

Bottom-up Chart Parsing: the CKY algorithm

Data Structures and Algorithms for Computational Linguistics III (ISCL-BA-07)

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Parsing so far

- Parsing is the task of automatic syntactic analysis
- For most practical purposes, context-free grammars are the most useful formalism for parsing
- We can formulate parsing as
 - Top-down: begin with the start symbol, try to *produce* the input string to be parsed
 - Bottom up: begin with the input, and try to *reduce* it to the start symbol
- Both strategies can be cast as search with backtracking
- Backtracking parsers are inefficient: they recompute sub-trees multiple times

Bottom-up parsing as search

the cat bites a dog

S \rightarrow NP VP

NP \rightarrow Det N

VP \rightarrow V NP

VP \rightarrow V

Det \rightarrow a

Det \rightarrow the

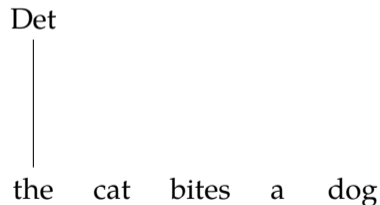
N \rightarrow cat

N \rightarrow dog

V \rightarrow bites

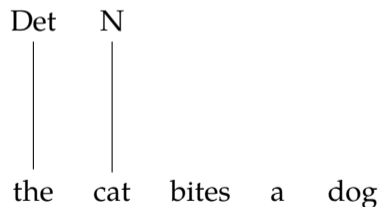
N \rightarrow bites

Bottom-up parsing as search



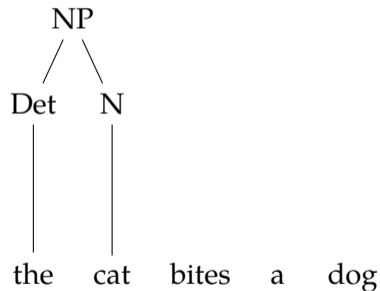
S → NP VP
NP → Det N
VP → V NP
VP → V
Det → a
Det → the
N → cat
N → dog
V → bites
N → bites

Bottom-up parsing as search



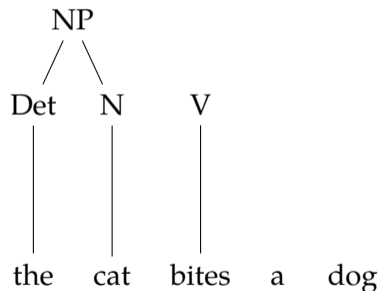
S	→	NP VP
NP	→	Det N
VP	→	V NP
VP	→	V
Det	→	a
Det	→	the
N	→	cat
N	→	dog
V	→	bites
N	→	bites

Bottom-up parsing as search



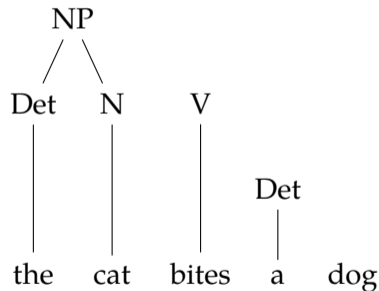
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 VP \rightarrow V NP
 VP \rightarrow V
 Det \rightarrow a
 Det \rightarrow the
 N \rightarrow cat
 N \rightarrow dog
 V \rightarrow bites
 N \rightarrow bites

Bottom-up parsing as search



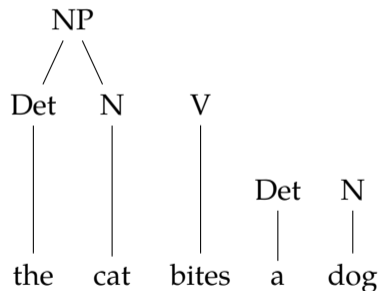
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 NP \rightarrow Det N
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 Det \rightarrow a
 Det \rightarrow the
 N \rightarrow cat
 N \rightarrow dog
 V \rightarrow bites
 N \rightarrow bites

Bottom-up parsing as search



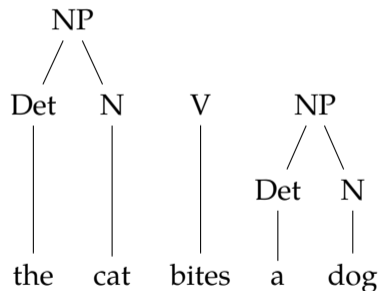
S	→	NP VP
NP	→	Det N
VP	→	V NP
VP	→	V
Det	→	a
Det	→	the
N	→	cat
N	→	dog
V	→	bites
N	→	bites

Bottom-up parsing as search



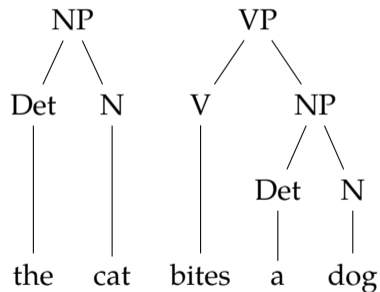
S \rightarrow NP VP
 NP \rightarrow Det N
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 VP \rightarrow V
 Det \rightarrow a
 Det \rightarrow the
 N \rightarrow cat
 N \rightarrow dog
 V \rightarrow bites
 N \rightarrow bites

Bottom-up parsing as search



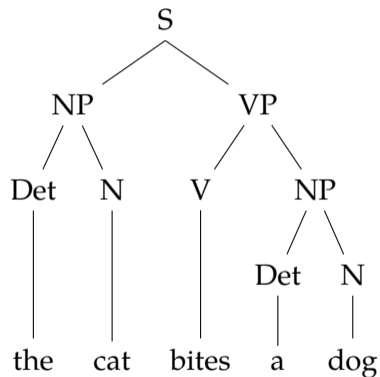
S \rightarrow NP VP
 NP \rightarrow Det N
 VP \rightarrow V NP
 VP \rightarrow V
 Det \rightarrow a
 Det \rightarrow the
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 N \rightarrow dog
 V \rightarrow bites
 N \rightarrow bites

Bottom-up parsing as search



S \rightarrow NP VP
 NP \rightarrow Det N
 VP \rightarrow **V NP**
 VP \rightarrow V
 Det \rightarrow a
 Det \rightarrow the
 N \rightarrow cat
 N \rightarrow dog
 V \rightarrow bites
 N \rightarrow bites

