CKY Parsing

LING 571 — Deep Processing Techniques for NLP Shane Steinert-Threlkeld

Announcements

- HW1 grades coming soon
- Reference code in hw1/ref on dropbox
 - Will try to give reference implementations for many assignments (not all, where it is less applicable)
 - Please do not distribute them!
- HW2: only need the three operations we discussed on the slides
 - NB: order of application matters!

Supported in ≥3.6

```
from nltk.grammar import Production

def fix_hybrid_production(hybrid_prod: Production) -> list[Production]:
    ...
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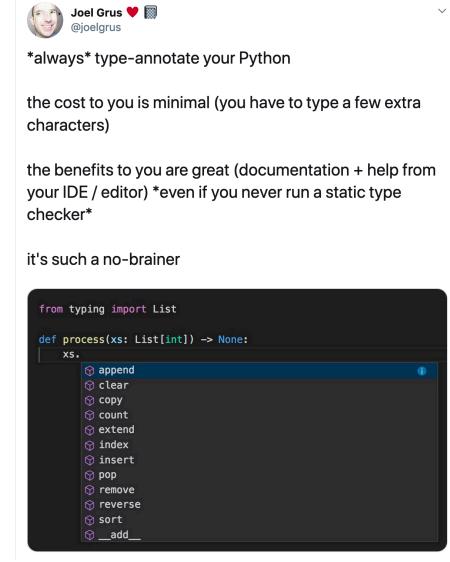
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- https://peps.python.org/pep-0483/

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- https://mypy.readthedocs.io/en/stable/cheat_sheet_py3.html
- https://peps.python.org/pep-0483/
- Tools for your editor:
 - Mypy
 - Pyright: a great default to use!



Roadmap

CKY Parsing Algorithm

Dynamic programming structure

Algorithm and example

Analysis & Discussion

Next time: Probabilistic CFGs

Motivation: Ambiguity

Augmenting CFGs with probabilities

CKY Parsing

- (Relatively) efficient parsing algorithm
- Based on tabulating substring parses to avoid repeat work
- Approach:
 - Use CNF Grammar
 - Build an $(n + 1) \times (n + 1)$ matrix to store subtrees
 - Upper triangular portion
 - Incrementally build parse spanning whole input string



• Given an input string S of length n

- Given an input string *S* of length *n*
- Build table $(n + 1) \times (n + 1)$

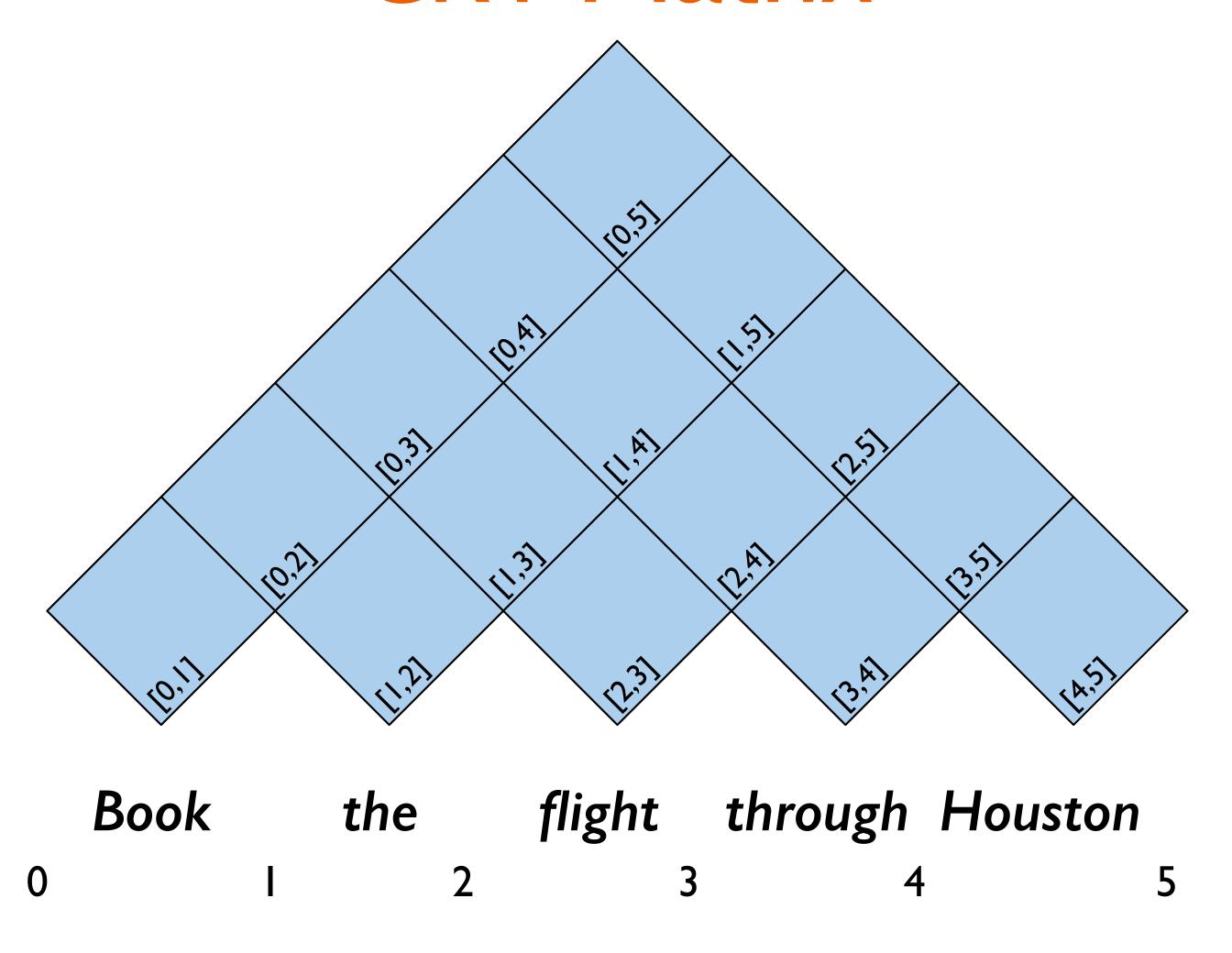
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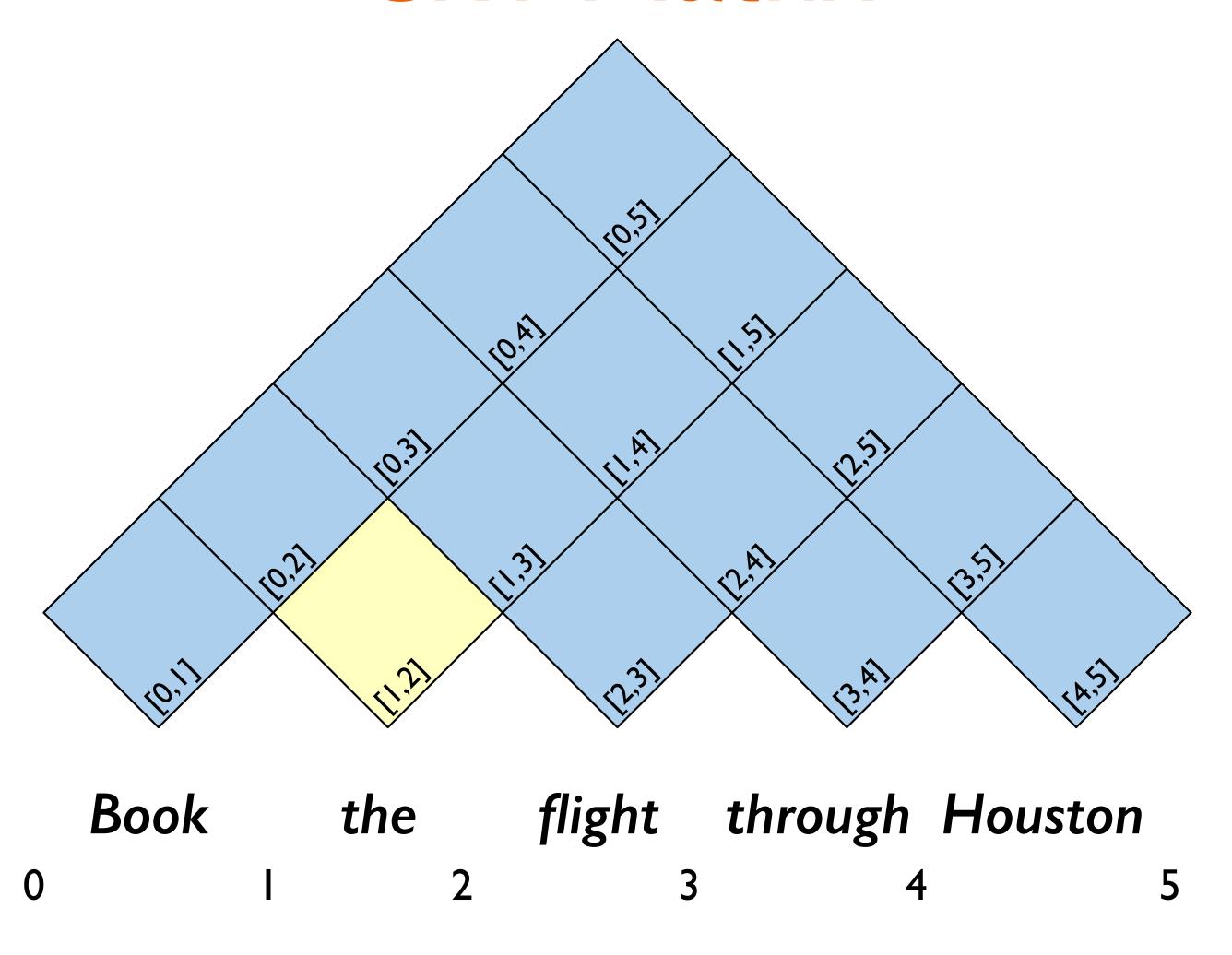
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- Each cell [i, j] contains SETS { } of non-terminals with derivations spanning i, j

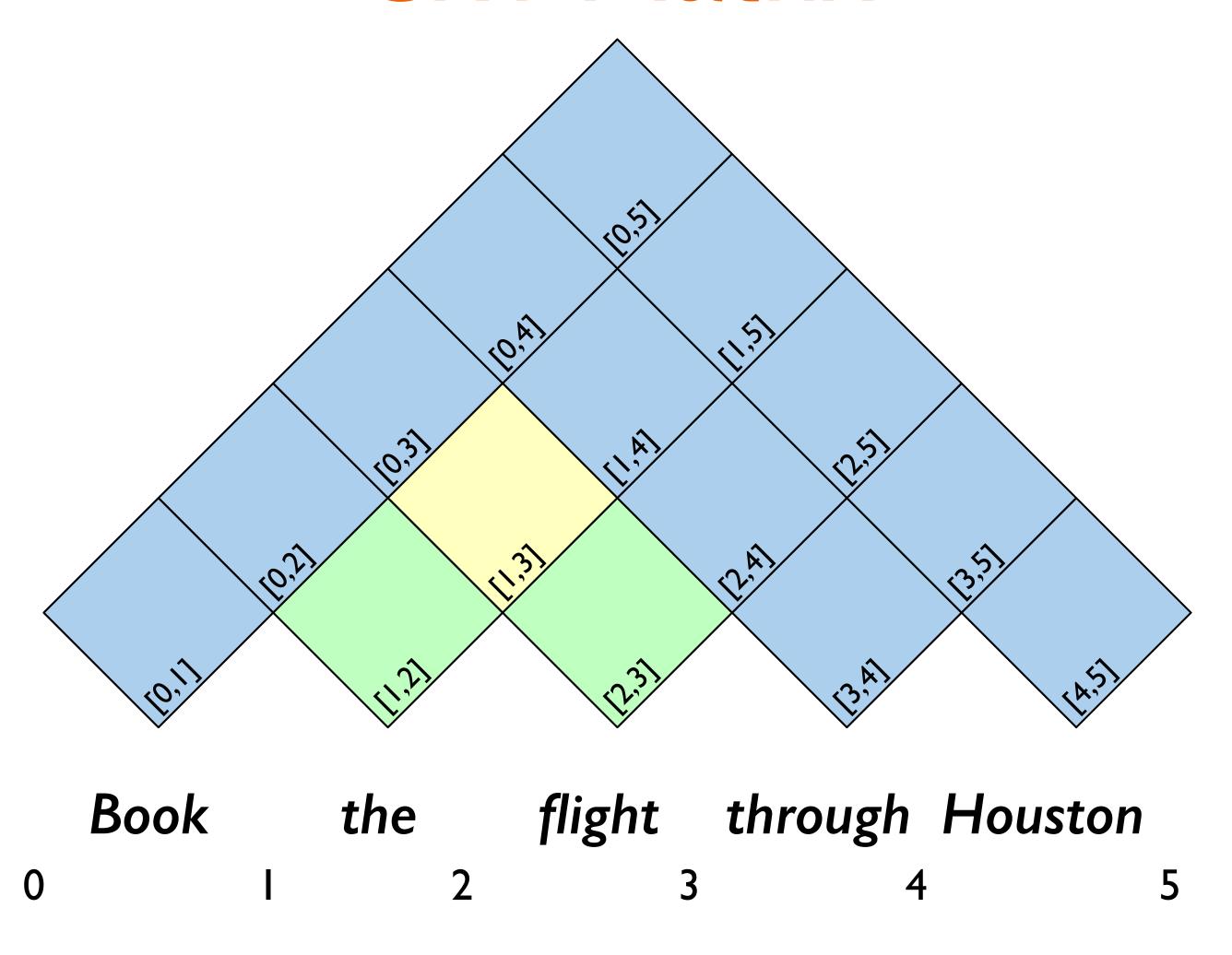
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 - [j-1,j] contains pre-terminals

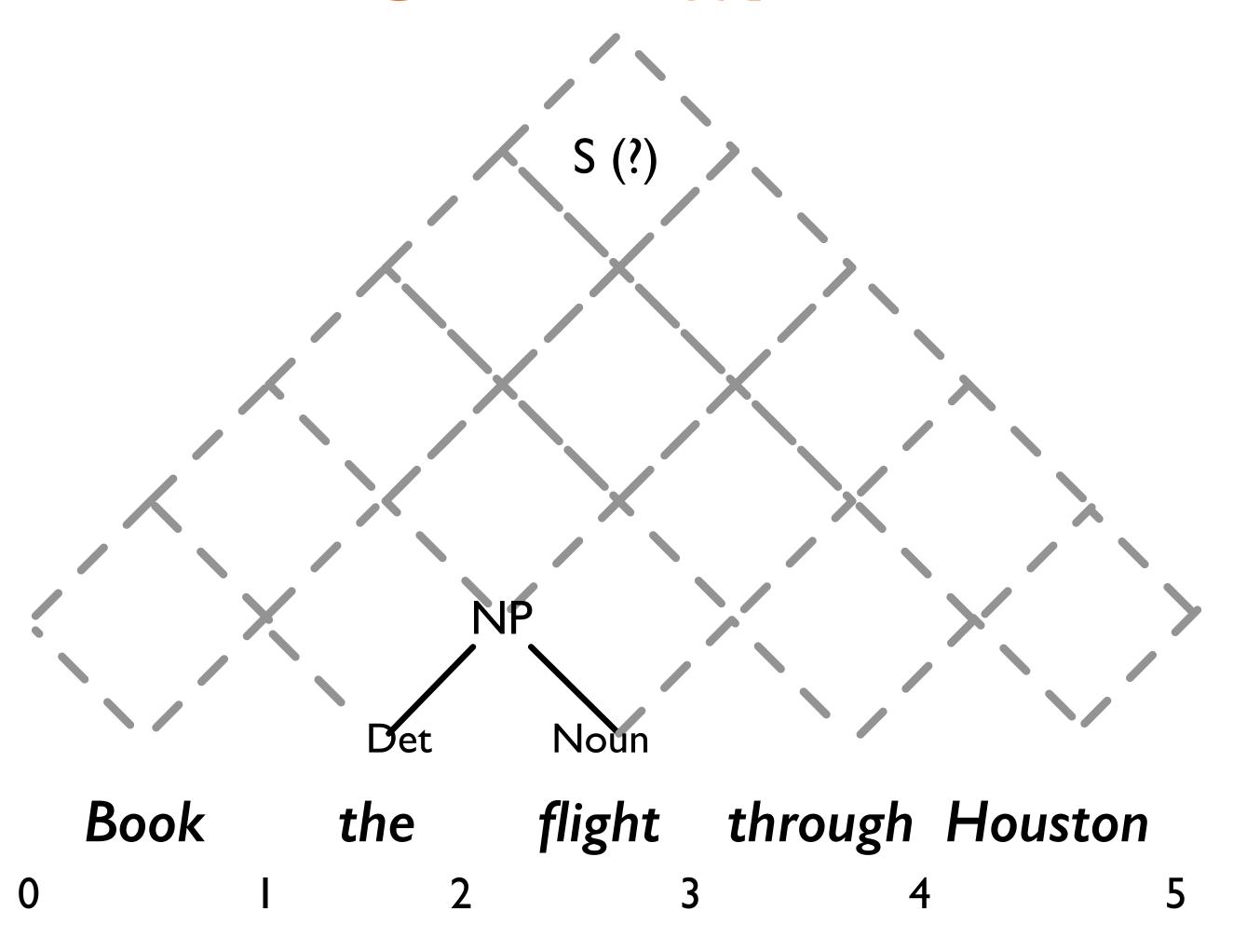
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- Each cell [i, j] contains SETS { } of non-terminals with derivations spanning *i*, *j*
 - [j-1,j] contains pre-terminals
 - if [0, n] contains the start symbol, the sentence is *accepted*

Book	the	flight	through	Houston
[0,1]	[0,2]	[0,3]	[0,4]	[0,5]
	[1,2]	[1,3]	[1,4]	[1,5]
		[2,3]	[2,4]	[2,5]
			[3,4]	[3,5]
				[4,5]







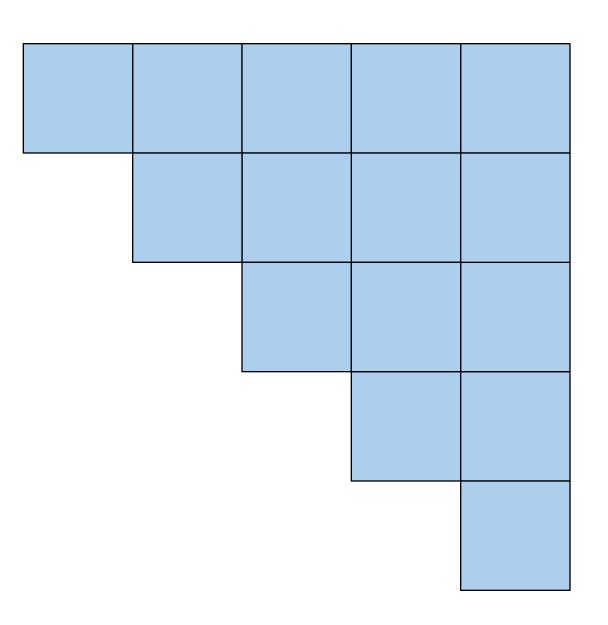


Dynamic Programming in CKY

- Key idea:
 - for *i* < *k* < *j*
 - ...and a parse spanning substring [i, j]
 - There is a **k** such that there are parses spanning [**i**, **k**] and [**k**, **j**]
 - We can construct parses for whole sentences by building from these partial parses
- So to have a rule $A \rightarrow BC$ in [i, j]
