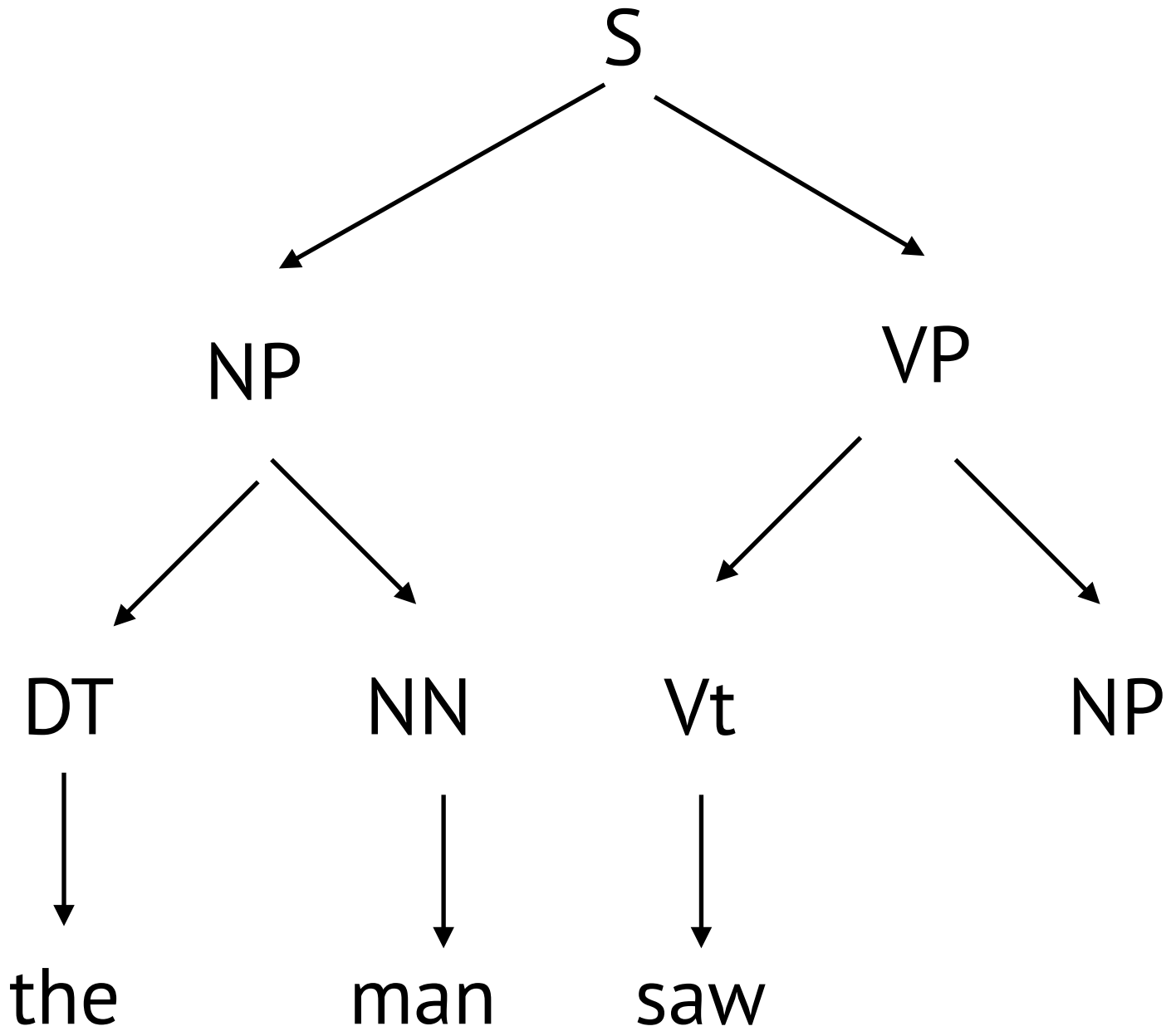


(the man Vt NP)

Left-Most Derivations

$R =$

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

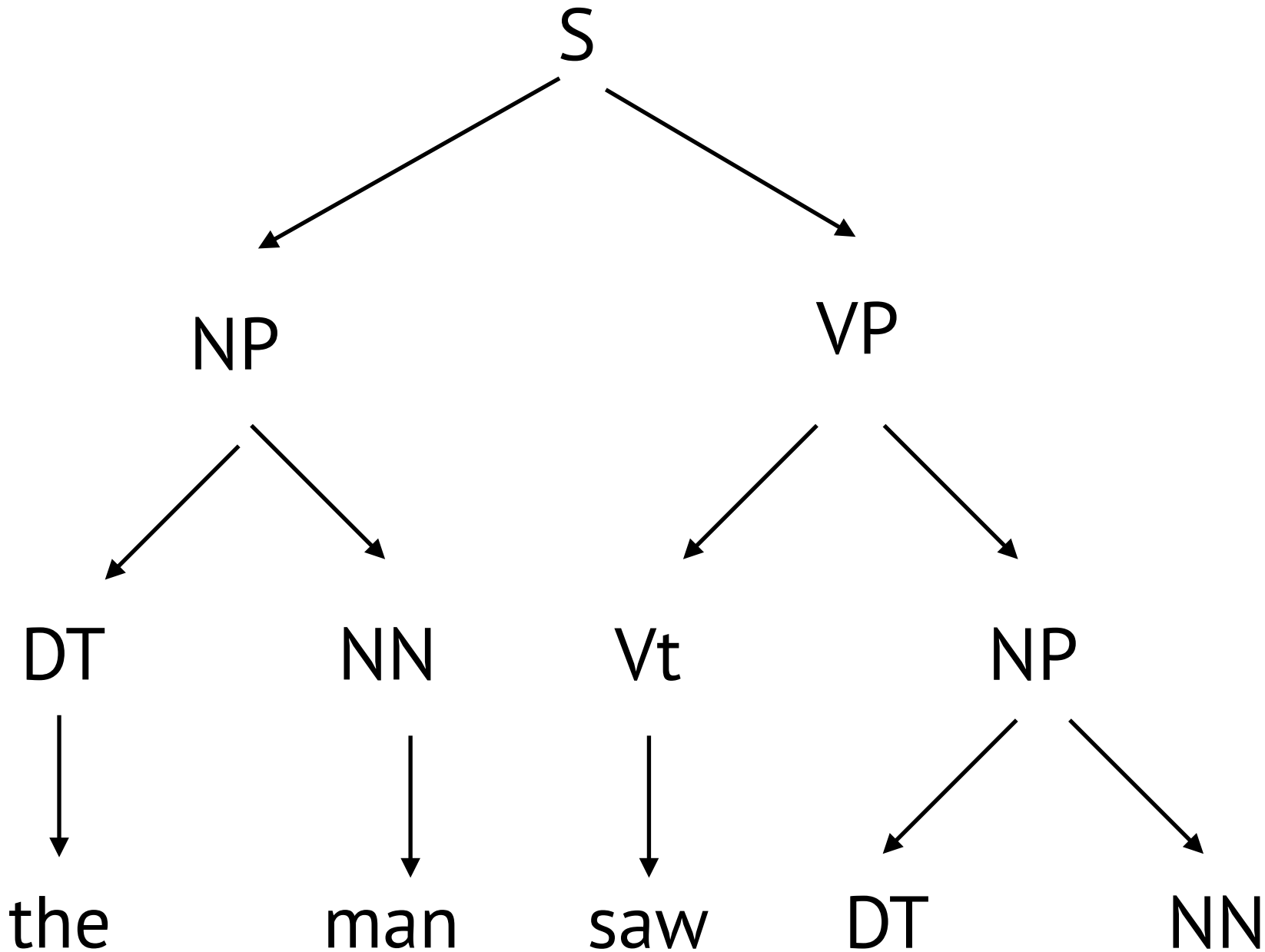


(the man saw NP)

Left-Most Derivations

$R =$

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

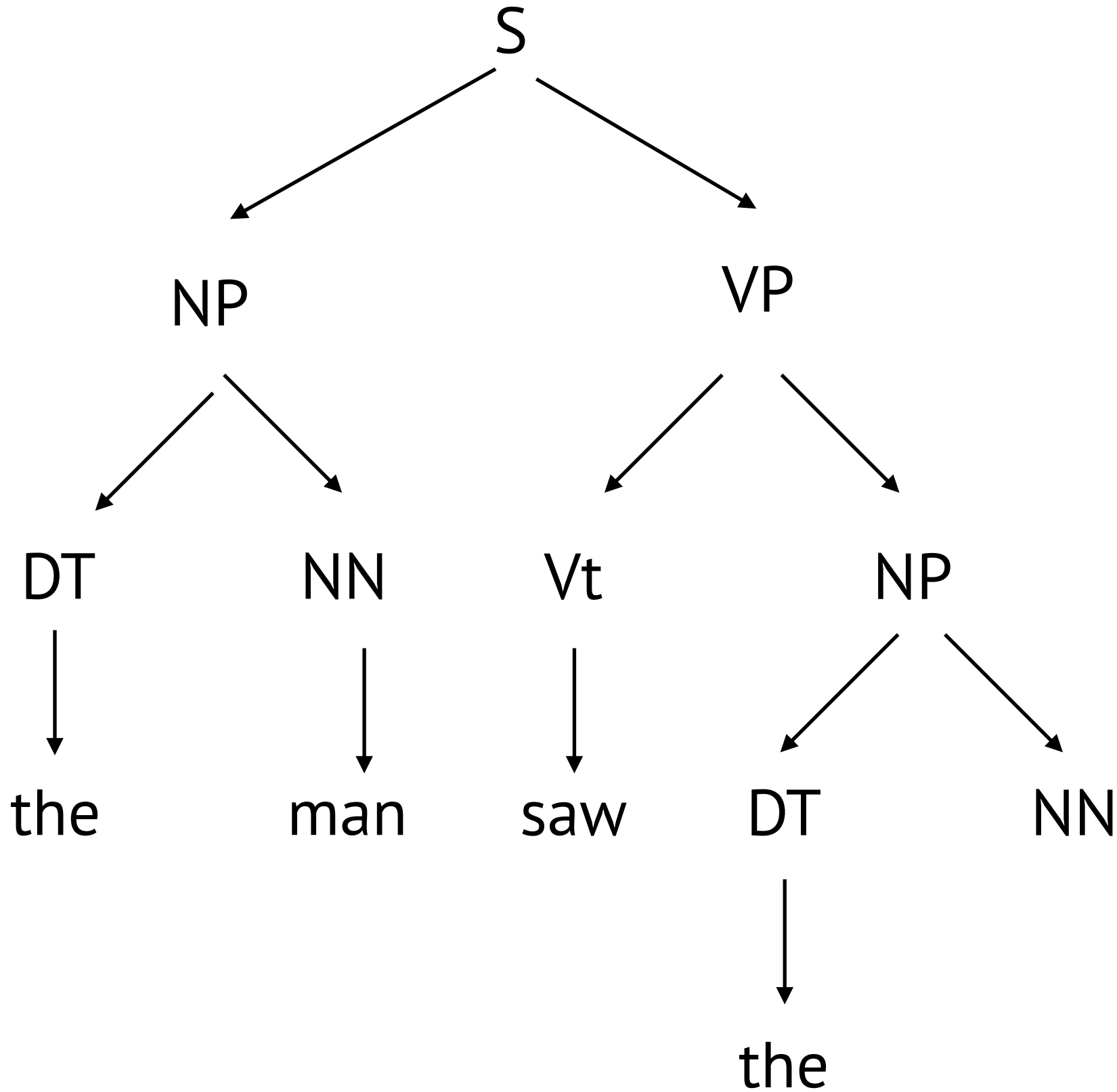


(the man saw DT NN)

Left-Most Derivations

$R =$

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

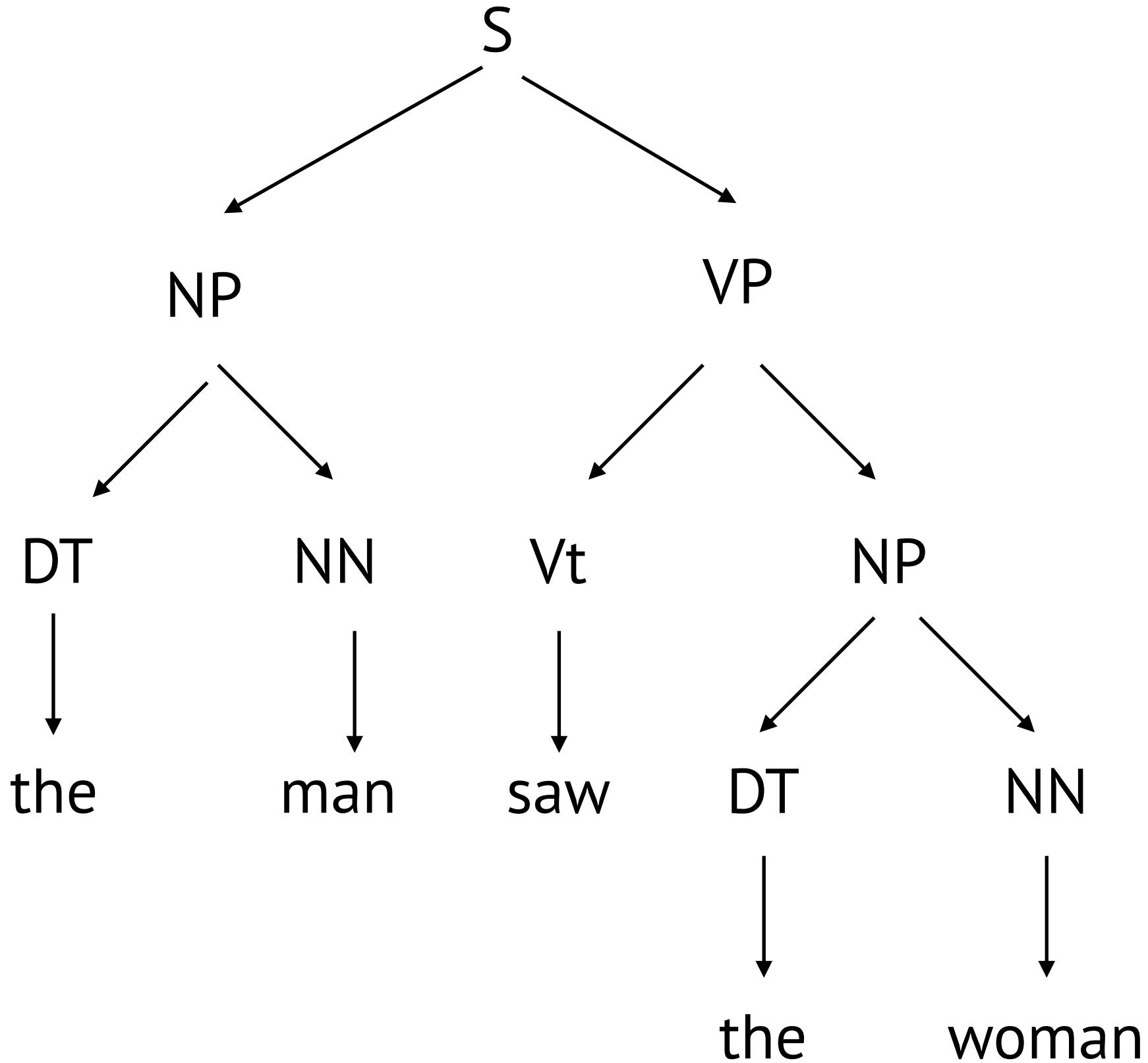


(the man saw the NN)

Left-Most Derivations

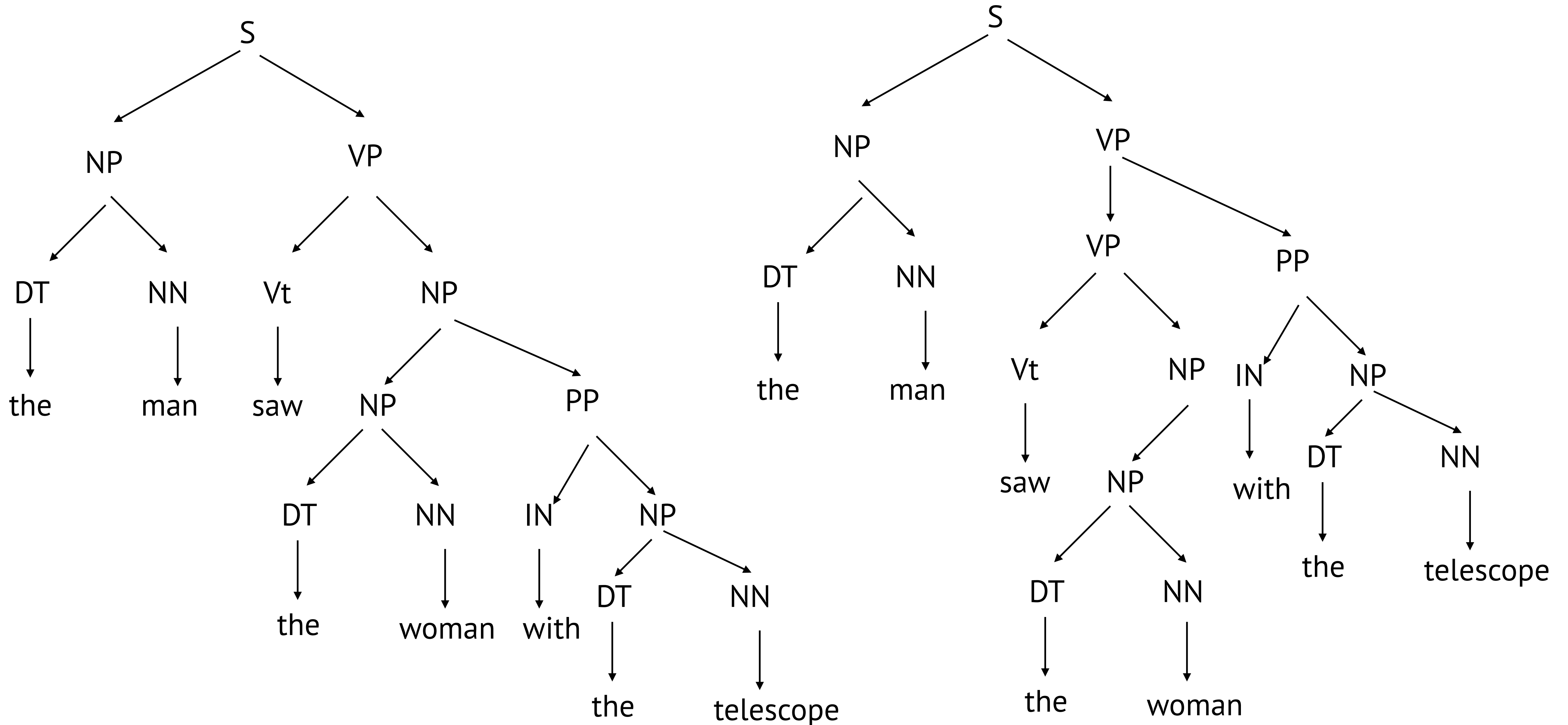
$R =$

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



(the man saw the woman)

Different Derivations Can Lead to the Same String



“Context-Free” — What does it mean?

