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Natural Language Parsing: Syntactic parsing

presented by

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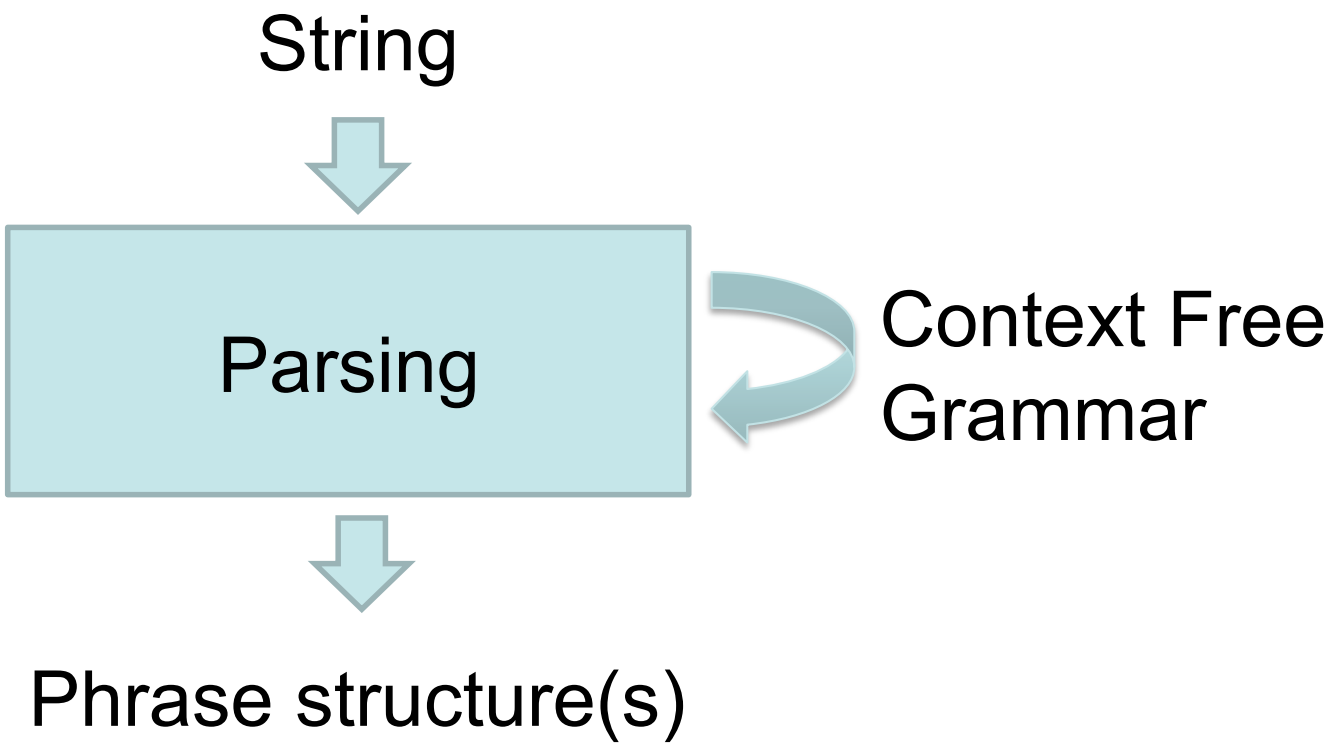
CSC421 Natural Language Processing

Review

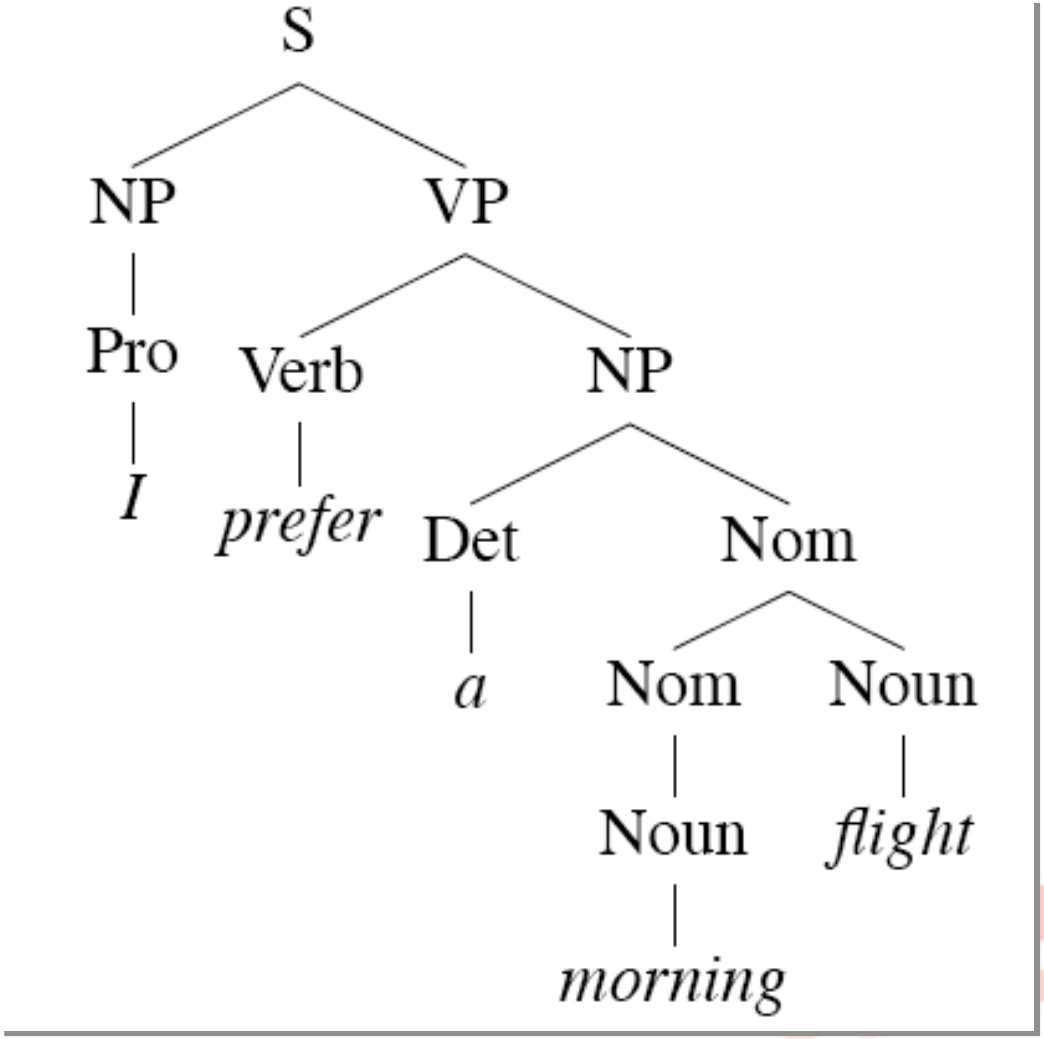
Syntactic parsing in the course



Review

Phrase structure

- Organizes words into nested constituents

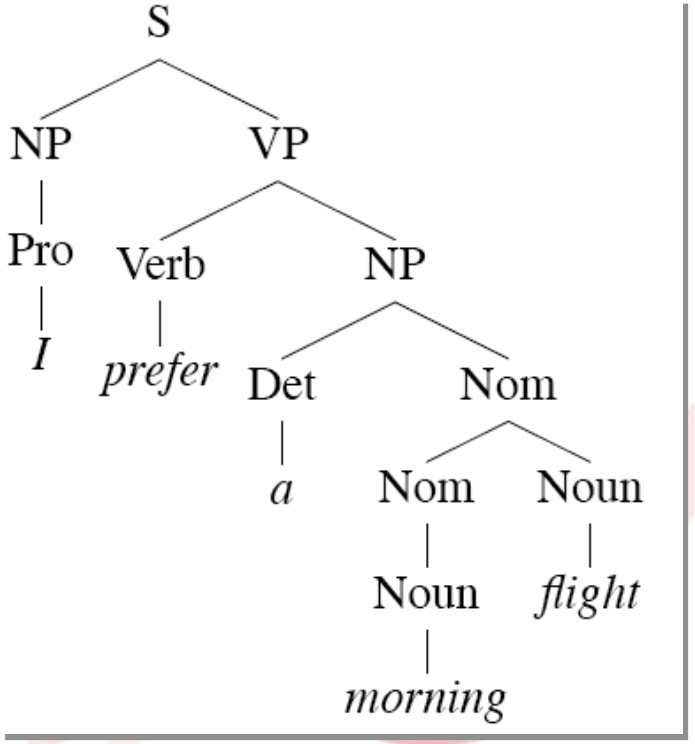


Review

Context-free grammar

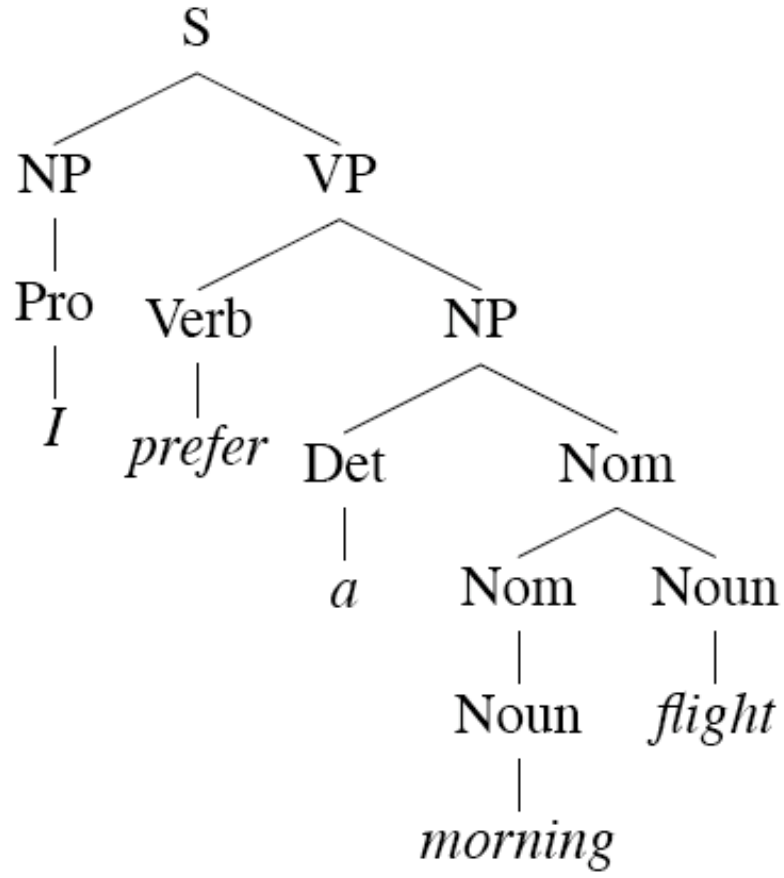
- G = (T, N, S, R)
  - T: a set of terminals (e.g. ‘flight’)
  - N: a set of nonterminals (e.g. Noun)
  - S: the start symbol, a nonterminal
  - R: rules of the form X →γ
    - X: a nonterminal
    - γ: a sequence of terminals and nonterminals

