CKY Parsing

Ling571
Deep Processing Approaches to NLP
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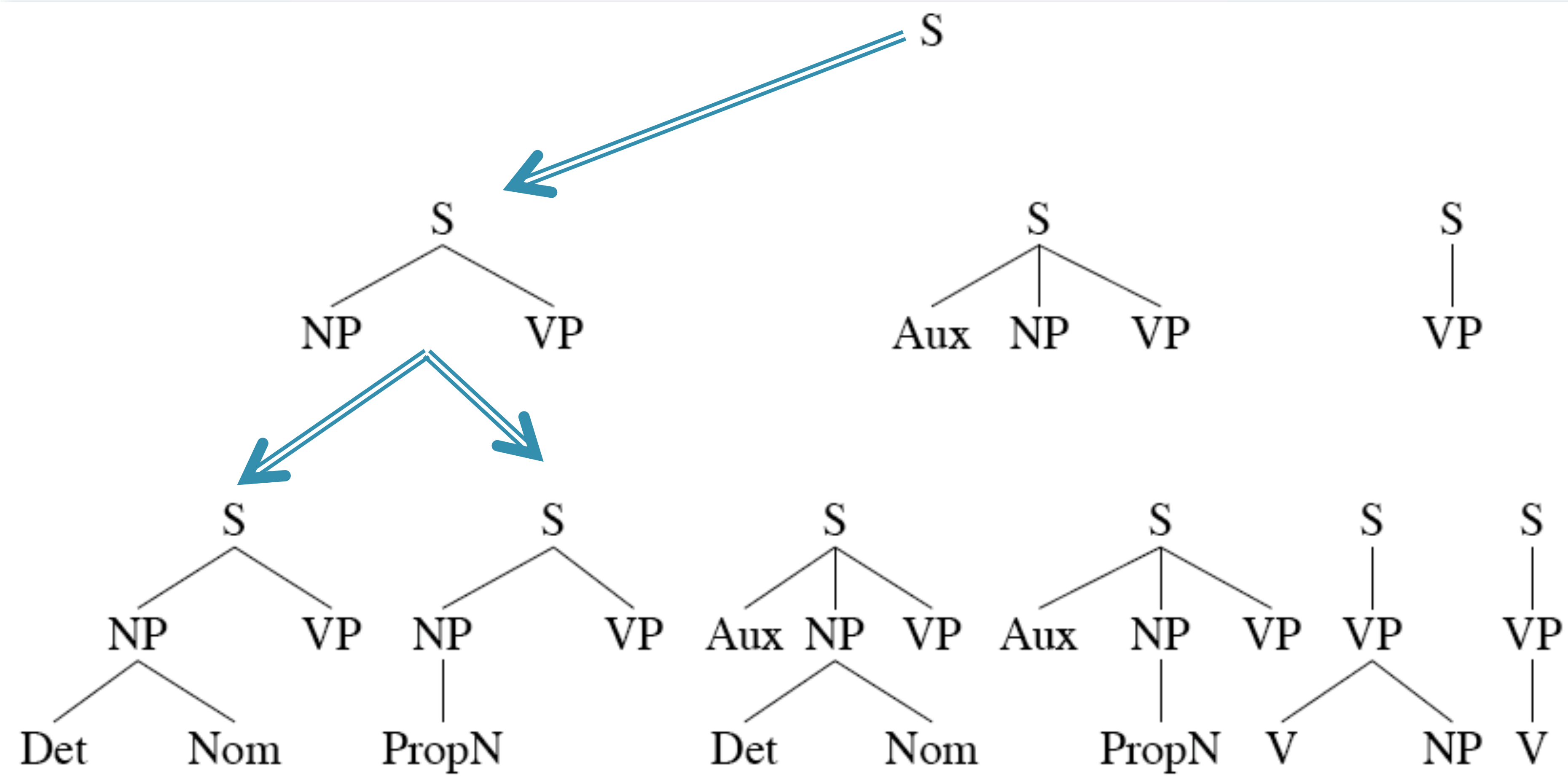
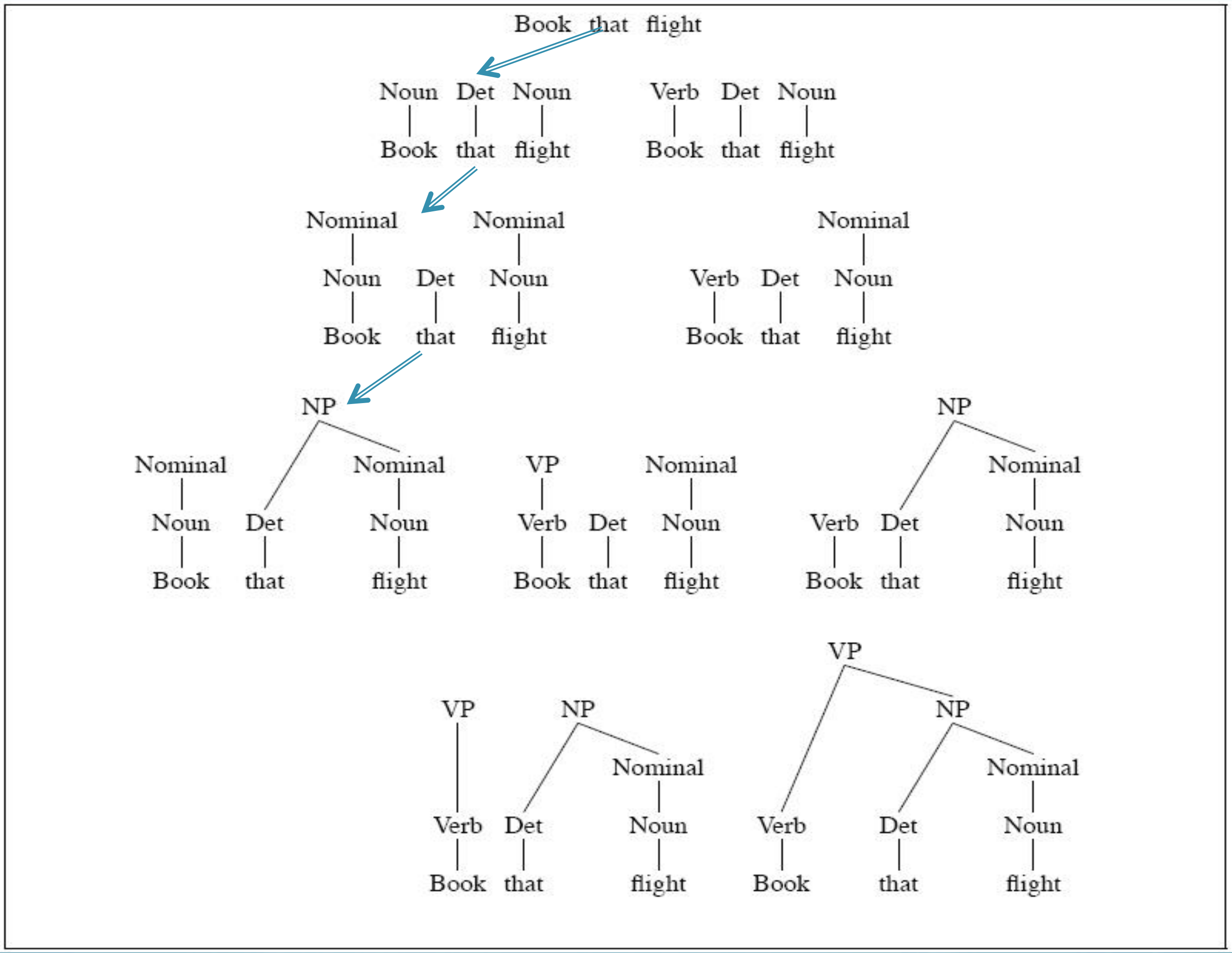
Roadmap