$N = \{S, NP, VP, PP, DT, Vi, Vt, NN, IN\}$

$S = S$

$\Sigma = \{\text{sleeps, saw, man, woman, telescope, the, with, in}\}$

$R =$

$S \longrightarrow NP VP$	$Vi \longrightarrow \text{sleeps}$
$VP \longrightarrow Vi$	$Vt \longrightarrow \text{saw}$
$VP \longrightarrow Vt NP$	$NN \longrightarrow \text{man}$
$VP \longrightarrow VP PP$	$NN \longrightarrow \text{woman}$
$NP \longrightarrow DT NN$	$NN \longrightarrow \text{telescope}$
$NP \longrightarrow NP PP$	$DT \longrightarrow \text{the}$
$PP \longrightarrow IN NP$	$IN \longrightarrow \text{with}$
	$IN \longrightarrow \text{in}$

$Vt NP \longrightarrow Vt NP PP$

“Context-Free” — What does it mean?

$N = \{S, NP, VP, PP, DT, Vi, Vt, NN, IN\}$

$S = S$

$\Sigma = \{\text{sleeps, saw, man, woman, telescope, the, with, in}\}$

$R =$

$S \longrightarrow NP VP$	$Vi \longrightarrow \text{sleeps}$
$VP \longrightarrow Vi$	$Vt \longrightarrow \text{saw}$
$VP \longrightarrow Vt NP$	$NN \longrightarrow \text{man}$
$VP \longrightarrow VP PP$	$NN \longrightarrow \text{woman}$
$NP \longrightarrow DT NN$	$NN \longrightarrow \text{telescope}$
$Vt NP \longrightarrow Vt NP PP$	$DT \longrightarrow \text{the}$
$PP \longrightarrow IN NP$	$IN \longrightarrow \text{with}$
	$IN \longrightarrow \text{in}$

non-context-free

Probabilistic Context-Free Grammars

$R =$

S \longrightarrow NP VP 1.0

VP \longrightarrow Vi 0.4

VP \longrightarrow Vt NP 0.4

VP \longrightarrow VP PP 0.2

NP \longrightarrow DT NN 0.3

NP \longrightarrow NP PP 0.7

PP \longrightarrow IN NP 1.0

Vi \longrightarrow sleeps 1.0

Vt \longrightarrow saw 1.0

NN \longrightarrow man 0.7

NN \longrightarrow woman 0.2

NN \longrightarrow telescope 0.1

DT \longrightarrow the 1.0

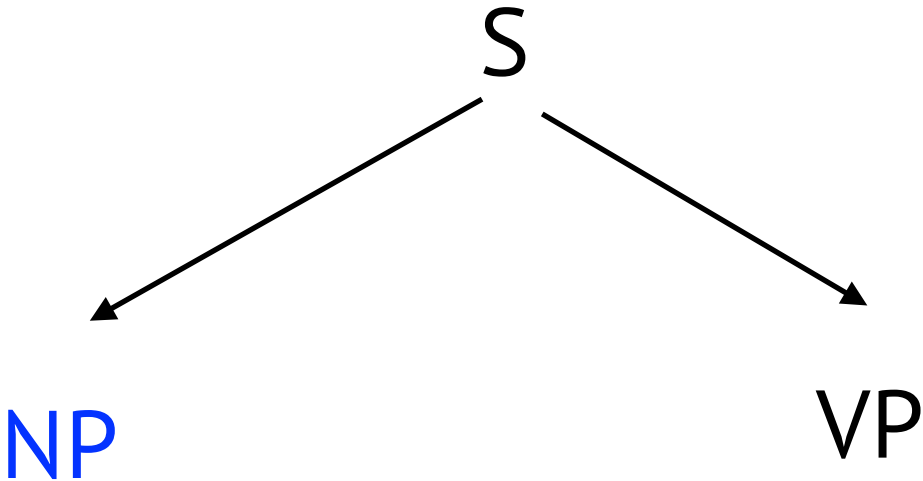
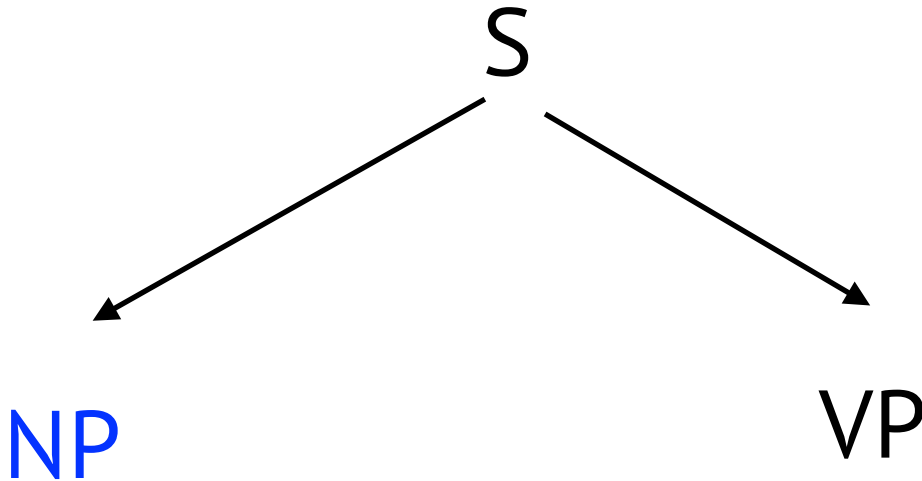
IN \longrightarrow with 0.5

IN \longrightarrow in 0.5

Probabilistic Context-Free Grammars

$R =$

S	→	NP VP	1.0	Vi	→	sleeps	1.0
VP	→	Vi	0.4	Vt	→	saw	1.0
VP	→	Vt NP	0.4	NN	→	man	0.7
VP	→	VP PP	0.2	NN	→	woman	0.2
NP	→	DT NN	0.3	NN	→	telescope	0.1
NP	→	NP PP	0.7	DT	→	the	1.0
PP	→	IN NP	1.0	IN	→	with	0.5
				IN	→	in	0.5



Probabilistic Context-Free Grammars

$R =$

S \longrightarrow NP VP 1.0

VP \longrightarrow Vi 0.4

VP \longrightarrow Vt NP 0.4

VP \longrightarrow VP PP 0.2

NP \longrightarrow DT NN 0.3

NP \longrightarrow NP PP 0.7

PP \longrightarrow IN NP 1.0

Vi \longrightarrow sleeps 1.0

Vt \longrightarrow saw 1.0

NN \longrightarrow man 0.7

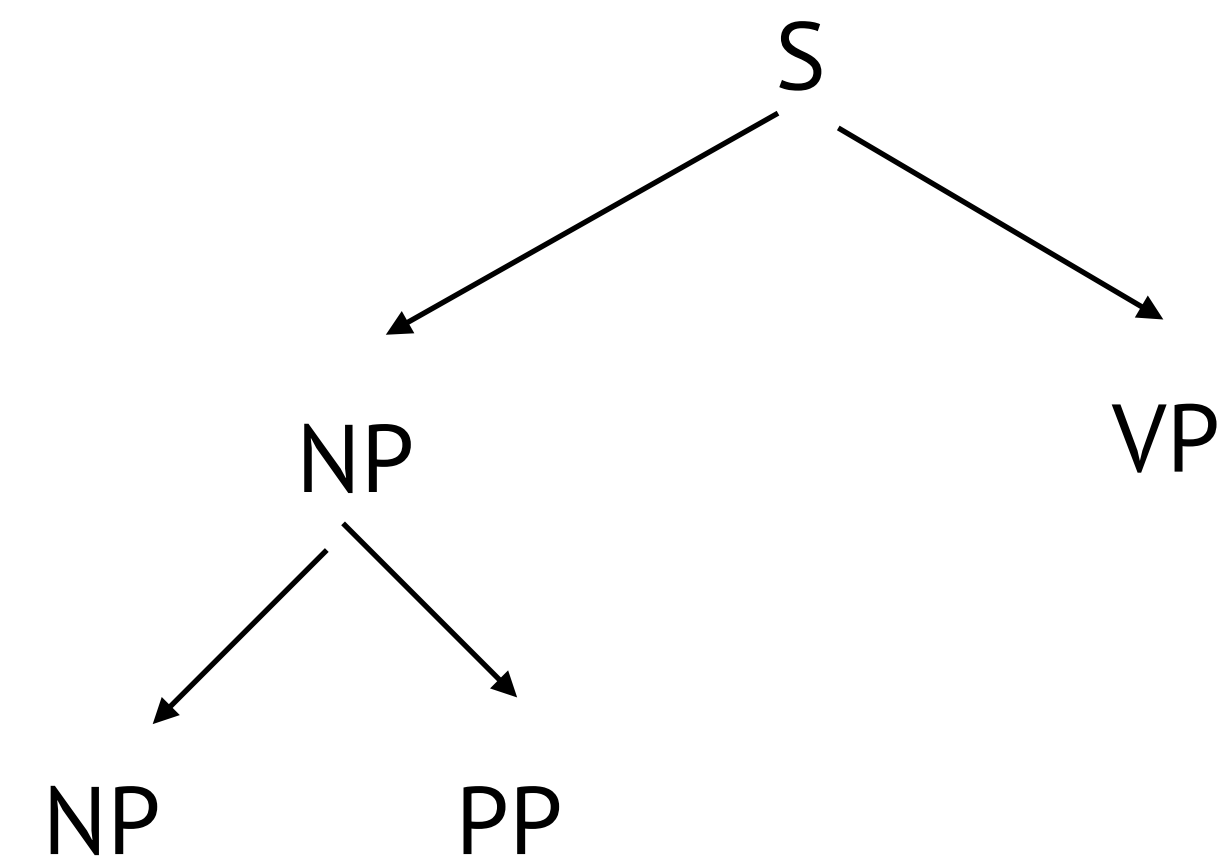
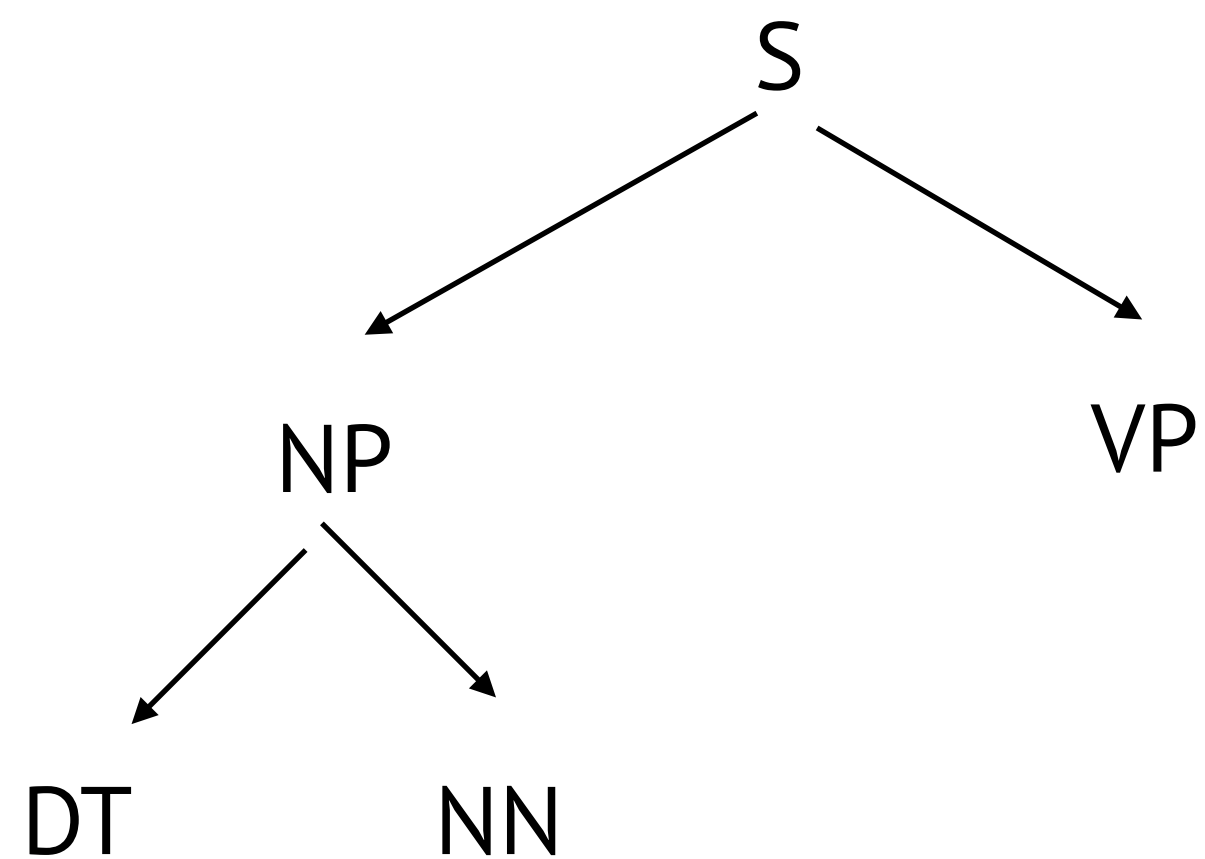
NN \longrightarrow woman 0.2

NN \longrightarrow telescope 0.1

DT \longrightarrow the 1.0

IN \longrightarrow with 0.5

IN \longrightarrow in 0.5



Probabilistic Context-Free Grammars

$R =$

S	→	NP VP	1.0	Vi	→	sleeps	1.0
VP	→	Vi	0.4	Vt	→	saw	1.0
VP	→	Vt NP	0.4	NN	→	man	0.7
VP	→	VP PP	0.2	NN	→	woman	0.2
NP	→	DT NN	0.3	NN	→	telescope	0.1
NP	→	NP PP	0.7	DT	→	the	1.0
PP	→	IN NP	1.0	IN	→	with	0.5
				IN	→	in	0.5

Derivation Example

$R =$

S	→	NP VP	1.0	Vi	→	sleeps	1.0
				Vt	→	saw	1.0
VP	→	Vi	0.4				
VP	→	Vt NP	0.4	NN	→	man	0.7
VP	→	VP PP	0.2	NN	→	woman	0.2
				NN	→	telescope	0.1
NP	→	DT NN	0.3	DT	→	the	1.0
NP	→	NP PP	0.7				
PP	→	IN NP	1.0	IN	→	with	0.5
				IN	→	in	0.5