 - Must have \boldsymbol{B} in [i, k] and \boldsymbol{C} in [k, j] for some i < k < j
 - CNF forces this for all j > i + 1

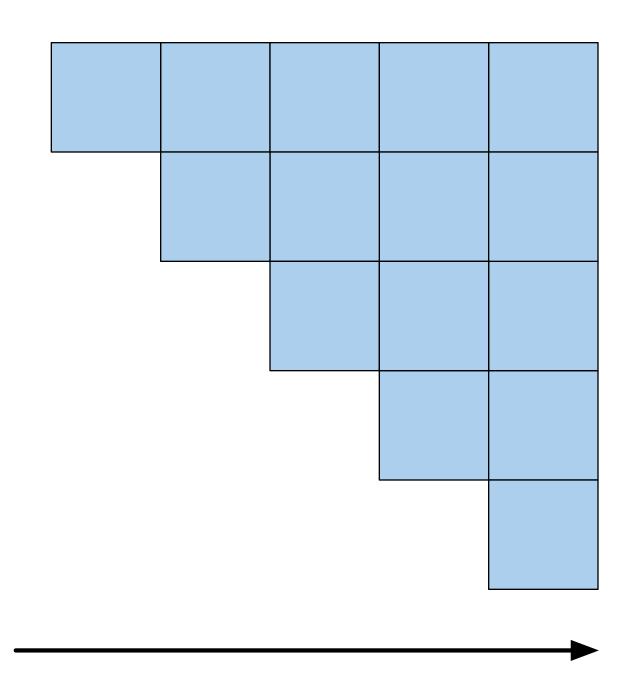


Table fills:



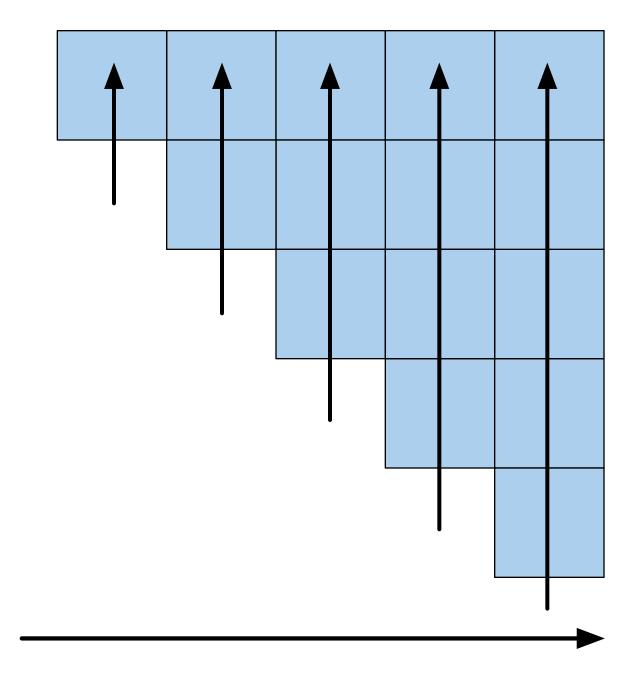


- Table fills:
 - Column-by-column, left-to-right



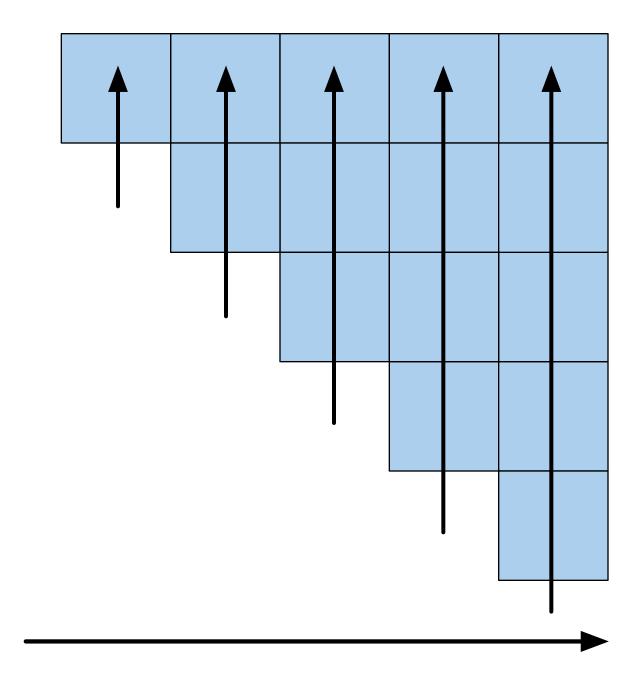


- Table fills:
 - Column-by-column, left-to-right
 - bottom-to-top



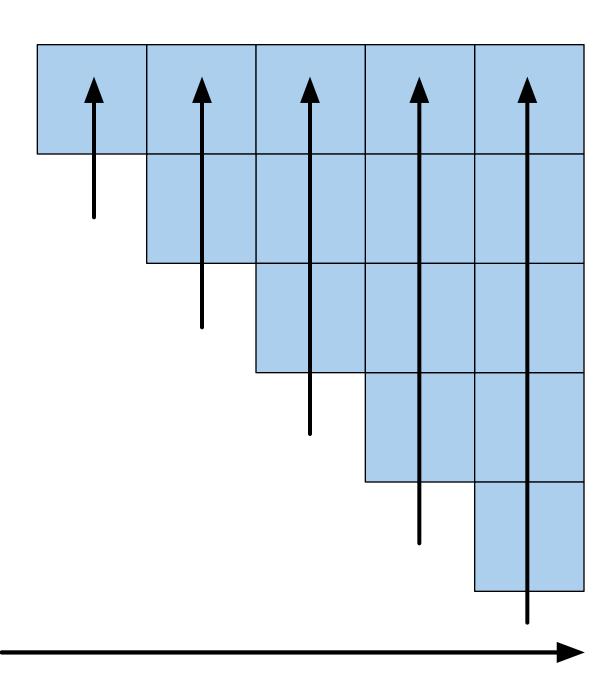


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- Why?



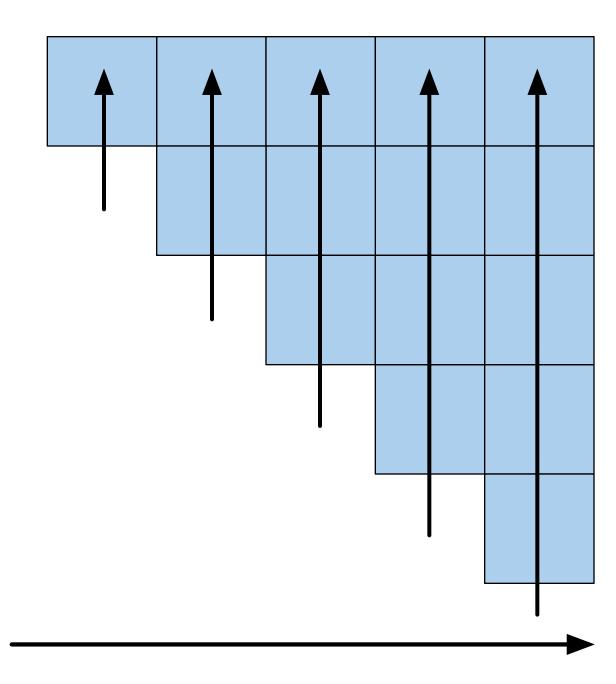


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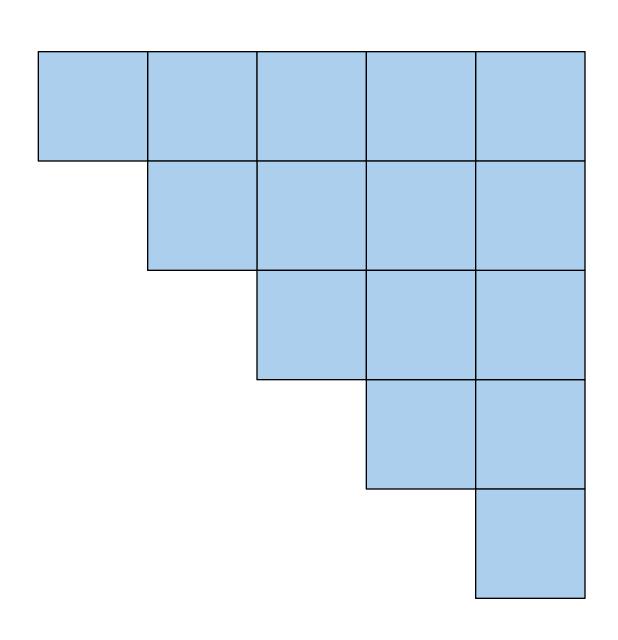


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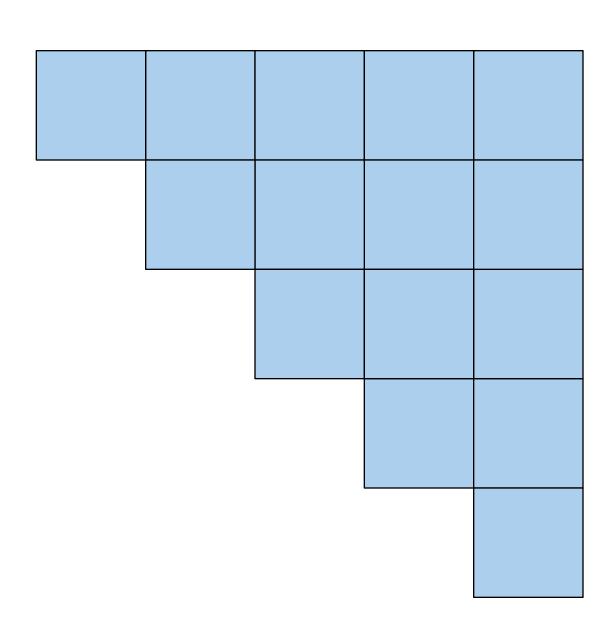


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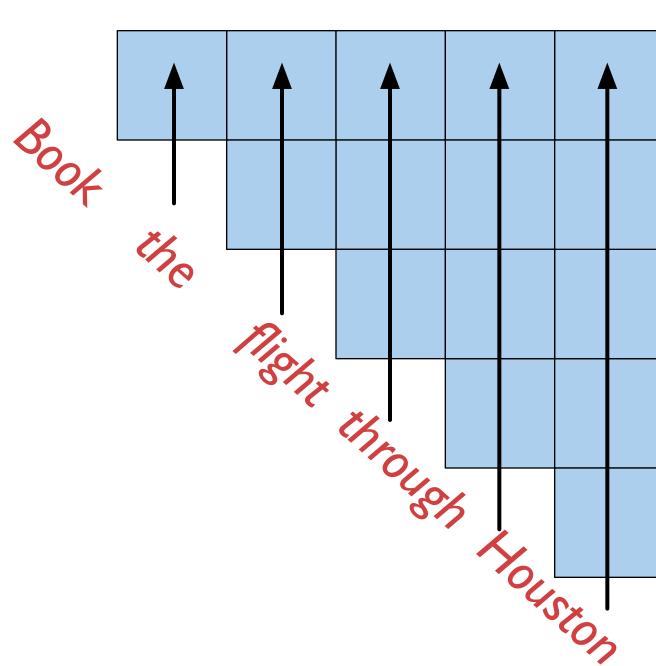


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```
function CKY-PARSE(words, grammar) returns table for j ← from 1 to LENGTH(words) do
     table[j-1,j] \leftarrow \{A \mid A \rightarrow words[j] \in grammar\}
         for i \leftarrow \text{from } j - 2 \text{ downto } 0 \text{ do}
             for k \leftarrow i + 1 to i - 1 do
                 table[i, j] \leftarrow table[i, j] \cup
                      {A \mid A \rightarrow BC \in grammar}
                      B \in table[i, k],
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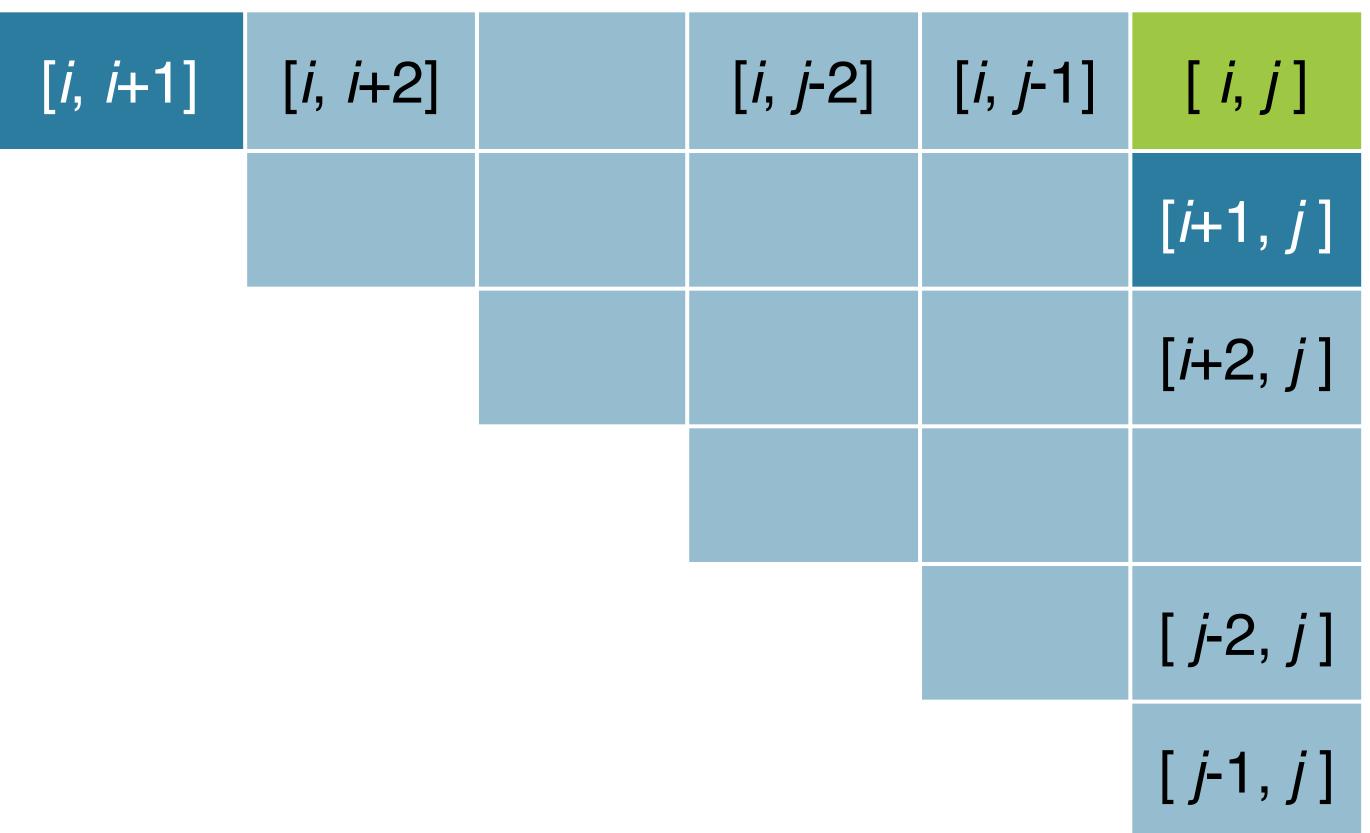
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Left-to-right, bottom-to-top
Sliding k as the pivot for child nodes

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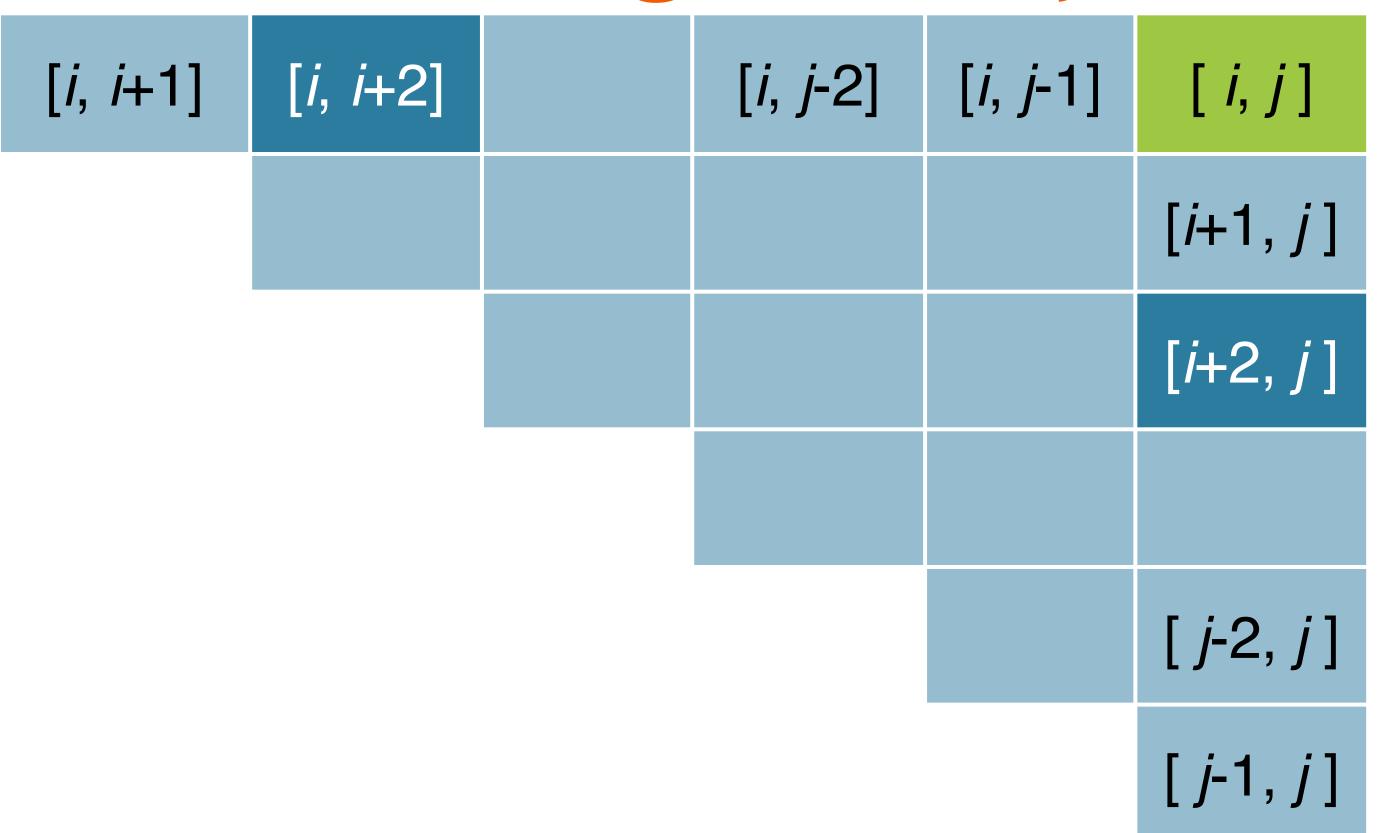
Left-to-right, bottom-to-top
Sliding k as the pivot for child nodes
Filling the cell with set of applicable rules

Filling Cell [i, j]



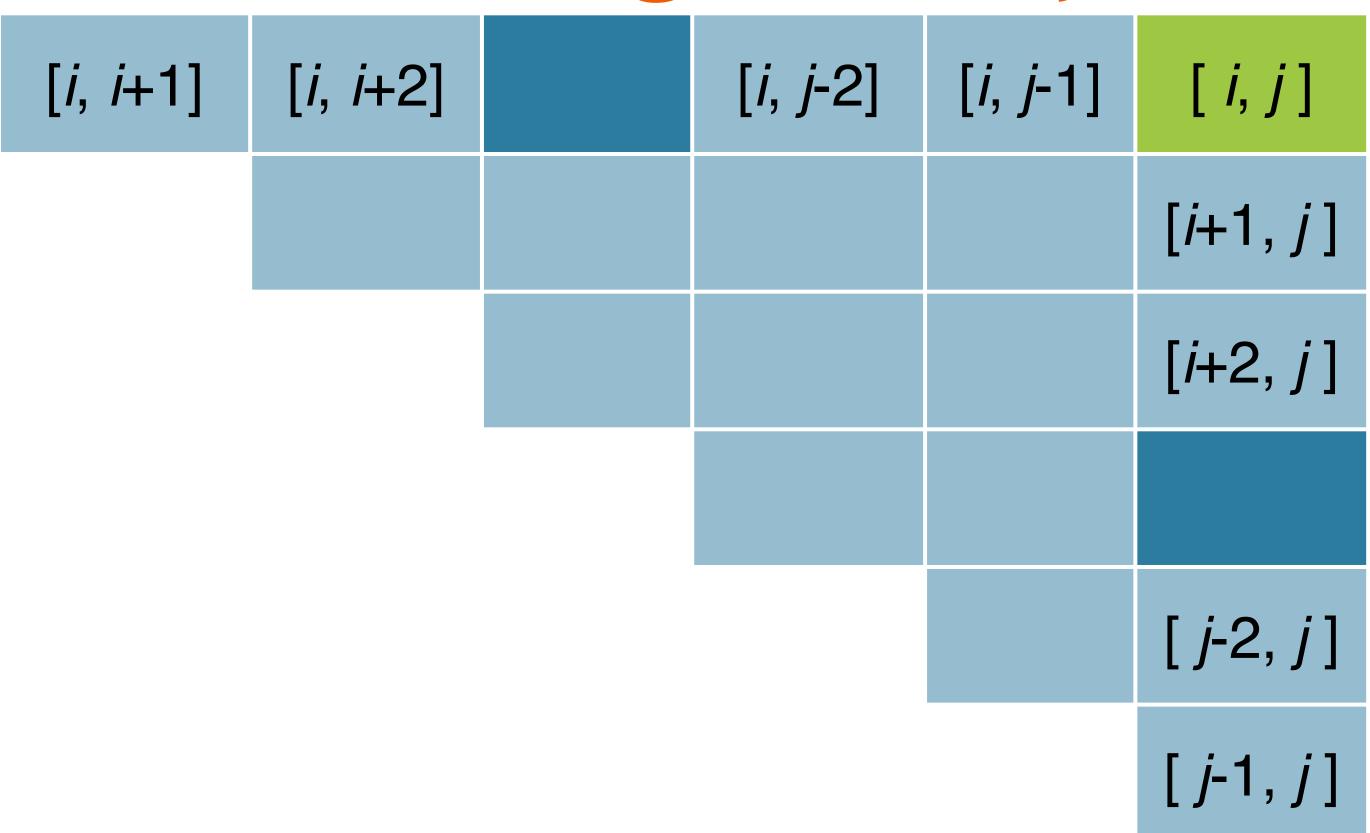
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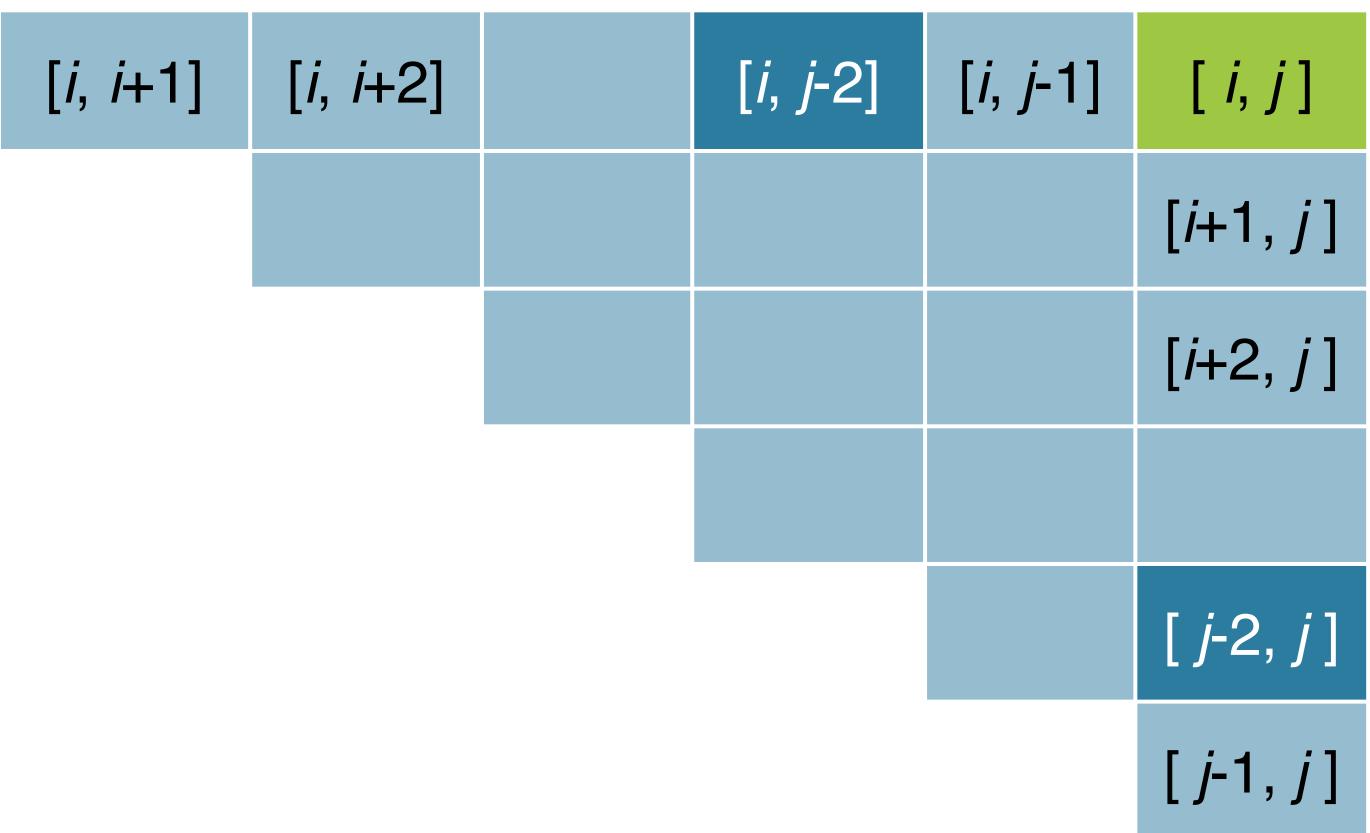
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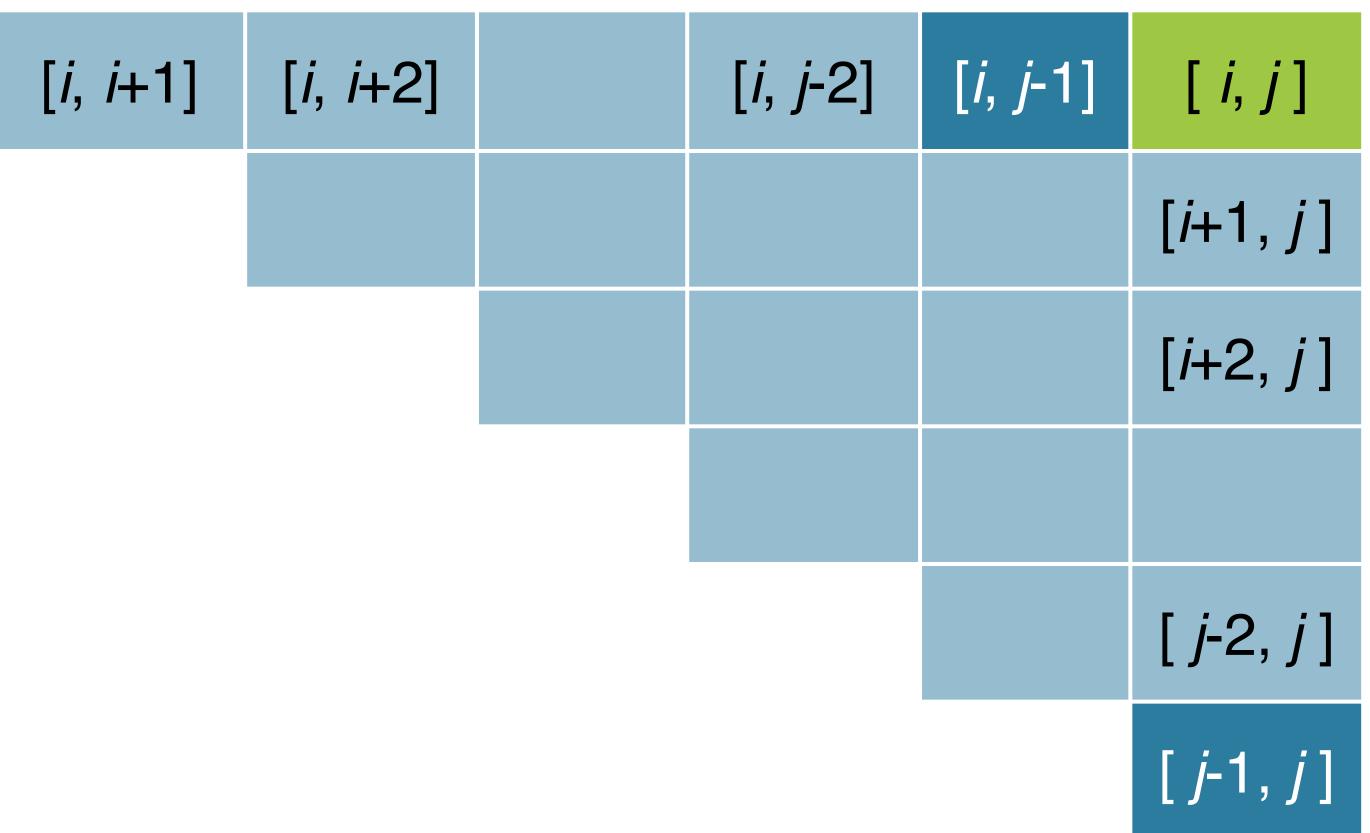
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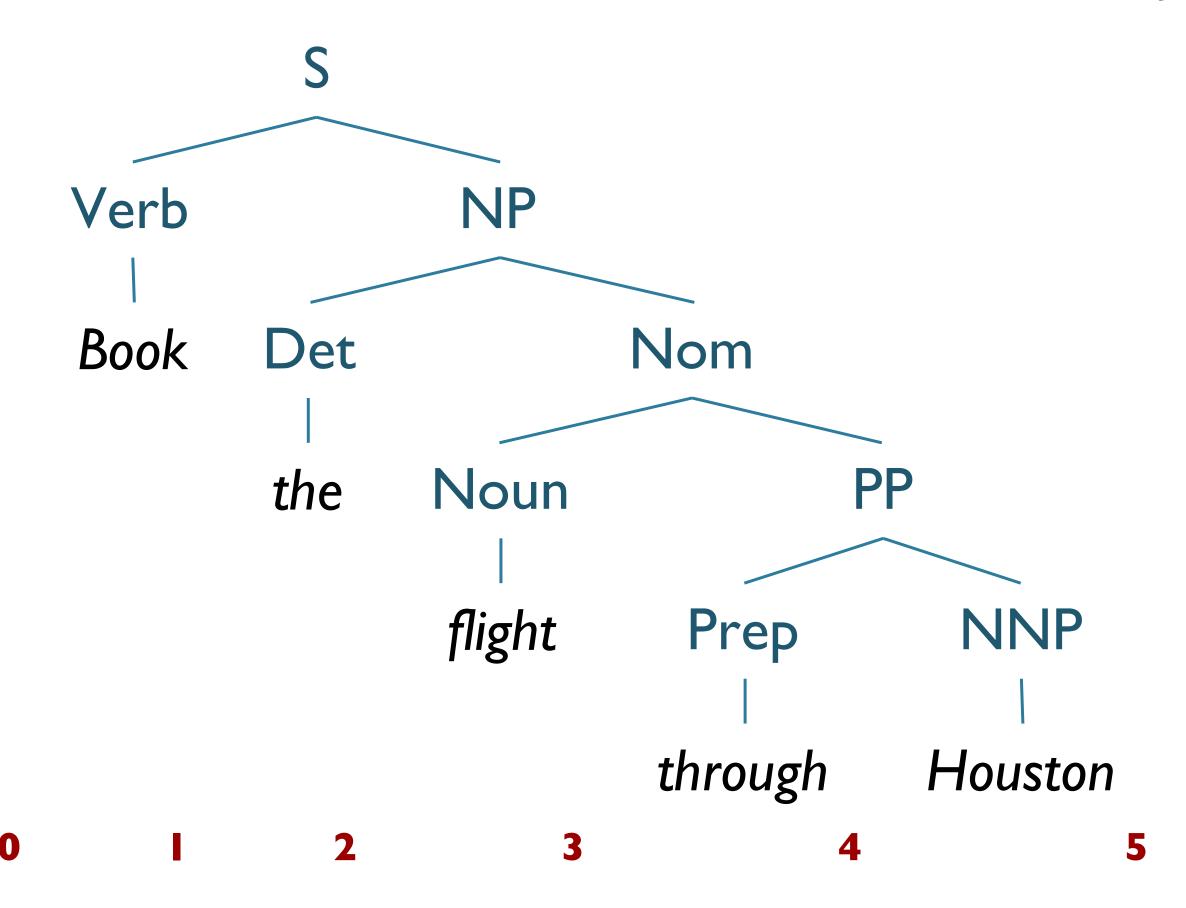


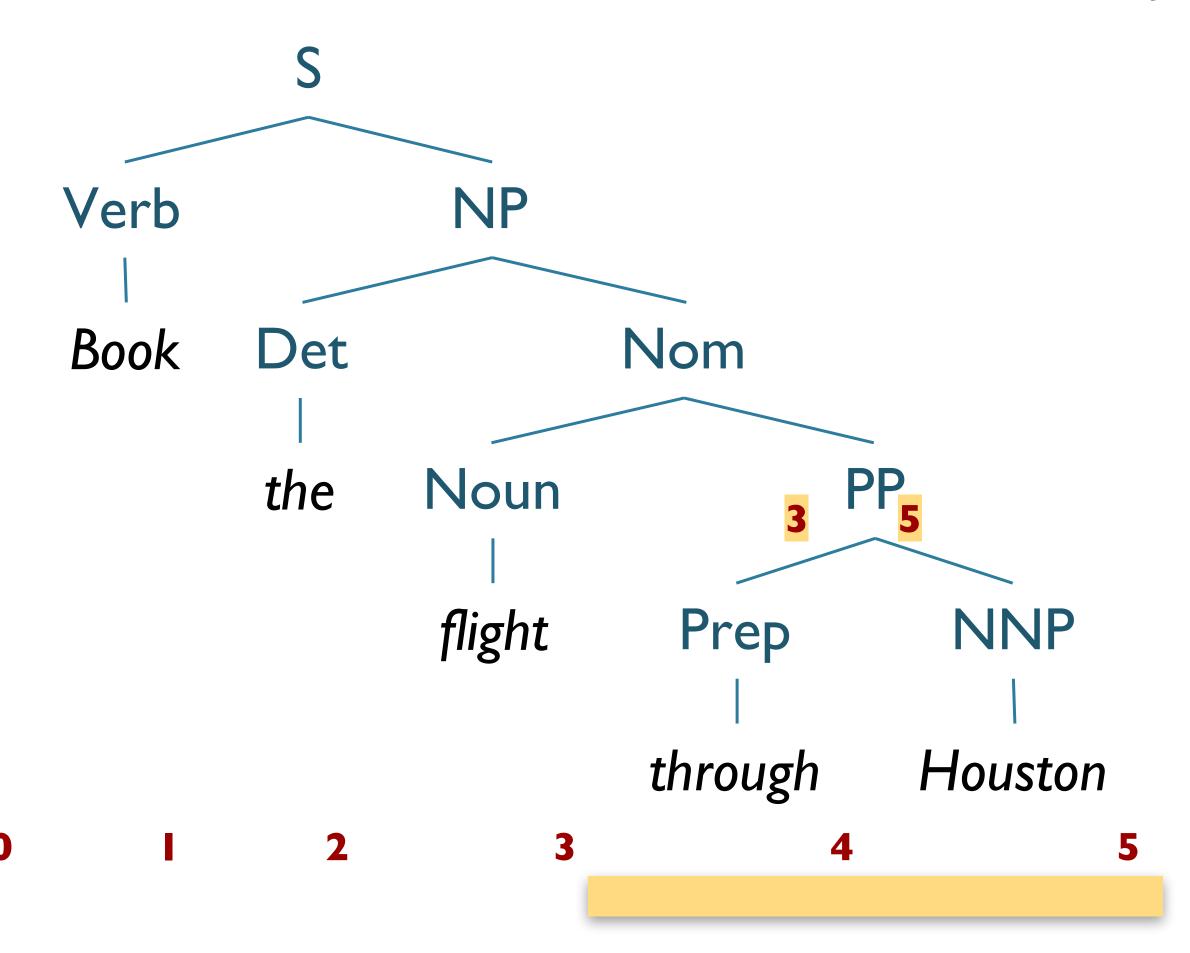
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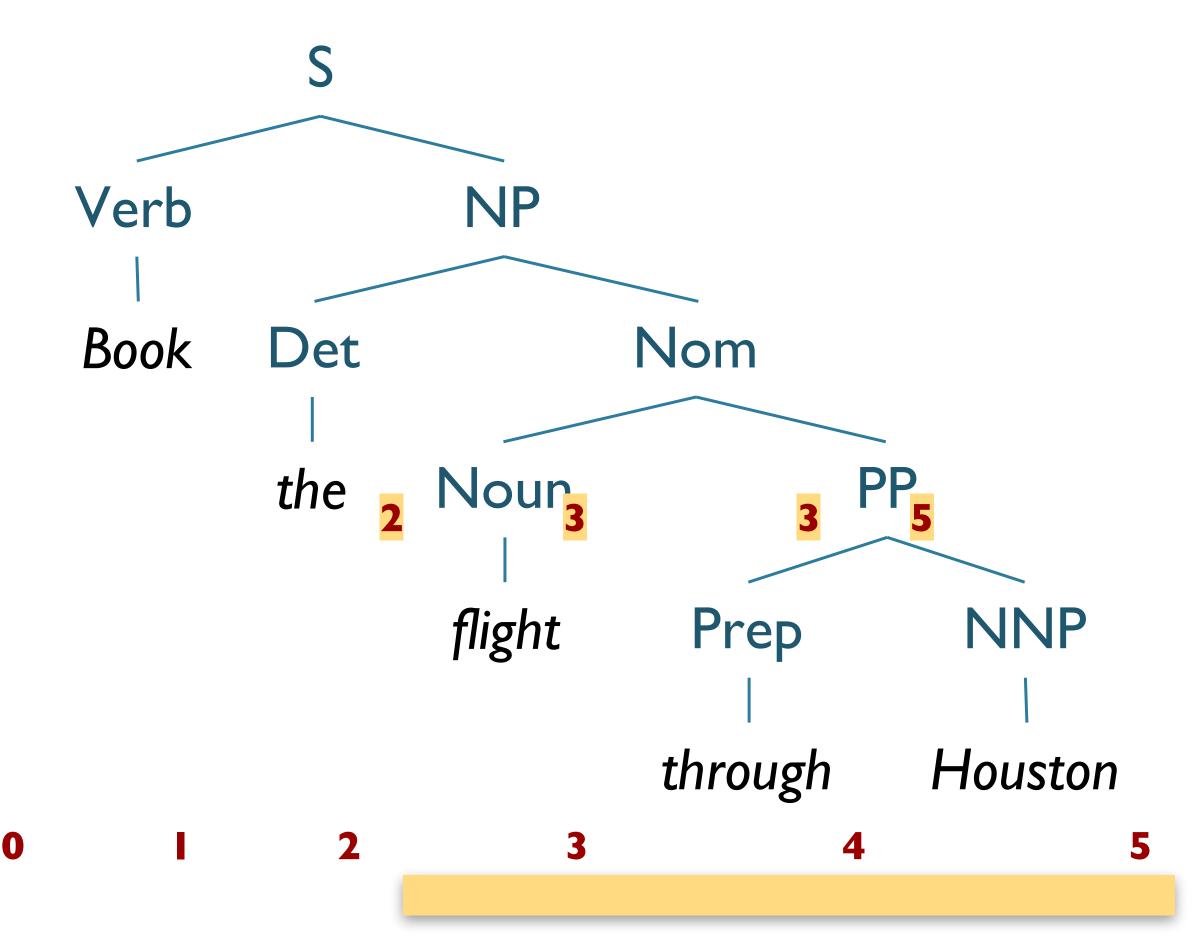
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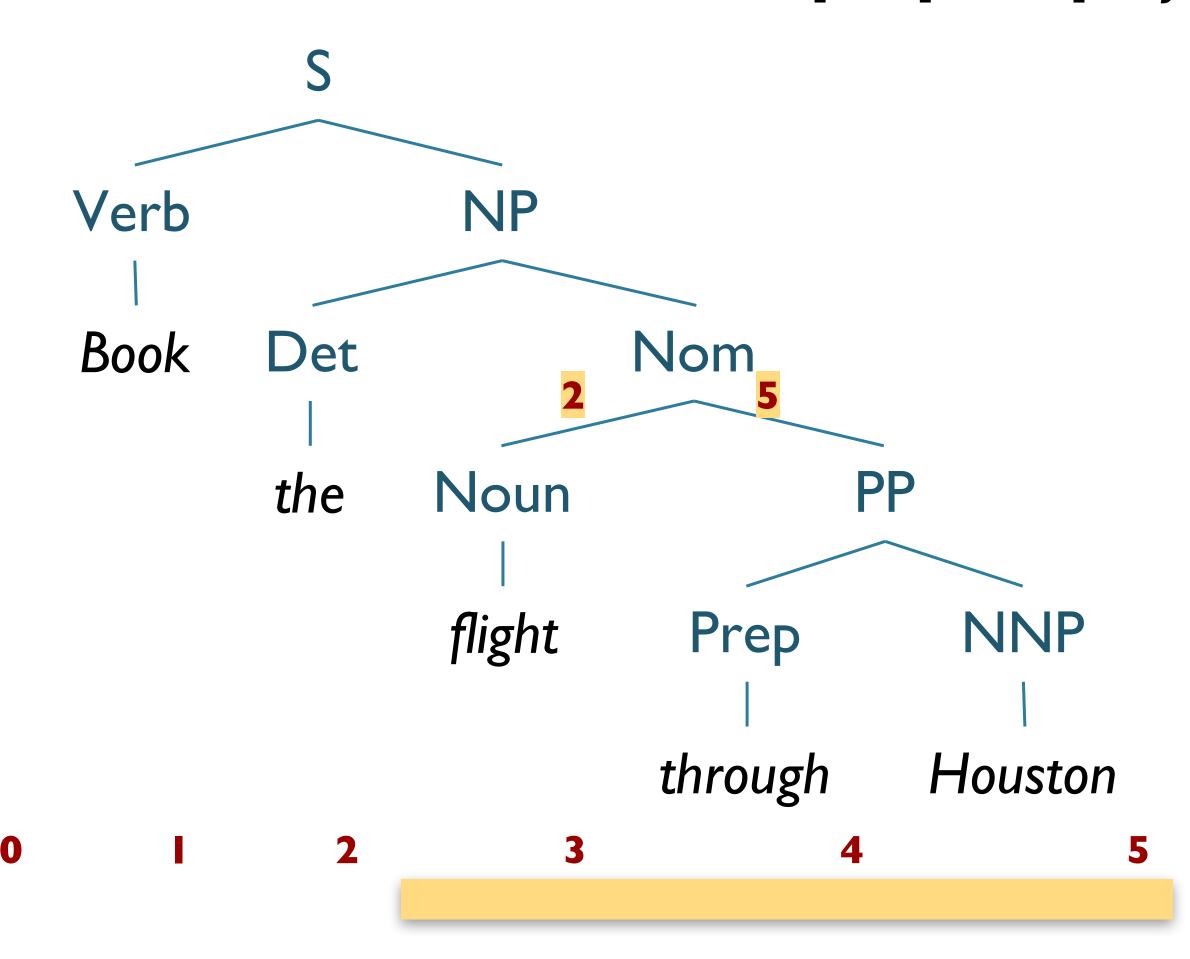


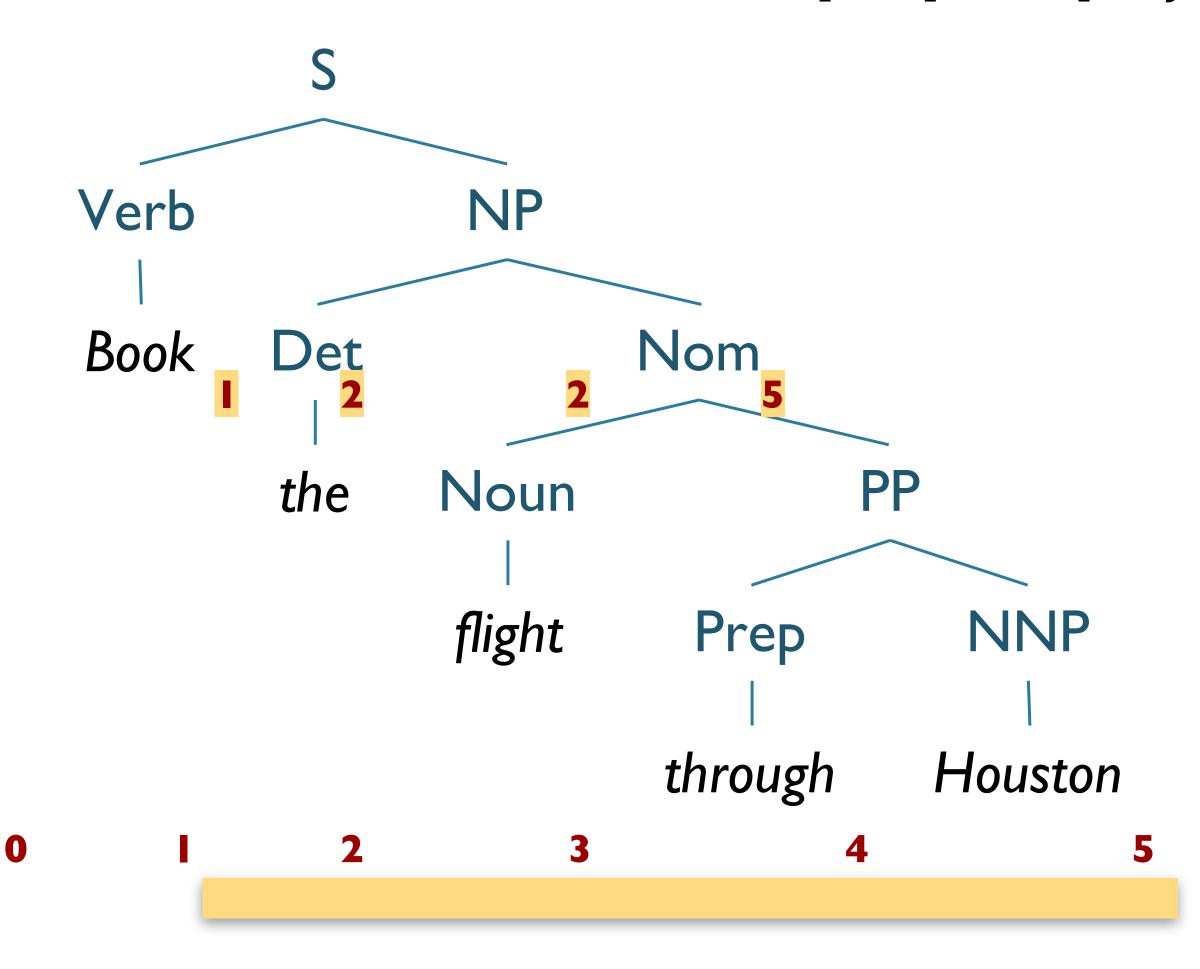
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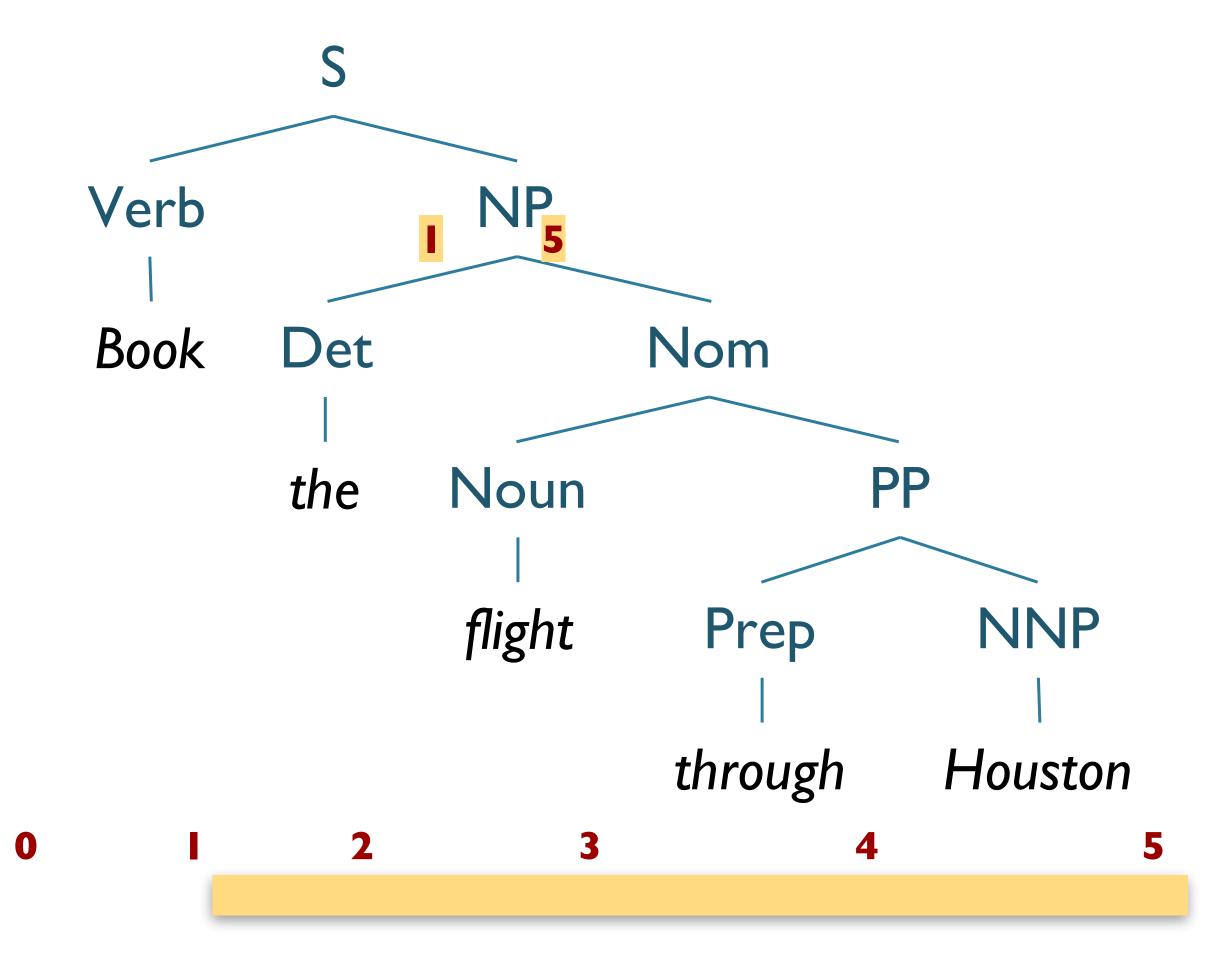


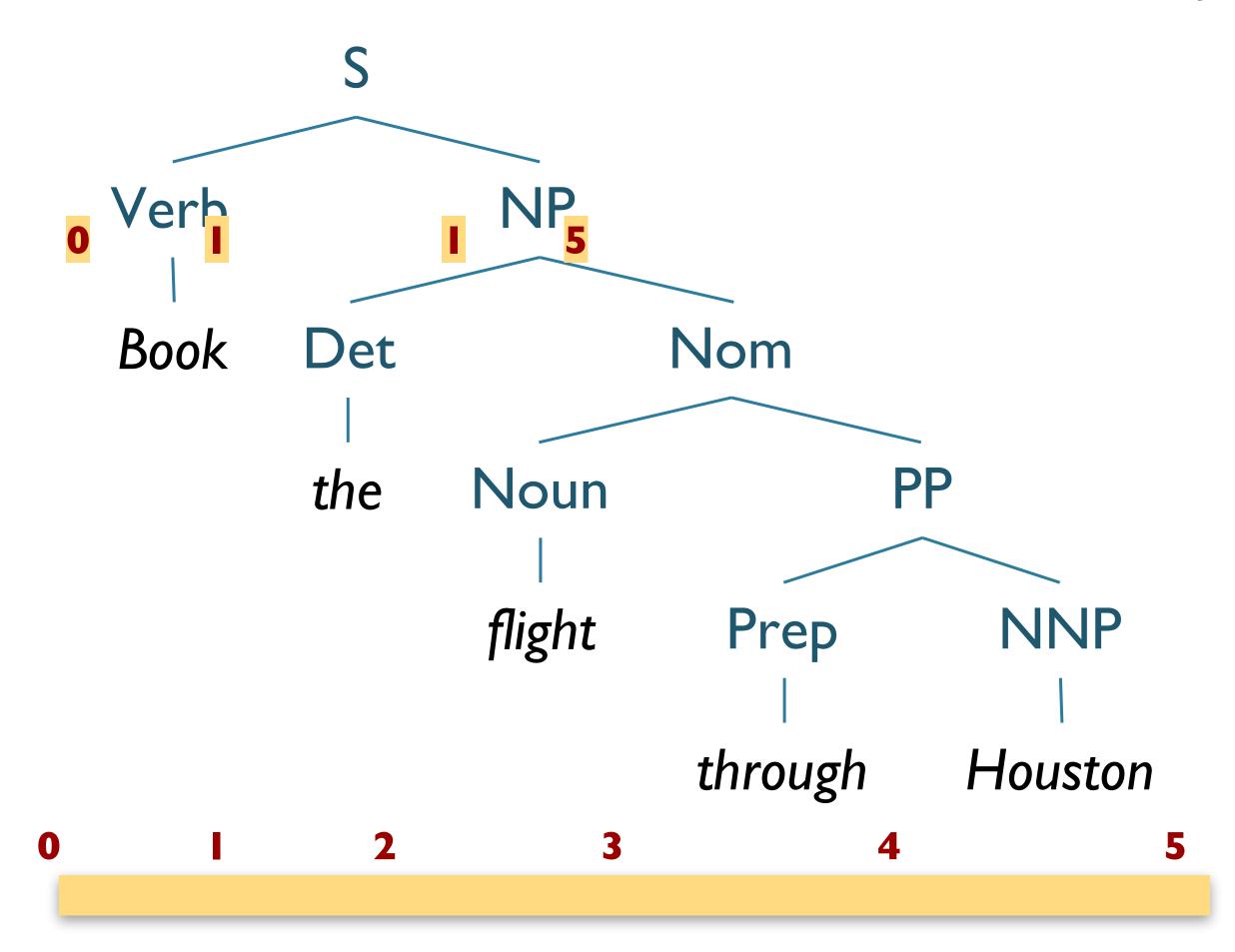


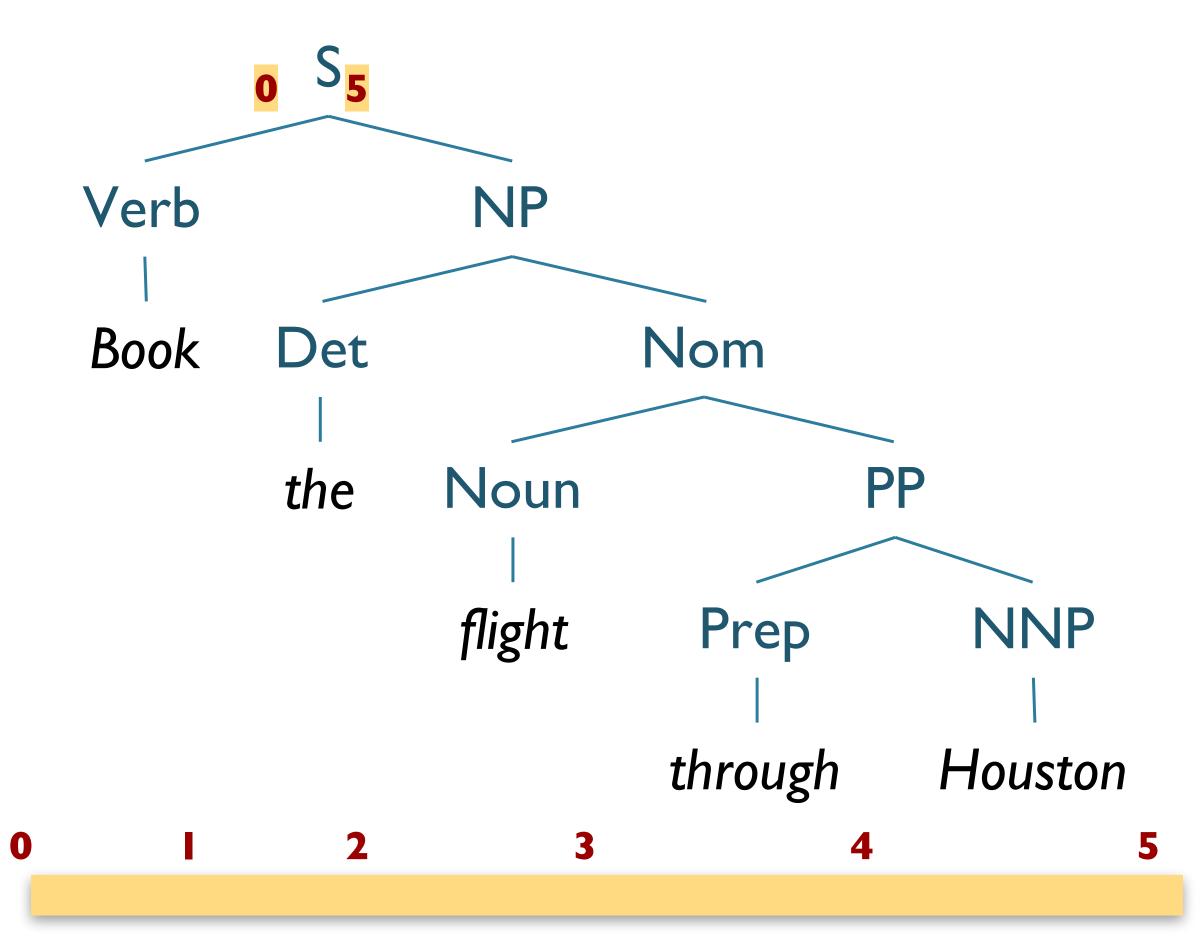


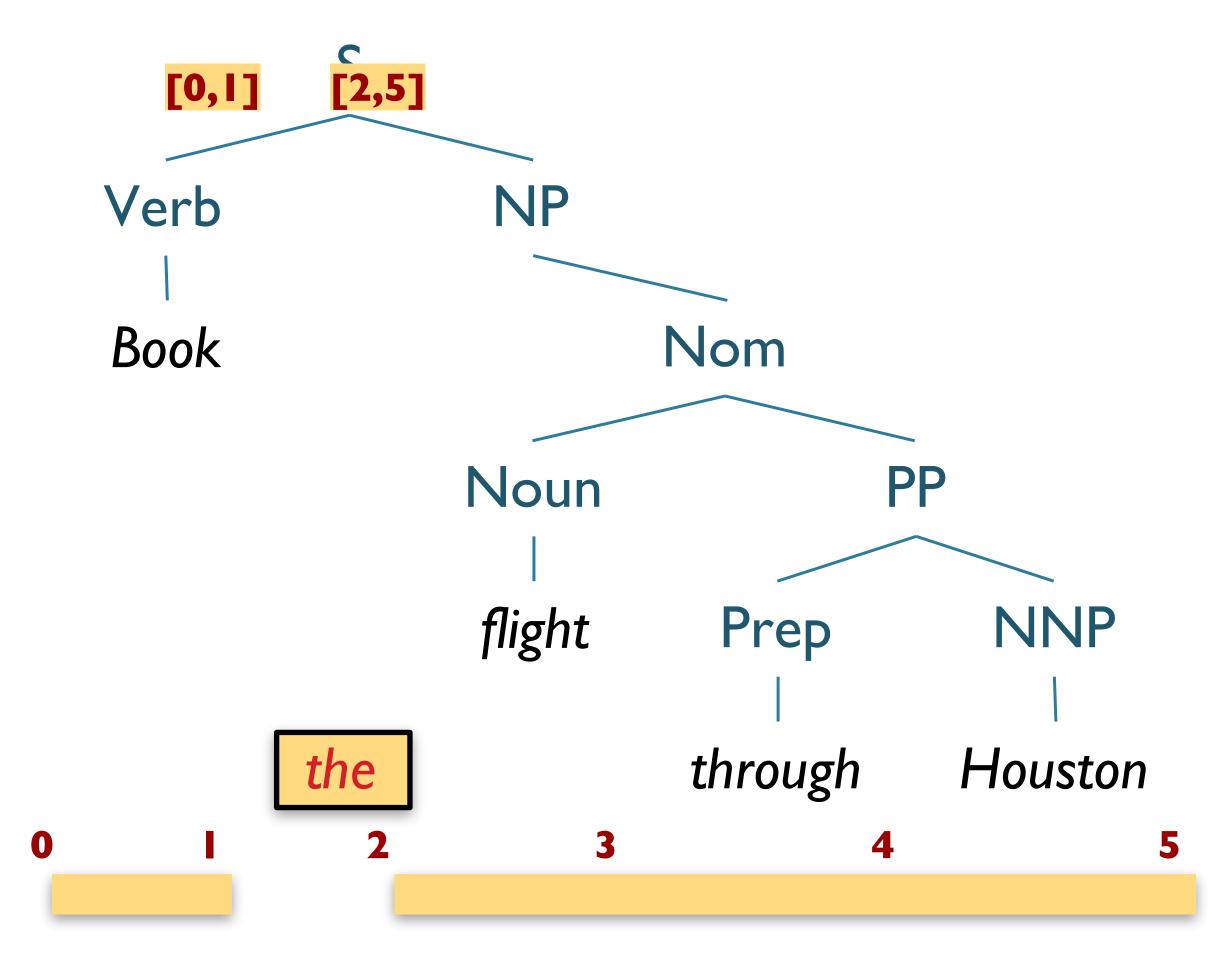


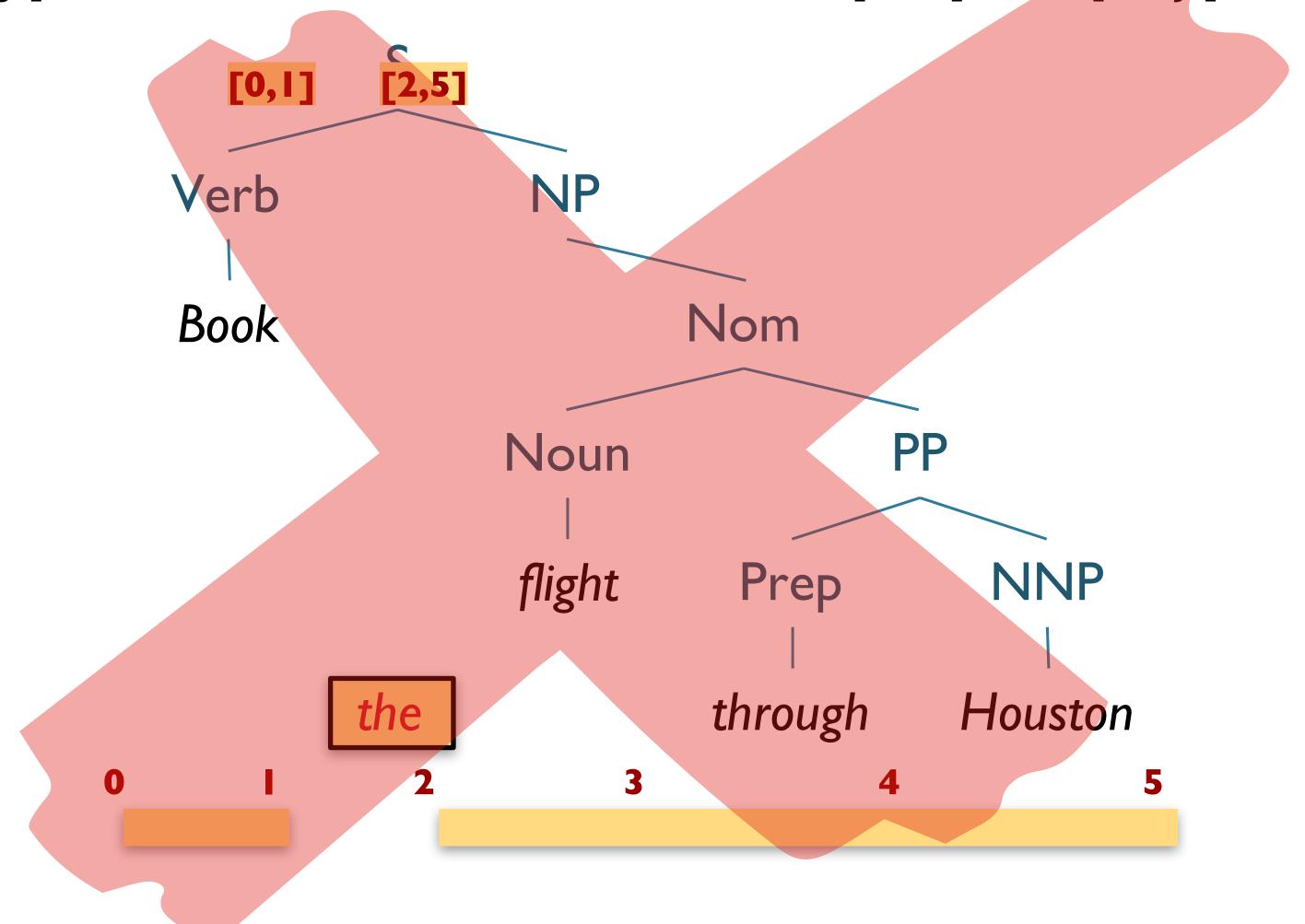












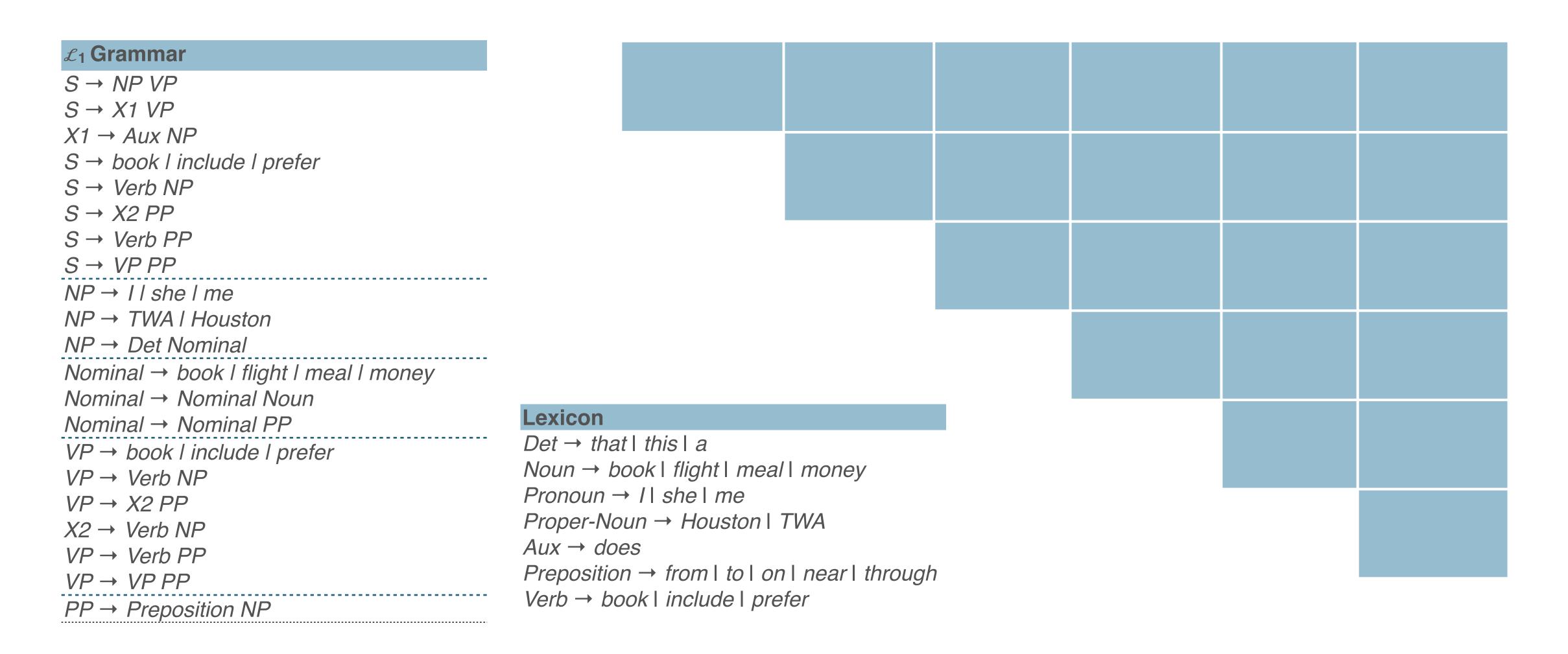


Would you say CKY is a top-down or a bottom-up parsing algorithm?