NP	→	*Det Nominal*
NP	→	*ProperNoun*
Nominal	→	*Noun* | *Nominal Noun*



Parsing strategies

Top-down parsing

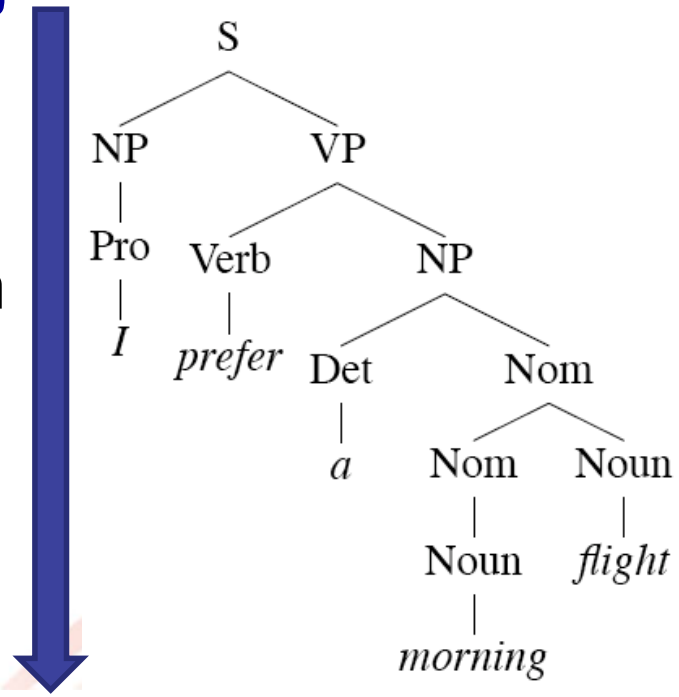


Bottom-up parsing

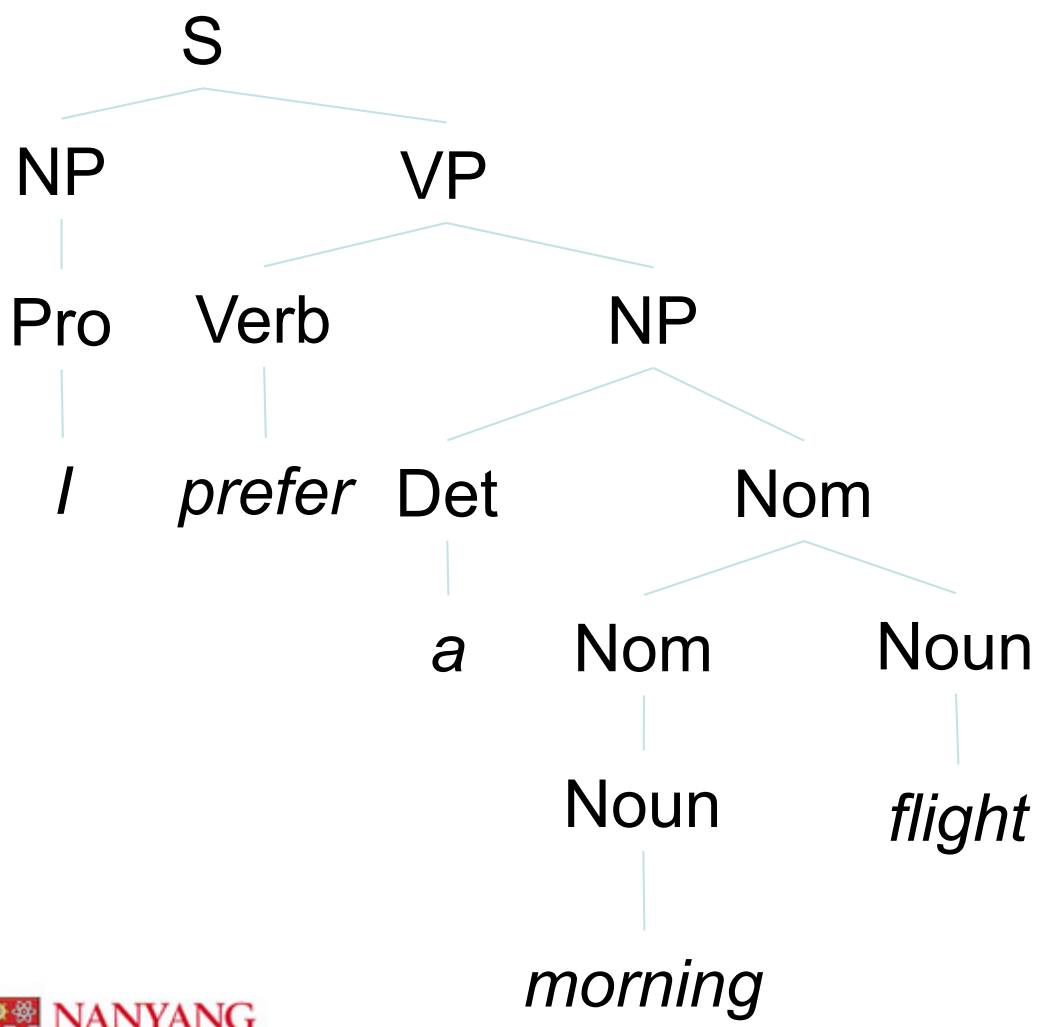
Top-down parsing

- Goal-directed
  - Start from ‘S’
- Rewrite the goal(s) with the RHS of relevant rules
  - E.g. S → NP VP, VP → Verb NP
- Parsing is finished when the rewriting generates the whole string

Top-down parsing



Top-down parsing: Example



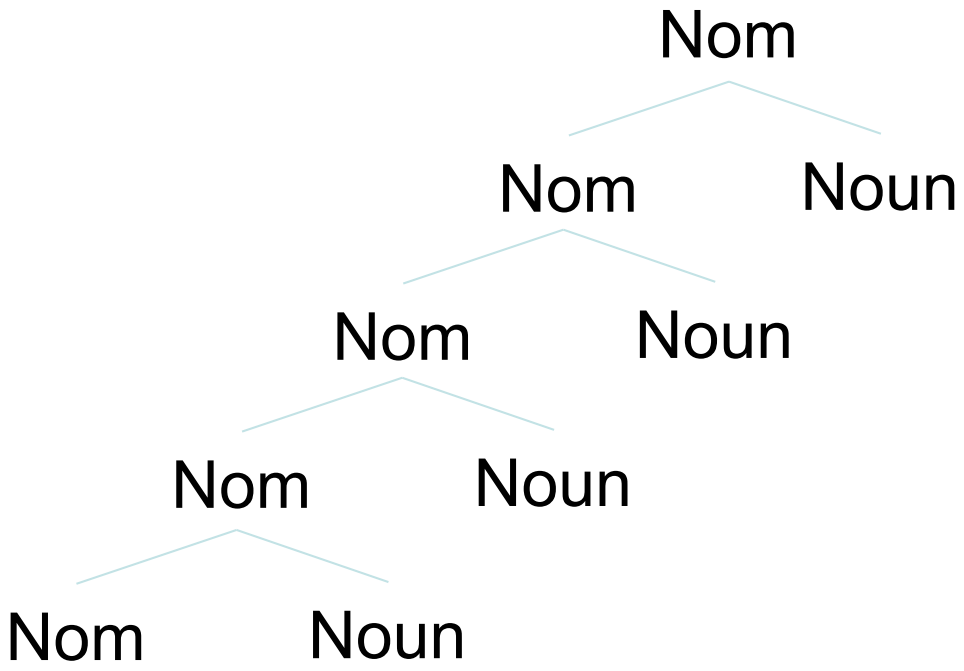
1. S → NP VP
2. NP → Pro
   Pro → *I*
3. VP → Verb NP
   Verb → *prefer*
4. NP → Det Nom
   Det → *a*
5. Nom → Nom Noun
   Noun → *flight*
6. Nom → Noun
   Noun → *morning*

e.g. I prefer a morning flight.

Top-down parsing: Issues (1/2)

- If a goal can be written in several ways, there is a choice of which rule to apply
  - E.g. NP → Pro, NP → Det Nom
  - Search problem
    - Search methods: Depth-first, breadth-first, goal-ordering, etc
  - Need grammar-driven control for optimization
    - Otherwise, may waste lots of time in trying rules that are inconsistent with the input string
    - E.g. left recursive rules (e.g. Nom → Nom Noun)

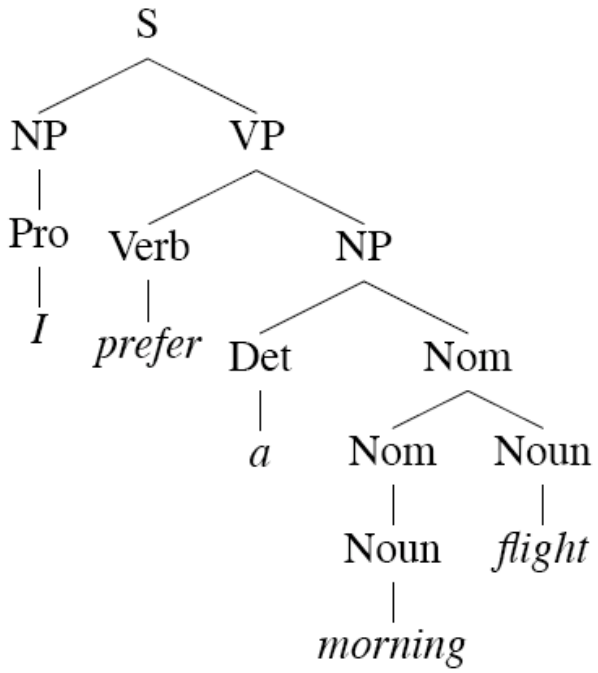
Top-down parsing: left recursive rules



e.g. Southeast Asia Public Interest Research Group

Top-down parsing: Issues (2/2)

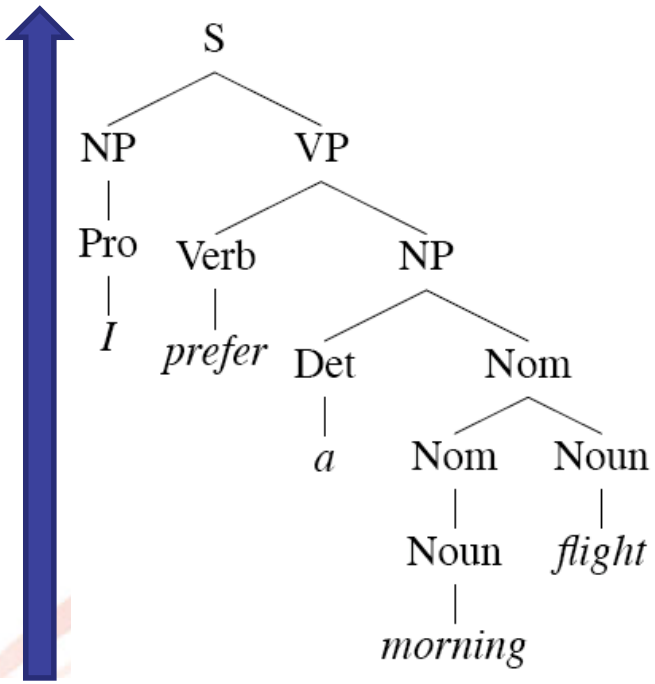
- In practice, part-of-speech tags are predetermined



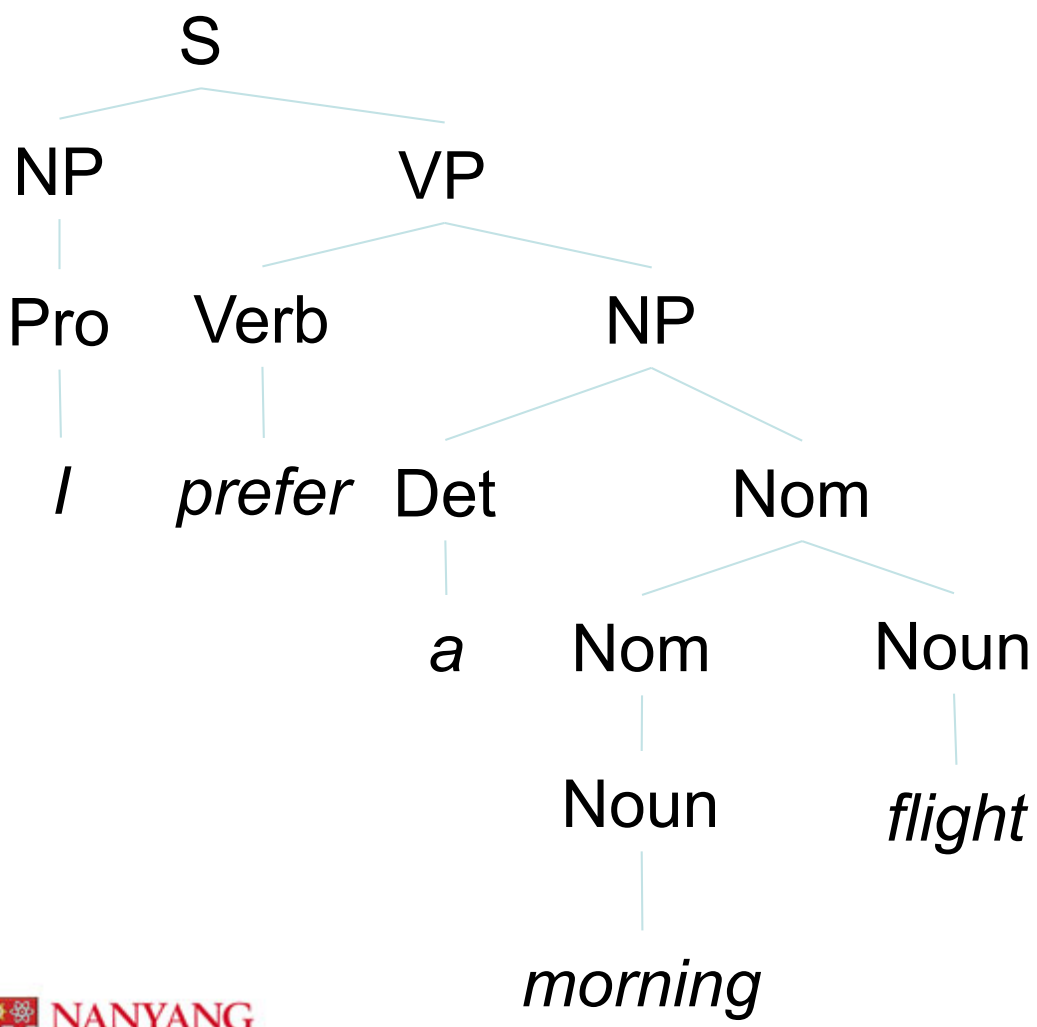
1. S → NP VP
2. NP → Pro
   Pro → *I*
3. VP → Verb NP
   Verb → *prefer*
4. NP → Det Nom
   Det → *a*
5. Nom → Nom Noun
   Noun → *flight*
6. Nom → Noun
   Noun → *morning*

Bottom-up parsing

- Data-directed
  - Start with words
- If a substring matches the RHS of a rule, replace the substring with the LHS
  - E.g. Nom → Noun (“morning”)
  - *E.g.* Nom → Nom Noun (“*morning flight*”)
- Parsing is finished when the whole string is replaced with a goal



Bottom-up approach: Example



6. S → NP VP

5. Pro → *I*
   NP → Pro

4. Verb → *prefer*
   VP → Verb NP

3. Det → *a*
   NP → Det Nom

2. Noun → *flight*
   Nom → Nom Noun

1. Noun → *morning*
   Nom → Noun

e.g. I prefer a morning flight.