S

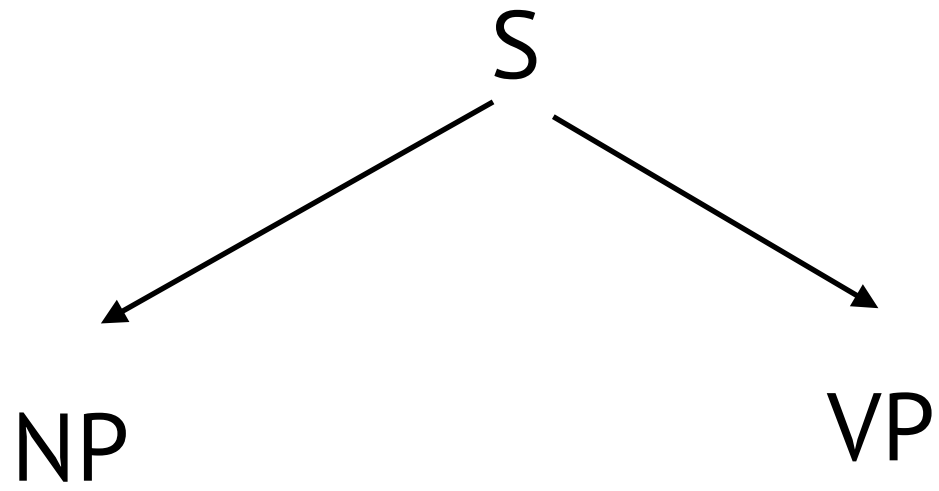
(S)

$P(x, y) =$

Derivation Example

$R =$

S	→	NP VP	1.0	Vi	→	sleeps	1.0
				Vt	→	saw	1.0
VP	→	Vi	0.4				
VP	→	Vt NP	0.4	NN	→	man	0.7
VP	→	VP PP	0.2	NN	→	woman	0.2
				NN	→	telescope	0.1
NP	→	DT NN	0.3	DT	→	the	1.0
NP	→	NP PP	0.7				
PP	→	IN NP	1.0	IN	→	with	0.5
				IN	→	in	0.5



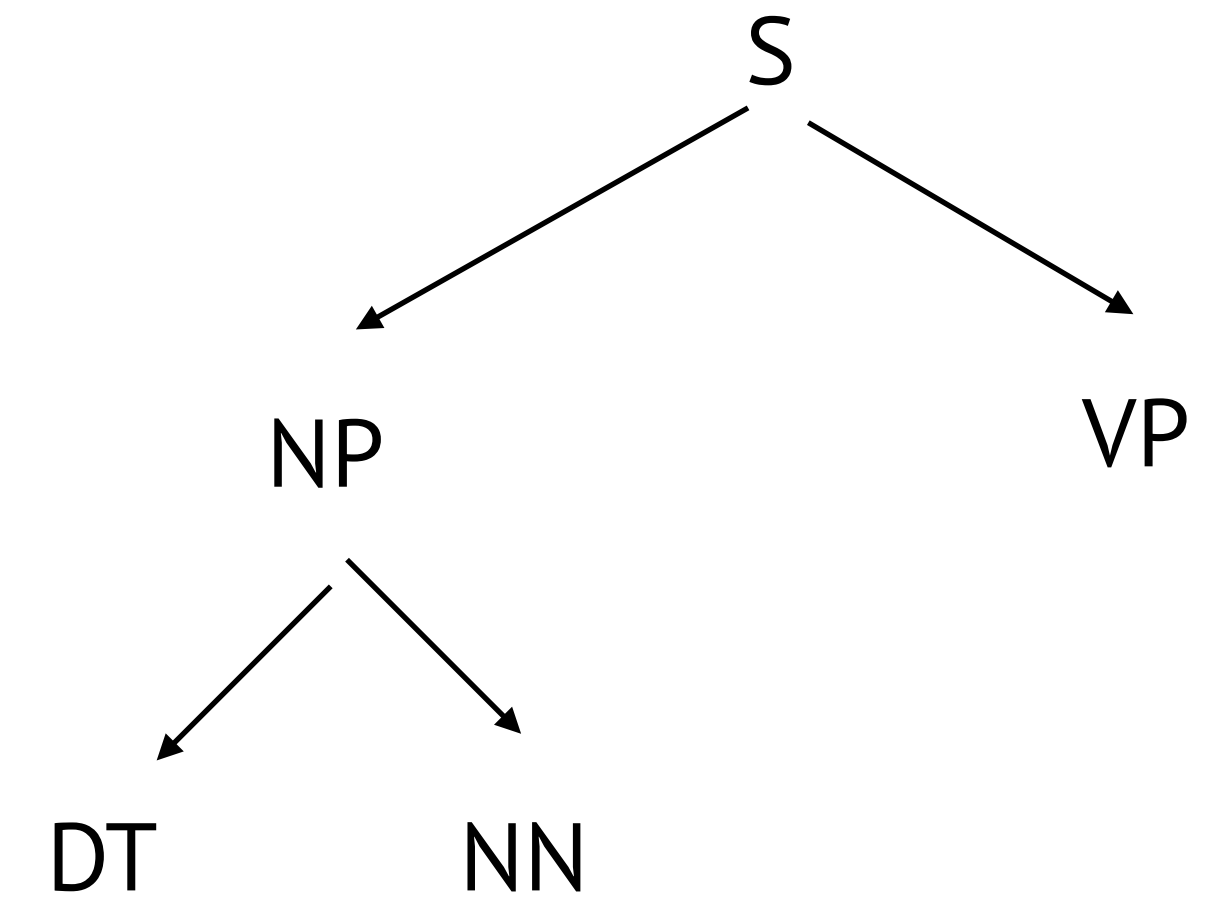
(S (NP VP))

$P(x, y) = 1 \times$

Derivation Example

$R =$

S	→	NP VP	1.0	Vi	→	sleeps	1.0
				Vt	→	saw	1.0
VP	→	Vi	0.4				
VP	→	Vt NP	0.4	NN	→	man	0.7
VP	→	VP PP	0.2	NN	→	woman	0.2
				NN	→	telescope	0.1
NP	→	DT NN	0.3	DT	→	the	1.0
NP	→	NP PP	0.7				
PP	→	IN NP	1.0	IN	→	with	0.5
				IN	→	in	0.5



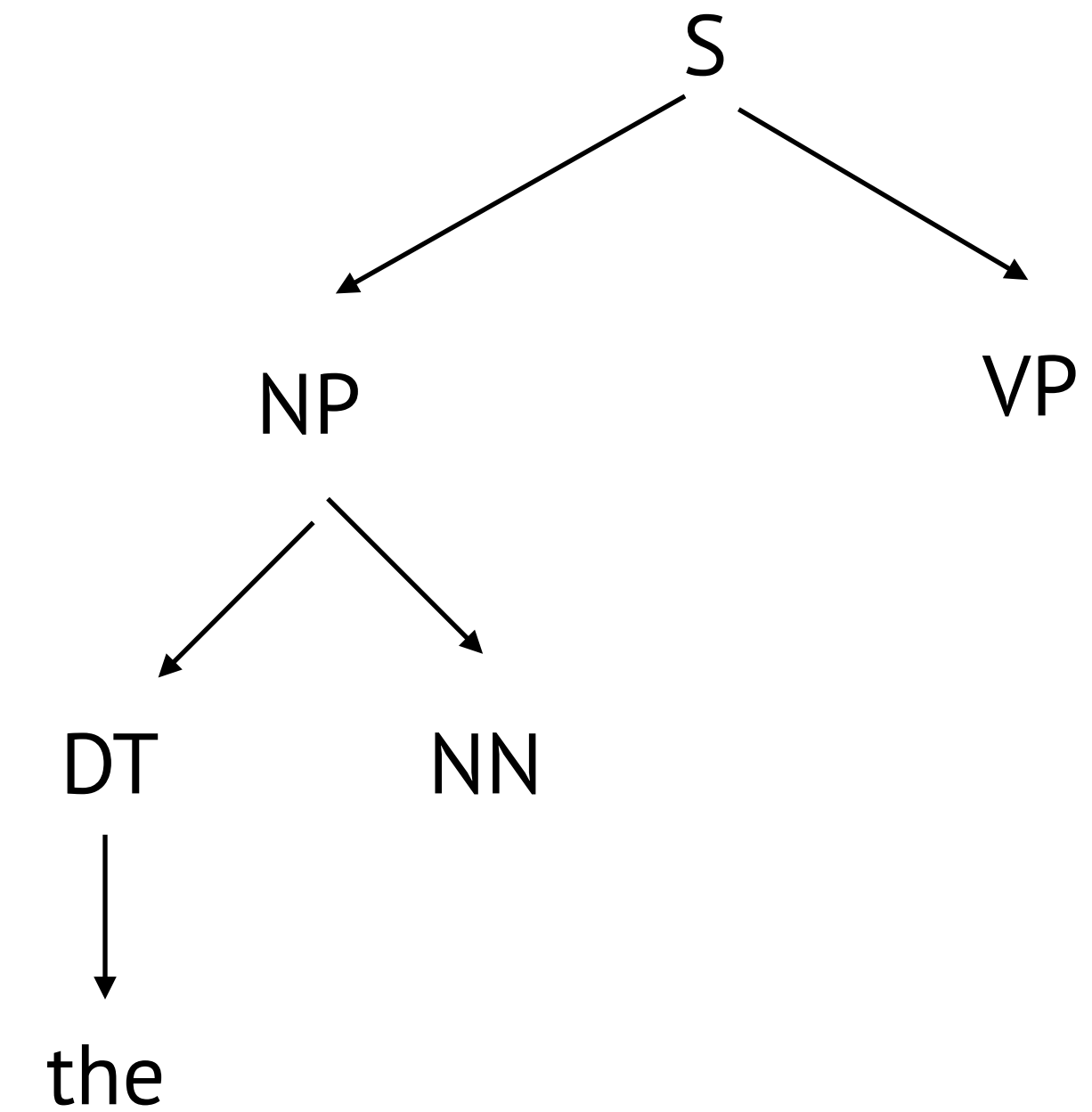
(S (NP (DT NN) VP))

$$P(\mathbf{x}, \mathbf{y}) = 1 \times 0.3 \times$$

Derivation Example

$R =$

S	→	NP VP	1.0	Vi	→	sleeps	1.0
				Vt	→	saw	1.0
VP	→	Vi	0.4				
VP	→	Vt NP	0.4	NN	→	man	0.7
VP	→	VP PP	0.2	NN	→	woman	0.2
				NN	→	telescope	0.1
NP	→	DT NN	0.3	DT	→	the	1.0
NP	→	NP PP	0.7				
PP	→	IN NP	1.0	IN	→	with	0.5
				IN	→	in	0.5



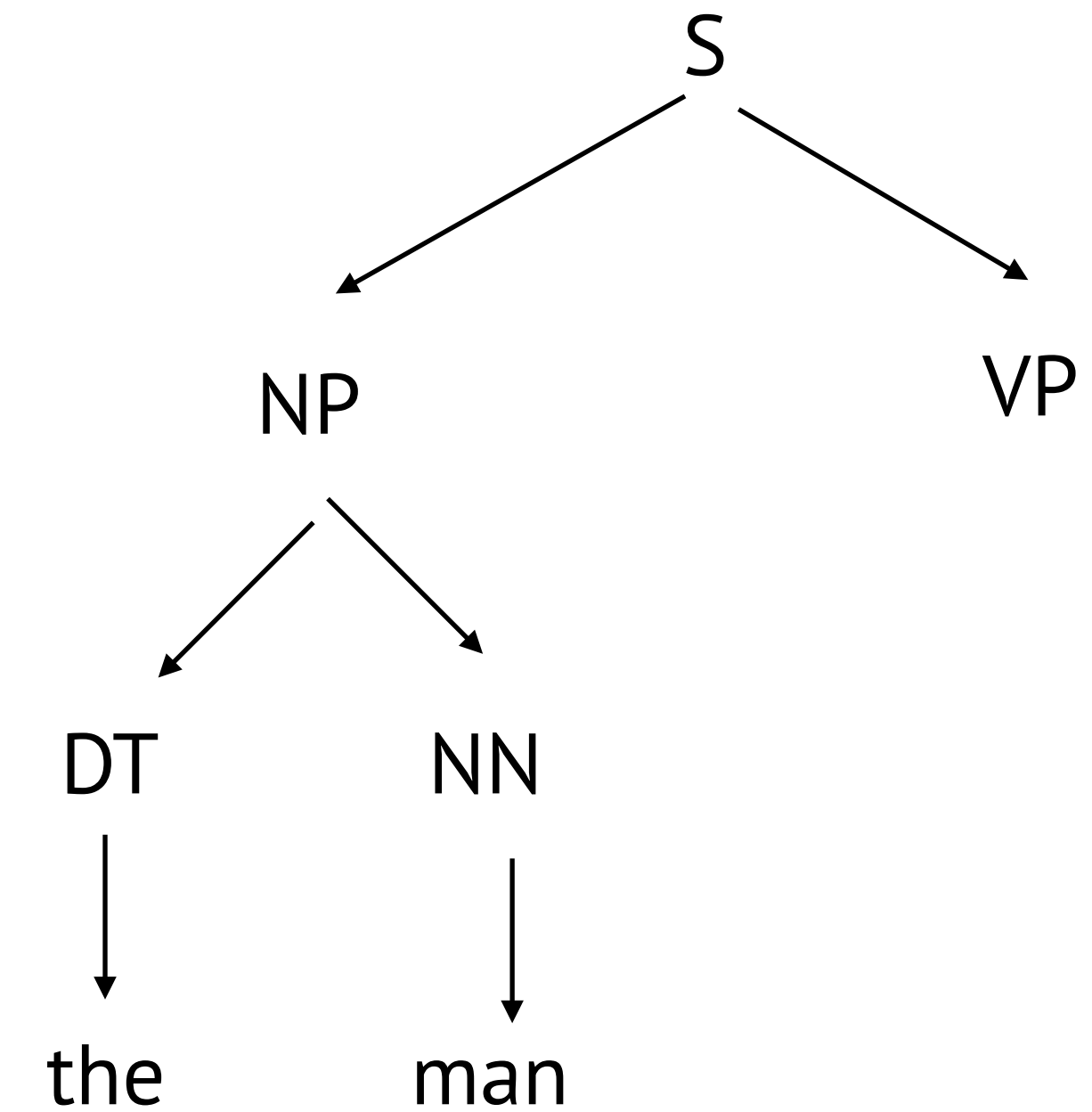
(S (NP ((DT the) NN) VP))

$$P(\mathbf{x}, \mathbf{y}) = 1 \times 0.3 \times 1 \times$$

Derivation Example

$R =$

S	→	NP VP	1.0	Vi	→	sleeps	1.0
				Vt	→	saw	1.0
VP	→	Vi	0.4				
VP	→	Vt NP	0.4	NN	→	man	0.7
VP	→	VP PP	0.2	NN	→	woman	0.2
				NN	→	telescope	0.1
NP	→	DT NN	0.3	DT	→	the	1.0
NP	→	NP PP	0.7	IN	→	with	0.5
PP	→	IN NP	1.0	IN	→	in	0.5