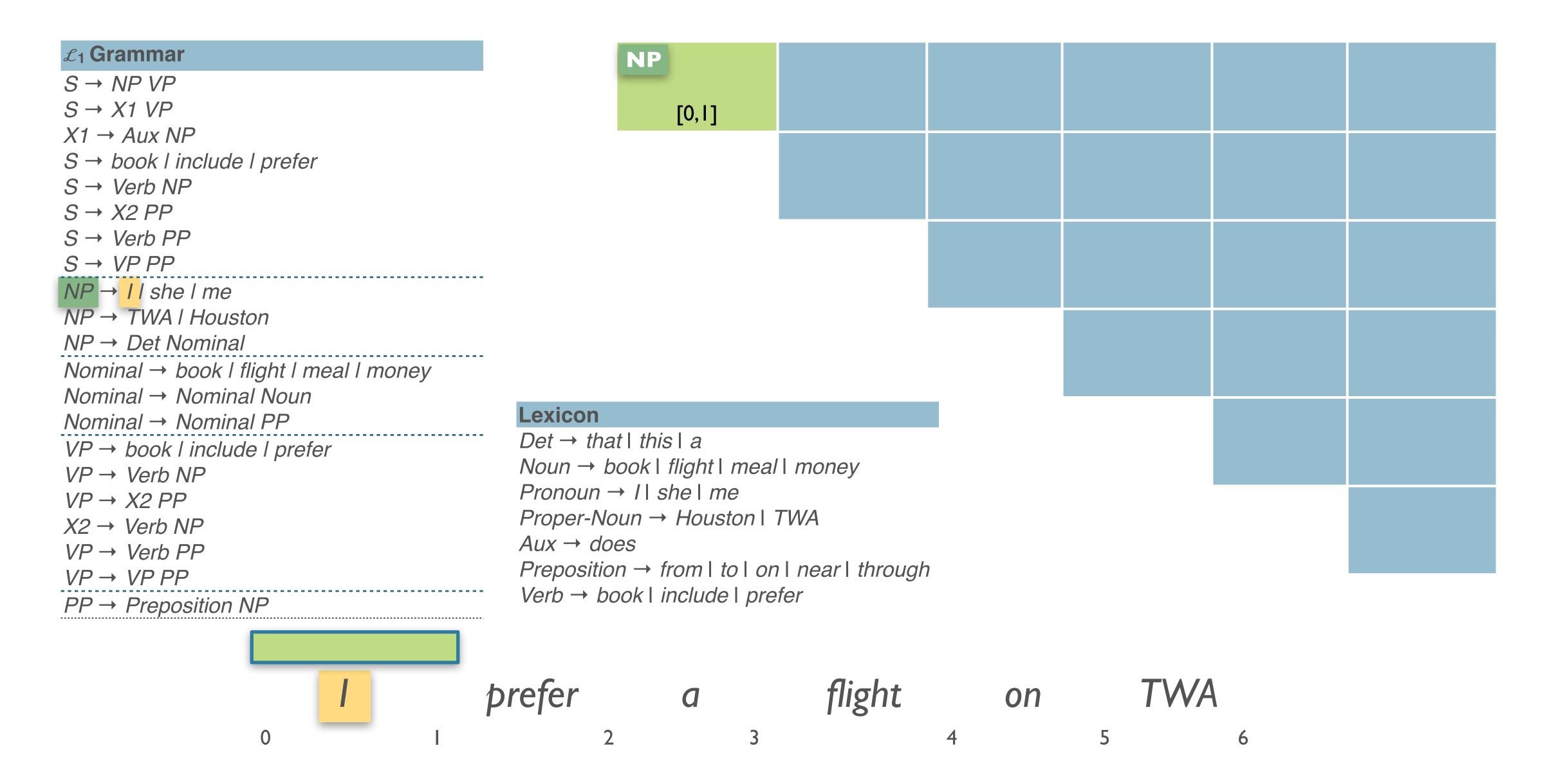


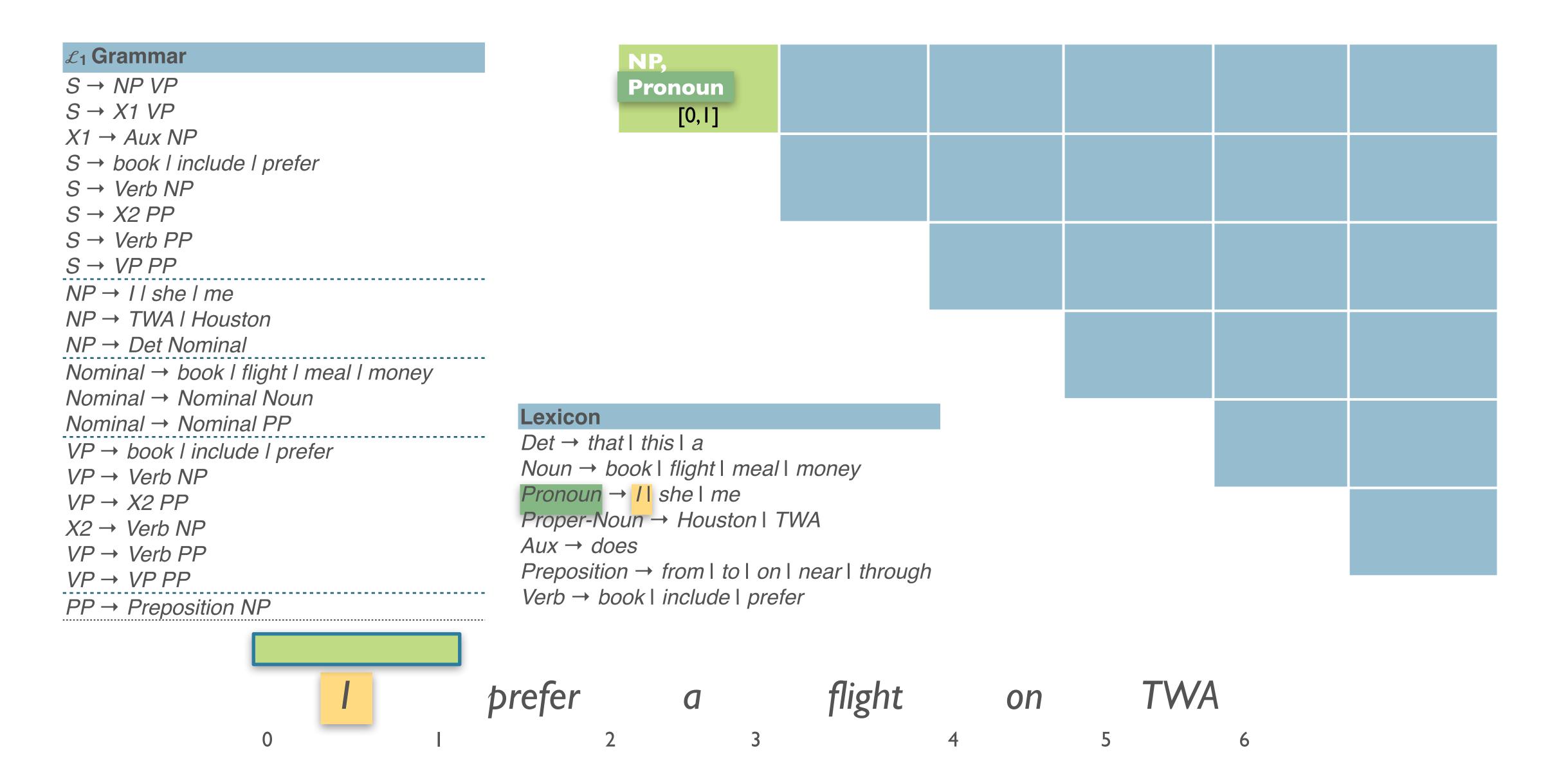
Top-down		
Bottom-up		

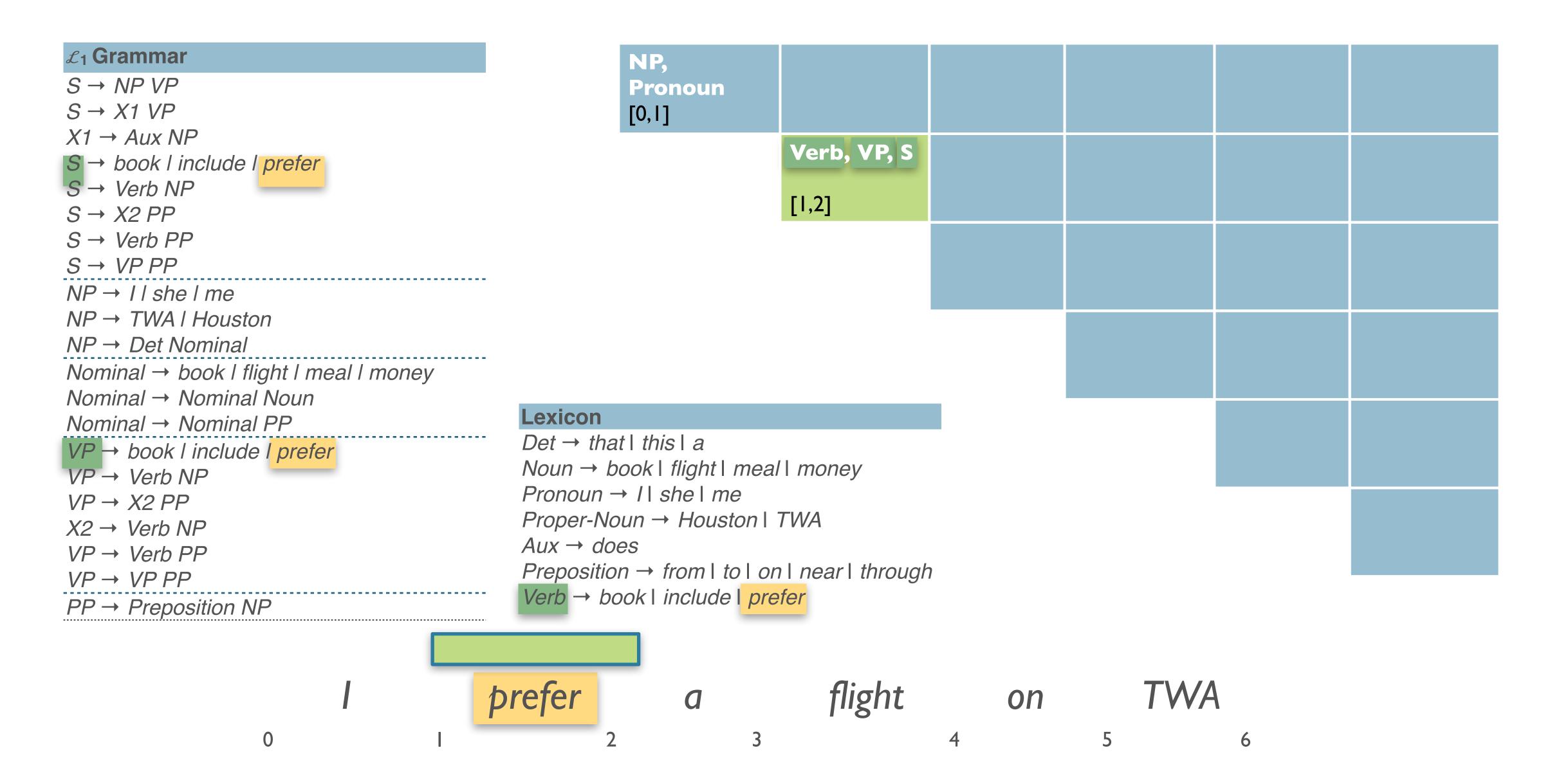
CKY Parsing Example

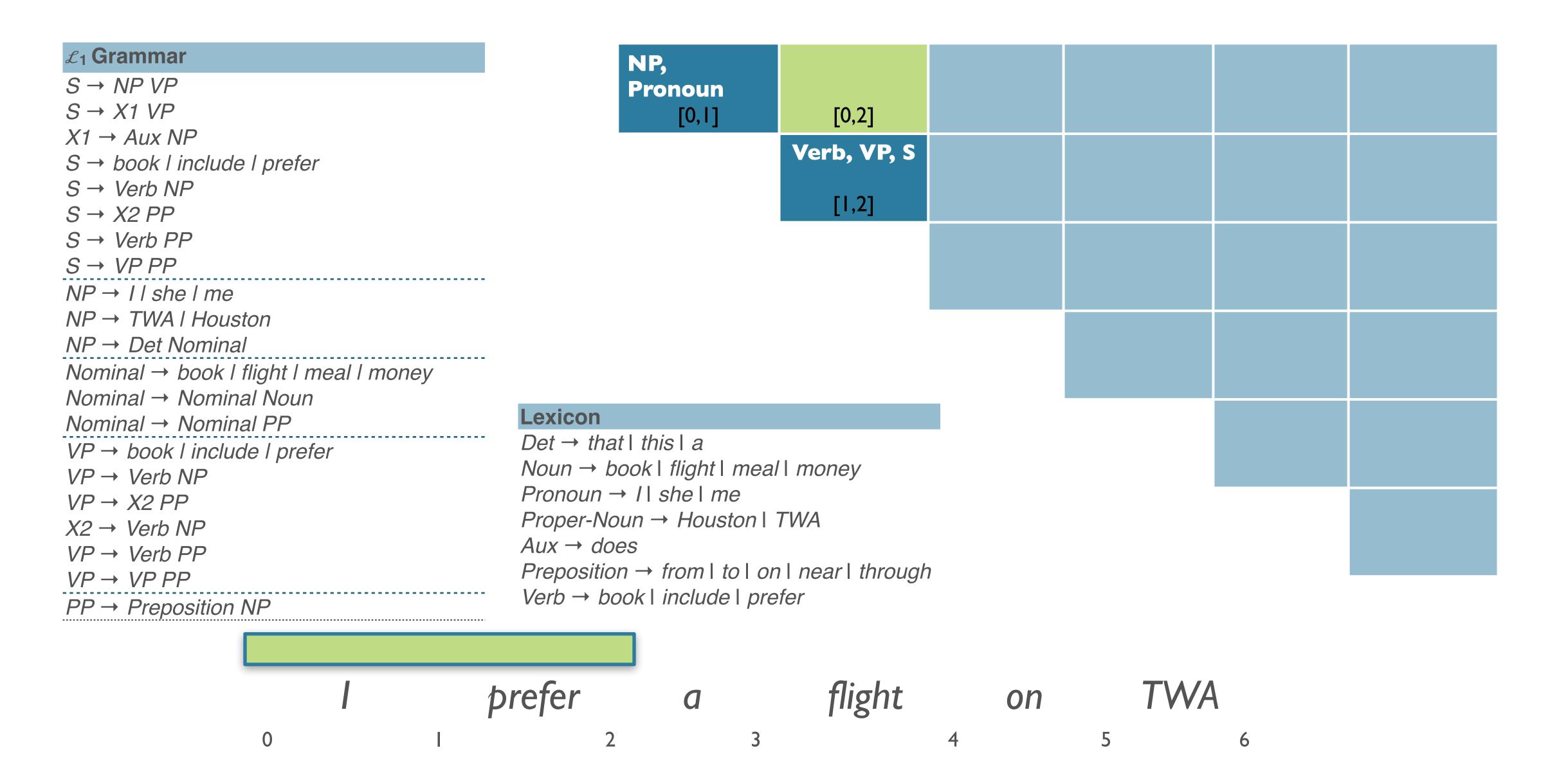


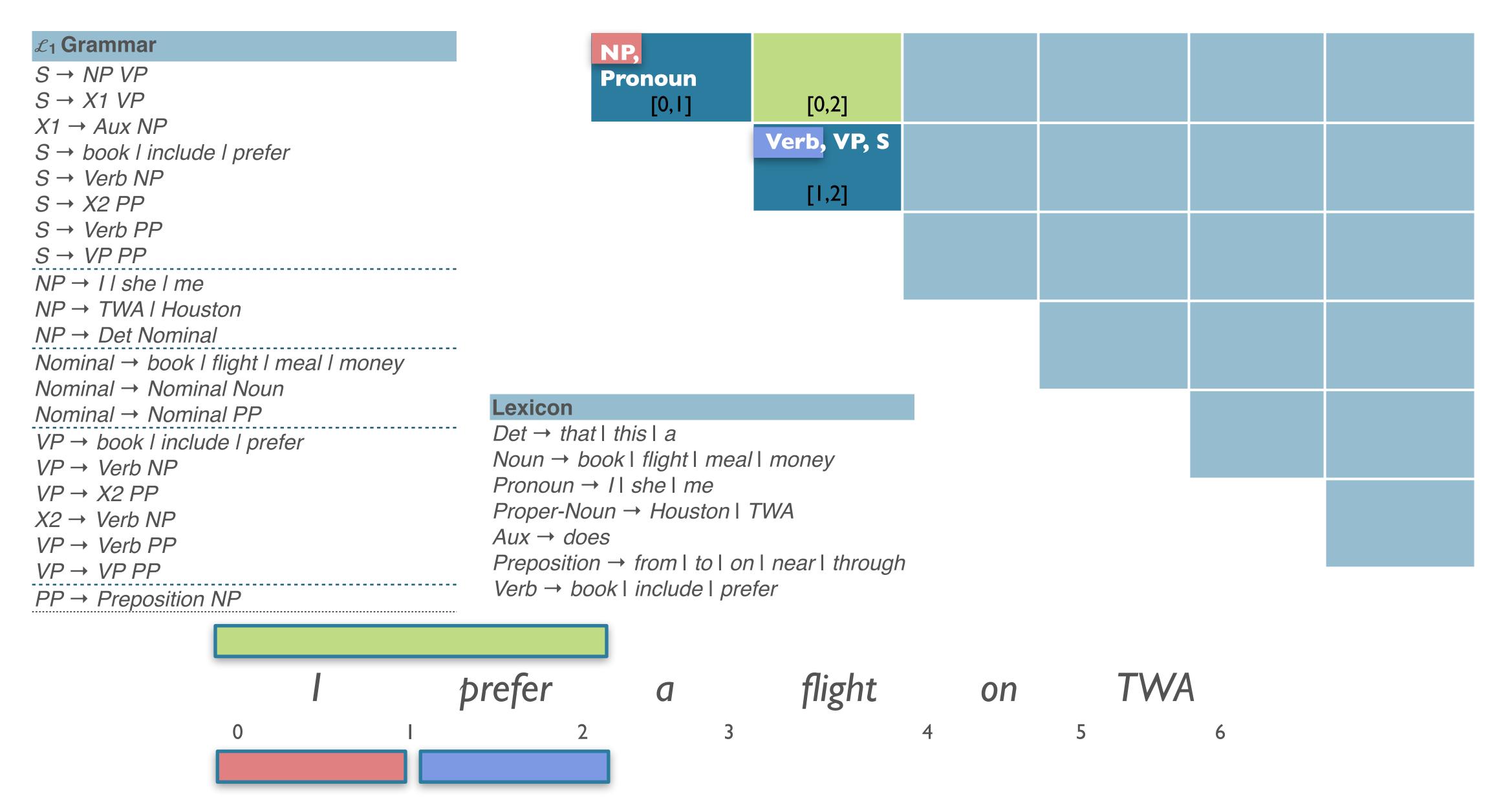


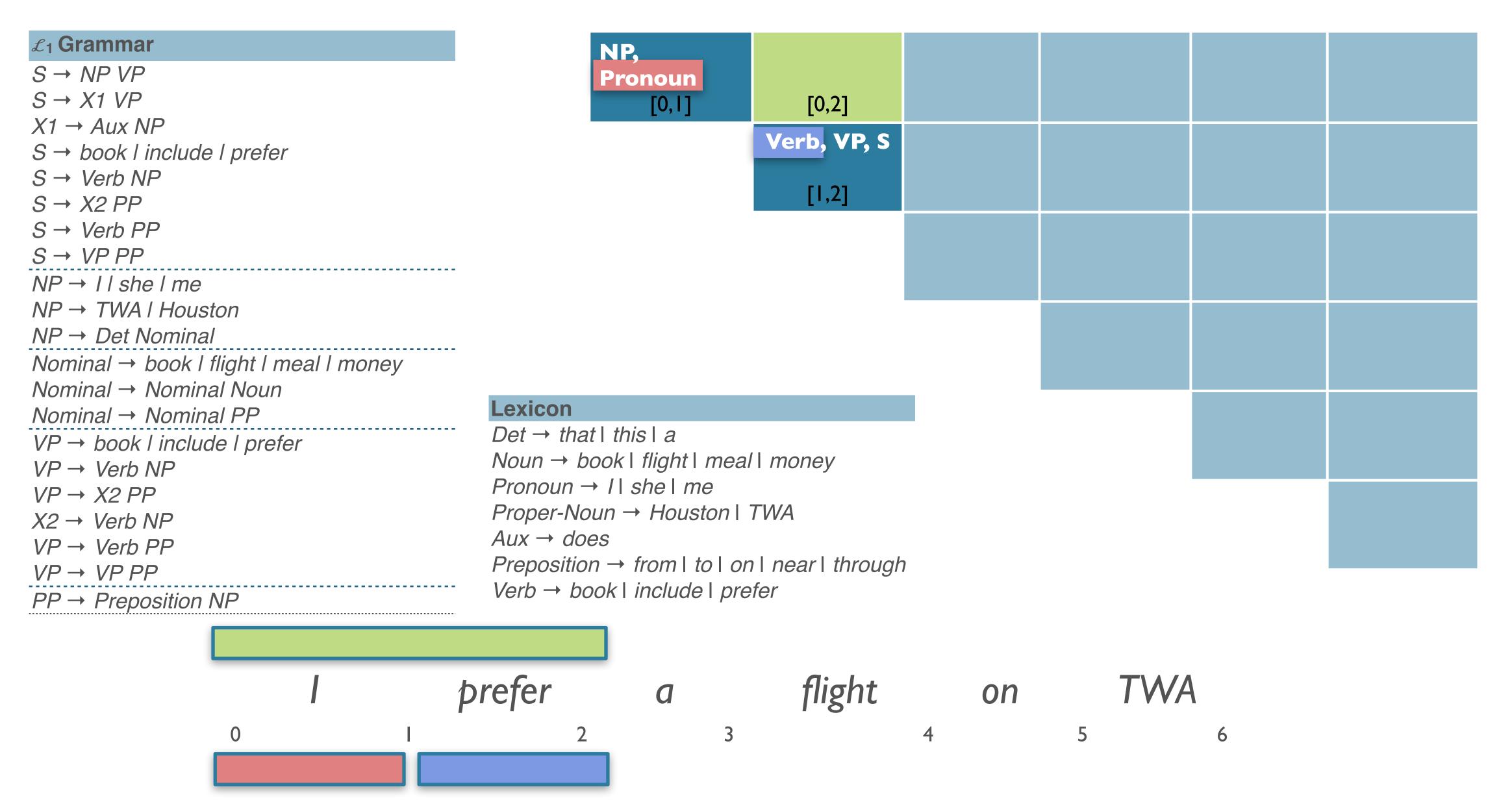


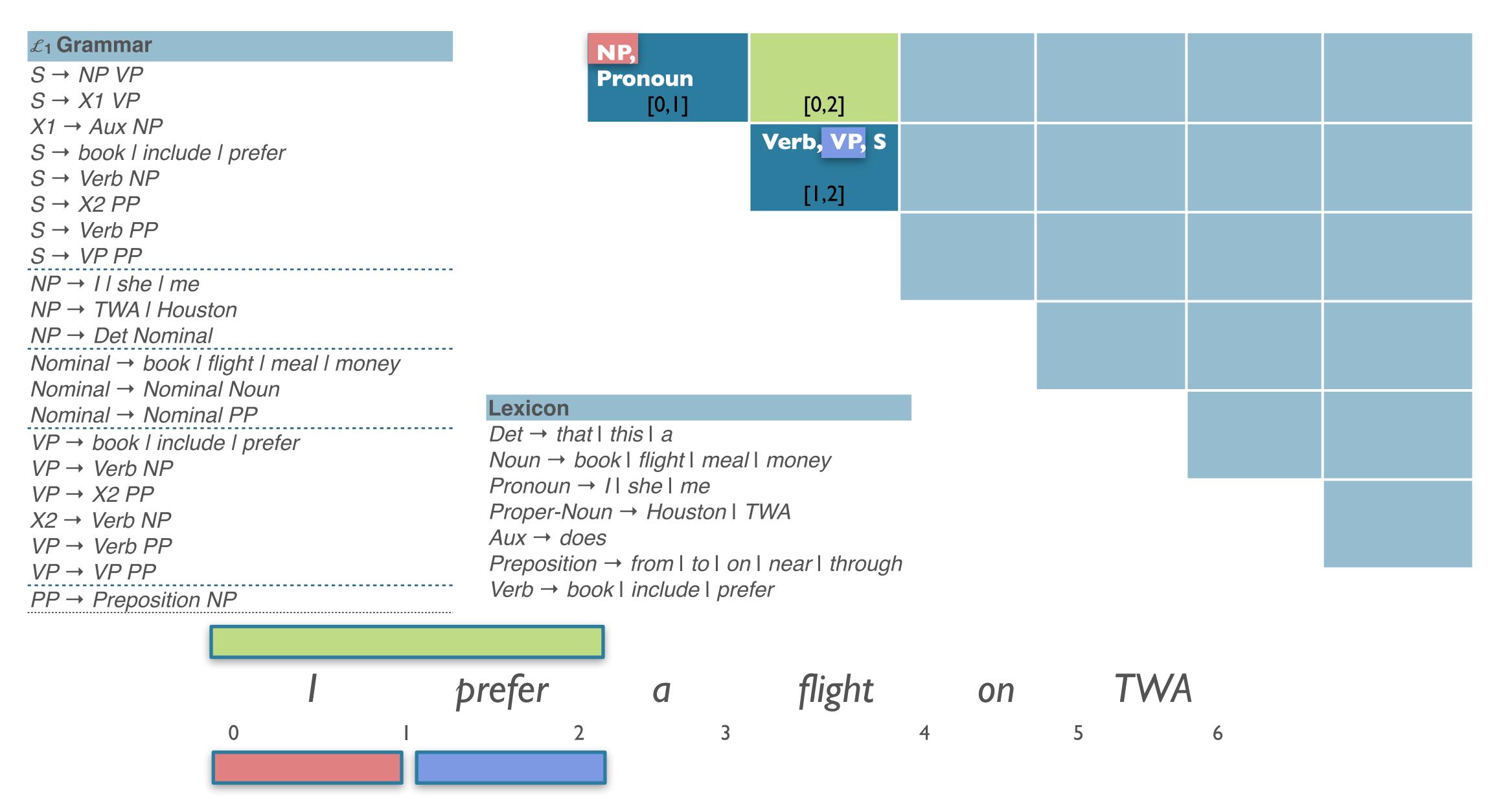


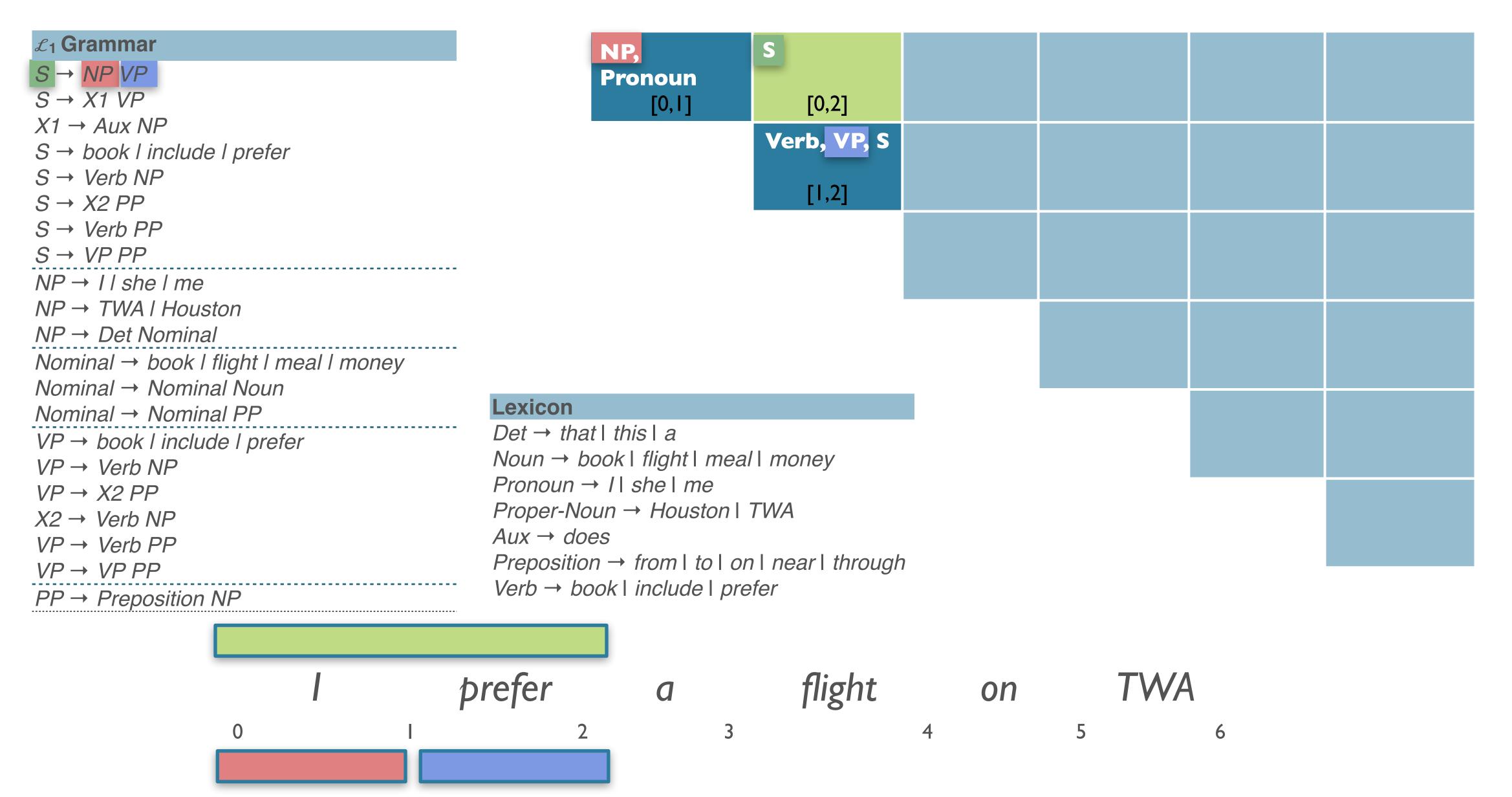


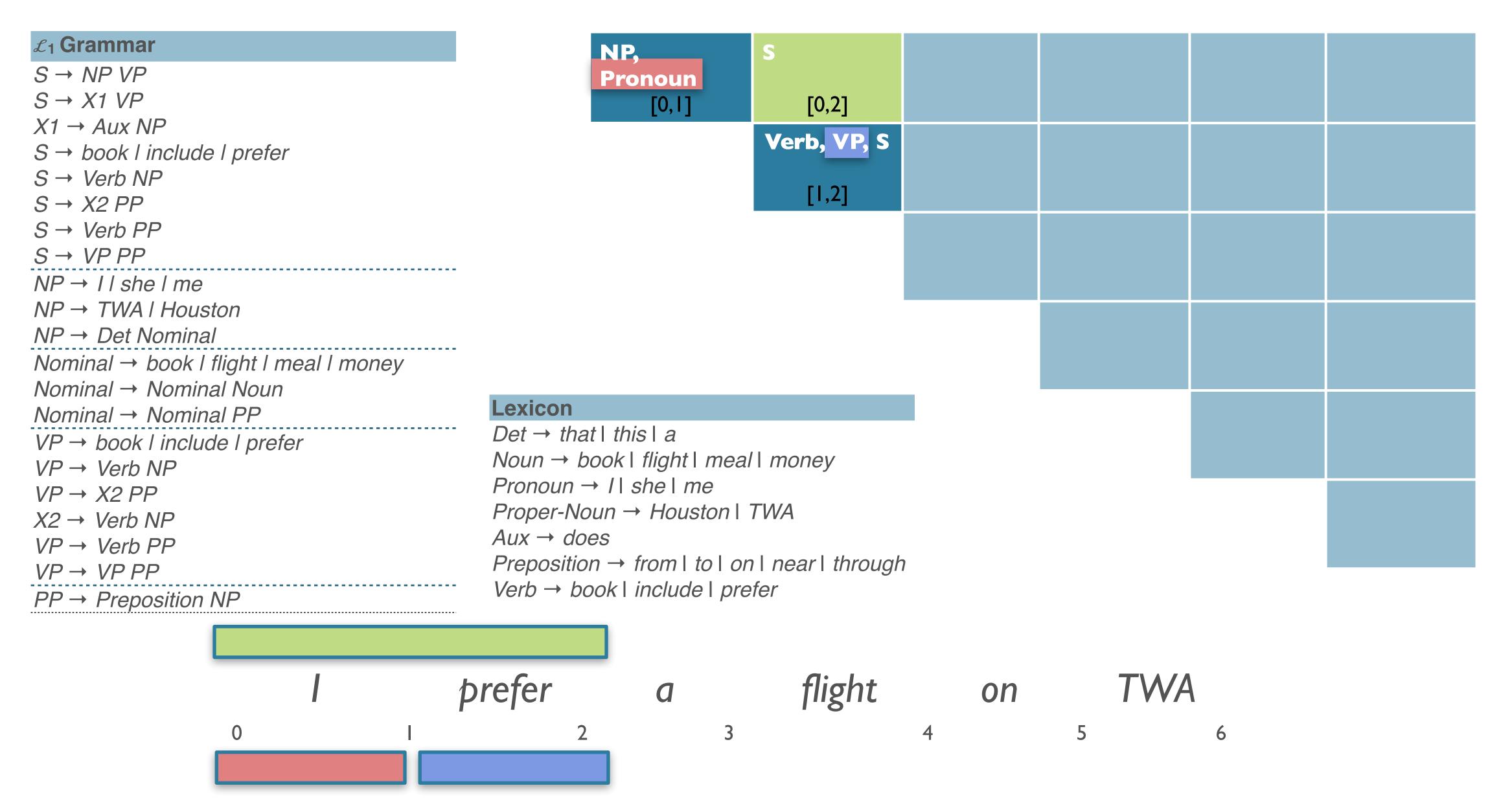


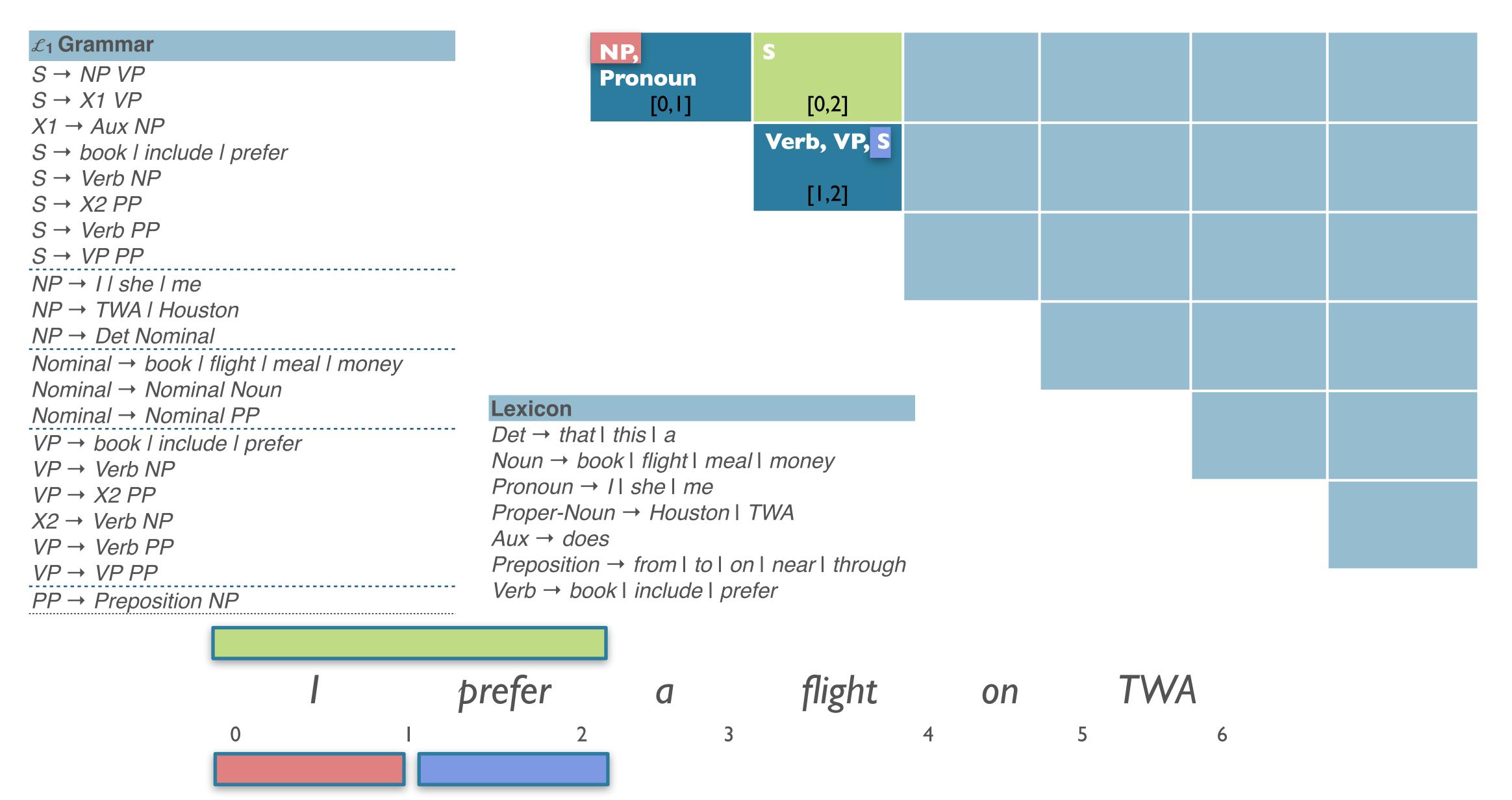


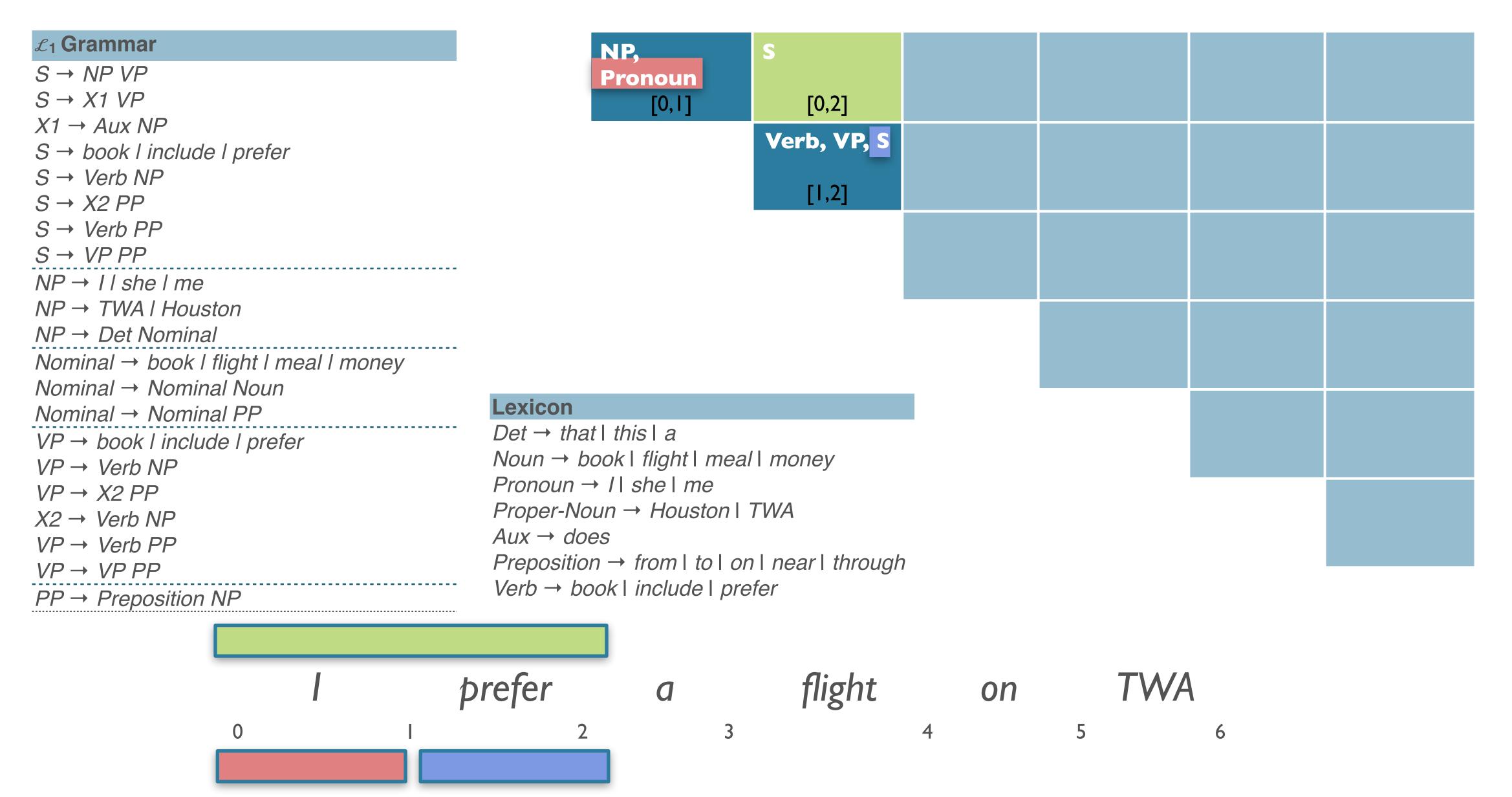


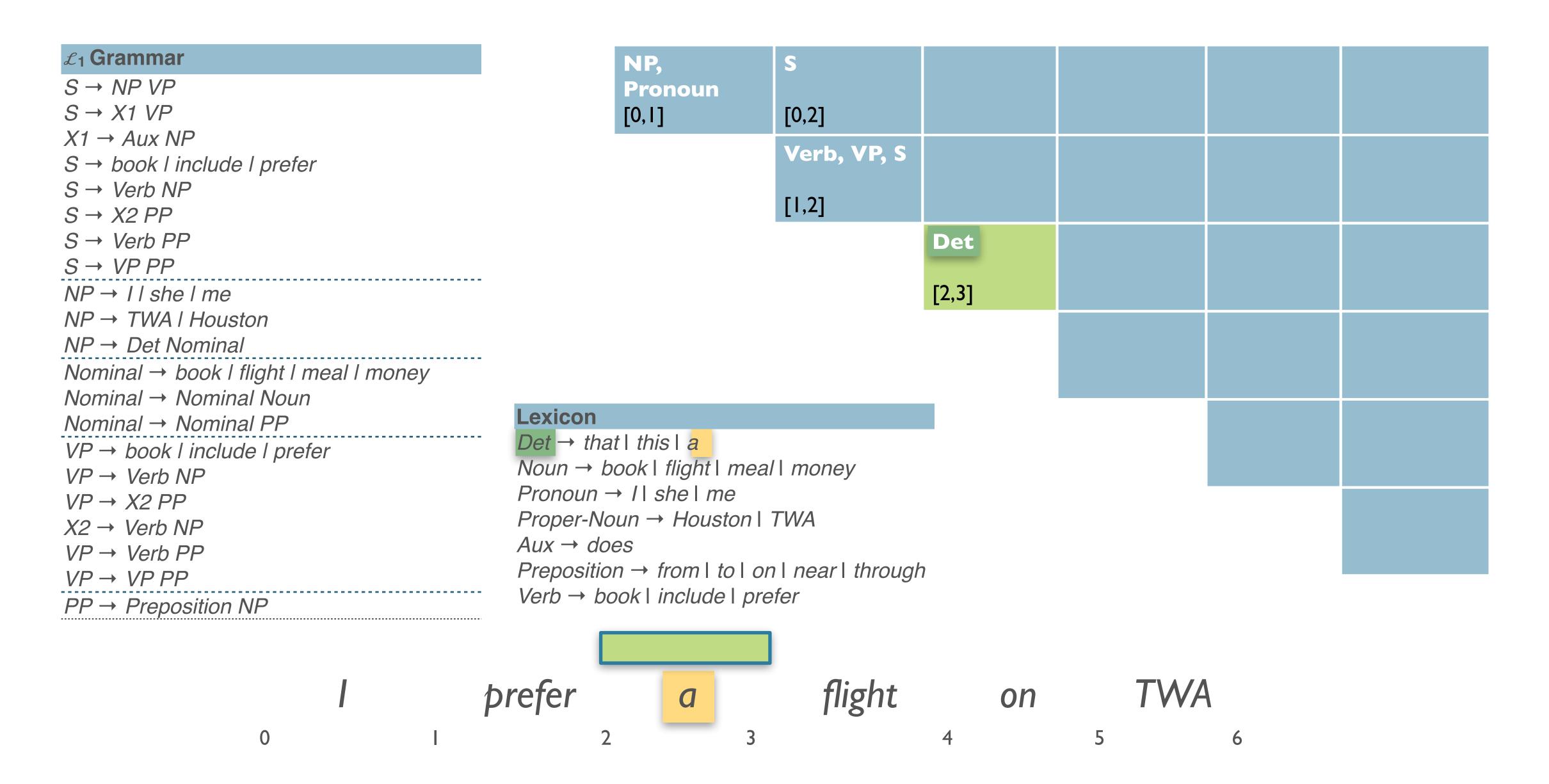


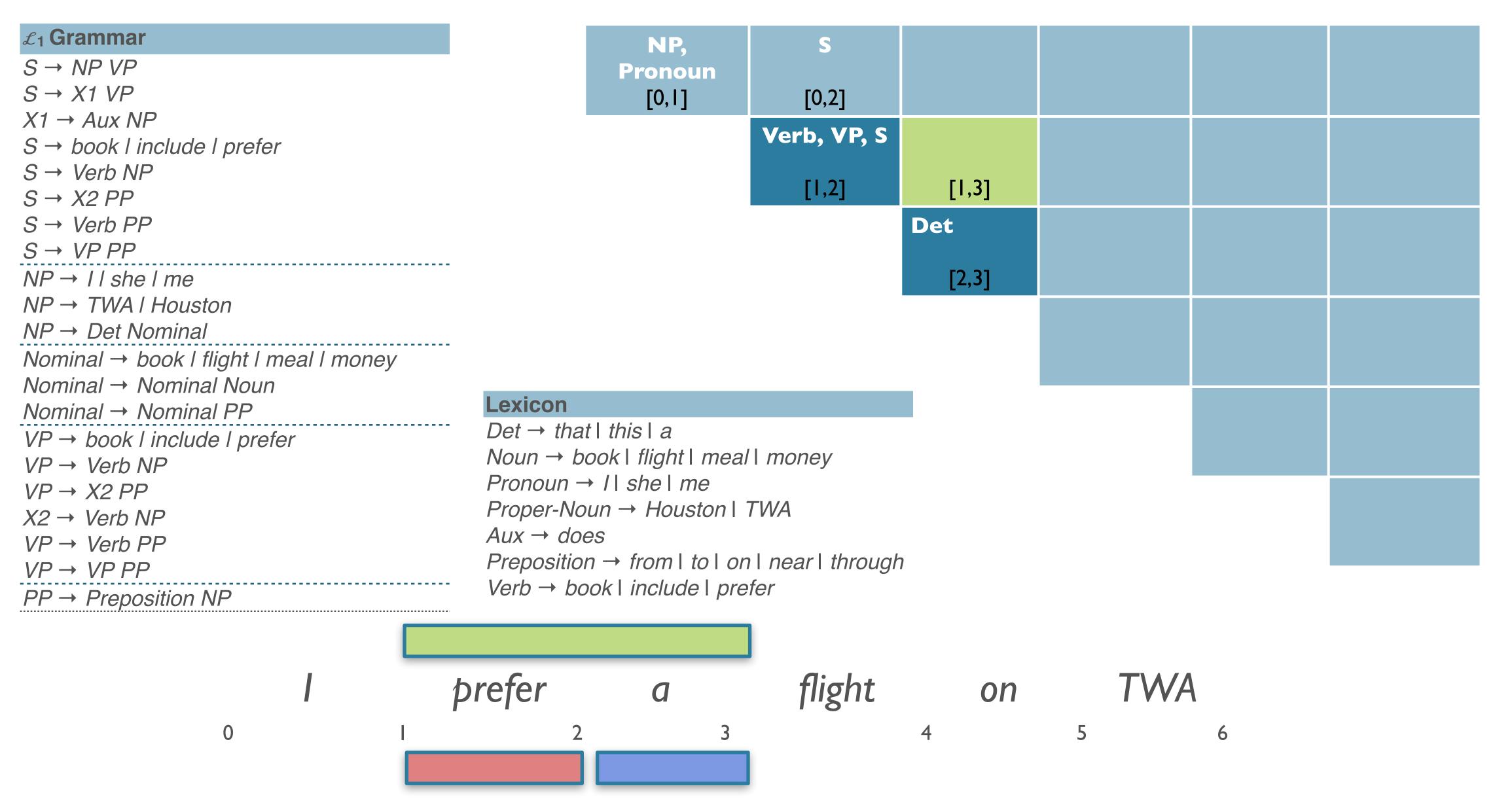


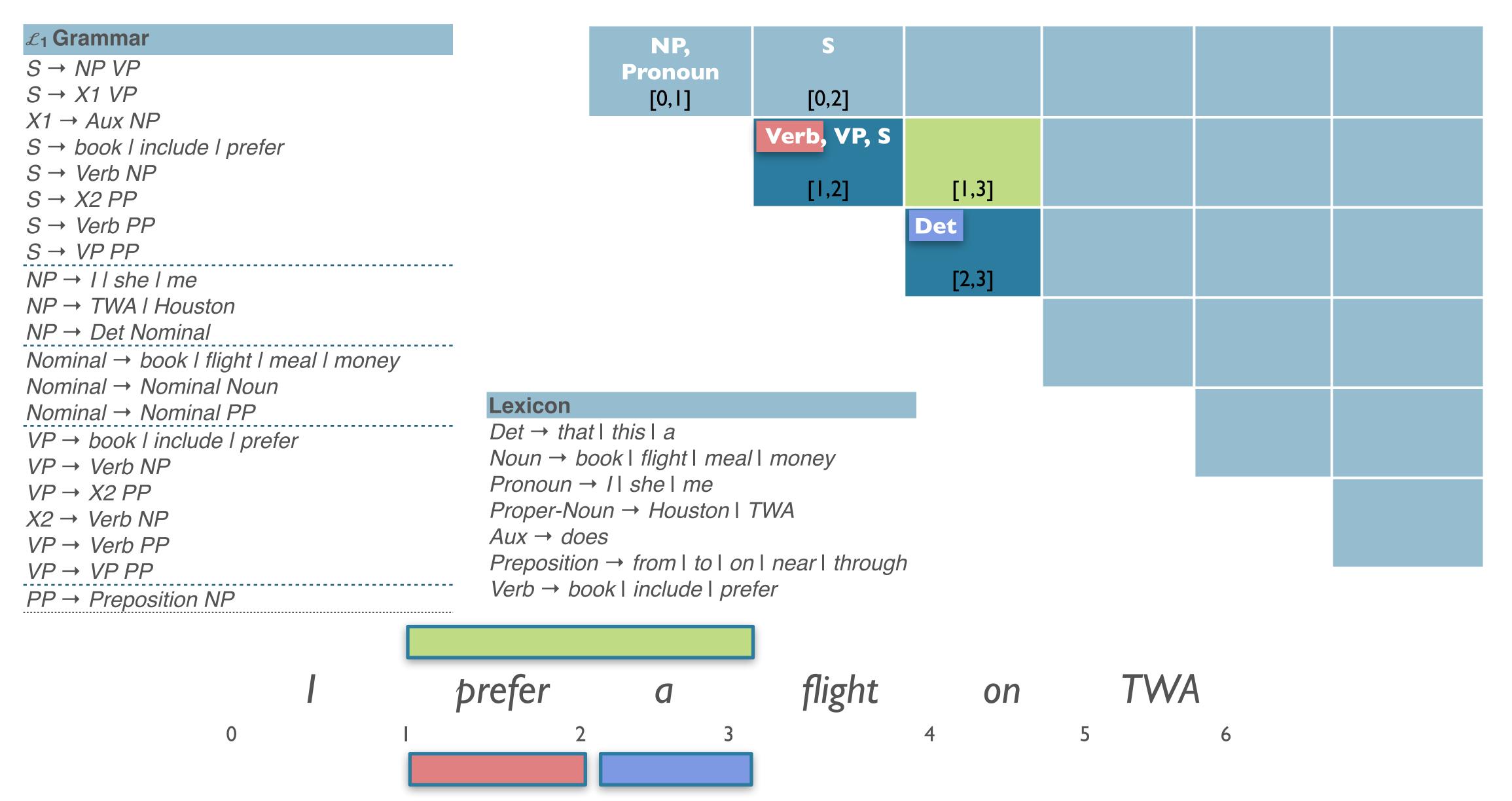


