AI6122 Text Data Management & Analysis

Topic: Parsing

Syntax

- **The way words are arranged together**
  - Implicit knowledge of your native language that you had mastered by the time you were young without explicit instruction
  - Not the kind of stuff you were later taught in “grammar” school

- Why should we care?
  - Syntax is the key concept for many NLP tasks
    - E.g. information extraction, grammar checking
  - An **approximation** would be still useful

Key notions

- Constituency
  - Groups of words that behave as **a single unit** or **phrase**
  - E.g., a few words form a noun phrase
- Grammatical relations
  - Syntactic relations between constituents
  - E.g., Subject – verb, verb – object
- Subcategorization
  - Certain kinds of relation between words and phrases
    - transitive words, which can take a direct object
    - intransitive words which cannot take a direct object

Constituent

- Groups of words that behave as a single unit or phrase
  - Can all appear in similar syntactic environments

- Example: Noun phrases (NPs) can occur before verbs
  - Three example sentences starting with NPs
    - <u>three parties from Brooklyn </u>*arrive* …
    - <u>a high-class spot such as Mindy's </u>*attracts* …
    - <u>the Broadway coppers </u>*love* …

  - While the whole noun phrase can occur before a verb, it is not true of each of the individual words that make up a noun phrase

Constituent

- Evidence for constituency
  - Stick together through pre-/post-posed constructions (example using a prepositional phrase)
    - On September seventeenth, I'd like to fly from Atlanta to Denver.
    - I'd like to fly on September seventeenth from Atlanta to Denver.
    - I'd like to fly from Atlanta to Denver on September seventeenth.
  - Individual words making of the phrase cannot be placed differently.
    - *On, I'd like to fly from Atlanta to Denver September seventeenth.
- Non-standard constructions (or constituents)
  - I gave John a watch and Mary a doll.
  - *I gave John a watch Mary and a doll.

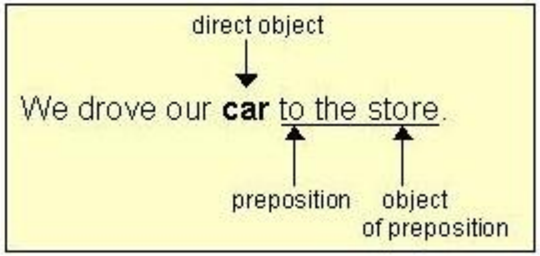
For your information only (details in textbook)

- Noun phrase (NP), verb phrase (VP), prepositional phrase (PP), adjective phrase

- Declarative, imperative, clause
  - Declarative sentences have a subject noun phrase followed by a verb phrase. “I prefer a morning flight”
  - Imperative sentences begin with a verb and have no subject. “Show me the code”.
- Determiner, nominal, quantifier
  - Noun phrases can begin with determiners or quantifier. “a bus stop” “a non-stop flight”
- Auxiliaries, passive, perfect, progressive
  - Auxiliaries include modal verb can could shall, perfect auxiliary have, progressive auxiliary be and passive auxiliary be
- Coordination, conjunction
  - A coordinate noun phrase can consist of two noun phrases by a conjunction: “course code and course title”

Grammatical relations

- Syntactic relations **between constituents**
  - Subject-verb: I love him.
  - Verb-object: I love him.
  - Verb-PrepositionalPhrase: I study at the library.
  - Noun-PrepositionalPhrase: The history of Singapore
  - Preposition-object



https://webapps.towson.edu/ows/prepositions.htm

Verb phrases (VPs): Sample patterns

- Verb
  - disappear
  - *prefer

- Verb Object
  - prefer a morning flight
  - *disappear a morning flight

- Verb IObject DObject (indirect object, direct object)
  - give John a watch
  - *prefer John a watch

- Verb Object PrepositionalPhrase(PP)
  - leave Boston in the morning

- Verb PP
  - leave on Thursday

Subcategorization

- ‘Subcategories’ of different types of verbs, by the constituents complement them

– Verb	“disappear”
– Verb NP	“prefer a morning flight”
– Verb NP NP	“give John a watch”
– Verb NP PP	“leave Boston in the morning”
– Verb PP	“leave on Thursday”

- Subcategorization frame
  - A possible set of complements for a verb
    - e.g. ‘give’: {}, {NP}, {NP, NP}, {NP, PPto}, {PP}
  - Verb: function, complements: arguments
    - e.g. def buy(Person: buyer, Thing: product)

Syntactic structure

- Why do we learn about syntax in NLP course?
  - To identify and understand the syntactic structures of sentences

- **Parse tree**
  - Structural representation of grammatical relations expressed in a string

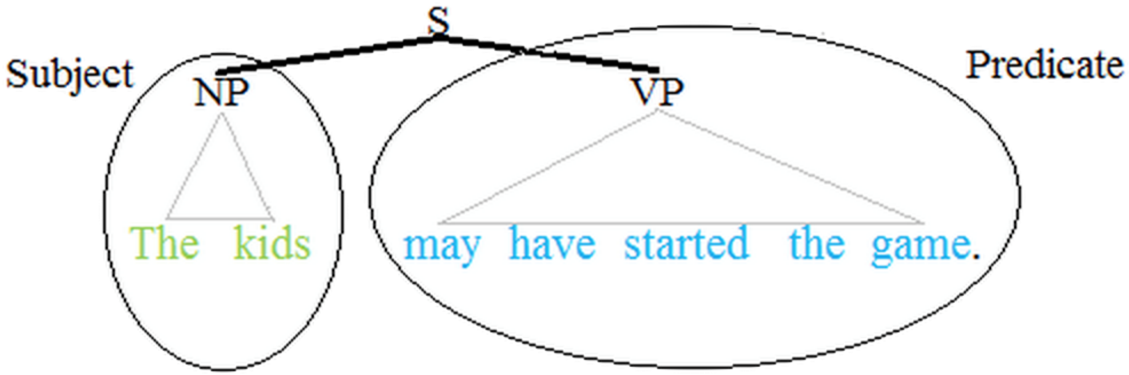
- Representations
  - Phrase structure
  - Dependency structure
  - Predicate-argument structure

Syntactic ≠ Semantic

- iPhone7 is nice but expensive
- iPhone7 is expensive but nice

Phrase Structure

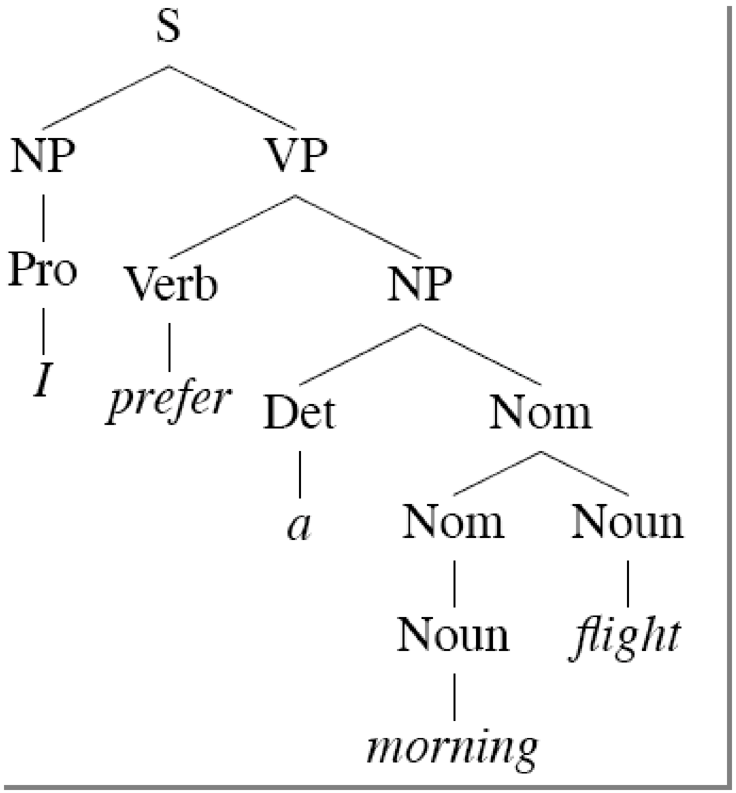
- Phrase structure rules are used to break down a natural language sentence into its constituent parts (also known as syntactic categories), including both lexical categories (parts of speech) and phrasal categories
  - Split a sentence (S) into subject (NP) and predicate (VP)
  - Split subject and predicate into smaller parts
  - Continue until terminal nodes are reached



Phrase Structure

- Organizes words into nested constituents
  - Example sentence: “I prefer a morning flight”

```
(S
 (NP (Pro I))
 (VP (Verb prefer)
  (NP (Det a)
   (Nom
    (Nom (Noun morning))
    (Noun flight)))))
```



Nominal: (i) noun phrase without determiner; and
(ii) the noun that modifies the head noun in a noun phrase.

Exercise: Phrase structure

- Give the phrase structures of the two sentences:
  - (S1) John gives a present to Mary.
  - (S2) John gives Mary a present.

- POS tags:
  - E.g. ProperNoun: John, Mary
  - E.g. Verb, Det, Noun, Prep

- Example syntactic tags
  - E.g. S, NP, VP, PP_{XX}

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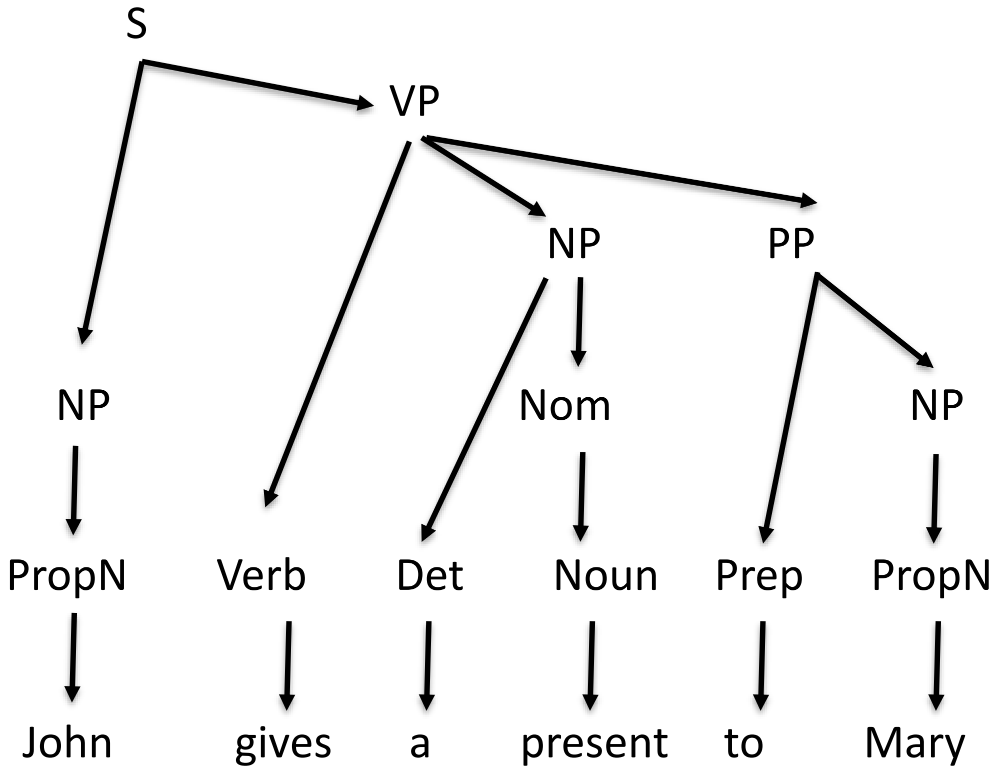
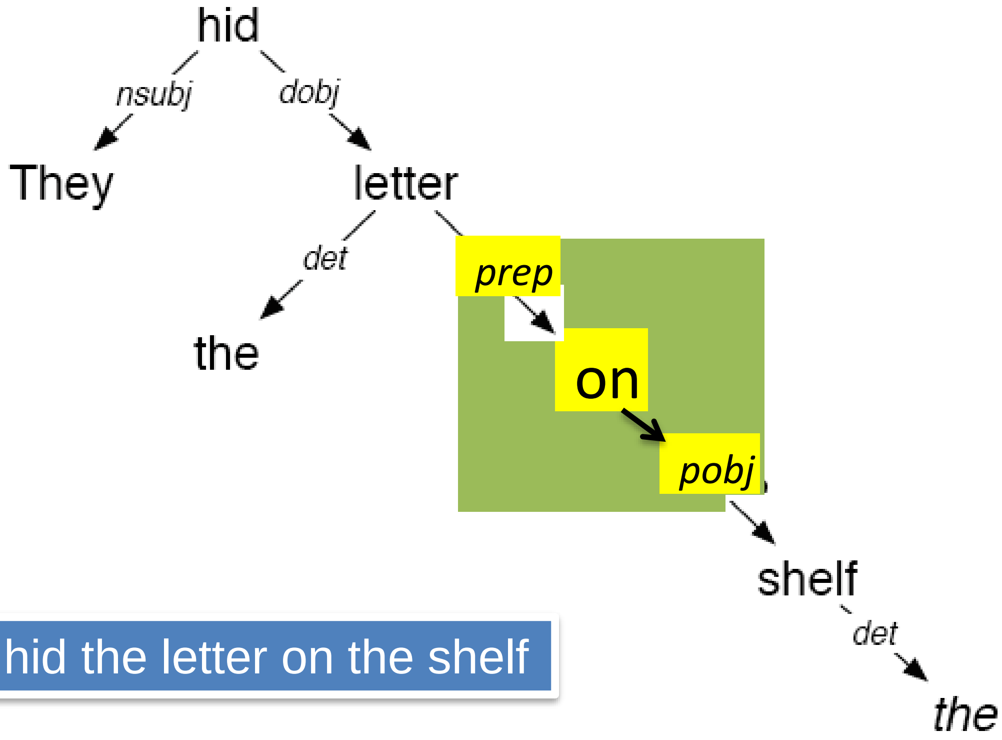


Dependency structure

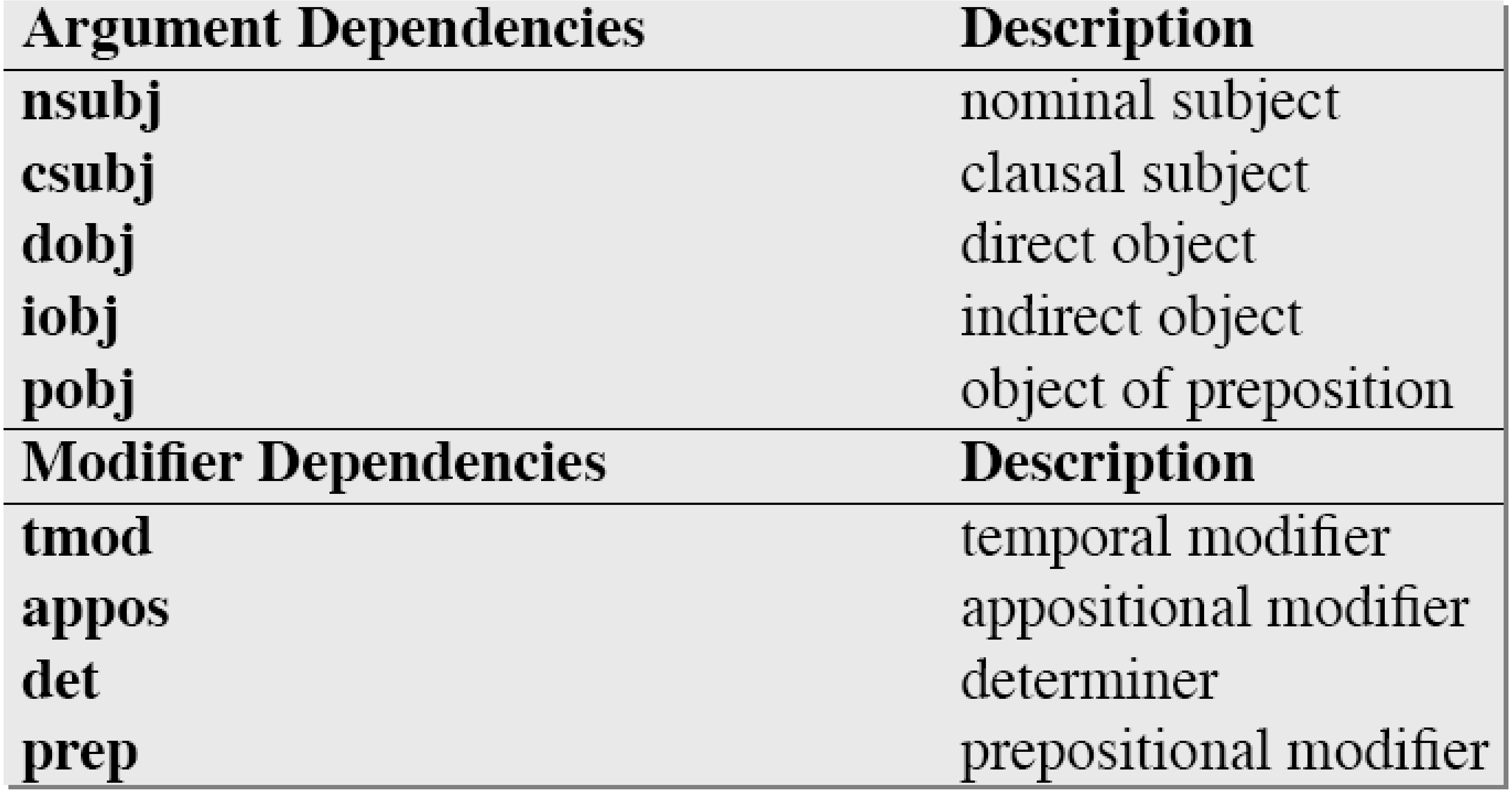
- Represents grammatical (dependency) relations between pairs of words: head, dependent

- Head: Grammatically most important word in a phrase
  - Verb of VP
  - Noun of NP
  - Prep of PP
  - Adj of AdjP
  - …



They hid the letter on the shelf

Dependency Relations

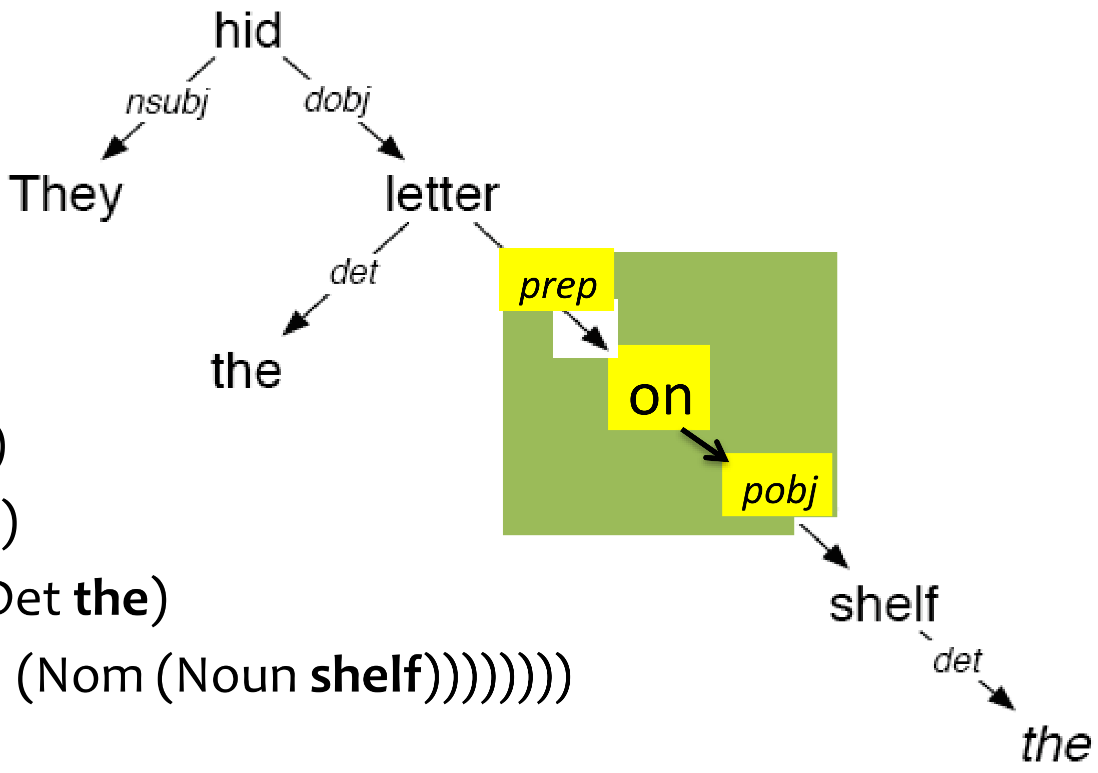


Argument Dependencies	Description
nsubj	nominal subject
csubj	clausal subject
dobj	direct object
iobj	indirect object
pobj	object of preposition
Modifier Dependencies	**Description**
tmod	temporal modifier
appos	appositional modifier
det	determiner
prep	prepositional modifier

http://universaldependencies.org/u/dep/index.html

Phrase structure vs. Dependency structure

(S
  (NP (Pro **They**))
  (VP
    (Verb **hid**)
    (NP (Det **the**)
      (Nom (Noun **letter**)
        (PP (Prep **on**)
          (NP (Det **the**)
            (Nom (Noun **shelf**))))))))

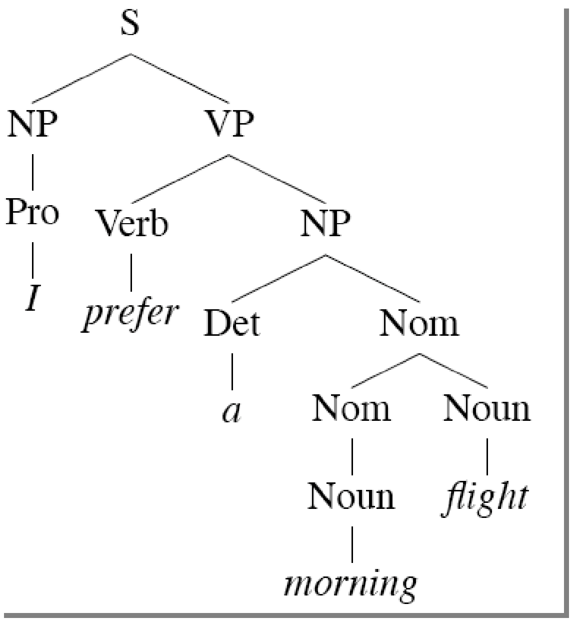


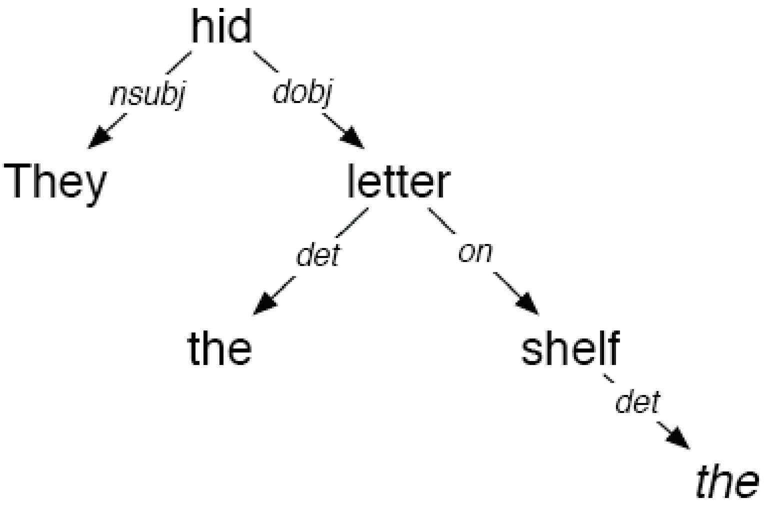
They hid the letter on the shelf

Phrase vs. dependency structure

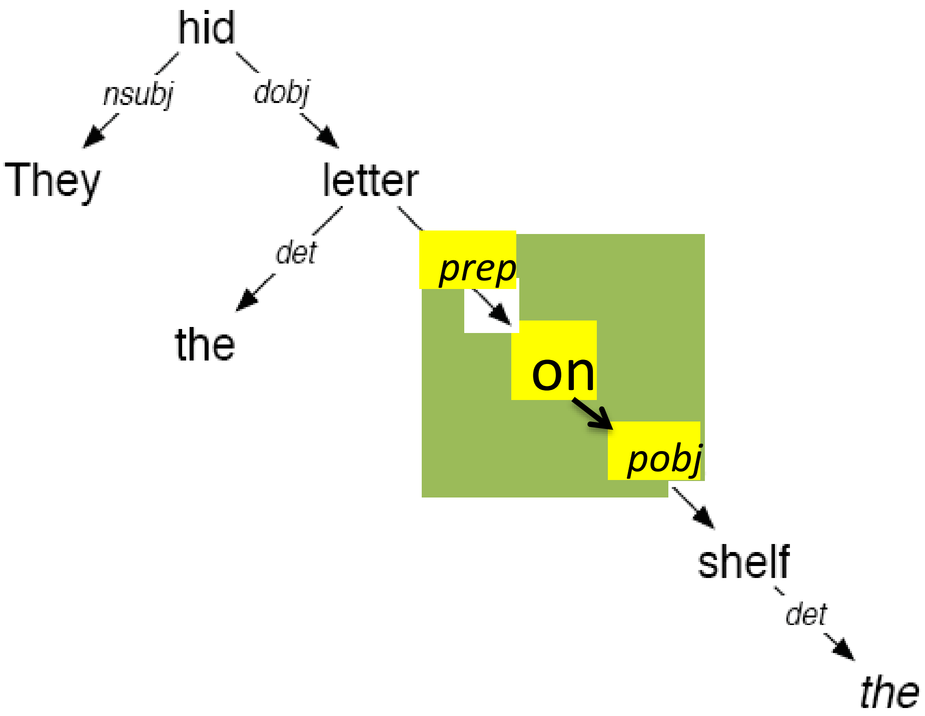
- Constituents are specified
- Grammatical relations are implied
  - Can be deduced from phrase structure

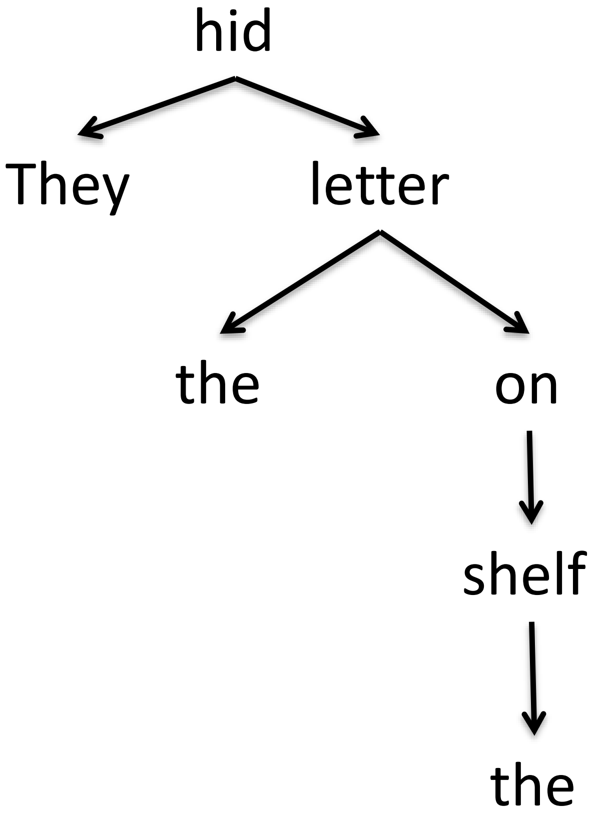
- Grammatical relations are specified
- A subtree corresponds to a constituent
  - Syntactic tag is implied by the root of subtree



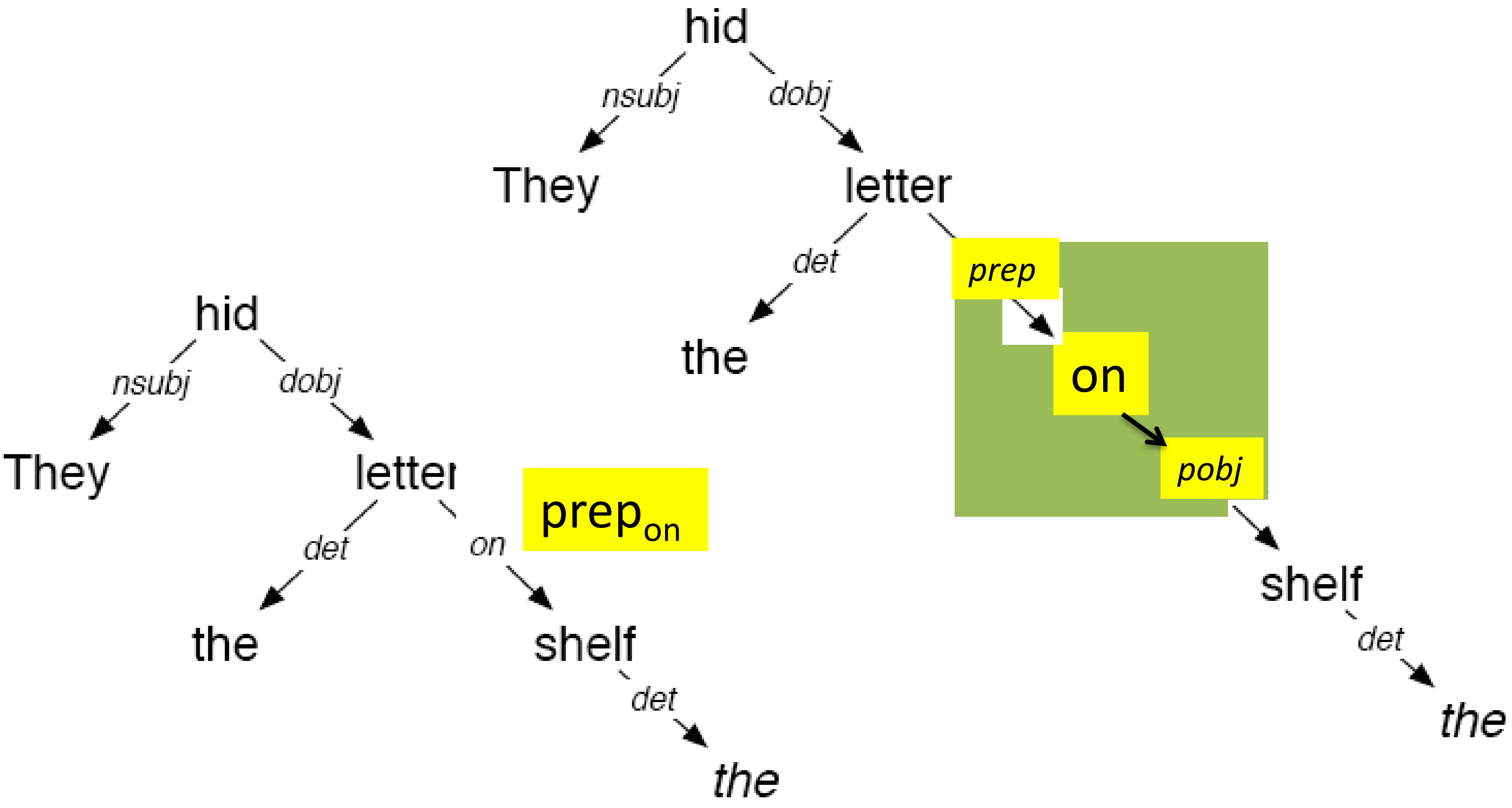


Typed dependency vs. untyped dependency





Typed dependency vs. Collapsed typed dependency



Preposition word followed by its object

Exercise: Dependency structure

- Give the dependency structures of the two sentences:
  - (S1) John gives a present to Mary.
  - (S2) John gives Mary a present.