- Motivation:
  - Inefficiencies of parsing-as-search
- Strategy: Dynamic Programming
- Chomsky Normal Form
  - Weak and strong equivalence
- CKY parsing algorithm

Top-down parsing (DFS)



Bottom-Up Search



Parsing Challenges

- Ambiguity
- Repeated substructure
- Recursion

Parsing Ambiguity

- Many sources of parse ambiguity
  - Lexical ambiguity
    - Book/N; Book/V

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    - Attachment ambiguity
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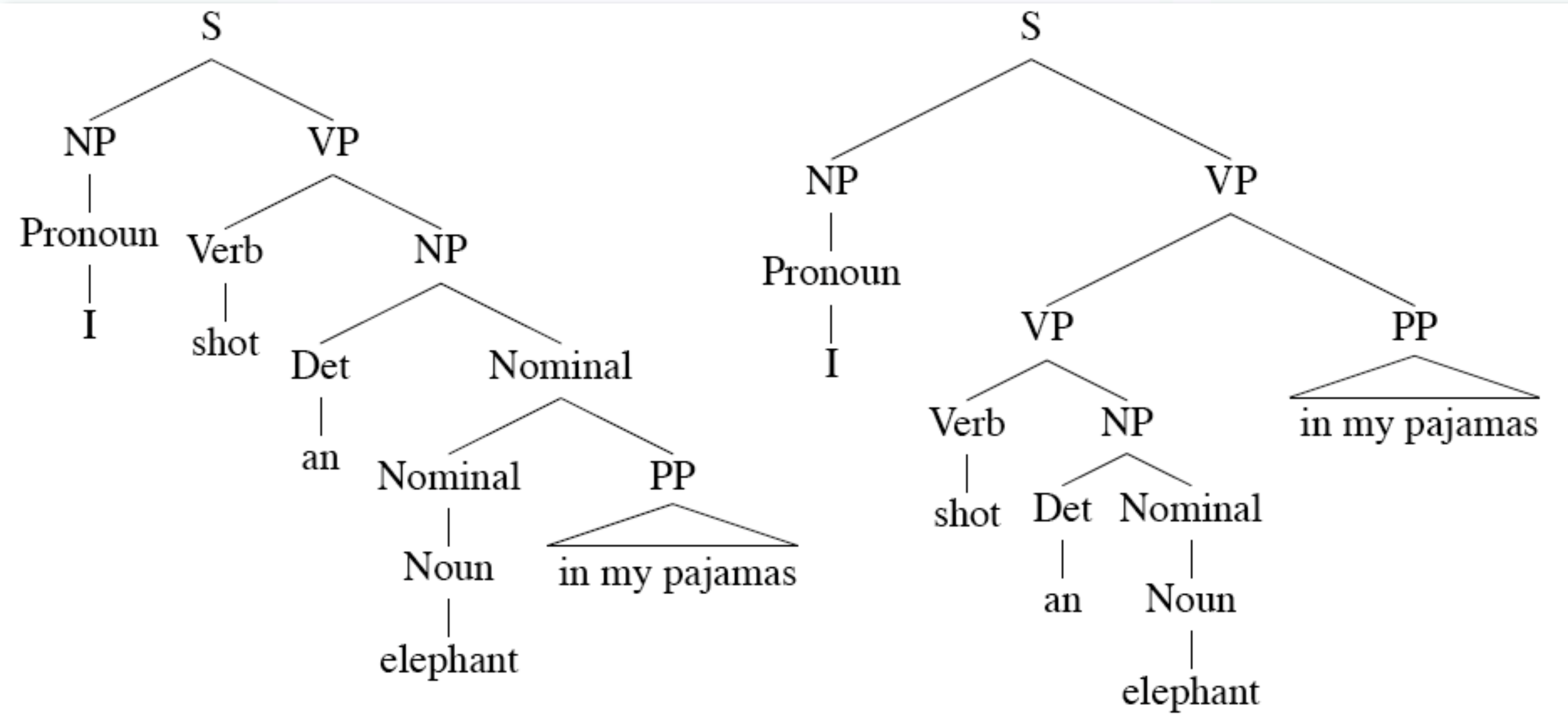
    - Attachment ambiguity
      - Constituent can attach in multiple places
        - *I shot an elephant in my pyjamas*.
    - Coordination ambiguity
      - Different constituents can be conjoined
        - *Old men and women*

Ambiguity


S
NP
VP
Pronoun
Verb
NP
I
shot
Det
Nominal
an
Nominal
PP
Noun
in my pajamas
elephant
S
NP
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Disambiguation

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  - Need strategy to select correct one
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- Local ambiguity:
  - Ambiguity in subtree, resolved globally

Repeated Work

- Top-down and bottom-up parsing both lead to repeated substructures
  - Globally bad parses can construct good subtrees
    - But overall parse will fail
    - Require reconstruction on other branch
  - No static backtracking strategy can avoid

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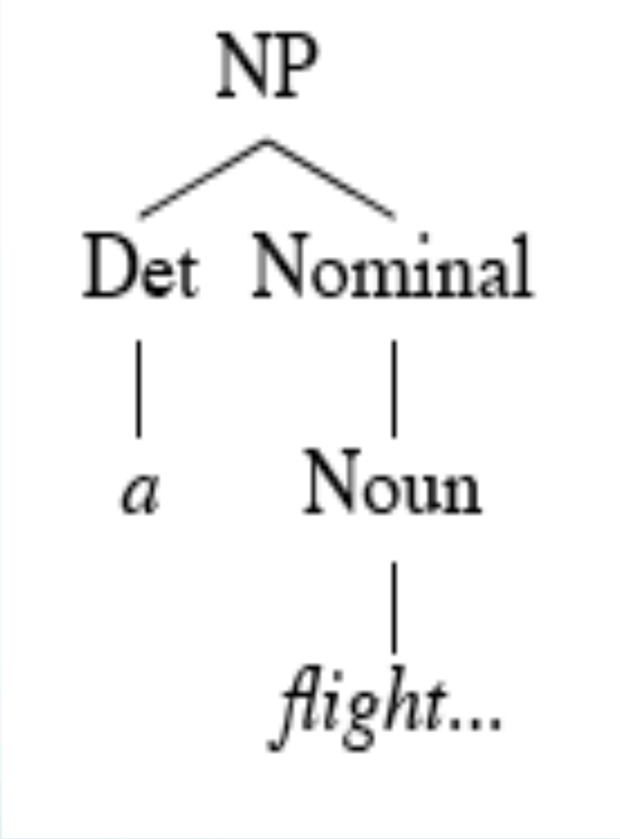
- Efficient parsing techniques require storage of shared substructure
  - Typically with dynamic programming
- Example: *a flight from Indianapolis to Houston on TWA*