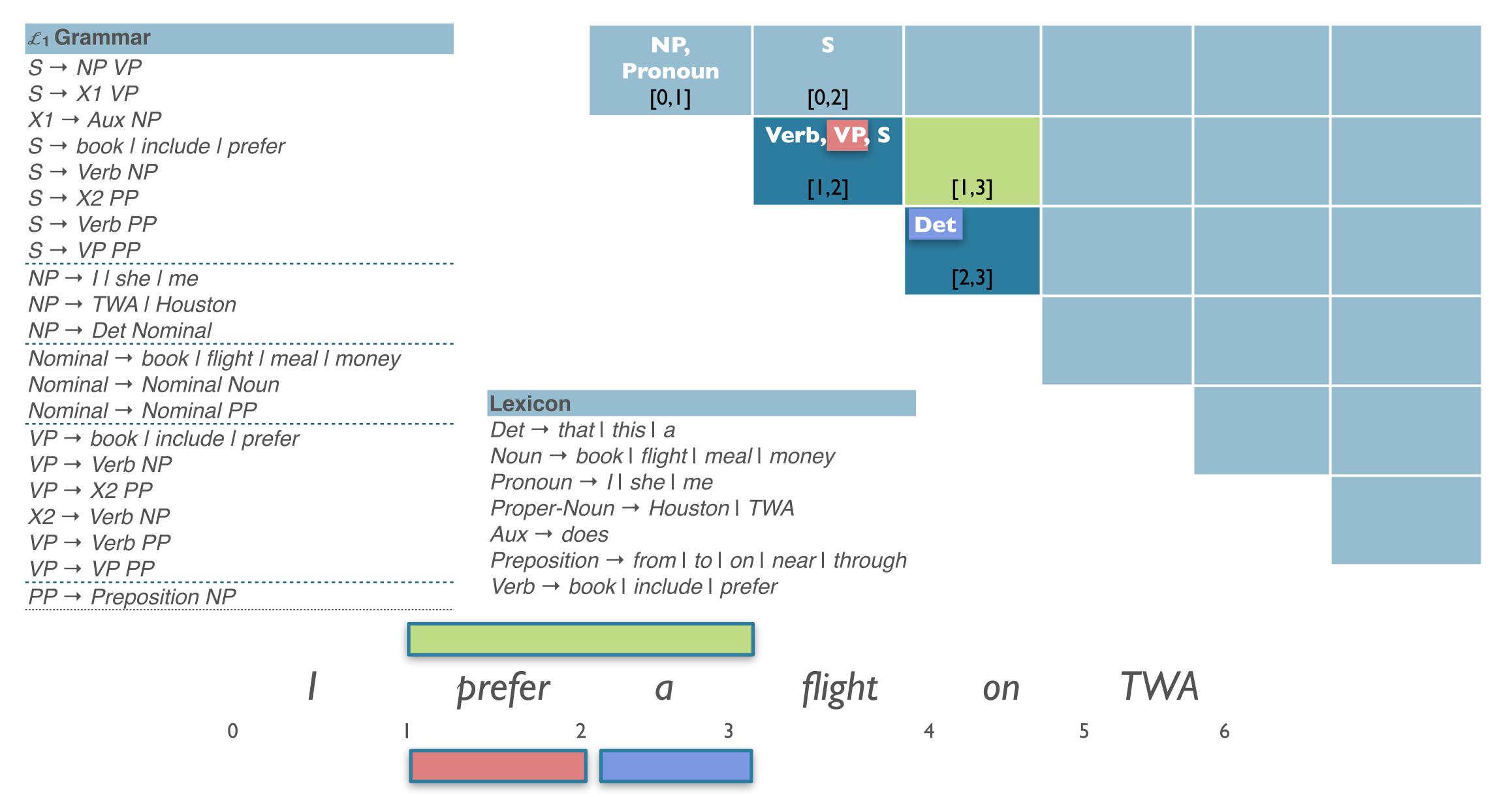


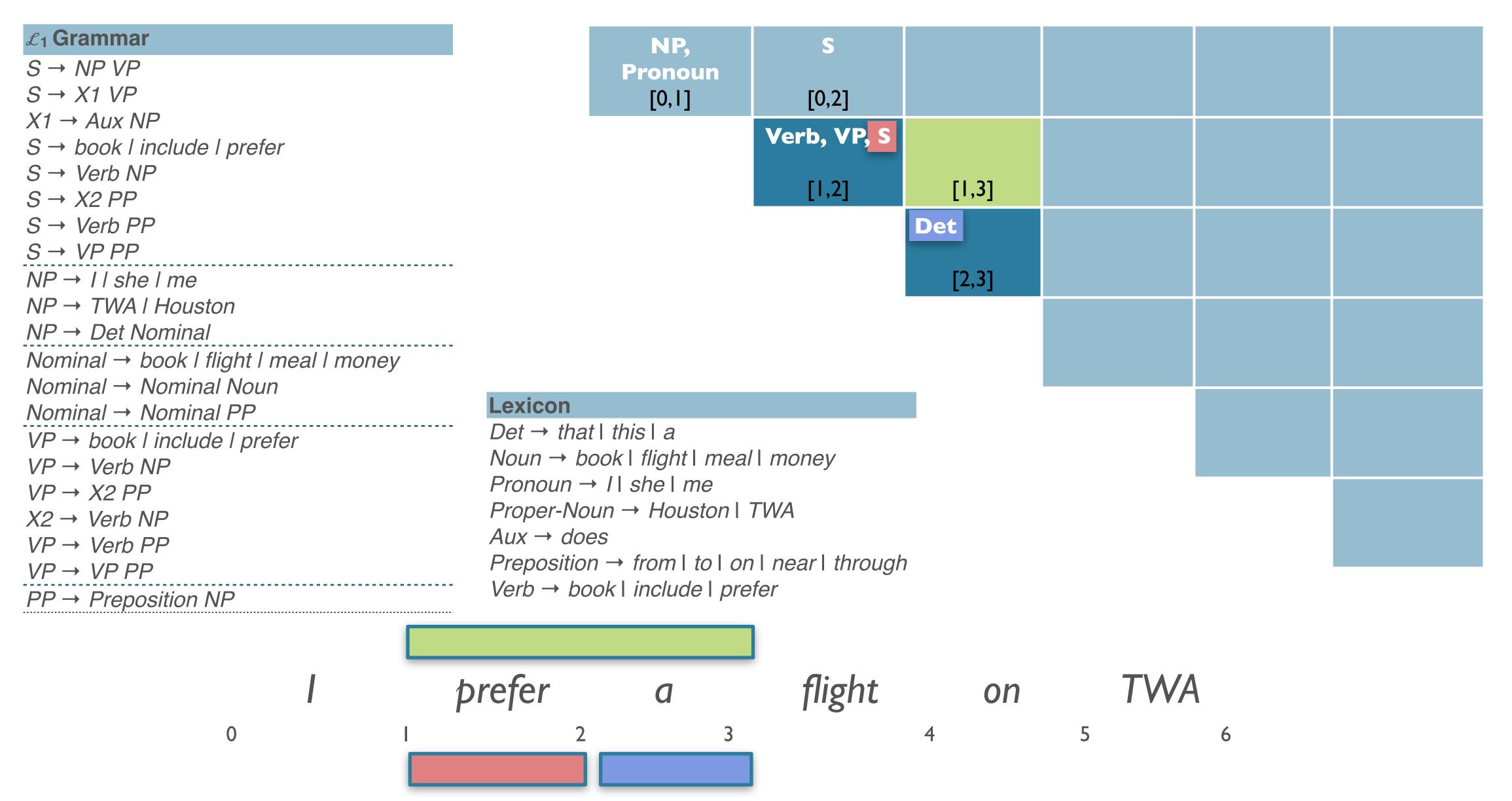


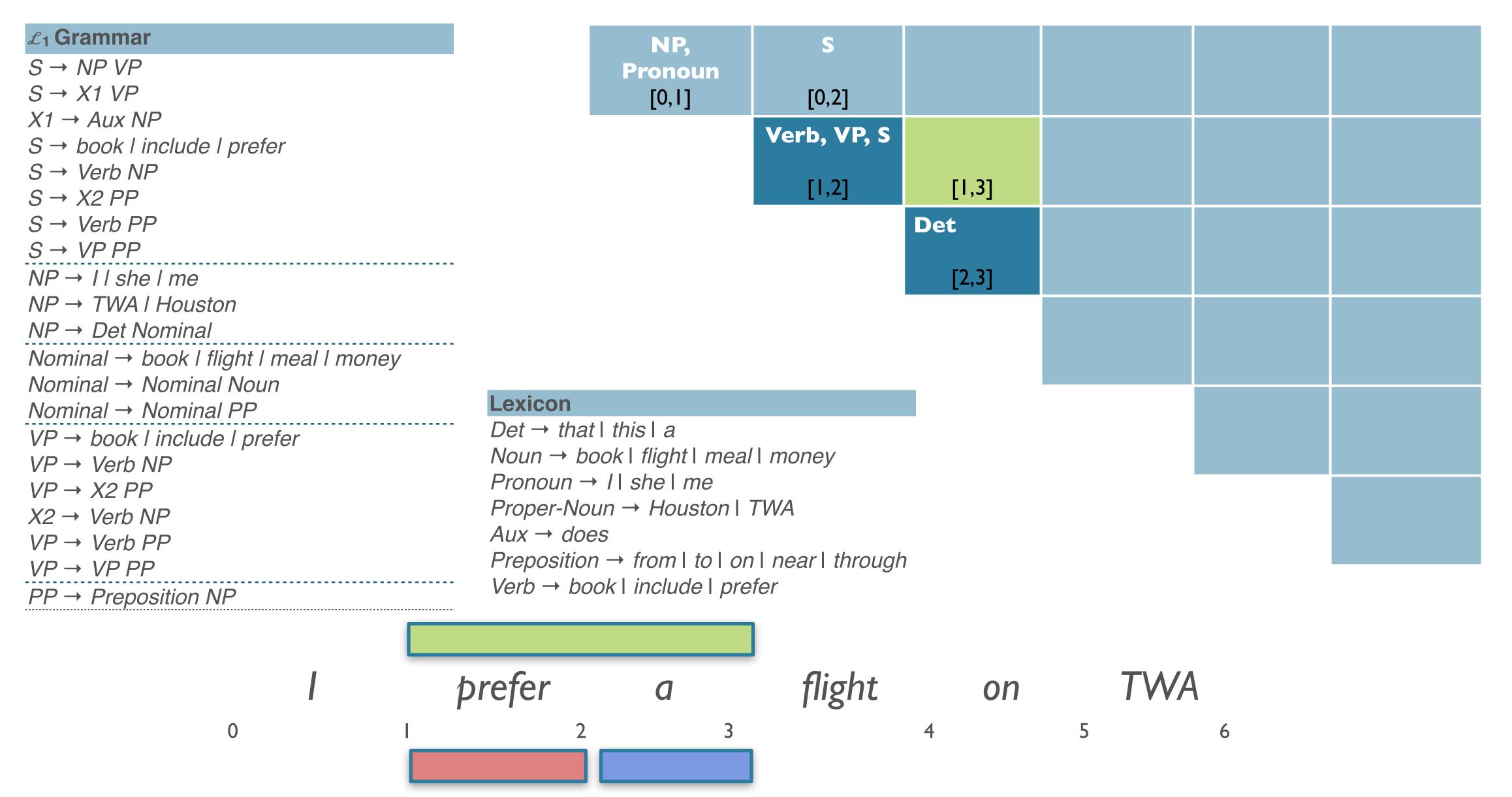


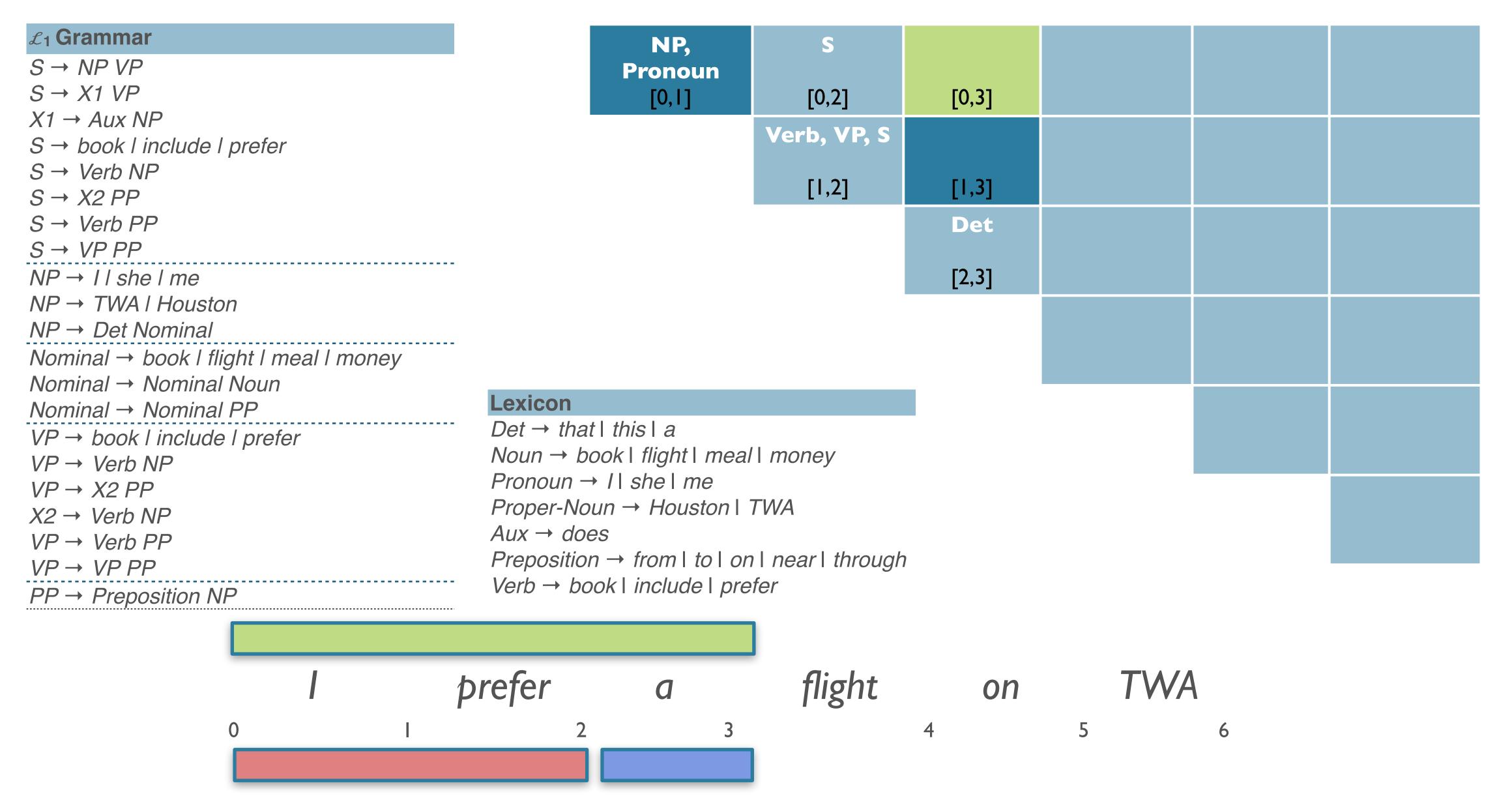


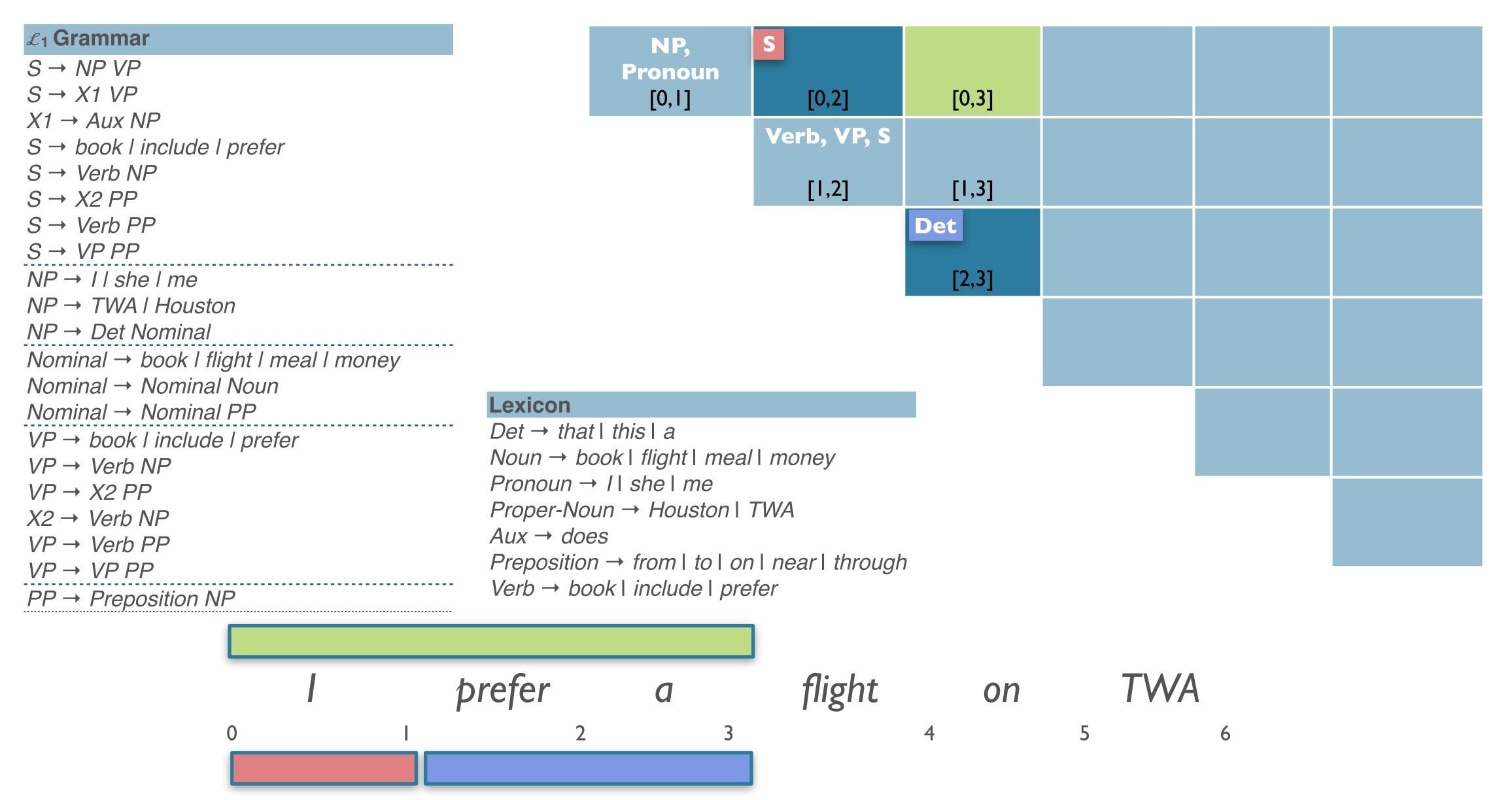


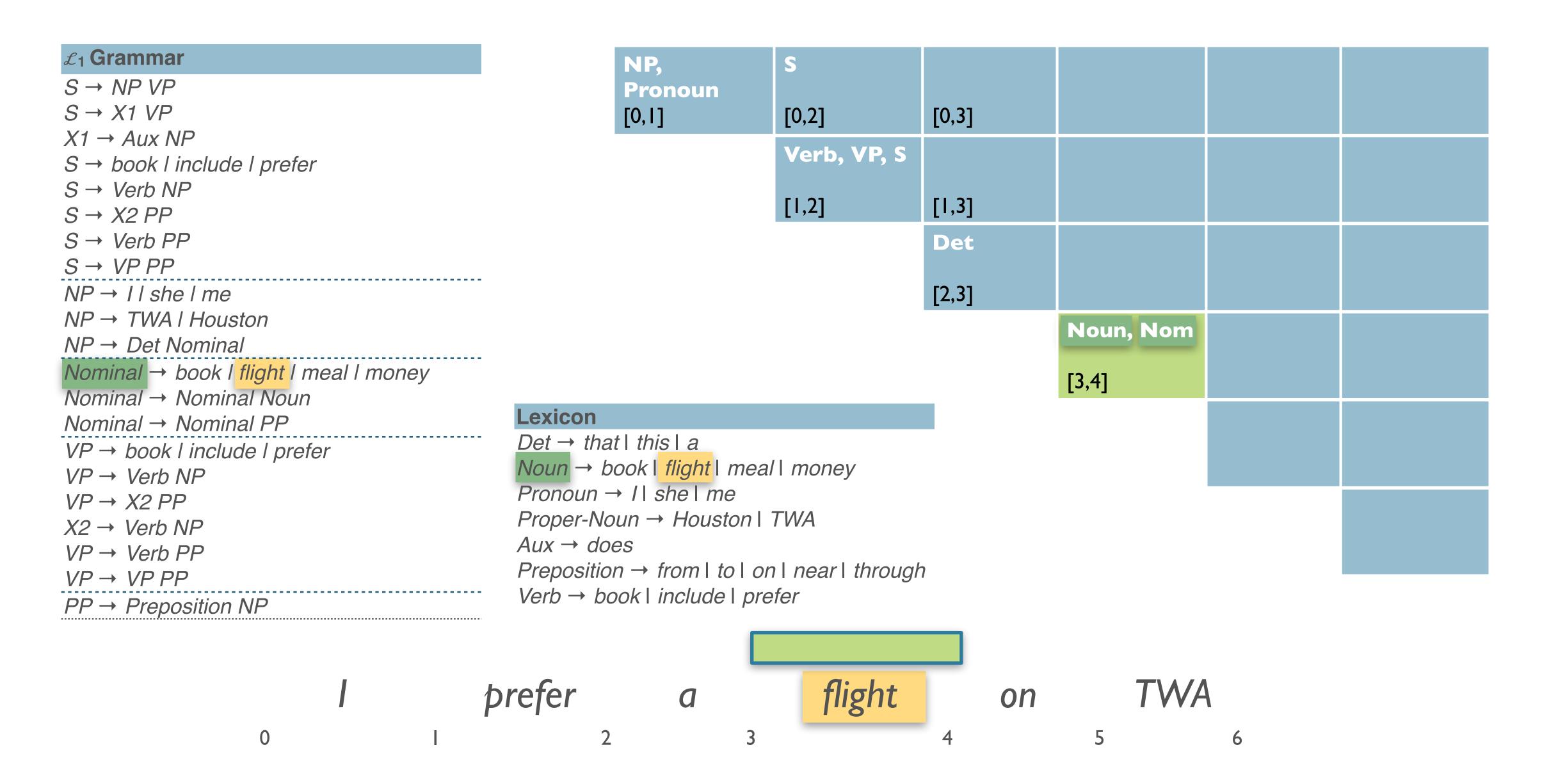


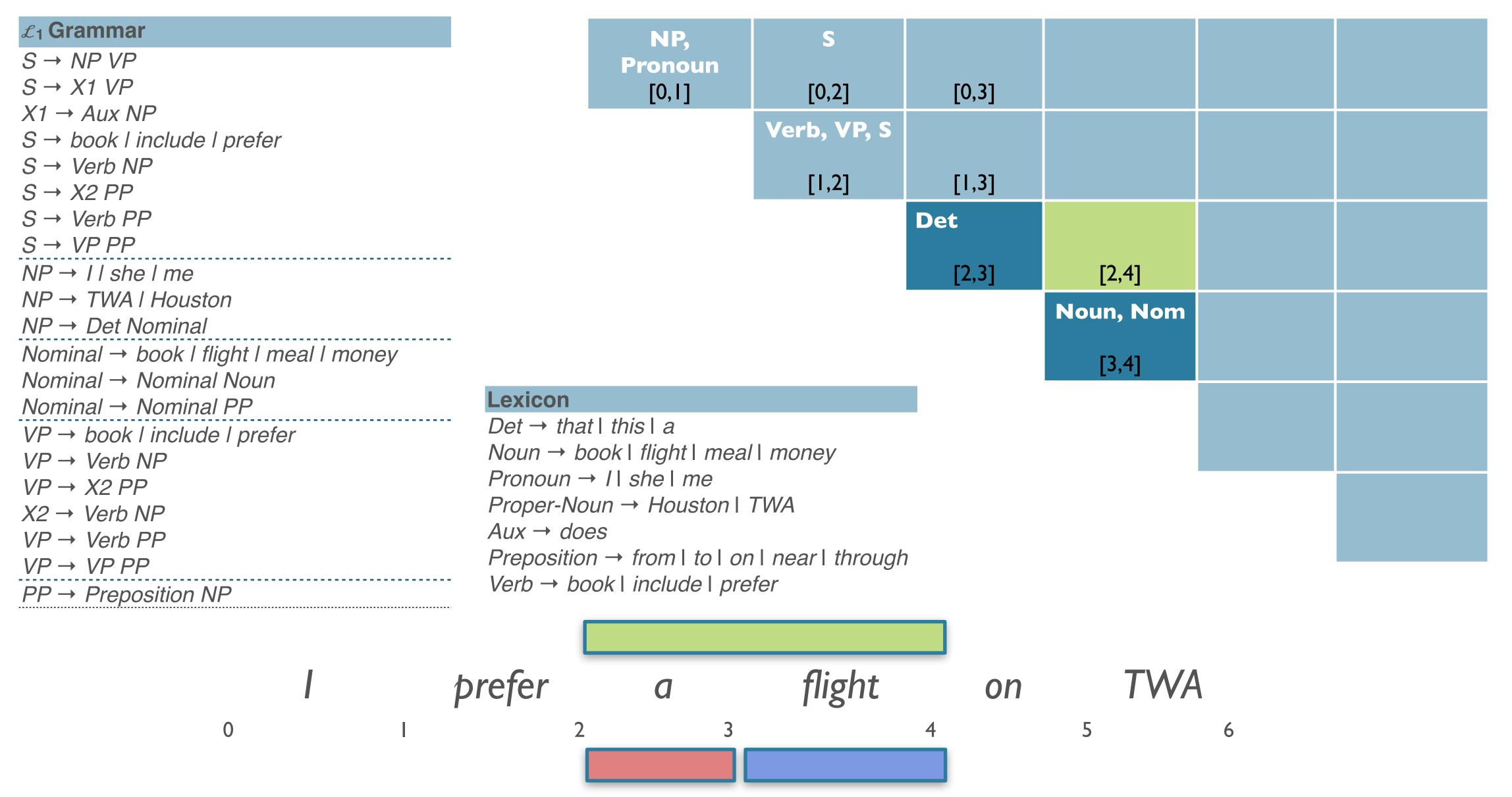


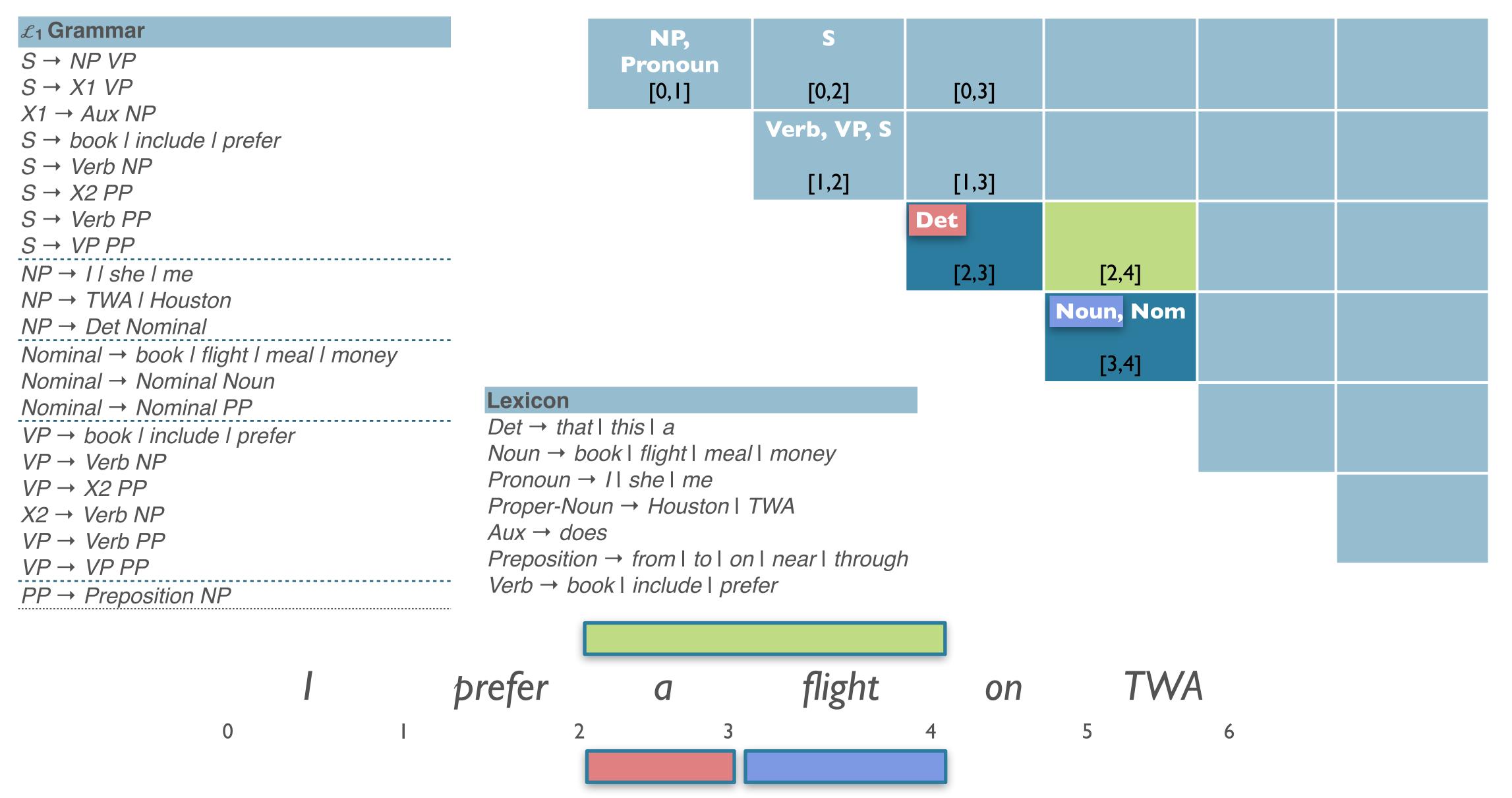


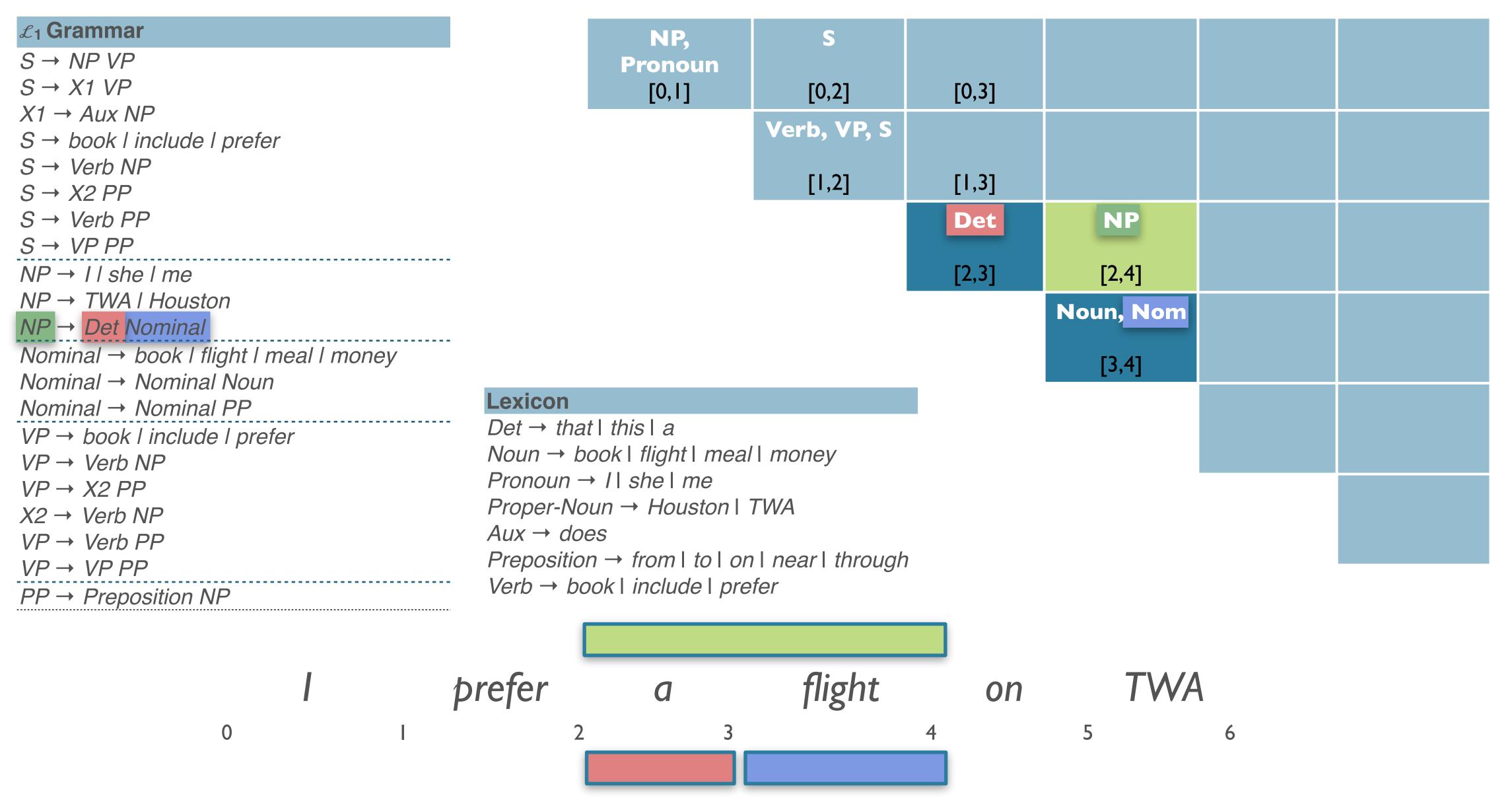


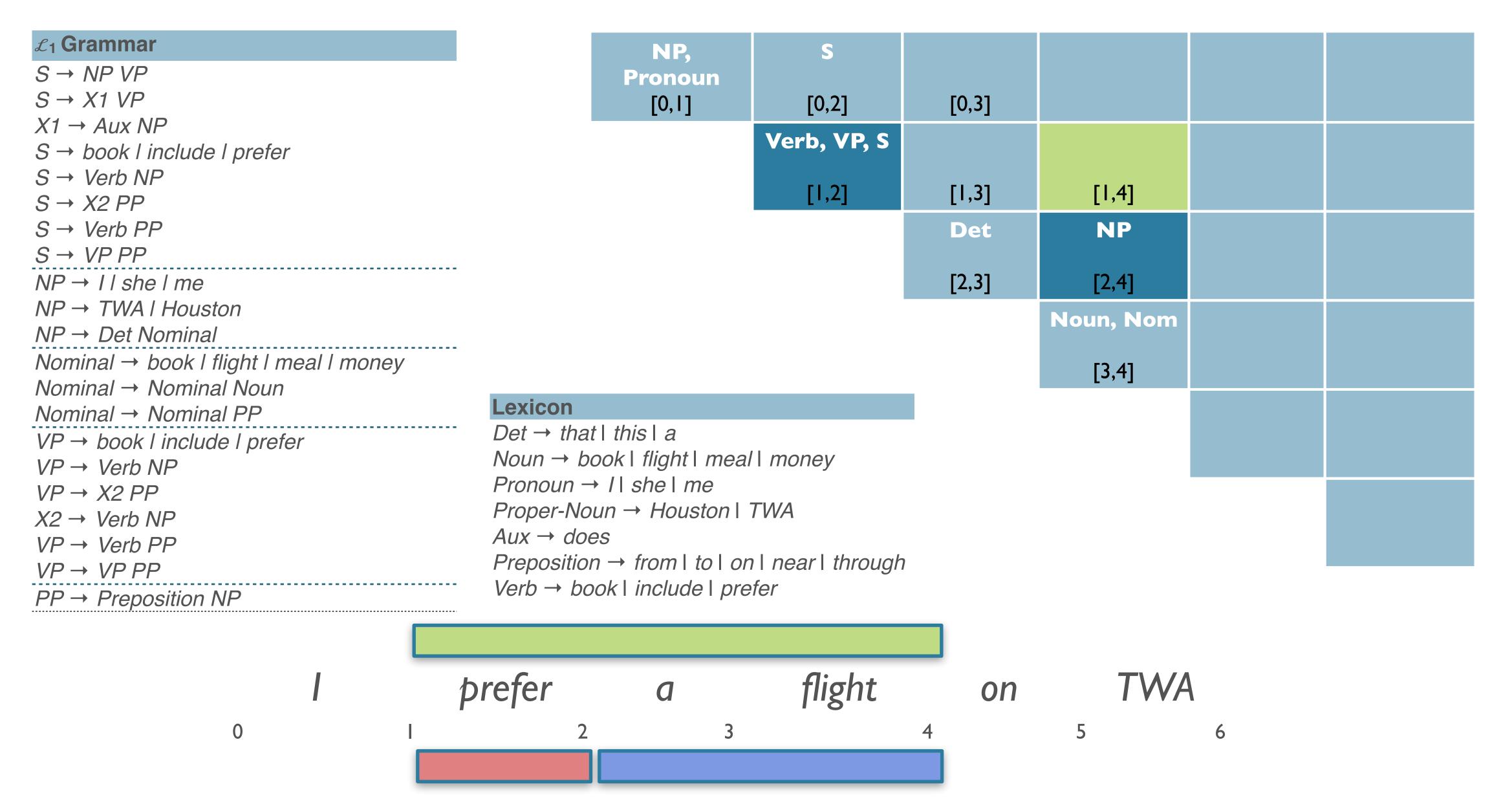


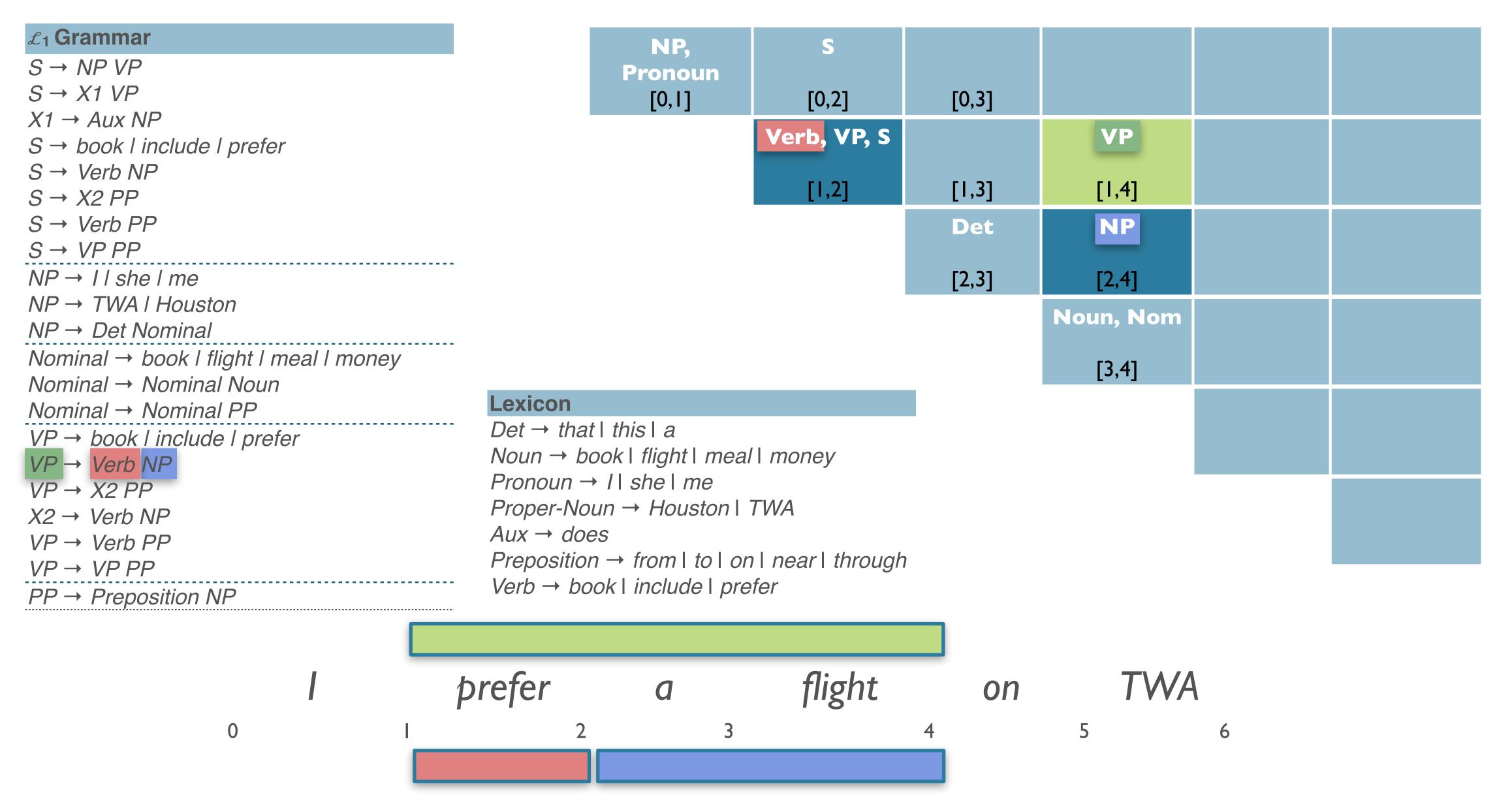


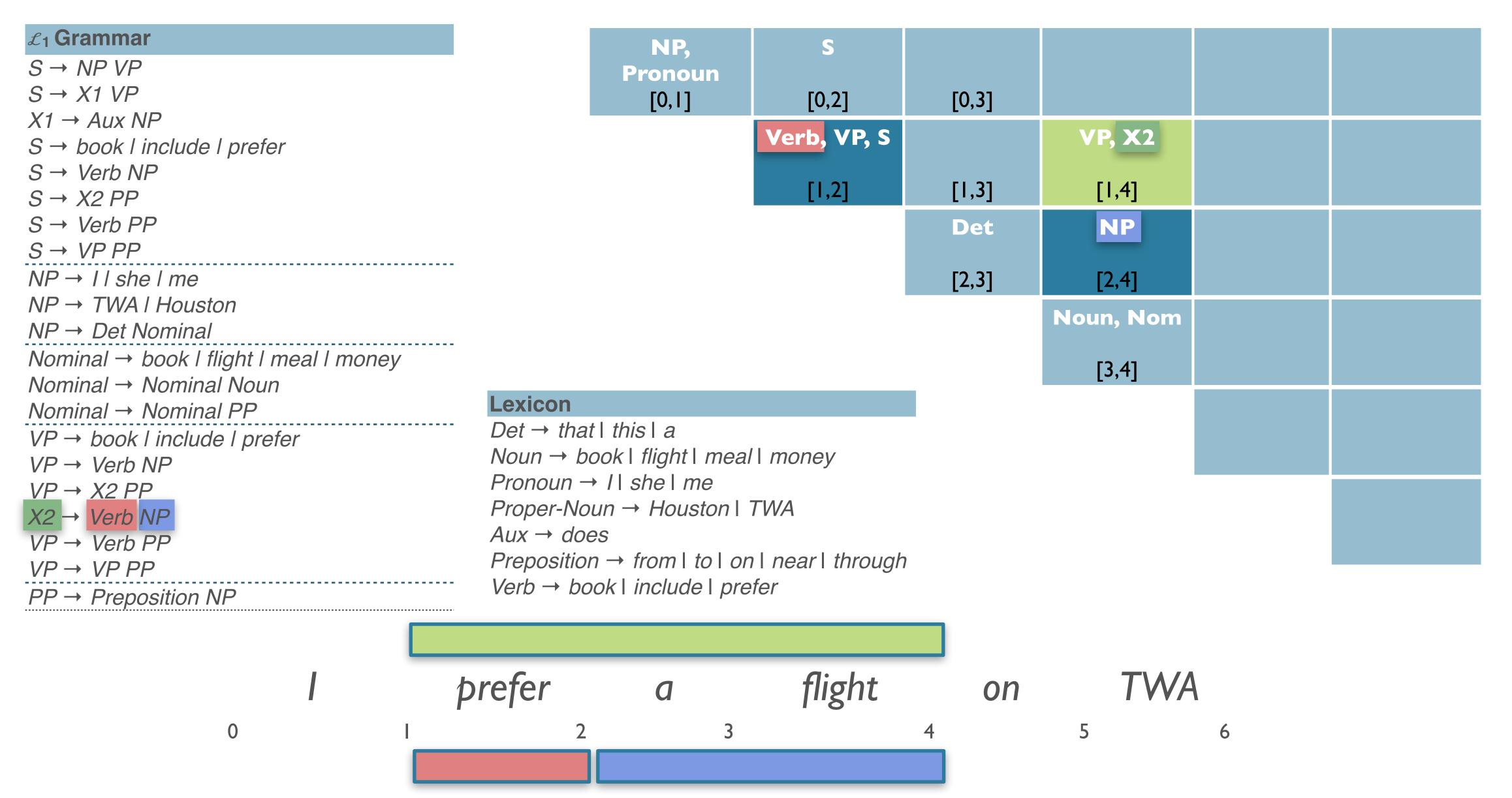


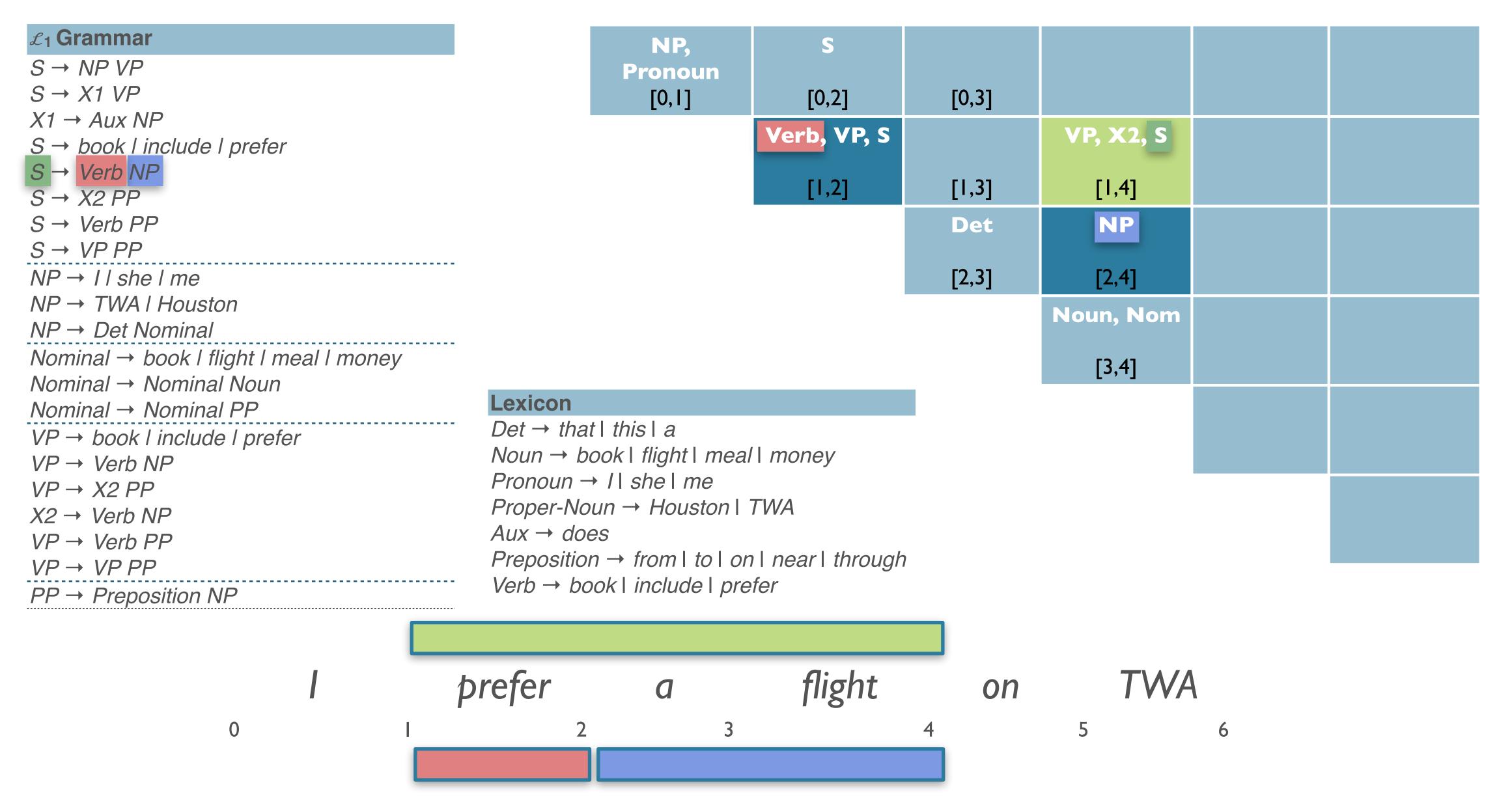


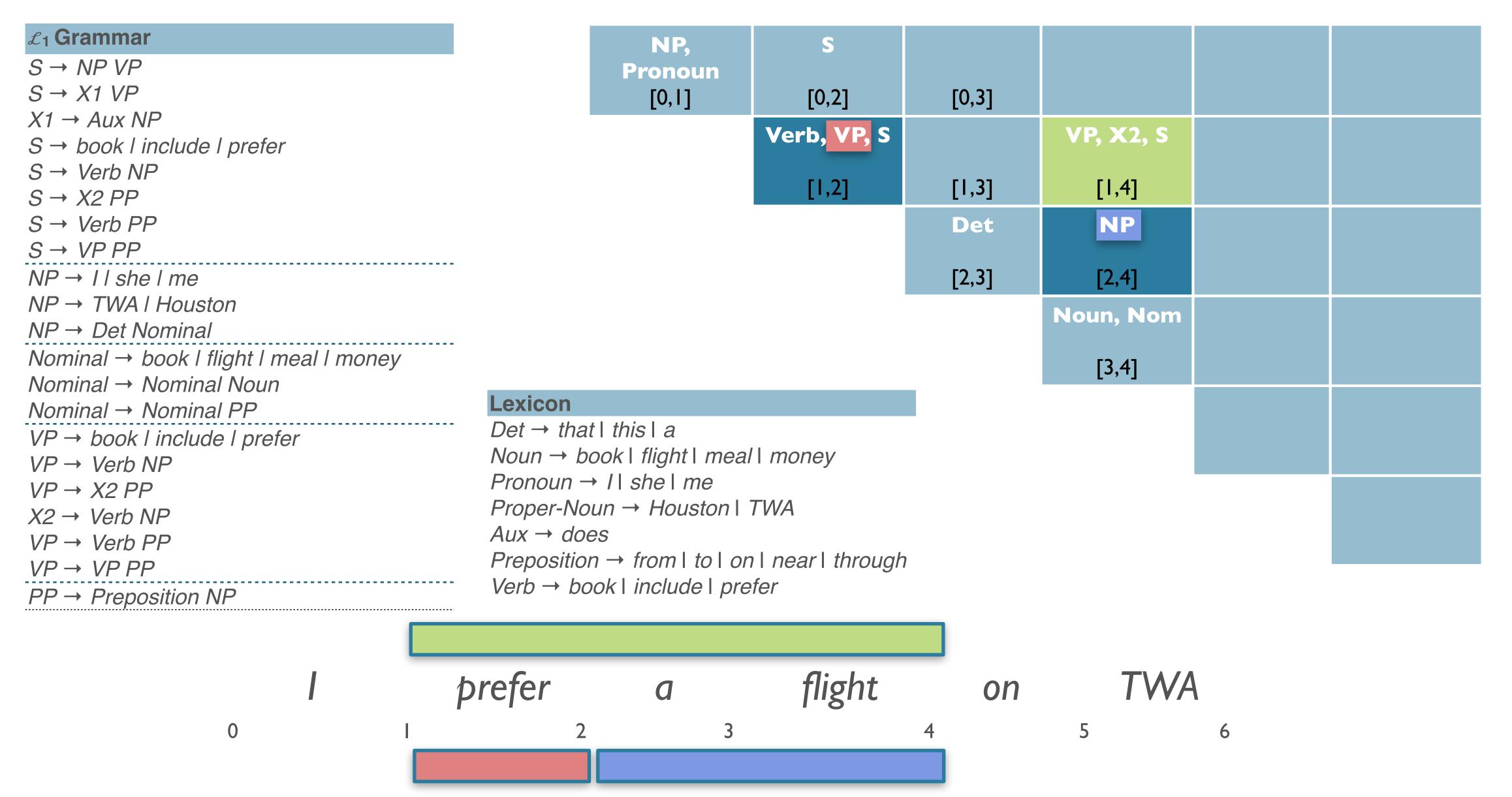


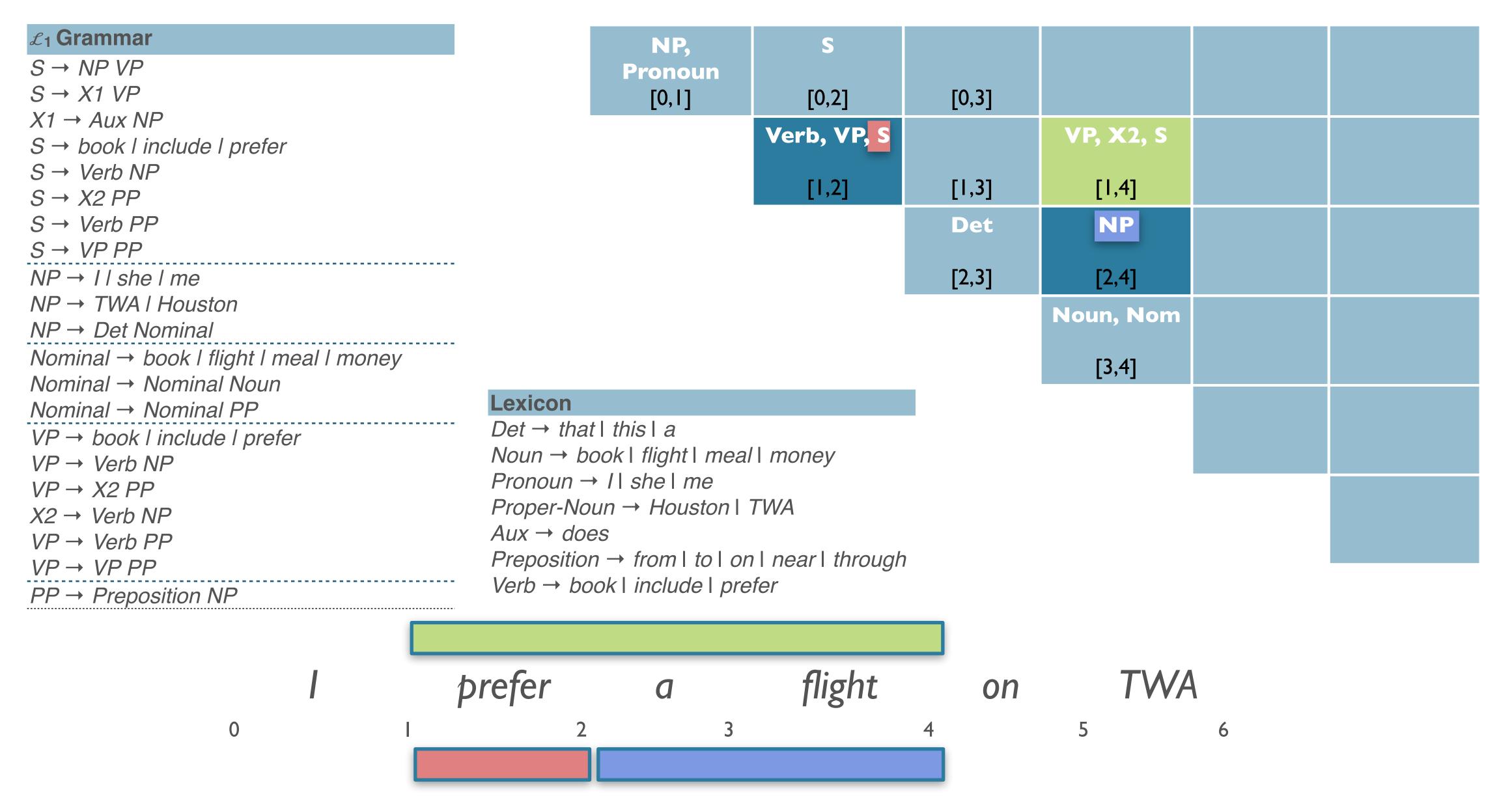




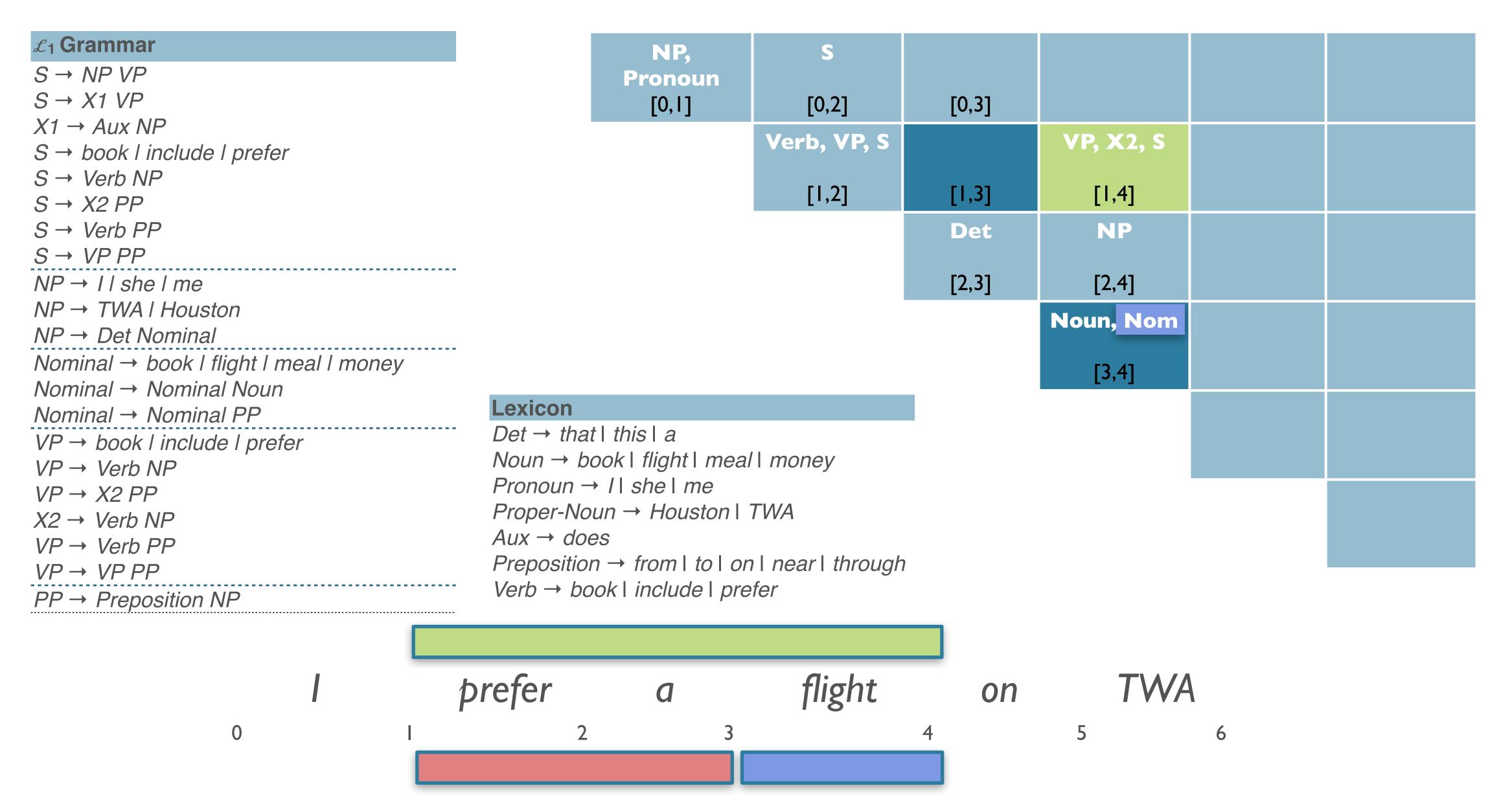