Parsing strategies

Top-down parsing

- Goal-directed
  - Start from ‘S’
- Rewrite the goal(s) with the RHS of relevant rules
  - E.g. S → NP VP
- Parsing is finished when the rewriting generates the whole string

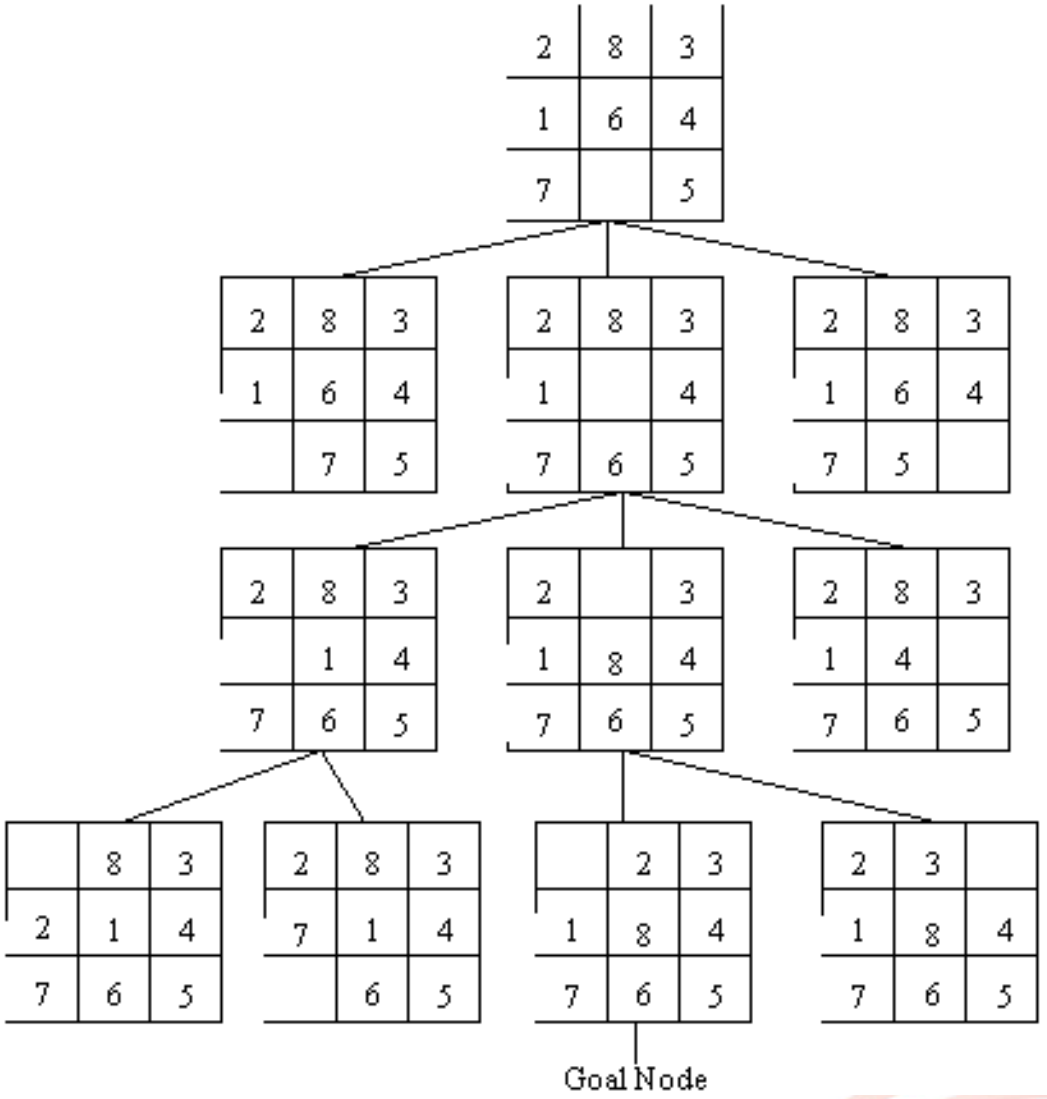
Bottom-up parsing

- Data-directed
  - Start with words
- If a substring matches the RHS of a rule, replace the substring with the LHS
  - E.g. Nom → Noun
  - *E.g. a morning*(Noun) *flight* ➔ *a* Nom *flight*
- Parsing is finished when the whole string is replaced with a goal

Top-down vs. Bottom-up parsing

- Waste lots of time in trying inconsistent rule applications
- Never explore subtrees that cannot find a place in some S-rooted tree
- Never suggest trees that are not grounded in the input string
- Trees that have no hope of leading to an S are generated

Search problem: example



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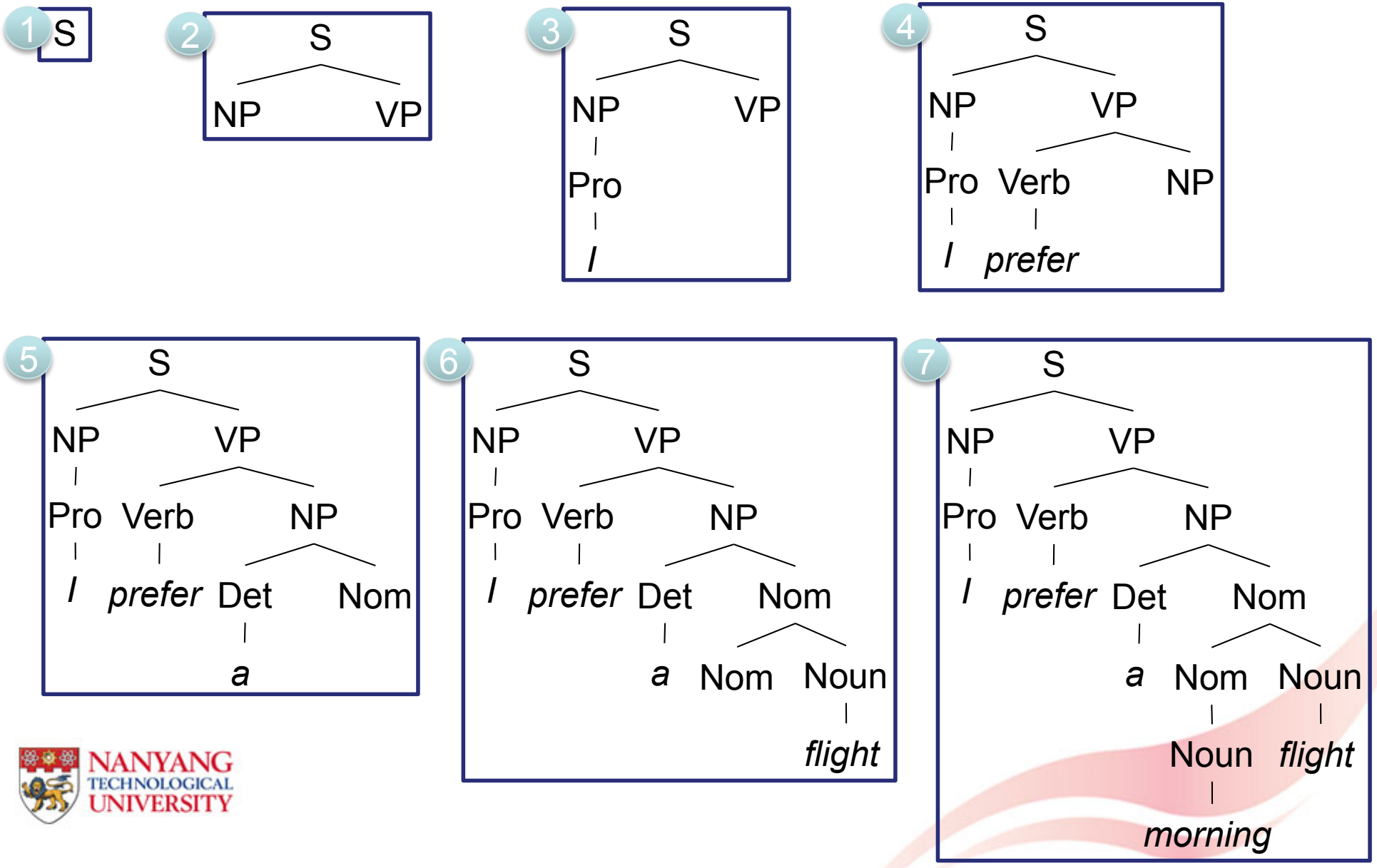
Parsing as search



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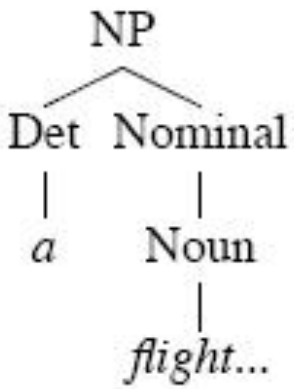
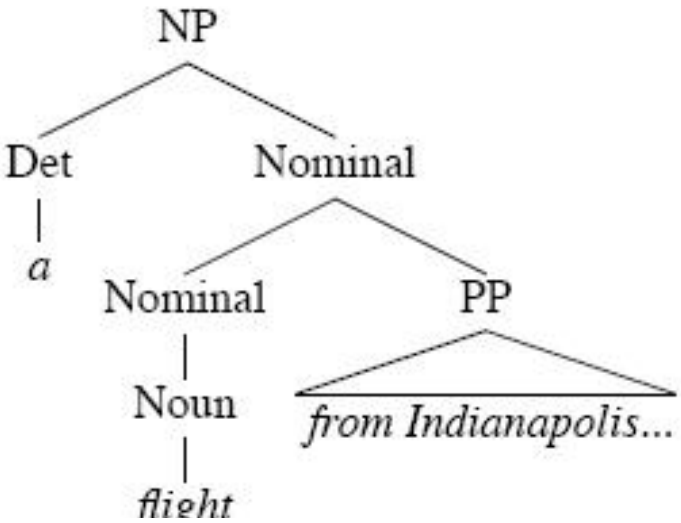
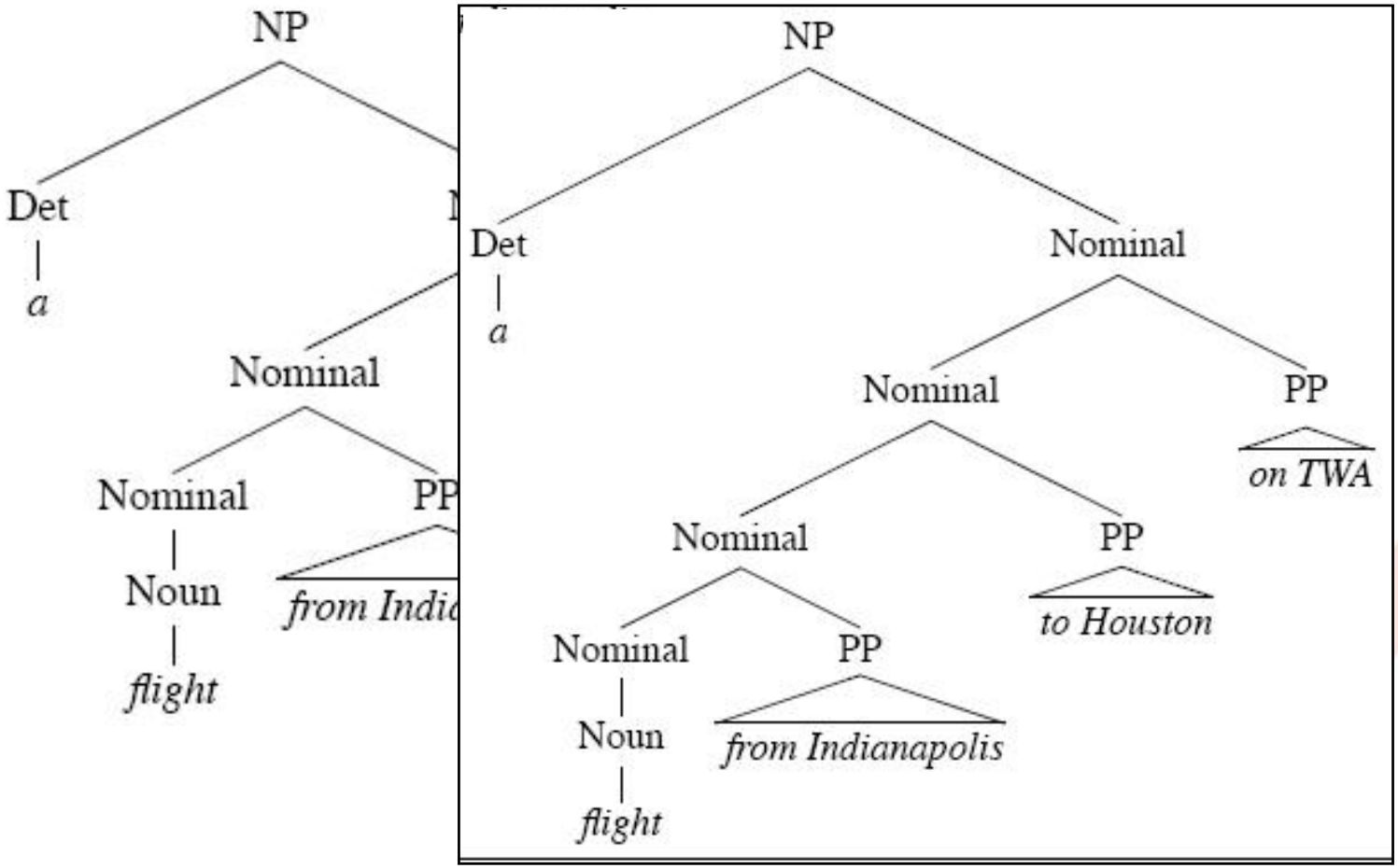
Repeated work in parsing-as-search