- Example dependency relations
  - E.g. nsubj, iobj, dobj, det, prep$_{XX}$

Exercise: Dependency structure

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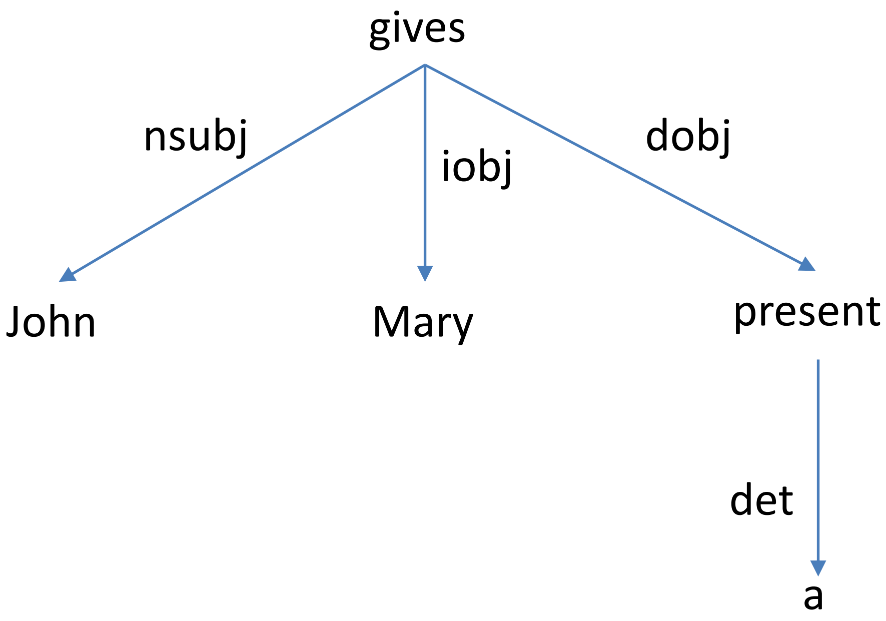


Predicate-argument structure

- Review: Subcategorization frame
  - Verb: function/predicate, complements: arguments

- Generalize to all types of words that have complements
  - E.g. Preposition: predicate, object: argument
  - E.g. They hid **the$_1$** letter on **the$_2$** shelf.

Relation type	Predicate	Argument 1	Argument 2
verb_arg12	hid	They	letter
det_arg1	the$_1$	letter	
prep_arg12	on	letter	shelf
det_arg1	the$_2$	shelf	

Dependency structure vs. Predicate-argument structure

- Sentence: They hid the letter on the shelf

Dependency structure

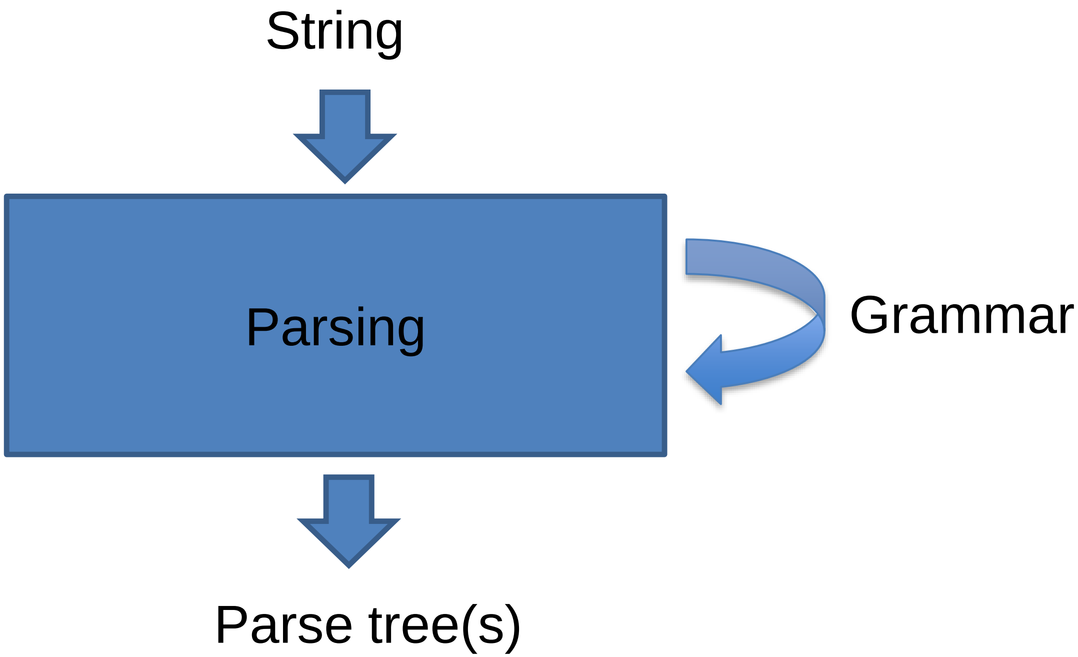
root(ROOT-0, hid-2)
nsubj(hid-2, They-1)
dobj(hid-2, letter-4)
det(letter-4, the-3)
prep_on(letter-4, shelf-7)
det(shelf-7, the-6)

Predicate-argument structure

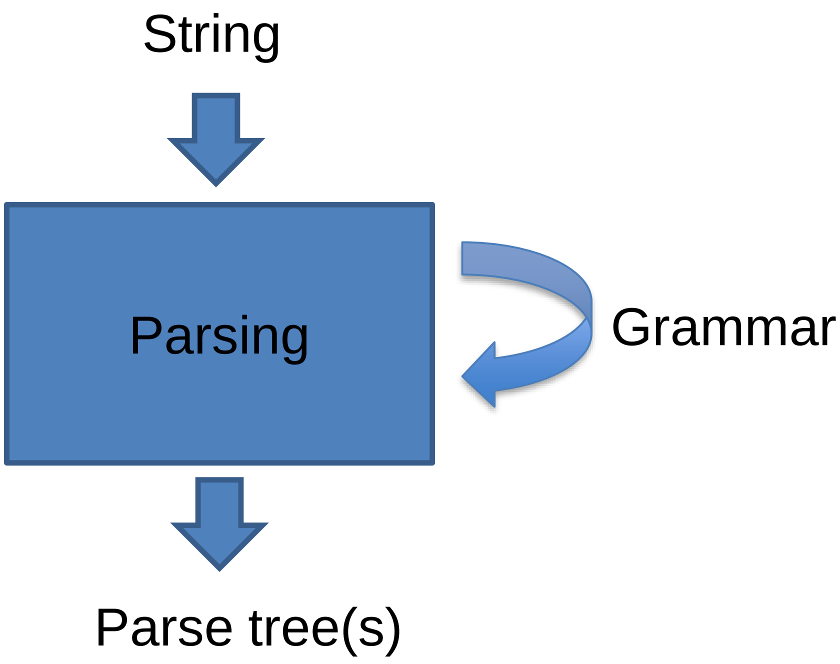
verb_arg12(hid-2, They-1, letter-4)
det_arg1(the-3, letter-4)
prep_arg12(on-6, letter-4, shelf-7)
det_arg1(the-6, shelf-7)

Syntactic parsing

- The process of taking a string and a grammar and returning parse tree(s) for that string



Syntactic parsing in the course



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

- Examples on next slide

Context-free grammar (1/2)

- G = (T, N, S, R)
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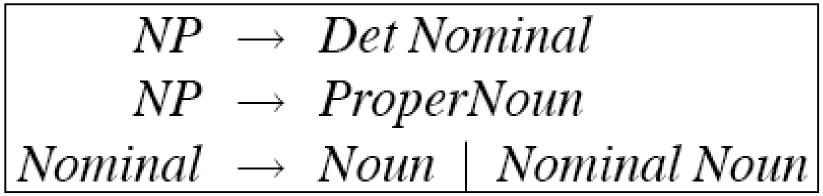
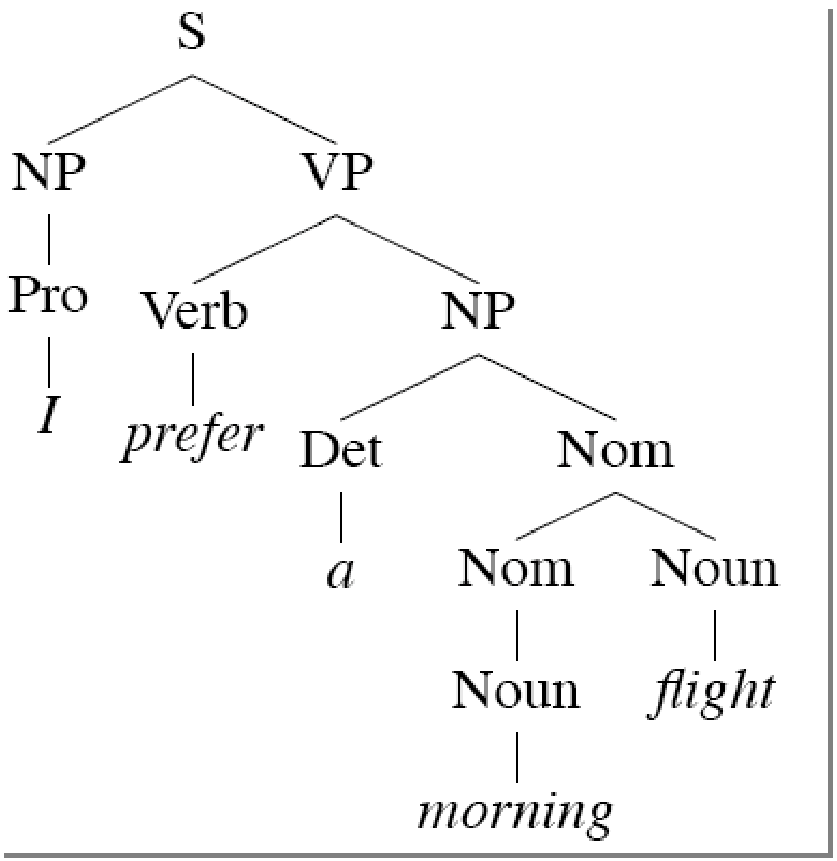


$$\begin{array}{rcl} NP & \rightarrow & Det\ Nominal \\ NP & \rightarrow & ProperNoun \\ Nominal & \rightarrow & Noun \mid Nominal\ Noun \end{array}$$

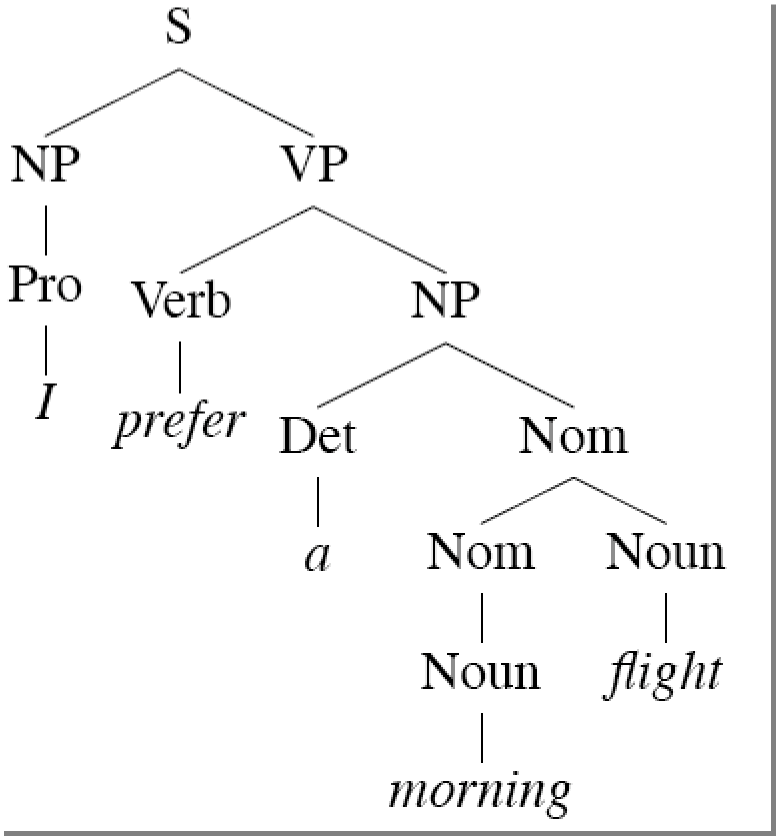


Context-free grammar (2/2)

- A grammar G **generates** a language L
  - **A language is a set of sentences**

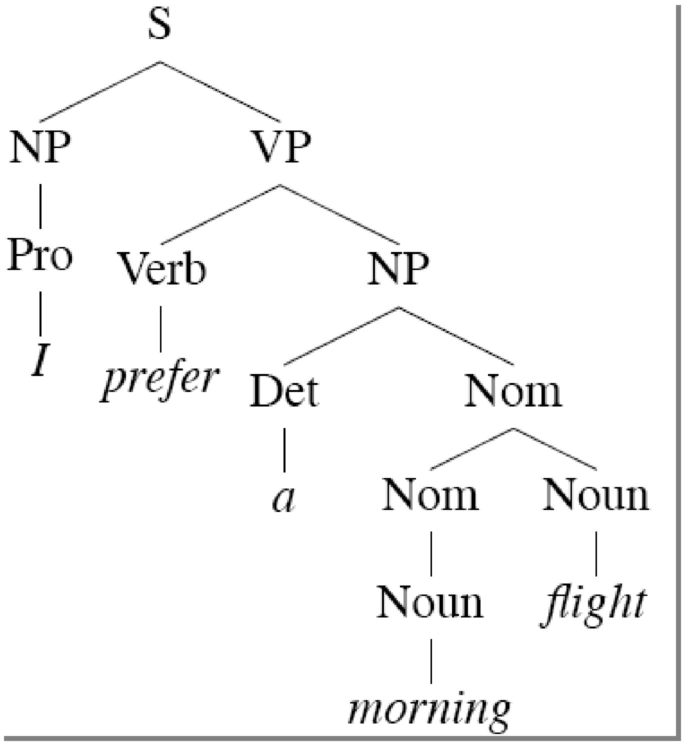
- G = (T, N, S, R)
  - T: **words or tokens**
  - N: **POS tags, syntactic tags**
  - S: the start symbol
  - R: rules of the form X →γ
    - X: a non-terminal
    - γ: the sequence of X's children

$$
\begin{aligned}
NP &\rightarrow Det\ Nominal \\
NP &\rightarrow ProperNoun \\
Nominal &\rightarrow Noun \mid Nominal\ Noun
\end{aligned}
$$



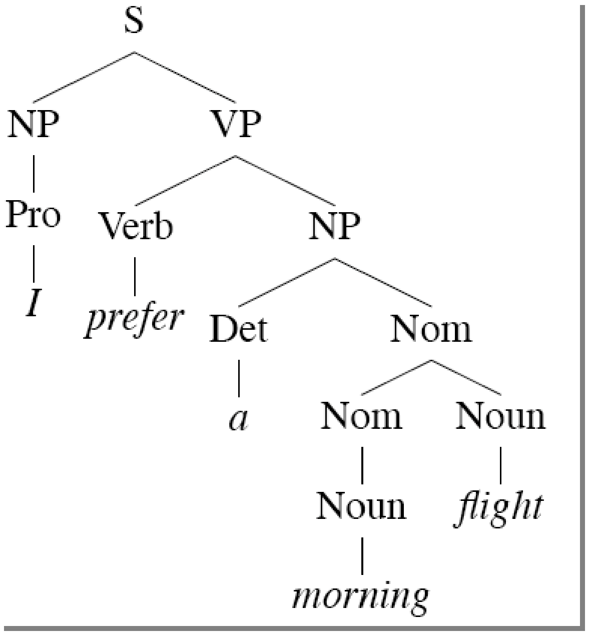
Exercise: Context free grammar

- Give a context free grammar to generate the parse tree

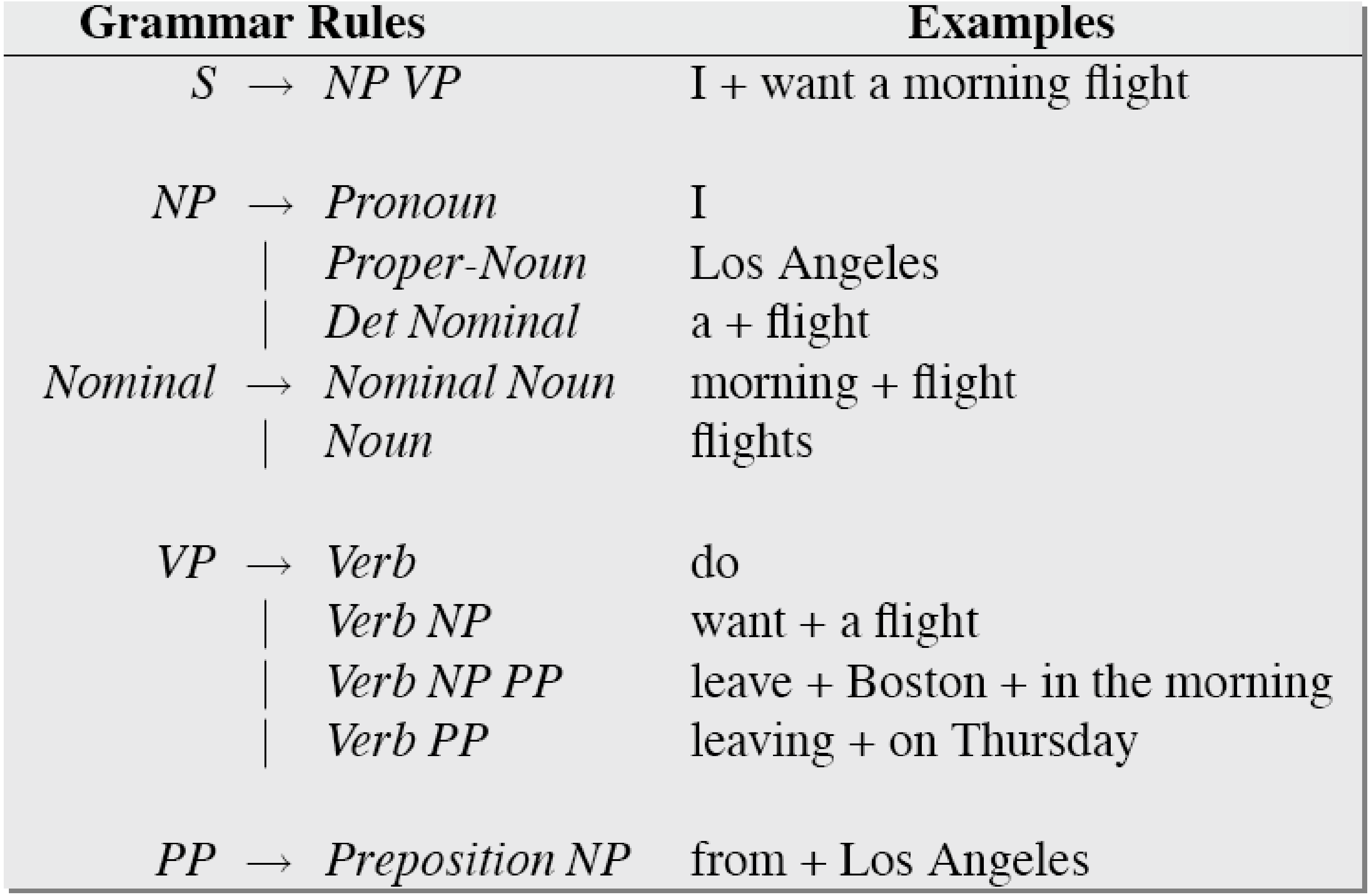


Exercise: Context free grammar

- Give a context free grammar to generate the parse tree
  - T: {I, prefer, a, morning, flight}
  - N: {VP, VP, Pro, Verb, Det, Nom, Noun}
  - S: S
  - R:
    - S -> NP VP
    - NP -> Pro
    - VP -> Verb NP
    - Verb -> prefer
    - NP -> Det Nom
    - Nom -> Nom Noun | Noun
    - Noun -> morning | flight
    - Det -> a
    - Pro -> I



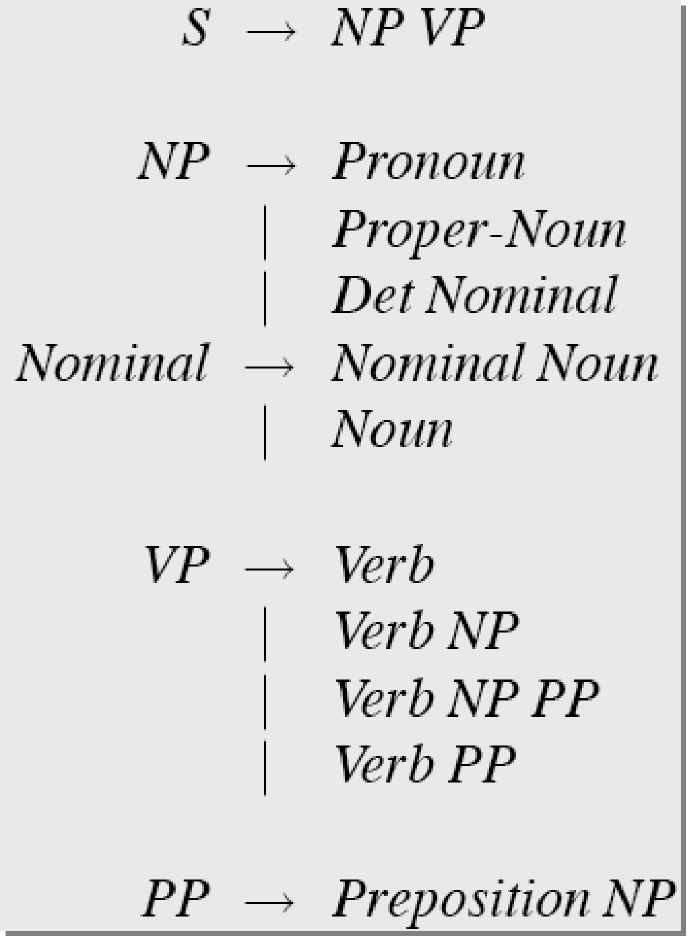
L0 grammar



Grammar Rules			Examples
S	→	*NP VP*	I + want a morning flight
NP	→	*Pronoun*	I
	|	*Proper-Noun*	Los Angeles
	|	*Det Nominal*	a + flight
Nominal	→	*Nominal Noun*	morning + flight
	|	*Noun*	flights
VP	→	*Verb*	do
	|	*Verb NP*	want + a flight
	|	*Verb NP PP*	leave + Boston + in the morning
	|	*Verb PP*	leaving + on Thursday
PP	→	*Preposition NP*	from + Los Angeles

Derivation

- A sequence of rules applied to a string that accounts for that string



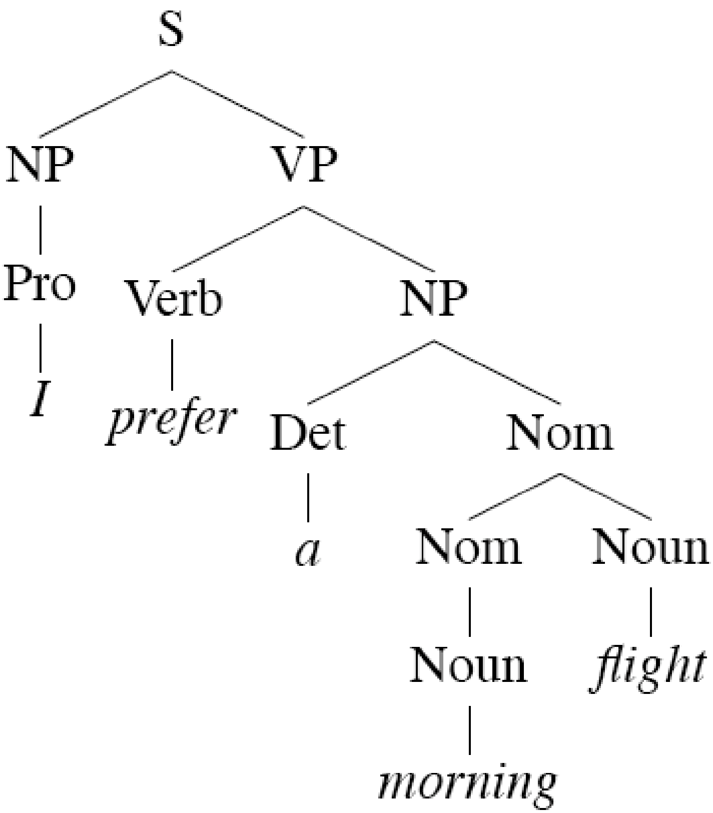
S → *NP VP*

NP → *Pronoun*
| *Proper-Noun*
| *Det Nominal*

Nominal → *Nominal Noun*
| *Noun*

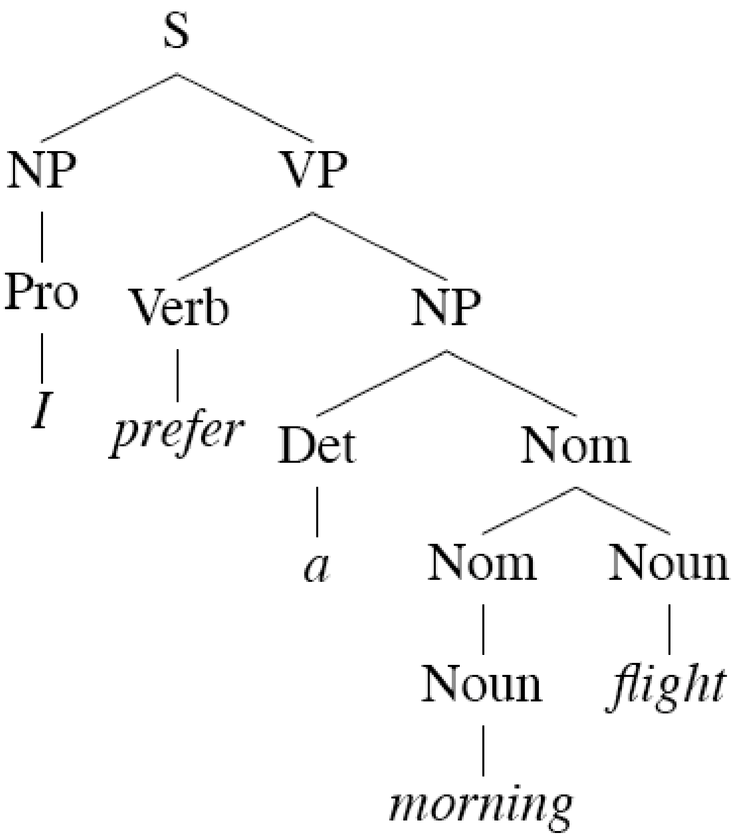
VP → *Verb*
| *Verb NP*
| *Verb NP PP*
| *Verb PP*

PP → *Preposition NP*



I prefer a morning flight.