Shared Sub-Problems



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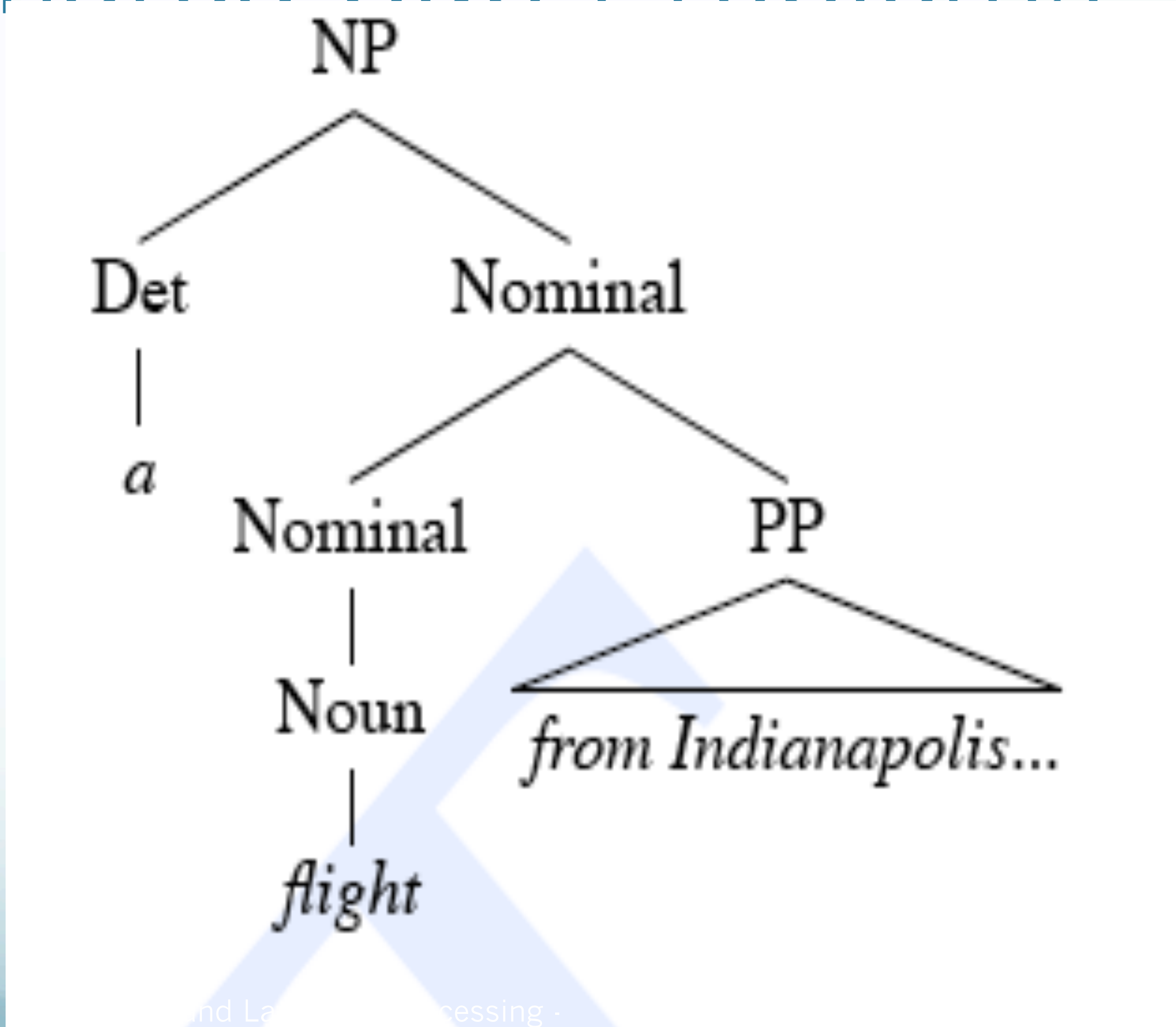

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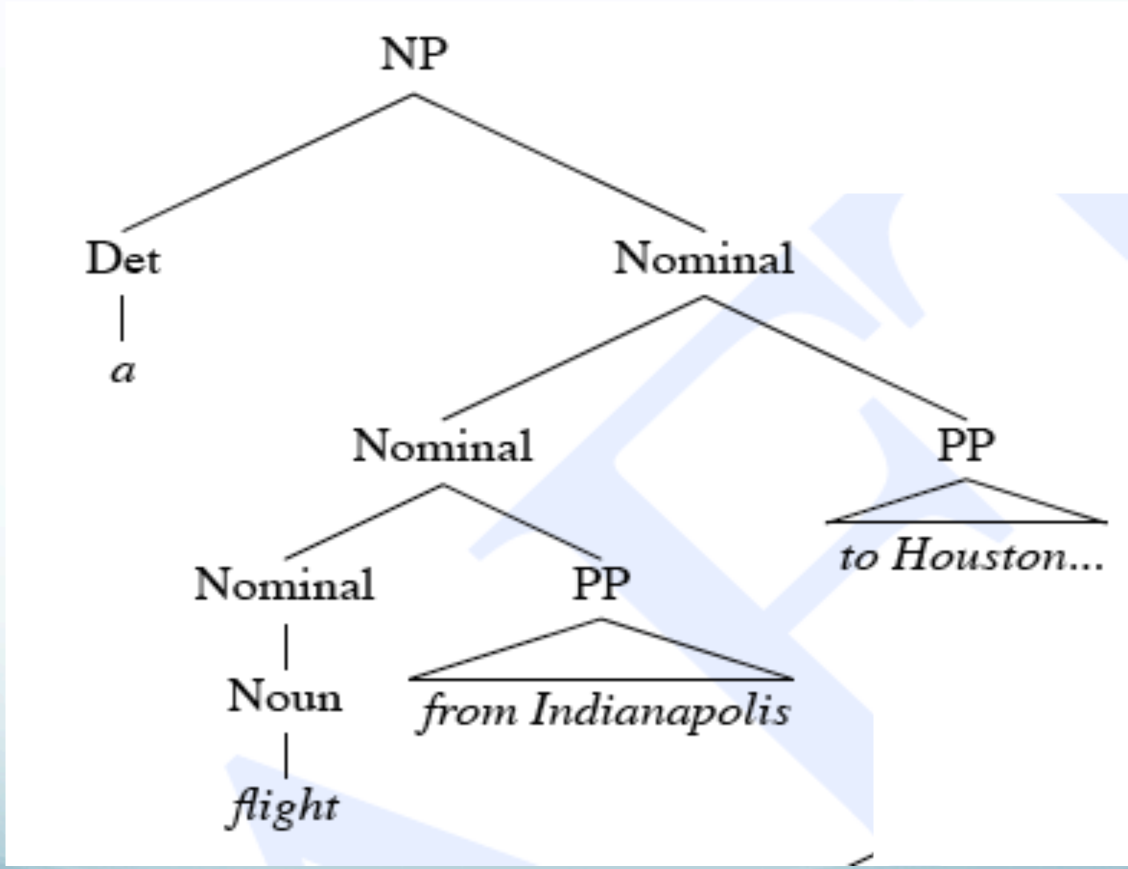