Top-down parsing for "a flight from Indianapolis to Houston on NWA" (Figure 13.7)



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State Space Search

- States represent pairings of partially processed inputs with partially constructed representations.
- Goals are inputs paired with completed representations that satisfy some criteria.
- As with most interesting problems the spaces are normally too large to exhaustively explore.
  - We need heuristics to guide the search
  - Criteria to trim the space
- Instead, use dynamic programming
  - Don't do the same work over and over

Dynamic programming parsing methods

- Parsing-as-search may have exponentially many parse states
- Dynamic programming solves the problem of doing repeated work
  - Other solution example
    - Memorization (remembering solved subproblems)
- Bottom-up approach: CKY parsing
  - Parse table
- Top-down approach: Earley parsing
  - Dotted rules

Exercise: Parse tree

- Draw the parse tree for the sentence “John gives a present to Mary” by using the L_1 grammar

$\mathscr{L}_1$ Grammar
$S \rightarrow NP\ VP$
$S \rightarrow Aux\ NP\ VP$
$S \rightarrow VP$
$NP \rightarrow Pronoun$
$NP \rightarrow Proper\text{-}Noun$
$NP \rightarrow Det\ Nominal$
$Nominal \rightarrow Noun$
$Nominal \rightarrow Nominal\ Noun$
$Nominal \rightarrow Nominal\ PP$
$VP \rightarrow Verb$
$VP \rightarrow Verb\ NP$
$VP \rightarrow Verb\ NP\ PP$
$VP \rightarrow Verb\ PP$
$VP \rightarrow VP\ PP$
$PP \rightarrow Preposition\ NP$

Parse table

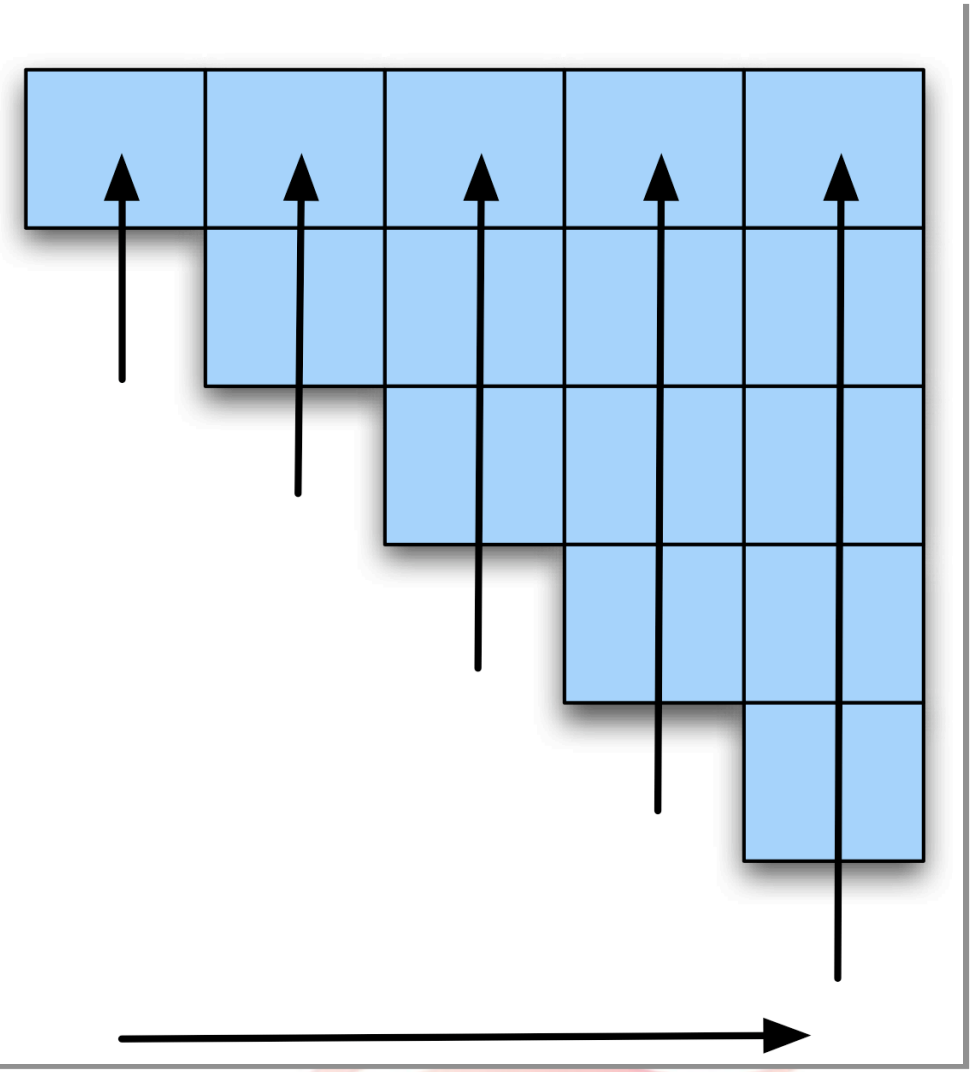
- Cell [i,j] contains the syntactic structures of the substring from the (*i+1*)th word to the *j* th word

	Book	the	flight	through	Houston
	0	1	2	3	4	5
0	S, VP, Verb Nominal, Noun [0,1]	[0,2]	S,VP [0,3]	[0,4]	S,VP [0,5]
1	Det [1,2]	NP [1,3]	[1,4]	NP [1,5]	
2	Nominal, Noun [2,3]	[2,4]	Nominal [2,5]		
3	Prep [3,4]	PP [3,5]			
4	NP, Proper-Noun [4,5]				

$\mathscr{L}_1$ Grammar	
$S \rightarrow NP\ VP$	$NP \rightarrow Pronoun$
$S \rightarrow Aux\ NP\ VP$	$NP \rightarrow Proper\text{-}Noun$
$S \rightarrow VP$	$NP \rightarrow Det\ Nominal$
$VP \rightarrow Verb\ PP$	$Nominal \rightarrow Noun$
$VP \rightarrow VP\ PP$	$Nominal \rightarrow Nominal\ Noun$
$PP \rightarrow Preposition\ NP$	$Nominal \rightarrow Nominal\ PP$
	$VP \rightarrow Verb$
	$VP \rightarrow Verb\ NP$
	$VP \rightarrow Verb\ NP\ PP$

Parse table: Parsing sequence

Book	*the*	*flight*	*through*	*Houston*
S, VP, Verb Nominal, Noun [0,1]	[0,2]	S,VP [0,3]	[0,4]	S,VP [0,5]
	Det [1,2]	NP [1,3]	[1,4]	NP [1,5]
		Nominal, Noun [2,3]	[2,4]	Nominal [2,5]
			Prep [3,4]	PP [3,5]
				NP, Proper-Noun [4,5]



Parse table:
A fast method of filling in each cell

Assume an RHS
has exactly two items

[$word_{i+1}$] [$word_{i+2}$ $word_{i+3}$ … $word_j$]

[i,i+1] [i+1,j]

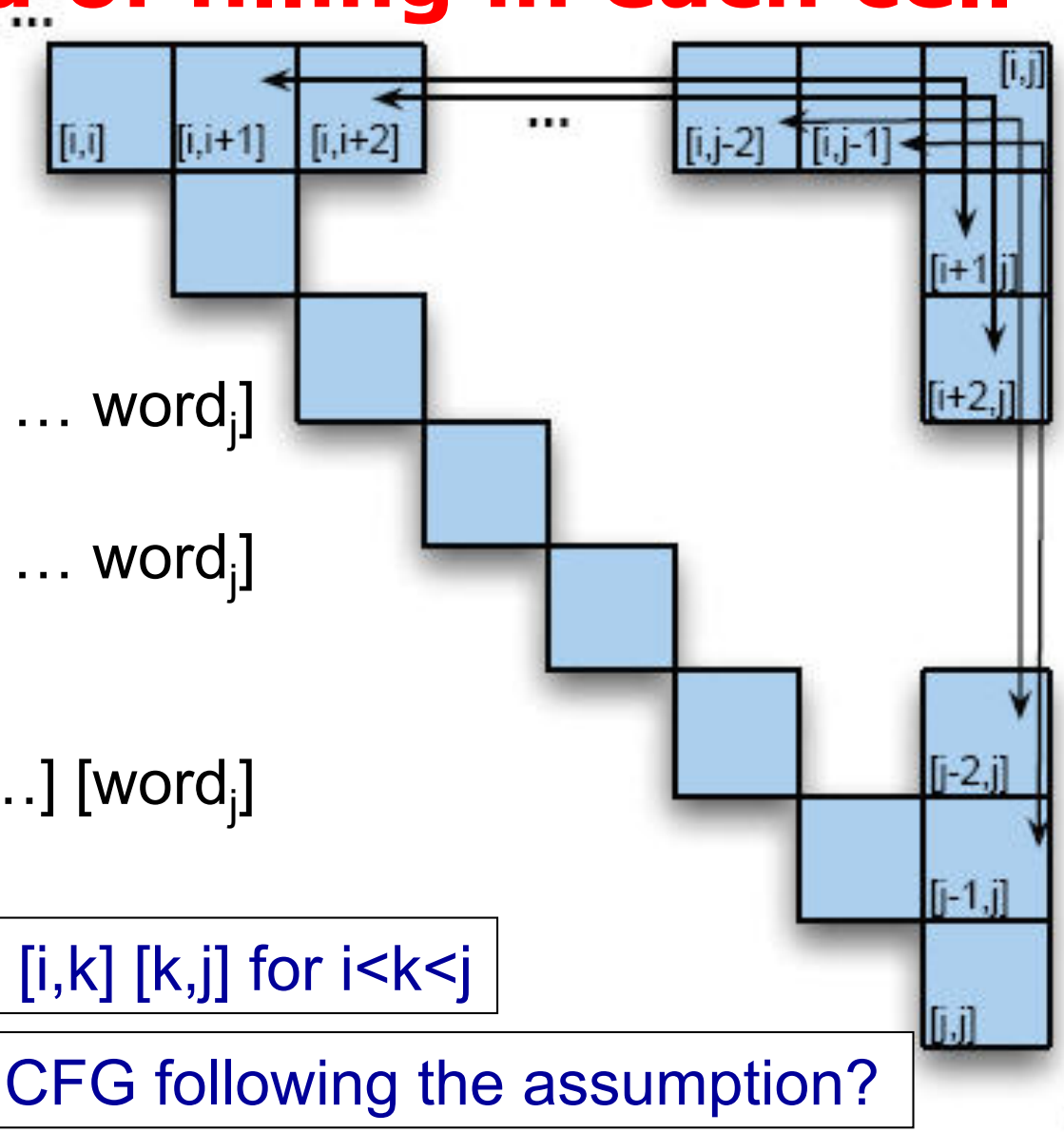
[$word_{i+1}$ $word_{i+2}$] [$word_{i+3}$ … $word_j$]

[i,i+2] [i+2,j]

…

[$word_{i+1}$ $word_{i+2}$ $word_{i+3}$ …] [$word_j$]

[i,j-1] [j-1,j]



[i,j] → [i,k] [k,j] for i<k<j

How can we create a CFG following the assumption?