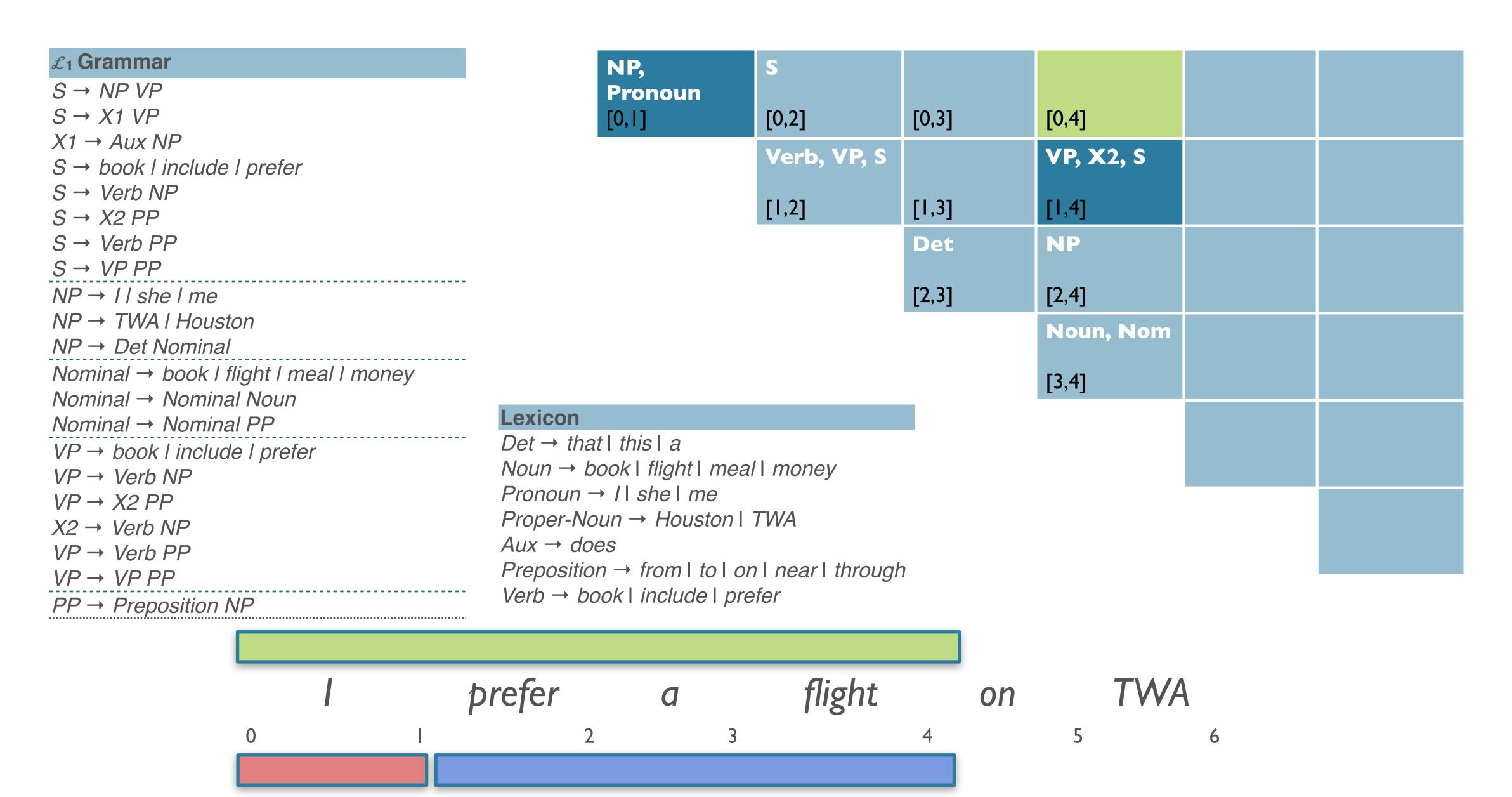


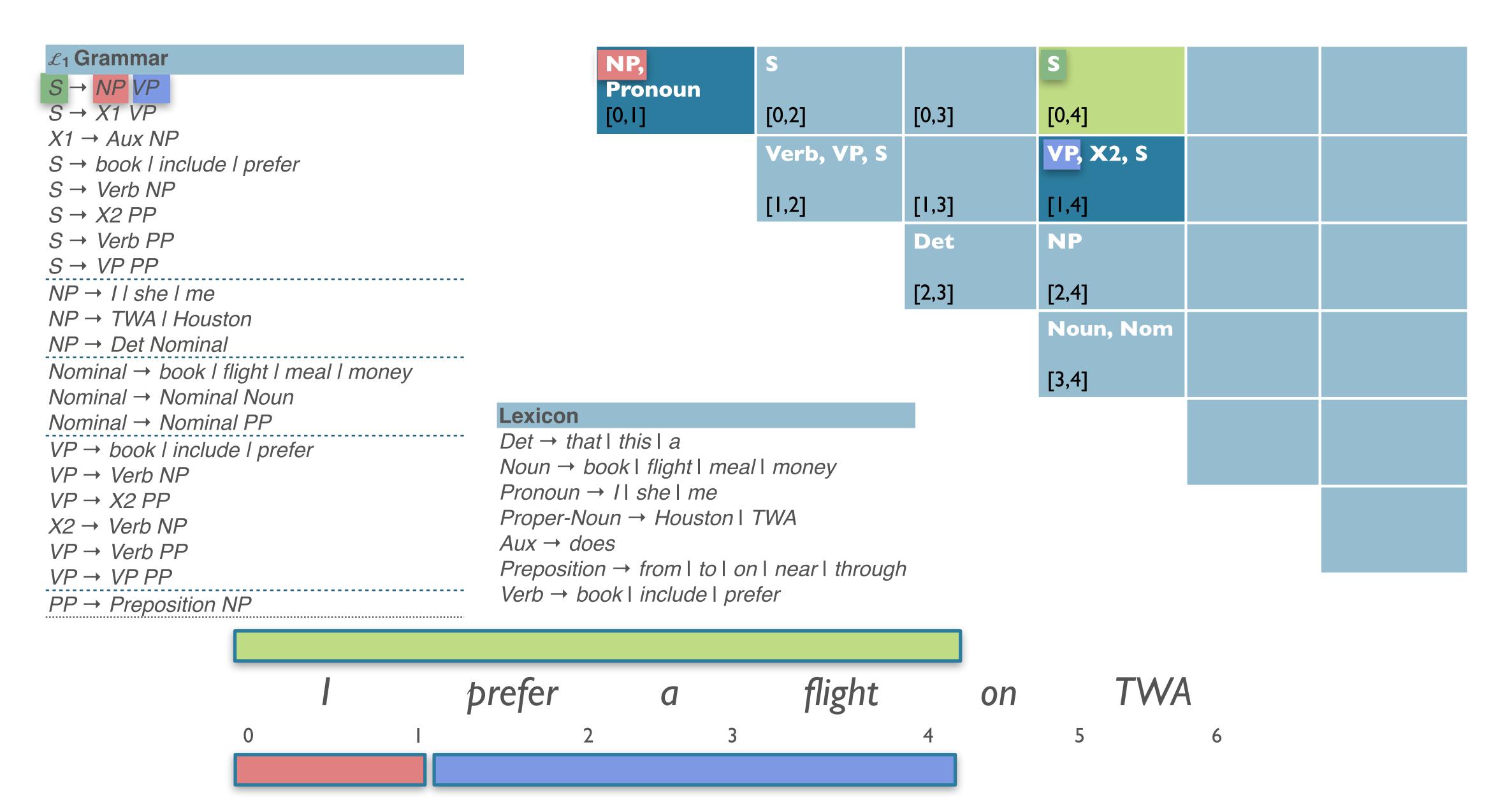


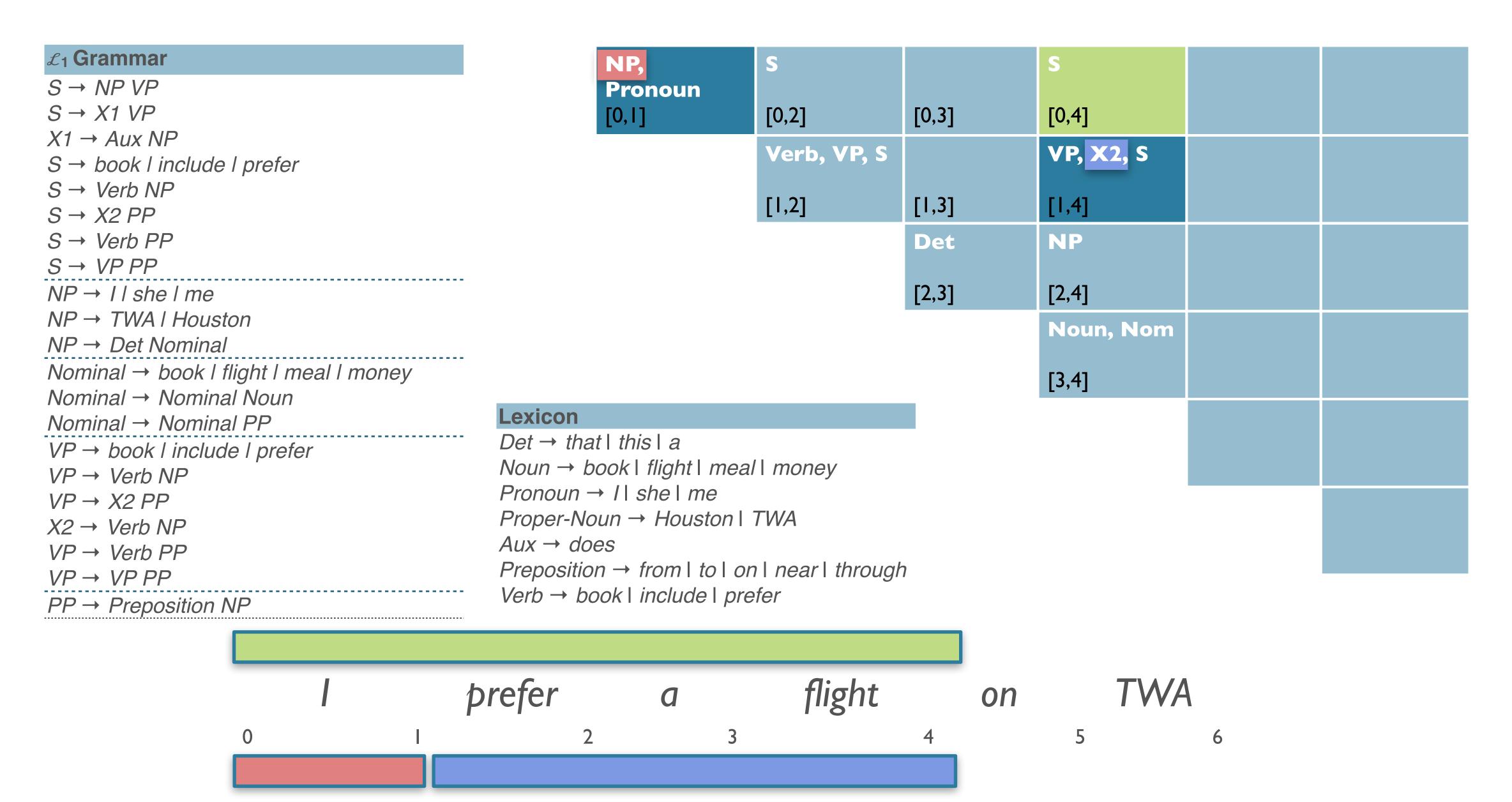


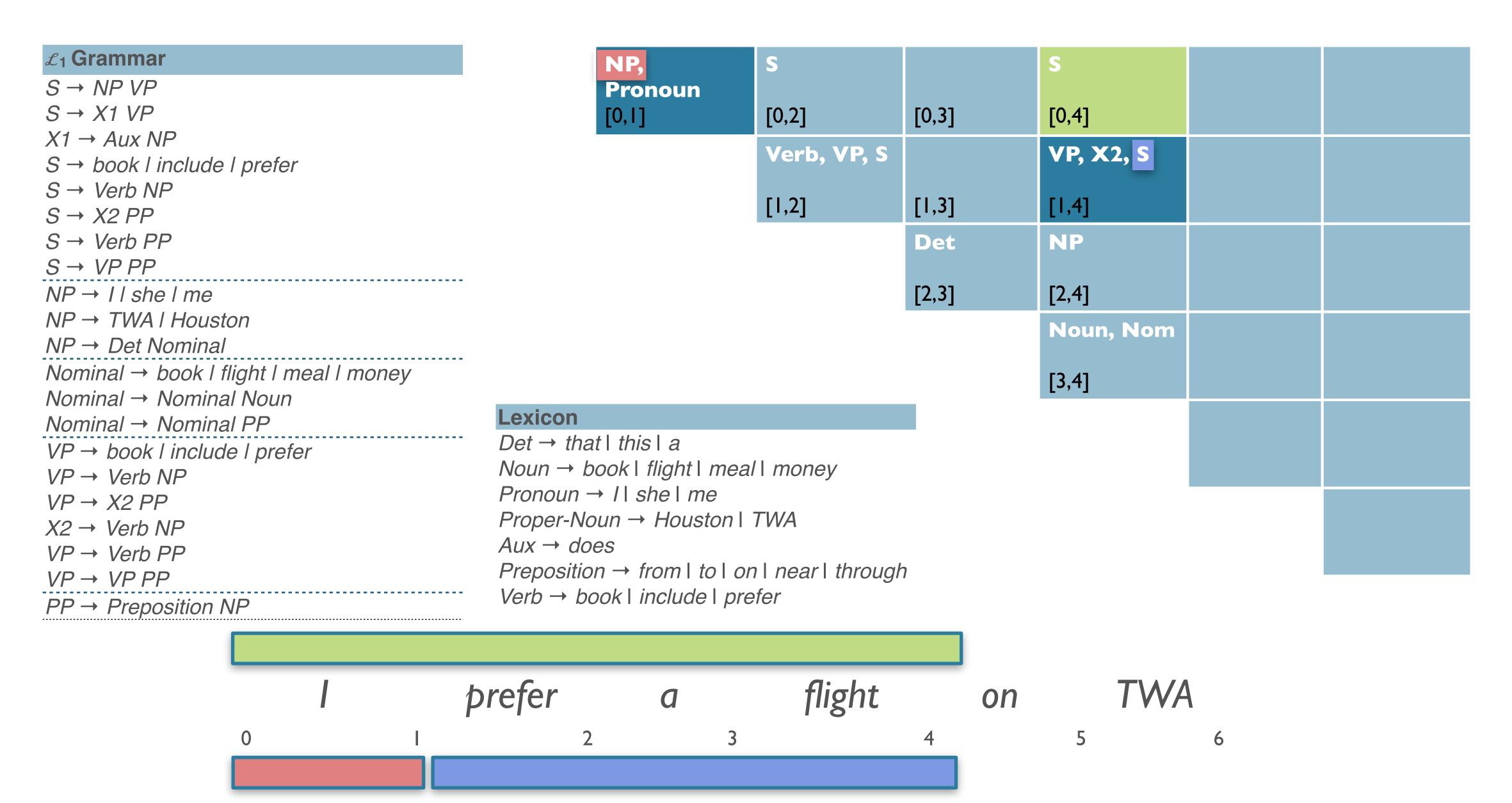
£ ₁ Grammar	NP,	S				
$S \rightarrow NP VP$	Pronoun					
$S \rightarrow X1 VP$	[0,1]	[0,2]	[0,3]			
$X1 \rightarrow Aux NP$				VD V2 C		
S → book I include I prefer		Verb, VP, S		VP, X2, S		
S → Verb NP		FL 23	FL 21	FT 47		
$S \rightarrow X2 PP$		[1,2]	[1,3]	[1,4]		
S → Verb PP			Det	NP		
$S \rightarrow VP PP$						
NP → I I she I me			[2,3]	[2,4]		
NP → TWA I Houston				Noun, Nom		
NP → Det Nominal				reduit, rediii		
Nominal → book flight meal money				[3,4]		