Bottom-up parsing as search



S → NP VP

NP → Det N

VP → V NP

VP → V

Det → a

Det → the

N → cat

N → dog

V → bites

N → bites

Dealing with ambiguity

I saw her duck

S \rightarrow NP VP

NP \rightarrow Prn N

NP \rightarrow Prn

VP \rightarrow V NP

VP \rightarrow V

VP \rightarrow V S

N \rightarrow duck

V \rightarrow duck

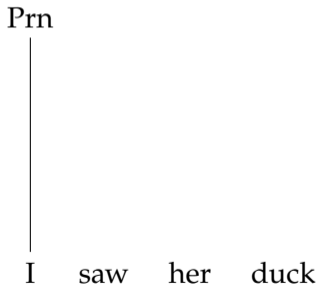
V \rightarrow saw

Prn \rightarrow I \leftarrow

Prn \rightarrow she

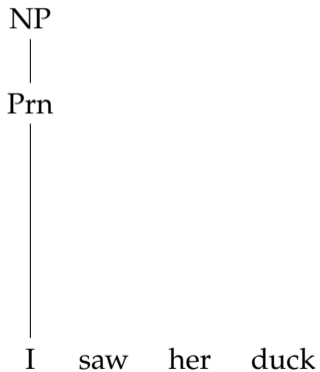
Prn \rightarrow her

Dealing with ambiguity



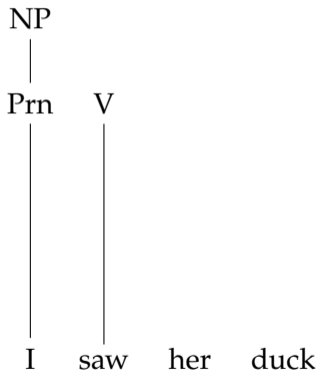
$S \rightarrow NP VP$
 $NP \rightarrow Prn N$
 $NP \rightarrow \text{Prn} \quad \leftarrow$
 $VP \rightarrow V NP$
 $VP \rightarrow V$
 $VP \rightarrow V S$
 $N \rightarrow \text{duck}$
 $V \rightarrow \text{duck}$
 $V \rightarrow \text{saw}$
 $Prn \rightarrow I$
 $Prn \rightarrow \text{she}$
 $Prn \rightarrow \text{her}$

Dealing with ambiguity



S \rightarrow NP VP
 NP \rightarrow Prn N
 NP \rightarrow Prn
 VP \rightarrow V NP
 VP \rightarrow V
 VP \rightarrow V S
 N \rightarrow duck
 V \rightarrow duck
 V \rightarrow saw \leftarrow
 Prn \rightarrow I
 Prn \rightarrow she
 Prn \rightarrow her

Dealing with ambiguity



S \rightarrow NP VP

NP \rightarrow Prn N

NP \rightarrow Prn

VP \rightarrow V NP

VP \rightarrow V

VP \rightarrow V S

N \rightarrow duck

V \rightarrow duck

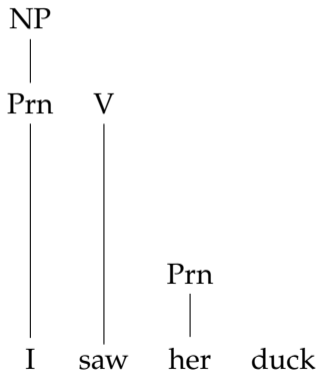
V \rightarrow saw

Prn \rightarrow I

Prn \rightarrow she

Prn \rightarrow her \leftarrow

Dealing with ambiguity



S \rightarrow NP VP

NP \rightarrow Prn N

NP \rightarrow Prn \leftarrow

VP \rightarrow V NP

VP \rightarrow V

VP \rightarrow V S

N \rightarrow duck

V \rightarrow duck

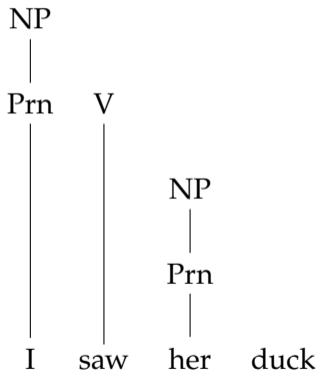
V \rightarrow saw

Prn \rightarrow I

Prn \rightarrow she

Prn \rightarrow her

Dealing with ambiguity



S \rightarrow NP VP

NP \rightarrow Prn N

NP \rightarrow Prn

VP \rightarrow V NP

VP \rightarrow V

VP \rightarrow V S

N \rightarrow duck

V \rightarrow duck

←

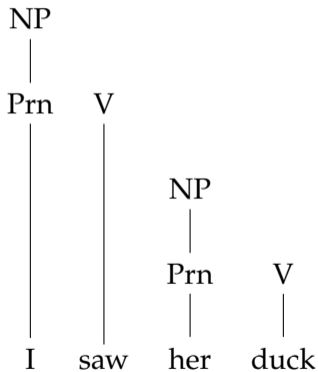
V \rightarrow saw

Prn \rightarrow I

Prn \rightarrow she

Prn \rightarrow her

Dealing with ambiguity



S → NP VP

NP → Prn N

NP → Prn

VP → V NP

VP → V ←

VP → V S

N → duck

V → duck

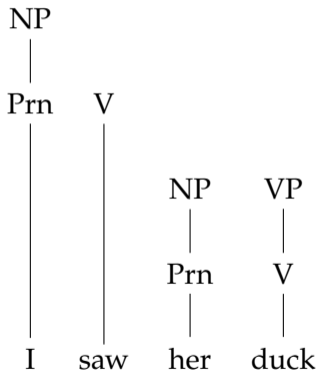
V → saw

Prn → I

Prn → she

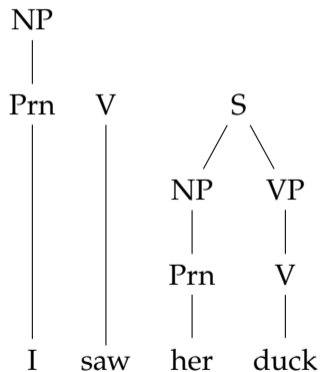
Prn → her

Dealing with ambiguity



$S \rightarrow \text{NP VP} \quad \leftarrow$
 $\text{NP} \rightarrow \text{Prn N}$
 $\text{NP} \rightarrow \text{Prn}$
 $\text{VP} \rightarrow \text{V NP}$
 $\text{VP} \rightarrow \text{V}$
 $\text{VP} \rightarrow \text{V S}$
 $\text{N} \rightarrow \text{duck}$
 $\text{V} \rightarrow \text{duck}$
 $\text{V} \rightarrow \text{saw}$
 $\text{Prn} \rightarrow \text{I}$
 $\text{Prn} \rightarrow \text{she}$
 $\text{Prn} \rightarrow \text{her}$