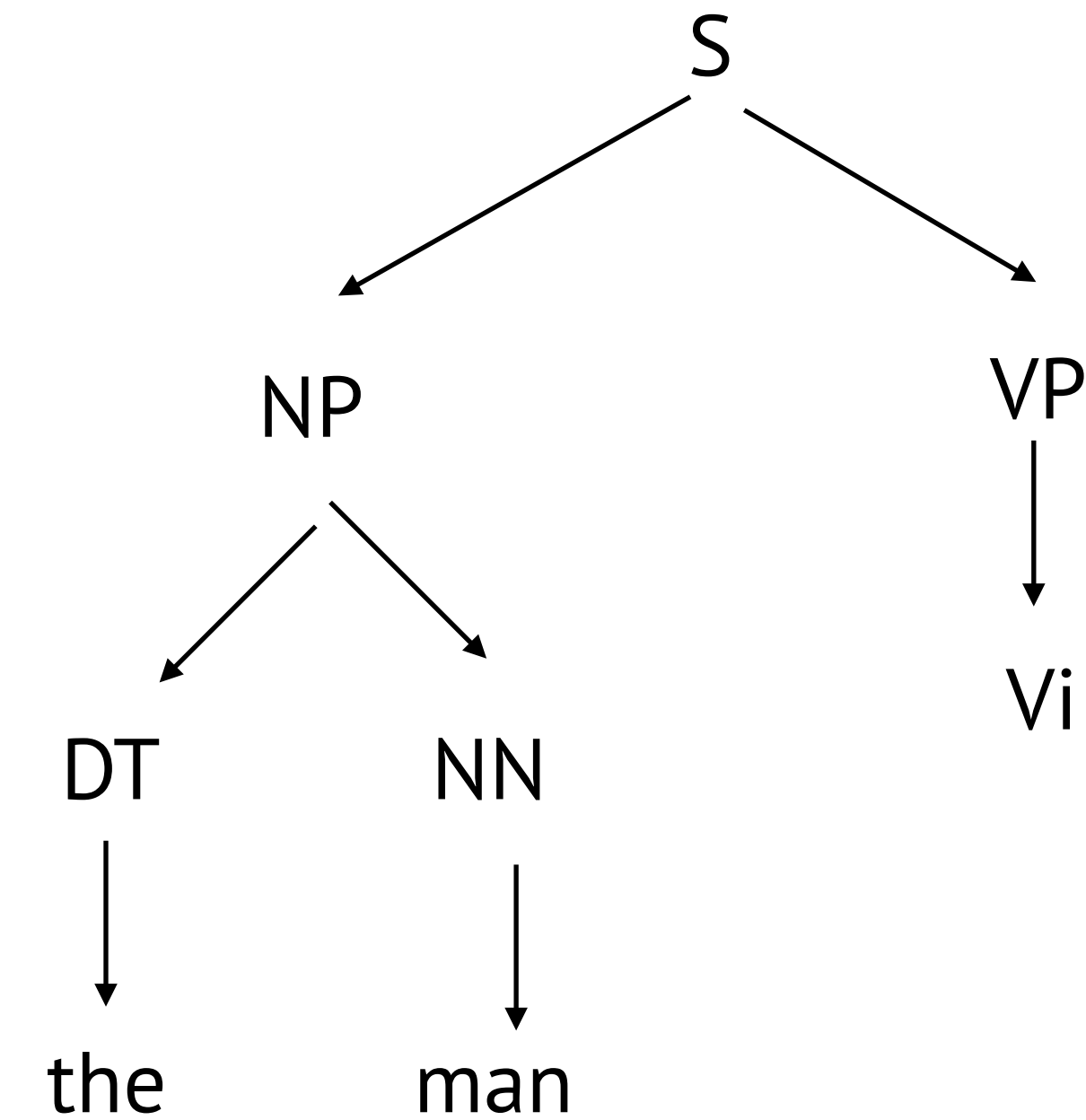
(S (NP ((DT the) (NN man)) VP))

$$P(x, y) = 1 \times 0.3 \times 1 \times 0.7 \times$$

Derivation Example

$R =$

S	→	NP VP	1.0	Vi	→	sleeps	1.0
				Vt	→	saw	1.0
VP	→	Vi	0.4	NN	→	man	0.7
VP	→	Vt NP	0.4	NN	→	woman	0.2
VP	→	VP PP	0.2	NN	→	telescope	0.1
NP	→	DT NN	0.3	DT	→	the	1.0
NP	→	NP PP	0.7	IN	→	with	0.5
PP	→	IN NP	1.0	IN	→	in	0.5



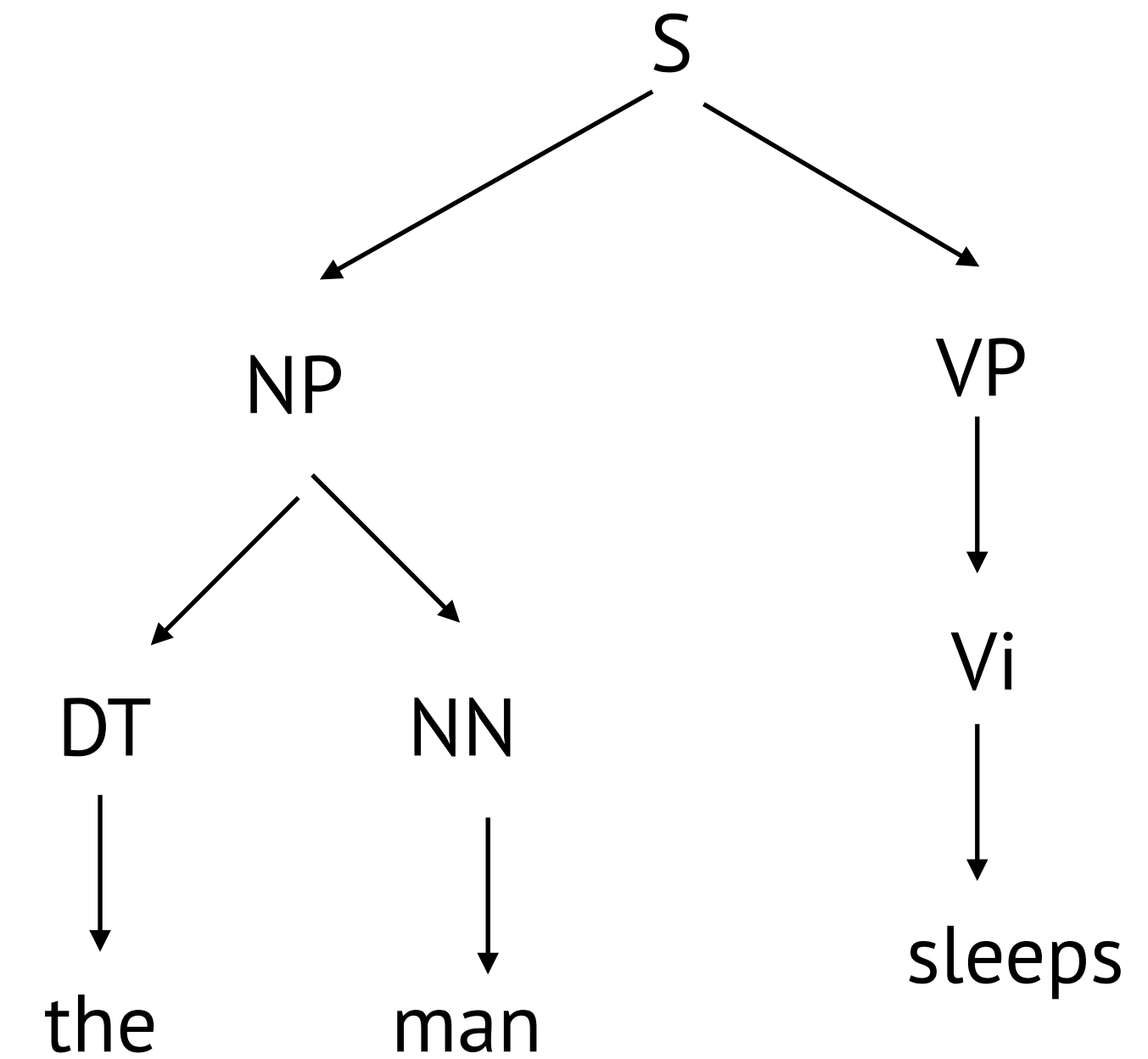
(S (NP ((DT the) (NN man)) (VP (Vi))))

$$P(\mathbf{x}, \mathbf{y}) = 1 \times 0.3 \times 1 \times 0.7 \times 0.4 \times$$

Derivation Example

$R =$

S	→	NP VP	1.0	Vi	→	sleeps	1.0
				Vt	→	saw	1.0
VP	→	Vi	0.4				
VP	→	Vt NP	0.4	NN	→	man	0.7
VP	→	VP PP	0.2	NN	→	woman	0.2
				NN	→	telescope	0.1
NP	→	DT NN	0.3	DT	→	the	1.0
NP	→	NP PP	0.7	IN	→	with	0.5
PP	→	IN NP	1.0	IN	→	in	0.5



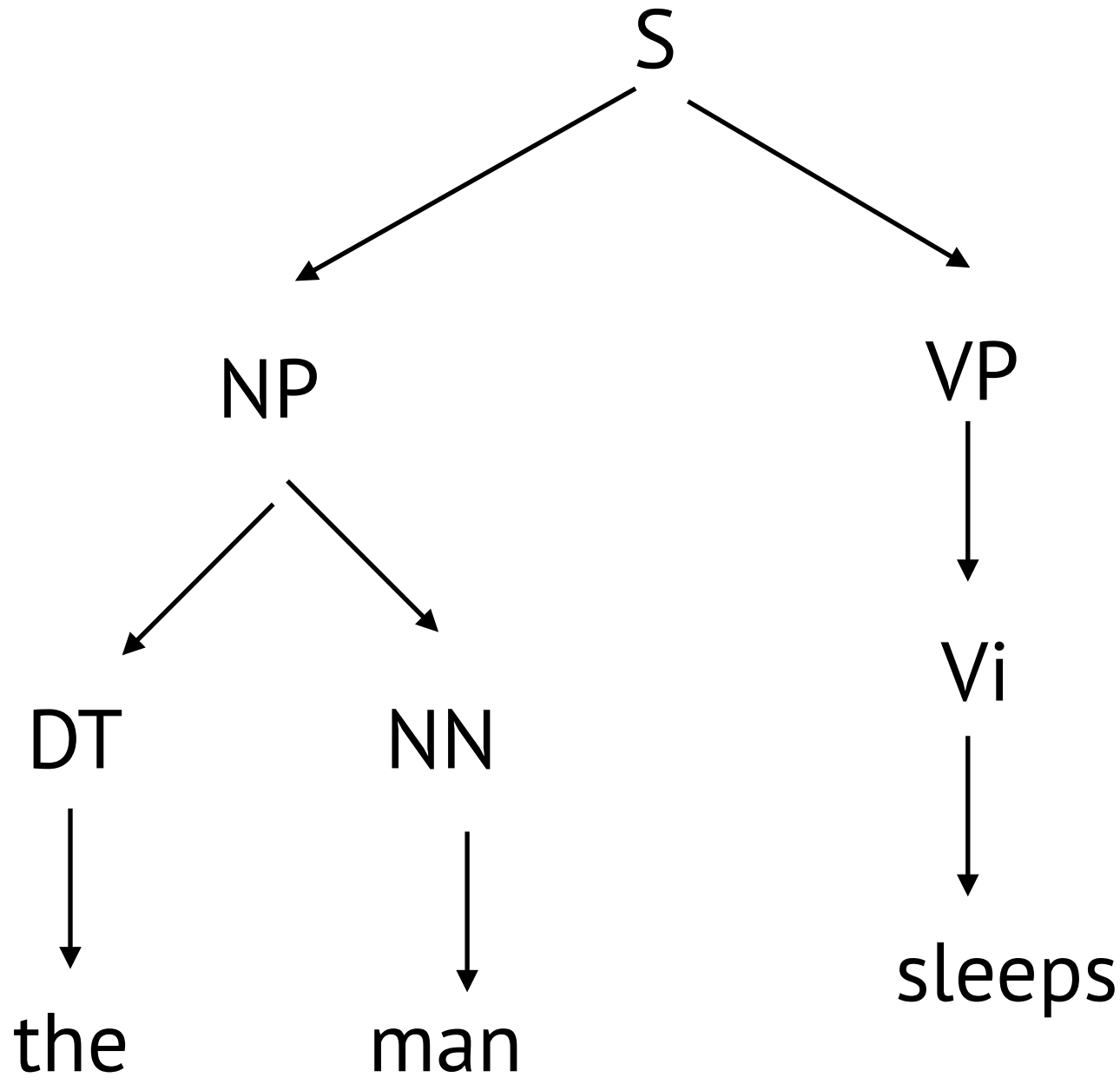
(S (NP ((DT the) (NN man)) (VP (Vi sleeps))))

$$P(\mathbf{x}, \mathbf{y}) = 1 \times 0.3 \times 1 \times 0.7 \times 0.4 \times 1$$

Derivation Example

$R =$

S	→	NP VP	1.0	Vi	→	sleeps	1.0
				Vt	→	saw	1.0
VP	→	Vi	0.4				
VP	→	Vt NP	0.4	NN	→	man	0.7
VP	→	VP PP	0.2	NN	→	woman	0.2
				NN	→	telescope	0.1
NP	→	DT NN	0.3	DT	→	the	1.0
NP	→	NP PP	0.7	IN	→	with	0.5
PP	→	IN NP	1.0	IN	→	in	0.5



(S (NP ((DT the) (NN man)) (VP (Vi sleeps)))))

Probabilistic Context-Free Grammars

$R =$

S	→	NP VP	1.0	Vi	→	sleeps	1.0
VP	→	Vi	0.4	Vt	→	saw	1.0
VP	→	Vt NP	0.4	NN	→	man	0.7
VP	→	VP PP	0.2	NN	→	woman	0.2
NP	→	DT NN	0.3	NN	→	telescope	0.1
NP	→	NP PP	0.7	DT	→	the	1.0
PP	→	IN NP	1.0	IN	→	with	0.5
				IN	→	in	0.5

1. How do we get those weights?

2. How to get the (marginal) probability of this sentence and the most likely parse?

the man saw the woman with a telescope

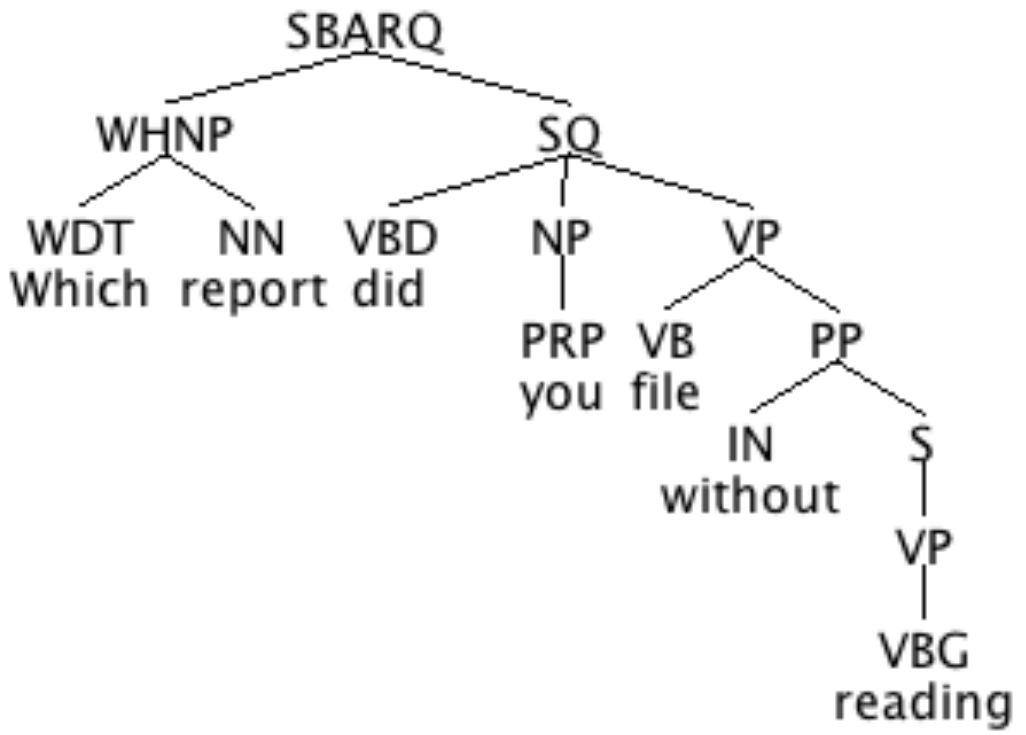
Treebanks (Penn Treebank)

tk treebank viewer

TREEBANK VIEWER Sandiway Fong University of Arizona (dec 2006: freeware version)

Sentence File /Users/sandiway/Desktop/treeprint/lu.lisp Prolog Tree File /Users/sandiway/Desktop/treeprint/lu2.pl Load

((John (NNP)) (said (VBD)) (that (IN)) (his (PRPS)) (brothe
((We (PRP)) (believed (VBD)) (Mary (NNP)) (to (TO)) (like
((He (PRP)) (thinks (VBZ)) (Mary (NNP)) (likes (NNS)) (Joh
((Who (NNP)) (does (VBZ)) (he (PRP)) (like (VB)))
((Who (NNP)) (was (VBD)) (arrested (VBN)))
((John (NNP)) (tried (VBD)) (to (TO)) (win (VB)) (the (DT))
((John (NNP)) (seems (VBZ)) (to (TO)) (be (VB)) (crazy (N
((John (NNP)) (was (VBD)) (arrested (VBN)) (after (IN)) (le
((John (NNP)) (is (VBZ)) (too (RB)) (dumb (JJ)) (to (TO)) (ta
((Who (NN)) (did (VBD)) (he (PRP)) (try (VB)) (to (TO)) (wi
((Which (NNP)) (report (NN)) (did (VBD)) (you (PRP)) (file
((Which (NNP)) (book (NN)) (did (VBD)) (you (PRP)) (file (V
((Who (NNP)) (filed (VBN)) (which (WDT)) (report (NN)) (v
((The (DT)) (report (NN)) (was (VBD)) (filed (VBN)) (withc
((The (DT)) (report (NN)) (fell (VBD)) (on (IN)) (the (DT))
((The (DT)) (teacher (NN)) (fell (VBD)) (on (IN)) (the (DT))
((Which (NNP)) (report (NN)) (did (VBD)) (you (PRP)) (file
((The (DT)) (report (NN)) (was (VBD)) (filed (VBN)) (after
((What (WP)) (was (VBD)) (filed (VBN)) (without (IN)) (beir
((The (DT)) (report (NN)) (was (VBD)) (filed (VBN)) (withc
((The (DT)) (report (NN)) (disappeared (VBD)) (without (IN))
((The (DT)) (teacher (NN)) (was (VBD)) (fired (VBN)) (with
((The (DT)) (teacher (NN)) (was (VBD)) (fired (VBN)) (afte
((The (DT)) (teacher (NN)) (resigned (VBD)) (after (IN)) (t
((Who (NNP)) (resigned (VBD)) (before (IN)) (we (PRP)) (c
((Who (NNP)) (resigned (VBD)) (before (IN)) (we (PRP)) (c
((Who (NNP)) (did (VBD)) (you (PRP)) (hire (VBD)) (becau