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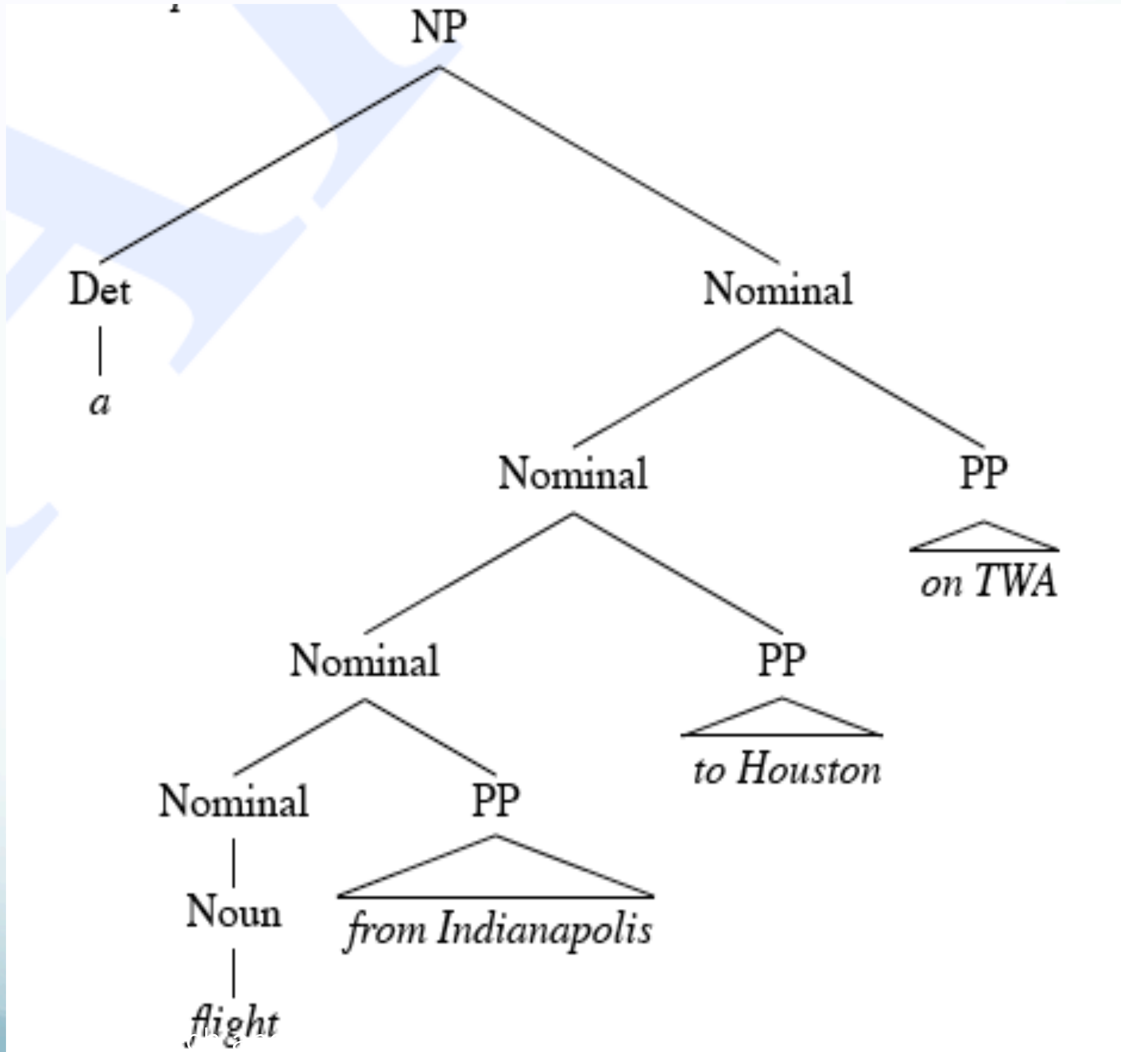

Recursion

- Many grammars have recursive rules
  - E.g., S → S Conj S

- In search approaches, recursion is problematic
  - Can yield infinite searches
    - Esp., top-down

Dynamic Programming

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- Insight:
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  - Can record parses of substructures
- Dynamic programming avoids repeated work by tabulating solutions to subproblems
  - Here, stores subtrees

Parsing w/Dynamic Programming

- Avoids repeated work
- Allows implementation of (relatively) efficient parsing algorithms
  - Polynomial time in input length
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- Avoids repeated work
- Allows implementation of (relatively) efficient parsing algorithms
  - Polynomial time in input length
    - Typically cubic (n^3) or less
- Several different implementations
  - Cocke-Kasami-Younger (CKY) algorithm
  - Earley algorithm
  - Chart parsing

Chomsky Normal Form (CNF)

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- Chomsky Normal Form
  - All productions of the form:
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  - E.g., S → Wh-NP Aux NP VP

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- Chomsky Normal Form
  - All productions of the form:
    - A → B C, or
    - A → a
- However, most of our grammars are not of this form
  - E.g., S → Wh-NP Aux NP VP
- Need a general conversion procedure
  - Any arbitrary grammar can be converted to CNF

CNF Conversion

- Three main conditions:

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    - INF-VP → to VP

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  - Unit productions:
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  - Long productions:
    - A → B C D

CNF Conversion

- Hybrid rule conversion:
  - Replace all terminals with dummy non-terminals
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    - INF-VP → TO VP; TO → to

CNF Conversion

- Hybrid rule conversion:
  - Replace all terminals with dummy non-terminals
  - E.g., INF-VP → to VP
    - INF-VP → TO VP; TO → to
- Unit productions:
  - Rewrite RHS with RHS of all derivable non-unit productions
    - If $A \stackrel{*}{\Rightarrow} B$ and B → w, then add A → w

CNF Conversion

- Long productions:
  - Introduce new non-terminals and spread over rules
  - S → Aux NP VP

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    - S → X1 VP; X1 → Aux NP

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  - Introduce new non-terminals and spread over rules
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- For all non-conforming rules,
  - Convert terminals to dummy non-terminals
  - Convert unit productions
  - Binarize all resulting rules