CKY parsing

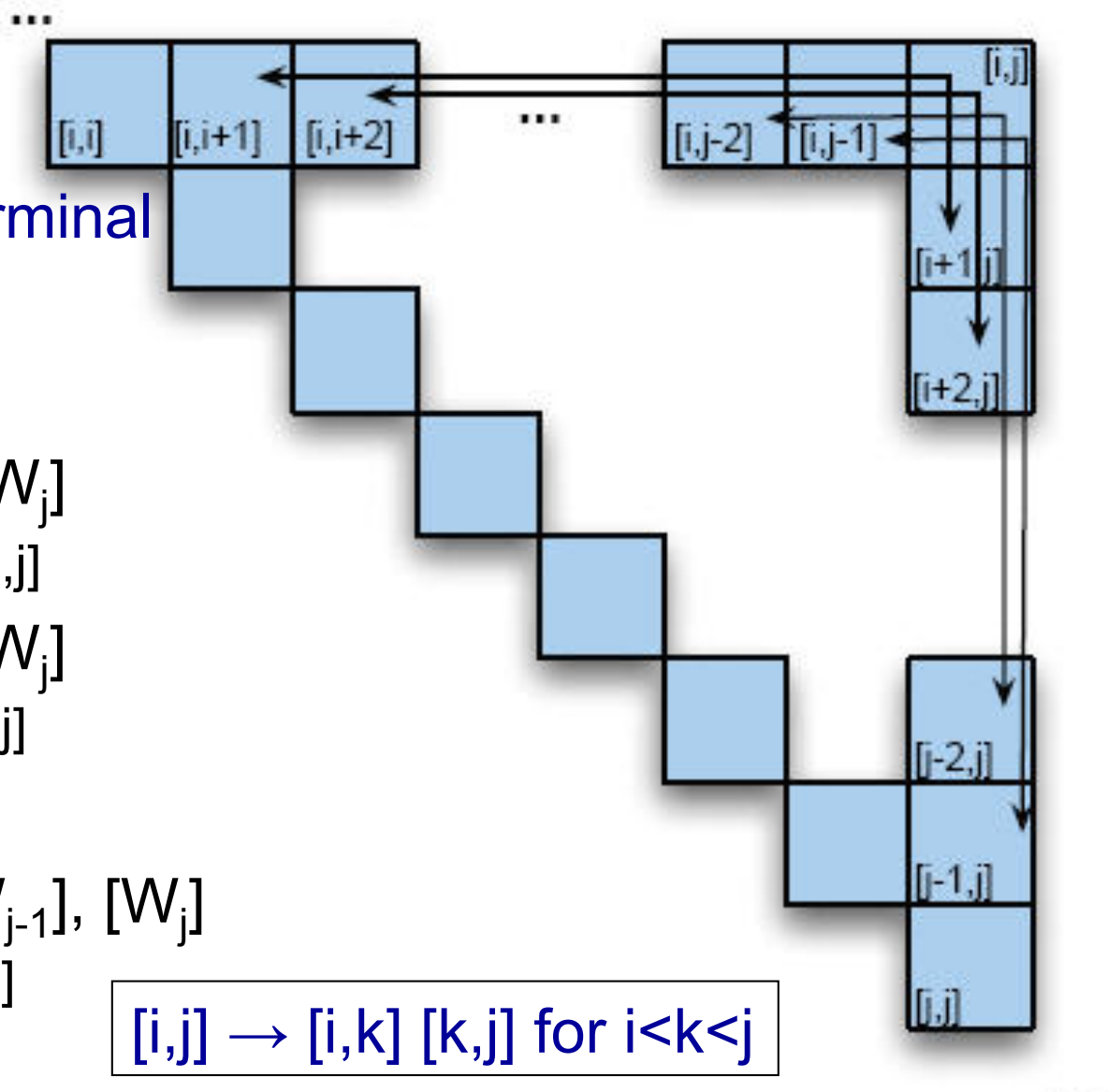
- Requirement
  - All rules should be in Chomsky normal form (CNF)
- CNF rules have the form of either
  - $A \rightarrow B\ C$
  - Or, $A \rightarrow w$ (w is a terminal)
  - RHS must have two non-terminals or one terminal
- Conversion to CNF
  - Read Section 13.4.1

CNF grammar: example

$\mathcal{L}_1$ Grammar	$\mathcal{L}_1$ in CNF
$S \rightarrow NP\ VP$	$S \rightarrow NP\ VP$
$S \rightarrow Aux\ NP\ VP$	$S \rightarrow X1\ VP$
	$X1 \rightarrow Aux\ NP$
$S \rightarrow VP$	$S \rightarrow book \mid include \mid prefer$
	$S \rightarrow Verb\ NP$
	$S \rightarrow X2\ PP$
	$S \rightarrow Verb\ PP$
	$S \rightarrow VP\ PP$
$NP \rightarrow Pronoun$	$NP \rightarrow I \mid she \mid me$
$NP \rightarrow Proper\text{-}Noun$	$NP \rightarrow TWA \mid Houston$
$NP \rightarrow Det\ Nominal$	$NP \rightarrow Det\ Nominal$
$Nominal \rightarrow Noun$	$Nominal \rightarrow book \mid flight \mid meal \mid money$
$Nominal \rightarrow Nominal\ Noun$	$Nominal \rightarrow Nominal\ Noun$
$Nominal \rightarrow Nominal\ PP$	$Nominal \rightarrow Nominal\ PP$
$VP \rightarrow Verb$	$VP \rightarrow book \mid include \mid prefer$
$VP \rightarrow Verb\ NP$	$VP \rightarrow Verb\ NP$
$VP \rightarrow Verb\ NP\ PP$	$VP \rightarrow X2\ PP$
	$X2 \rightarrow Verb\ NP$
$VP \rightarrow Verb\ PP$	$VP \rightarrow Verb\ PP$
$VP \rightarrow VP\ PP$	$VP \rightarrow VP\ PP$
$PP \rightarrow Preposition\ NP$	$PP \rightarrow Preposition\ NP$

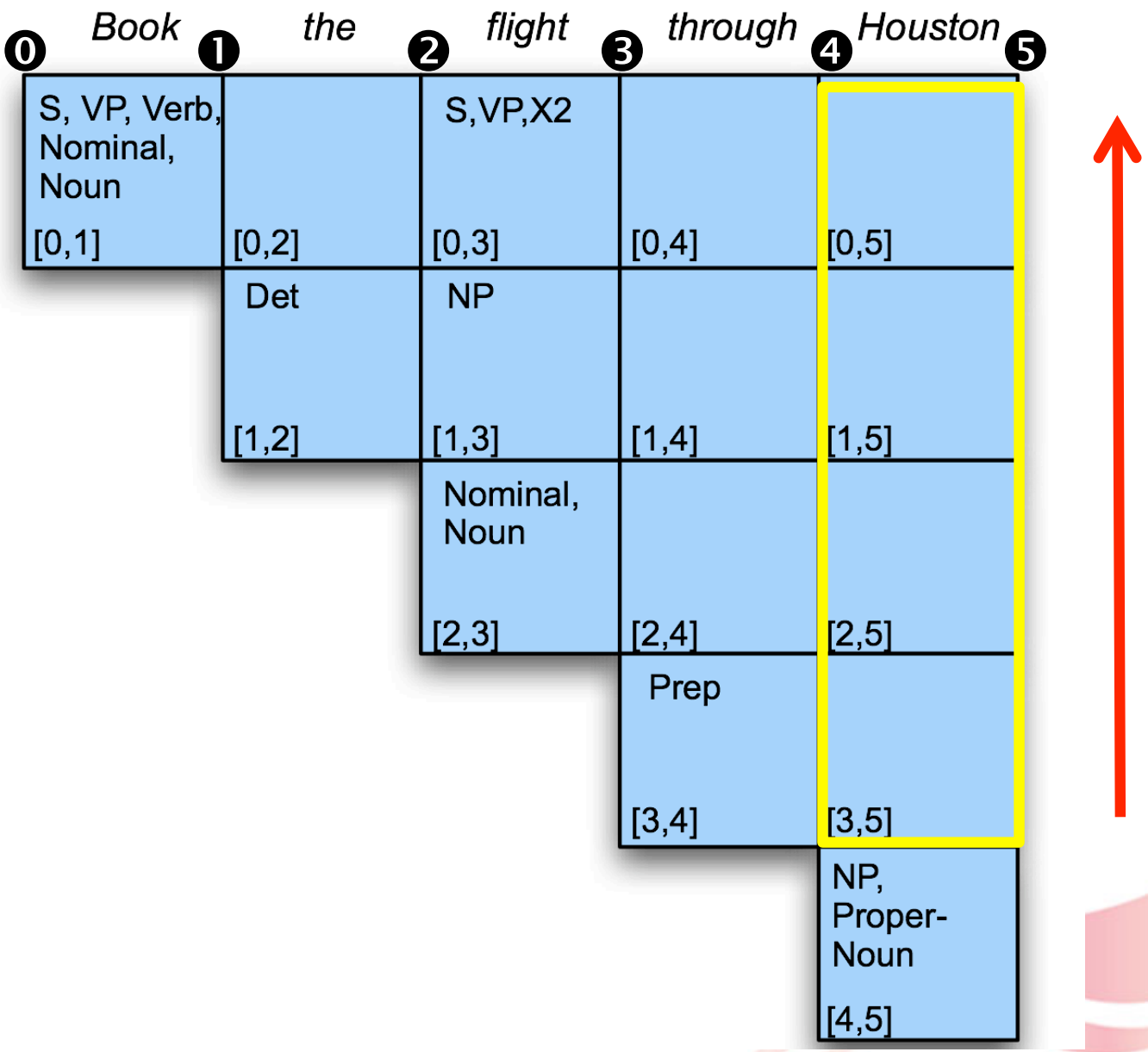
CKY parsing for [i,j] cell

- CNF rule for non-terminal
  - $A \rightarrow B\ C$
- $W_{i+1}, W_{i+2}, \ldots, W_j$
  - $[W_{i+1}], [W_{i+2}, \ldots, W_j]$
    - $[i,j] \rightarrow [i,i+1]\ \ [i+1,j]$
  - $[W_{i+1}, W_{i+2}], [\ldots, W_j]$
    - $[i,j] \rightarrow [i,i+2]\ \ [i+2,j]$
  - …
  - $[W_{i+1}, W_{i+2}, \ldots, W_{j-1}], [W_j]$
    - $[i,j] \rightarrow [i,j-1]\ \ [j-1,j]$