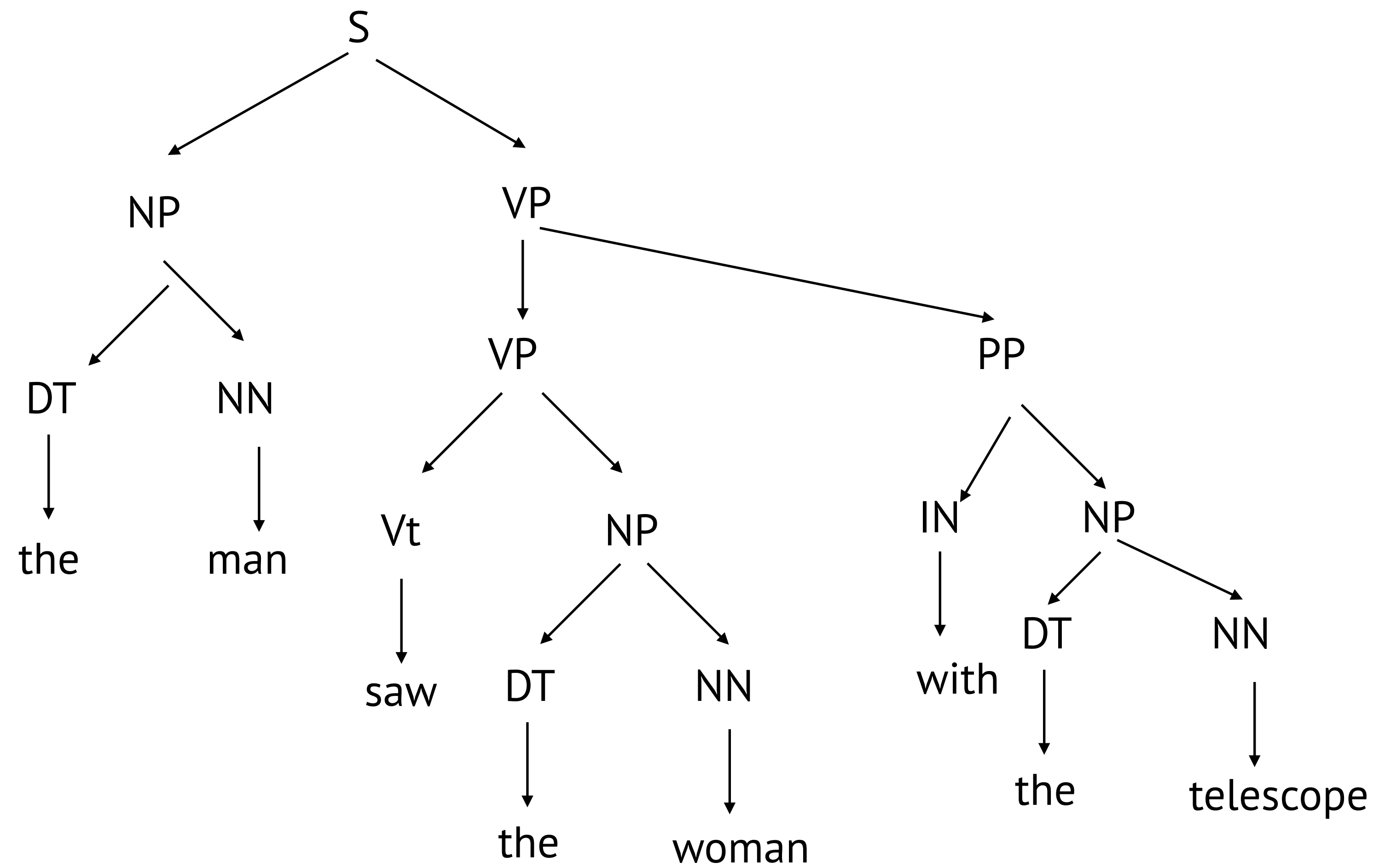
```
graph TD
    SBARQ --> WHNP[WHNP]
    SBARQ --> SQ[SQ]
    WHNP --> WDT[WDT]
    WHNP --> NN[NN]
    WDT --> Which[Which]
    NN --> report[report]
    SQ --> NP[NP]
    SQ --> VP1[VP]
    NP --> PRP[PRP]
    PRP --> you[you]
    VP1 --> VB[VB]
    VB --> file[file]
    VP1 --> PP[PP]
    PP --> IN[IN]
    IN --> without[without]
    PP --> S[S]
    S --> VP2[VP]
    VP2 --> VBG[VBG]
    VBG --> reading[reading]
```

4.5 million words of
American English



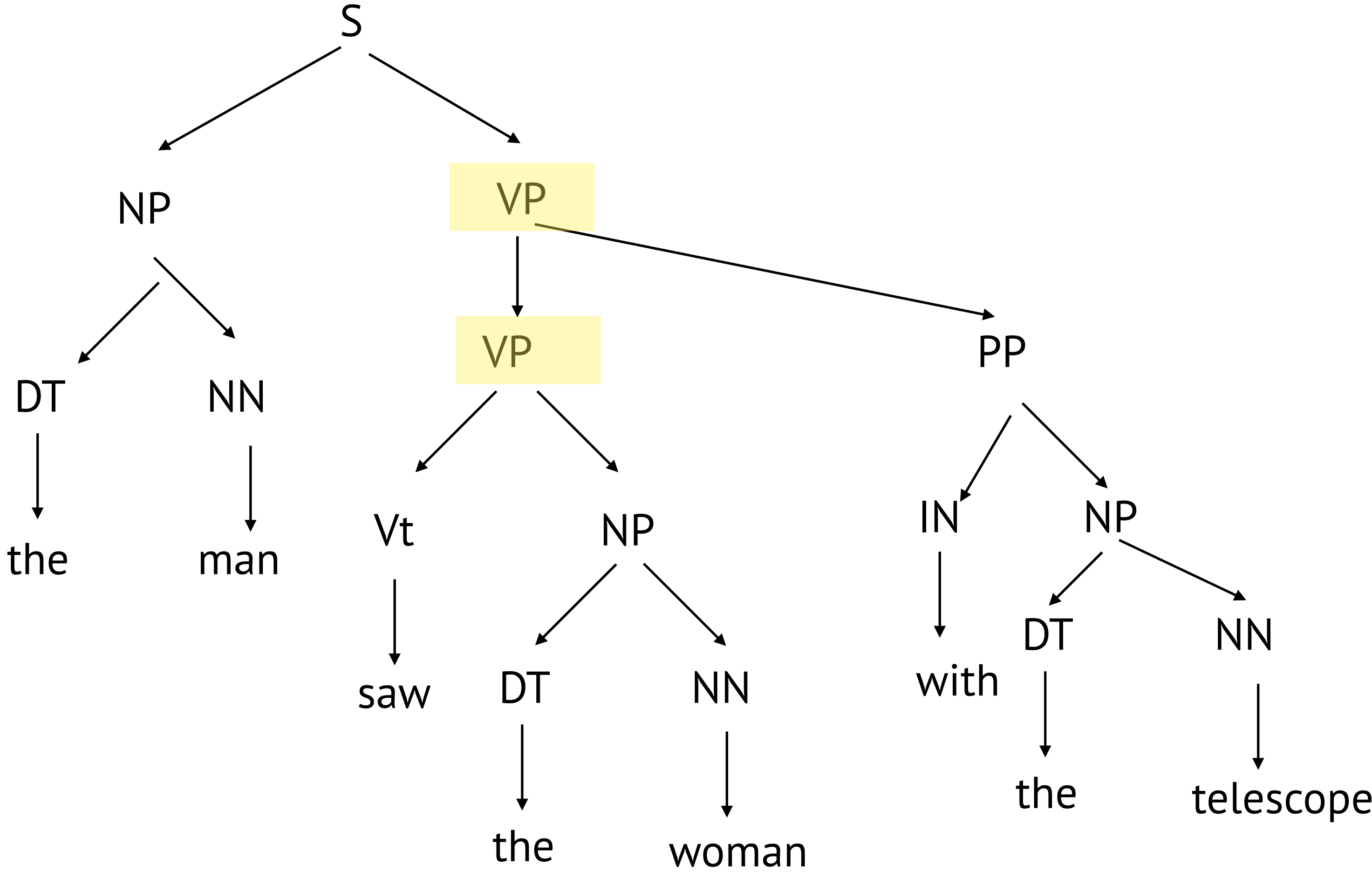
Mitch Marcus

Estimating the Probabilities from the Treebank



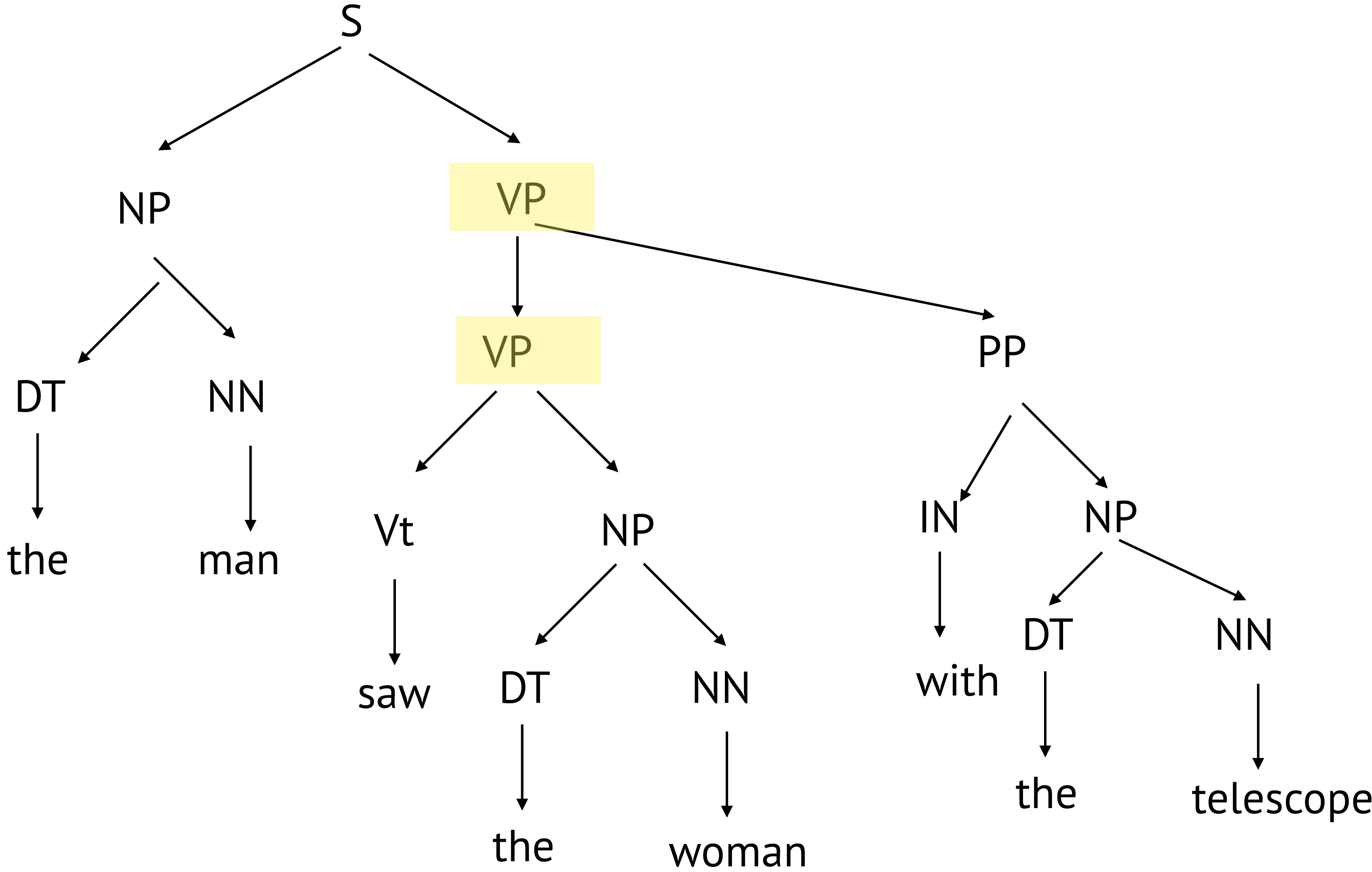
$$p(\text{VP} \rightarrow \text{VP PP}) = ?$$

Estimating the Probabilities from the Treebank



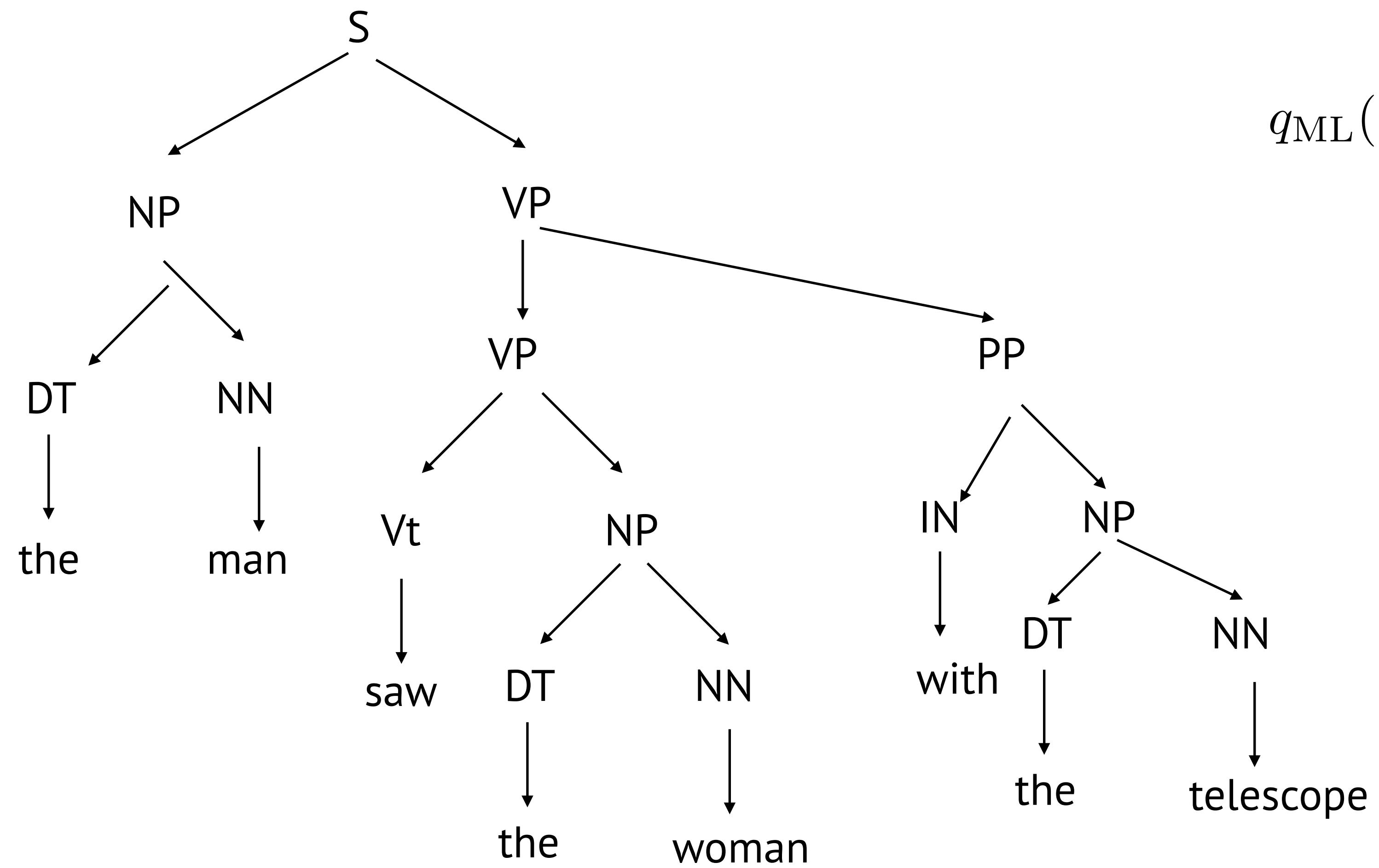
$$p(\text{VP} \rightarrow \text{VP PP}) = ?$$