Dealing with ambiguity



S → NP VP

NP → Prn N

NP → Prn

VP → V NP

VP → V

VP → **V S** ←

N → duck

V → duck

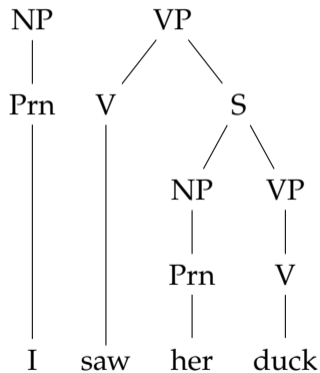
V → saw

Prn → I

Prn → she

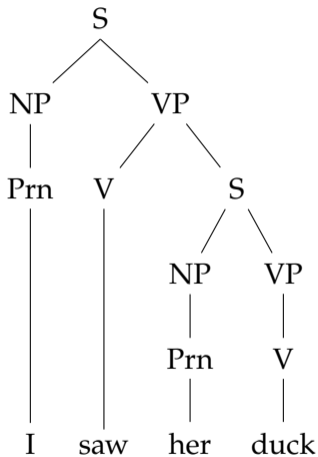
Prn → her

Dealing with ambiguity



$S \rightarrow \text{NP VP} \quad \leftarrow$
 $\text{NP} \rightarrow \text{Prn N}$
 $\text{NP} \rightarrow \text{Prn}$
 $\text{VP} \rightarrow \text{V NP}$
 $\text{VP} \rightarrow \text{V}$
 $\text{VP} \rightarrow \text{V S}$
 $\text{N} \rightarrow \text{duck}$
 $\text{V} \rightarrow \text{duck}$
 $\text{V} \rightarrow \text{saw}$
 $\text{Prn} \rightarrow \text{I}$
 $\text{Prn} \rightarrow \text{she}$
 $\text{Prn} \rightarrow \text{her}$

Dealing with ambiguity



$$S \rightarrow NP VP$$

$$NP \rightarrow Prn N$$

$$NP \rightarrow Prn$$

$$VP \rightarrow V NP$$

$$VP \rightarrow V$$

$$VP \rightarrow V S$$

$$N \rightarrow \text{duck}$$

$$V \rightarrow \text{duck}$$

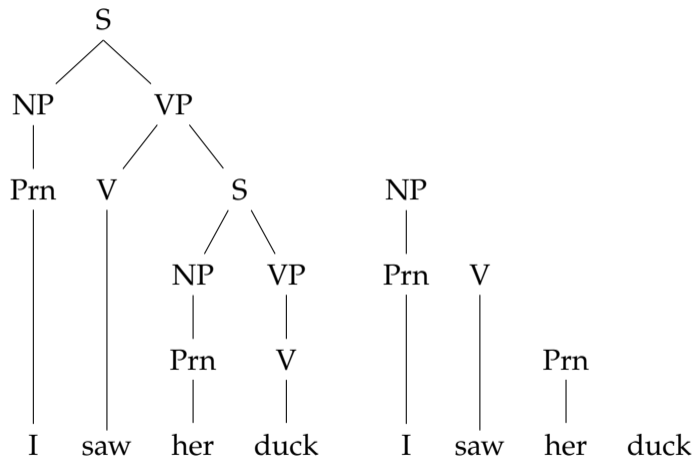
$$V \rightarrow \text{saw}$$

$$Prn \rightarrow I$$

$$Prn \rightarrow \text{she}$$

$$Prn \rightarrow \text{her}$$

Dealing with ambiguity



$$S \rightarrow NP VP$$

$$NP \rightarrow Prn N$$

$$NP \rightarrow \text{Prn}$$

$$VP \rightarrow V NP$$

$$VP \rightarrow V$$

$$VP \rightarrow V S$$

$$N \rightarrow \text{duck} \quad \leftarrow$$

$$V \rightarrow \text{duck}$$

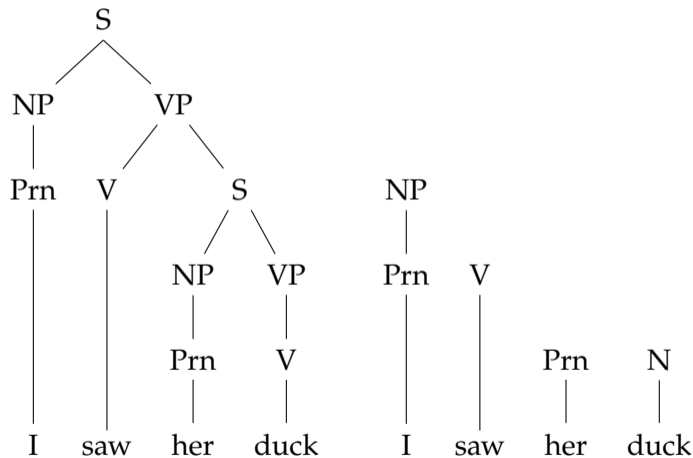
$$V \rightarrow \text{saw}$$

$$Prn \rightarrow I$$

$$Prn \rightarrow \text{she}$$

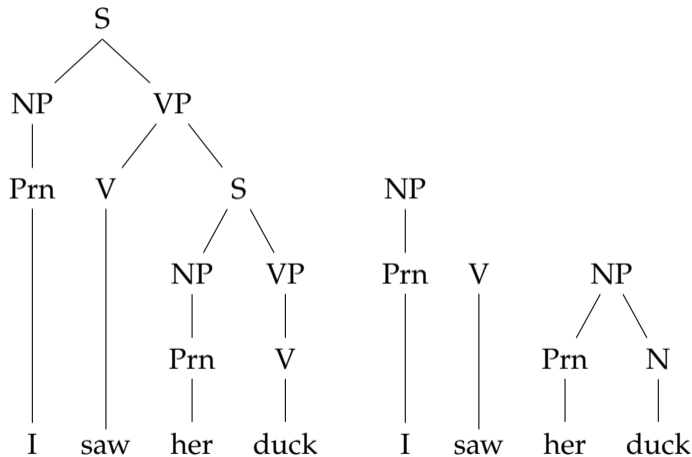
$$Prn \rightarrow \text{her}$$

Dealing with ambiguity



$S \rightarrow NP VP$
 $NP \rightarrow \text{Prn } N \quad \leftarrow$
 $NP \rightarrow \text{Prn}$
 $VP \rightarrow V NP$
 $VP \rightarrow V$
 $VP \rightarrow V S$
 $N \rightarrow \text{duck}$
 $V \rightarrow \text{duck}$
 $V \rightarrow \text{saw}$
 $\text{Prn} \rightarrow I$
 $\text{Prn} \rightarrow \text{she}$
 $\text{Prn} \rightarrow \text{her}$