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

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$Nominal \rightarrow Noun$	
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$Nominal \rightarrow Nominal\ PP$	
$VP \rightarrow Verb$	
$VP \rightarrow Verb\ NP$	
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	$X1 \rightarrow Aux\ NP$
$S \rightarrow VP$	
$NP \rightarrow Pronoun$	
$NP \rightarrow Proper\text{-}Noun$	
$NP \rightarrow Det\ Nominal$	
$Nominal \rightarrow Noun$	
$Nominal \rightarrow Nominal\ Noun$	
$Nominal \rightarrow Nominal\ PP$	
$VP \rightarrow Verb$	
$VP \rightarrow Verb\ NP$	
$VP \rightarrow Verb\ NP\ PP$	
$VP \rightarrow Verb\ PP$	
$VP \rightarrow VP\ PP$	
$PP \rightarrow Preposition\ NP$	

$\mathscr{L}_1$ **Grammar**	$\mathscr{L}_1$ **in CNF**
$S \longrightarrow NP\ VP$	$S \longrightarrow NP\ VP$
$S \longrightarrow Aux\ NP\ VP$	$S \longrightarrow X1\ VP$
	$X1 \longrightarrow Aux\ NP$
$S \longrightarrow VP$	$S \longrightarrow book \mid include \mid prefer$
$NP \longrightarrow Pronoun$	
$NP \longrightarrow Proper\text{-}Noun$	
$NP \longrightarrow Det\ Nominal$	
$Nominal \longrightarrow Noun$	
$Nominal \longrightarrow Nominal\ Noun$	
$Nominal \longrightarrow Nominal\ PP$	
$VP \longrightarrow Verb$	
$VP \longrightarrow Verb\ NP$	
$VP \longrightarrow Verb\ NP\ PP$	
$VP \longrightarrow Verb\ PP$	
$VP \longrightarrow VP\ PP$	
$PP \longrightarrow Preposition\ NP$	

$\mathscr{L}_1$ **Grammar**	$\mathscr{L}_1$ **in CNF**
S → *NP VP*	*S* → *NP VP*
S → *Aux NP VP*	*S* → *X1 VP*
	X1 → *Aux NP*
S → *VP*	*S* → *book* | *include* | *prefer*
	S → *Verb NP*
	S → *X2 PP*
	S → *Verb PP*
	S → *VP PP*
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*	
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$\mathscr{L}_1$ **Grammar**	$\mathscr{L}_1$ **in CNF**
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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-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*

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  - (Relatively) efficient bottom-up parsing algorithm based on tabulating substring parses to avoid repeated work

CKY Parsing

- Cocke-Kasami-Younger parsing algorithm:
  - (Relatively) efficient bottom-up parsing algorithm based on tabulating substring parses to avoid repeated work
  - Approach:
    - Use a CNF grammar
    - Build an (n+1) x (n+1) matrix to store subtrees
      - Upper triangular portion
    - Incrementally build parse spanning whole input string

Dynamic Programming in CKY

- Key idea:
  - For a parse spanning substring [i,j] , there exists some k such there are parses spanning [i,k] and [k,j]
    - We can construct parses for whole sentence by building up from these stored partial parses

Dynamic Programming in CKY

- Key idea:
  - For a parse spanning substring [i,j] , there exists some k such there are parses spanning [i,k] and [k,j]
    - We can construct parses for whole sentence by building up from these stored partial parses
- So,
  - To have a rule A → B C in [i,j],
    - We must have B in [i,k] and C in [k,j], for some i<k<j
      - CNF grammar forces this for all j>i+1

CKY

- Given an input string S of length n,
  - Build table (n+1) x (n+1)
  - Indexes correspond to inter-word positions
    - E.g., 0 Book 1 That 2 Flight 3

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- Cells [i,j] contain sets of non-terminals of ALL constituents spanning i,j
  - [j-1,j] contains pre-terminals
  - If [0,n] contains Start, the input is recognized

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**

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

Is this a parser?

CKY Parsing

- Table fills:
  - Column-by-column
  - Left-to-right
  - Bottom-to-top
- Why?

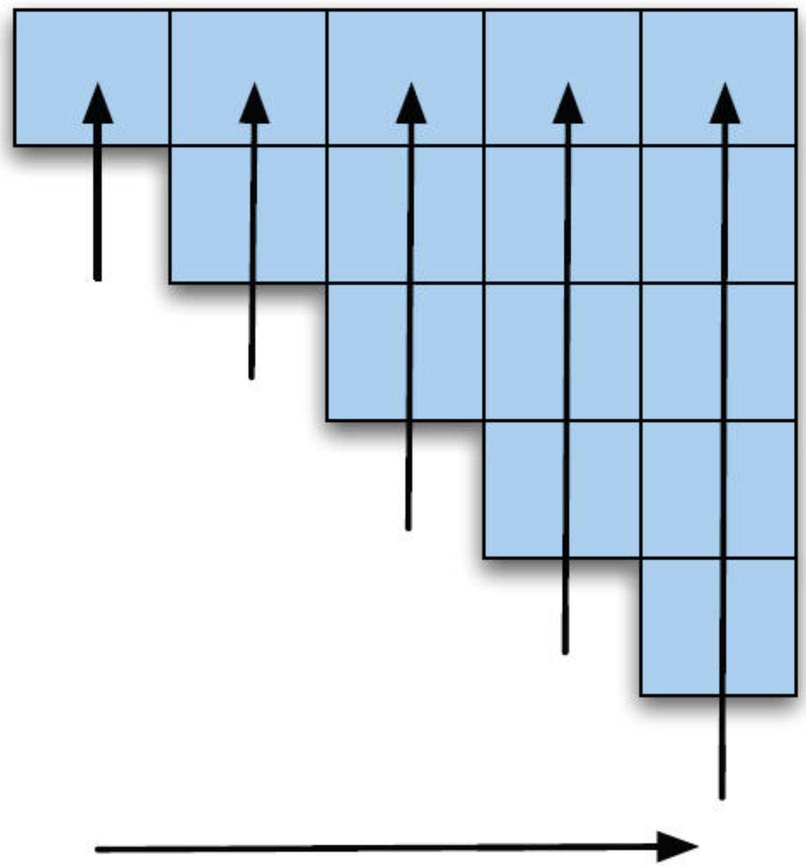
CKY Parsing

- Table fills:
  - Column-by-column
  - Left-to-right
  - Bottom-to-top
- Why?
  - Necessary info available (below and left)
  - Allows online sentence analysis
    - Works across input string as it arrives