Estimating the Probabilities from the Treebank



$$p(\text{VP} \rightarrow \text{VP PP}) = \frac{1}{2}$$

Estimating the Probabilities from the Treebank

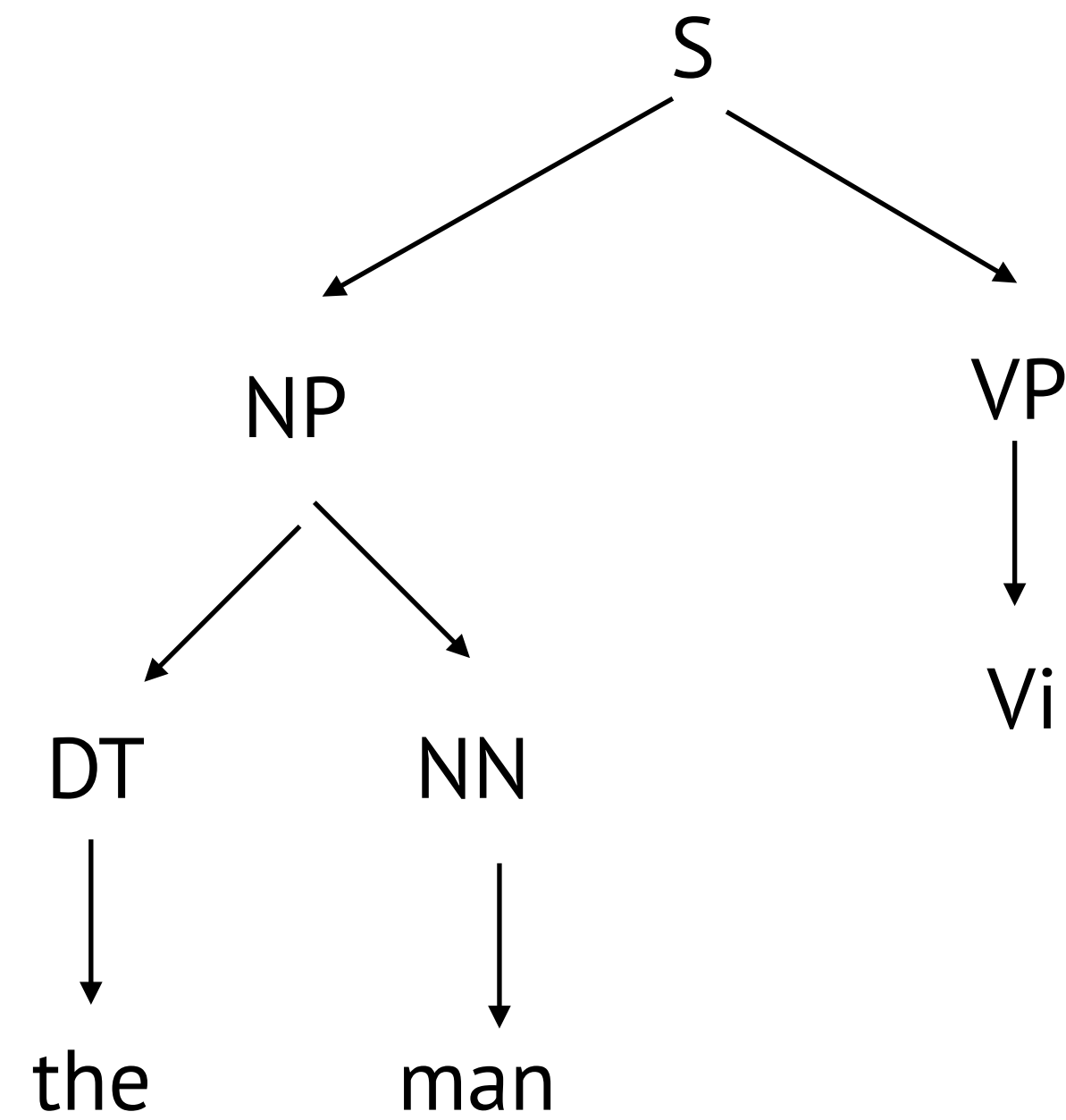


$$q_{\text{ML}}(\alpha \rightarrow \beta) = \frac{\text{Count}(\alpha \rightarrow \beta)}{\text{Count}(\alpha)}$$

MLE estimation!

Parsing with PCFGs

Parsing: $\arg \max_{y \in Y} p(x, y)$



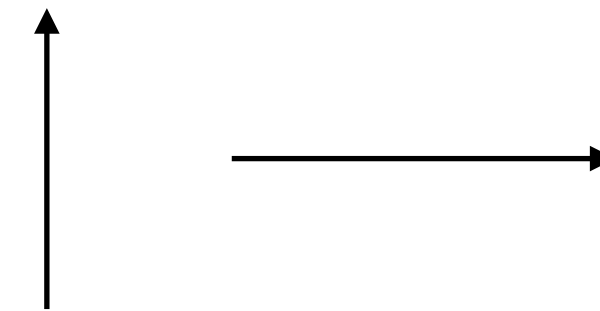
(S (NP ((DT the) (NN man)) (VP (Vi sleeps)))))

$$P(x, y) = 1 \times 0.3 \times 1 \times 0.7 \times 0.4 \times 1$$


Dynamic Programming

8	2	9	7
5	4	3	1
2	6	1	1
 2	5	4	2

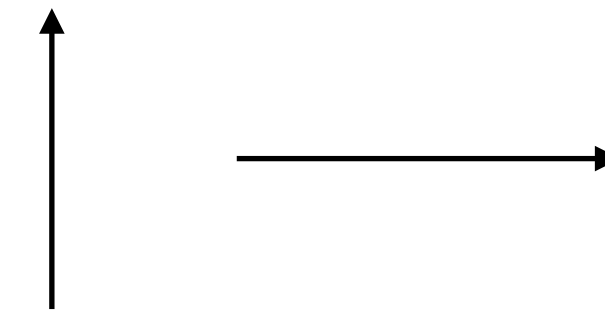
Find the lowest cost path from
bottom left corner to the upper
right corner



Dynamic Programming


8	2	9	7
5	4	3	1
2	6	1	1
 2	5	4	2

Find the lowest cost path from bottom left corner to the upper right corner

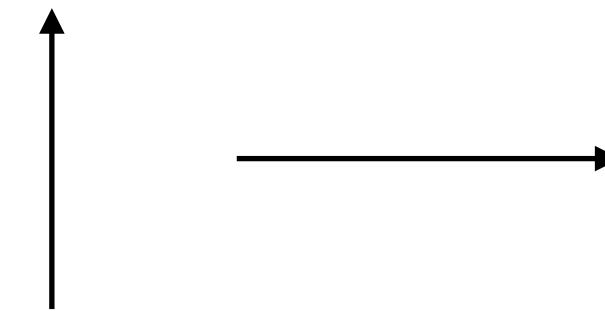


$$2 + 2 + 5 + 4 + 2 + 9 + 7 = 31$$

Dynamic Programming

8	2	9	7
5	4	3	1
2	6	1	1
 2	5	4	2

Find the lowest cost path from bottom left corner to the upper right corner



$$2 + 2 + 6 + 1 + 1 + 1 + 7 = 20$$

Dynamic Programming

8	2	9	7
5	4	3	1
2	6	1	1
2	5	4	2

2			

Dynamic Programming

8	2	9	7
5	4	3	1
2	6	1	1
2	5	4	2

17 (d)			
9 (d)			
4 (d)			
2	7 (l)	11 (l)	13 (l)

Dynamic Programming

8	2	9	7
5	4	3	1
2	6	1	1
2	5	4	2

17 (d)			
9 (d)			
4 (d)			
2	7 (l)	11 (l)	13 (l)

Dynamic Programming

8	2	9	7
5	4	3	1
2	6	1	1
2	5	4	2

17 (d)			
9 (d)			
4 (d)	10 (l)		
2	7 (l)	11 (l)	13 (l)

Dynamic Programming

8	2	9	7
5	4	3	1
2	6	1	1
2	5	4	2

17 (d)			
9 (d)	13 (l)		
4 (d)	10 (l)	11 (l)	
2	7 (l)	11 (l)	13 (l)

Dynamic Programming

8	2	9	7
5	4	3	1
2	6	1	1
2	5	4	2

17 (d)	15 (d)		
9 (d)	13 (l)	14 (d)	
4 (d)	10 (l)	11 (l)	12 (l)
2	7 (l)	11 (l)	13 (l)

Dynamic Programming

8	2	9	7
5	4	3	1
2	6	1	1
2	5	4	2

17 (d)	15 (d)	23 (d)	
9 (d)	13 (l)	14 (d)	13 (d)
4 (d)	10 (l)	11 (l)	12 (l)
2	7 (l)	11 (l)	13 (l)

Dynamic Programming

8	2	9	7
5	4	3	1
2	6	1	1
2	5	4	2

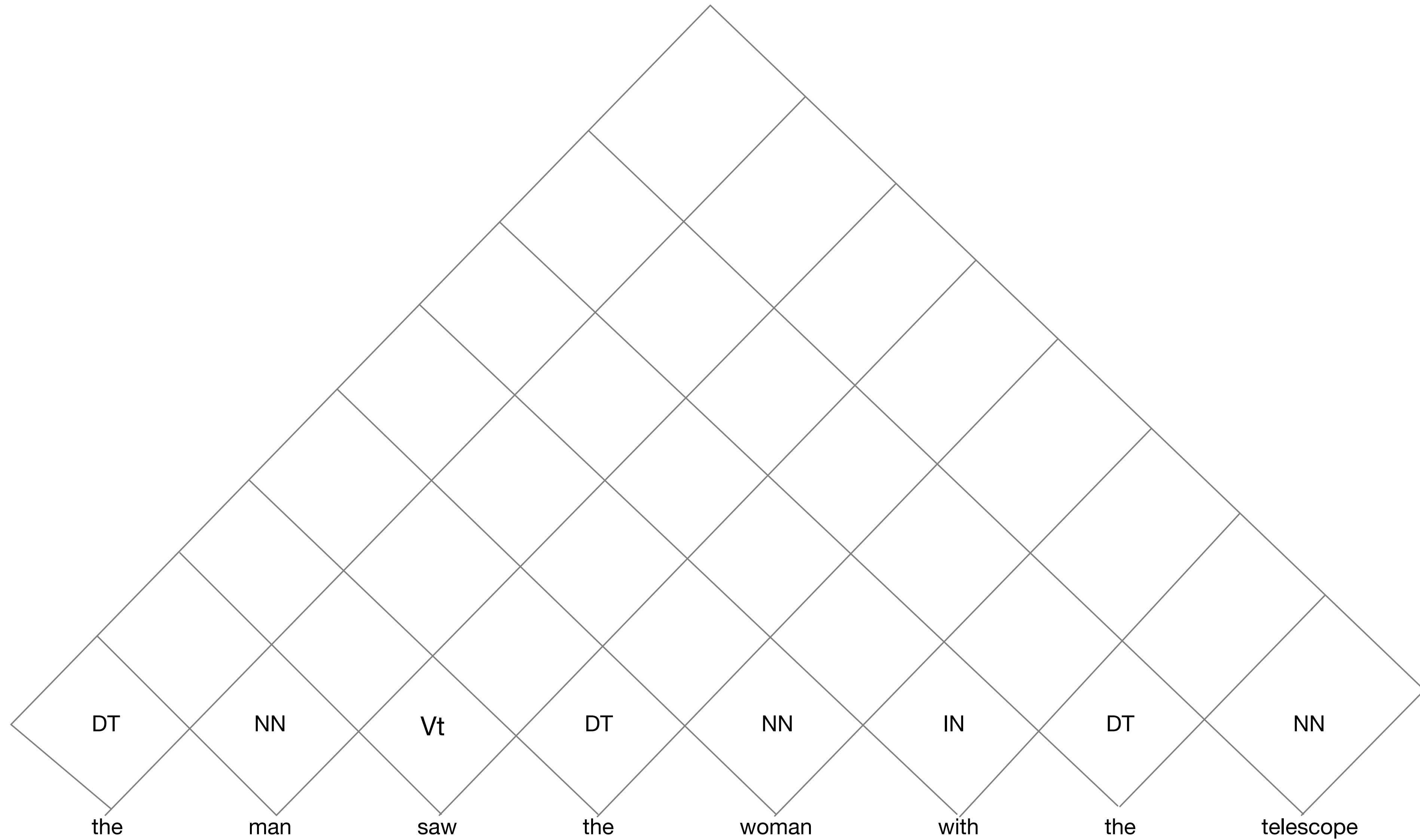
17 (d)	15 (d)	23 (d)	20 (d)
9 (d)	13 (l)	14 (d)	13 (d)
4 (d)	10 (l)	11 (l)	12 (l)
2	7 (l)	11 (l)	13 (l)

Parsing with PCFGs

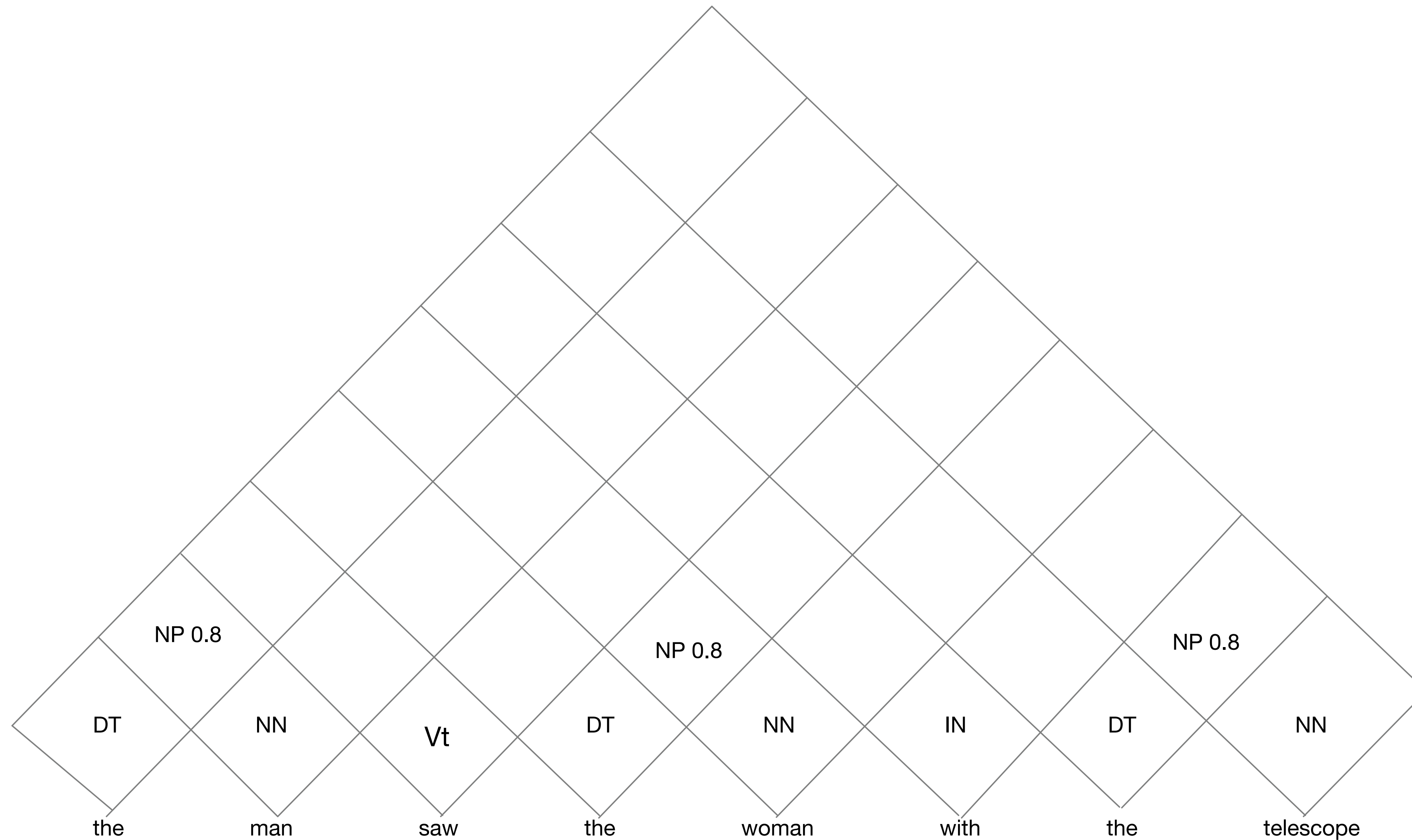
$R =$

S	→	NP VP	1.0	Vt	→	saw	1.0
				NN	→	man	0.1
VP	→	Vt NP	0.8	NN	→	woman	0.1
VP	→	VP PP	0.2	NN	→	telescope	0.3
				NN	→	dog	0.5
NP	→	DT NN	0.8	DT	→	the	1.0
NP	→	NP PP	0.2	IN	→	with	0.6
PP	→	IN NP	1.0	IN	→	in	0.4