Dealing with ambiguity



$$S \rightarrow NP VP$$

$$NP \rightarrow Prn N$$

$$NP \rightarrow Prn$$

$$VP \rightarrow V NP \quad \leftarrow$$

$$VP \rightarrow V$$

$$VP \rightarrow V S$$

$$N \rightarrow duck$$

$$V \rightarrow duck$$

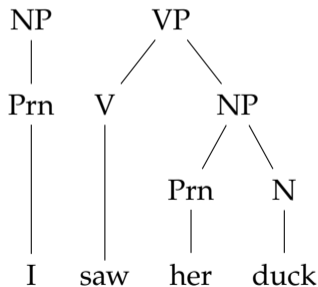
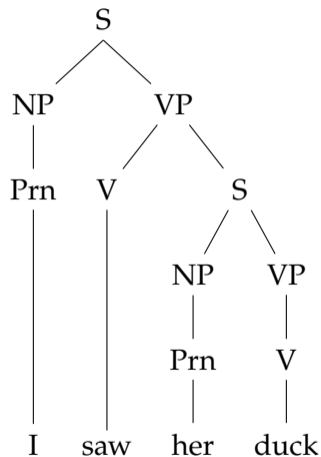
$$V \rightarrow saw$$

$$Prn \rightarrow I$$

$$Prn \rightarrow she$$

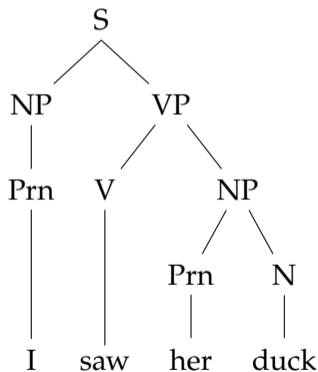
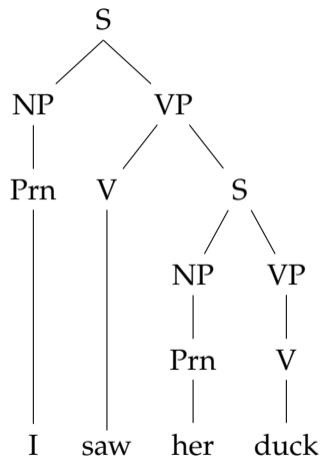
$$Prn \rightarrow her$$

Dealing with ambiguity



$S \rightarrow \text{NP VP} \quad \leftarrow$
 $\text{NP} \rightarrow \text{Prn N}$
 $\text{NP} \rightarrow \text{Prn}$
 $\text{VP} \rightarrow \text{V NP}$
 $\text{VP} \rightarrow \text{V}$
 $\text{VP} \rightarrow \text{V S}$
 $\text{N} \rightarrow \text{duck}$
 $\text{V} \rightarrow \text{duck}$
 $\text{V} \rightarrow \text{saw}$
 $\text{Prn} \rightarrow \text{I}$
 $\text{Prn} \rightarrow \text{she}$
 $\text{Prn} \rightarrow \text{her}$

Dealing with ambiguity



$S \rightarrow NP VP$

$NP \rightarrow Prn N$

$NP \rightarrow Prn$

$VP \rightarrow V NP$

$VP \rightarrow V$

$VP \rightarrow V S$

$N \rightarrow \text{duck}$

$V \rightarrow \text{duck}$

$V \rightarrow \text{saw}$

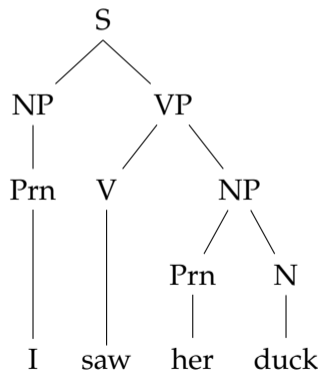
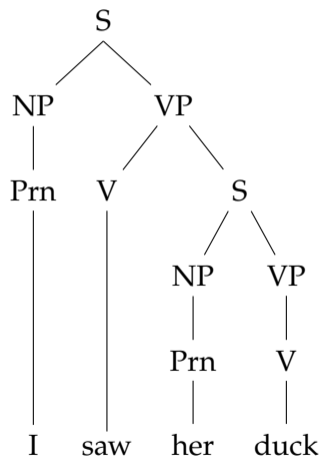
$Prn \rightarrow I$

$Prn \rightarrow \text{she}$

$Prn \rightarrow \text{her}$

How to represent multiple parses

parse forest grammar



$S_{0:4}$	\rightarrow	$NP_{0:1}$	$VP_{1:4}$
$NP_{0:1}$	\rightarrow	$Prn_{0:1}$	
$Prn_{0:1}$	\rightarrow	$I_{0:1}$	
$V_{1:2}$	\rightarrow	$saw_{1:2}$	
$Prn_{2:3}$	\rightarrow	$her_{2:3}$	
<hr/>			
$VP_{1:4}$	\rightarrow	$V_{1:2}$	$S_{2:4}$
$S_{2:4}$	\rightarrow	$Prn_{2:3}$	$V_{3:4}$
$V_{3:4}$	\rightarrow	$duck_{3:4}$	
<hr/>			
$VP_{1:4}$	\rightarrow	$V_{1:2}$	$NP_{2:4}$
$NP_{2:4}$	\rightarrow	$Prn_{2:3}$	$N_{3:4}$
$N_{3:4}$	\rightarrow	$duck_{3:4}$	

CKY algorithm

- The CKY (Cocke–Kasami–Younger) parsing algorithm is a dynamic programming algorithm
- It processes the input *bottom up*, and saves the intermediate results on a *chart*
- Time complexity for *recognition* is $O(n^3)$
- Space complexity is $O(n^2)$
- It requires the CFG to be in *Chomsky normal form* (CNF) (can somewhat be relaxed, but not common)

Chomsky normal form (CNF)

- A CFG is in CNF, if the rewrite rules are in one of the following forms
 - $A \rightarrow BC$
 - $A \rightarrow a$

where A, B, C are non-terminals and a is a terminal

- Any CFG can be converted to CNF
- Resulting grammar is *weakly equivalent* to the original grammar:
 - it generates/accepts the same language
 - but the derivations are different

Converting to CNF: example

S → NP VP
S → Aux NP VP
NP → the N
VP → V NP
VP → V
N → cat
N → dog
V → bites
N → bites