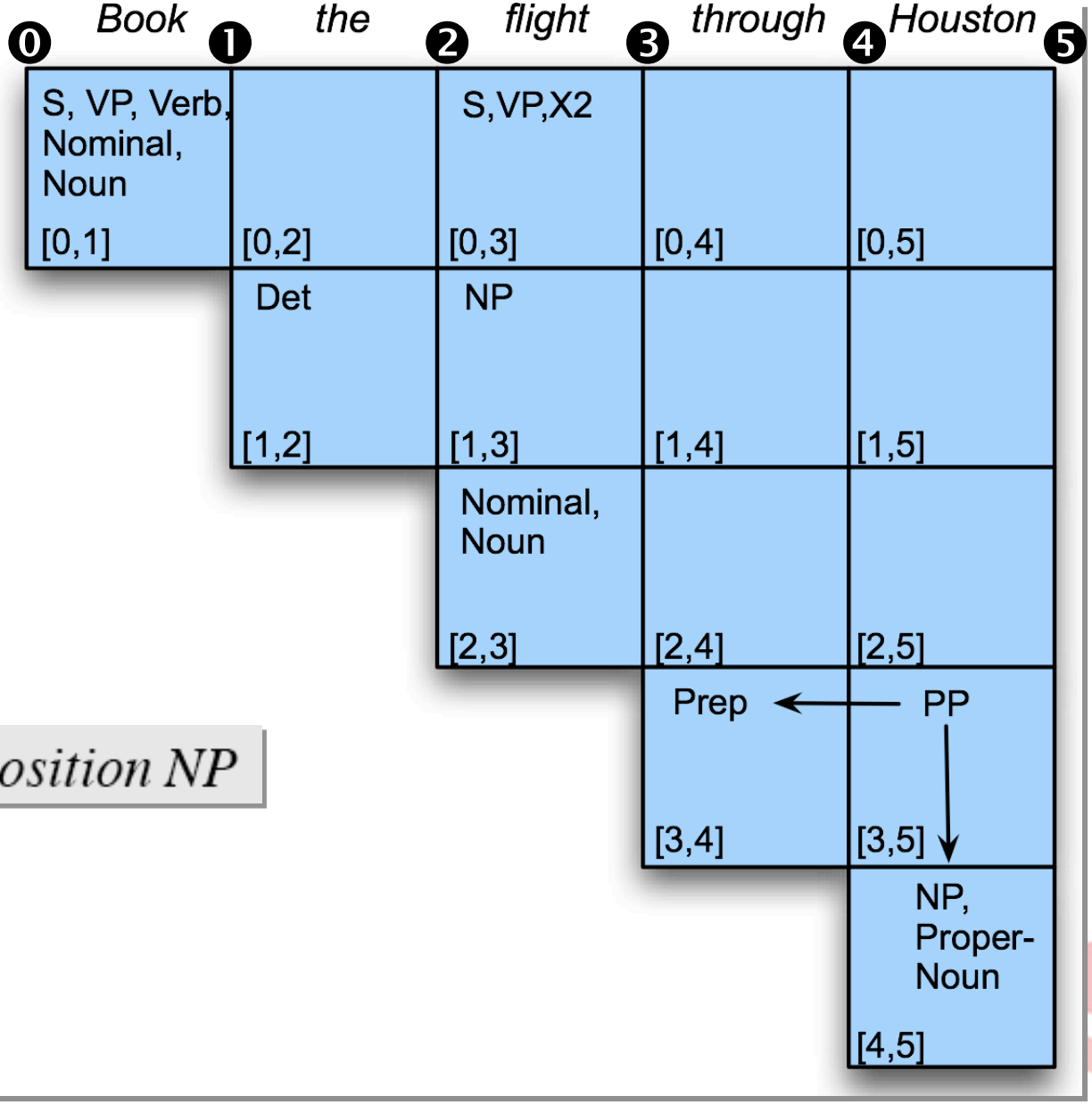


$[i,j] \rightarrow [i,k]\ [k,j]$ for $i<k<j$

Example : filling the 5th column



Example : filling the 5th column



$PP \rightarrow Preposition\ NP$

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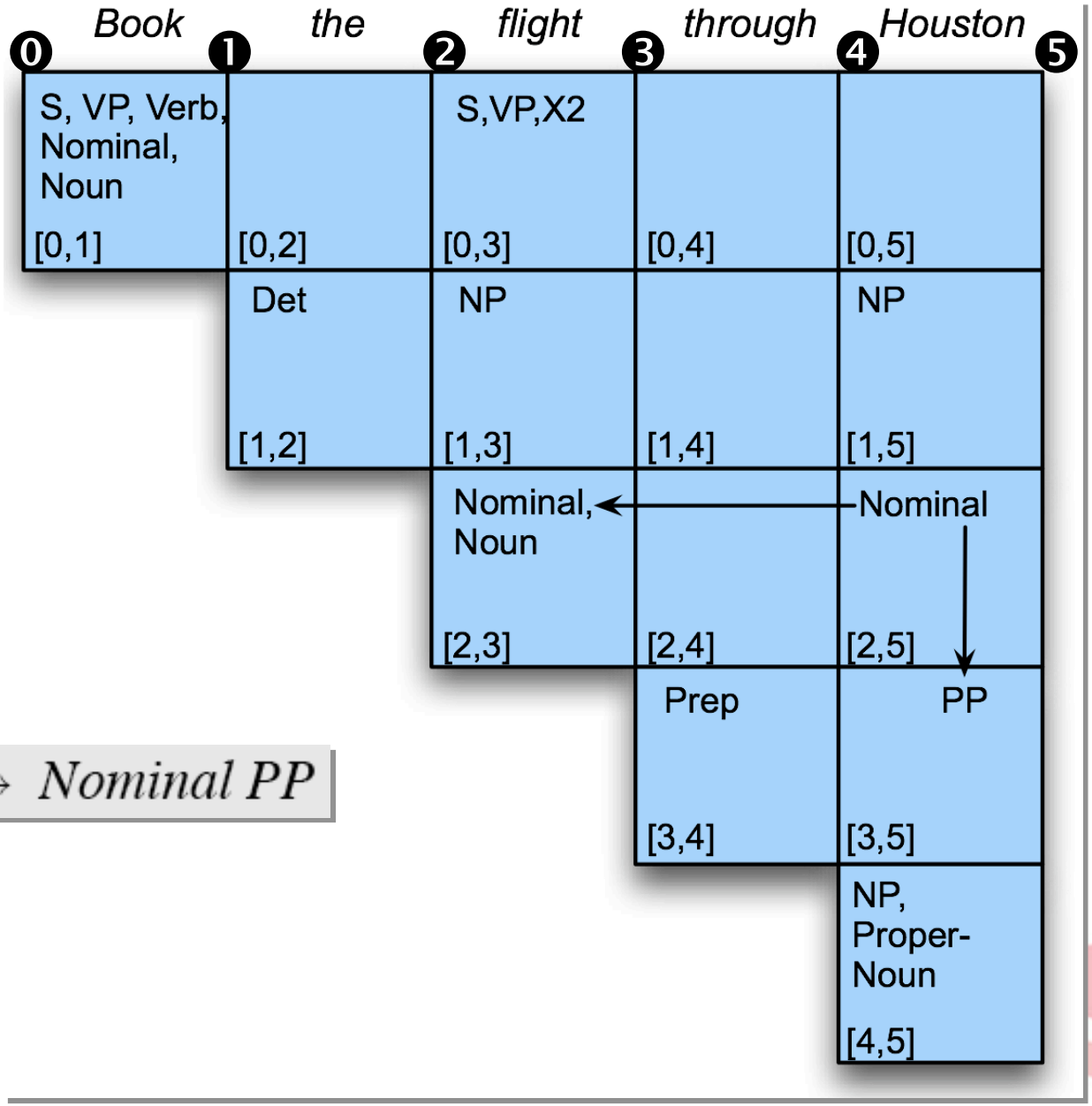
Example : filling the 5th column



$$Nominal \rightarrow Nominal\ PP$$

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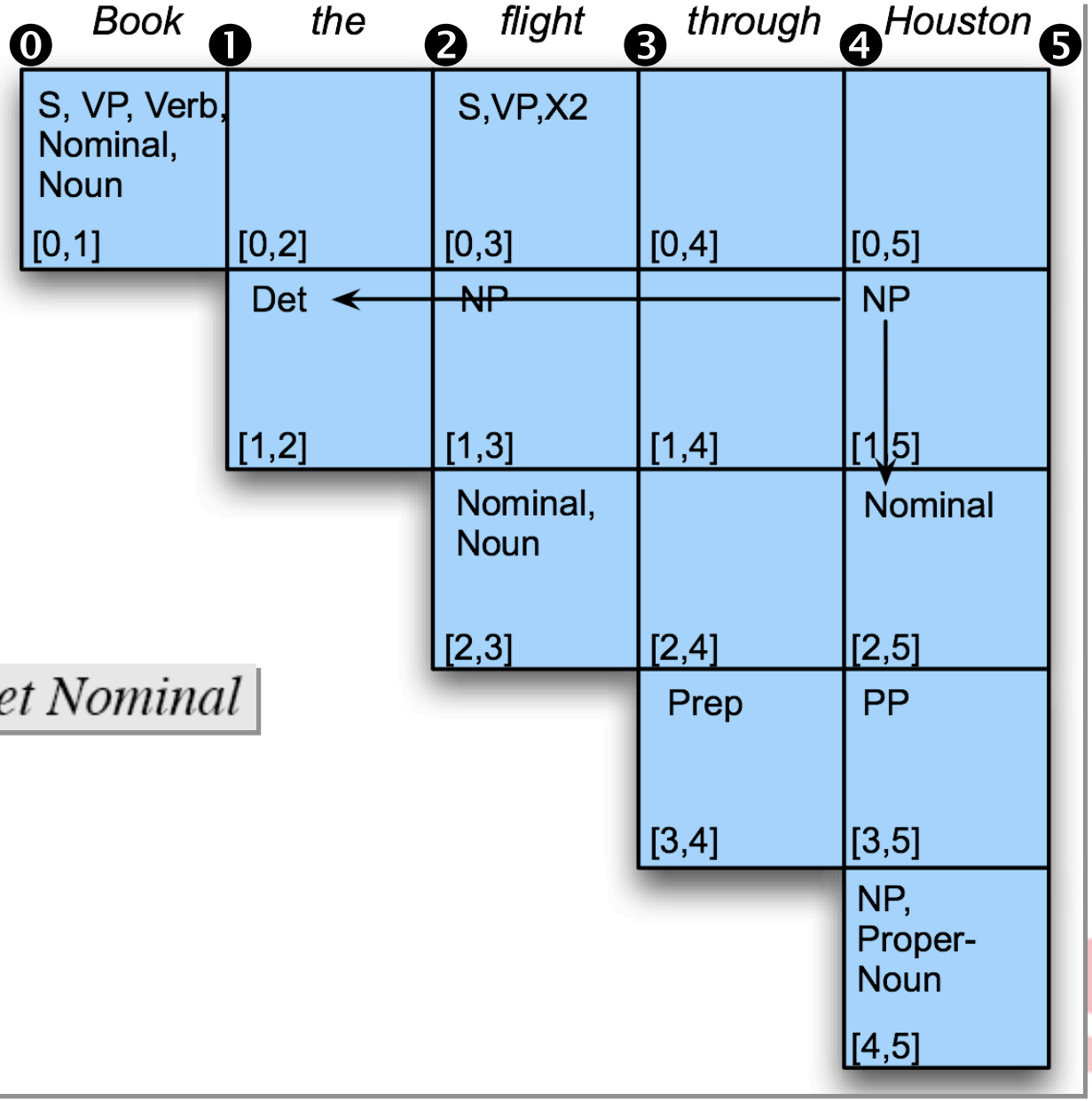
Example : filling the 5th column