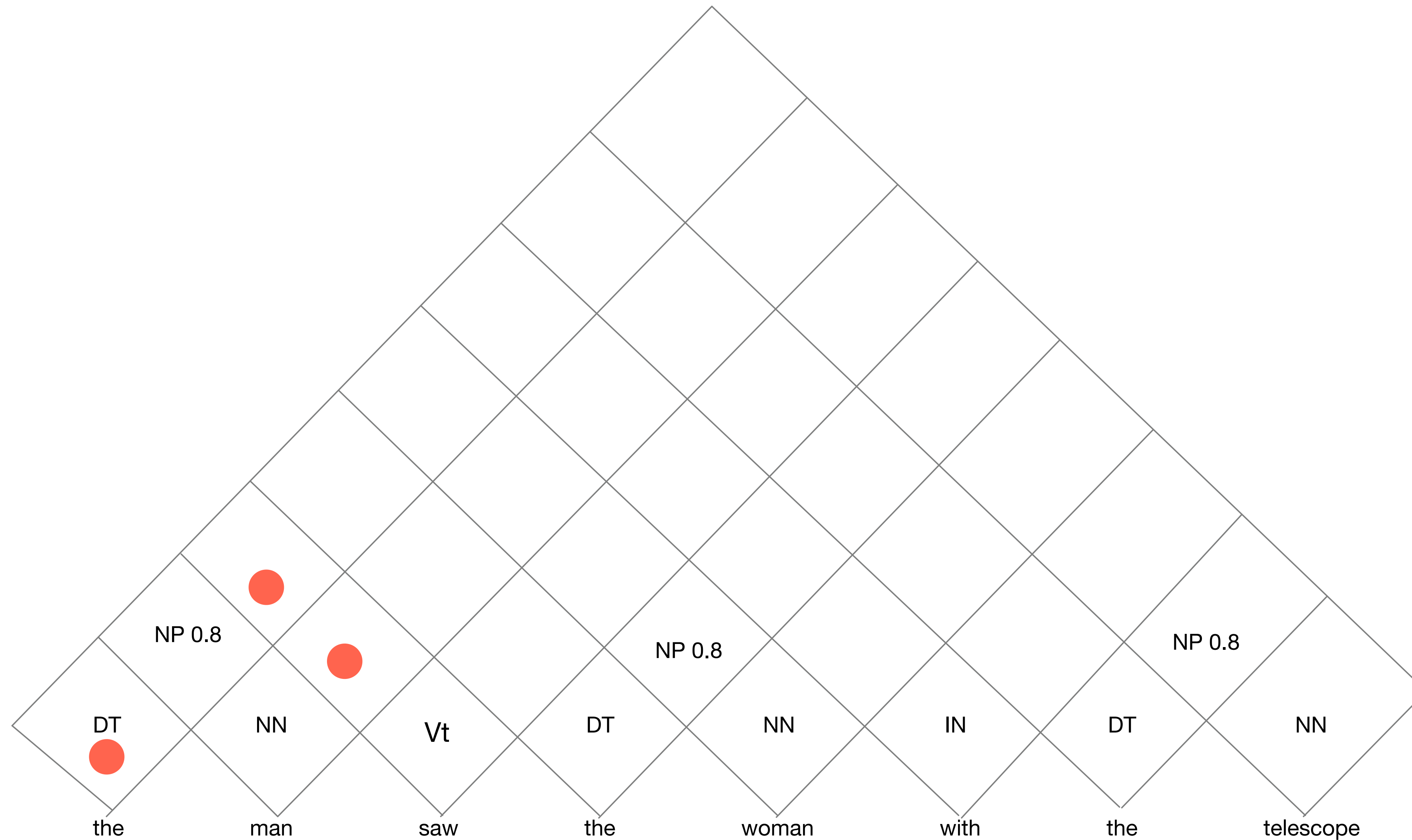
Parsing with PCFGs



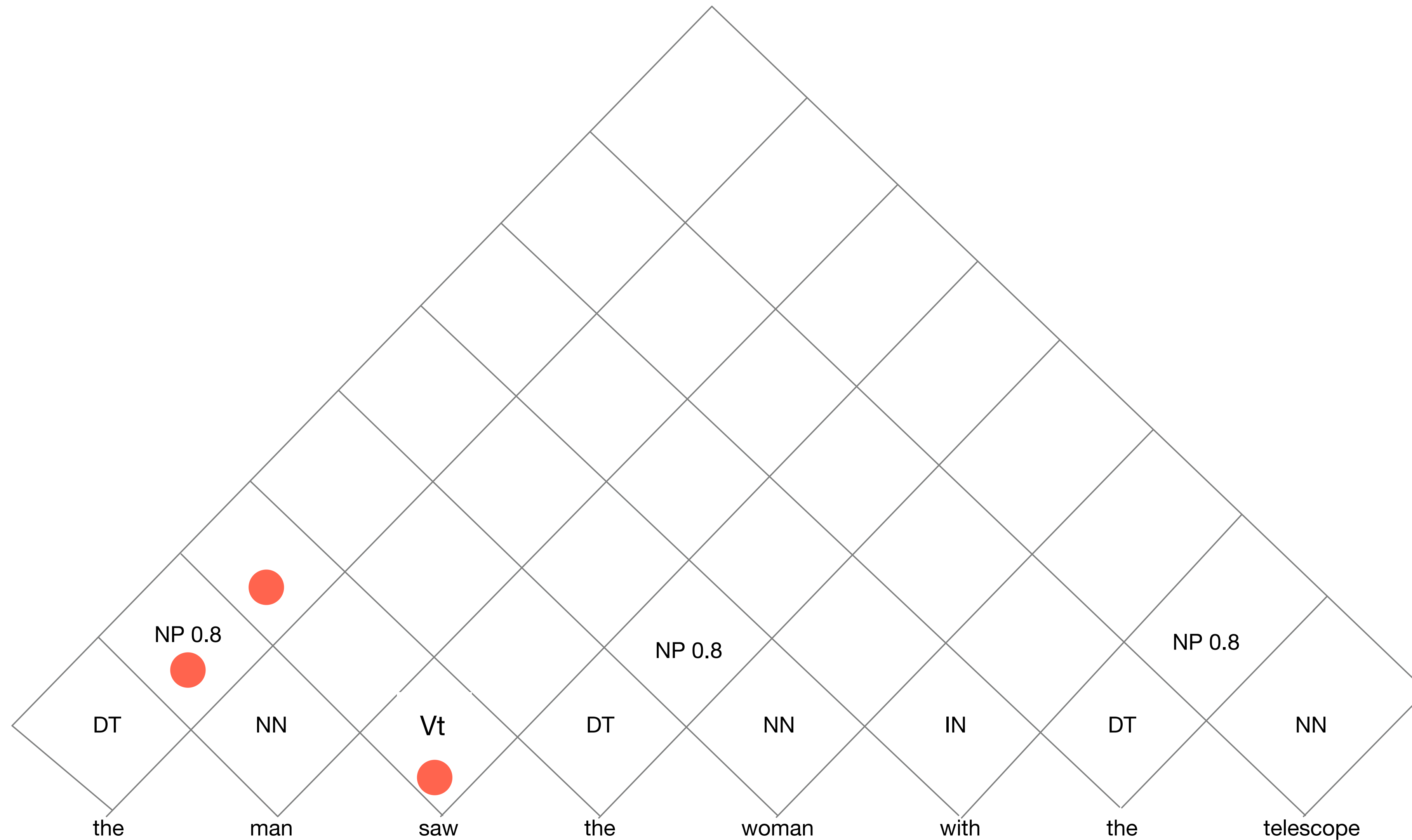
Parsing with PCFGs



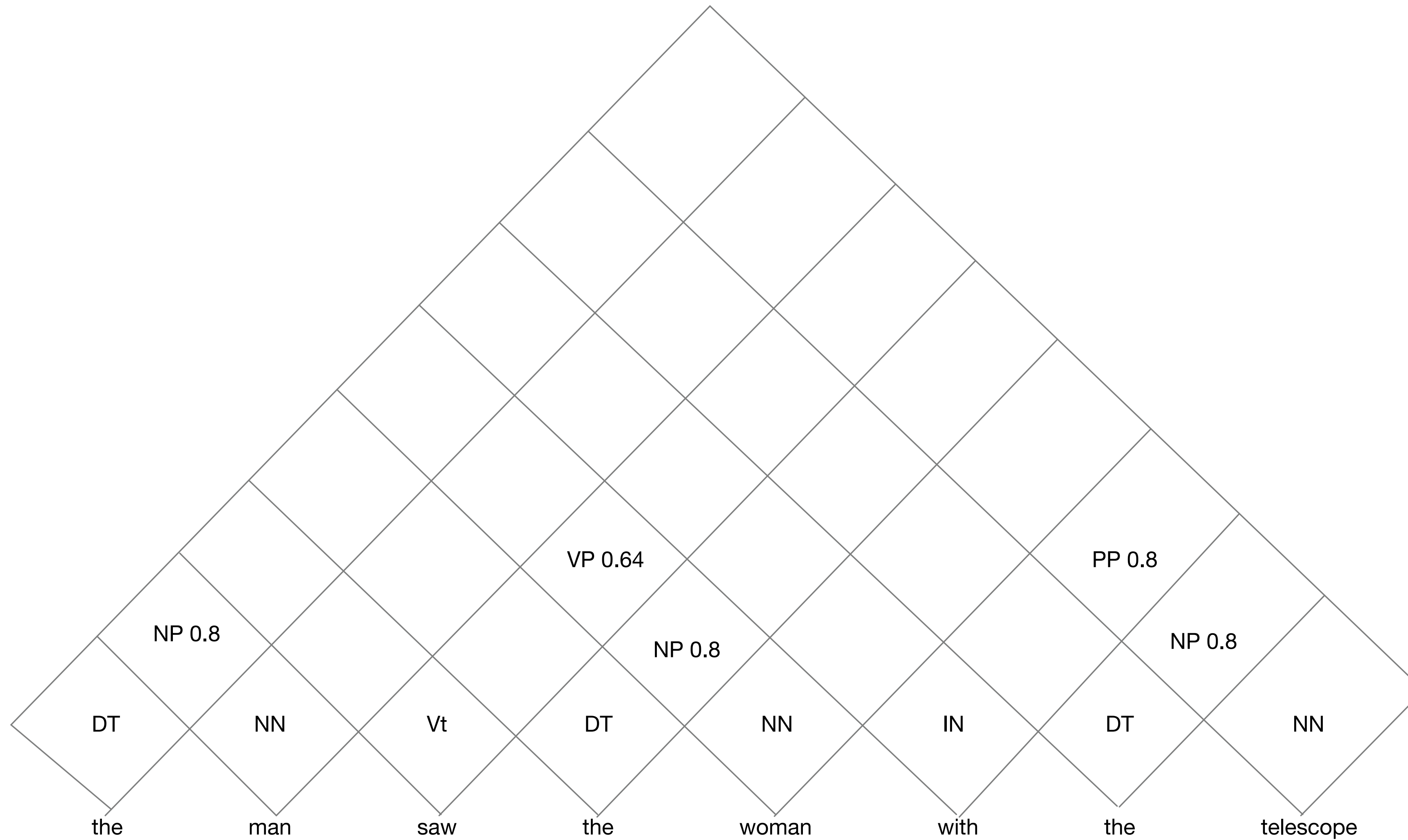
Parsing with PCFGs



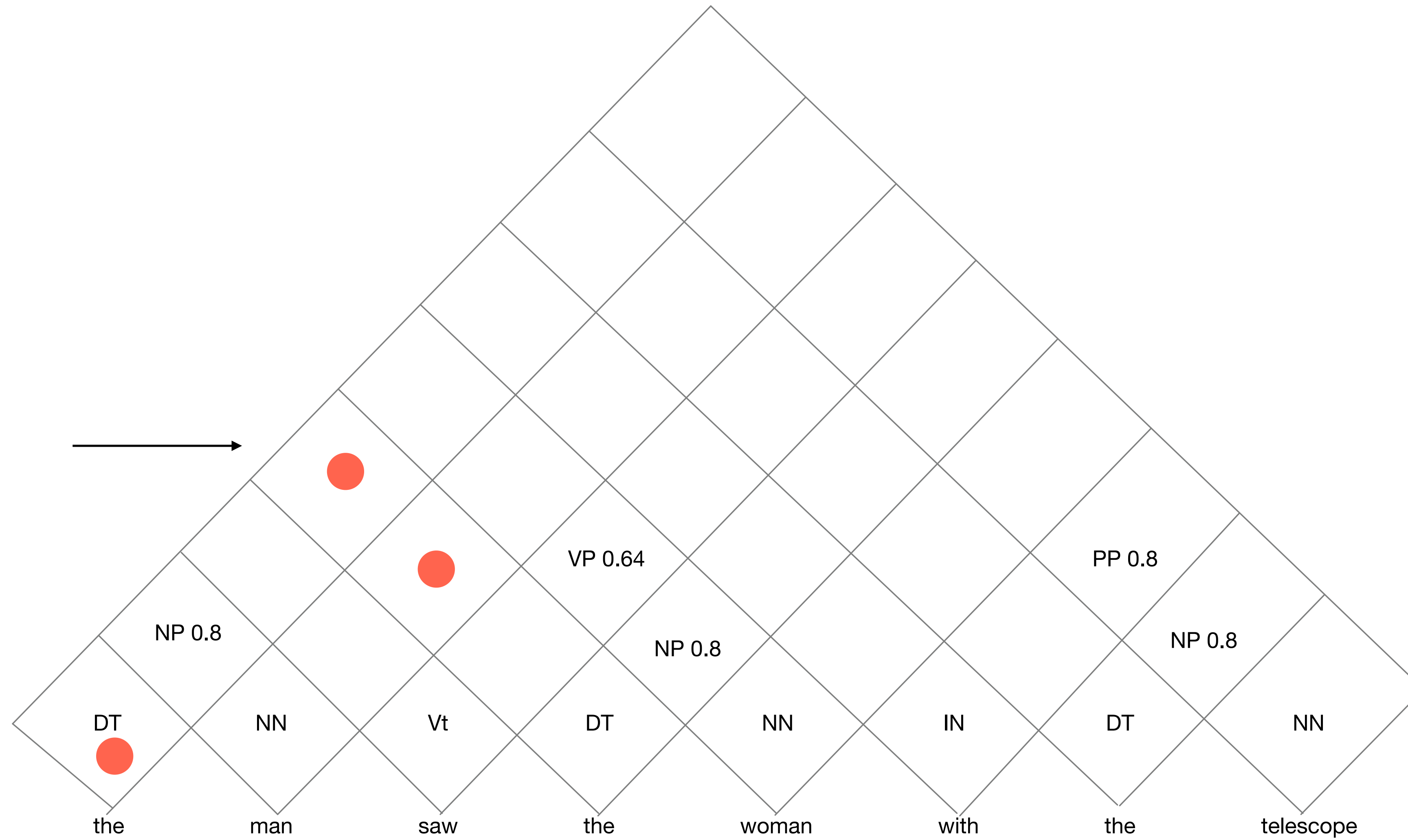
Parsing with PCFGs



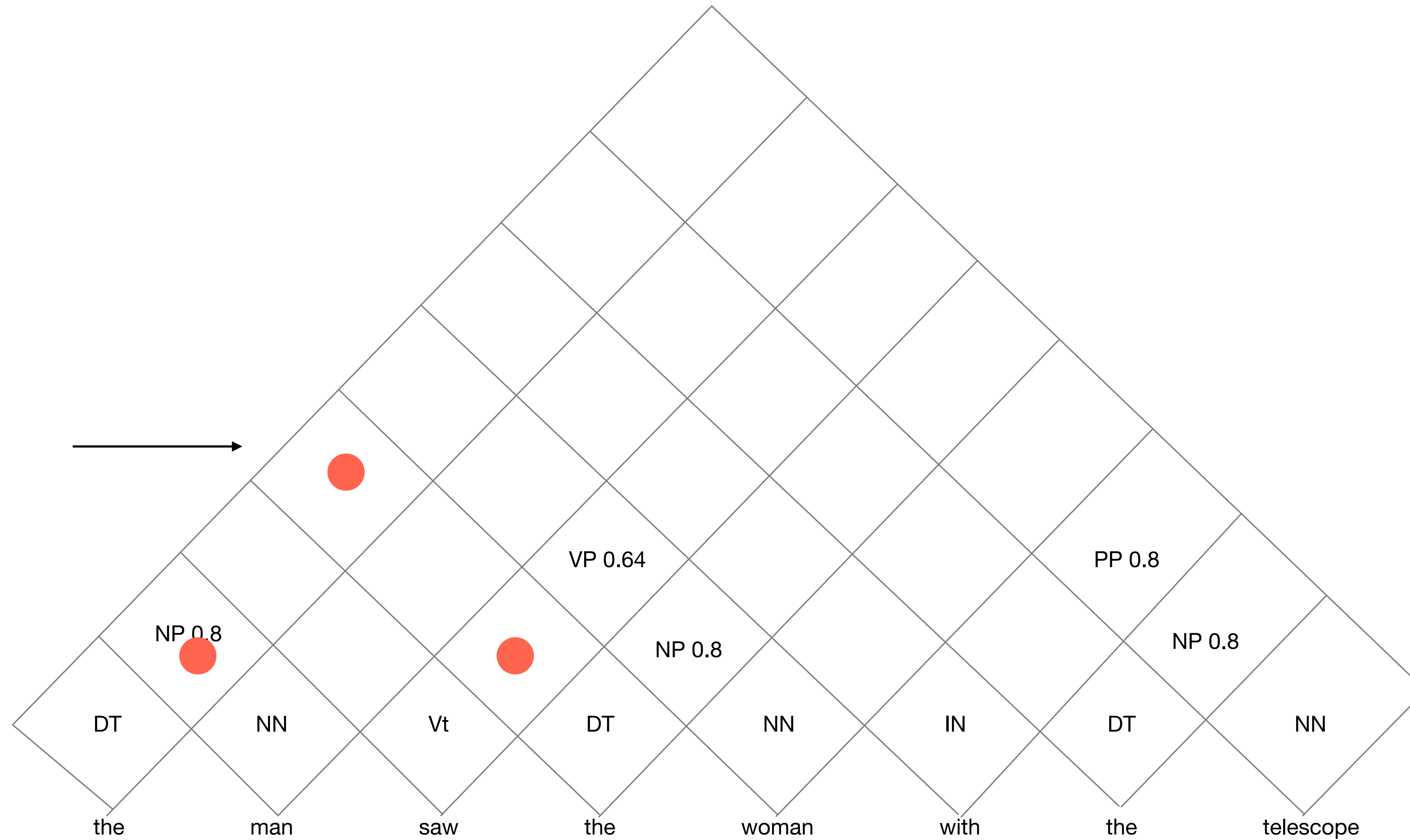
Parsing with PCFGs



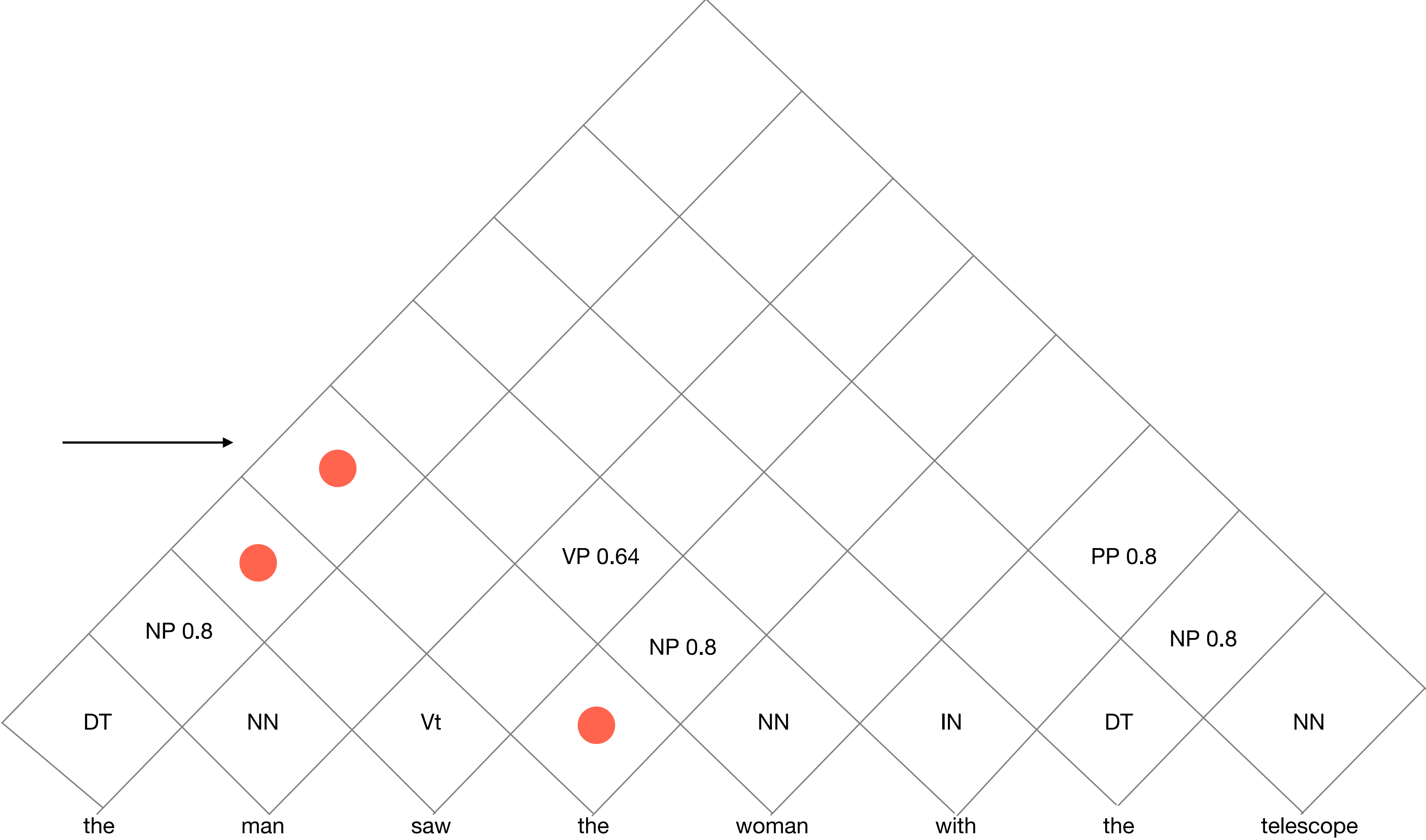
Parsing with PCFGs