Converting to CNF: example

$S \rightarrow NP VP$

$S \rightarrow Aux NP VP$

$NP \rightarrow the N$

$VP \rightarrow V NP$

$VP \rightarrow V$

$N \rightarrow cat$

$N \rightarrow dog$

$V \rightarrow bites$

$N \rightarrow bites$

- $S \rightarrow Aux NP VP$
 $S \rightarrow Aux NP VP \Rightarrow \begin{array}{l} S \rightarrow Aux X \\ X \rightarrow NP VP \end{array}$

Converting to CNF: example

$S \rightarrow NP VP$

$S \rightarrow Aux NP VP$

$NP \rightarrow the N$

$VP \rightarrow V NP$

$VP \rightarrow V$

$N \rightarrow cat$

$N \rightarrow dog$

$V \rightarrow bites$

$N \rightarrow bites$

- $S \rightarrow Aux NP VP$
 $S \rightarrow Aux NP VP \Rightarrow S \rightarrow Aux X$
 $X \rightarrow NP VP$
- $NP \rightarrow the N$
 $NP \rightarrow the N \Rightarrow NP \rightarrow X N$
 $X \rightarrow the$

Converting to CNF: example

$S \rightarrow NP VP$
 $S \rightarrow \text{Aux } NP VP$
 $NP \rightarrow \text{the } N$
 $VP \rightarrow V NP$
 $VP \rightarrow V$
 $N \rightarrow \text{cat}$
 $N \rightarrow \text{dog}$
 $V \rightarrow \text{bites}$
 $N \rightarrow \text{bites}$

- $S \rightarrow \text{Aux } NP VP$
 $S \rightarrow \text{Aux } NP VP \Rightarrow S \rightarrow \text{Aux } X$
 $X \rightarrow NP VP$
- $NP \rightarrow \text{the } N$
 $NP \rightarrow \text{the } N \Rightarrow NP \rightarrow X N$
 $X \rightarrow \text{the}$
- $VP \rightarrow V$
 $VP \rightarrow V \Rightarrow VP \rightarrow \text{bites}$

Converting to CNF

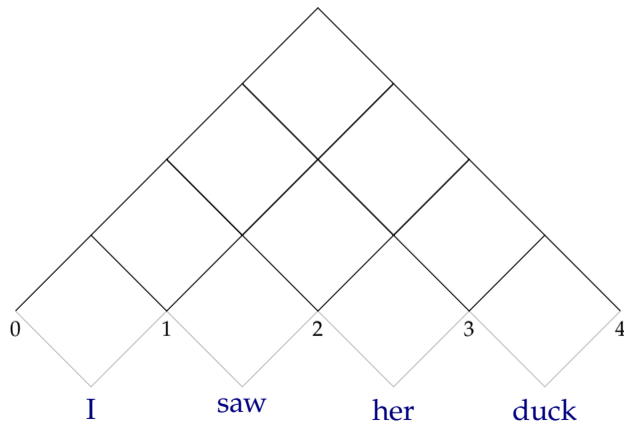
1. Eliminate the ϵ rules: if $A \rightarrow \epsilon$ is in the grammar
 - replace any rule $B \rightarrow \alpha A \beta$ with two rules

$$B \rightarrow \alpha \beta$$

$$B \rightarrow \alpha A' \beta$$
 - add $A' \rightarrow \alpha$ for all α (except ϵ) whose LHS is A
 - repeat the process for newly created ϵ rules
 - remove the rules with ϵ on the RHS (except $S \rightarrow \epsilon$)
2. Eliminate unit rules: for a rule $A \rightarrow B$
 - Replace the rule with $A \rightarrow \alpha_1 \mid \dots \mid \alpha_n$, where $\alpha_1, \dots, \alpha_n$ are all RHS or rule B
 - Remove the rule $A \rightarrow B$
 - Repeat the process until no unit rules remain
3. Binarize all the non-binary rules with non-terminal on the RHS: for a rule $A \rightarrow X_1 X_2 \dots X_n$:
 - Replace the rule with $A \rightarrow A_1 X_3 \dots X_n$, and add $A_1 \rightarrow X_1 X_2$
 - Repeat the process until all new rules are binary

CKY demonstration

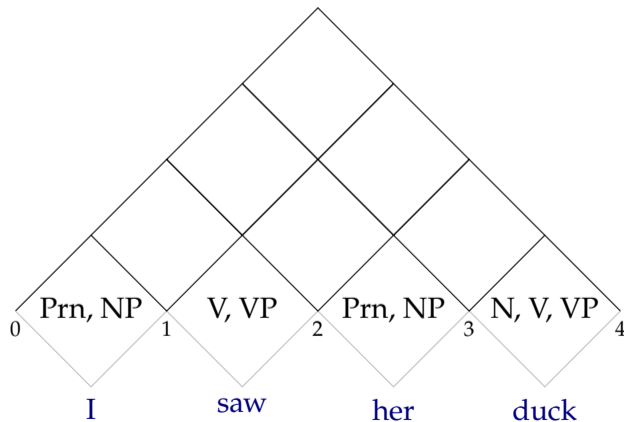
an ambiguous example



$S \rightarrow NP VP$
 $NP \rightarrow Prn N$
 $VP \rightarrow V NP$
 $VP \rightarrow V S$
 $N \rightarrow \text{duck}$
 $VP \rightarrow \text{duck} \mid \text{saw}$
 $V \rightarrow \text{duck} \mid \text{saw}$
 $Prn \rightarrow I \mid \text{she} \mid \text{her}$
 $NP \rightarrow I \mid \text{she} \mid \text{her}$

CKY demonstration

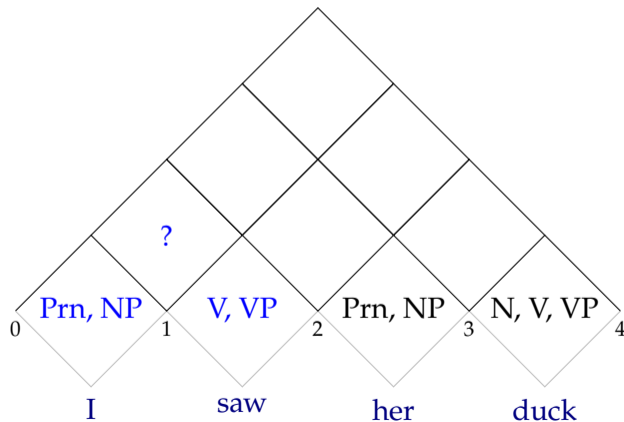
an ambiguous example



$S \rightarrow \text{NP VP}$
 $\text{NP} \rightarrow \text{Prn N}$
 $\text{VP} \rightarrow \text{V NP}$
 $\text{VP} \rightarrow \text{V S}$
 $\text{N} \rightarrow \text{duck}$
 $\text{VP} \rightarrow \text{duck} \mid \text{saw}$
 $\text{V} \rightarrow \text{duck} \mid \text{saw}$
 $\text{Prn} \rightarrow \text{I} \mid \text{she} \mid \text{her}$
 $\text{NP} \rightarrow \text{I} \mid \text{she} \mid \text{her}$