Derivation (2)



S → NP VP
NP → Pro
Pro → ***I***
VP → Verb NP
Verb → ***prefer***
NP → Det Nom
Det → ***a***
Nom → Nom Noun
Nom → Noun
Noun → ***morning***
Noun → ***flight***

Summary: CFG & phrase structure

- G = (T, N, S, R)
  - Terminals: words
  - Non-terminals: constituent names (e.g. NP, VP)
  - Start symbol: S (sentence) or NP (noun phrase)
  - Rules: e.g. subcategorization frames for verbs

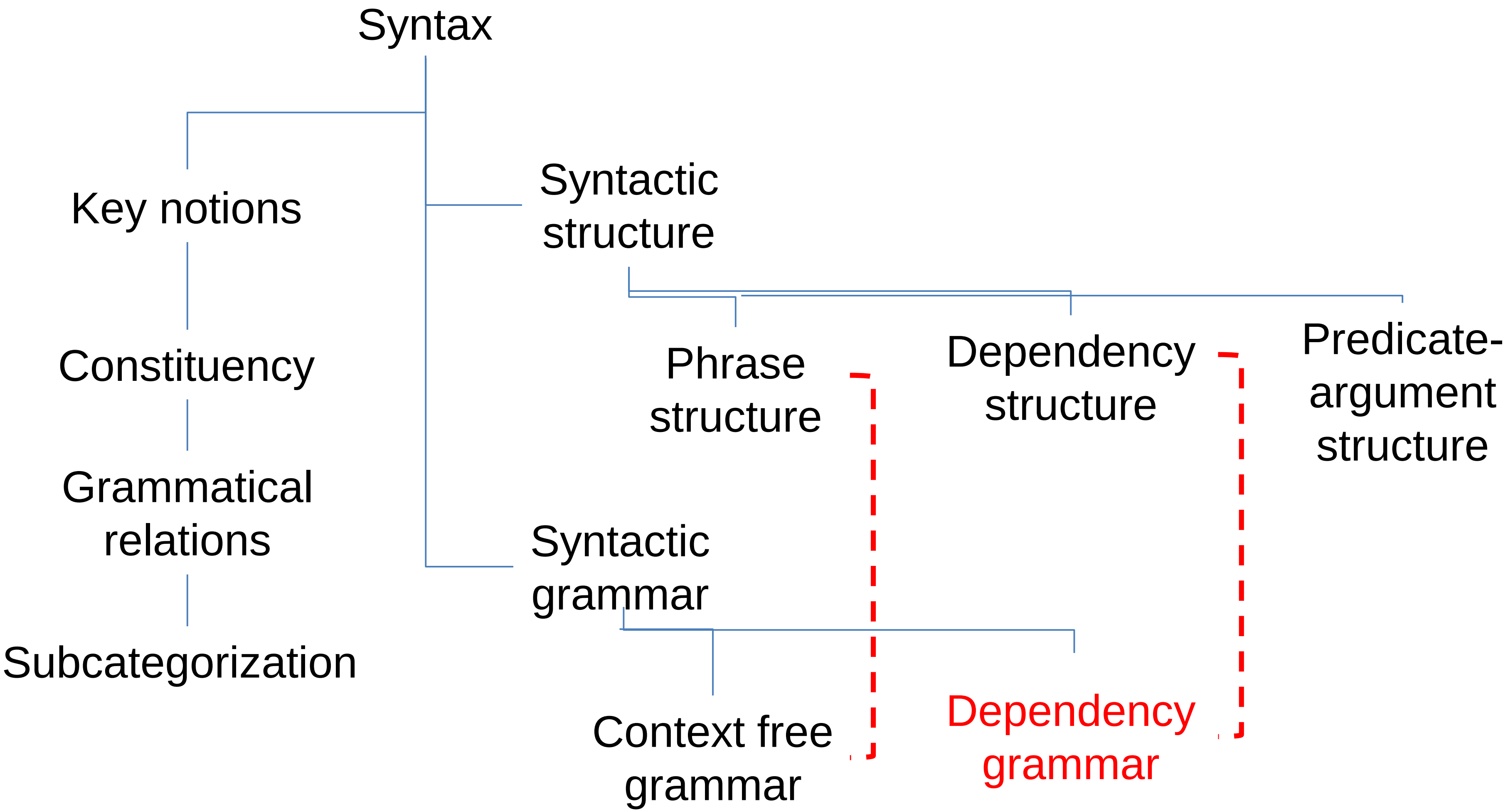
- Derivation will generate the phrase structure of an input

Example grammar formalisms

- Context free grammar (CFG)
- Combinatory categorial grammar (CCG)
- Dependency grammar (DG)

- HPSG: head-driven phrase structure grammar
- LFG: lexical functional grammar
- TAG: tree-adjoining grammar

Summary



Syntax

Key notions

Constituency

Grammatical relations

Subcategorization

Syntactic structure

Phrase structure

Dependency structure

Predicate-argument structure

Syntactic grammar

Context free grammar

Dependency grammar

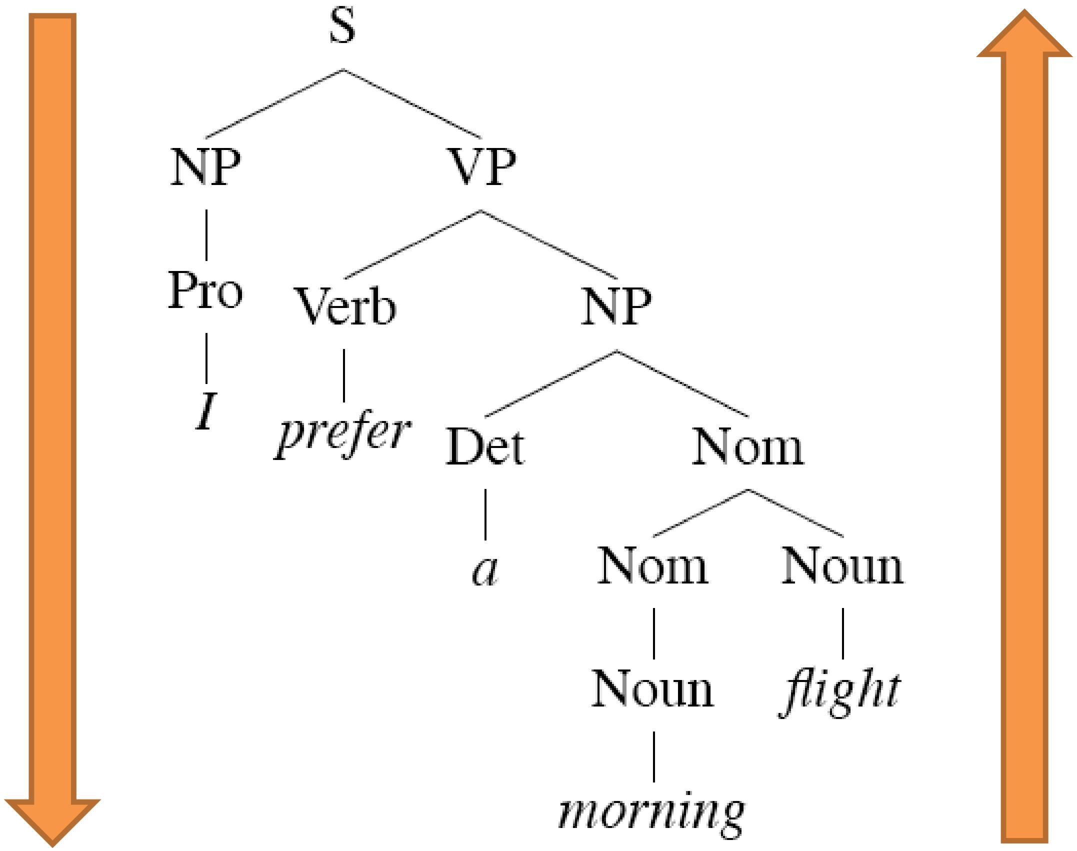
We focus on CFG!

- Classic approach
  - Still widely used for practical parsing systems

- Theoretically well-studied
  - Equivalent to Backus-Naur Form (BNF)
  - SQL is formally defined in BNF

Parsing strategies

Top-down parsing



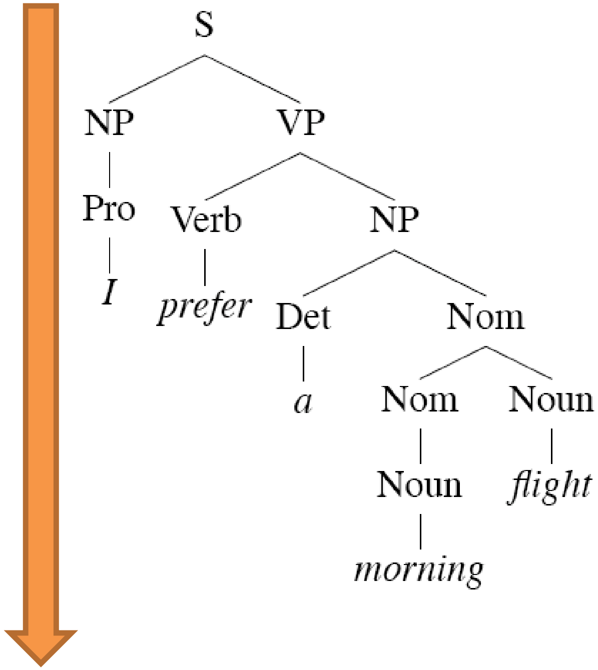
Bottom-up parsing

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

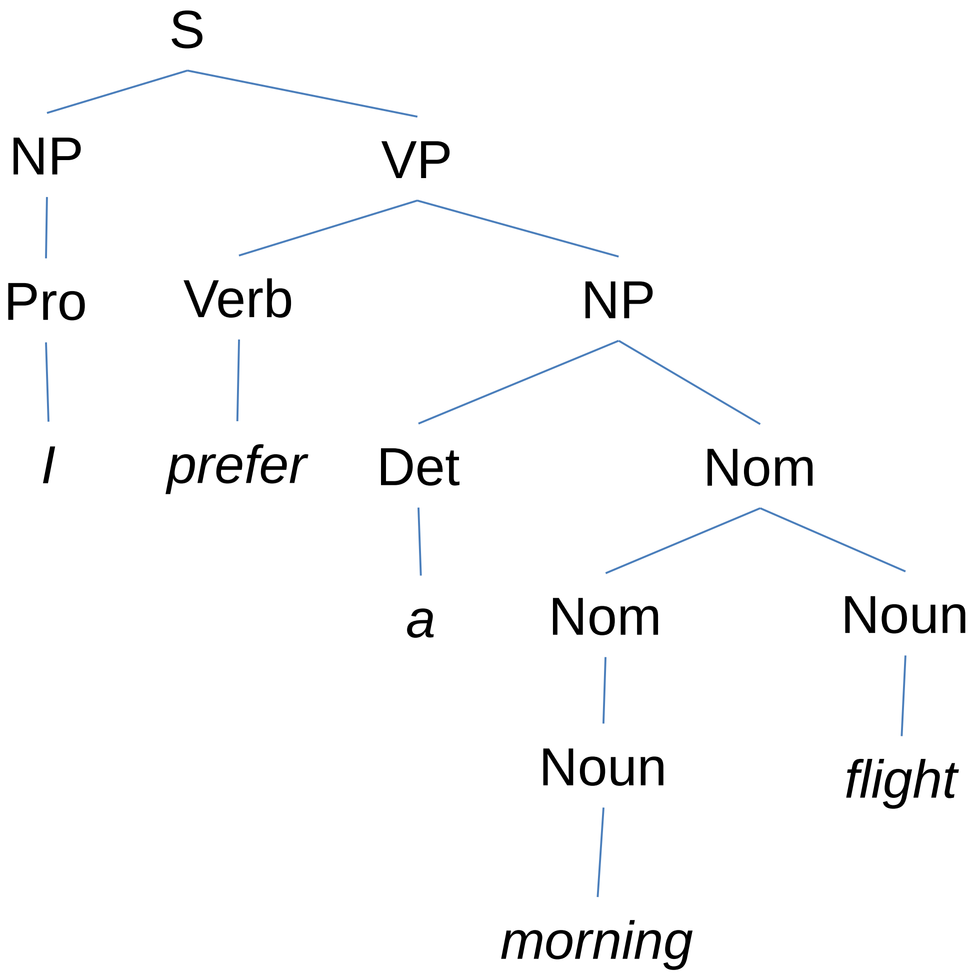
- Parsing is finished when the rewriting generates the whole string



Top-down parsing

Top-down parsing: Example

I prefer a morning flight.



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*

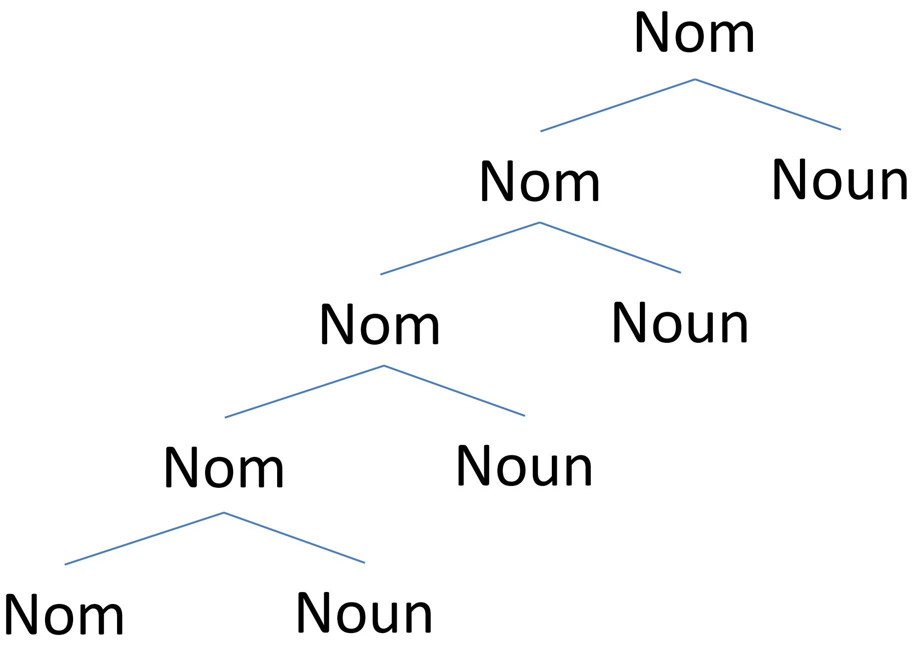
Top-down parsing: Issues (1/2)

- If a goal can be written in several ways, there is a choice of which rule to apply
  - Example: NP → Pro, NP → Det Nom

- Search problem
  - Search methods: Depth-first, breadth-first, goal-ordering, etc.

- Need grammar-driven control for optimization
  - May waste lots of time in trying rules that are inconsistent with the input string
  - Example: left recursive rules (e.g. Nom → Nom Noun)

Top-down parsing: left recursive rules

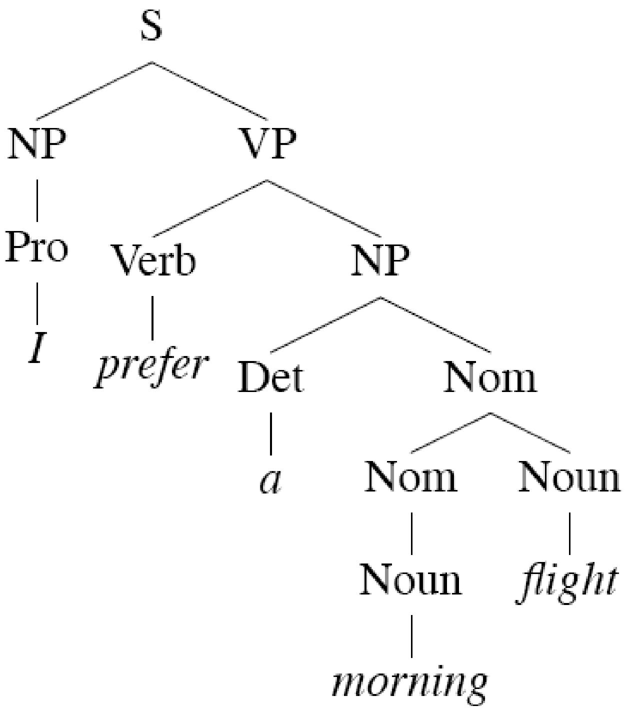


Example: Southeast Asia Public Interest Research Group

Top-down parsing: Issues (2/2)

- A part-of-speech like Noun can be replaced with any noun; trying out all rules of a part-of-speech is time consuming

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



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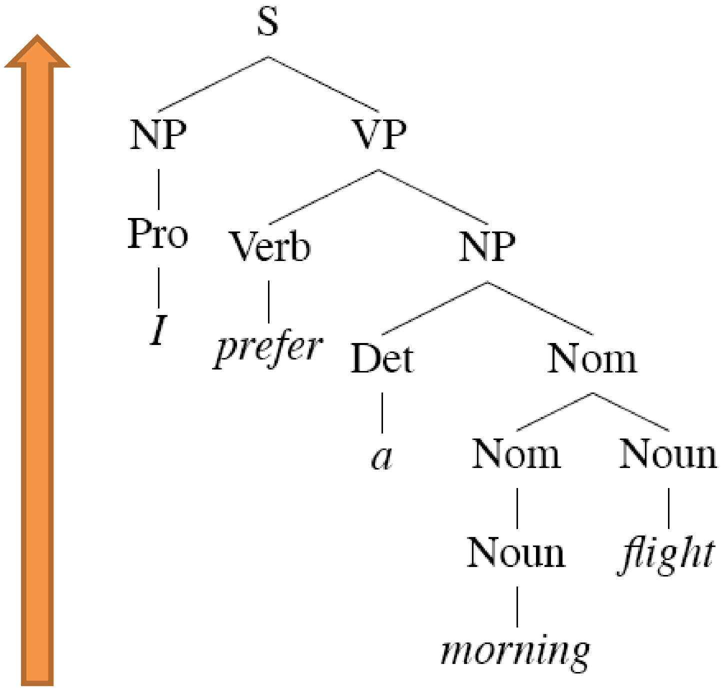
   Noun → *flight*
6. Nom → Noun
   Noun → *morning*

Bottom-up parsing

- Data-directed
  - Start with words

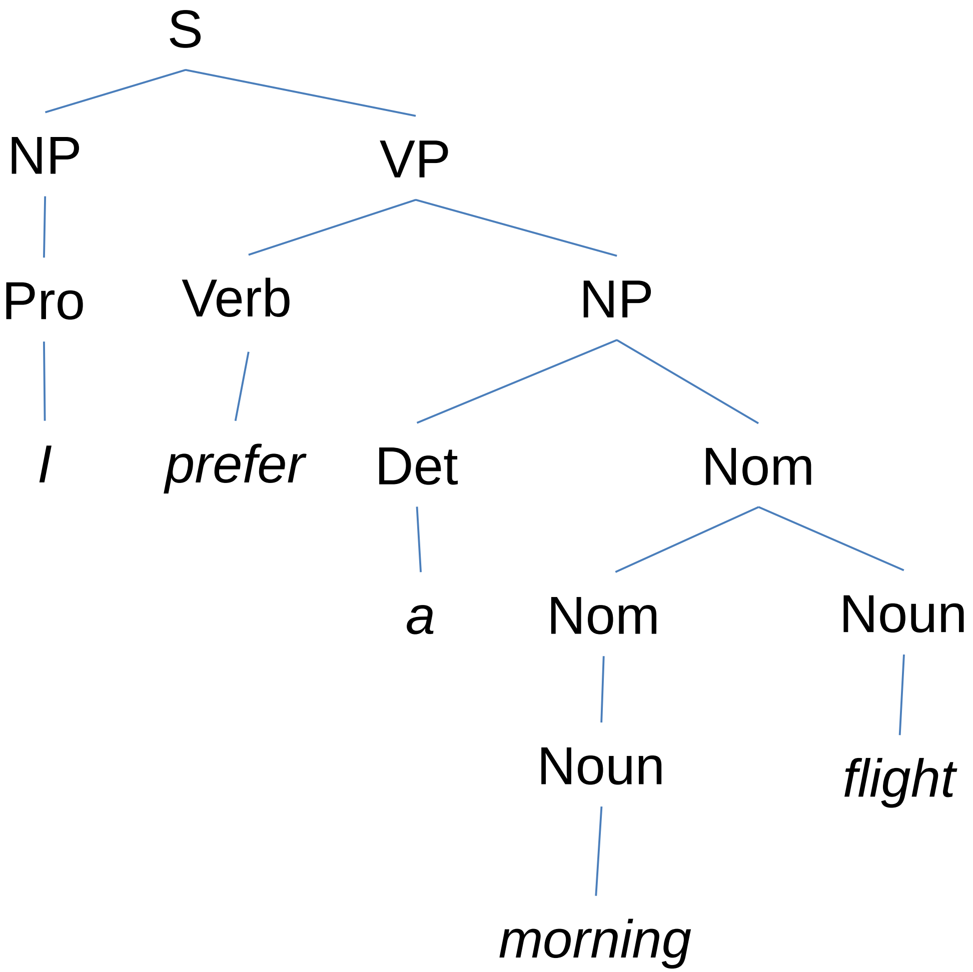
- If a substring matches the RHS of a rule, replace the substring with the LHS
  - Example: Nom → Noun (“morning”)
  - Example: Nom → Nom Noun (“*morning flight*”)

- Parsing is finished when the whole string is replaced with a goal



Bottom-up approach: Example

I prefer a morning flight.



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

Parsing strategies

Top-down parsing

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

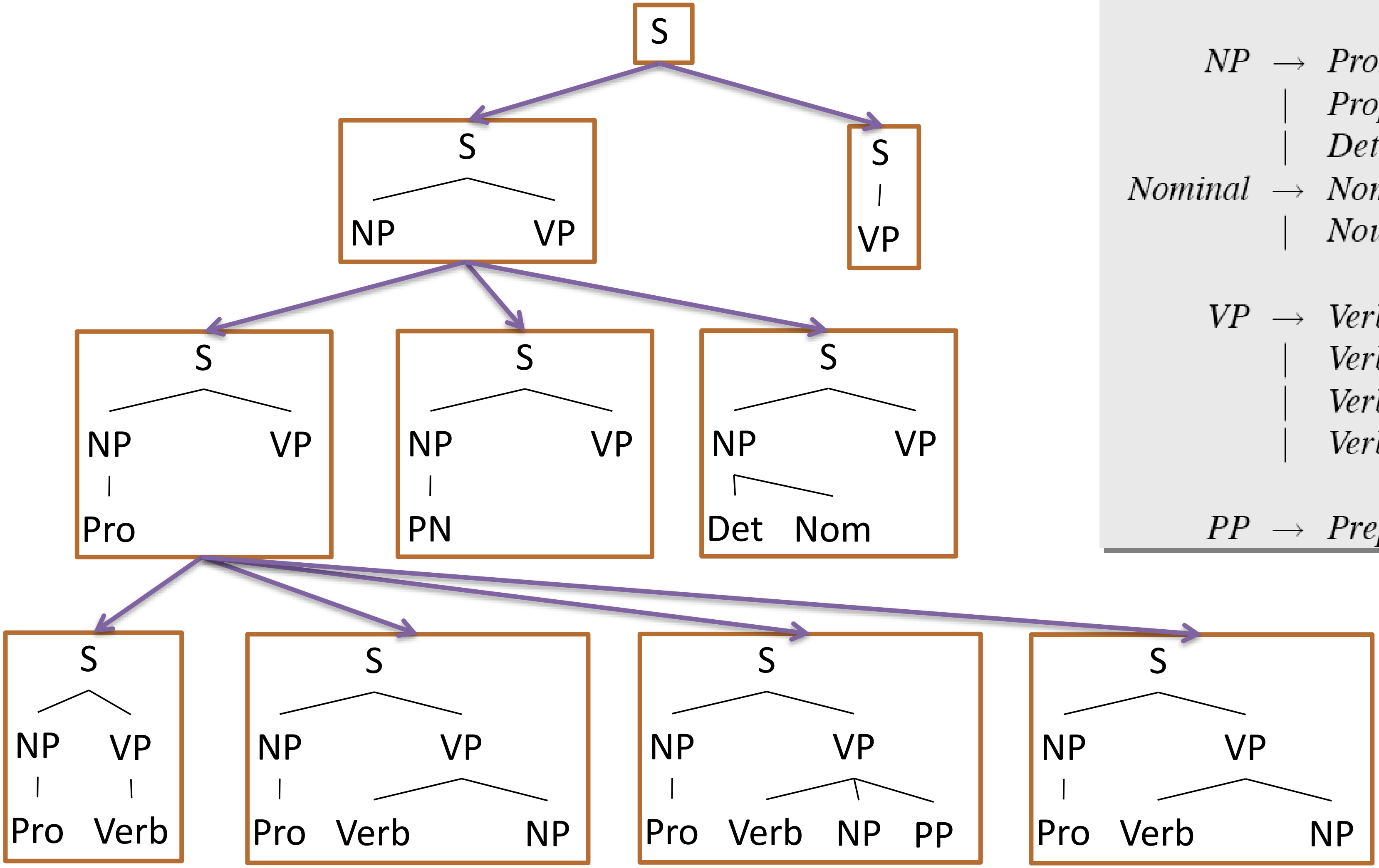
Bottom-up parsing

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

Top-down vs. Bottom-up parsing

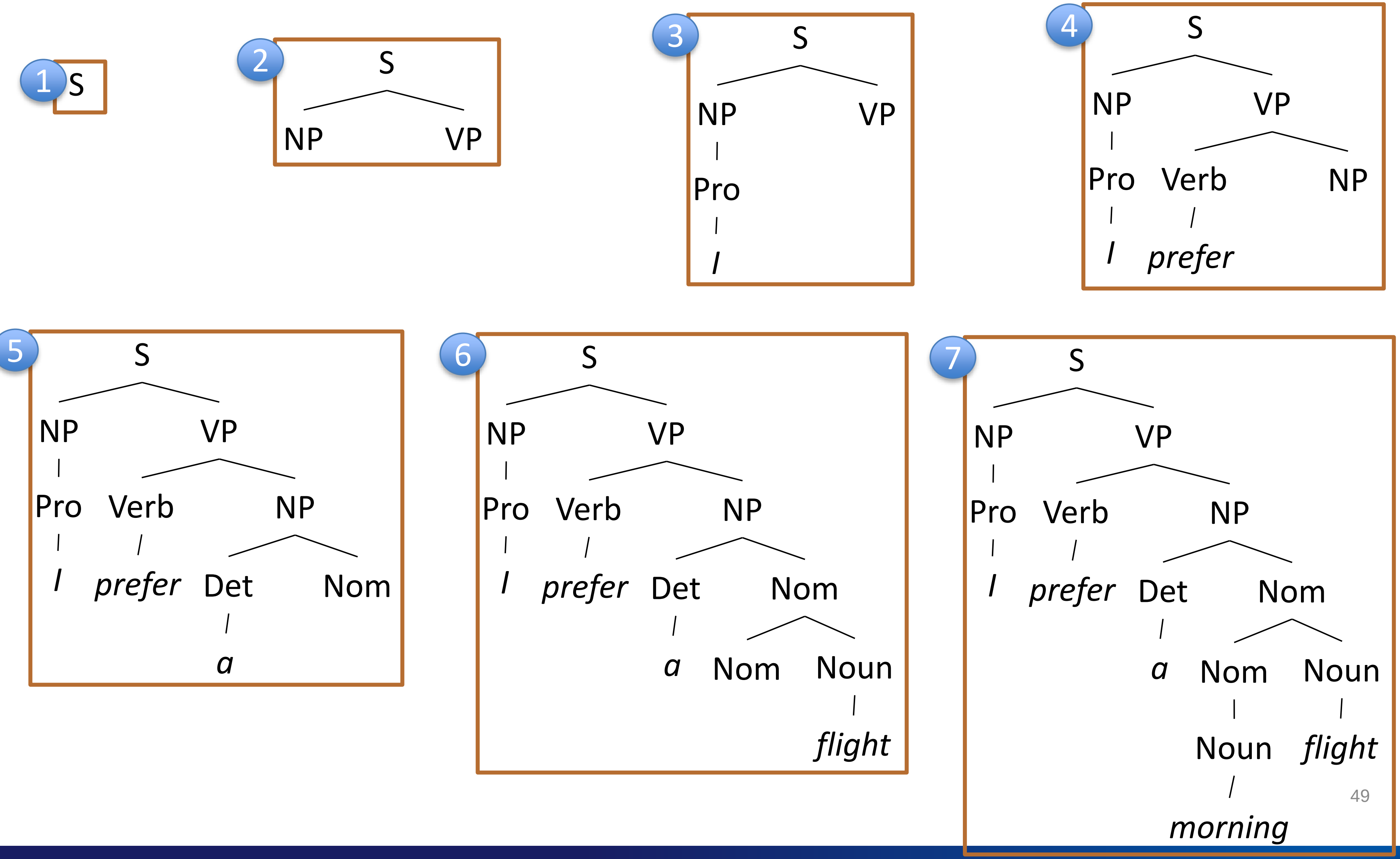
- Top-down
  - Waste lots of time in trying inconsistent rule applications. The application of the rules does not lead the generation of the given string
  - Never explore subtrees that cannot find a place in some S-rooted tree. All trees are generated starting with S.
- Bottom-up
  - Never suggest trees that are not grounded in the input string; All trees are generated based on input string
  - Trees that have no hope of leading to an S are generated; Some trees cannot proceed further to reach S

Parsing as search (e.g. I prefer a morning flight)



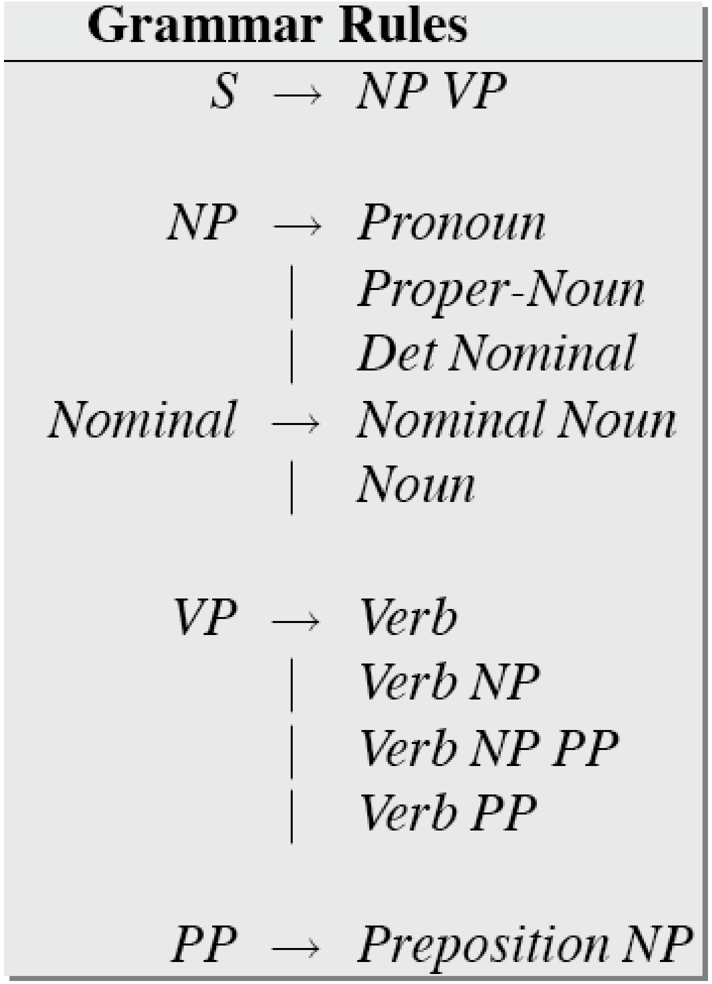
Grammar Rules		
S	→	*NP VP* | *VP*
NP	→	*Pronoun*
	|	*Proper-Noun*
	|	*Det Nominal*
Nominal	→	*Nominal Noun*
	|	*Noun*
VP	→	*Verb*
	|	*Verb NP*
	|	*Verb NP PP*
	|	*Verb PP*
PP	→	*Preposition NP*

Parsing as search



Exercise: Parsing as search

- Draw a search space for parsing “I sleep” in a top-down parsing based on L0 grammar