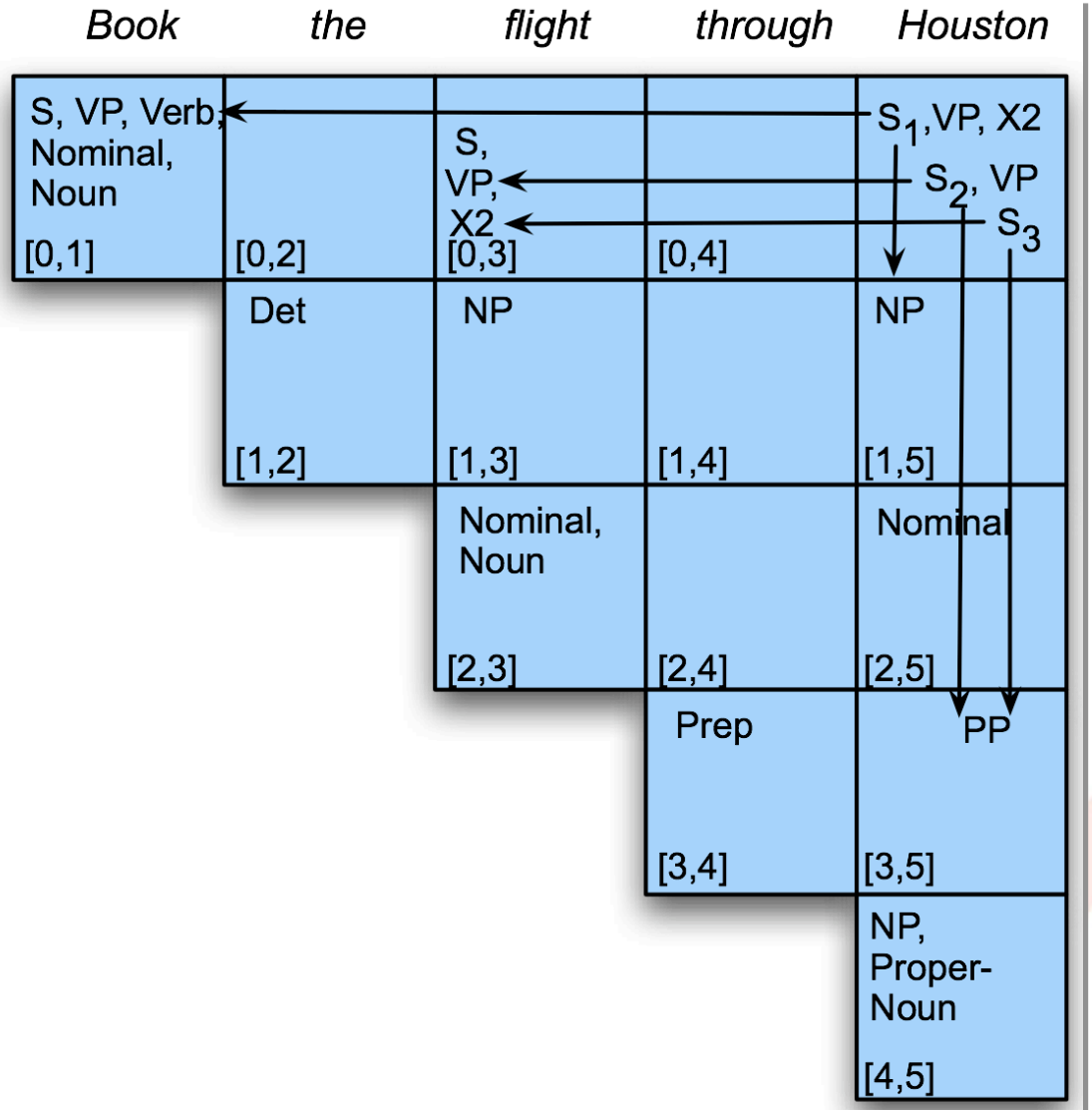


$$NP \rightarrow Det\ Nominal$$

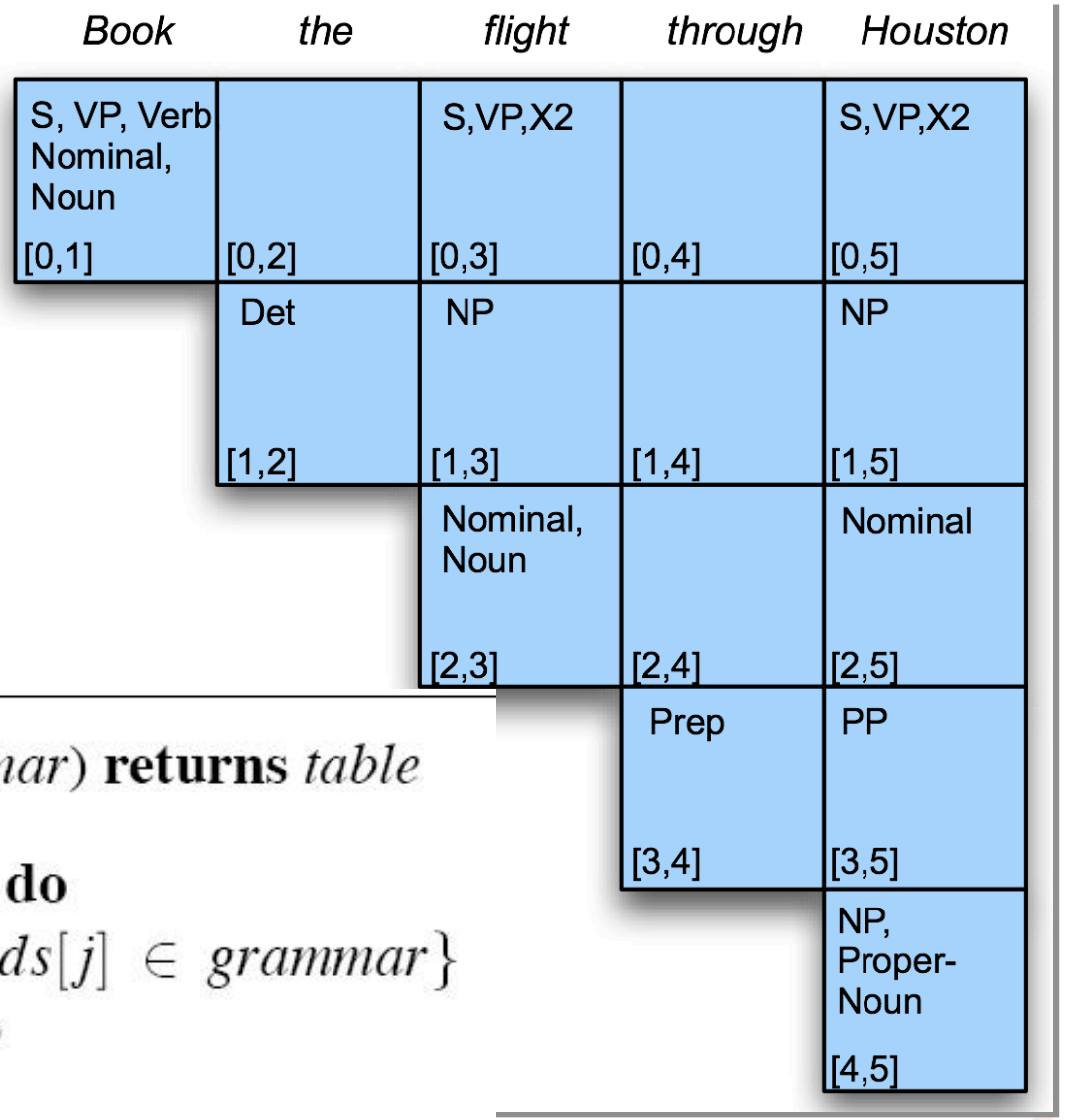
$S \rightarrow NP\ VP$
$S \rightarrow X1\ VP$
$X1 \rightarrow Aux\ NP$
$S \rightarrow book \mid include \mid prefer$
$S \rightarrow Verb\ NP$
$S \rightarrow X2\ PP$
$S \rightarrow Verb\ PP$
$S \rightarrow VP\ PP$
$NP \rightarrow I \mid she \mid me$
$NP \rightarrow TWA \mid Houston$
$NP \rightarrow Det\ Nominal$
$Nominal \rightarrow book \mid flight \mid meal \mid$
$Nominal \rightarrow Nominal\ Noun$
$Nominal \rightarrow Nominal\ PP$
$VP \rightarrow book \mid include \mid prefer$
$VP \rightarrow Verb\ NP$
$VP \rightarrow X2\ PP$
$X2 \rightarrow Verb\ NP$
$VP \rightarrow Verb\ PP$
$VP \rightarrow VP\ PP$
$PP \rightarrow Preposition\ NP$

Exercise: CKY parsing

Which rules are applied for [0,5]?



CKY algorithm



function CKY-PARSE(*words*, *grammar*) **returns** *table*

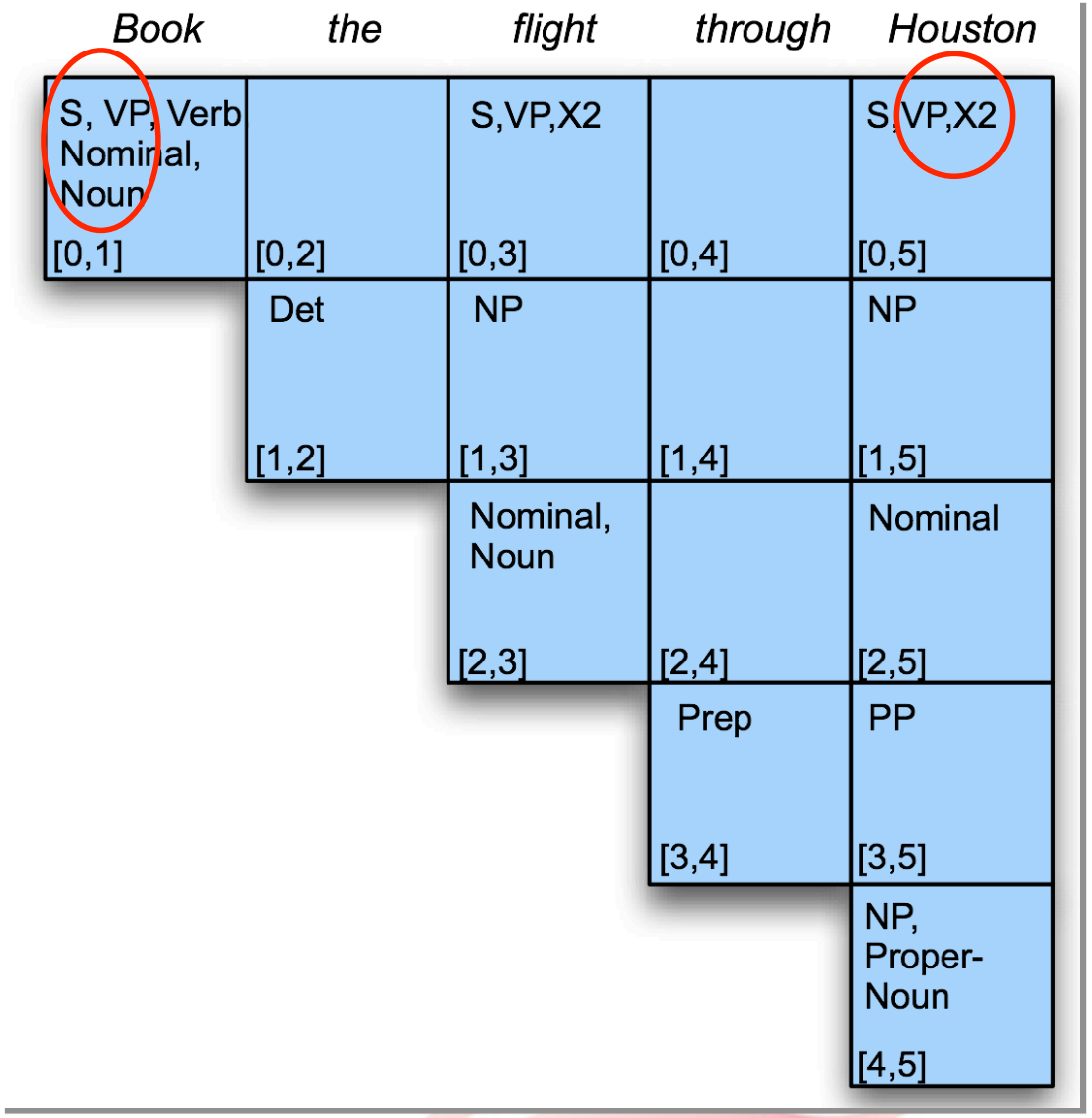
for $j \leftarrow$ **from** 1 **to** LENGTH(*words*) **do**
  $table[j-1, j] \leftarrow \{A \mid A \rightarrow words[j] \in grammar\}$
  for $i \leftarrow$ **from** $j-2$ **downto** 0 **do**
    for $k \leftarrow i+1$ **to** $j-1$ **do**
      $table[i,j] \leftarrow table[i,j] \cup$
        $\{A \mid A \rightarrow BC \in grammar,$
          $B \in table[i,k],$
          $C \in table[k,j]\}$

CKY parsing: summary

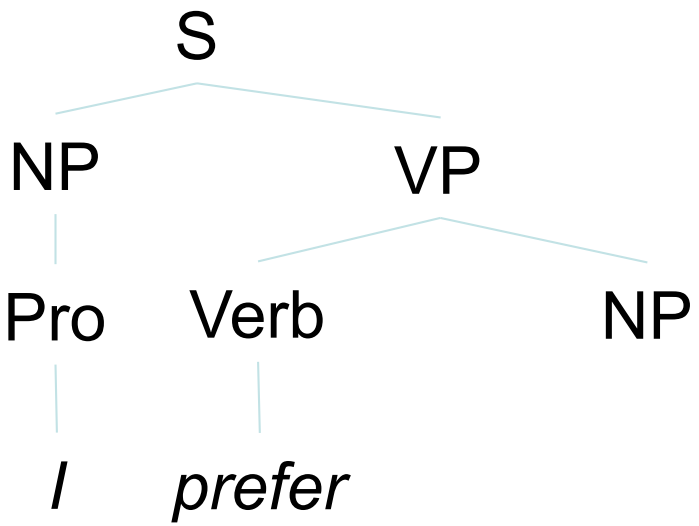
- Requirement: CNF grammar
  - Binarization: [i,j] → [i,k] [k,j] for i<k<j
- Bottom-up approach
  - Process from [j-1,j] to [0,j]
  - This assures us that whenever we're filling a cell, the parts needed to fill it are already in the table (to the left and below)
  - It's somewhat natural in that it processes the input, from left to right, a word at a time

CKY parsing: Issue

- Trees that have no hope of leading to an S are generated
  - To avoid this we can switch to a top-down control strategy
  - Or we can add some kind of filtering that blocks constituents where they cannot happen in a final analysis.