CKY demonstration

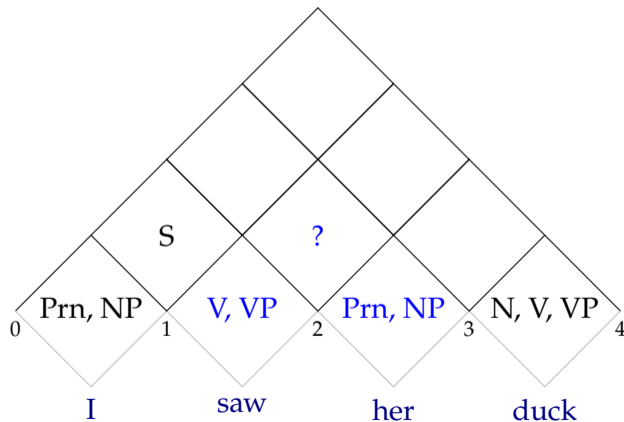
an ambiguous example

$$S \rightarrow NP VP$$


S \rightarrow NP VP
NP \rightarrow Prn N
VP \rightarrow V NP
VP \rightarrow V S
N \rightarrow duck
VP \rightarrow duck | saw
V \rightarrow duck | saw
Prn \rightarrow I | she | her
NP \rightarrow I | she | her

CKY demonstration

an ambiguous example

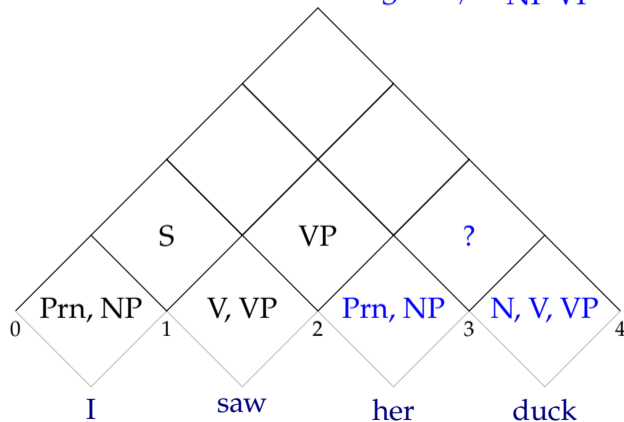
$$\text{VP} \rightarrow \text{V NP}$$


S \rightarrow NP VP
NP \rightarrow Prn N
VP \rightarrow V NP
VP \rightarrow V S
N \rightarrow duck
VP \rightarrow duck | saw
V \rightarrow duck | saw
Prn \rightarrow I | she | her
NP \rightarrow I | she | her

CKY demonstration

an ambiguous example

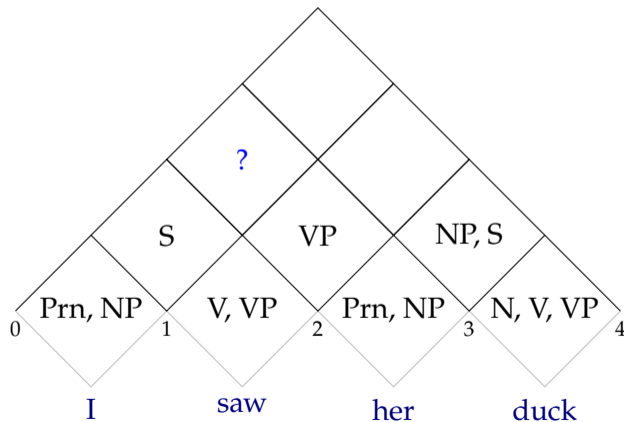
NP \rightarrow Prn N
S \rightarrow NP VP



S \rightarrow NP VP
NP \rightarrow Prn N
VP \rightarrow V NP
VP \rightarrow V S
N \rightarrow duck
VP \rightarrow duck | saw
V \rightarrow duck | saw
Prn \rightarrow I | she | her
NP \rightarrow I | she | her

CKY demonstration

an ambiguous example

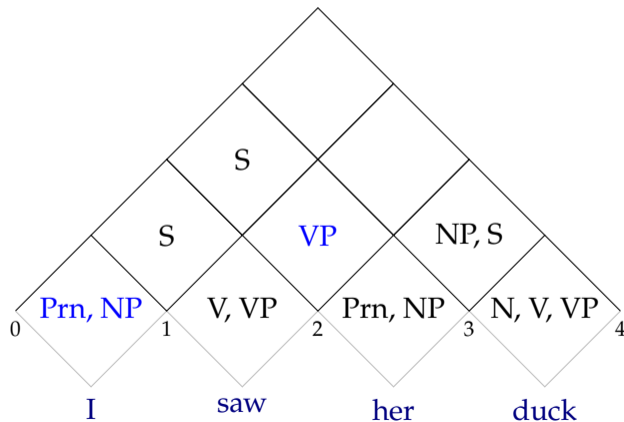


$S \rightarrow NP VP$
 $NP \rightarrow Prn N$
 $VP \rightarrow V NP$
 $VP \rightarrow V S$
 $N \rightarrow duck$
 $VP \rightarrow duck \mid saw$
 $V \rightarrow duck \mid saw$
 $Prn \rightarrow I \mid she \mid her$
 $NP \rightarrow I \mid she \mid her$