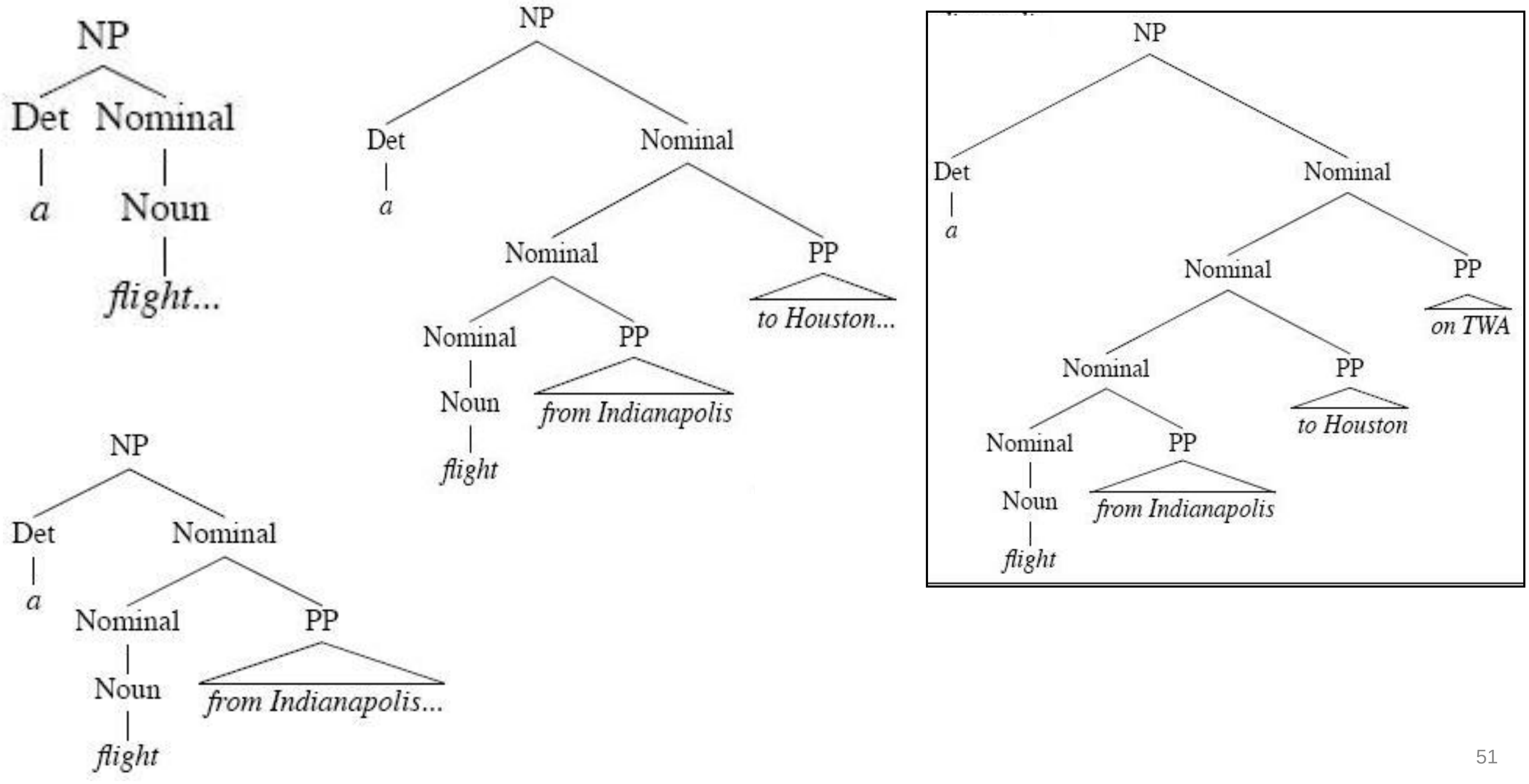


Grammar Rules

S	→	*NP VP*
NP	→	*Pronoun*
	|	*Proper-Noun*
	|	*Det Nominal*
Nominal	→	*Nominal Noun*
	|	*Noun*
VP	→	*Verb*
	|	*Verb NP*
	|	*Verb NP PP*
	|	*Verb PP*
PP	→	*Preposition NP*

Repeated work in parsing-as-search

- Parsing: “a flight from Indianapolis to Houston on TWA” (Figure 13.7)



Dynamic programming parsing methods

- Parsing-as-search may have exponentially many parse states

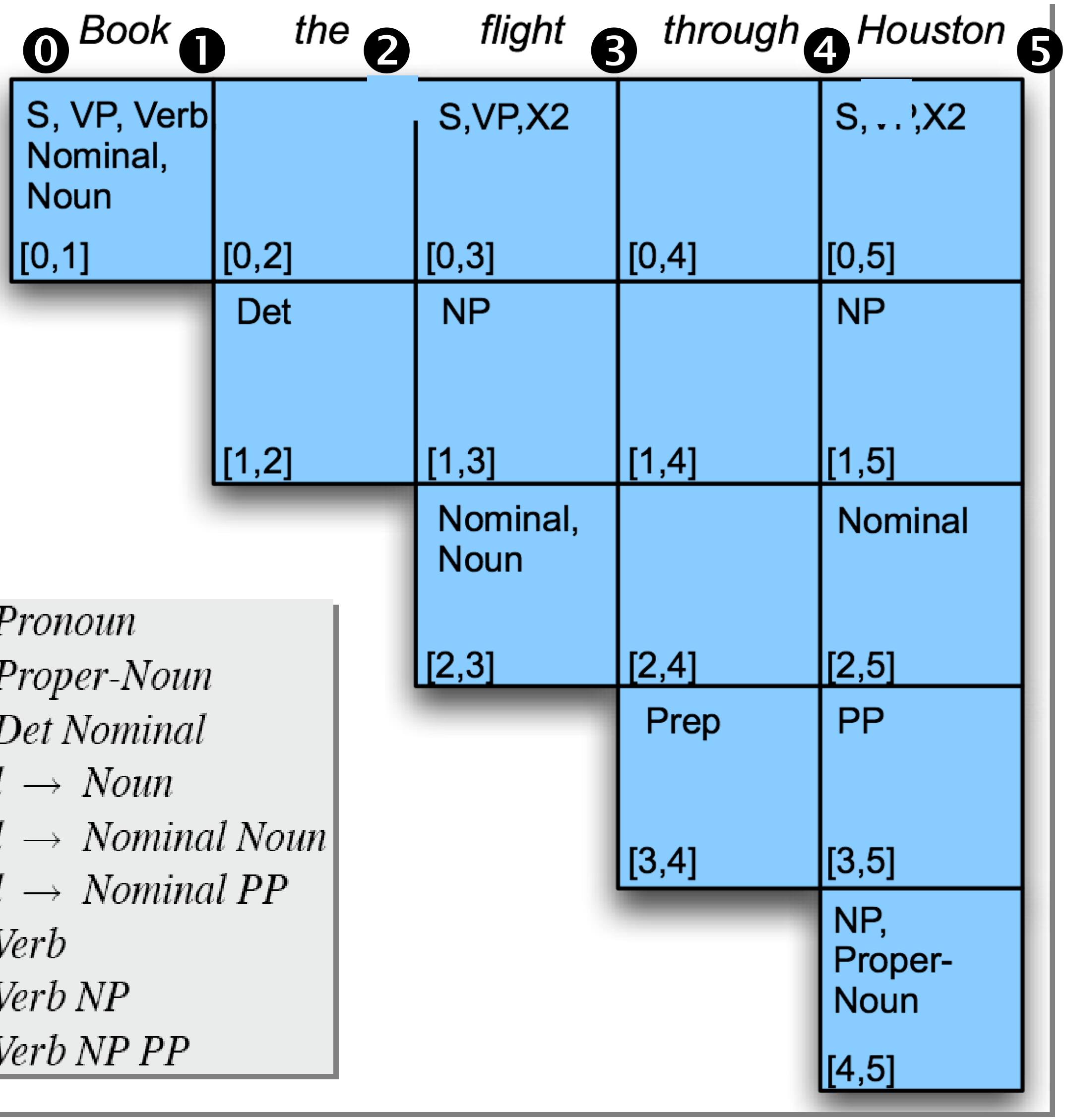
- Dynamic programming solves the problem of doing repeated work
  - Memorization (remembering solved subproblems)

- Bottom-up approach: CKY parsing
  - Parse table

- Top-down approach: Earley parsing
  - Dotted rules

Parse table

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



⓿ Book ❶ the ❷ flight ❸ through ❹ Houston ❺

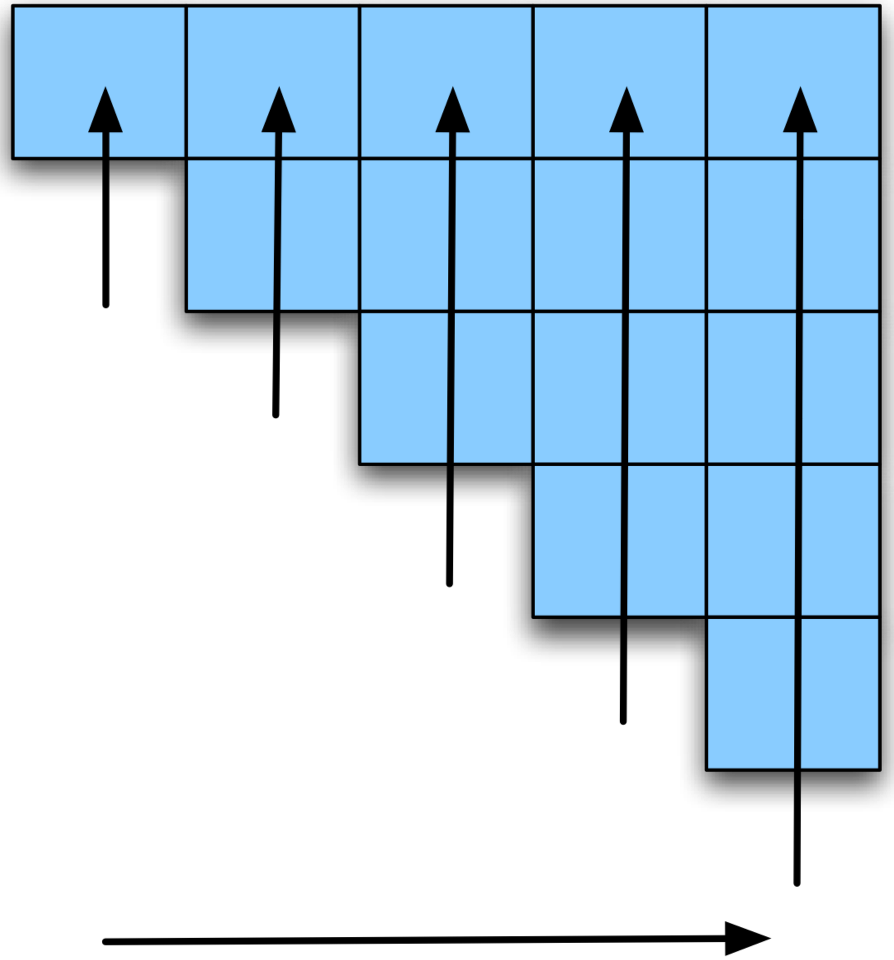
Book	the	flight	through	Houston
S, VP, Verb Nominal, Noun [0,1]	[0,2]	S,VP,X2 [0,3]	[0,4]	S, [illegible],X2 [0,5]
	Det [1,2]	NP [1,3]	[1,4]	NP [1,5]
		Nominal, Noun [2,3]	[2,4]	Nominal [2,5]
			Prep [3,4]	PP [3,5]
				NP, Proper- Noun [4,5]

$\mathscr{L}_1$ **Grammar**
$S \rightarrow NP\ VP$
$S \rightarrow Aux\ NP\ VP$
$S \rightarrow VP$
$VP \rightarrow Verb\ PP$
$VP \rightarrow VP\ PP$
$PP \rightarrow Preposition\ NP$

$NP \rightarrow Pronoun$
$NP \rightarrow Proper\text{-}Noun$
$NP \rightarrow Det\ Nominal$
$Nominal \rightarrow Noun$
$Nominal \rightarrow Nominal\ Noun$
$Nominal \rightarrow Nominal\ PP$
$VP \rightarrow Verb$
$VP \rightarrow Verb\ NP$
$VP \rightarrow Verb\ NP\ PP$

Parse table: Parsing sequence

Book	*the*	*flight*	*through*	*Houston*
S, VP, Verb Nominal, Noun [0,1]	[0,2]	S,VP,X2 [0,3]	[0,4]	S,VP,X2 [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 (X → Y Z)

[book$_1$] [the$_2$ flight$_3$ through$_4$ Houston$_5$]
[0,1] [1,5]
[book$_1$ the$_2$] [flight$_3$ through$_4$ Houston$_5$]
[0,2] [2,5]
…
[book$_1$ the$_2$ flight$_3$ through$_4$] [Houston$_5$]
[0,4] [4,5]

[0,5] → [0,k] [k,5] for 0<k<5

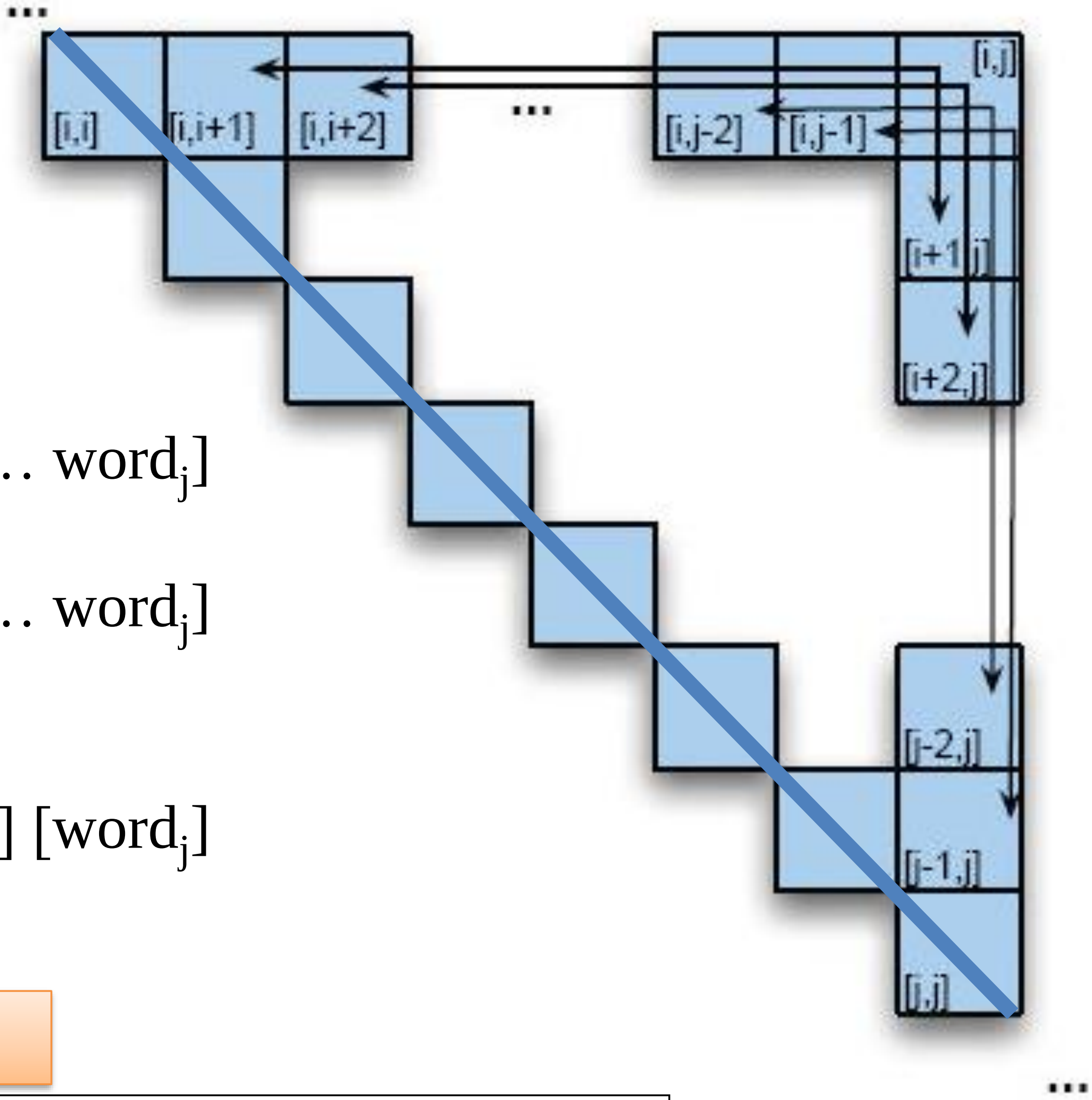
⓿ *Book* ❶ *the* ❷ *flight* ❸ *through* ❹ *Houston* ❺

Book	*the*	*flight*	*through*	*Houston*
S, VP, Verb Nominal, Noun [0,1]	[0,2]	S,VP,X2 [0,3]	[0,4]	S,VP,X2 [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:

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

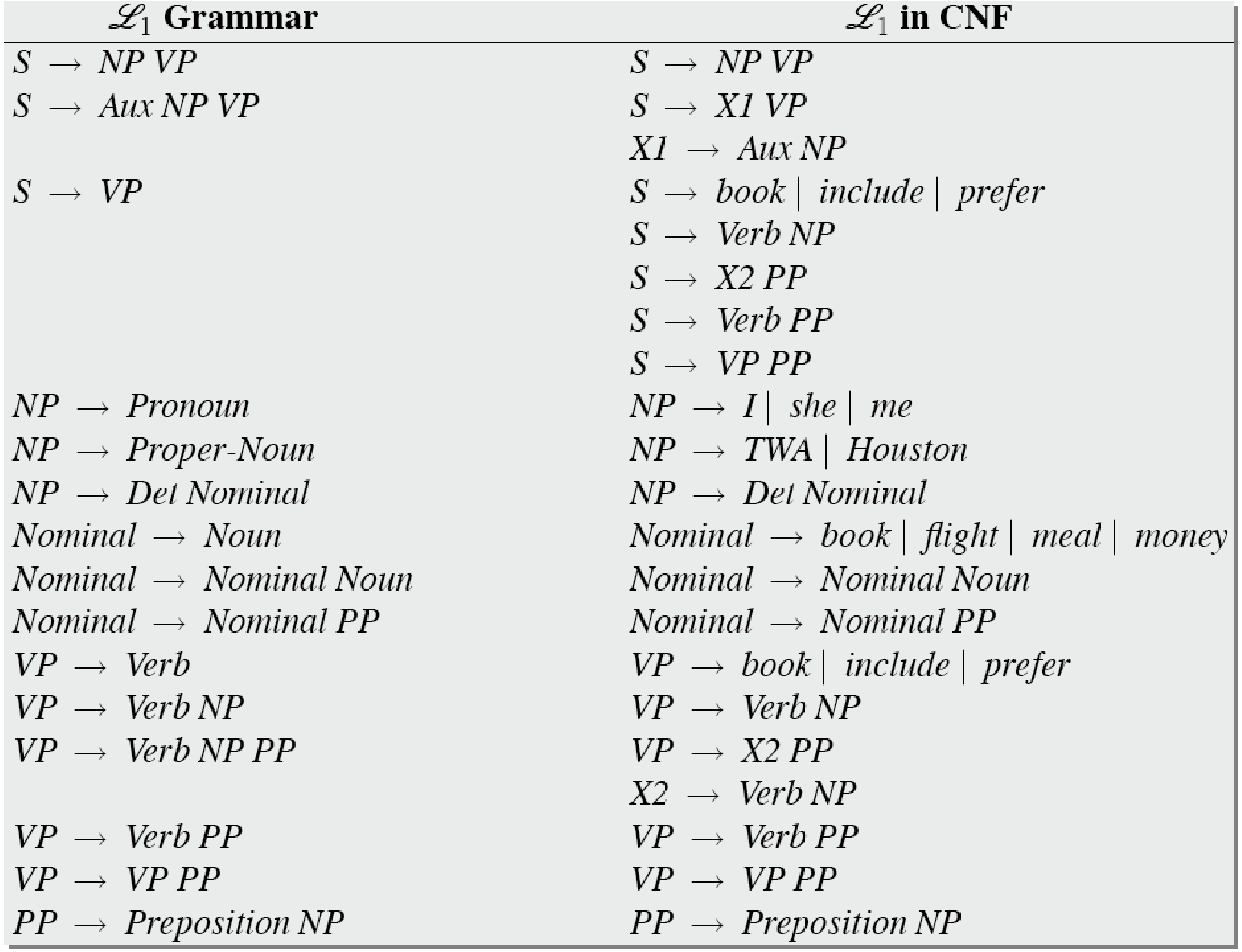
- Requirement
  - All rules should be in Chomsky normal form (CNF)

- CNF rules have the form of either
  - A → B C   or   A → w (w is a terminal)

    POS Tagging
  - RHS must have two non-terminals or one terminal

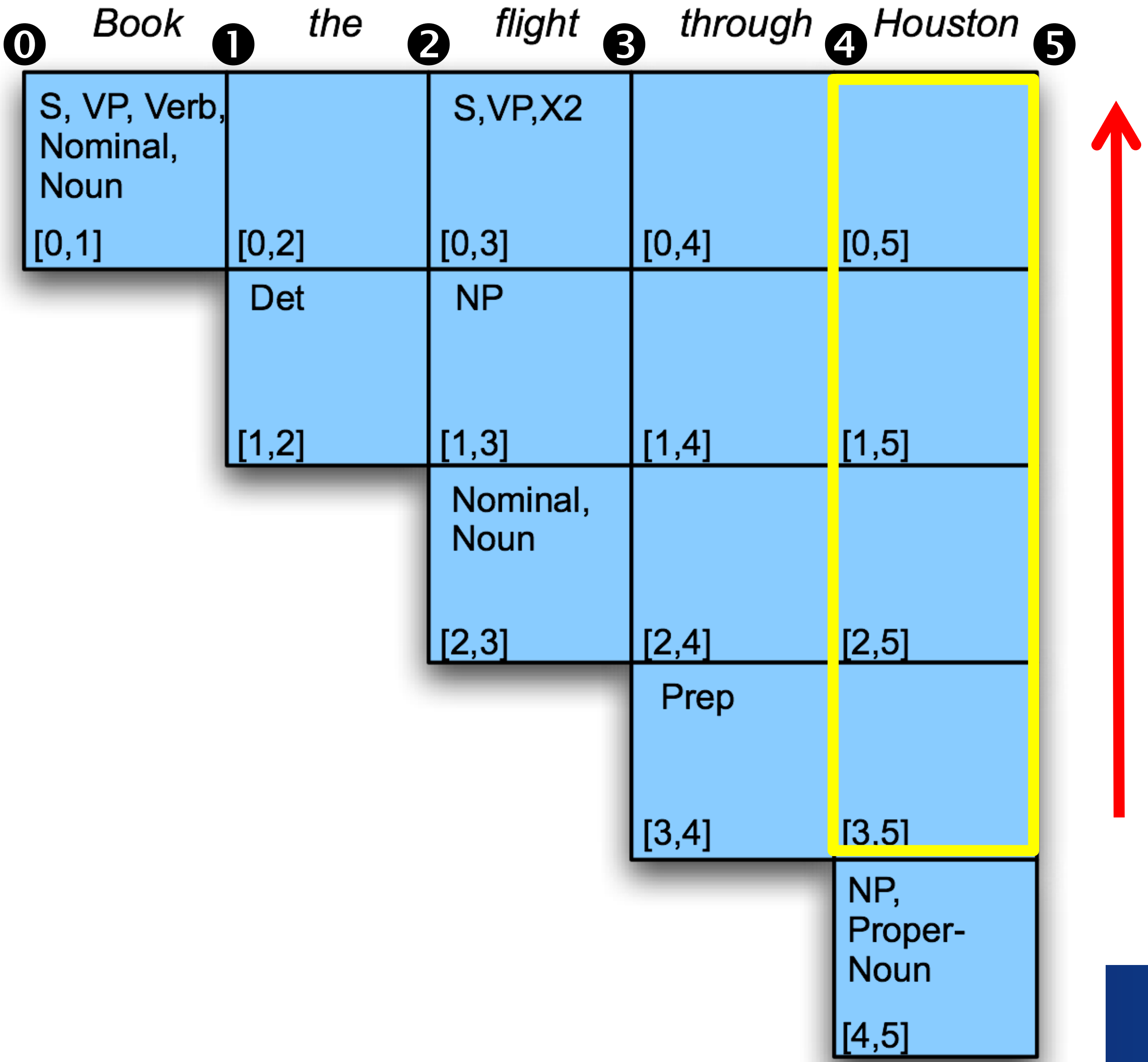
- Conversion to CNF
  - Example on next slide

CNF grammar: example



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

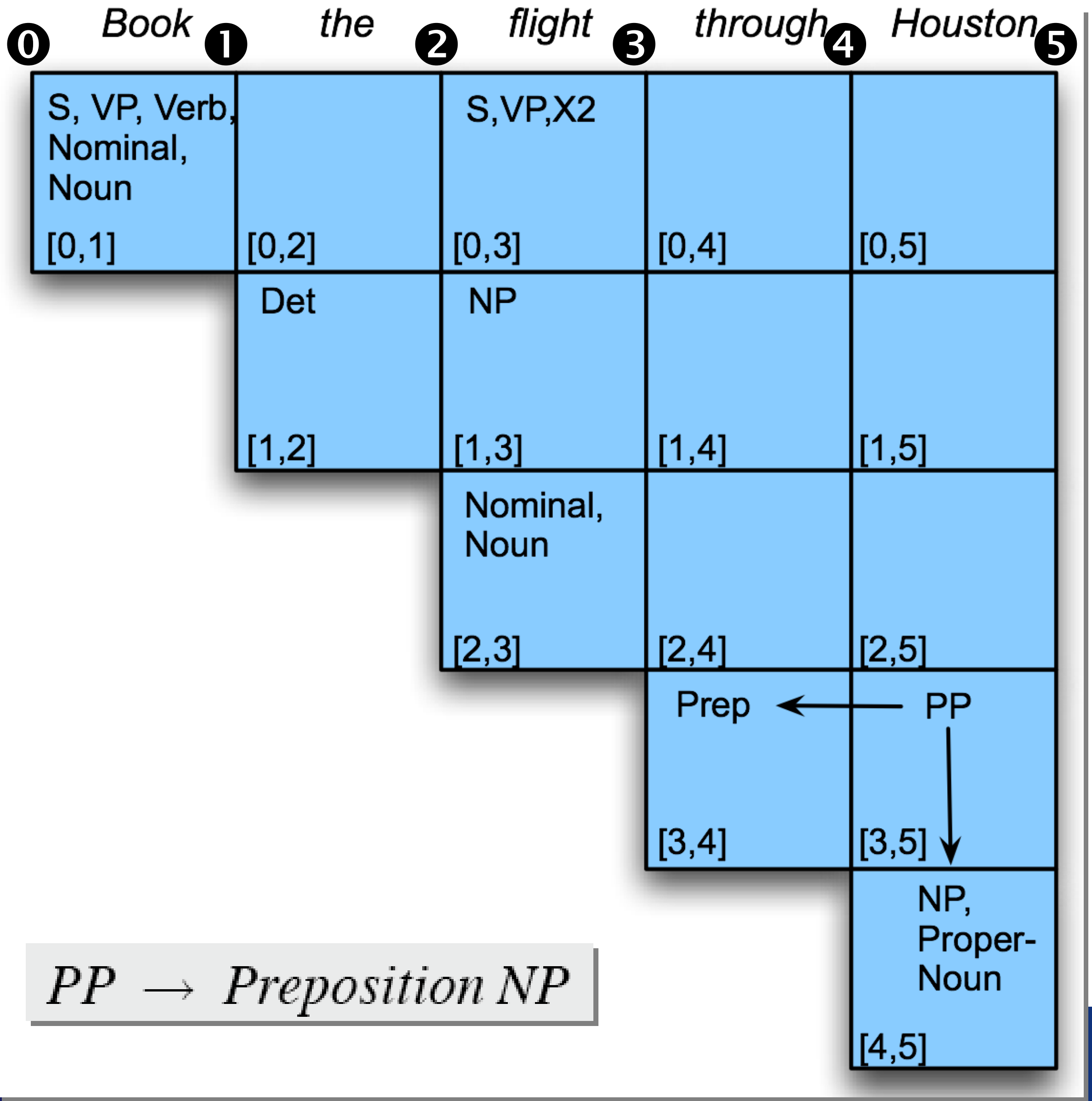
Example : filling the 5th column



Book	the	flight	through	Houston
S, VP, Verb, Nominal, Noun [0,1]	[0,2]	S,VP,X2 [0,3]	[0,4]	[0,5]
	Det [1,2]	NP [1,3]	[1,4]	[1,5]
		Nominal, Noun [2,3]	[2,4]	[2,5]
			Prep [3,4]	[3,5]
				NP, Proper-Noun [4,5]

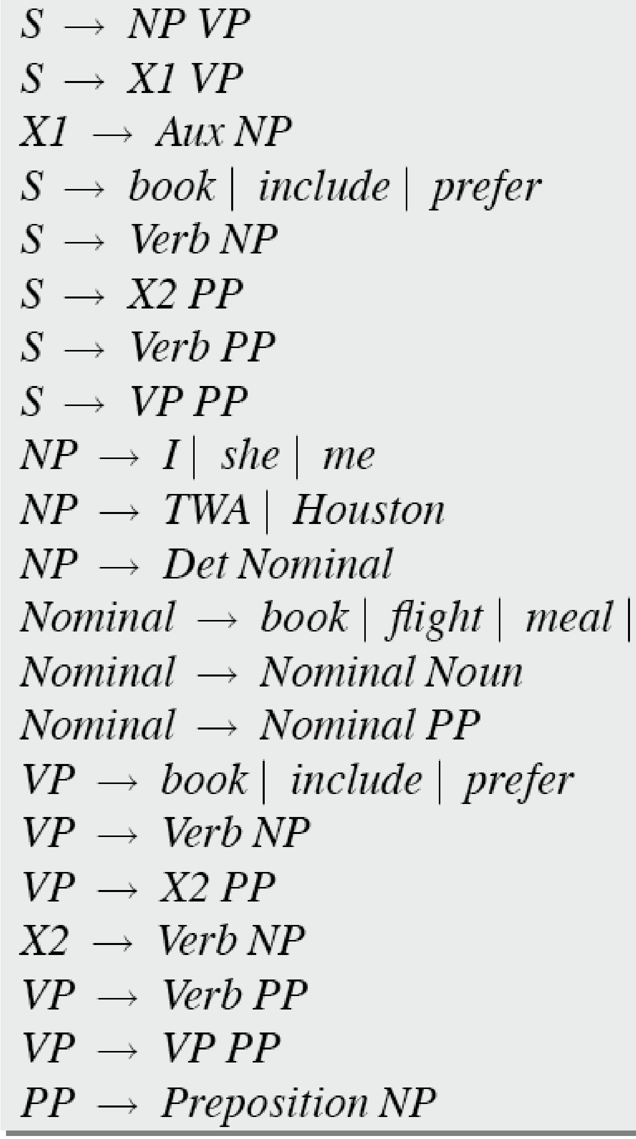
S → *NP VP*
S → *X1 VP*
X1 → *Aux NP*
S → *book* | *include* | *prefer*
S → *Verb NP*
S → *X2 PP*
S → *Verb PP*
S → *VP PP*
NP → *I* | *she* | *me*
NP → *TWA* | *Houston*
NP → *Det Nominal*
Nominal → *book* | *flight* | *meal* |
Nominal → *Nominal Noun*
Nominal → *Nominal PP*
VP → *book* | *include* | *prefer*
VP → *Verb NP*
VP → *X2 PP*
X2 → *Verb NP*
VP → *Verb PP*
VP → *VP PP*
PP → *Preposition NP*