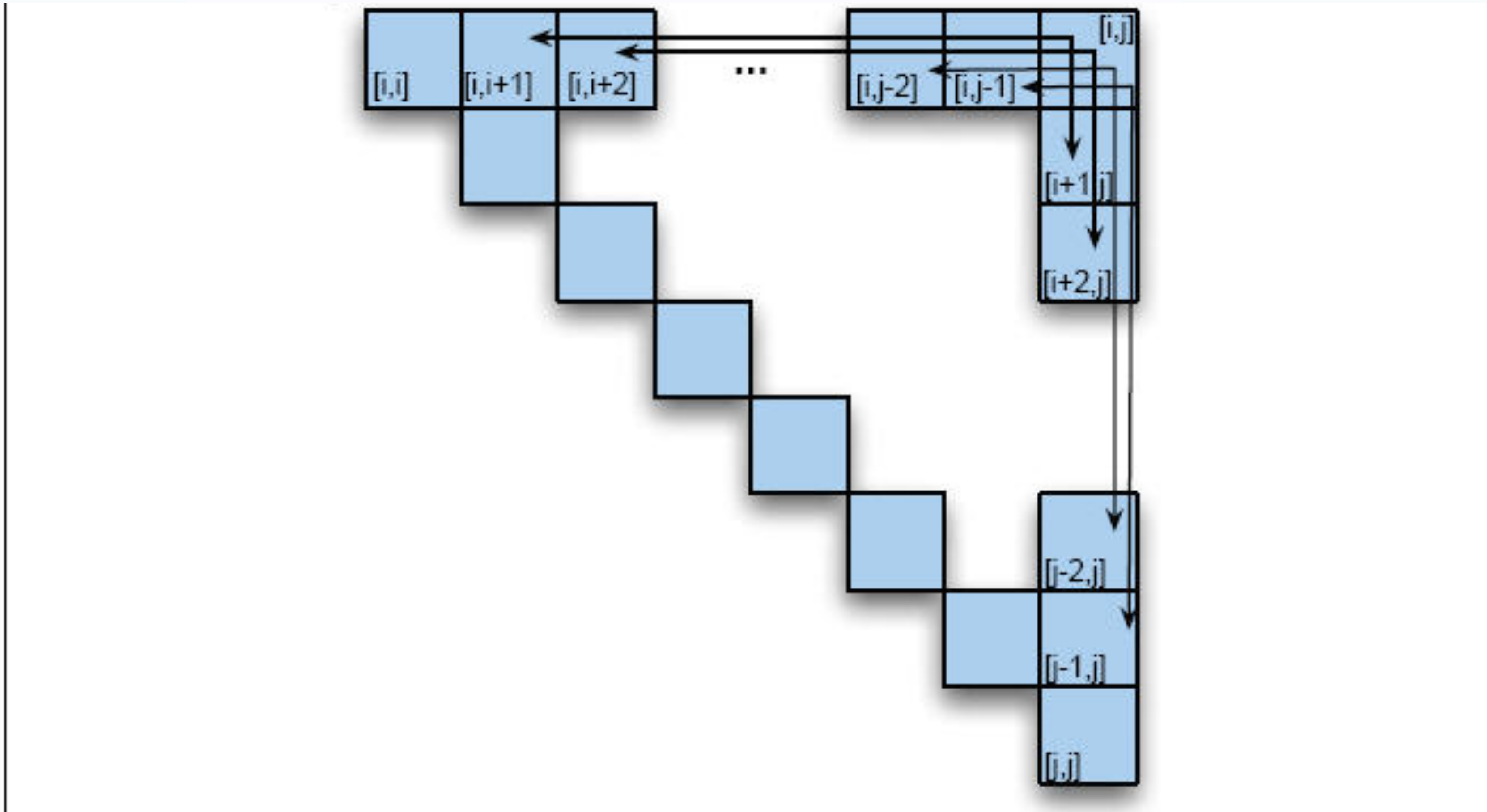
CKY Table

- Book the flight through Houston

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



Filling CKY cell



0 Book 1 the 2 flight 3 through 4 Houston 5

Book	the	Flight	through	Houston
NN, VB, Nominal, VP, S [0,1]				

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Book	the	Flight	through	Houston
NN, VB, Nominal, VP, S [0,1]				
	Det [1,2]			

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Book	the	Flight	Through	Houston
NN, VB, Nominal, VP, S [0,1]	[0,2]			
	Det [1,2]			

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Book	the	Flight	through	Houston
NN, VB, Nominal, VP, S [0,1]	[0,2]			
	Det [1,2]			
		NN, Nominal [2,3]		

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Book	the	Flight	through	Houston
NN, VB, Nominal, VP, S [0,1]	[0,2]			
	Det [1,2]	NP [1,3]		
		NN, Nominal [2,3]		

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Book	the	Flight	Through	Houston
NN, VB, Nominal, VP, S [0,1]	[0,2]	S, VP, X2 [0,3]		
	Det [1,2]	NP [1,3]		
		NN, Nominal [2,3]		

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Book	the	Flight	Through	Houston
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		NN, Nominal [2,3]		
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		NN, Nominal [2,3]	[2,4]	
			Prep [3,4]	