Nominal → Nominal Noun			_	[3, 1]		
Nominal → Nominal PP	Lexicon					
VP → book I include I prefer	Det → that this a					
VP → Verb NP	Noun → book flight mea	II money				
$VP \rightarrow X2 PP$	Pronoun → II she I me					
X2 → Verb NP	Proper-Noun → Houston I	TVVA				
VP → Verb PP	Aux → does					
$VP \rightarrow VP PP$	Preposition → from to or		7			
PP → Preposition NP	Verb → book include pre	efer				
,	brofor	flight	On	TWA		
	prețer a	flight	on	I VV/	1	
0	2 3		4	5	6	

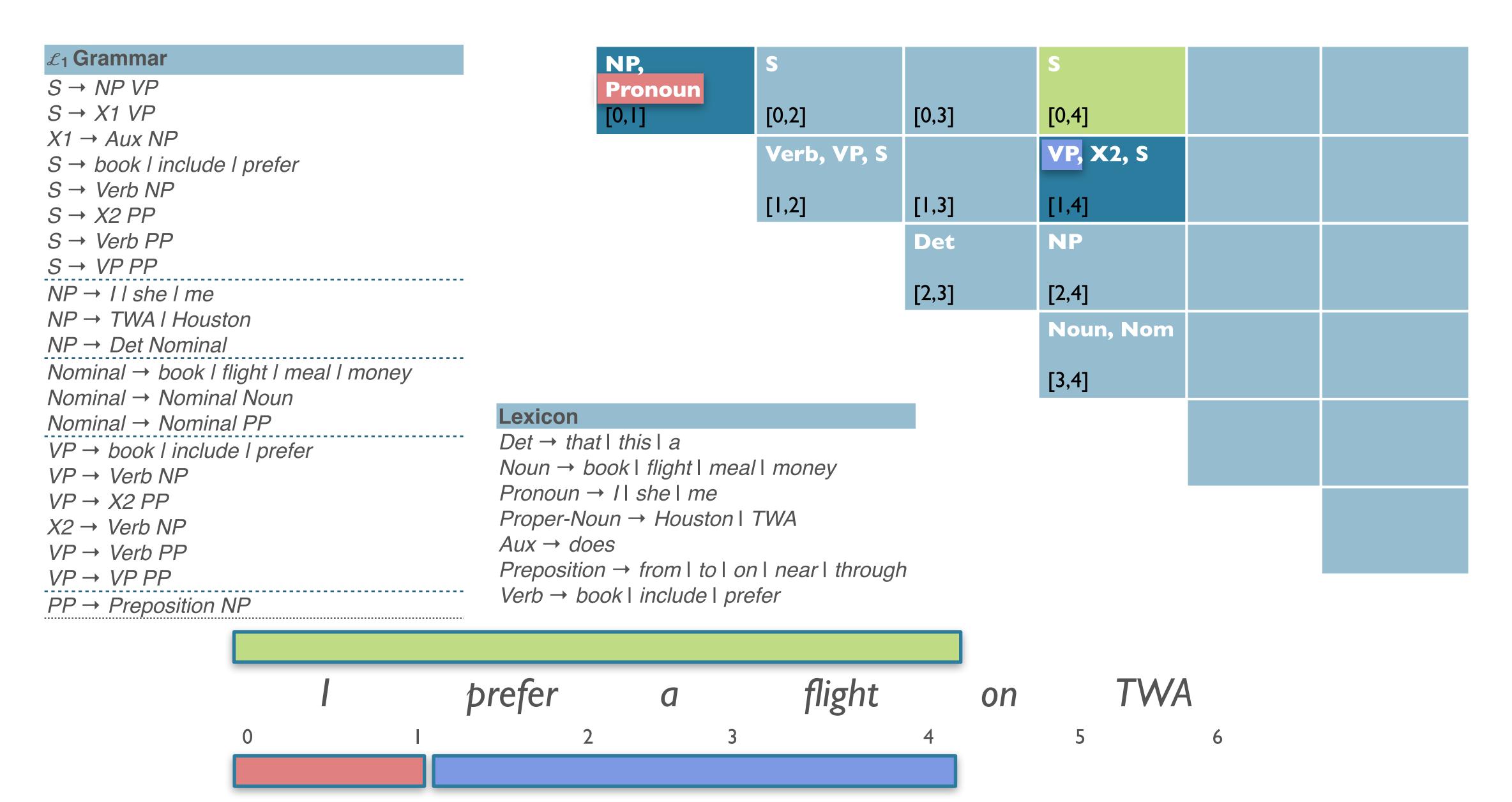


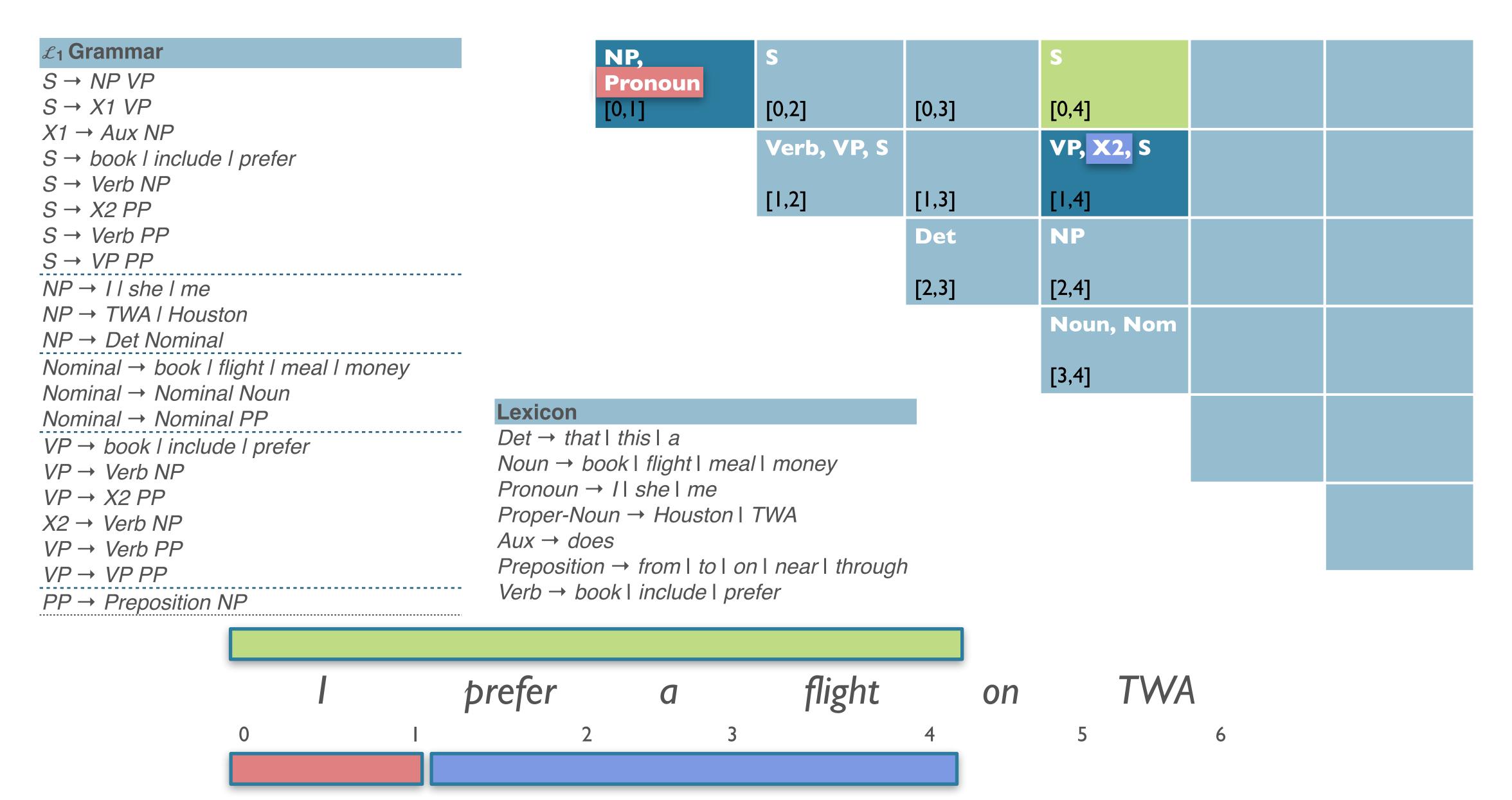


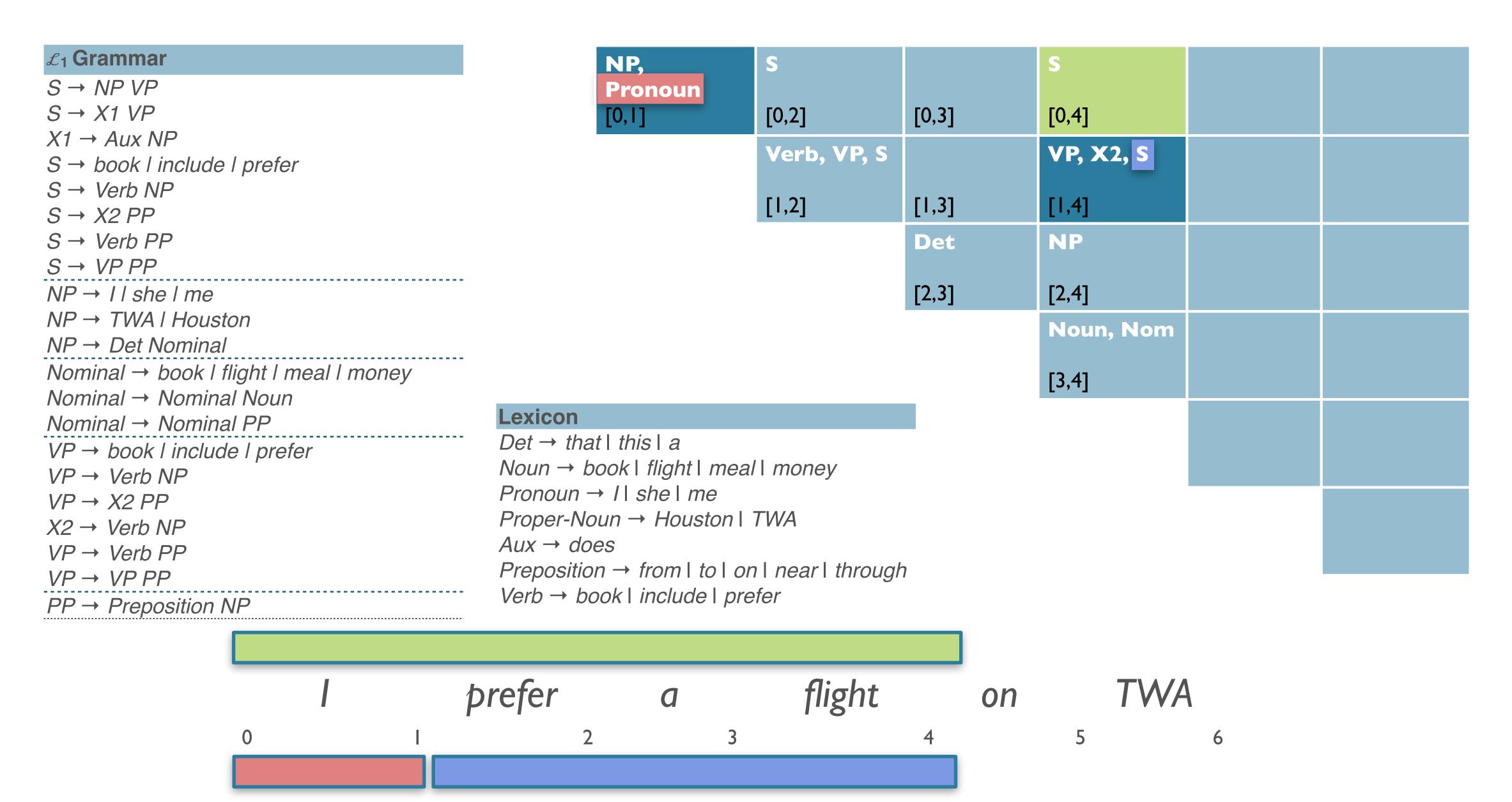


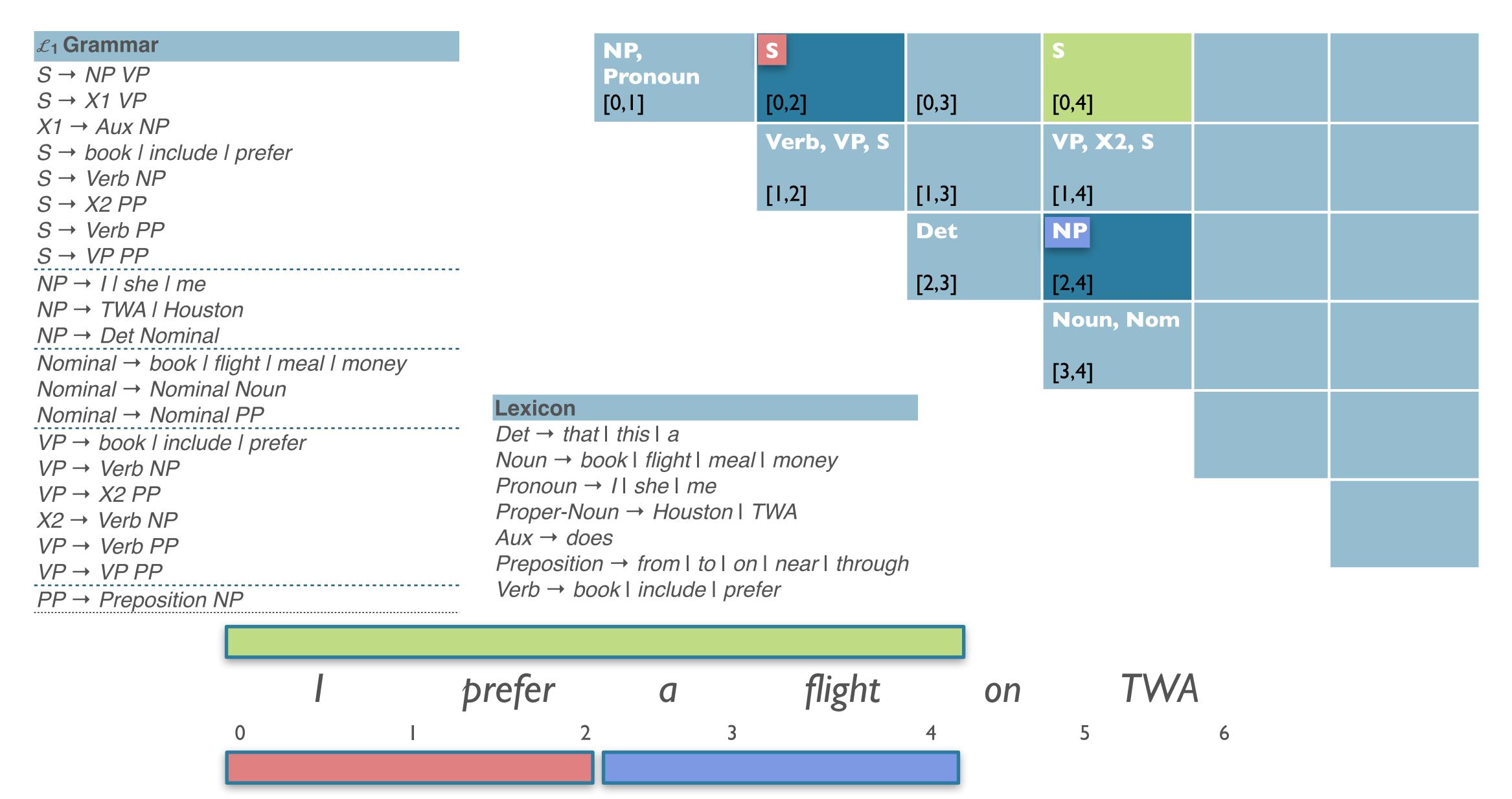












£ ₁ Grammar	NID.					