Example : filling the 5th column



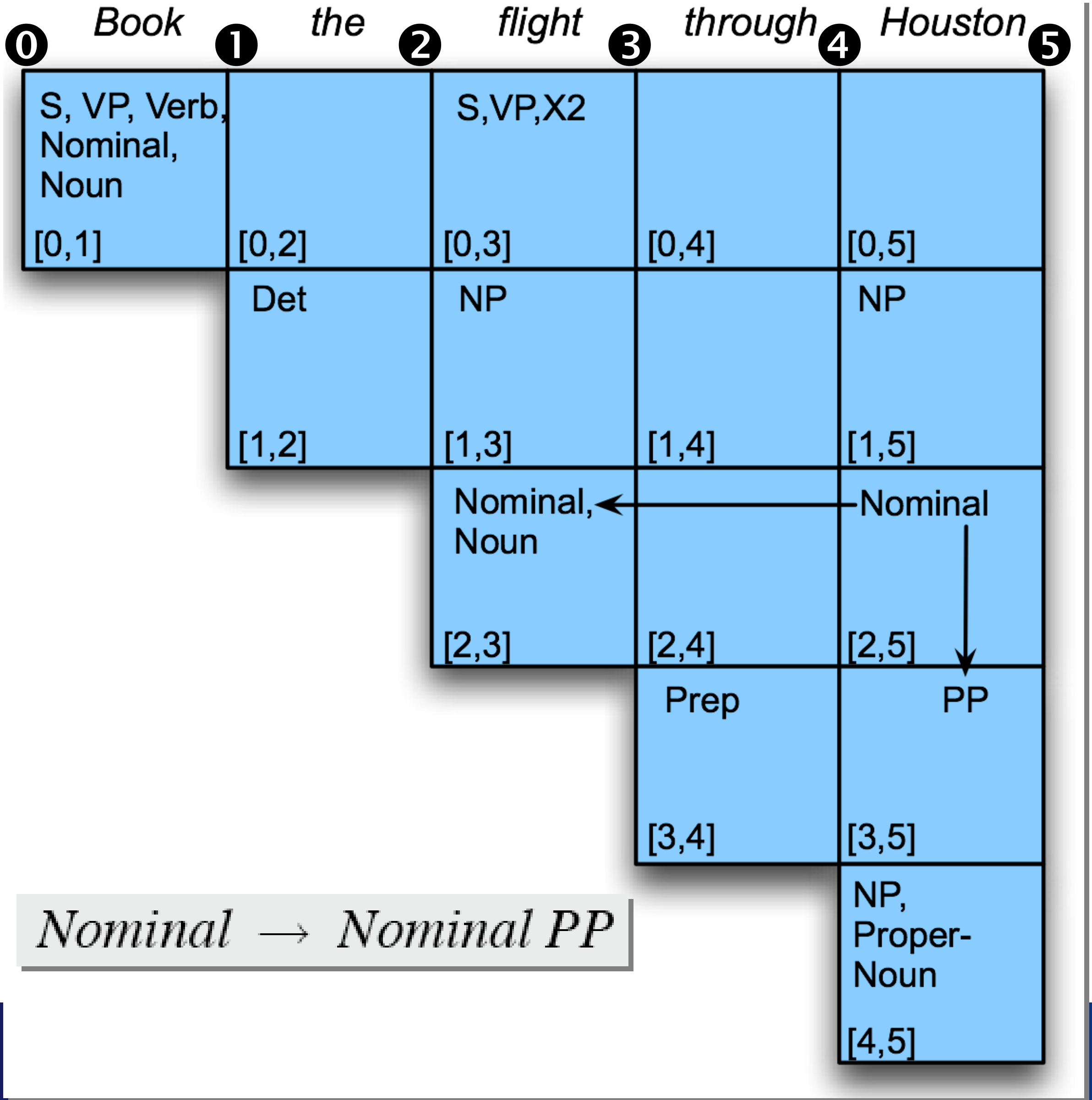
Book	the	flight	through	Houston
S, VP, Verb, Nominal, Noun [0,1]	[0,2]	S,VP,X2 [0,3]	[0,4]	[0,5]
	Det [1,2]	NP [1,3]	[1,4]	[1,5]
		Nominal, Noun [2,3]	[2,4]	[2,5]
			Prep [3,4]	PP [3,5]
				NP, Proper- Noun [4,5]

PP → *Preposition NP*



S → *NP VP*
S → *X1 VP*
X1 → *Aux NP*
S → *book* | *include* | *prefer*
S → *Verb NP*
S → *X2 PP*
S → *Verb PP*
S → *VP PP*
NP → *I* | *she* | *me*
NP → *TWA* | *Houston*
NP → *Det Nominal*
Nominal → *book* | *flight* | *meal* |
Nominal → *Nominal Noun*
Nominal → *Nominal PP*
VP → *book* | *include* | *prefer*
VP → *Verb NP*
VP → *X2 PP*
X2 → *Verb NP*
VP → *Verb PP*
VP → *VP PP*
PP → *Preposition NP*

Example : filling the 5th column

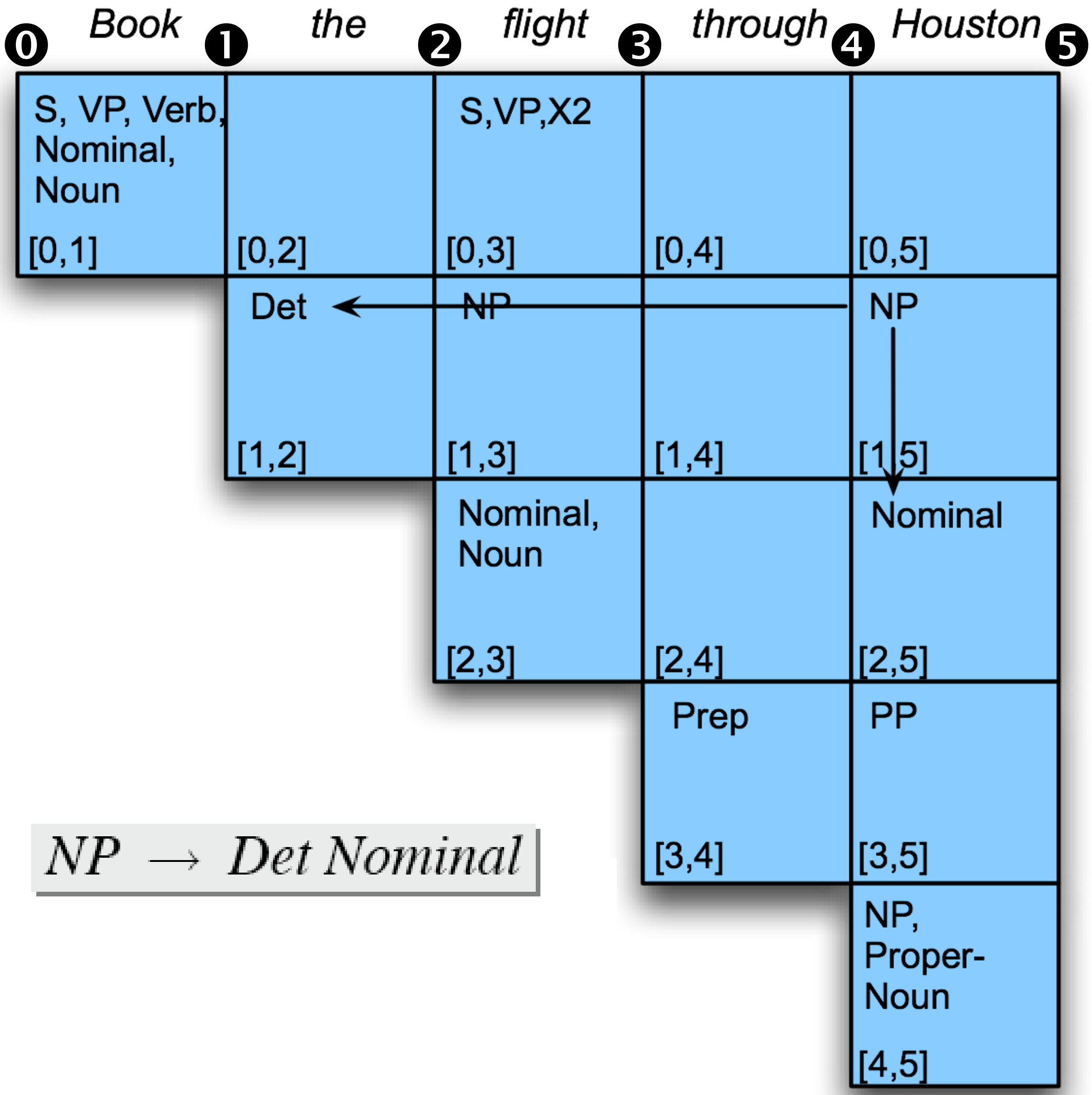


⓿ Book ❶	the ❷	flight ❸	through ❹	Houston ❺
S, VP, Verb, Nominal, Noun [0,1]	[0,2]	S,VP,X2 [0,3]	[0,4]	[0,5]
	Det [1,2]	NP [1,3]	[1,4]	NP [1,5]
		Nominal, Noun [2,3]	[2,4]	Nominal [2,5]
			Prep [3,4]	PP [3,5]
				NP, Proper-Noun [4,5]

$Nominal \rightarrow Nominal\ PP$

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

Example : filling the 5th column

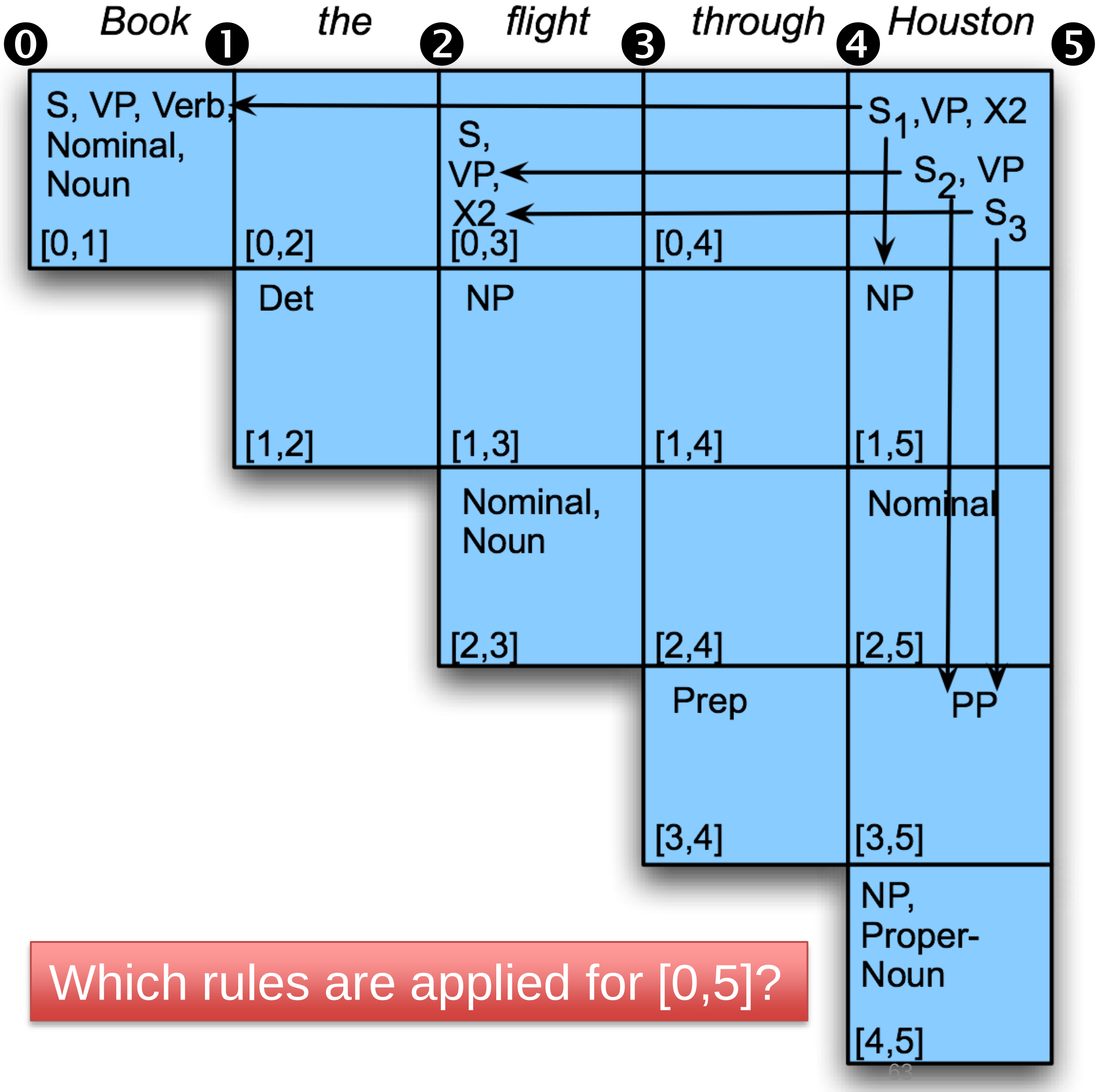


	0 Book 1	the 2	flight 3	through 4	Houston 5
0	S, VP, Verb, Nominal, Noun [0,1]	[0,2]	S,VP,X2 [0,3]	[0,4]	[0,5]
1		Det [1,2]	NP [1,3]	[1,4]	NP [1,5]
2			Nominal, Noun [2,3]	[2,4]	Nominal [2,5]
3				Prep [3,4]	PP [3,5]
4					NP, Proper-Noun [4,5]

$NP \rightarrow Det\ Nominal$

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

Exercise: CKY parsing

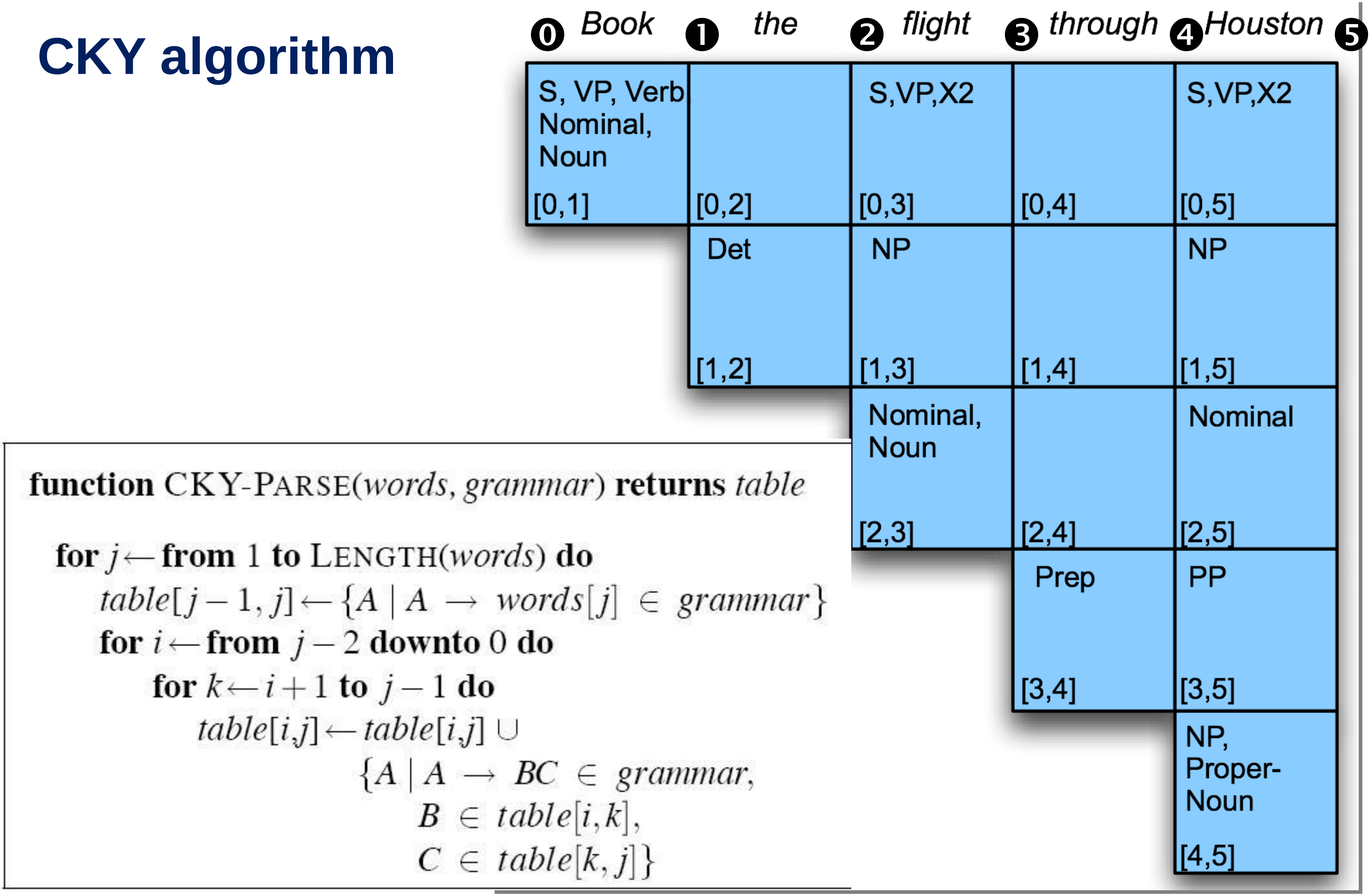


	1	2	3	4	5
0	S, VP, Verb, Nominal, Noun [0,1]	[0,2]	S, VP, X2 [0,3]	[0,4]	S_1,VP, X2 S_2, VP S_3
1		Det [1,2]	NP [1,3]	[1,4]	NP [1,5]
2			Nominal, Noun [2,3]	[2,4]	Nominal [2,5]
3				Prep [3,4]	PP [3,5]
4					NP, Proper-Noun [4,5]

Which rules are applied for [0,5]?

S → NP VP
S → X1 VP
X1 → Aux NP
S → book | include | prefer
S → Verb NP
S → X2 PP
S → Verb PP
S → VP PP
NP → I | she | me
NP → TWA | Houston
NP → Det Nominal
Nominal → book | flight | meal |
Nominal → Nominal Noun
Nominal → Nominal PP
VP → book | include | prefer
VP → Verb NP
VP → X2 PP
X2 → Verb NP
VP → Verb PP
VP → VP PP
PP → Preposition NP

CKY algorithm



⓿ Book ❶ the ❷ flight ❸ through ❹ Houston ❺

S, VP, Verb Nominal, Noun [0,1]	[0,2]	S,VP,X2 [0,3]	[0,4]	S,VP,X2 [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]

```
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
              $table[i,j] \leftarrow table[i,j] \cup$
                         $\{A \mid A \rightarrow BC \in grammar,$
                              $B \in table[i,k],$
                              $C \in table[k,j]\}$
```

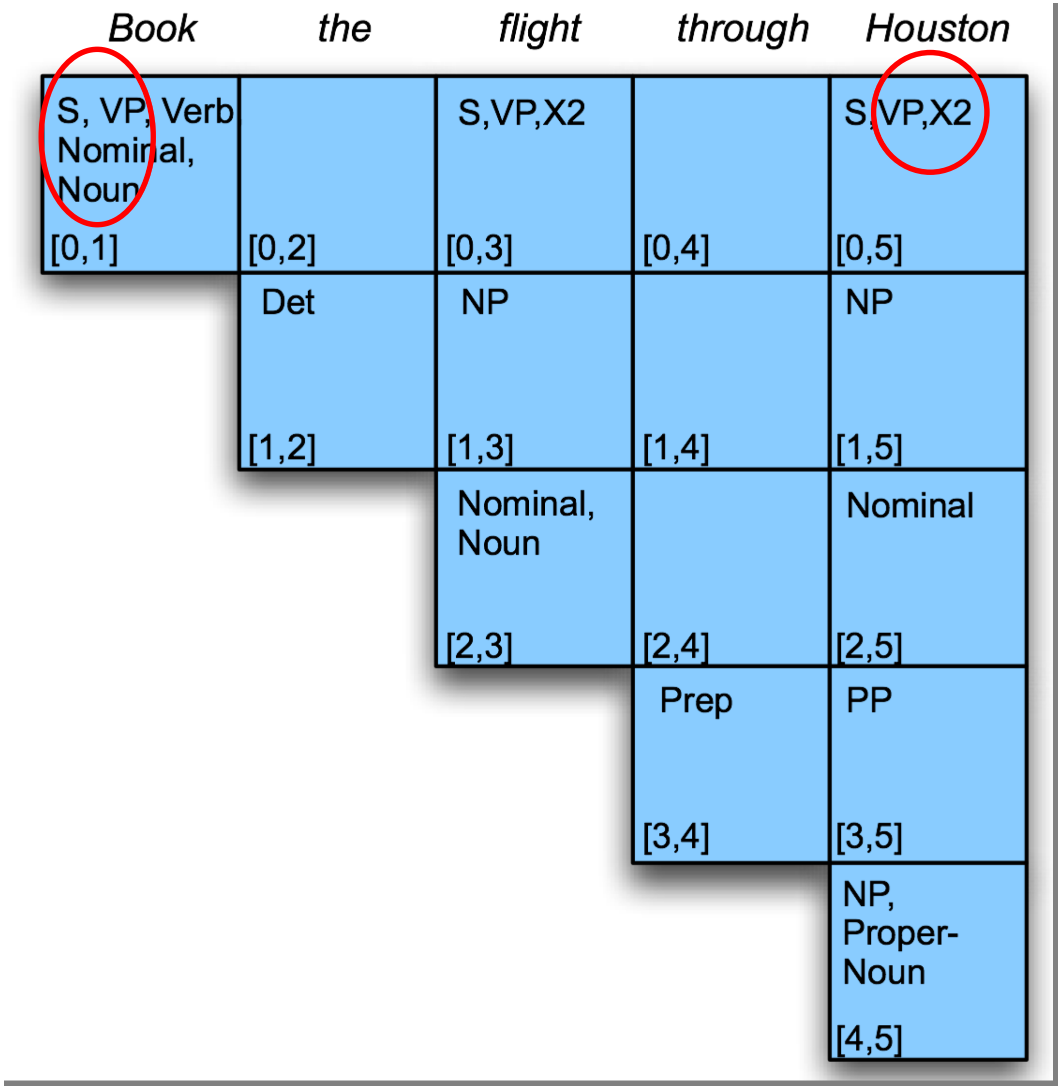
CKY parsing: summary

- 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

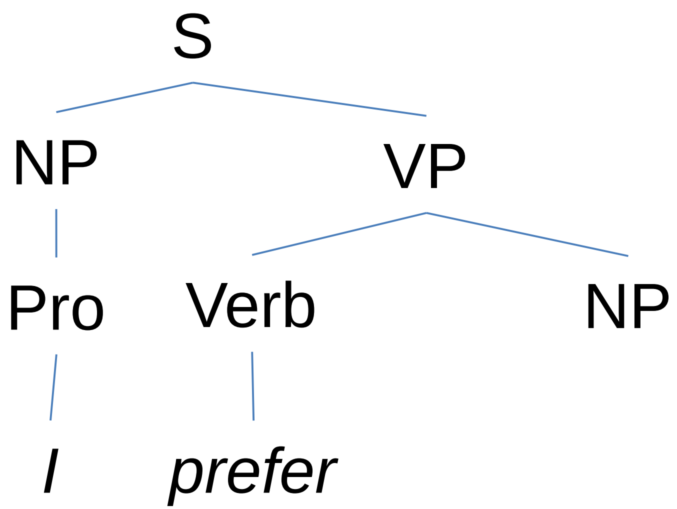
CKY parsing: Issue

- 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.



Book	*the*	*flight*	*through*	*Houston*
S, VP, Verb Nominal, Noun [0,1]	[0,2]	S,VP,X2 [0,3]	[0,4]	S,VP,X2 [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]

Top-down parsing: intermediate state example



1. S → NP VP

2. NP → Pro
   Pro → *I*

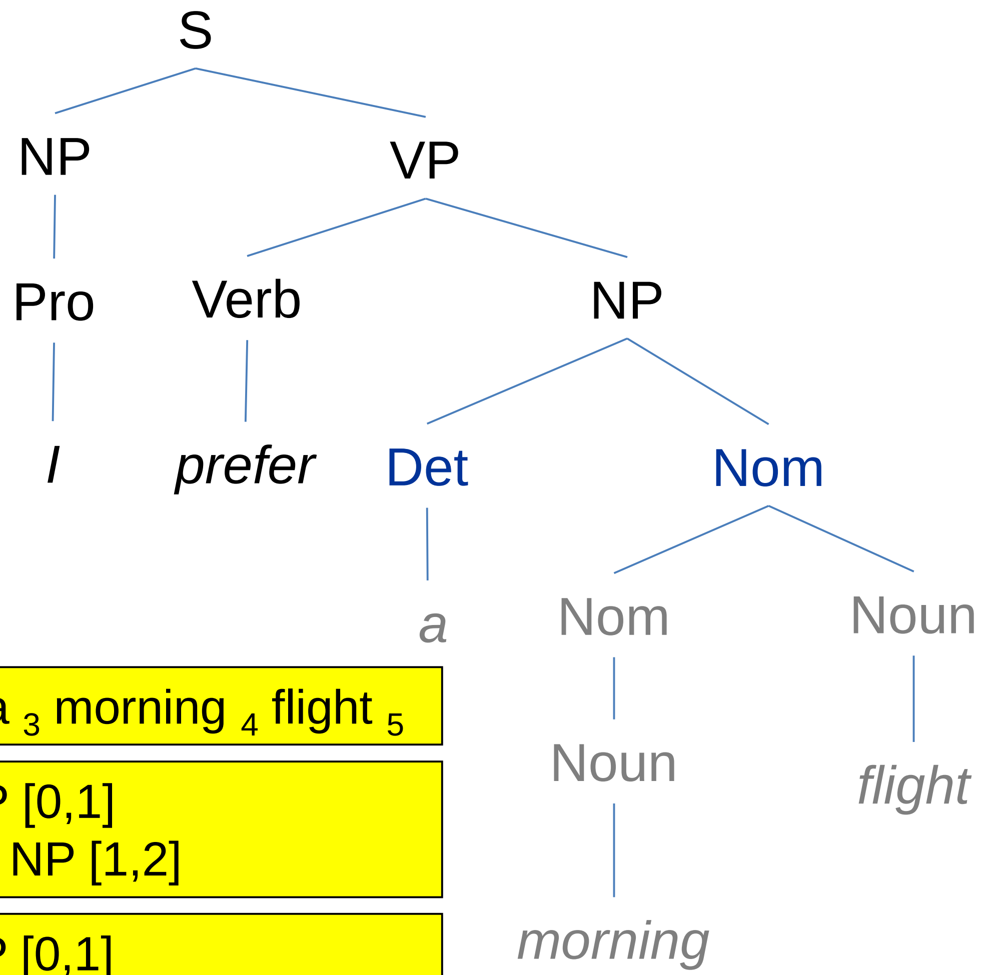
3. VP → Verb NP
   Verb → *prefer*

$_0$ 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

5. Nom → Nom Noun
   Noun → *flight*

6. Nom → Noun
   Noun → *morning*

$_0$ 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

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

- 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

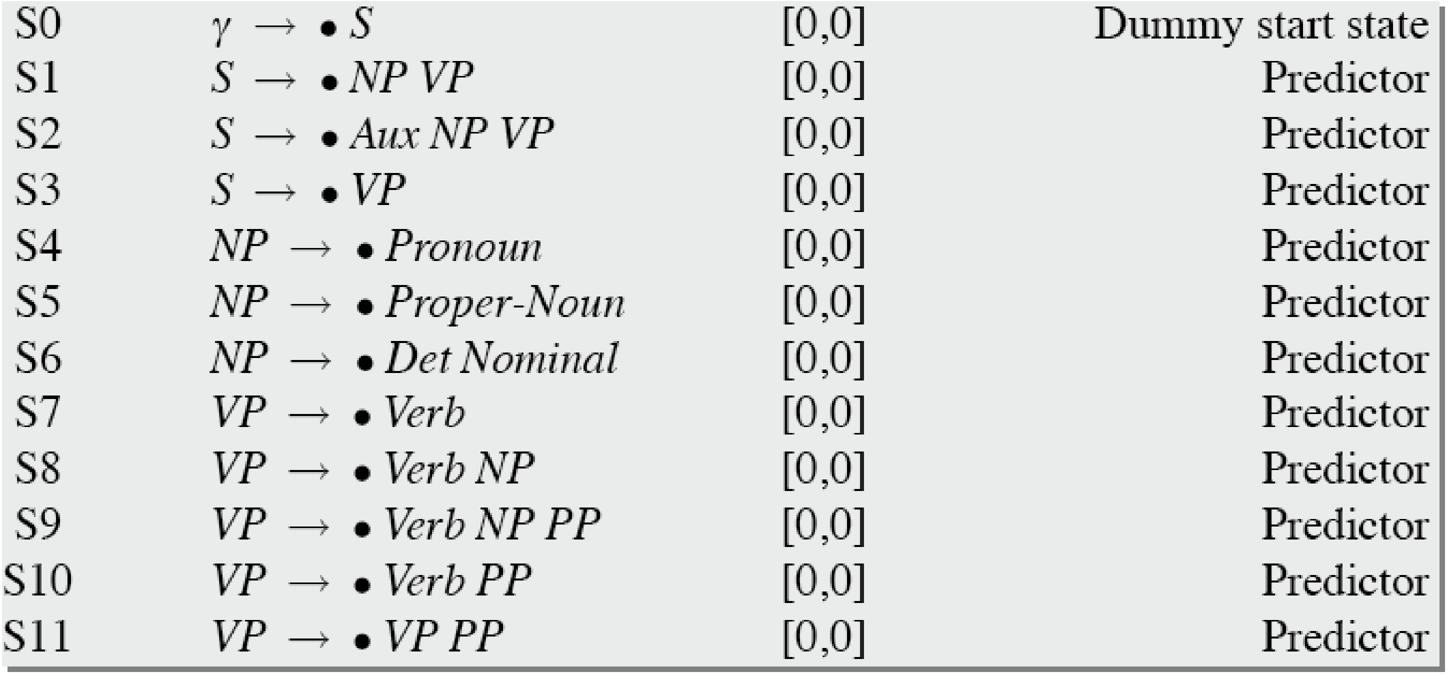
Earley algorithm: How it works

1. Predict all the states you can upfront [**Predictor**]

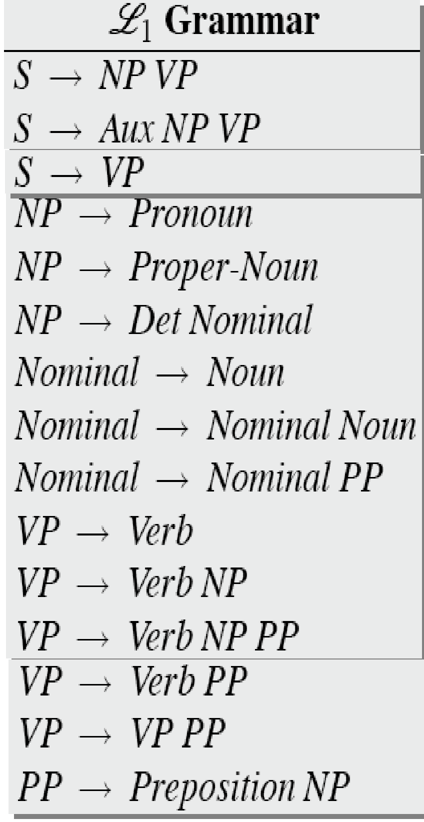
2. Read a word [**Scanner**]
   - Extend states based on matches [**Completer**]
   - Generate new predictions
   - Repeat step 2