Top-down parsing: intermediate state example



1. S → NP VP

2. NP → Pro
   Pro → *I*

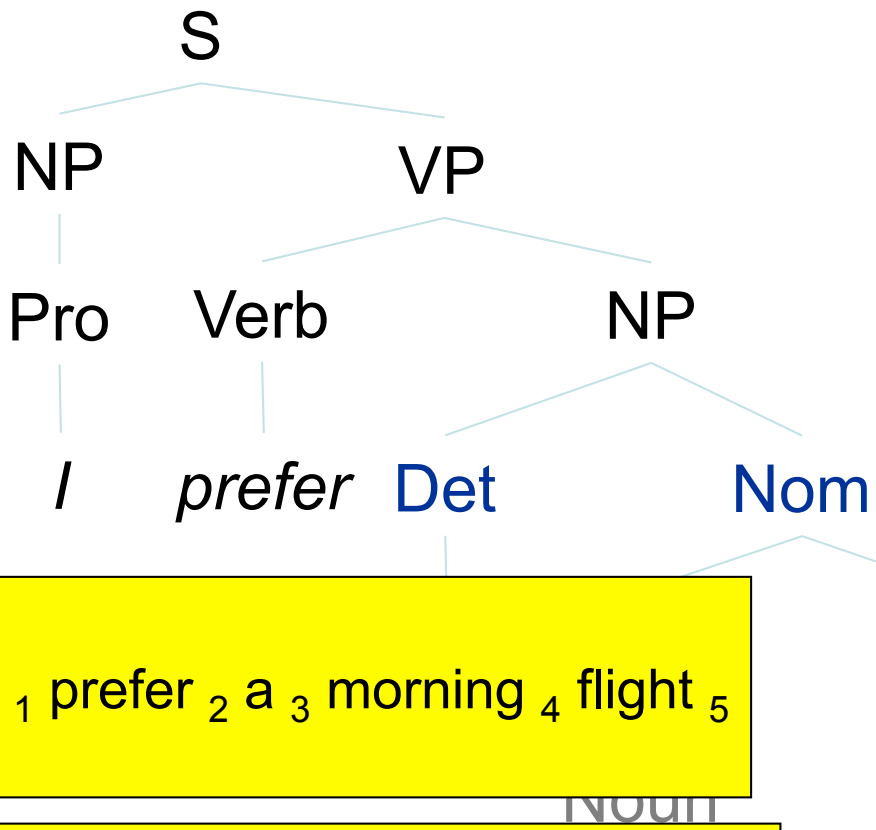
3. VP → Verb NP
   Verb → *prefer*

$_0$ I $_1$ prefer $_2$ a $_3$ morning $_4$ flight $_5$

Dotted rules

S → NP • VP [0,1]
VP → Verb • NP [1,2]

Top-down parsing: Next state



1. S → NP VP
2. NP → Pro
   Pro → *I*
3. VP → Verb NP
   Verb → *prefer*
4. NP → Det Nom
   Det → a

$_0$ I $_1$ prefer $_2$ a $_3$ morning $_4$ flight $_5$

S → NP • VP [0,1]
VP → Verb • NP [1,2]

S → NP • VP [0,1]
VP → Verb • NP [1,2]
NP → • Det Nom [2,2]

Earley algorithm: States

- NP → • Det Nom [2,2]
  - A Det is predicted at position 2
- VP → Verb • NP [1,2]
  - A VP is in progress; the Verb goes from 1 to 2
- VP → Verb NP • [1,4]
  - A VP has been found, starting at 1 and ending at 4
- S → α • [0,N]
  - Parsing is finished

Earley algorithm: How it works

1. *Predict* all the states you can upfront
2. Read a word
    1. Extend states based on matches
    2. Generate new predictions
    3. Repeat step 2
3. When you're out of words, look at the chart to see if you have a winner

Earley algorithm: Example (1)
e.g. $_0$ Book $_1$ that $_2$ flight $_3$

S0	$\gamma \rightarrow \bullet S$	[0,0]	Dummy start state
S1	$S \rightarrow \bullet NP\ VP$	[0,0]	Predictor
S2	$S \rightarrow \bullet Aux\ NP\ VP$	[0,0]	Predictor
S3	$S \rightarrow \bullet VP$	[0,0]	Predictor
S4	$NP \rightarrow \bullet Pronoun$	[0,0]	Predictor
S5	$NP \rightarrow \bullet Proper\text{-}Noun$	[0,0]	Predictor
S6	$NP \rightarrow \bullet Det\ Nominal$	[0,0]	Predictor
S7	$VP \rightarrow \bullet Verb$	[0,0]	Predictor
S8	$VP \rightarrow \bullet Verb\ NP$	[0,0]	Predictor
S9	$VP \rightarrow \bullet Verb\ NP\ PP$	[0,0]	Predictor
S10	$VP \rightarrow \bullet Verb\ PP$	[0,0]	Predictor
S11	$VP \rightarrow \bullet VP\ PP$	[0,0]	Predictor

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Note that given a grammar, these entries are the same for all inputs; they can be pre-loaded.

Earley algorithm: Example (2)
e.g. $_0$ Book $_1$ that $_2$ flight $_3$

S12	*Verb* → *book* •	[0,1]	Scanner
S13	*VP* → *Verb* •	[0,1]	Completer
S14	*VP* → *Verb* • *NP*	[0,1]	Completer
S15	*VP* → *Verb* • *NP PP*	[0,1]	Completer
S16	*VP* → *Verb* • *PP*	[0,1]	Completer
S17	*S* → *VP* •	[0,1]	Completer
S18	*VP* → *VP* • *PP*	[0,1]	Completer
S19	*NP* → • *Pronoun*	[1,1]	Predictor
S20	*NP* → • *Proper-Noun*	[1,1]	Predictor
S21	*NP* → • *Det Nominal*	[1,1]	Predictor
S22	*PP* → • *Prep NP*	[1,1]	Predictor

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Note that "Noun → book•" can be also scanned

Earley algorithm: Example (3)
e.g. $_0$ Book $_1$ that $_2$ flight $_3$

S23	*Det* → *that* •	[1,2]	Scanner
S24	*NP* → *Det* • *Nominal*	[1,2]	Completer
S25	*Nominal* → • *Noun*	[2,2]	Predictor
S26	*Nominal* → • *Nominal Noun*	[2,2]	Predictor
S27	*Nominal* → • *Nominal PP*	[2,2]	Predictor
S28	*Noun* → *flight* •	[2,3]	Scanner
S29	*Nominal* → *Noun* •	[2,3]	Completer
S30	*NP* → *Det Nominal* •	[1,3]	Completer
S31	*Nominal* → *Nominal* • *Noun*	[2,3]	Completer
S32	*Nominal* → *Nominal* • *PP*	[2,3]	Completer
S33	*VP* → *Verb NP* •	[0,3]	Completer
S34	*VP* → *Verb NP* • *PP*	[0,3]	Completer
S35	*PP* → • *Prep NP*	[3,3]	Predictor
S36	*S* → *VP* •	[0,3]	Completer
S37	*VP* → *VP* • *PP*	[0,3]	Completer

Exercise: Earley parsing

- Parse the sentence “I prefer a morning flight” with L1 grammar by using Earley parsing

$\mathscr{L}_1$ Grammar
$S \rightarrow NP\ VP$
$S \rightarrow Aux\ NP\ VP$
$S \rightarrow VP$
$NP \rightarrow Pronoun$
$NP \rightarrow Proper\text{-}Noun$
$NP \rightarrow Det\ Nominal$
$Nominal \rightarrow Noun$
$Nominal \rightarrow Nominal\ Noun$
$Nominal \rightarrow Nominal\ PP$
$VP \rightarrow Verb$
$VP \rightarrow Verb\ NP$
$VP \rightarrow Verb\ NP\ PP$
$VP \rightarrow Verb\ PP$
$VP \rightarrow VP\ PP$
$PP \rightarrow Preposition\ NP$

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Earley algorithm: Pseudo codes

- Read Section 13.4.2

Earley algorithm: Summary

- Top-down approach
  - Breadth-first search
  - State representation
    - Cf. the cells of parse tree in CKY algorithm: subtrees
- Waste lots of time in trying inconsistent rule applications

S31	$Nominal \rightarrow Nominal \bullet Noun$	[2,3]	Completer
S32	$Nominal \rightarrow Nominal \bullet PP$	[2,3]	Completer
S33	$VP \rightarrow Verb\ NP \bullet$	[0,3]	Completer
S34	$VP \rightarrow Verb\ NP \bullet PP$	[0,3]	Completer
S35	$PP \rightarrow \bullet Prep\ NP$	[3,3]	Predictor
S36	$S \rightarrow VP \bullet$	[0,3]	Completer
S37	$VP \rightarrow VP \bullet PP$	[0,3]	Completer

Top-down vs. Bottom-up parsing

- Waste lots of time in trying inconsistent rule applications
- Never explore subtrees that cannot find a place in some S-rooted tree
- Never suggest trees that are not grounded in the input string
- Trees that have no hope of leading to an S are generated

Soundness and completeness

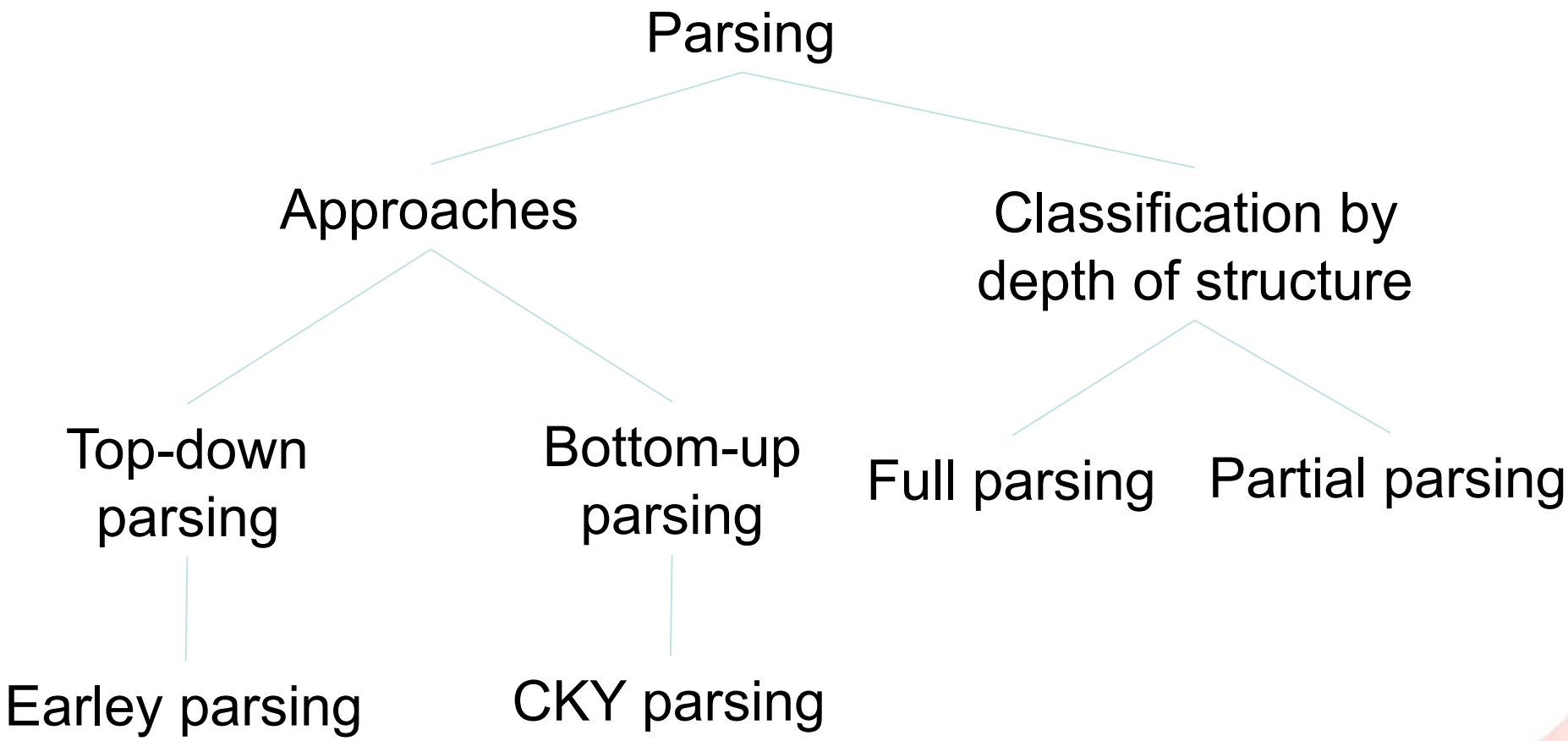
- A parser is *sound* if every parse result it returns is valid/ correct
- A parser *terminates* if it is guaranteed to not go off into an infinite loop
- A parser is *complete* if for any given grammar and string,
  - It is sound
  - It produces all valid parse results for the string, and
  - It terminates
- For practical purposes, we settle for sound and terminating, but incomplete parsers
  - E.g. *k*-best parse results

Full parsing vs. Partial parsing

- Identify the complete syntactic structure of a sentence
- Oftentimes, parsing is the most time-consuming part

- Identify parts of the syntactic structure of a sentence
- Not all applications require full syntactic structures
- Read Section 13.5

Summary


Parsing
Approaches
Classification by depth of structure
Top-down parsing
Bottom-up parsing
Full parsing
Partial parsing
Earley parsing
CKY parsing

Next class

Next class topics

- Statistical parsing
- Ambiguity in parsing
  - Attachment ambiguity

Reading assignments

- Sections 14.0-7
- Section 12.4
- (Advanced) Sections 14.8-10