CKY demonstration

an ambiguous example

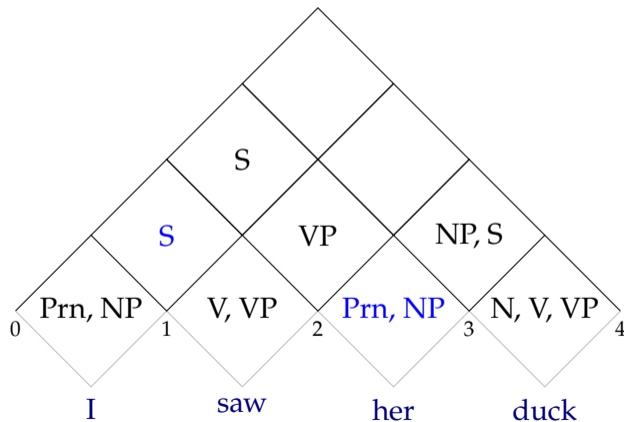
$S \rightarrow NP VP$



$S \rightarrow NP VP$
 $NP \rightarrow Prn N$
 $VP \rightarrow V NP$
 $VP \rightarrow V S$
 $N \rightarrow duck$
 $VP \rightarrow duck \mid saw$
 $V \rightarrow duck \mid saw$
 $Prn \rightarrow I \mid she \mid her$
 $NP \rightarrow I \mid she \mid her$

CKY demonstration

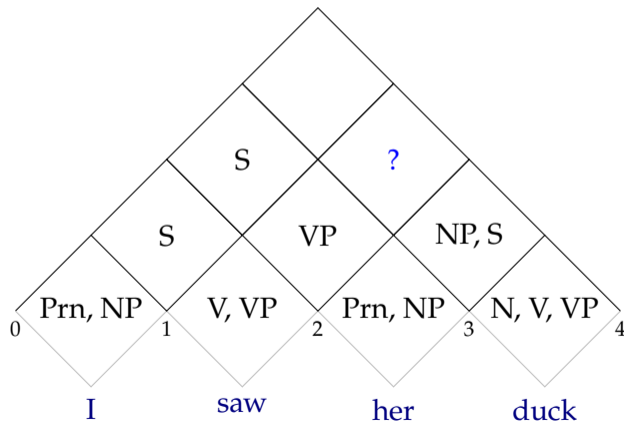
an ambiguous example



$S \rightarrow NP VP$
 $NP \rightarrow Prn N$
 $VP \rightarrow V NP$
 $VP \rightarrow V S$
 $N \rightarrow \text{duck}$
 $VP \rightarrow \text{duck} \mid \text{saw}$
 $V \rightarrow \text{duck} \mid \text{saw}$
 $Prn \rightarrow I \mid \text{she} \mid \text{her}$
 $NP \rightarrow I \mid \text{she} \mid \text{her}$

CKY demonstration

an ambiguous example

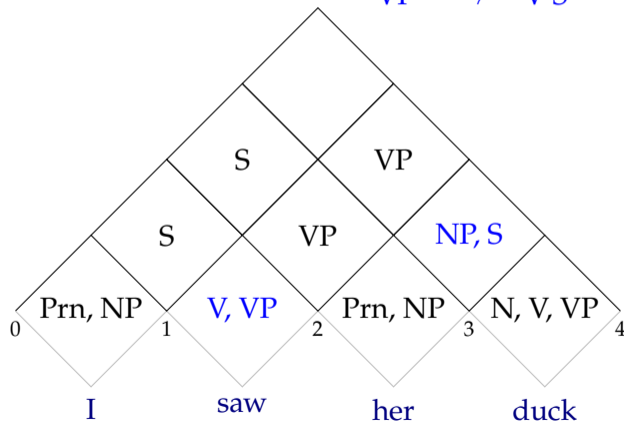


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 $NP \rightarrow Prn N$
 $VP \rightarrow V NP$
 $VP \rightarrow V S$
 $N \rightarrow duck$
 $VP \rightarrow duck \mid saw$
 $V \rightarrow duck \mid saw$
 $Prn \rightarrow I \mid she \mid her$
 $NP \rightarrow I \mid she \mid her$

CKY demonstration

an ambiguous example

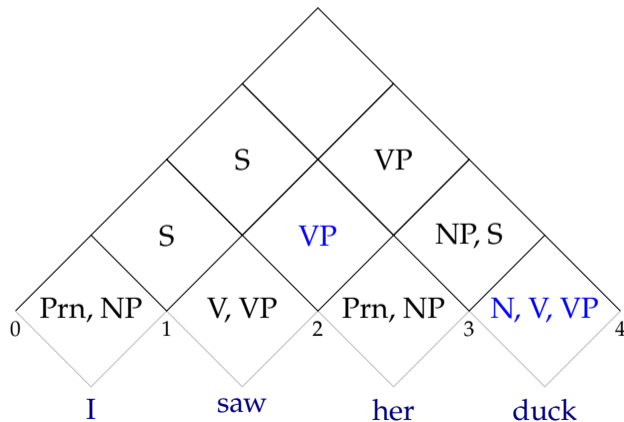
VP \rightarrow V NP
VP \rightarrow V S



S \rightarrow NP VP
 NP \rightarrow Prn N
 VP \rightarrow V NP
 VP \rightarrow V S
 N \rightarrow duck
 VP \rightarrow duck | saw
 V \rightarrow duck | saw
 Prn \rightarrow I | she | her
 NP \rightarrow I | she | her

CKY demonstration

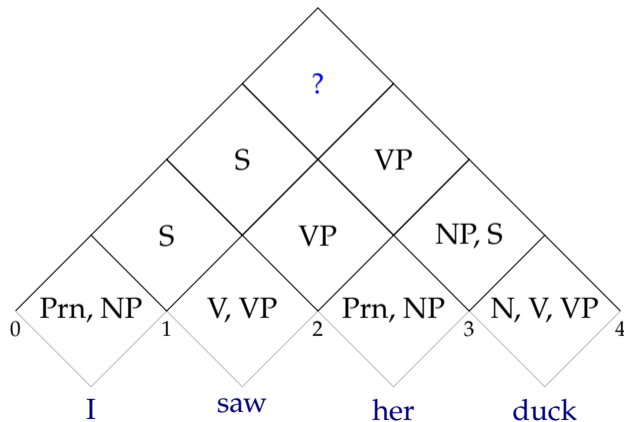
an ambiguous example



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 $V \rightarrow duck \mid saw$
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CKY demonstration

an ambiguous example

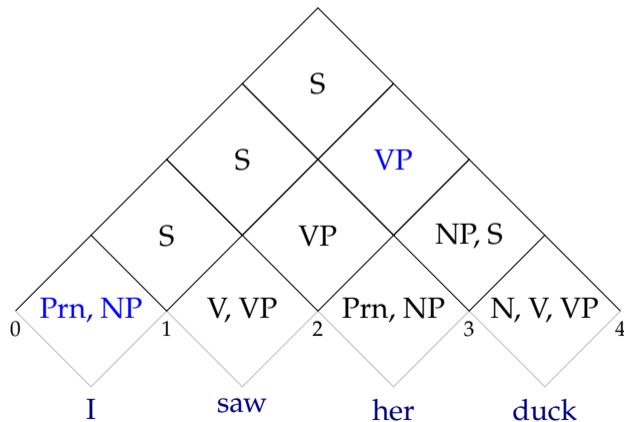


$S \rightarrow NP VP$
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CKY demonstration