3. When you’re out of words, look at the chart to see if you have a winner

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



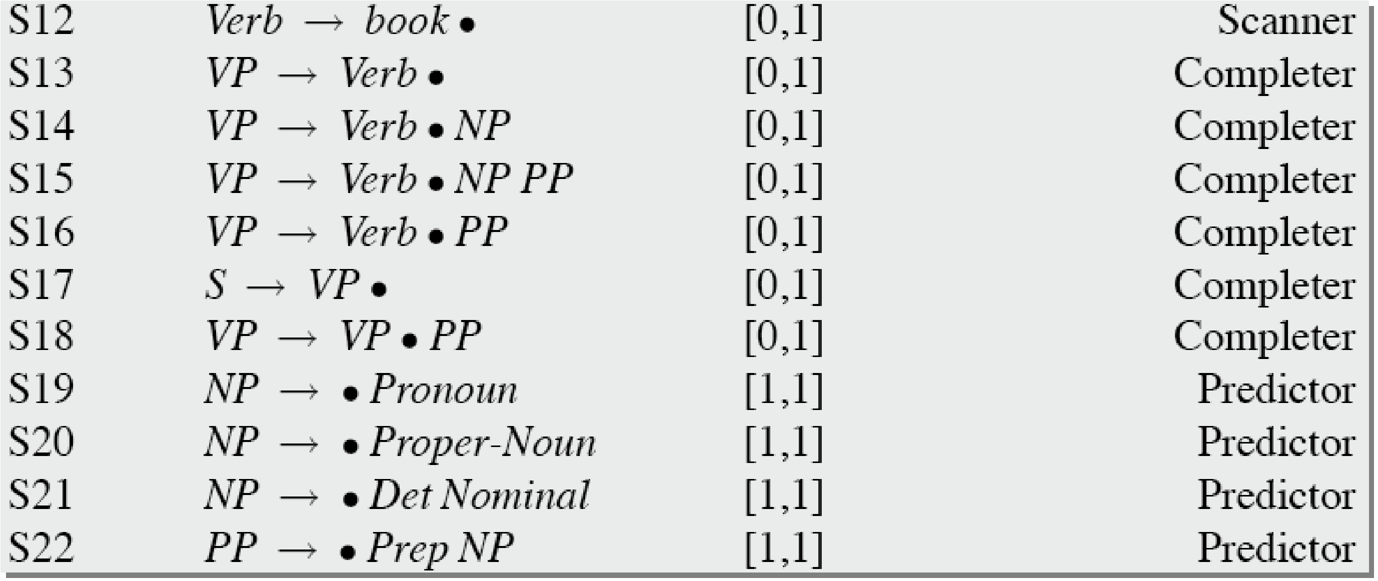
S0	$\gamma \rightarrow \bullet S$	[0,0]	Dummy start state
S1	$S \rightarrow \bullet NP\ VP$	[0,0]	Predictor
S2	$S \rightarrow \bullet Aux\ NP\ VP$	[0,0]	Predictor
S3	$S \rightarrow \bullet VP$	[0,0]	Predictor
S4	$NP \rightarrow \bullet Pronoun$	[0,0]	Predictor
S5	$NP \rightarrow \bullet Proper\text{-}Noun$	[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



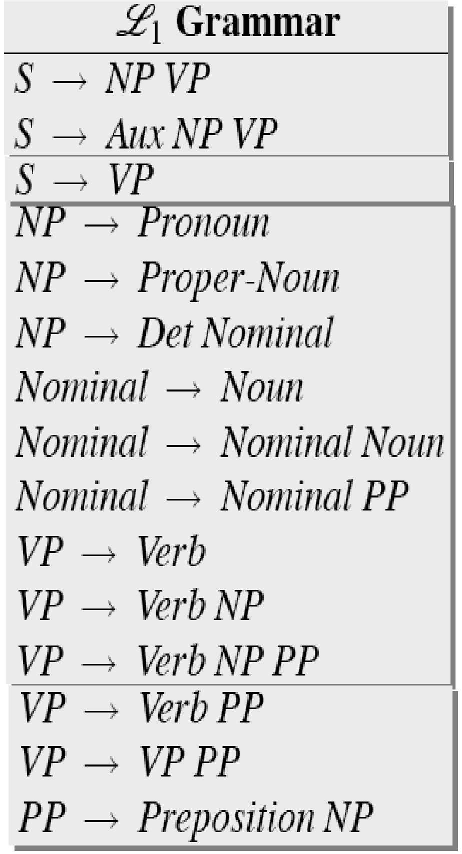
$\mathscr{L}_1$ **Grammar**
$S \rightarrow NP\ VP$
$S \rightarrow Aux\ NP\ VP$
$S \rightarrow VP$
$NP \rightarrow Pronoun$
$NP \rightarrow Proper\text{-}Noun$
$NP \rightarrow Det\ Nominal$
$Nominal \rightarrow Noun$
$Nominal \rightarrow Nominal\ Noun$
$Nominal \rightarrow Nominal\ PP$
$VP \rightarrow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

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

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



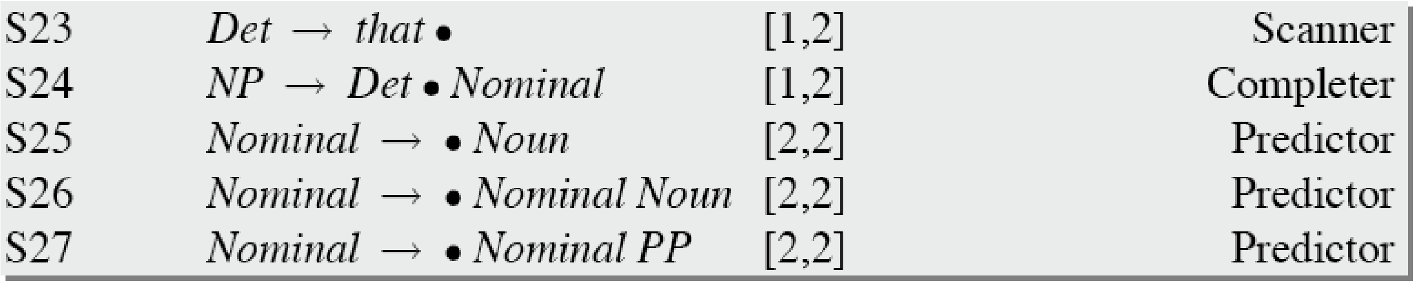
S12	*Verb* → *book* •	[0,1]	Scanner
S13	*VP* → *Verb* •	[0,1]	Completer
S14	*VP* → *Verb* • *NP*	[0,1]	Completer
S15	*VP* → *Verb* • *NP PP*	[0,1]	Completer
S16	*VP* → *Verb* • *PP*	[0,1]	Completer
S17	*S* → *VP* •	[0,1]	Completer
S18	*VP* → *VP* • *PP*	[0,1]	Completer
S19	*NP* → • *Pronoun*	[1,1]	Predictor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



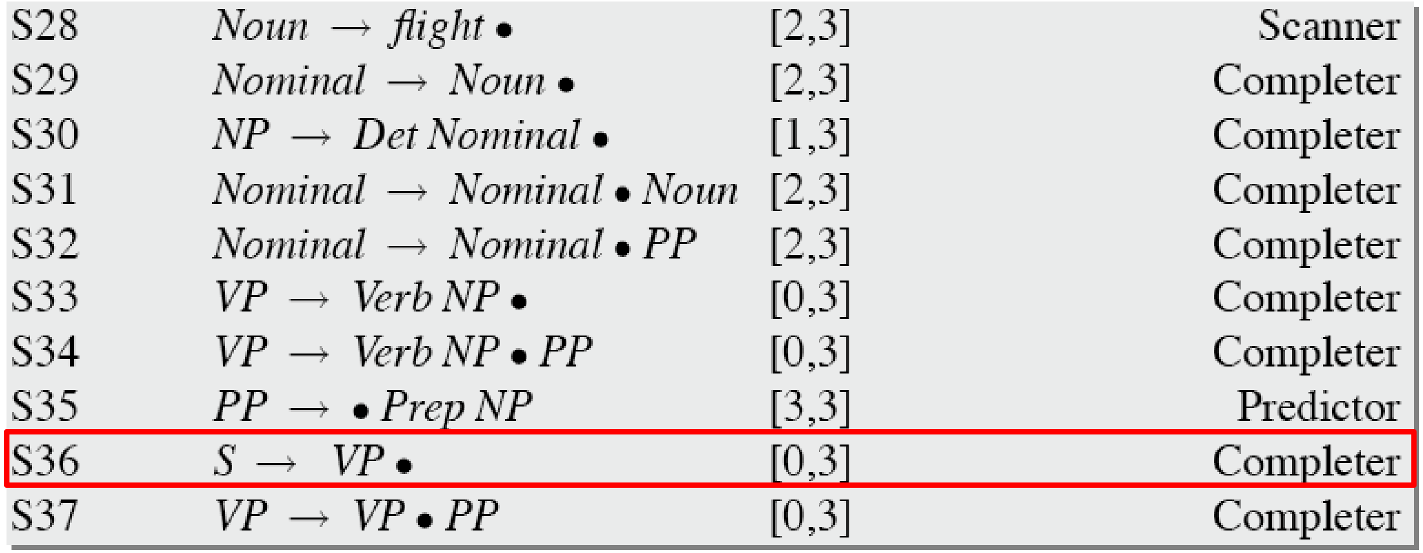
$\mathscr{L}_1$ **Grammar**
S → *NP VP*
S → *Aux NP VP*
S → *VP*
NP → *Pronoun*
NP → *Proper-Noun*
NP → *Det Nominal*
Nominal → *Noun*
Nominal → *Nominal Noun*
Nominal → *Nominal PP*
VP → *Verb*
VP → *Verb NP*
VP → *Verb NP PP*
VP → *Verb PP*
VP → *VP PP*
PP → *Preposition NP*

Note that “Noun → book• [,] can be also scanned

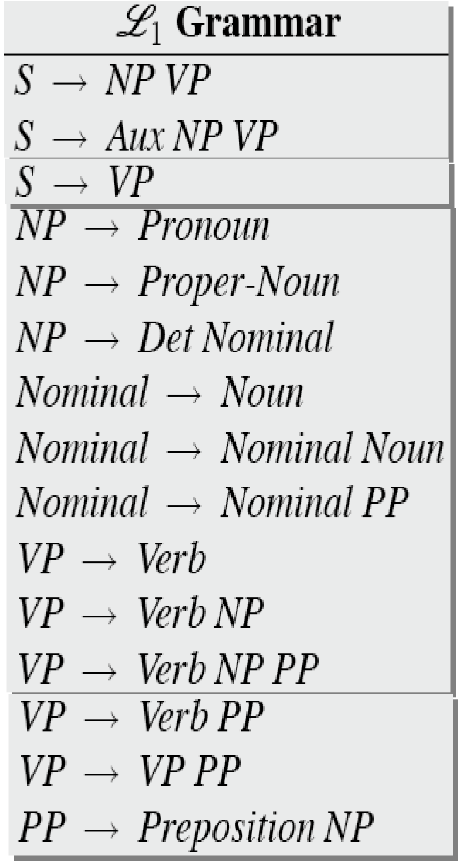
Earley algorithm: Example (3) $_0$ Book $_1$ that $_2$ flight $_3$



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

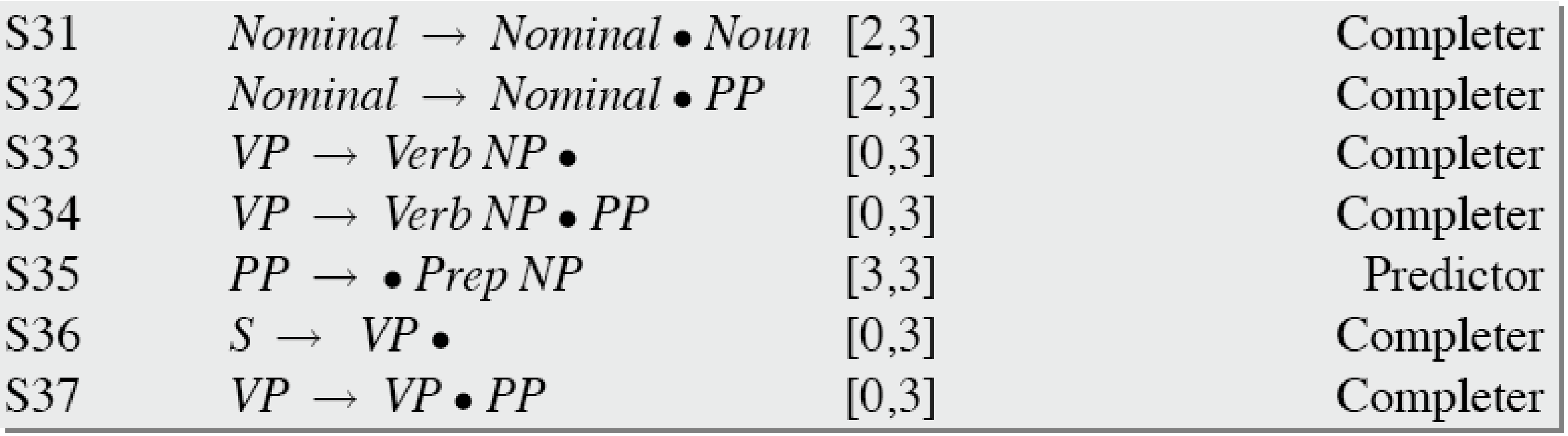


$\mathscr{L}_1$ **Grammar**
S → *NP VP*
S → *Aux NP VP*
S → *VP*
NP → *Pronoun*
NP → *Proper-Noun*
NP → *Det Nominal*
Nominal → *Noun*
Nominal → *Nominal Noun*
Nominal → *Nominal PP*
VP → *Verb*
VP → *Verb NP*
VP → *Verb NP PP*
VP → *Verb PP*
VP → *VP PP*
PP → *Preposition NP*

Earley algorithm: Summary (Pseudo codes: Section 13.4.2)

- Top-down approach
  - Breadth-first search
  - State representation
    - (compare with 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

Review

Top-down vs. Bottom-up parsing

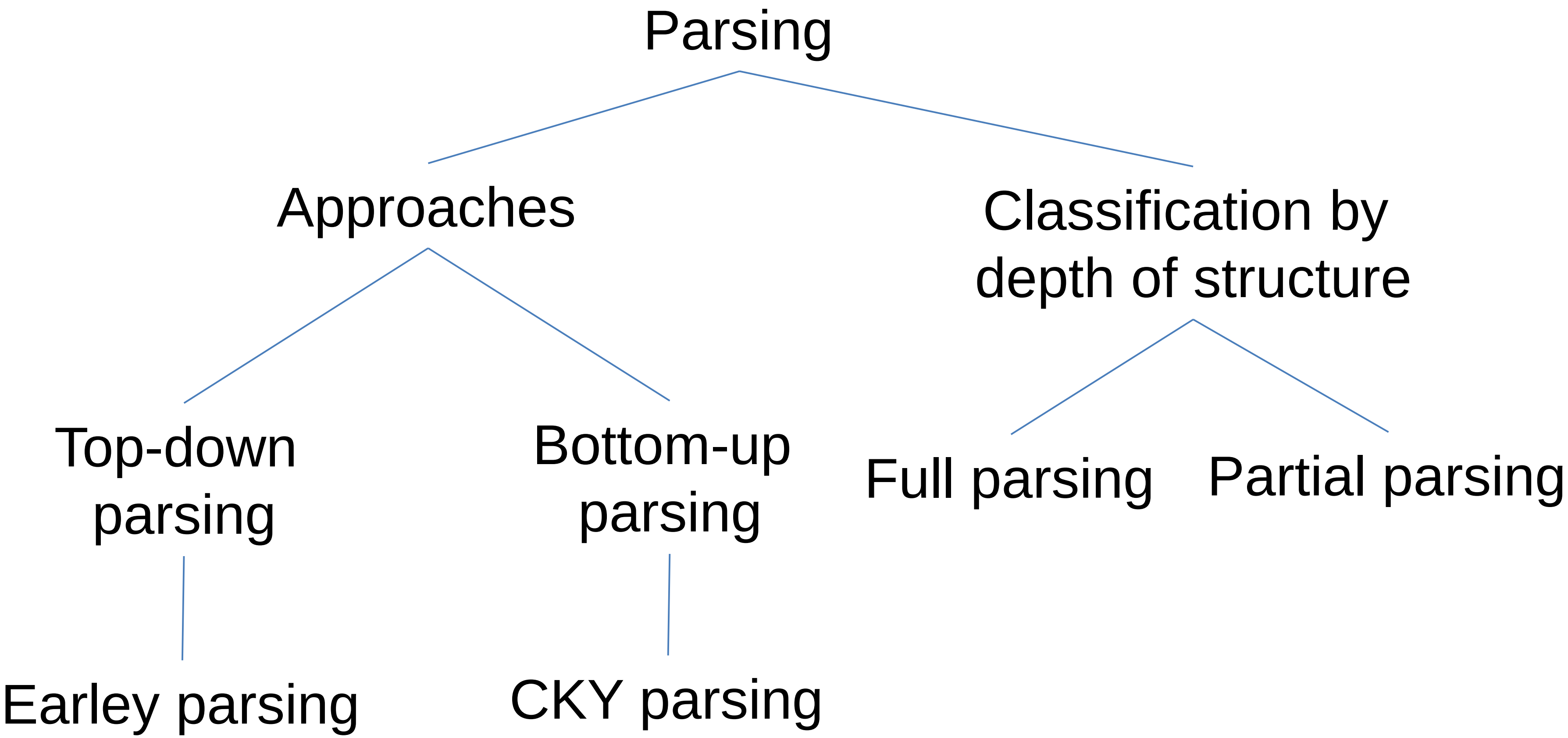
- Top-down
  - Waste lots of time in trying inconsistent rule applications. The application of the rules does not lead the generation of the given string
  - Never explore subtrees that cannot find a place in some S-rooted tree. All trees are generated starting with S.
- Bottom-up
  - Never suggest trees that are not grounded in the input string. All trees are generated based on input string
  - Trees that have no hope of leading to an S are generated. Some trees cannot proceed further to reach S

Full parsing vs. Partial parsing

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

- Partial parsing
  - Identify parts of the syntactic structure of a sentence
  - Not all applications require full syntactic structures. Example: only Noun phrases need to be extracted in some applications but not the full syntactic structure of the sentence.

Summary



Parsing

Approaches

Classification by depth of structure

Top-down parsing

Bottom-up parsing

Full parsing

Partial parsing

Earley parsing

CKY parsing

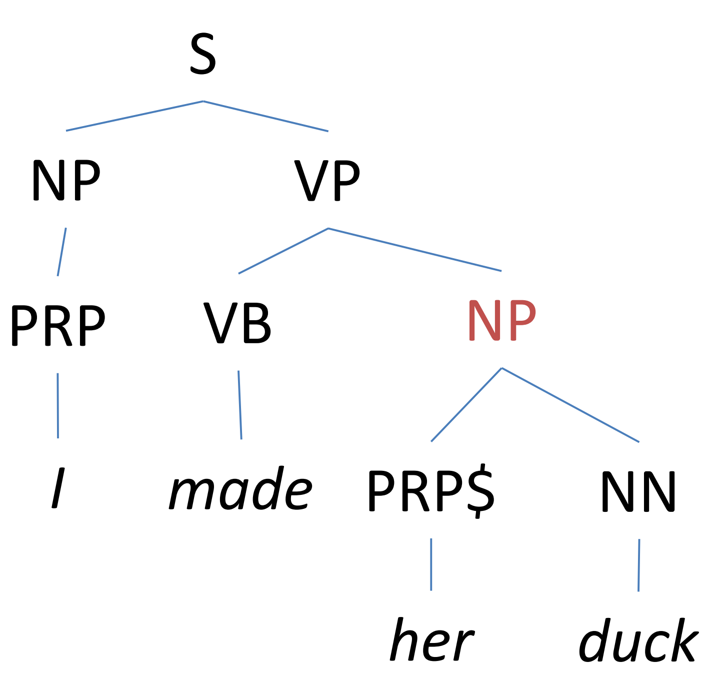
Review

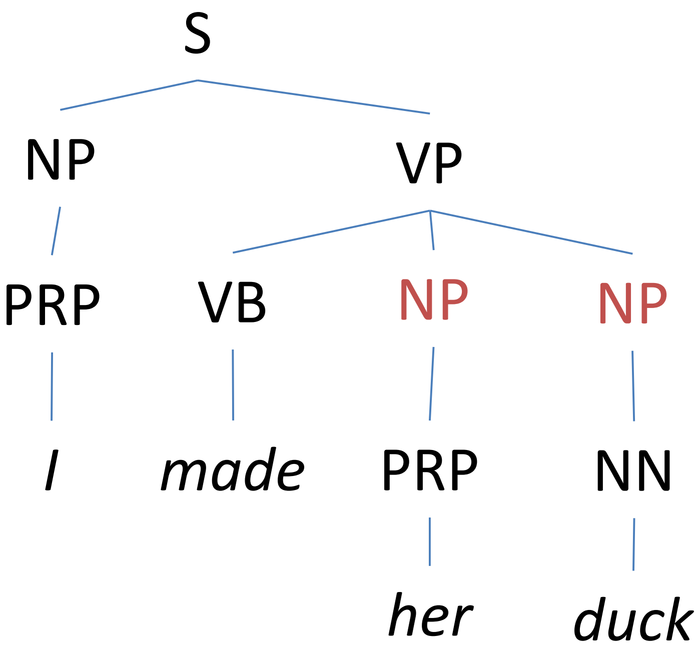
Ambiguity is Pervasive

- Find at least 5 meanings of this sentence: **I made her duck**

- Possible meanings
  - I cooked waterfowl for her
  - I cooked waterfowl belonging to her
  - I created the (plaster?) duck she owns
  - I caused her to quickly lower her head and body
  - I waved my magic wand and turned her into undifferentiated waterfowl

Ambiguity Resolution by Syntactic Structures





I cooked waterfowl belonging to her
I created the duck she owns

I cooked waterfowl for her benefit
I waved my magic wand and turned
her into undifferentiated waterfowl

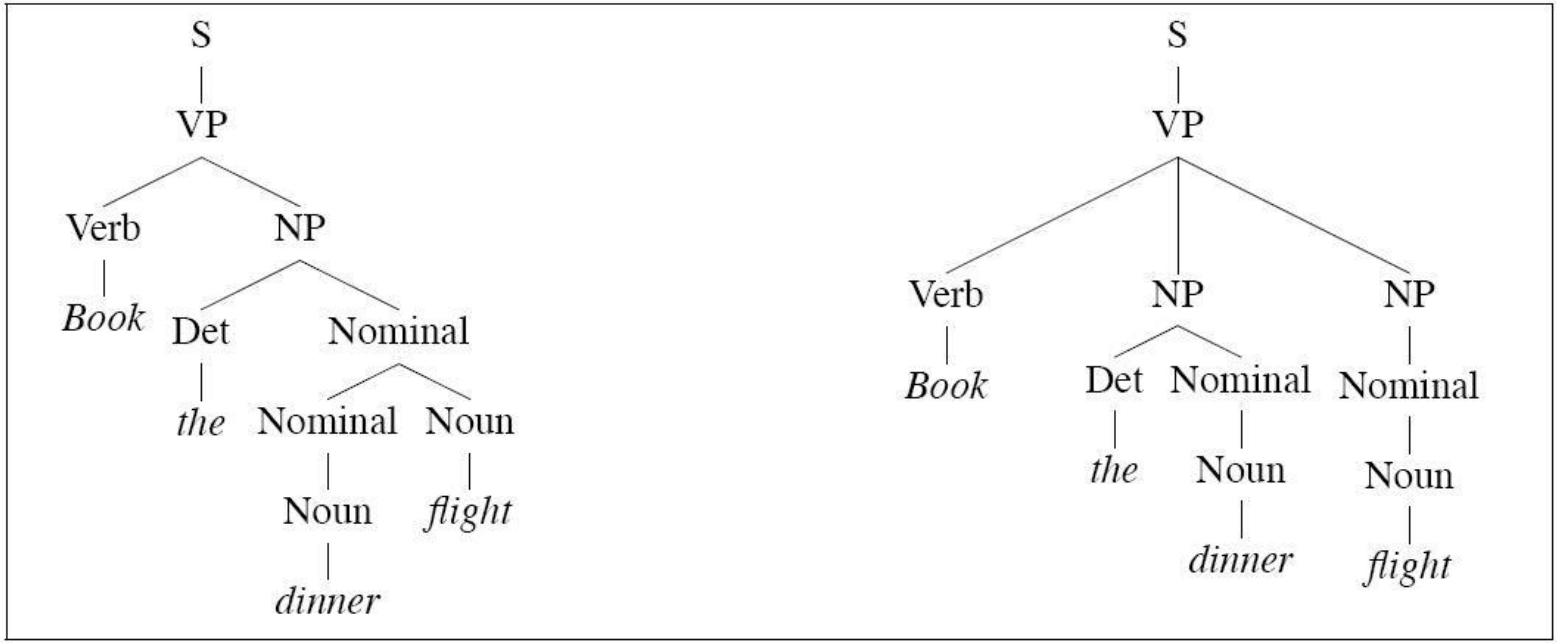
Exercise: Attachment Ambiguity

- How many distinct phrase structures may the following sentence have due to the prepositional phrase attachment ambiguities?

John wrote the book with a pen in the room

Need for Syntactic Disambiguation

- Consider the two parses of “Book the dinner flight”
- The left parse is sensible, while the right is not
  - How about “Can you book John a flight?”