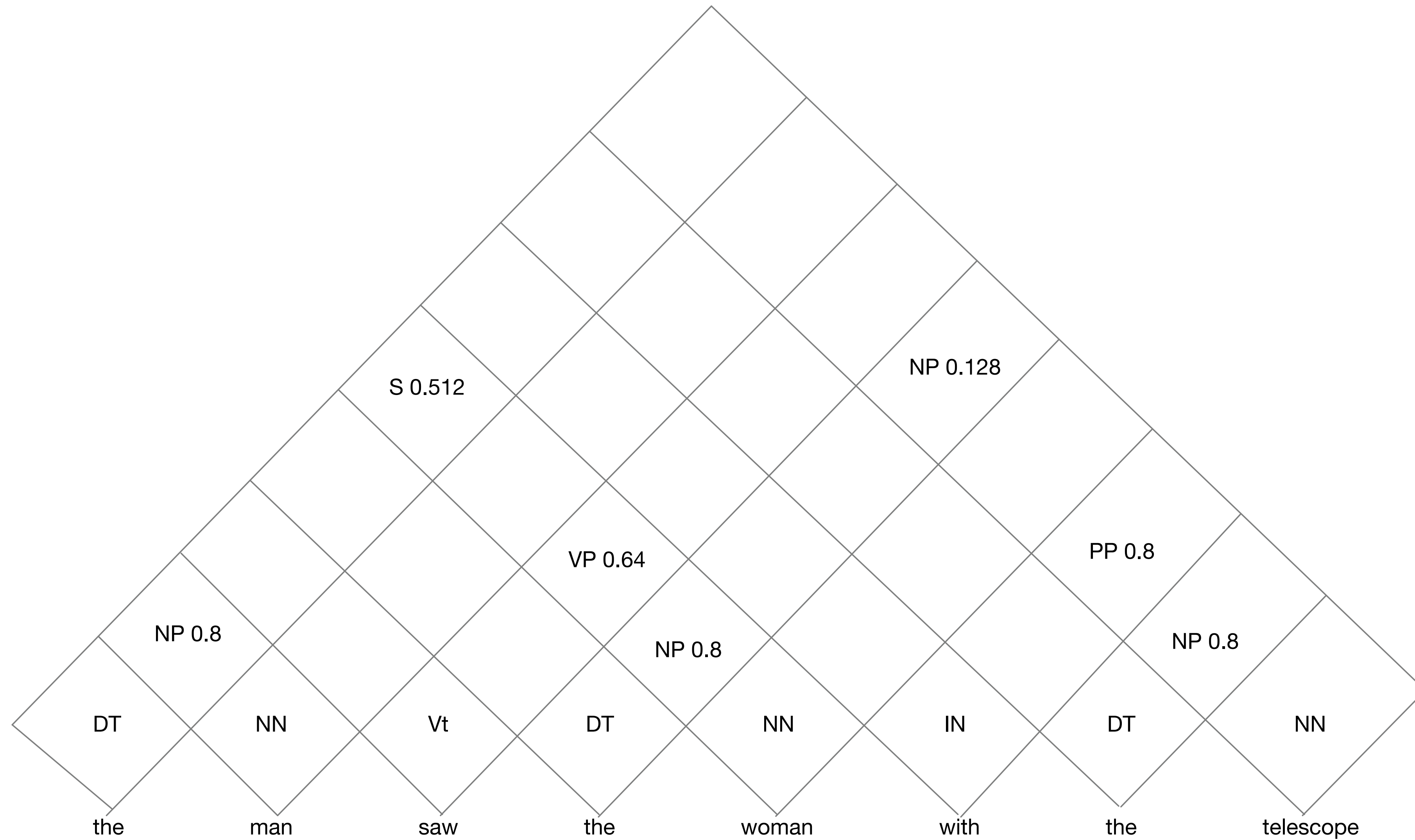
Parsing with PCFGs



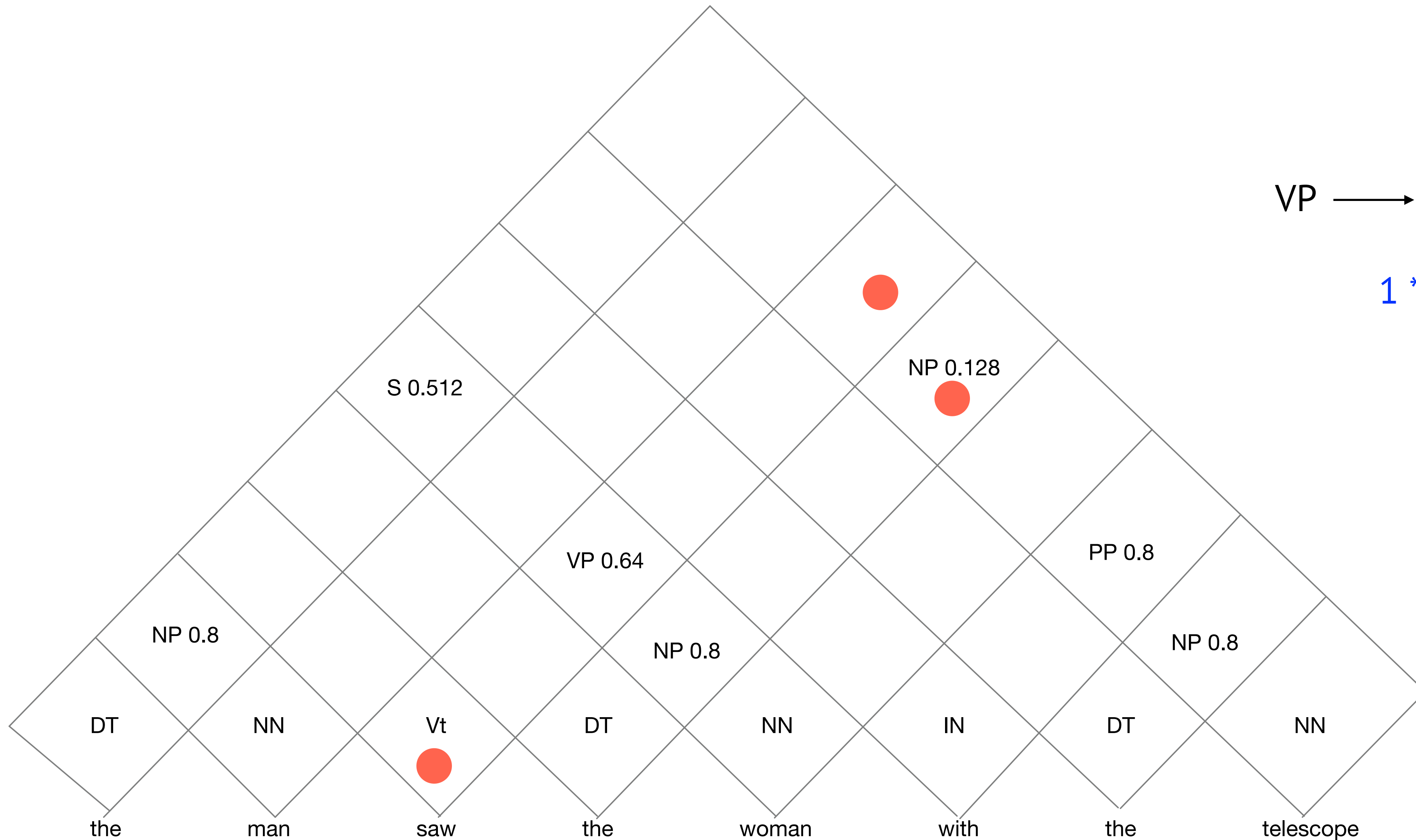
Parsing with PCFGs



Parsing with PCFGs



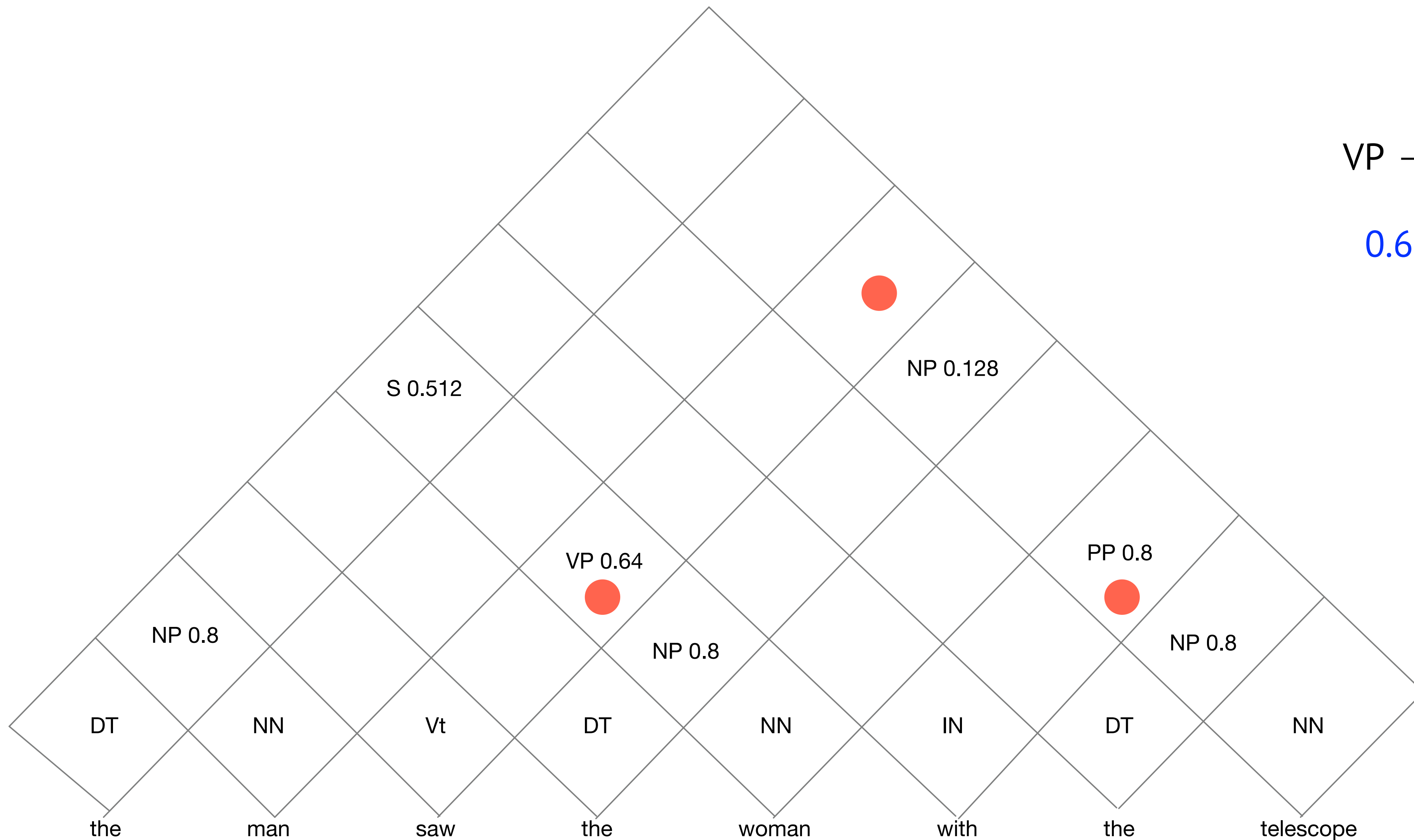
Parsing with PCFGs



VP \longrightarrow Vt NP 0.8

$$1 * 0.128 * 0.8 = 0.1024$$

Parsing with PCFGs



VP \longrightarrow VP PP 0.2

$$0.64 * 0.8 * 0.2 = 0.1024$$

Parsing with PCFGs (CYK Algorithm)