$S \rightarrow NP VP$	NP, Pronoun	5		S		
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S → Verb NP		FL 21	FI 21	ΓΙ <i>4</i> 1		
$S \rightarrow X2 PP$		[1,2]	[1,3]	[1,4]		
S → Verb PP			Det	NP		
$S \rightarrow VP PP$						
NP → I I she I me			[2,3]	[2,4]		
NP → TWA Houston				Noun, Nom		
NP → Det Nominal						
Nominal → book flight meal money Nominal → Nominal Noun				[3,4]		
Nominal → Nominal Nouri Nominal → Nominal PP	Lexicon					
VP → book I include I prefer	Det → that this a					
VP → Verb NP	Noun → book flight meal	II money				
$VP \rightarrow X2 PP$	Pronoun → II she I me					
$X2 \rightarrow Verb NP$	Proper-Noun → Houston	TWA				
VP → Verb PP	Aux → does					
$VP \rightarrow VP PP$	Preposition → from to or					
PP → Preposition NP	Verb → book include pre	eter				
	prefer a	flight	on	TWA		
	2 2	, 0	1	5	6	

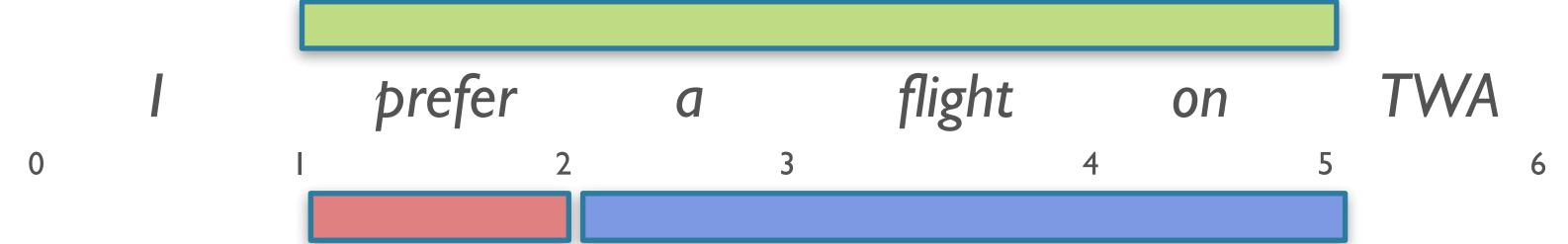
£ ₁ Grammar		NP,	S		S		
$S \rightarrow NP VP$		Pronoun					
$S \rightarrow X1 VP$		[0,1]	[0,2]	[0,3]	[0,4]		
$X1 \rightarrow Aux NP$			Verb, VP, S		VP, X2, S		
S → book I include I prefer			verb, vr, s		VF, AZ, 5		
$S \rightarrow Verb NP$			[1,2]	[1,3]	[1,4]		
$S \rightarrow X2PP$			[', 4]				
$S \rightarrow Verb PP$				Det	NP		
$S \rightarrow VP PP$				F0 07	FO 47		
NP → I I she I me				[2,3]	[2,4]		
NP → TWA Houston					Noun, Nom		
NP → Det Nominal							
Nominal → book flight meal money					[3,4]		
Nominal → Nominal Noun Nominal → Nominal PP	Lexicon					Prep	
	Det → that	this I a					
VP → book I include I prefer VP → Verb NP		ok flight me	eal I money			[4,5]	
$VP \rightarrow X2 PP$	Pronoun →	•				L / J	
$X2 \rightarrow Verb NP$	Proper-Nou	$n \rightarrow Houston$	I TWA				
$VP \rightarrow Verb PP$	Aux → does	5					
$VP \rightarrow VP PP$	Preposition	\rightarrow from to	<mark>on</mark> I near I througl	ל			
PP → Preposition NP	Verb → boo	k include i p	refer				
- /							
1	þrefer	а	flight	or	TW	A	
	Piclei	G	1"8"		1 4 4 /		

\mathcal{L}_1 Grammar $S \to NP VP$ $S \to X1 VP$		NP, Pronoun [0,1]	S [0,2]	[0,3]	S [0,4]		
$X1 \rightarrow Aux NP$			Verb, VP, S		VP, X2, S		
S → book I include I prefer S → Verb NP							
$S \rightarrow X2PP$			[1,2]	[1,3]	[1,4]		
S → Verb PP				Det	NP		
$S \rightarrow VP PP$							
NP → II she I me				[2,3]	[2,4]		
NP → TWA Houston					Noun, Nom		
NP → Det Nominal Nominal → book flight meal money							
Nominal → Nominal Noun				_	[3,4]	[3,5]	
Nominal → Nominal PP	Lexicon					Prep	
VP → book I include I prefer	Det → that \ th		II manay			F4 F3	
VP → Verb NP	Noun → book Pronoun → 11		i i money			[4,5]	
$VP \rightarrow X2 PP$ $X2 \rightarrow Verb NP$	Proper-Noun		TWA				
$VP \rightarrow Verb PP$	Aux → does						
$VP \rightarrow VP PP$	•		n near through				
PP → Preposition NP	Verb → book l	include pre	efer				
	þrefer	a	flight	on	TWA		

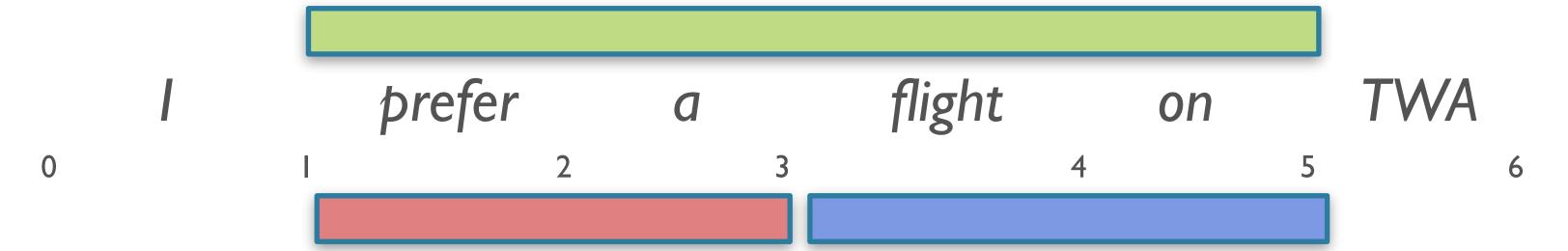
£ ₁ Grammar	NP,	C		S		
$S \rightarrow NP VP$	Pronoun					
$S \rightarrow X1 VP$	[0,1]	[0,2]	[0,3]	[0,4]		
$X1 \rightarrow Aux NP$			L / J			
S → book I include I prefer		Verb, VP, S		VP, X2, S		
S → Verb NP		ΓI 21	ΓI 31	[1,4]		
$S \rightarrow X2 PP$		[1,2]	[1,3]			
S → Verb PP			Det	NP		
$S \rightarrow VP PP$			FO 07	FO 47	FO F3	
NP → II she I me			[2,3]	[2,4]	[2,5]	
NP → TWA I Houston NP → Det Nominal				Noun, Nom		
NP → Det Normhai Nominal → book flight meal money						
Nominal → Dook i mgm i mear i money Nominal → Nominal Noun				[3,4]	[3,5]	
Nominal → Nominal PP	Lexicon				Prep	
VP → book I include I prefer	Det → that this a					
VP → Verb NP	Noun → book flight mea	II money			[4,5]	
$VP \rightarrow X2 PP$	Pronoun → II she I me					
X2 → Verb NP	Proper-Noun → Houston	TWA				
VP → Verb PP	Aux → does					
$VP \rightarrow VP PP$	Preposition → from to or					
PP → Preposition NP	Verb → book include pre	eier				
	prefer a	flight	on	TWA		
		1-0	4	г		
U	2 3		4	5	6	

\mathcal{L}_1 Grammar $S \to NP VP$ $S \to X1 VP$	NP, Pronoun	S [0.21	Γ Ω 21	S [0 4]		
$X1 \rightarrow Aux NP$	[0,1]	[0,2]	[0,3]	[0,4]		
S → book I include I prefer		Verb, VP, S		VP, X2, S		
S → Verb NP		[1,2]	[1,3]	[1,4]		
$S \rightarrow X2 PP$ $S \rightarrow Verb PP$		[·,—]	Det	NP		
$S \rightarrow VPPP$			Det	NP		
NP → I I she I me			[2,3]	[2,4]	[2,5]	
NP → TWA Houston				Noun, Nom		
NP → Det Nominal						
Nominal → book flight meal money Nominal → Nominal Noun				[3,4]	[3,5]	
Nominal → Nominal PP	Lexicon				Prep	
VP → book I include I prefer	Det → that this a	//			F 4 F 7	
VP → Verb NP	Noun → book flight mea Pronoun → she me	i i money			[4,5]	
$VP \rightarrow X2 PP$ $X2 \rightarrow Verb NP$	Proper-Noun → Houston	TWA				
$VP \rightarrow Verb PP$	Aux → does					
$VP \rightarrow VP PP$	Preposition → from to or					
PP → Preposition NP	Verb → book include pre	efer				
#						
	prefer a	flight	on	TWA		
0	2 3	-	4	5	6	

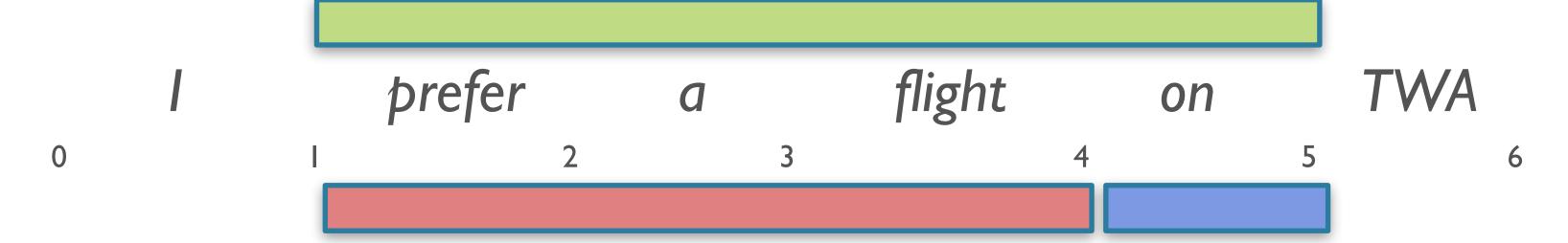
$\mathcal{L}_{1} \mathbf{Grammar}$ $S \to NP VP$ $S \to X1 VP$	NP, Pronoun [0,1]	S [0,2]	[0,3]	S [0,4]		
$X1 \rightarrow Aux NP$ $S \rightarrow book \ l \ include \ l \ prefer$ $S \rightarrow Verb \ NP$		Verb, VP, S [1,2]	[1,3]	VP, X2, S [1,4]	[1,5]	
$S \rightarrow X2 PP$ $S \rightarrow Verb PP$ $S \rightarrow VP PP$			Det	NP		
NP → I I she I me NP → TWA I Houston NP → Det Nominal			[2,3]	[2,4] Noun, Nom	[2,5]	
Nominal → book I flight I meal I money Nominal → Nominal Noun Nominal → Nominal PP	Lexicon			[3,4]	[3,5] Prep	
VP → book I include I prefer VP → Verb NP VP → X2 PP	Det → that this a Noun → book flight mea Pronoun → she me				[4,5]	
$X2 \rightarrow Verb NP$ $VP \rightarrow Verb PP$ $VP \rightarrow VP PP$	Proper-Noun → Houston Aux → does Preposition → from to or		7			
PP → Preposition NP	Verb → book include pre	efer				



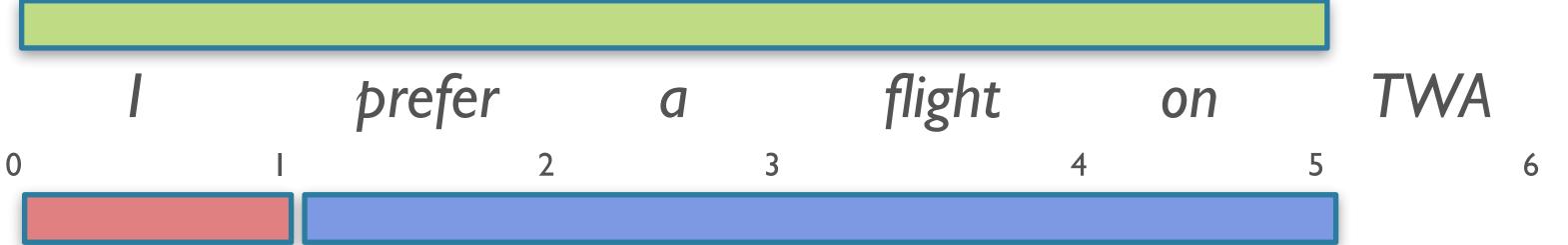
$\mathcal{L}_{1} \mathbf{Grammar}$ $S \to NP VP$ $S \to X1 VP$	NP, Pronoun [0,1]	S [0,2]	[0,3]	S [0,4]		
X1 → Aux NP S → book I include I prefer		Verb, VP, S		VP, X2, S		
$S \rightarrow Verb NP$ $S \rightarrow X2 PP$		[1,2]	[1,3]	[1,4]	[1,5]	
$S \rightarrow Verb PP$ $S \rightarrow VP PP$			Det	NP		
NP → I I she I me			[2,3]	[2,4]	[2,5]	
NP → TWA I Houston NP → Det Nominal				Noun, Nom		
Nominal → book flight meal money Nominal → Nominal Noun				[3,4]	[3,5]	
Nominal → Nominal PP	Lexicon Det → that this a				Prep	
VP → book I include I prefer VP → Verb NP	Noun → book flight mea	II money			[4,5]	
$VP \rightarrow X2 PP$ $X2 \rightarrow Verb NP$	Proper-Noun → Houston					
VP → Verb PP	Aux → does Preposition → from to or	al nearl through	n			
VP → VP PP PP → Preposition NP	Verb → book include pre	•	I			



\mathcal{L}_1 Grammar $S \to NP VP$	NP, Pronoun	S		S		
$S \rightarrow X1 VP$	[0,1]	[0,2]	[0,3]	[0,4]		
$X1 \rightarrow Aux NP$		Verb, VP, S		VP, X2, S		
S → book I include I prefer S → Verb NP						
$S \rightarrow Verb NP$ $S \rightarrow X2 PP$		[1,2]	[1,3]	[1,4]	[1,5]	
$S \rightarrow Verb PP$			Det	NP		
$S \rightarrow VP PP$						
NP → I I she I me			[2,3]	[2,4]	[2,5]	
NP → TWA Houston				Noun, Nom		
NP → Det Nominal						
Nominal → book flight meal money				[3,4]	[3,5]	
Nominal → Nominal Noun	Lovicon					
Nominal → Nominal PP	Lexicon Det → that this a				Prep	
VP → book I include I prefer	Noun → book flight mea	II money			Γ 4 51	
VP → Verb NP	Pronoun $\rightarrow 11$ she 1 me	i i iiioii o y			[4,5]	
$VP \rightarrow X2 PP$	Proper-Noun → Houston	TWA				
X2 → Verb NP	Aux → does	7 7 7 7				
$VP \rightarrow Verb PP$ $VP \rightarrow VP PP$	Preposition → from to or	n I near I through	7			
PP → Preposition NP	Verb → book include pre					

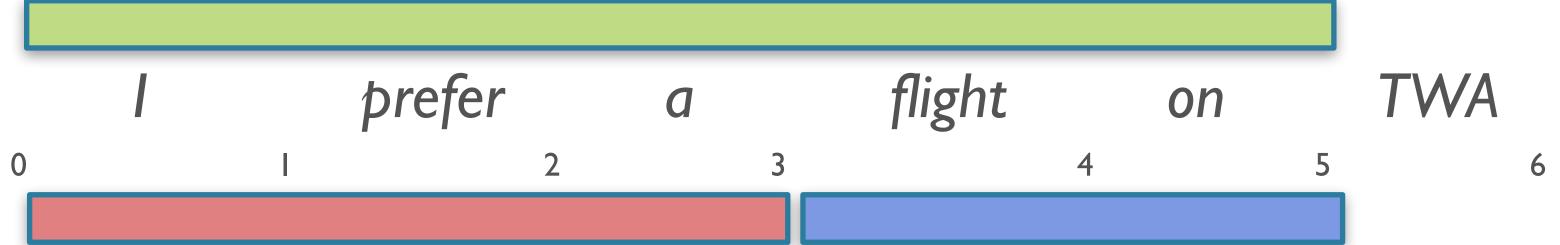


$S \rightarrow NP VP$ $S \rightarrow X1 VP$	NP, Pronoun [0,1]	[0,2]	[0,3]	[0,4]	[0,5]	
X1 → Aux NP S → book I include I prefer S → Verb NP		Verb, VP, S		VP, X2, S		
$S \rightarrow X2PP$		[1,2]	[1,3]		[1,5]	
$S \rightarrow Verb PP$ $S \rightarrow VP PP$			Det	NP		
NP → I I she I me			[2,3]	[2,4]	[2,5]	
NP → TWA Houston NP → Det Nominal				Noun, Nom		
Nominal → book flight meal money Nominal → Nominal Noun				[3,4]	[3,5]	
Nominal → Nominal PP	Lexicon Det a thort think of				Prep	
VP → book I include I prefer VP → Verb NP	Noun → book flight meal	l money			[4,5]	
$VP \rightarrow X2 PP$ $X2 \rightarrow Verb NP$	Pronoun → 11 she 1 me Proper-Noun → Houston 1 7	ΓWA				
VP → Verb PP	Aux → does Preposition → from to on					
VP → VP PP PP → Preposition NP	Verb → book include prei		•			
$VP \rightarrow book\ I\ include\ I\ prefer$ $VP \rightarrow Verb\ NP$ $VP \rightarrow X2\ PP$ $X2 \rightarrow Verb\ NP$ $VP \rightarrow Verb\ PP$ $VP \rightarrow VP\ PP$	Det → that this a Noun → book flight meal Pronoun → she me Proper-Noun → Houston 7 Aux → does Preposition → from to on	ΓWA near through	7			

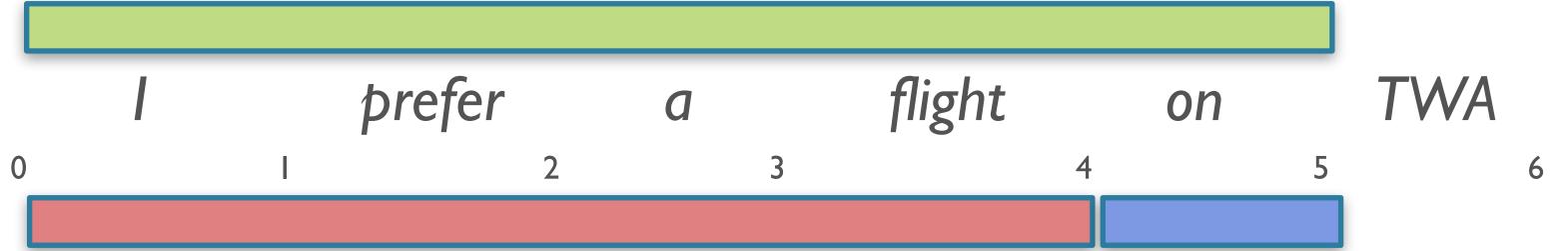


\mathcal{L}_1 Grammar $S \to NP VP$ $S \to X1 VP$ $X1 \to Aux NP$ $S \to book \ l \ include \ l \ prefer$	NP, Pronoun [0,1]	S [0,2] Verb, VP, S	[0,3]	S [0,4] VP, X2, S	[0,5]	
$S \rightarrow Verb NP$ $S \rightarrow X2 PP$ $S \rightarrow Verb PP$		[1,2]	[1,3] Det	[1,4] NP	[1,5]	
$S \rightarrow VP PP$ $NP \rightarrow I \mid she \mid me$ $NP \rightarrow TWA \mid Houston$	-		[2,3]	[2,4] Noun, Nom	[2,5]	
NP → Det Nominal Nominal → book flight meal money Nominal → Nominal Noun	Lexicon			[3,4]	[3,5] Prep	
Nominal → Nominal PP VP → book I include I prefer VP → Verb NP VP → X2 PP	Det → that this a Noun → book flight mea	ll money			[4,5]	
$XP \rightarrow XP + NP$ $XP \rightarrow Verb PP$ $VP \rightarrow VP PP$	Proper-Noun → Houston Aux → does Preposition → from to or		7			
PP → Preposition NP	- Verb → book include pre	efer				
	prefer a	flight	on	TWA	1	

\mathcal{L}_1 Grammar $S \to NP VP$ $S \to X1 VP$	NP, Pronoun [0,1]	S [0,2]	[0,3]	S [0,4]	[0,5]		
$X1 \rightarrow Aux NP$ $S \rightarrow book \ l \ include \ l \ prefer$ $S \rightarrow Verb \ NP$		Verb, VP, S [1,2]	[1,3]	VP, X2, S [1,4]	[1,5]		
$S \rightarrow X2 PP$ $S \rightarrow Verb PP$ $S \rightarrow VP PP$		[1,4]	Det	NP	[ו,ט]		
NP → I I she I me NP → TWA I Houston NP → Det Nominal			[2,3]	[2,4] Noun, Nom	[2,5]		
Nominal → book I flight I meal I money Nominal → Nominal Noun Nominal → Nominal PP	Lexicon			[3,4]	[3,5] Prep		
VP → book I include I prefer VP → Verb NP	Det → that this a Noun → book flight mea	II money			[4,5]		
$VP \rightarrow X2 PP$ $X2 \rightarrow Verb NP$ $VP \rightarrow Verb PP$	Pronoun → she me Proper-Noun → Houston TWA Aux → does						
VP → VP PP PP → Preposition NP	Preposition → from to or Verb → book include pre		1				



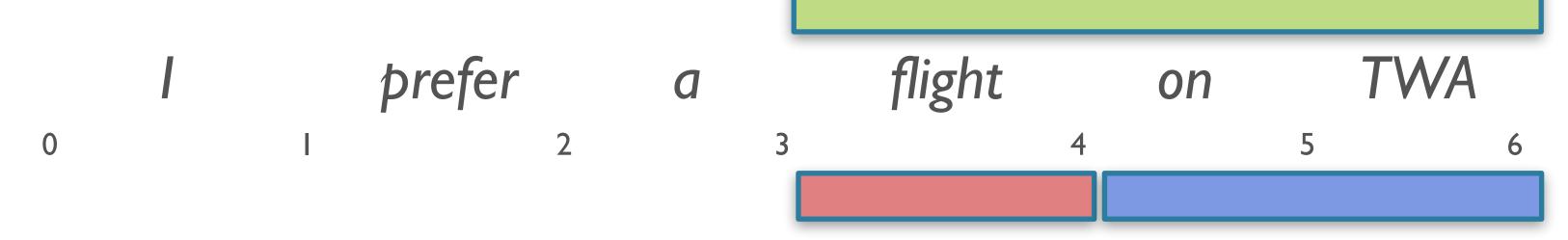
$\mathcal{L}_{1} \mathbf{Grammar}$ $S \to NP VP$ $S \to X1 VP$	NP, Pronoun [0,1]	S [0,2]	[0,3]	S [0,4]	[0,5]	
$X1 \rightarrow Aux NP$ $S \rightarrow book \ l \ include \ l \ prefer$ $S \rightarrow Verb \ NP$		Verb, VP, S		VP, X2, S	F1 F3	
$S \rightarrow X2 PP$ $S \rightarrow Verb PP$ $S \rightarrow VP PP$		[1,2]	[1,3] Det	[1,4] NP	[1,5]	
NP → I I she I me NP → TWA I Houston NP → Det Nominal			[2,3]	[2,4] Noun, Nom	[2,5]	
Nominal → book flight meal money Nominal → Nominal Noun	Lexicon			[3,4]	[3,5]	
Nominal → Nominal PP VP → book I include I prefer VP → Verb NP VP → X2 PP	Det → that this a Noun → book flight mea Pronoun → she me				Prep [4,5]	
$X2 \rightarrow Verb NP$ $VP \rightarrow Verb PP$ $VP \rightarrow VP PP$	Proper-Noun → Houston TWA Aux → does Preposition → from to on near through Verb → book include prefer					
PP → Preposition NP	vero , book i iliciade i pre	71 G1				



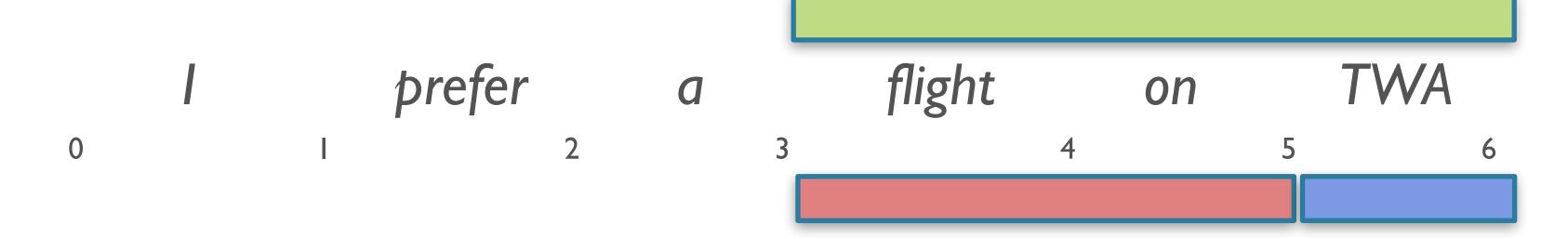
£ ₁ Grammar	NP,	S		S		
$S \rightarrow NP VP$	Pronoun					
$S \rightarrow X1 VP$	[0,1]	[0,2]	[0,3]	[0,4]	[0,5]	
$X1 \rightarrow Aux NP$		Verb, VP, S		VP, X2, S		
S → book I include I prefer		verb, vr, s		V F, AZ, S		
$S \rightarrow Verb NP$		[1,2]	[1,3]	[1,4]	[1,5]	
$S \rightarrow X2 PP$ $S \rightarrow Verb PP$		L·				
$S \rightarrow VPPP$			Det	NP		
$NP \rightarrow IIsheIme$	•		[2,3]	[2,4]	[2,5]	
NP → TWA Houston				Noun, Nom		
NP → Det Nominal				Moun, Mon		
Nominal → book flight meal money				[3,4]	[3,5]	
Nominal → Nominal Noun	Lexicon			[-, .]		