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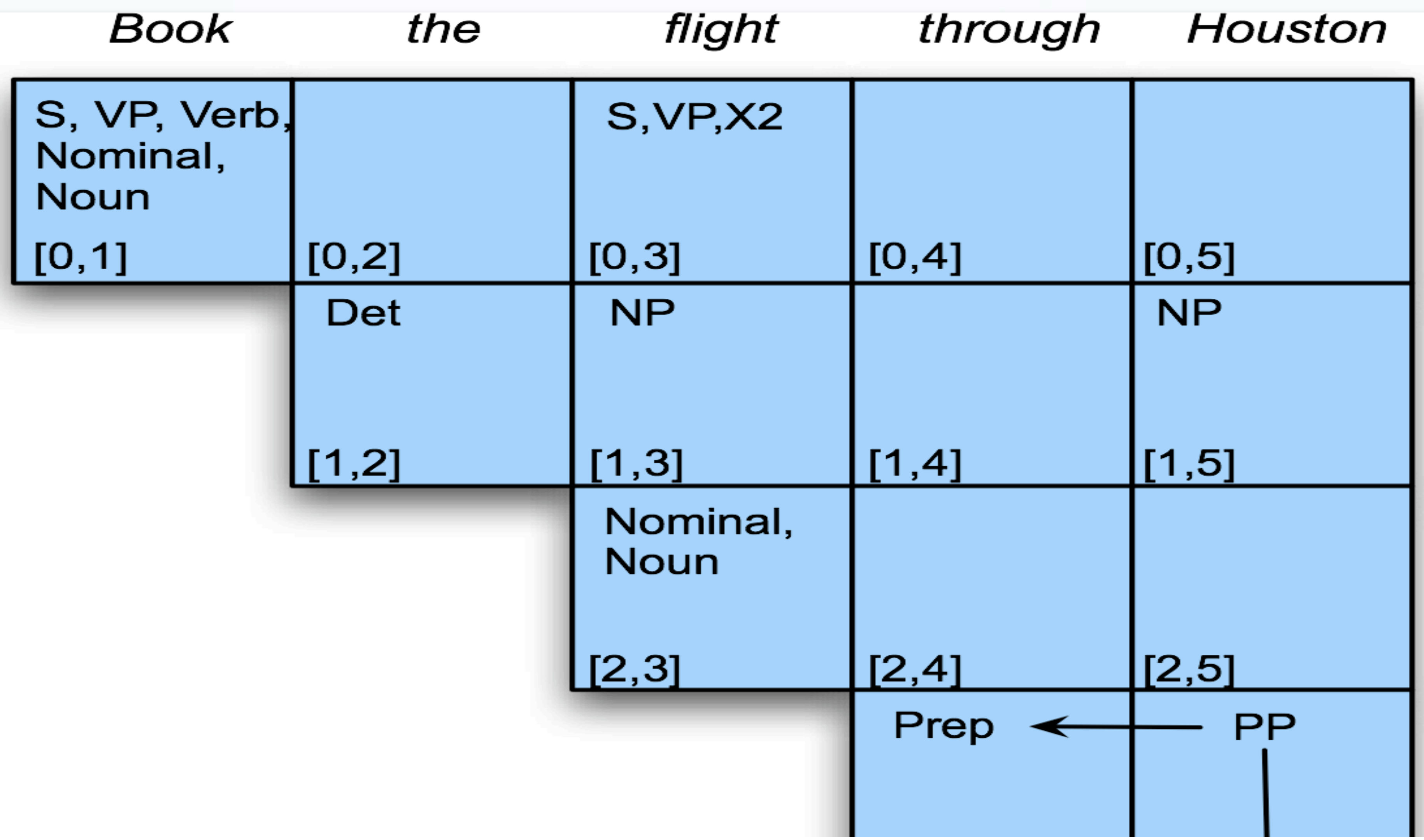
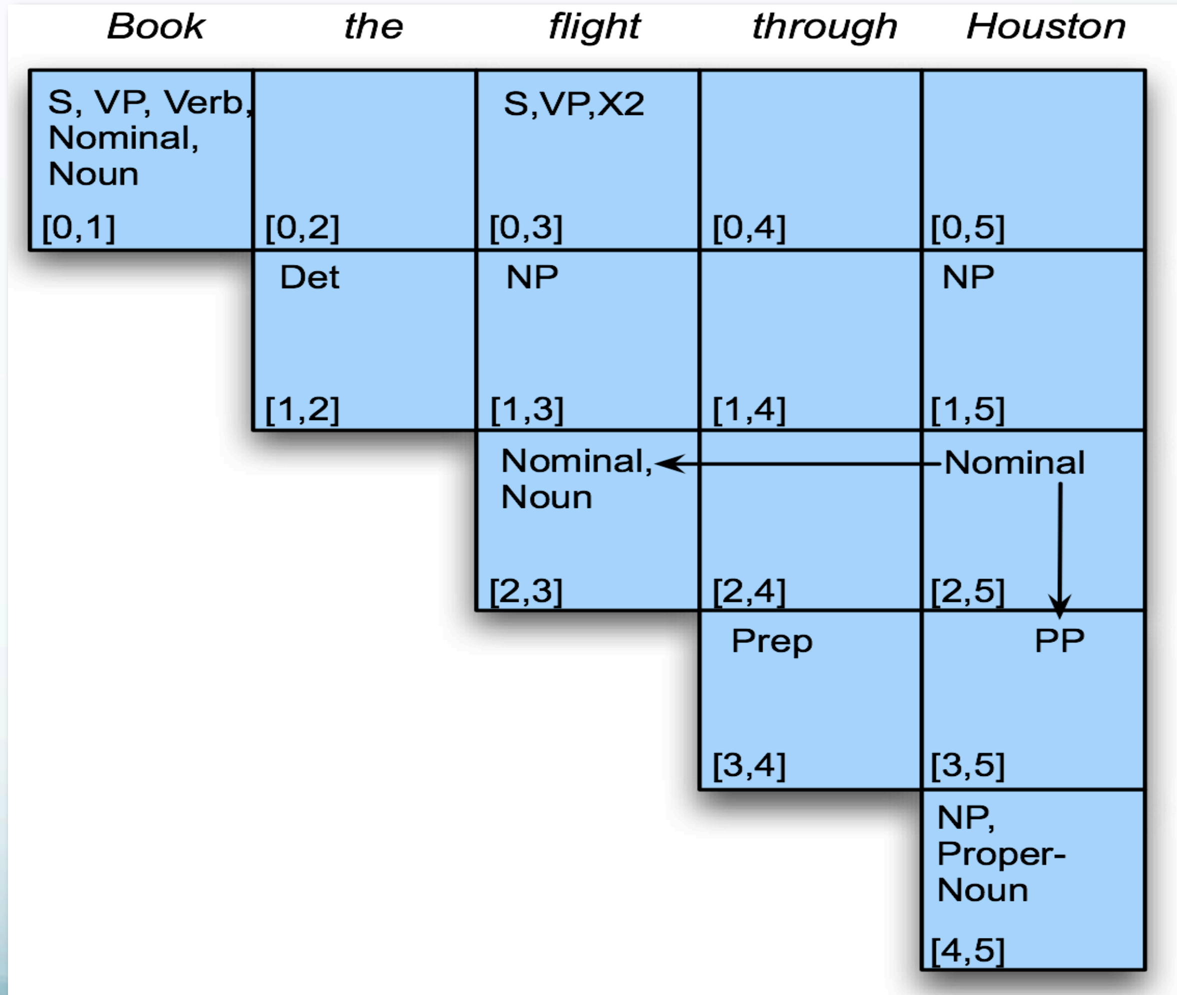
  - Pair each non-terminal with pointers to cells
    - Backpointers
  - Last step: construct trees from back-pointers in [0,n]