an ambiguous example

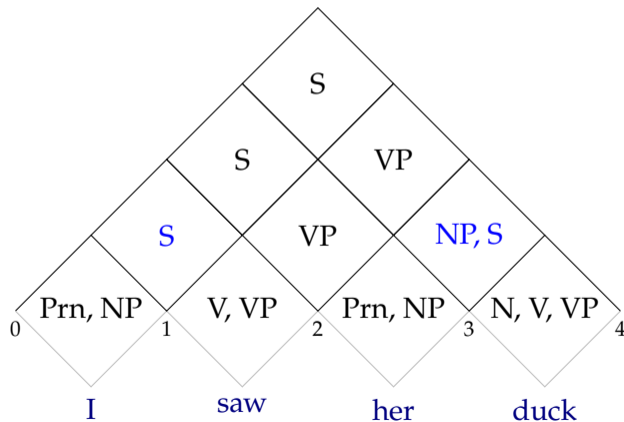
$S \rightarrow NP VP$



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CKY demonstration

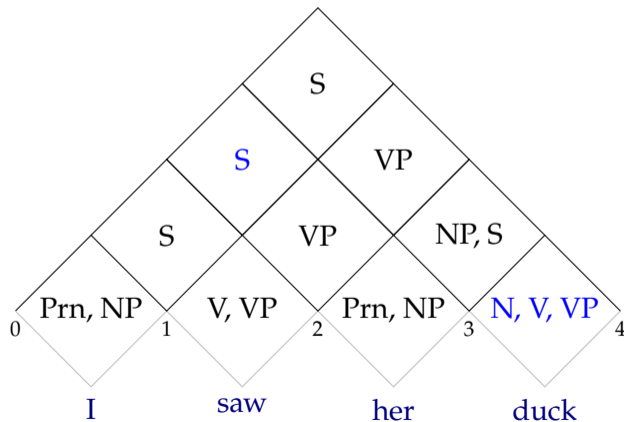
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$S \rightarrow NP VP$
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CKY demonstration

an ambiguous example



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 $N \rightarrow duck$
 $VP \rightarrow duck \mid saw$
 $V \rightarrow duck \mid saw$
 $Prn \rightarrow I \mid she \mid her$
 $NP \rightarrow I \mid she \mid her$

CKY demonstration: the chart

our chart is a 2D array

NP, Prn	S	S	S					
	V, VP	VP	VP					
		Prn	NP, S					
			V, N, NP					
0	she	1	saw	2	her	3	duck	4

Space complexity is $O(n^2)$.

CKY demonstration: the chart

our chart is a 2D array – this is more convenient for programming

S				
S	VP			
S	VP	NP, S		
NP, Prn	V, VP	Prn, NP	V, N, NP	
0	1	2	3	4
she	saw	her	duck	

Space complexity is $O(n^2)$.

Parsing vs. recognition

- We went through a recognition example
- Note that the algorithm is not directional: it takes the complete input
- Recognition accepts or rejects a sentence based on a grammar
- For parsing, we want to know the derivations that yielded a correct parse
- To recover parse trees, we
 - follow the same procedure as recognition
 - add back links to keep track of the derivations

Chart parsing example (CKY parsing)

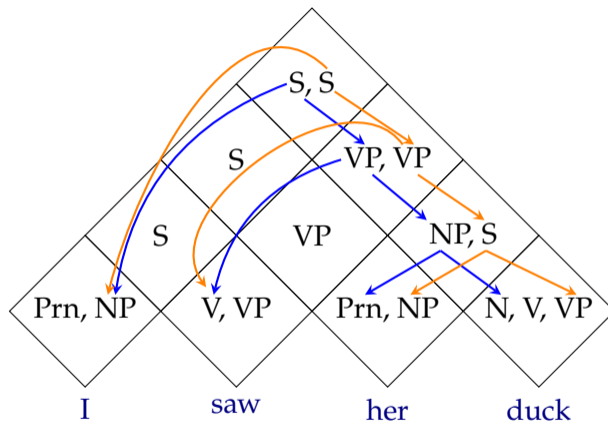
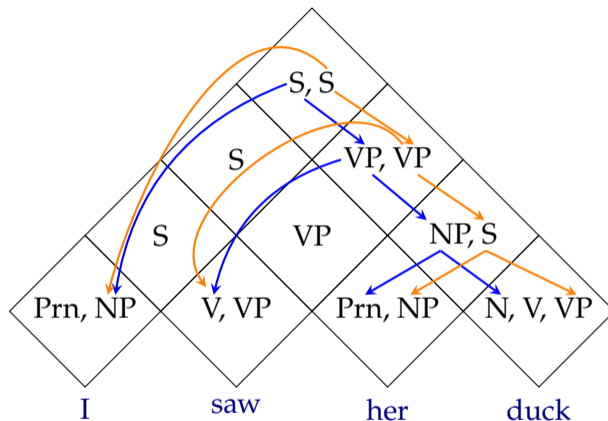


Chart parsing example (CKY parsing)



The chart stores a *parse forest* efficiently.

Summary

- + CKY avoids re-computing the analyses by storing the earlier analyses (of sub-spans) in a table
- It still computes lower level constituents that are not allowed by the grammar
- CKY requires the grammar to be in CNF
 - CKY has $O(n^3)$ recognition complexity
 - For parsing we need to keep track of backlinks
 - CKY can efficiently store all possible parses in a chart
 - Enumerating all possible parses have exponential complexity (worst case)
 - Suggested reading: Jurafsky and Martin (chapter 18 2009, 3rd ed draft)

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Next:

- Top-down chart parsing: Earley algorithm
- Suggested reading:
 - Grune and Jacobs (2007, section 7.2)

Acknowledgments, references, additional reading material



Grune, Dick and Ceriel J.H. Jacobs (2007). *Parsing Techniques: A Practical Guide*. second. Monographs in Computer Science. The first edition is available at http://dickgrune.com/Books/PTAPG_1st_Edition/BookBody.pdf. Springer New York. ISBN: 9780387689548.



Jurafsky, Daniel and James H. Martin (2009). *Speech and Language Processing: An Introduction to Natural Language Processing, Computational Linguistics, and Speech Recognition*. second edition. Pearson Prentice Hall. ISBN: 978-0-13-504196-3.