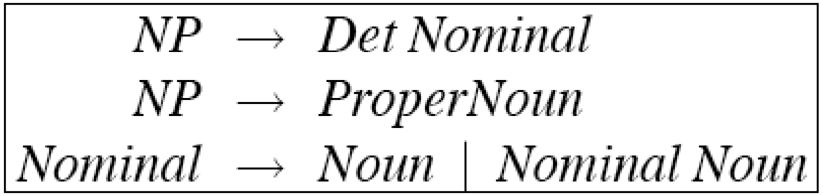
Need for Common Sense

- People usually provide **only useful information** and take the rest for granted. The rest is common-sense: obvious things people know and usually leave unstated

Context-Free Grammar

Review

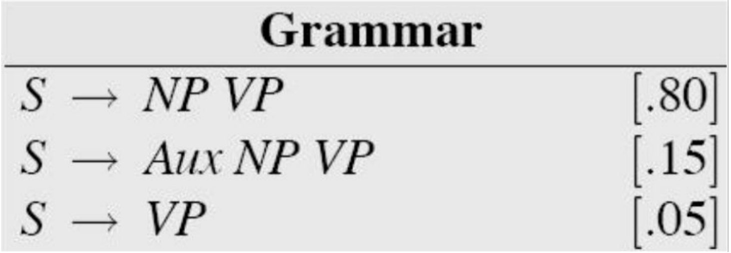
- G = (T, N, S, R)
  - T: a set of terminals (e.g. ‘flight’)
  - N: a set of non-terminals (e.g. Noun)
  - S: the start symbol, a non-terminal
  - R: rules of the form X →γ
    - X: a non-terminal
    - γ: a sequence of terminals and non-terminals



$$\begin{array}{rcl} NP & \longrightarrow & Det\ Nominal \\ NP & \longrightarrow & ProperNoun \\ Nominal & \longrightarrow & Noun \mid Nominal\ Noun \end{array}$$

Probabilistic Context-Free Grammar (PCFG)

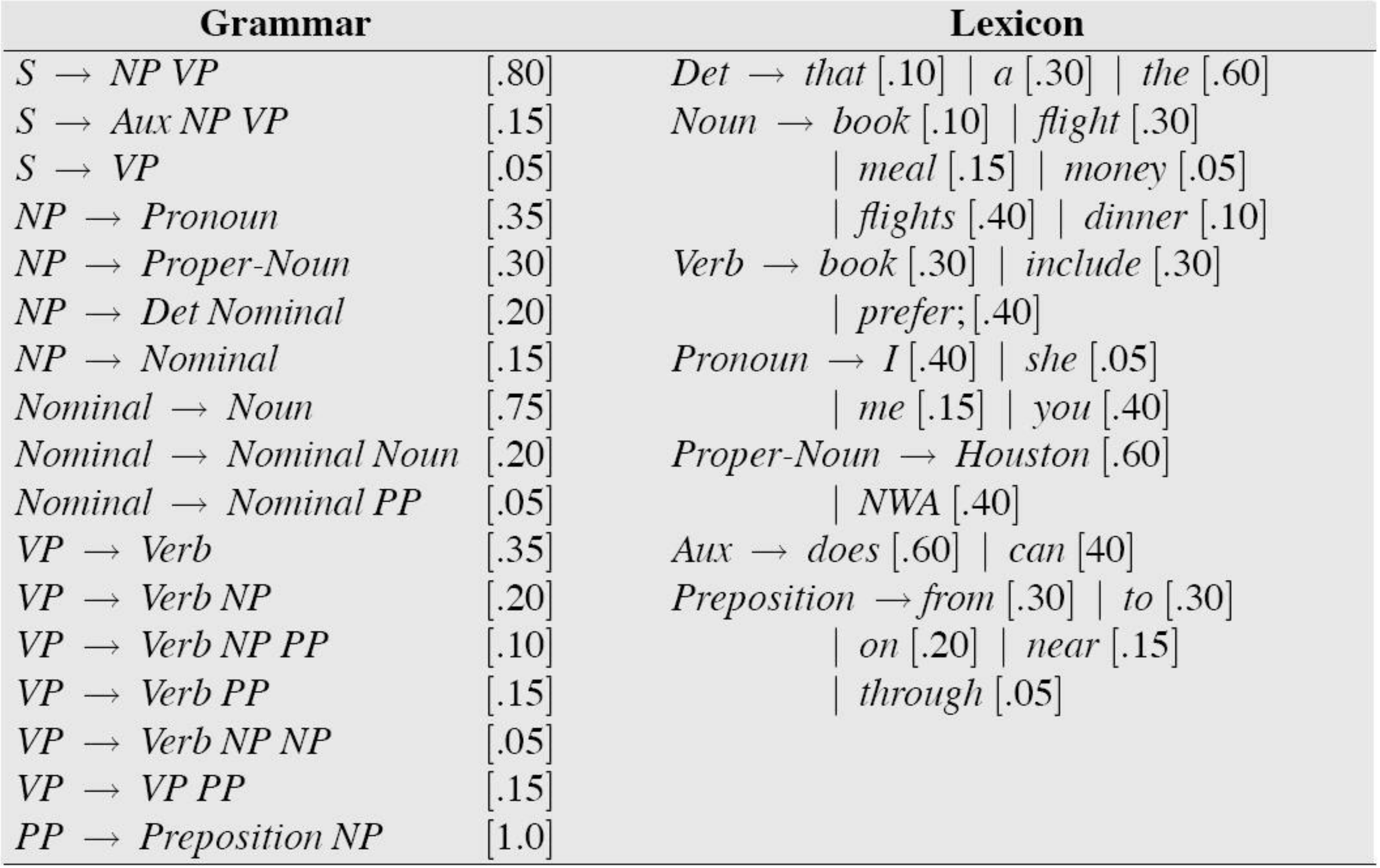
- G = (T, N, S, R, P)
  - T: a set of terminals (e.g. ‘boy’)
  - N: a set of non-terminals (e.g. Noun)
  - S: the start symbol, a non-terminal
  - R: rules of the form X →γ
  - P(R) gives the probability of each rule



Grammar	
$S \rightarrow NP\ VP$	[.80]
$S \rightarrow Aux\ NP\ VP$	[.15]
$S \rightarrow VP$	[.05]

$$\forall X \in N, \sum_{X \rightarrow \gamma \in R} P(X \rightarrow \gamma) = 1$$

PCFG: Example



Grammar		Lexicon
S → *NP VP*	[.80]	*Det* → *that* [.10] | *a* [.30] | *the* [.60]
S → *Aux NP VP*	[.15]	*Noun* → *book* [.10] | *flight* [.30]
S → *VP*	[.05]	| *meal* [.15] | *money* [.05]
NP → *Pronoun*	[.35]	| *flights* [.40] | *dinner* [.10]
NP → *Proper-Noun*	[.30]	*Verb* → *book* [.30] | *include* [.30]
NP → *Det Nominal*	[.20]	| *prefer;* [.40]
NP → *Nominal*	[.15]	*Pronoun* → *I* [.40] | *she* [.05]
Nominal → *Noun*	[.75]	| *me* [.15] | *you* [.40]
Nominal → *Nominal Noun*	[.20]	*Proper-Noun* → *Houston* [.60]
Nominal → *Nominal PP*	[.05]	| *NWA* [.40]
VP → *Verb*	[.35]	*Aux* → *does* [.60] | *can* [40]
VP → *Verb NP*	[.20]	*Preposition* → *from* [.30] | *to* [.30]
VP → *Verb NP PP*	[.10]	| *on* [.20] | *near* [.15]
VP → *Verb PP*	[.15]	| *through* [.05]
VP → *Verb NP NP*	[.05]	
VP → *VP PP*	[.15]	
PP → *Preposition NP*	[1.0]	

PCFG

- How to learn the probability of rules?

$$\forall X \in N, \sum_{X \to \gamma \in R} P(X \to \gamma) = 1$$

- How to estimate the probability of parse trees with a PCFG?

- Once we have probabilities of possible parse trees, we can select the parse tree with the highest probability as the parse result for a given string

Probability of Rules

- Need for treebanks! $P(X \to \beta \mid X)$

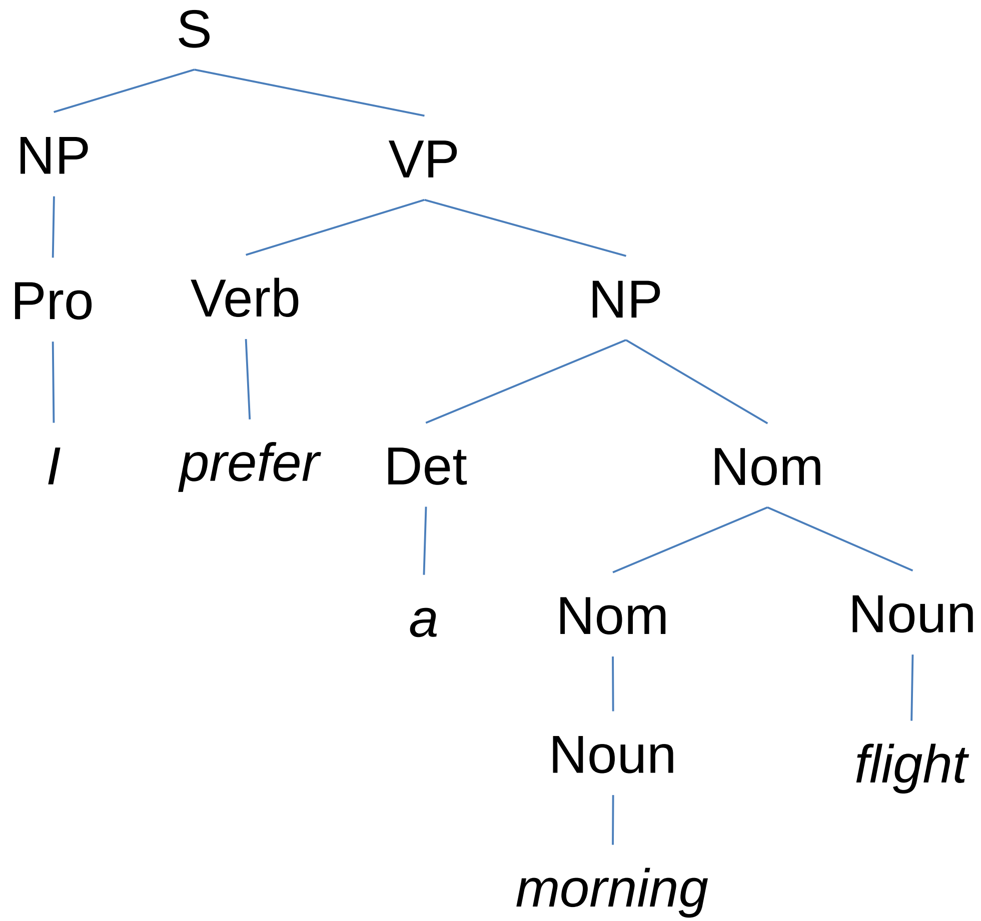
$$P(X \to \beta \mid X) = \frac{\text{count}(X \to \beta)}{\sum_{\gamma} \text{count}(X \to \gamma)} = \frac{\text{count}(X \to \beta)}{\text{count}(X)}$$

$$\forall X \in N, \; \sum_{X \to \gamma \in R} P(X \to \gamma) = 1$$

Review

Derivation

- A derivation (parse tree) consists of the bag of grammar rules that are in the tree



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 → morning
6. Nom → Noun
   Noun → flight

Probability of Parse Trees

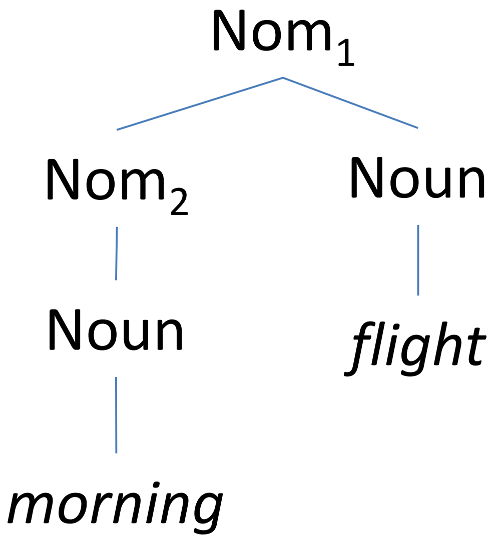
- A derivation (parse tree) consists of the bag of grammar rules that are in the tree
  - The probability of a tree is the product of the probabilities of the rules in the derivation.

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 → morning
6. Nom → Noun
   Noun → flight

$$P(T,S) = \prod_{node \in T} P(rule(n))$$

Probability of Parse Tree: Example

- Noun → morning [0.10]
- Noun → flight [0.40]
- Nom → Noun [0.75]
- Nom → Nom Noun [0.20]

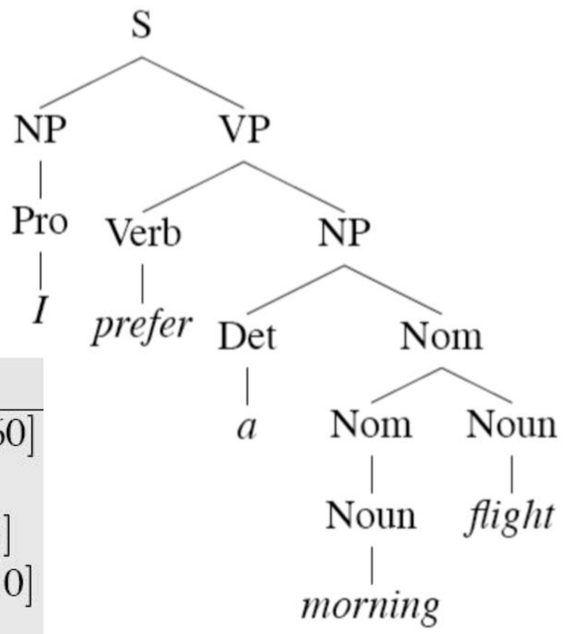


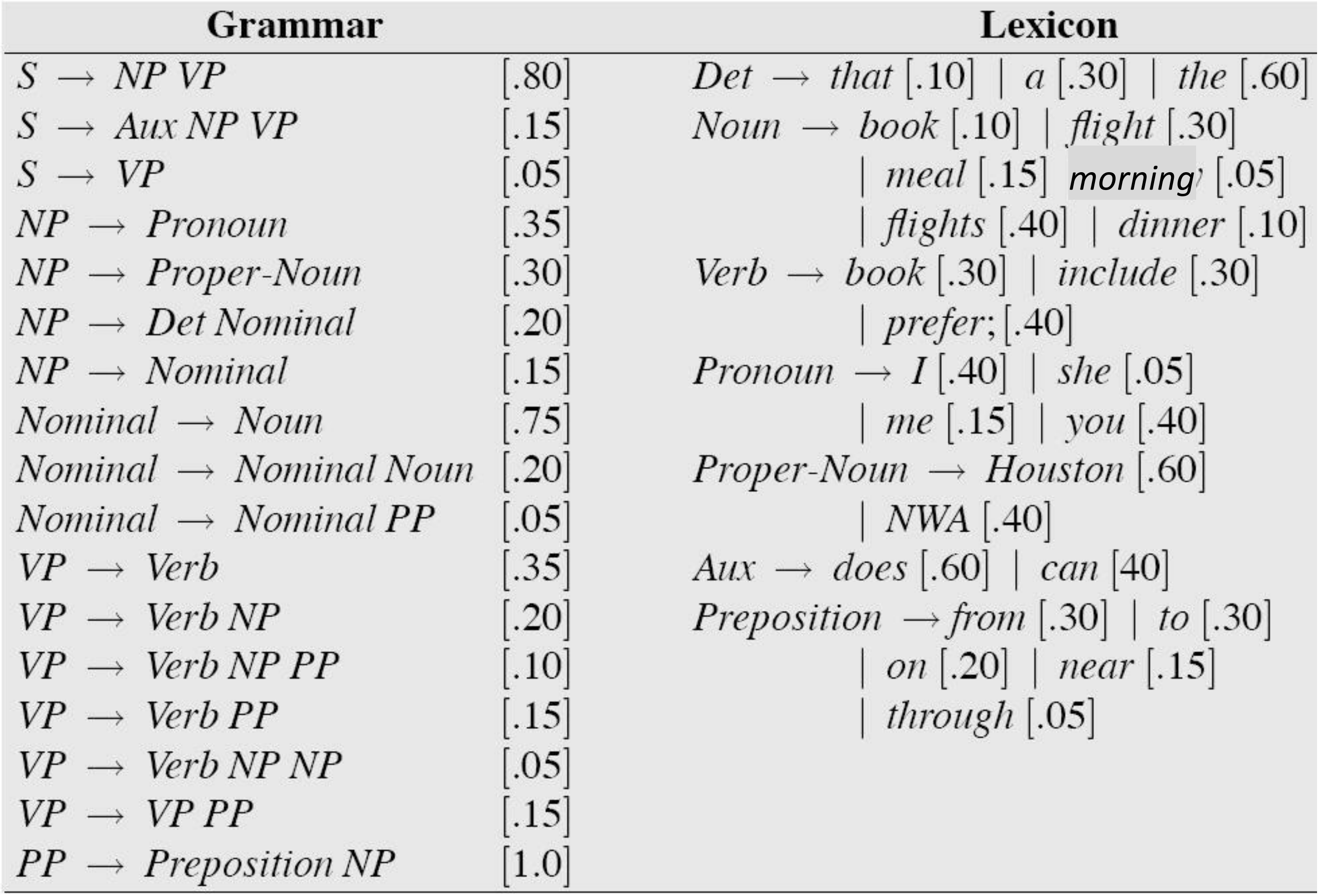
$$P(Nom_2) = 0.75 \times 0.1 = 0.75 \times 10^{-1}$$

$$P(Nom_1) = 0.2 \text{ ´ } 0.75 \text{ ´ } 10^{-1} \text{ ´ } 0.4 = 0.6 \text{ ´ } 10^{-2}$$

Exercise: Probability of Parse Tree

- Calculate the probability of the parse tree below





Grammar		Lexicon
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S → *VP*	[.05]	| *meal* [.15] morning [.05]
NP → *Pronoun*	[.35]	| *flights* [.40] | *dinner* [.10]
NP → *Proper-Noun*	[.30]	*Verb* → *book* [.30] | *include* [.30]
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NP → *Nominal*	[.15]	*Pronoun* → *I* [.40] | *she* [.05]
Nominal → *Noun*	[.75]	| *me* [.15] | *you* [.40]
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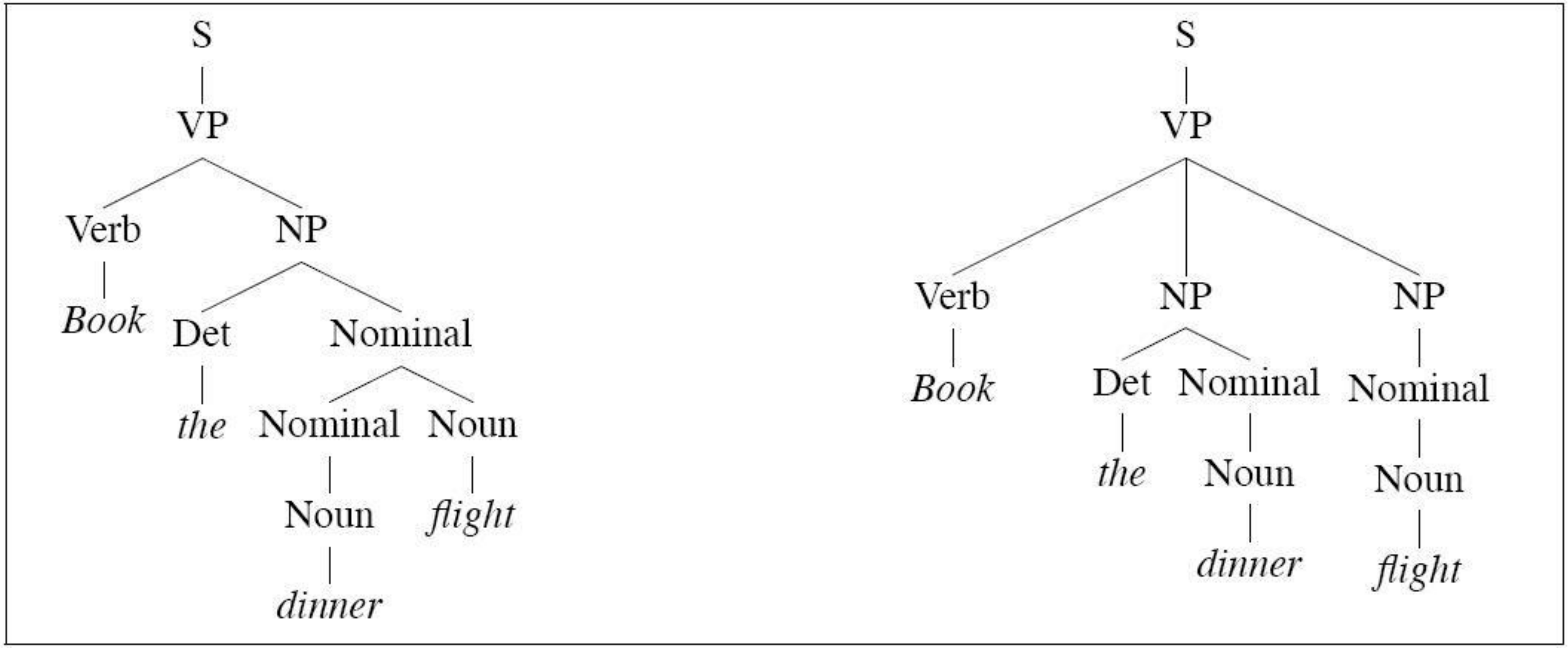
VP → *Verb NP PP*	[.10]	| *on* [.20] | *near* [.15]
VP → *Verb PP*	[.15]	| *through* [.05]
VP → *Verb NP NP*	[.05]	
VP → *VP PP*	[.15]	
PP → *Preposition NP*	[1.0]	

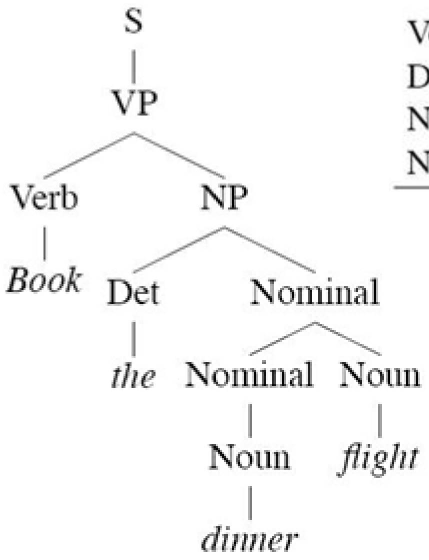
Why Do We Need Probability of Parse Trees?

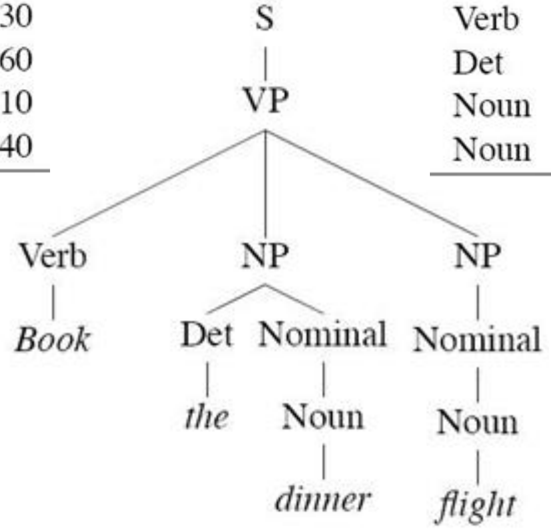
- Once we have probabilities of possible parse trees, we can select the parse tree with the highest probability as the parse result for a given string



Why Do We Need Probability of Parse Trees?

Rules			P
S	→	VP	.05
VP	→	Verb NP	.20
NP	→	Det Nominal	.20
Nominal	→	Nominal Noun	.20
Nominal	→	Noun	.75
Verb	→	book	.30
Det	→	the	.60
Noun	→	dinner	.10
Noun	→	flights	.40





Rules			P
S	→	VP	.05
VP	→	Verb NP NP	.10
NP	→	Det Nominal	.20
NP	→	Nominal	.15
Nominal	→	Noun	.75
Nominal	→	Noun	.75
Verb	→	book	.30
Det	→	the	.60
Noun	→	dinner	.10
Noun	→	flights	.40

$$P(T_{left}) = .05 * .20 * .20 * .20 * .75 * .30 * .60 * .10 * .40 = \mathbf{2.2 \times 10^{-6}}$$

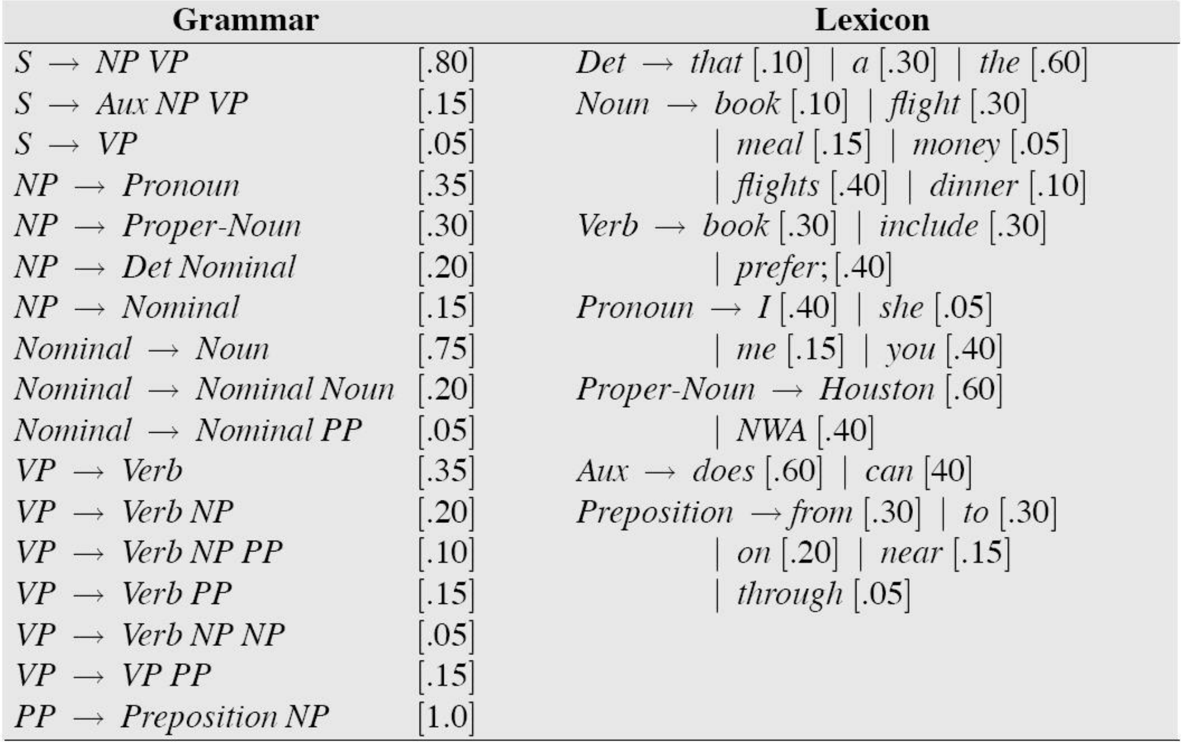
$$P(T_{right}) = .05 * .10 * .20 * .15 * .75 * .75 * .30 * .60 * .10 * .40 = \mathbf{6.1 \times 10^{-7}}$$

But How Accurate/General Are These Probabilities?

- Probabilities are bound to specific datasets or corpora and, in general, are not domain-independent

Problems with PCFG

- Doesn’t take the actual words (Grammar) into account
  - – e.g., verb subcategorization
- Doesn’t take into account where in the derivation a rule is used
  - – e.g., NPs that are syntactic objects are more likely to be Pronouns.



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VP → *Verb PP*	[.15]	| *through* [.05]
VP → *Verb NP NP*	[.05]	
VP → *VP PP*	[.15]	
PP → *Preposition NP*	[1.0]	

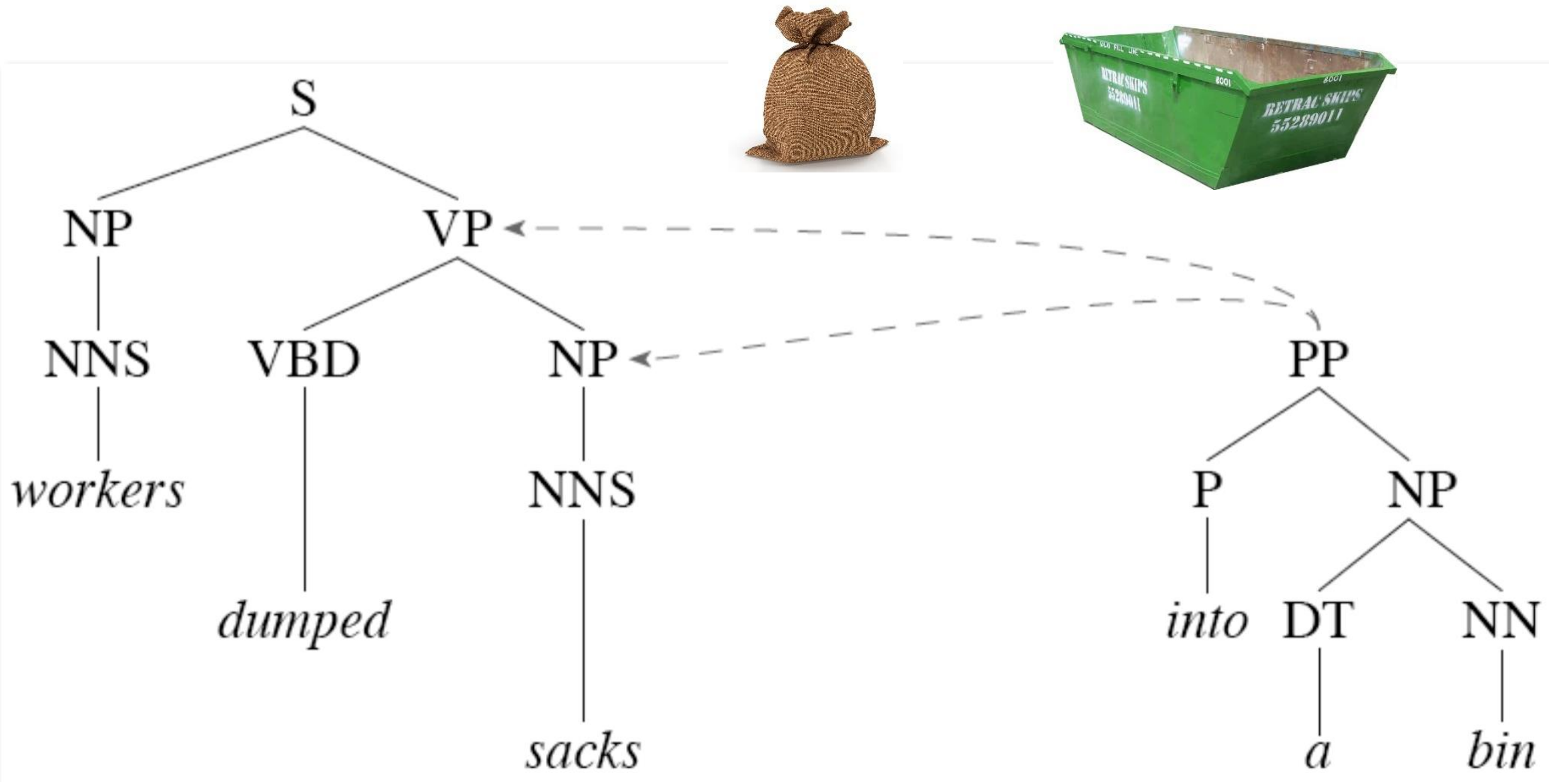
Specific Problems

- Attachment ambiguities
  - Prepositional phrase (PP) attachment
  - Coordination problem

- Structural dependencies between rules

PP Attachment

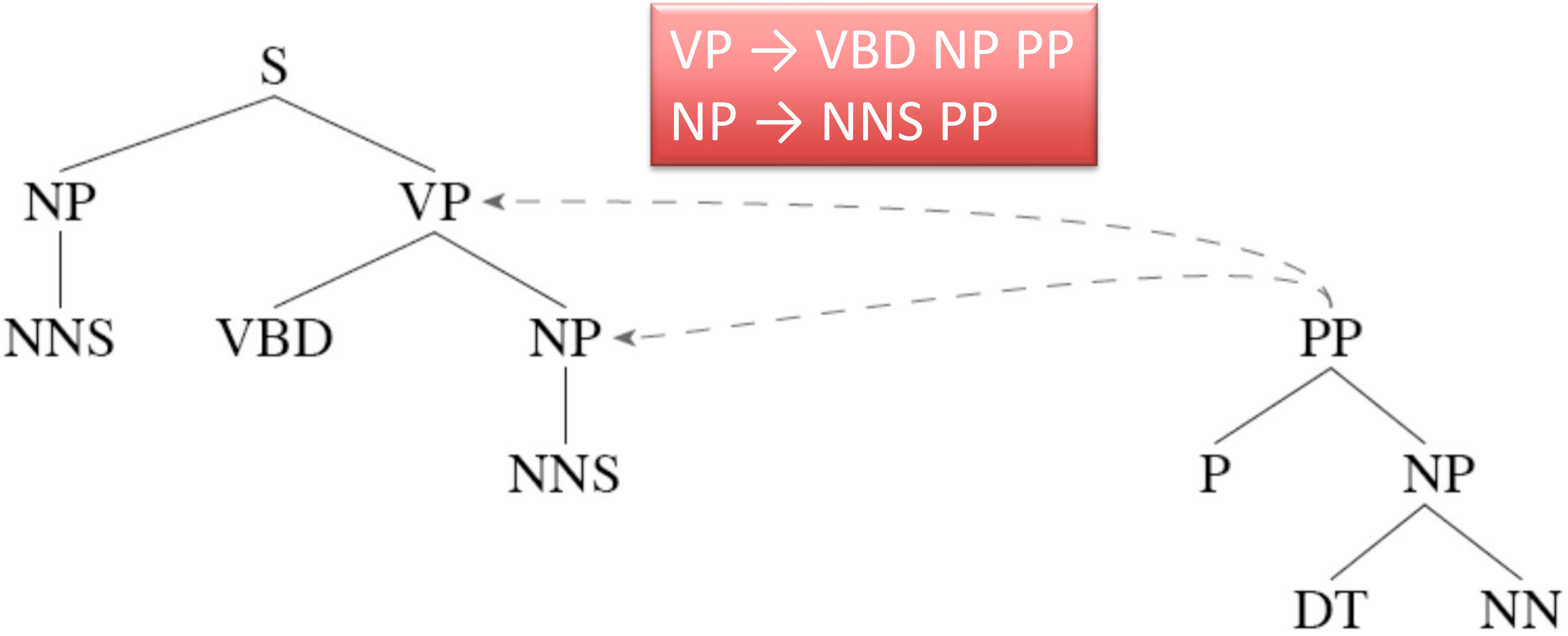
- Example sentence: Workers dumped sacks into a bin.