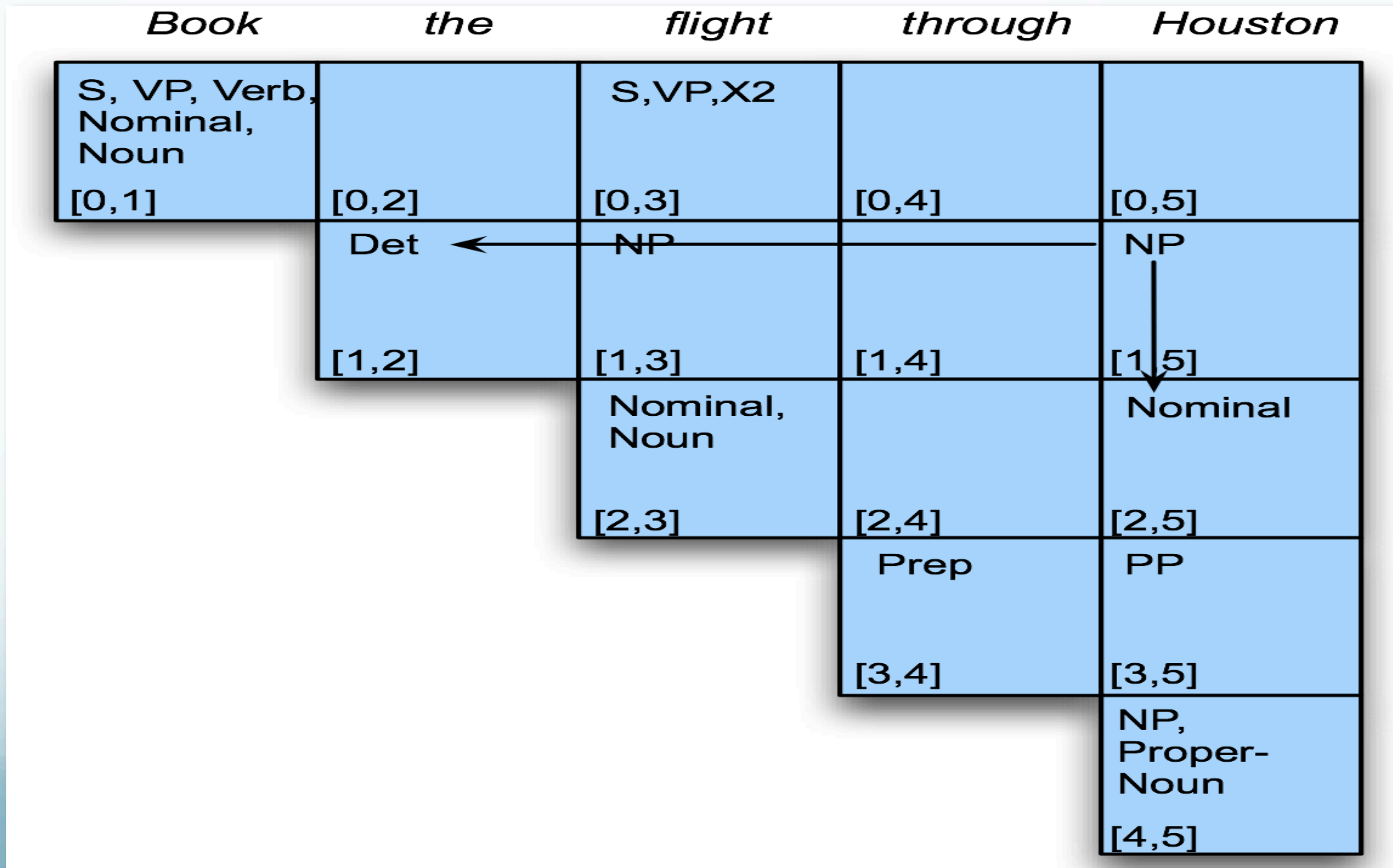
Filling column 5

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]	Nominal [2,5]
			Prep [3,4]	[3,5]
				NP, Proper-Noun [4,5]



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]
NP
[1,5]
Nominal, Noun
[2,3]
[2,4]
[2,5]
Prep
PP


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]
NP
[1,5]
Nominal, Noun
[2,3]
[2,4]
Nominal
[2,5]
Prep
[3,4]
PP
[3,5]
NP, Proper-Noun
[4,5]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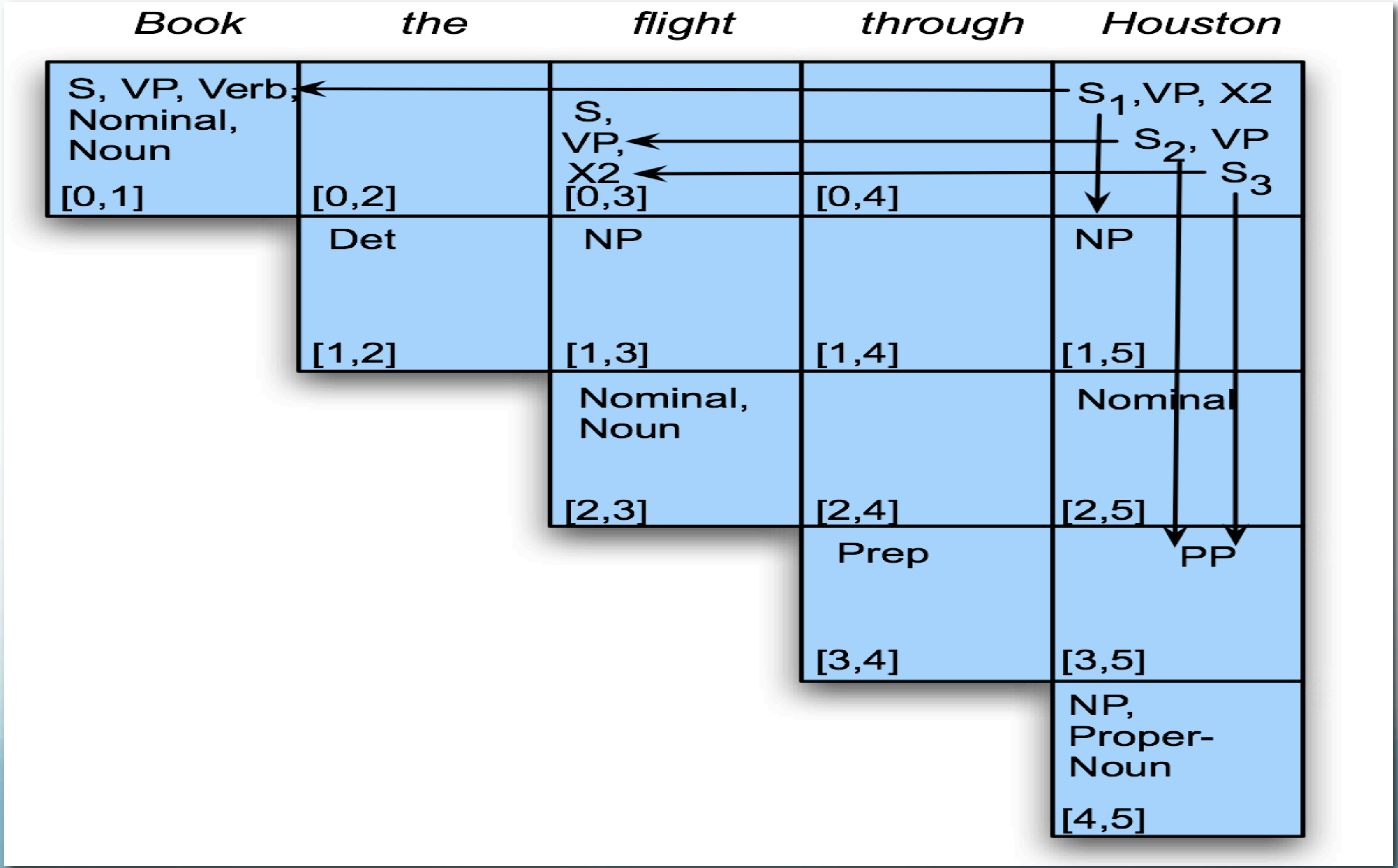

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S1,VP, X2
S2, VP
S3
Det
[1,2]
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[1,3]
[1,4]
NP
[1,5]
Nominal, Noun
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CKY Discussion

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      - Back-conversion?
        - Can do binarization, terminal conversion
        - Unit non-terminals require change in CKY