‘Dump’ has a stronger association with ‘into’

PP Attachment

- NNS VBD NNS P DT NN
  - Rule does not consider the actual words in the sentence.
  - So we are not using the actual words here, but only the rules

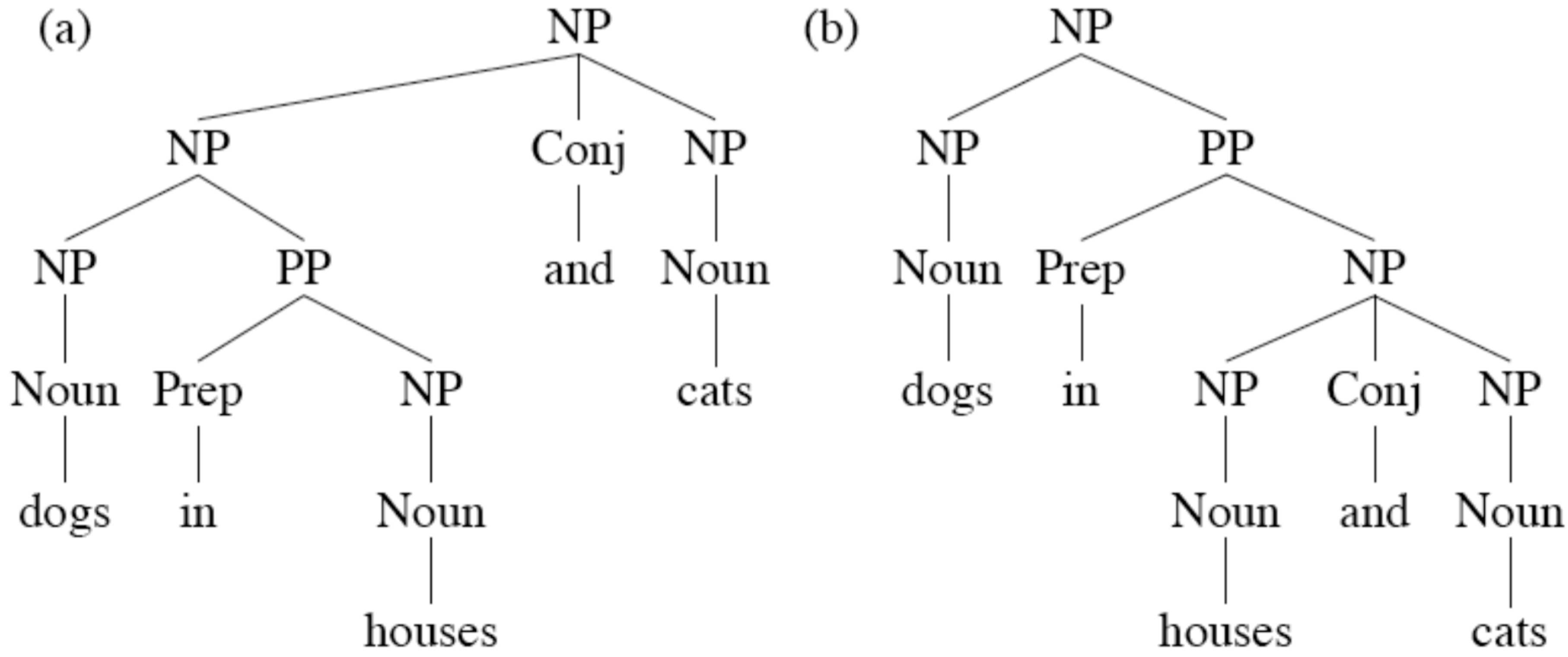

VP → VBD NP PP

NP → NNS PP

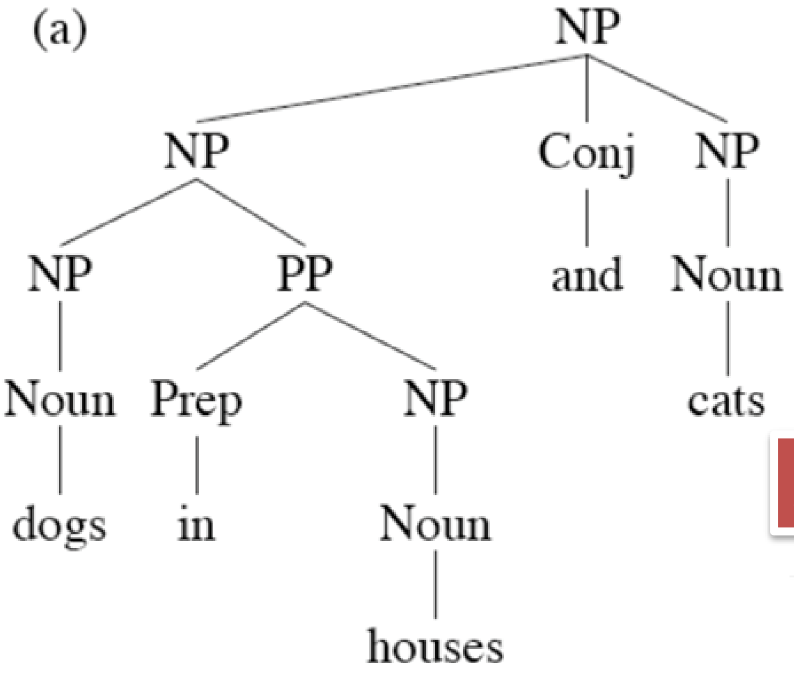
Both rules are valid, and we cannot determine the attachment here.

Coordination Problem

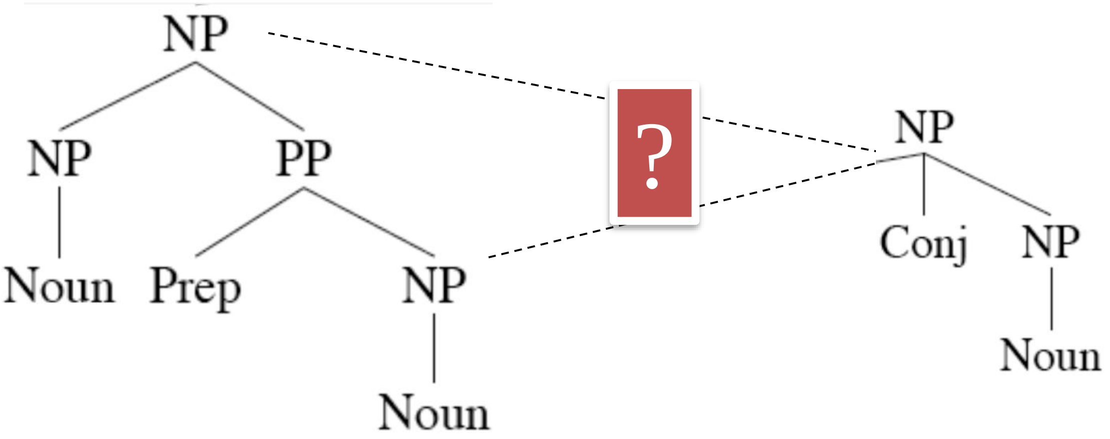
- Most grammars have such (implicit) rules as “X → X and X”
  - This leads to massive ambiguity problems.



Coordination Problem



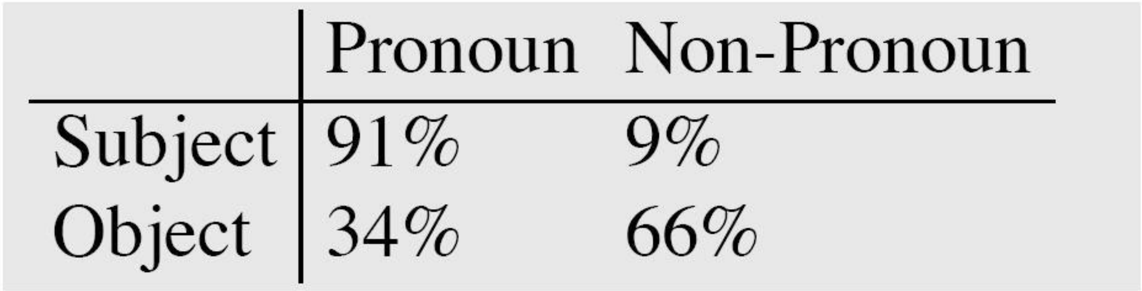
Again the rules do not consider the words



Structural Dependencies Between Rules

- Example probability for rules of NP
  - NP → DT NN (0.28)
  - NP → Pronoun (0.25)

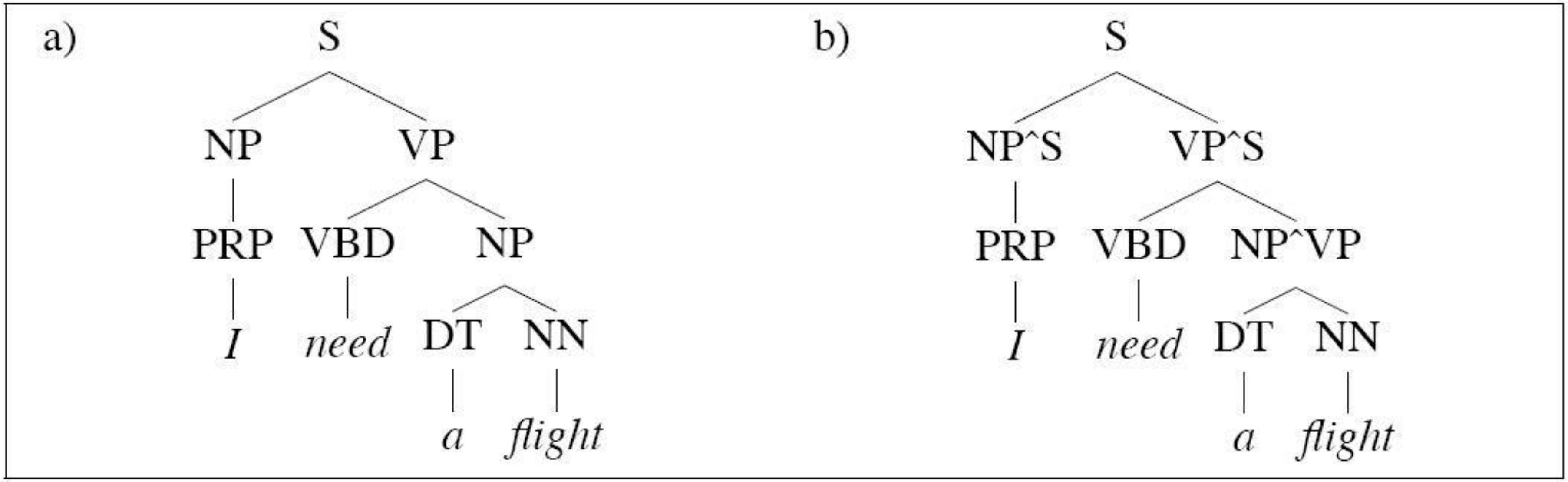
- Rules that involve NP
  - S → **NP** VP
  - VP → Verb **NP**



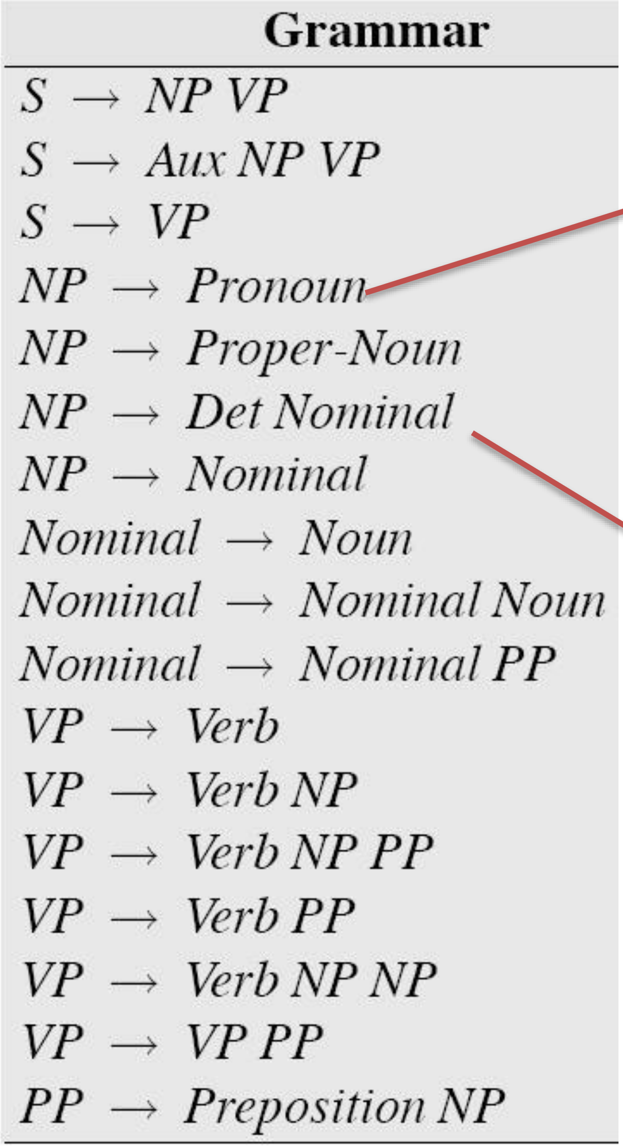
	Pronoun	Non-Pronoun
Subject	91%	9%
Object	34%	66%

Improving PCFG: Splitting Non-Terminals

- Encoding contextual dependencies into PCFG symbols
  - NP is a child of S → NP^S
  - NP is a child of VP → NP^VP



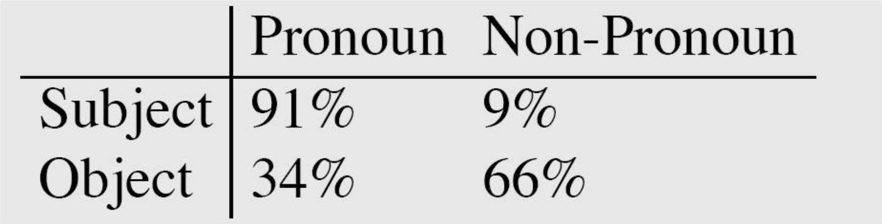
Improving PCFG: Splitting Non-Terminals



Grammar		
S	→	*NP VP*
S	→	*Aux NP VP*
S	→	*VP*
NP	→	*Pronoun*
NP	→	*Proper-Noun*
NP	→	*Det Nominal*
NP	→	*Nominal*
Nominal	→	*Noun*
Nominal	→	*Nominal Noun*
Nominal	→	*Nominal PP*
VP	→	*Verb*
VP	→	*Verb NP*
VP	→	*Verb NP PP*
VP	→	*Verb PP*
VP	→	*Verb NP NP*
VP	→	*VP PP*
PP	→	*Preposition NP*

NP^S → Pronoun
NP^VP → Pronoun
NP^PP → Pronoun

NP^S → Det Nominal^NP
NP^VP → Det Nominal^NP
NP^PP → Det Nominal^NP

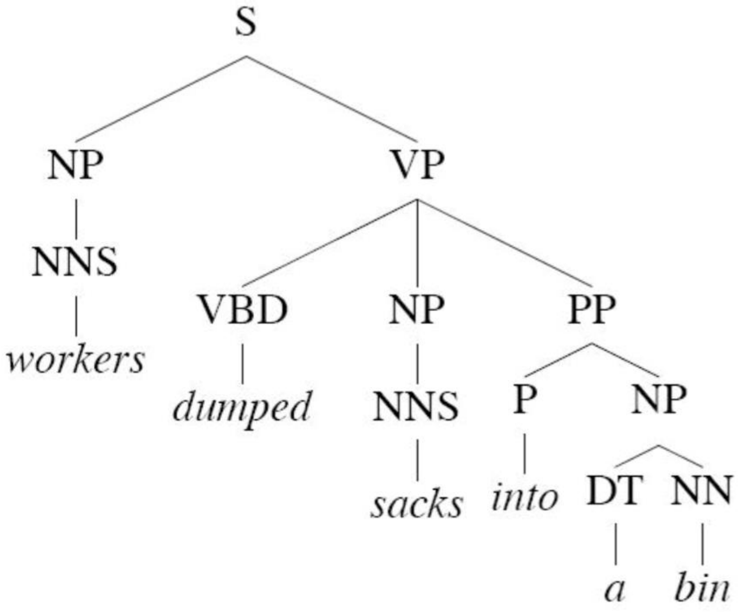


	Pronoun	Non-Pronoun
Subject	91%	9%
Object	34%	66%

Improving PCFG: Lexicalized PCFG

- How to add lexical information to rules?

- (Review) Lexical head
  - The word in the phrase that is grammatically the most important
  - E.g. N is the head of NP
  - E.g. V is the head of VP



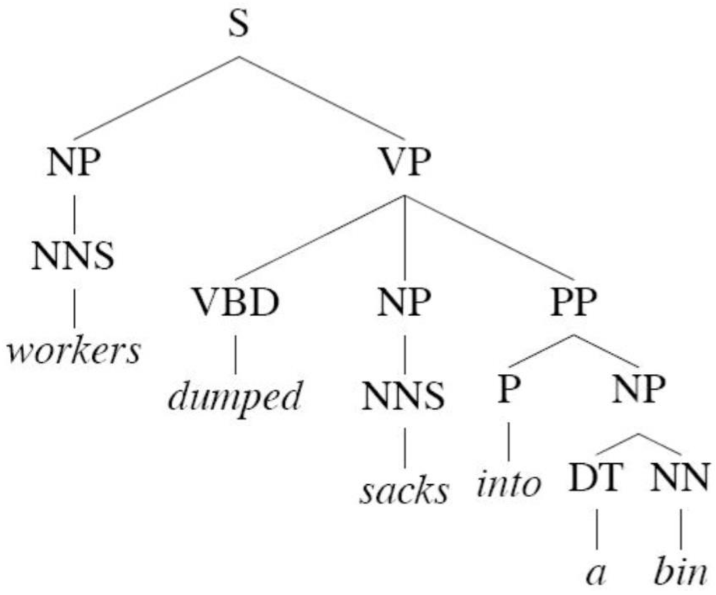
- Now, we put the **lexicon head** into the rules

- VP → VBD NP PP
  - VP(**dumped**) → VBD(dumped) NP(sacks) PP(into)
  - VP(**dumped,VBD**) → VBD(dumped,VBD) NP(sacks,NNS) PP(into,P)

Evaluating Parsing Accuracy

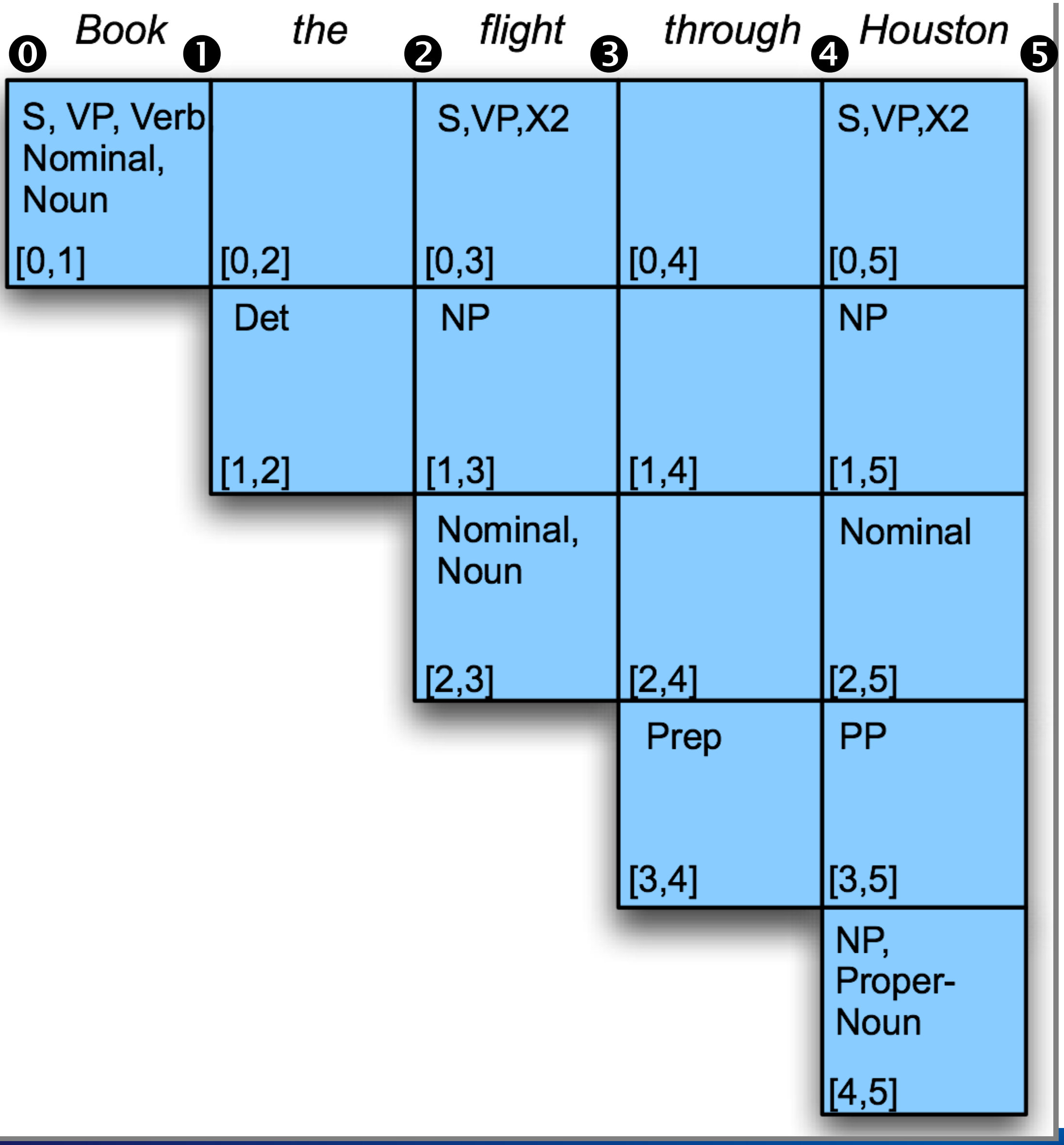
- Sentence-level accuracy
  - But most sentences are not given a completely correct parse by any existing parser

- Constituent-level accuracy
  - Constituent as labeled span: [label, start, finish], e.g. [NP, 0, 1]



Evaluating Parsing Accuracy: Labeled Spans

- [S, 0, 5]
- [VP, 0, 5]
- [Verb, 0, 1]
- [NP, 1, 5]
- [Det, 1, 2]
- [Nominal, 2, 5]
- [Noun, 2, 3]
- [PP, 3, 5]
- [Prep, 3, 4]
- [NP, 4, 5]
- [Noun, 4, 5]



⓿ *Book* ❶ *the* ❷ *flight* ❸ *through* ❹ *Houston* ❺

S, VP, Verb Nominal, Noun [0,1]	[0,2]	S,VP,X2 [0,3]	[0,4]	S,VP,X2 [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]

Example

```
(ROOT
  (S
    (INTJ (VB Please))
    (VP (VB repeat)
      (NP (DT that)))
    (. .)))
```

Ground truth

```
(ROOT
  (S
    (ADVP (RB Please))
    (VP (VB repeat)
      (NP (DT that)))
    (. .)))
```

TP = 5,

FP = 2,

FN = 2

(S, 0, 3)
(INTJ, 0, 1) (VB, 0, 1)
(VP, 1, 3) (VB, 1, 2)
(NP, 2, 3) (DT, 2, 3)

(S, 0, 3)
(ADVP, 0, 1) (RB, 0, 1)
(VP, 1, 3) (VB, 1, 2)
(NP, 2, 3) (DT, 2, 3)

Example

```
(S (NP (PRP I))
    (VP (VBP need)
      (S (VP (TO to)
          (VP (VB fly)
            (PP (IN between)
              (NP (NNP Philadelphia)
                (CC and)
                (NNP Atlanta))))))) (. .)))
```

Ground truth

```
(S (NP (PRP I))
    (VP (VBP need)
      (S (VP (TO to)
        (VP (VB fly)
          (PP (IN between)
            (NP
              (NP (NNP Philadelphia))
                (CC and)
              (NP (NNP Atlanta)))))))) (. .)))
```

(S,0,8) (NP,0,1) (PRP,0,1)
(VP,1,8) (VBP,1,2)
(S,2,8) (VP,2,8) (TO,2,3)
(VP,3,8) (VB,3,4)
(PP,4,8) (IN,4,5)
(NP,5,8) (NNP,5,6)
(CC,6,7) (NNP,7,8)

(S,0,8) (NP,0,1) (PRP,0,1)
(VP,1,8) (VBP,1,2)
(S,2,8) (VP,2,8) (TO,2,3)
(VP,3,8) (VB,3,4)
(PP,4,8) (IN,4,5)
(NP,5,8) (NP,5,6) (NNP,5,6)
(CC,6,7) (NP,7,8) (NNP,7,8)

TP = 16,

FP = 0,

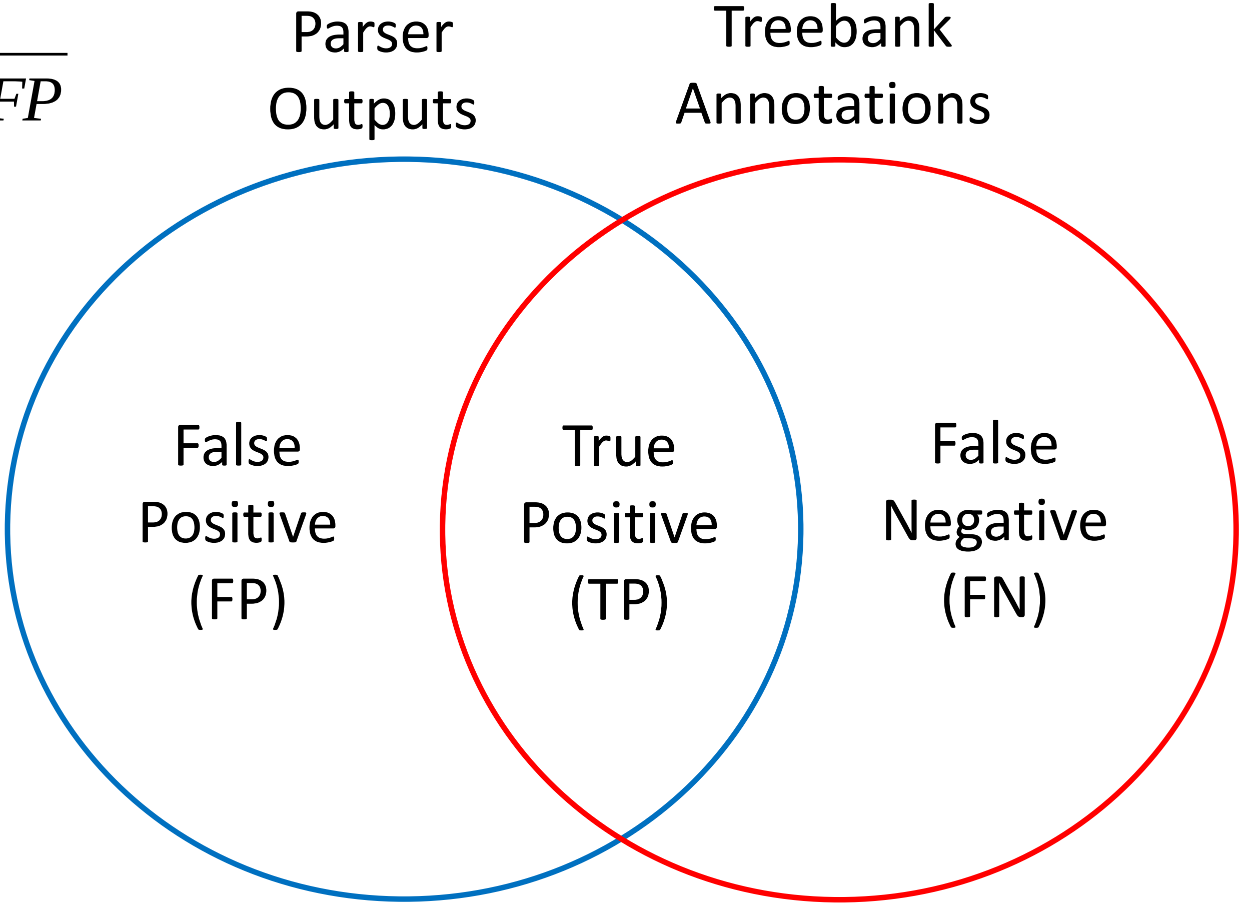
FN = 2

Evaluating Parsing Accuracy: Measures

$$\text{Precision}\ (P) = \frac{TP}{TP + FP}$$

$$\text{Recall}(R) = \frac{TP}{TP + FN}$$

$$F_1 = \frac{2PR}{P + R}$$


Parser Outputs
Treebank Annotations
False Positive (FP)
True Positive (TP)
False Negative (FN)