Nominal → Nominal PP	Det → that this a				Prep	
VP → book I include I prefer VP → Verb NP	Noun → book flight mea	II monev			[4,5]	
$VP \rightarrow Verb NP$ $VP \rightarrow X2 PP$	Pronoun → I she me					NINID NID
$X2 \rightarrow Verb NP$	Proper-Noun → Houston I	TWA				NNP, NP
VP → Verb PP	Aux → does					[5,6]
$VP \rightarrow VP PP$	Preposition → from to or		7			[5,0]
PP → Preposition NP	Verb → book include pre	eter				
	prefer a	flight	on	TWA		
	P. 9/9.	1"8"	4			
0	2 3		4	5	6	

\mathcal{L}_1 Grammar $S \to NP VP$ $S \to X1 VP$ $X1 \to Aux NP$	NP, Pronoun [0,1]	S [0,2]	[0,3]	S [0,4]	[0,5]	
$S \rightarrow book\ l\ include\ l\ prefer$ $S \rightarrow Verb\ NP$ $S \rightarrow X2\ PP$ $S \rightarrow Verb\ PP$		Verb, VP, S [1,2]	[1,3] Det	VP, X2, S [1,4] NP	[1,5]	
S → VP PP NP → I I she I me NP → TWA I Houston NP → Det Nominal			[2,3]	[2,4] Noun, Nom	[2,5]	
Nominal → book I flight I meal I money Nominal → Nominal Noun Nominal → Nominal PP	Lexicon Det → that this a			[3,4]	[3,5] Prep	PP
$VP \rightarrow book\ I \ include\ I \ prefer$ $VP \rightarrow Verb\ NP$ $VP \rightarrow X2\ PP$ $X2 \rightarrow Verb\ NP$ $VP \rightarrow Verb\ PP$	Noun → book flight mea Pronoun → she me Proper-Noun → Houston Aux → does	TWA			[4,5]	[4,6] NNP, NP [5,6]
VP → VP PP PP → Preposition NP	Preposition → from to or Verb → book include pre		7			
0	brefer a 2 3	flight	on	TW / ₅	6	

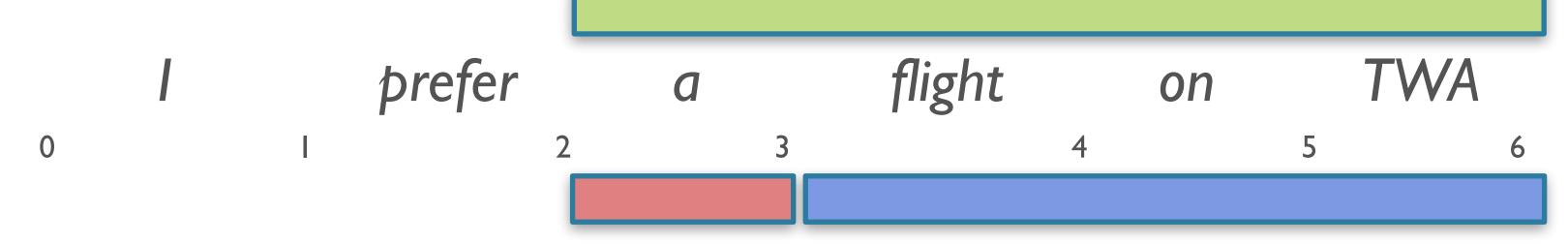
£ ₁ Grammar	NP,	S		S			
$S \rightarrow NP VP$	Pronoun						
$S \rightarrow X1 VP$	[0,1]	[0,2]	[0,3]	[0,4]	[0,5]		
$X1 \rightarrow Aux NP$				VD V2 C			
S → book I include I prefer		Verb, VP, S		VP, X2, S			
S → Verb NP		ΓΙ 2 1	FI 21	ΓΙ <i>Α</i> Ί	F1 F3		
$S \rightarrow X2 PP$		[1,2]	[1,3]	[1,4]	[1,5]		
S → Verb PP			Det	NP			
$S \rightarrow VP PP$							
NP → I I she I me			[2,3]	[2,4]	[2,5]		
NP → TWA Houston				Noun, Nom		Nom	
NP → Det Nominal							
Nominal → book flight meal money				[3,4]	[3,5]	[3,6]	
Nominal → Nominal Noun						PP	
Nominal → Nominal PP		Lexicon Prep					
VP → book I include I prefer	Det → that this a	/			F4 F3	F 4 23	
VP → Verb NP	Noun → book flight mea	i i money			[4,5]	[4,6]	
$VP \rightarrow X2 PP$	Pronoun → she me	T14/4				NNP, NP	
X2 → Verb NP	Proper-Noun → Houston i IVVA						
VP → Verb PP	Aux → does					[5,6]	
$VP \rightarrow VP PP$	Preposition - nomitoron near timougn					-	
PP → Preposition NP	verb → book i include i preter						
	Verb → book include pre		1				



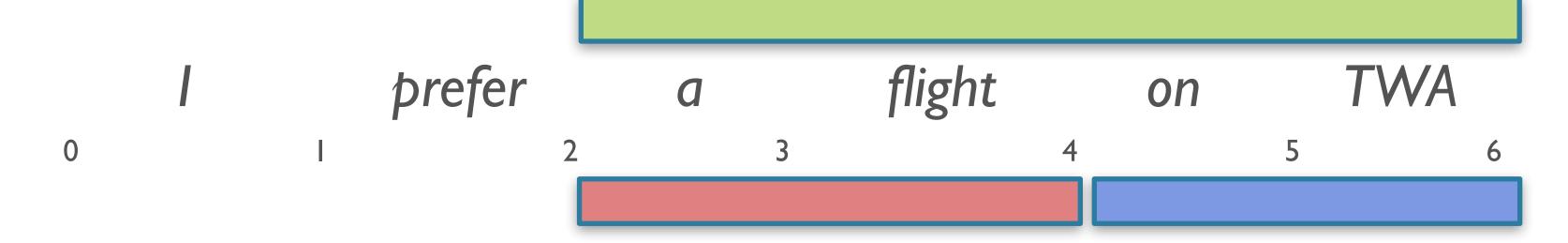
\mathcal{L}_1 Grammar	NP,	S		S		
$S \rightarrow NP VP$	Pronoun					
$S \rightarrow X1 VP$	[0,1]	[0,2]	[0,3]	[0,4]	[0,5]	
$X1 \rightarrow Aux NP$		Verb, VP, S		VP, X2, S		
S → book I include I prefer		verb, vr, s		VI, A2, 5		
S → Verb NP		[1,2]	[1,3]	[1,4]	[1,5]	
$S \rightarrow X2 PP$		[1,4]			[1,5]	
$S \rightarrow Verb PP$			Det	NP		
$S \rightarrow VP PP$						
NP → I I she I me			[2,3]	[2,4]	[2,5]	
NP → TWA I Houston				Noun, Nom		Nom
NP → Det Nominal						
Nominal → book flight meal money				[3,4]	[3,5]	[3,6]
Nominal → Nominal Noun	Levicon					
Nominal → Nominal PP	Lexicon Det → that this a				Prep	PP
VP → book I include I prefer	Noun \rightarrow book flight mea	II money			[/ E]	Γ / / / 1
VP → Verb NP	Pronoun → I she me	i i money			[4,5]	[4,6]
$VP \rightarrow X2 PP$	Pronoun → 11 sne 1 me Proper-Noun → Houston TWA					NNP, NP
X2 → Verb NP	$Aux \rightarrow does$	1 / / / /				
VP → Verb PP		7			[5,6]	
$VP \rightarrow VP PP$	Preposition → from I to I on I near I through Verb → book I include I prefer					
PP → Preposition NP	vois soon i moidae i pre	,101				



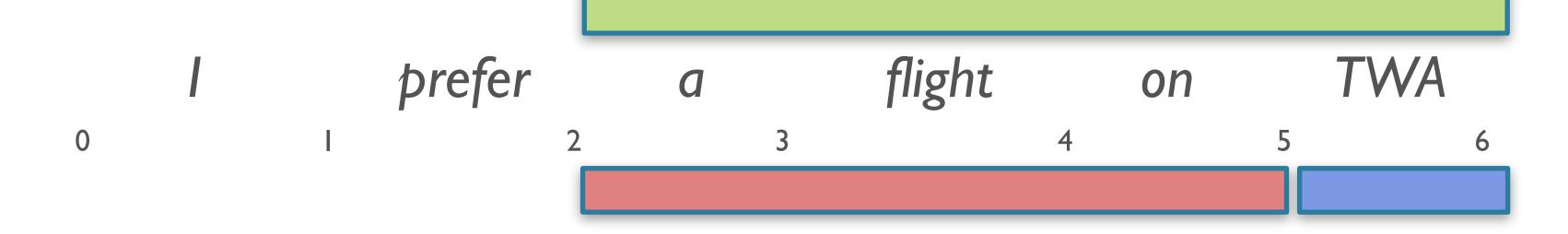
£ ₁ Grammar	NP,	S		S		
$S \rightarrow NP VP$	Pronoun					
$S \rightarrow X1 VP$	[0,1]	[0,2]	[0,3]	[0,4]	[0,5]	
$X1 \rightarrow Aux NP$						
S → book I include I prefer		Verb, VP, S		VP, X2, S		
S → Verb NP		F1 27	EL 27	F1 43	F1 F3	
$S \rightarrow X2PP$		[1,2]	[1,3]	[1,4]	[1,5]	
S → Verb PP			Det	NP		NP
$S \rightarrow VP PP$						
NP → I I she I me			[2,3]	[2,4]	[2,5]	[2,6]
NP → TWA I Houston				Noun, Nom		Nom
NP → Det Nominal						
Nominal → book flight meal money				[3,4]	[3,5]	[3,6]
Nominal → Nominal Noun	To an American					
Nominal → Nominal PP	Lexicon				Prep	PP
VP → book I include I prefer	Det → that this a	/			E 4 E 3	F 4 47
VP → Verb NP	Noun → book flight mea	i i money			[4,5]	[4,6]
$VP \rightarrow X2 PP$	Pronoun → II she I me	T14/4				NNP, NP
X2 → Verb NP	Proper-Noun → Houston	IVVA				
VP → Verb PP	Aux → does					[5,6]
$VP \rightarrow VP PP$	Preposition → from to on near through					
PP → Preposition NP	Verb → book include pre	eier				



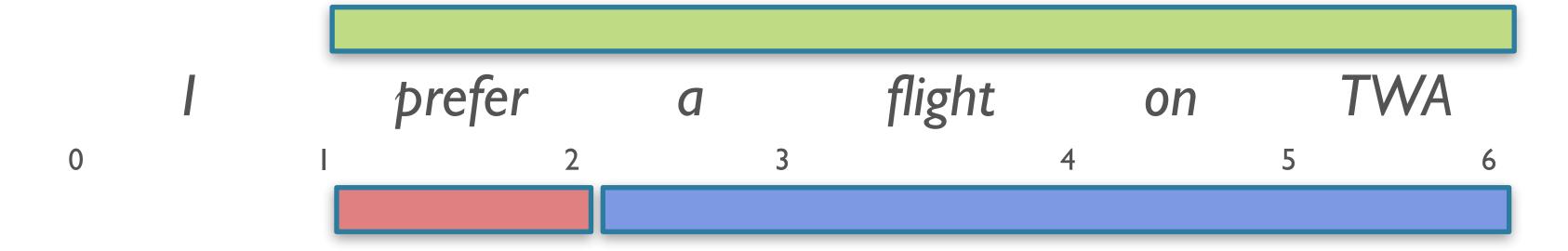
\mathcal{L}_1 Grammar $S \rightarrow NP VP$	NP, Pronoun	S	FA 27	S	FA F3	
$S \rightarrow X1 VP$ $X1 \rightarrow Aux NP$	[0,1]	[0,2]	[0,3]	[0,4]	[0,5]	
$S \rightarrow book \ l \ include \ l \ prefer$		Verb, VP, S		VP, X2, S		
$S \rightarrow Verb NP$				-1 4-		
$S \rightarrow X2PP$		[1,2]	[1,3]	[1,4]	[1,5]	
$S \rightarrow Verb PP$			Det	NP		NP
$S \rightarrow VP PP$						
$NP \rightarrow II she Ime$			[2,3]	[2,4]	[2,5]	[2,6]
NP → TWA Houston				Noun, Nom		Nom
NP → Det Nominal						
Nominal → book flight meal money Nominal → Nominal Noun				[3,4]	[3,5]	[3,6]
Nominal → Nominal PP	Lexicon				Prep	PP
VP → book I include I prefer	Det → that this a					
VP → Verb NP	Noun → book flight meal	II money			[4,5]	[4,6]
$VP \rightarrow X2 PP$	Pronoun → II she I me	-				NNP, NP
X2 → Verb NP	Proper-Noun → Houston TWA					
VP → Verb PP	Aux → does Proposition → from I to I on I poor I through					[5,6]
$VP \rightarrow VP PP$	Preposition → from to on near through Verb → book include prefer					
PP → Preposition NP	verb book i iliciade i pre	TOI				



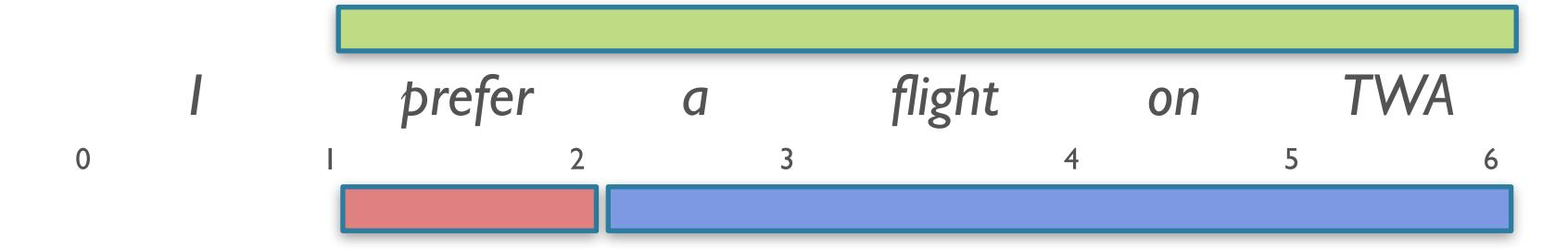
£ ₁ Grammar	NP,	S		S		
$S \rightarrow NP VP$	Pronoun					
$S \rightarrow X1 VP$	[0,1]	[0,2]	[0,3]	[0,4]	[0,5]	
$X1 \rightarrow Aux NP$		Voyb VD S		VP V2 S		
S → book I include I prefer		Verb, VP, S		VP, X2, S		
S → Verb NP		[] 21	F1 21	[F1 51	
$S \rightarrow X2 PP$		[1,2]	[1,3]	[1,4]	[1,5]	
S → Verb PP			Det	NP		NP
$S \rightarrow VP PP$			[2,3]			
NP → I I she I me		[2,5]	[2,6]			
NP → TWA Houston				Noun, Nom		Nom
NP → Det Nominal						
Nominal → book flight meal money				[3,4]	[3,5]	[3,6]
Nominal → Nominal Noun	Lovicon			-		
Nominal → Nominal PP	Lexicon Det → that this a				Prep	PP
VP → book I include I prefer	Noun \rightarrow book flight mea	II monov			Γ <i>Λ</i> Ε1	ΓΛ 6 1
VP → Verb NP	Pronoun $\rightarrow 11$ she 1 me	i i money			[4,5]	[4,6]
$VP \rightarrow X2 PP$		$TIM\Delta$				NNP, NP
X2 → Verb NP	Proper-Noun → Houston TWA Aux → does					
VP → Verb PP	Preposition → from to on near through					[5,6]
$VP \rightarrow VP PP$	Verb → book include prefer					
PP → Preposition NP	void book i ilidiade i pre	,101				



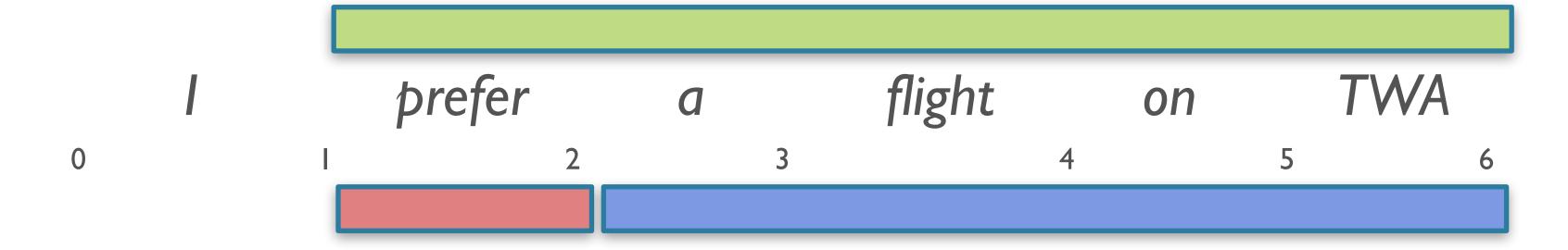
\mathcal{L}_1 Grammar $S \to NP VP$ $S \to X1 VP$	NP, Pronoun [0,1]	S [0,2]	[0,3]	S [0,4]	[0,5]	
$X1 \rightarrow Aux NP$	[0,1]	Verb, VP, S	[0,5]	VP, X2, S	[0,5]	
S → book I include I prefer						
$S \rightarrow Verb NP$ $S \rightarrow X2 PP$		[1,2]	[1,3]	[1,4]	[1,5]	[1,6]
$S \rightarrow Verb PP$			Det	NP		NP
$S \rightarrow VP PP$						
NP → I I she I me			[2,3]	[2,4]	[2,5]	[2,6]
NP → TWA I Houston				Noun, Nom		Nom
NP → Det Nominal						
Nominal → book flight meal money				[3,4]	[3,5]	[3,6]
Nominal → Nominal Noun Nominal → Nominal PP	Lexicon				Prep	PP
VP → book I include I prefer	Det → that this a					
VP → Verb NP	Noun → book flight meal	II money			[4,5]	[4,6]
$VP \rightarrow X2 PP$	Pronoun → II she I me					NNP, NP
X2 → Verb NP	Proper-Noun → Houston	TWA				
VP → Verb PP	Aux → does Preposition → from I to I or				[5,6]	
$VP \rightarrow VP PP$	Preposition → from to or Verb → book include pre		1			
PP → Preposition NP	void book i illoidae i pre	101				



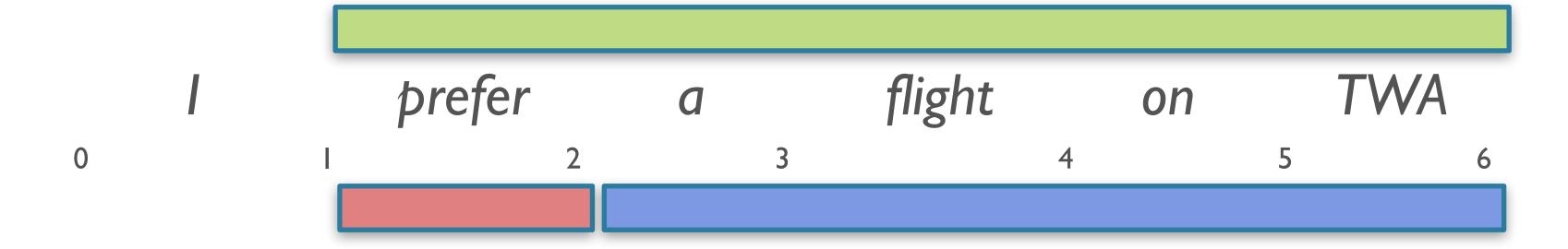
\mathcal{L}_1 Grammar $S \rightarrow NP VP$		NP, Pronoun	S		S		
$S \rightarrow X1 VP$		[0,1]	[0,2]	[0,3]	[0,4]	[0,5]	
X1 → Aux NP S → book I include I prefer			Verb, VP, S		VP, X2, S		VP
$S \rightarrow Verb NP$							
$S \rightarrow X2PP$			[1,2]	[1,3]	[1,4]	[1,5]	[1,6]
S → Verb PP				Det	NP		NP
$S \rightarrow VP PP$							
NP → I I she I me				[2,3]	[2,4]	[2,5]	[2,6]
NP → TWA Houston					Noun, Nom		Nom
NP → Det Nominal							
Nominal → book flight meal money					[3,4]	[3,5]	[3,6]
Nominal → Nominal Noun Nominal → Nominal PP	Lexicon					Prep	PP
$VP \rightarrow book \ l \ include \ l \ prefer$	Det → that	t I this I a					
VP → Verb NP	Noun → be	ook flight meal	I money			[4,5]	[4,6]
$VP \rightarrow X2 PP$		→ she me					NNP, NP
X2 → Verb NP	,	un → Houston l	TWA				, , , , , , , , , , , , , , , , , , , ,
VP → Verb PP	$Aux \rightarrow doe$		1				[5,6]
$VP \rightarrow VP PP$	Preposition → from to on near through Verb → book include prefer						
PP → Preposition NP	verb → bb	ok i iriciuae i pre	iei				



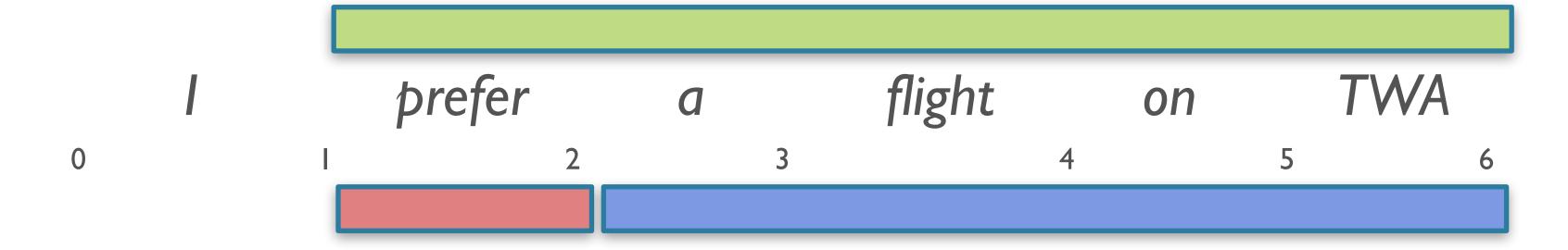
\mathcal{L}_1 Grammar $S \rightarrow NP VP$		NP, Pronoun	S		S		
$S \rightarrow X1 VP$		[0,1]	[0,2]	[0,3]	[0,4]	[0,5]	
$X1 \rightarrow Aux NP$ $S \rightarrow book \ l \ include \ l \ prefer$			Verb, VP, S		VP, X2, S		VP, X2
$S \rightarrow Verb NP$							
$S \rightarrow X2 PP$			[1,2]	[1,3]	[1,4]	[1,5]	[1,6]
S → Verb PP				Det	NP		NP
$S \rightarrow VP PP$							
$NP \rightarrow II sheIme$				[2,3]	[2,4]	[2,5]	[2,6]
NP → TWA Houston					Noun, Nom		Nom
NP → Det Nominal							
Nominal → book flight meal money					[3,4]	[3,5]	[3,6]
Nominal → Nominal Noun Nominal → Nominal PP	Lexicon					Prep	PP
$VP \rightarrow book \ l \ include \ l \ prefer$	Det → that I to	his I a					
VP → Verb NP	Noun → book	<pre>< flight meal</pre>	l money			[4,5]	[4,6]
$VP \rightarrow X2 PP$	Pronoun → I						NNP, NP
$X2 \rightarrow Verb NP$ $VP \rightarrow Verb PP$	Proper-Noun → Houston TWA						, , , , , , , , , , , , , , , , , , , ,
VP → Verb PP	Aux → does		. 4/2 /2				[5,6]
$VP \rightarrow VP PP$	Preposition → from to on near through Verb → book include prefer						
PP → Preposition NP	verb → book	i iriciuae i pre	ier				



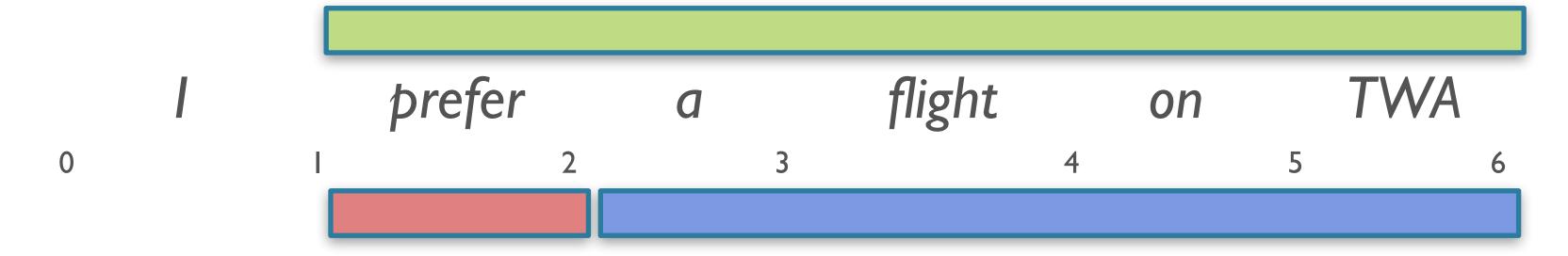
$\mathcal{L}_{1} \mathbf{Grammar}$ $S \to NP VP$ $S \to X1 VP$	NP, Pronoun [0,1]	S [0,2]	[0,3]	S [0,4]	[0,5]	
$X1 \rightarrow Aux NP$ $S \rightarrow book \ l \ include \ l \ prefer$		Verb, VP, S		VP, X2, S		VP, X2, S
$S \rightarrow Verb NP$ $S \rightarrow X2 PP$		[1,2]	[1,3]	[1,4]	[1,5]	[1,6]
$S \rightarrow Verb PP$			Det	NP		NP
$S \rightarrow VP PP$ $NP \rightarrow II she I me$			[2,3]	[2,4]	[2,5]	[2,6]
NP → TWA I Houston NP → Det Nominal				Noun, Nom		Nom
NP → Det Normhai Nominal → book flight meal money Nominal → Nominal Noun				[3,4]	[3,5]	[3,6]
Nominal → Nominal PP	Lexicon				Prep	PP
VP → book I include I prefer VP → Verb NP	Det → that this a Noun → book flight mea	ll money			[4,5]	[4,6]
$VP \rightarrow X2 PP$	Pronoun → she me Proper-Noun → Houston	TWA				NNP, NP
X2 → Verb NP VP → Verb PP VP → VP PP	Aux → does Preposition → from to or				[5,6]	
PP → Preposition NP	Verb → book include pre	efer				



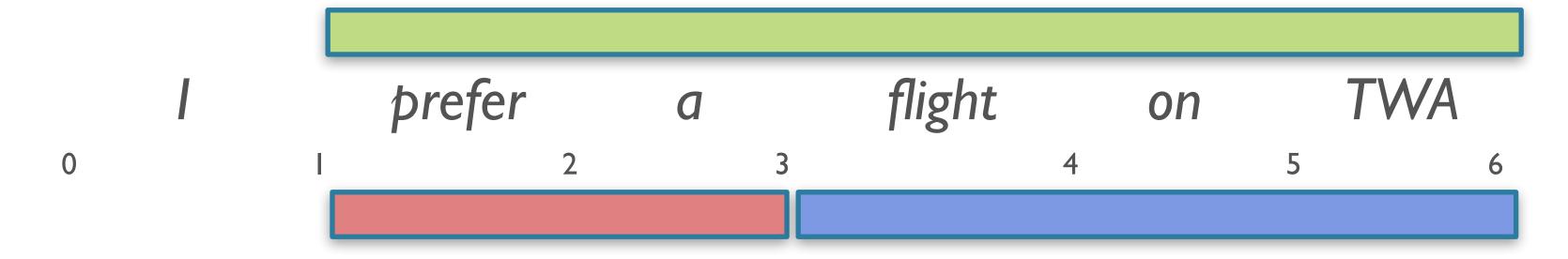
\mathcal{L}_1 Grammar $S \to NP VP$ $S \to X1 VP$		NP, Pronoun [0,1]	S [0,2]	[0,3]	S [0,4]	[0,5]	
X1 → Aux NP S → book Linglade Lorefor		[0,1]	Verb, VP, S	[0,5]	VP, X2, S	[0,5]	VP, X2, S
S → book I include I prefer S → Verb NP S → X2 PP			[1,2]	[1,3]	[1,4]	[1,5]	[1,6]
$S \rightarrow Verb PP$ $S \rightarrow VP PP$				Det	NP		NP
NP → I I she I me				[2,3]	[2,4]	[2,5]	[2,6]
NP → TWA I Houston NP → Det Nominal					Noun, Nom		Nom
Nominal → book flight meal money Nominal → Nominal Noun					[3,4]	[3,5]	[3,6]
Nominal → Nominal PP	Lexicon <i>Det → that</i>	t I thic I a				Prep	PP
VP → book I include I prefer VP → Verb NP	Noun → be	ook flight meal	I money			[4,5]	[4,6]
$VP \rightarrow X2 PP$ $X2 \rightarrow Verb NP$	Pronoun → she me Proper-Noun → Houston TWA						NNP, NP
VP → Verb PP	$Aux \rightarrow doe$						[5,6]
VP → VP PP PP → Preposition NP	•	ook include pre					



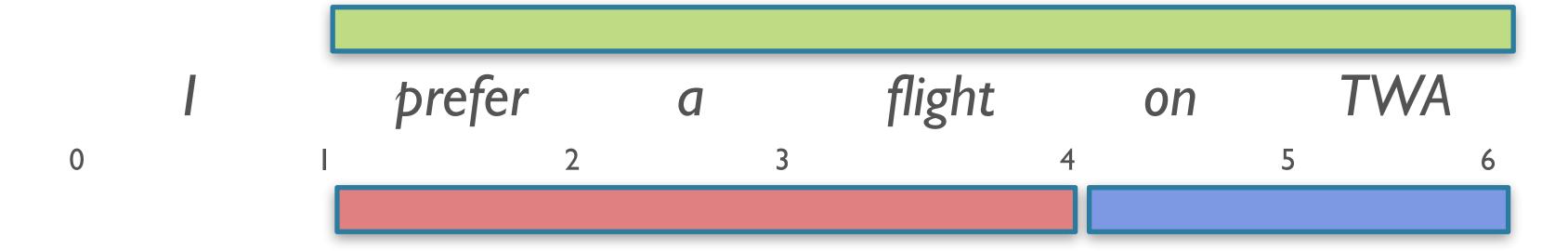
$\mathcal{L}_{1} \mathbf{Grammar}$ $S \to NP VP$ $S \to X1 VP$	NP, Pronoun [0,1]	S [0,2]	[0,3]	S [0,4]	[0,5]	
X1 → Aux NP S → book I include I prefer		Verb, VP, S		VP, X2, S		VP, X2, S
$S \rightarrow Verb NP$ $S \rightarrow X2 PP$		[1,2]	[1,3]	[1,4]	[1,5]	[1,6]
$S \rightarrow Verb PP$			Det	NP		NP
$S \rightarrow VP PP$ $NP \rightarrow I l she l me$			[2,3]	[2,4]	[2,5]	[2,6]
NP → TWA I Houston NP → Det Nominal				Noun, Nom		Nom
Nominal → book flight meal money Nominal → Nominal Noun				[3,4]	[3,5]	[3,6]
Nominal → Nominal PP	Lexicon Det Moet Libraria Le				Prep	PP
VP → book I include I prefer VP → Verb NP	Det → that this a Noun → book flight mea	II money			[4,5]	[4,6]
$VP \rightarrow X2 PP$ $X2 \rightarrow Verb NP$	Pronoun → she me Proper-Noun → Houston	TWA				NNP, NP
$VP \rightarrow Verb NN$ $VP \rightarrow Verb PP$ $VP \rightarrow VP PP$	Aux → does Preposition → from to or	1			[5,6]	
PP → Preposition NP	Verb → book include pre					



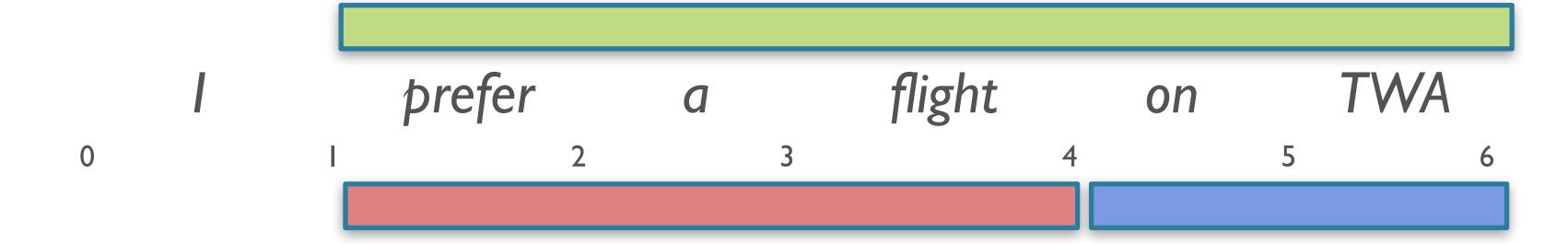
$\mathcal{L}_{1} \mathbf{Grammar}$ $S \to NP VP$ $S \to X1 VP$	NP, Pronoun [0,1]	S [0,2]	[0,3]	S [0,4]	[0,5]	
$X1 \rightarrow Aux NP$ $S \rightarrow book \ l \ include \ l \ prefer$		Verb, VP, S		VP, X2, S		VP, X2, S
$S \rightarrow Verb NP$ $S \rightarrow X2 PP$		[1,2]	[1,3]	[1,4]	[1,5]	[1,6]
$S \rightarrow Verb PP$			Det	NP		NP
$S \rightarrow VP PP$ $NP \rightarrow II she I me$			[2,3]	[2,4]	[2,5]	[2,6]
NP → TWA I Houston NP → Det Nominal				Noun, Nom		Nom
Nominal → book flight meal money Nominal → Nominal Noun				[3,4]	[3,5]	[3,6]
Nominal → Nominal PP	Lexicon				Prep	PP
VP → book I include I prefer VP → Verb NP	Det → that this a Noun → book flight meal	II money			[4,5]	[4,6]
$VP \rightarrow X2 PP$	Pronoun → she me Proper-Noun → Houston	TWA				NNP, NP
X2 → Verb NP VP → Verb PP VP → VP PP	Aux → does Preposition → from to or	7			[5,6]	
PP → Preposition NP	Verb → book include pre	efer				



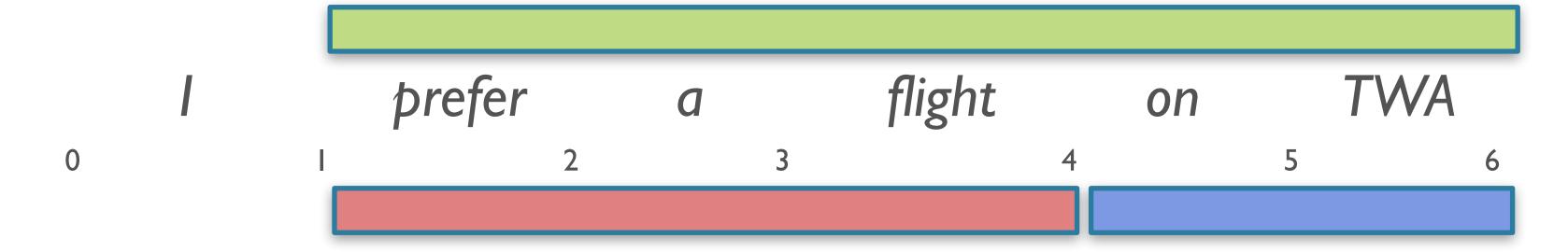
\mathcal{L}_1 Grammar $S \to NP VP$ $S \to X1 VP$	NP, Pronoun [0,1]	S [0,2]	[0,3]	S [0,4]	[0,5]	
$X1 \rightarrow Aux NP$ $S \rightarrow book \ l \ include \ l \ prefer$		Verb, VP, S		VP, X2, S		VP, X2, S
$S \rightarrow Sook + Mediade + prefer$ $S \rightarrow Verb NP$ $S \rightarrow X2 PP$		[1,2]	[1,3]	[1,4]	[1,5]	[1,6]
S → Verb PP			Det	NP		NP
$S \rightarrow VP PP$ $NP \rightarrow II she I me$			[2,3]	[2,4]	[2,5]	[2,6]
NP → TWA I Houston NP → Det Nominal				Noun, Nom		Nom
Nominal → book flight meal money Nominal → Nominal Noun				[3,4]	[3,5]	[3,6]
Nominal → Nominal PP	Lexicon				Prep	PP
VP → book I include I prefer VP → Verb NP	Det → that this a Noun → book flight meal	II money			[4,5]	[4,6]
$VP \rightarrow X2 PP$	Pronoun → she me Proper-Noun → Houston				NNP, NP	
$X2 \rightarrow Verb NP$ $VP \rightarrow Verb PP$ $VP \rightarrow VP PP$	Aux → does Preposition → from to or	7			[5,6]	
PP → Preposition NP	Verb → book include pre					



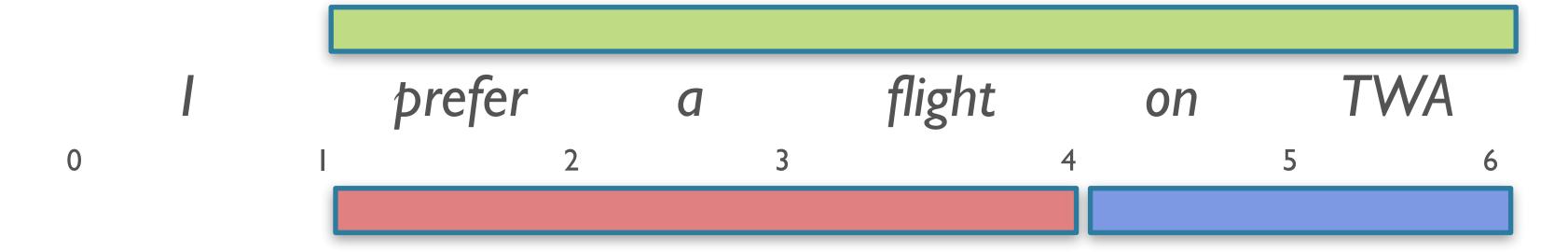
\mathcal{L}_1 Grammar $S \to NP VP$ $S \to X1 VP$	NP, Pronoun [0,1]	S [0,2]	[0,3]	S [0,4]	[0,5]	
$X1 \rightarrow Aux NP$ $S \rightarrow book \ l \ include \ l \ prefer$		Verb, VP, S		VP, X2, S		VP, X2, S
$S \rightarrow Verb NP$ $S \rightarrow X2 PP$		[1,2]	[1,3]	[1,4]	[1,5]	[1,6]
S → Verb PP			Det	NP		NP
$S \rightarrow VP PP$ $NP \rightarrow II she I me$			[2,3]	[2,4]	[2,5]	[2,6]
NP → TWA I Houston NP → Det Nominal				Noun, Nom		Nom
Nominal → book flight meal money Nominal → Nominal Noun				[3,4]	[3,5]	[3,6]
Nominal → Nominal PP	Lexicon				Prep	PP
VP → book I include I prefer VP → Verb NP	Det → that this a Noun → book flight meal	II money			[4,5]	[4,6]
$VP \rightarrow X2 PP$	Pronoun → she me Proper-Noun → Houston				NNP, NP	
$X2 \rightarrow Verb NP$ $VP \rightarrow Verb PP$ $VP \rightarrow VP PP$	Aux → does Preposition → from to on near through					[5,6]
PP → Preposition NP	Verb → book include pre	efer				



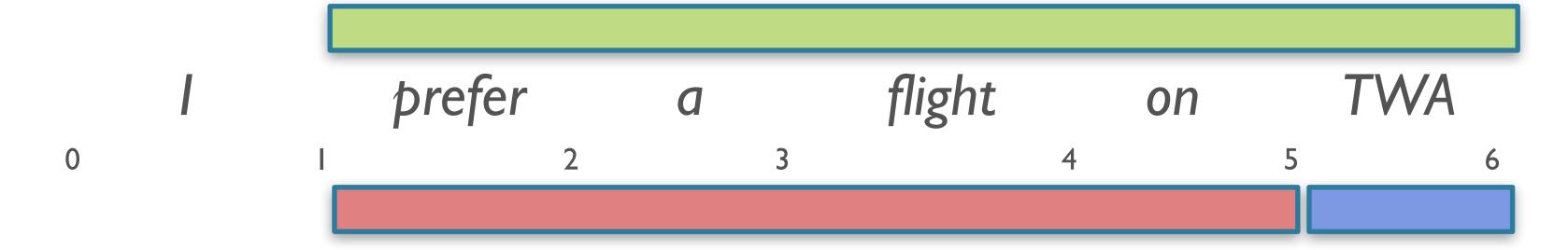
\mathcal{L}_1 Grammar $S \to NP VP$ $S \to X1 VP$	NP, Pronoun [0,1]	S [0,2]	[0,3]	S [0,4]	[0,5]	
$X1 \rightarrow Aux NP$ $S \rightarrow book \ l \ include \ l \ prefer$		Verb, VP, S		VP, X2, S		VP, X2, S
$S \rightarrow Verb NP$					-1 -1	
$S \rightarrow X2 PP$		[1,2]	[1,3]	[1,4]	[1,5]	[1,6]
S → Verb PP			Det	NP		NP
$S \rightarrow VP PP$						
NP → I I she I me			[2,3]	[2,4]	[2,5]	[2,6]
NP → TWA Houston				Noun, Nom		Nom
NP → Det Nominal						
Nominal → book flight meal money				[3,4]	[3,5]	[3,6]
Nominal → Nominal Noun	Lexicon				Prep	PP
Nominal → Nominal PP	Det → that this a				ПСР	_
VP → book l include l prefer VP → Verb NP	Noun → book flight meal	II money			[4,5]	[4,6]
$VP \rightarrow Verb NP$ $VP \rightarrow X2 PP$	Pronoun → II she I me	-				NNP, NP
X2 → Verb NP	Proper-Noun → Houston I				MINIT, INIT	
VP → Verb PP	Aux → does				[5,6]	
$VP \rightarrow VP PP$	Preposition → from to or					
PP → Preposition NP	Verb → book include pre	eter				



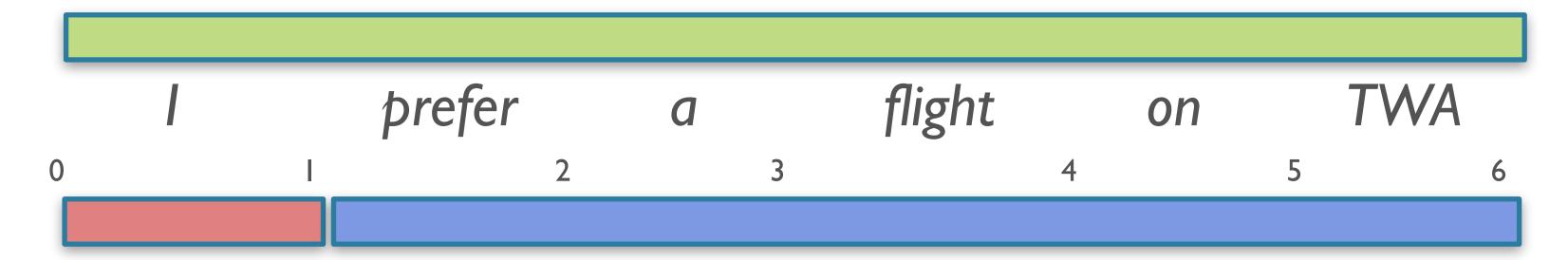
\mathcal{L}_1 Grammar $S \to NP VP$ $S \to X1 VP$	NP, Pronoun [0,1]	S [0,2]	[0,3]	S [0,4]	[0,5]	
X1 → Aux NP S → book I include I prefer		Verb, VP, S		VP, X2, S		VP, X2, S
$S \rightarrow Verb NP$ $S \rightarrow X2 PP$		[1,2]	[1,3]	[1,4]	[1,5]	[1,6]
S → Verb PP			Det	NP		NP
$S \rightarrow VP PP$ $NP \rightarrow I \mid she \mid me$			[2,3]	[2,4]	[2,5]	[2,6]
NP → TWA Houston NP → Det Nominal				Noun, Nom		Nom
Nominal → book flight meal money Nominal → Nominal Noun				[3,4]	[3,5]	[3,6]
Nominal → Nominal PP	Lexicon				Prep	PP
VP → book I include I prefer VP → Verb NP	Det → that this a Noun → book flight meal	II money			[4,5]	[4,6]
$VP \rightarrow X2 PP$ $X2 \rightarrow Verb NP$	Pronoun → she me Proper-Noun → Houston	TWA				NNP, NP
$VP \rightarrow Verb NP$ $VP \rightarrow Verb PP$ $VP \rightarrow VP PP$	Aux → does Preposition → from to or)			[5,6]
PP → Preposition NP	Verb → book include pre	efer				



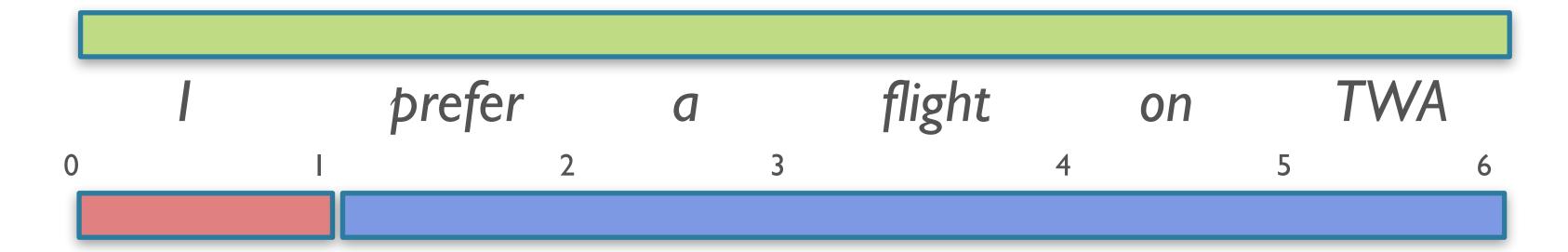
$\mathcal{L}_{1} \mathbf{Grammar}$ $S \to NP VP$ $S \to X1 VP$	NP, Pronoun [0,1]	S [0,2]	[0,3]	S [0,4]	[0,5]	
$X1 \rightarrow Aux NP$ $S \rightarrow book \ l \ include \ l \ prefer$		Verb, VP, S		VP, X2, S		VP, X2, S
$S \rightarrow Verb NP$ $S \rightarrow X2 PP$		[1,2]	[1,3]	[1,4]	[1,5]	[1,6]
S → Verb PP			Det	NP		NP
$S \rightarrow VP PP$ $NP \rightarrow I \mid she \mid me$			[2,3]	[2,4]	[2,5]	[2,6]
NP → TWA I Houston NP → Det Nominal				Noun, Nom		Nom
Nominal → book flight meal money Nominal → Nominal Noun				[3,4]	[3,5]	[3,6]
Nominal → Nominal PP	Lexicon				Prep	PP
VP → book I include I prefer VP → Verb NP	Det → that this a Noun → book flight mea	II money			[4,5]	[4,6]
$VP \rightarrow X2 PP$ $X2 \rightarrow Verb NP$	Pronoun → she me Proper-Noun → Houston	TWA				NNP, NP
$VP \rightarrow Verb NP$ $VP \rightarrow Verb PP$ $VP \rightarrow VP PP$	Aux → does Preposition → from to or	n near through	7			[5,6]
PP → Preposition NP	Verb → book include pre	eter				



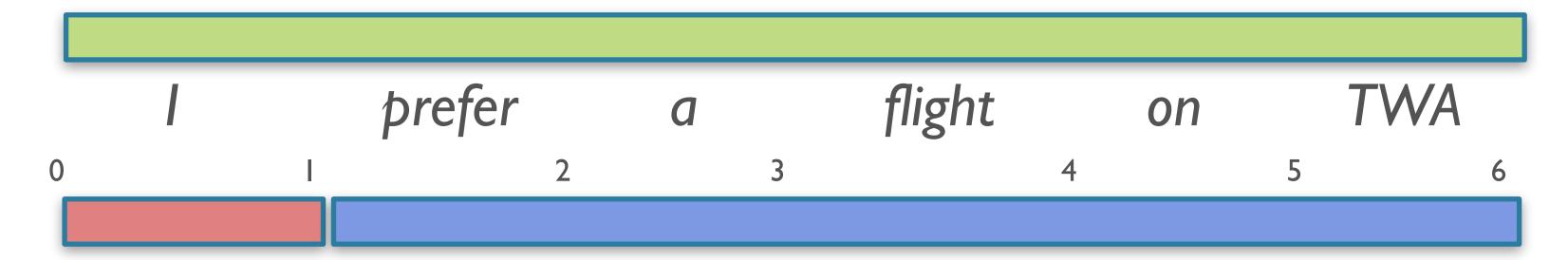
\mathcal{L}_1 Grammar $S \rightarrow NP VP$	NP, Pronoun	S		S		
$S \rightarrow X1 VP$	[0,1]	[0,2]	[0,3]	[0,4]	[0,5]	[0,6]
$X1 \rightarrow Aux NP$		Verb, VP, S		VP, X2, S		VP, X2, S
S → book include prefer						
$S \rightarrow Verb NP$ $S \rightarrow X2 PP$		[1,2]	[1,3]	[1,4]	[1,5]	[1,6]
$S \rightarrow Verb PP$			Det	NP		NP
$S \rightarrow VP PP$						
NP → I I she I me			[2,3]	[2,4]	[2,5]	[2,6]
NP → TWA I Houston				Noun, Nom		Nom
NP → Det Nominal						
Nominal → book flight meal money				[3,4]	[3,5]	[3,6]
Nominal → Nominal Noun	Lexicon			L / L		
Nominal → Nominal PP	Det → that this a				Prep	PP
VP → book I include I prefer	Noun → book flight meal	II monev			[4,5]	Γ4 61
VP → Verb NP	Pronoun → she me	rinoncy			[7,5]	[4,6]
$VP \rightarrow X2 PP$	Proper-Noun → Houston	TWA				NNP, NP
X2 → Verb NP VP → Verb PP	Aux → does					FF /3
$VP \rightarrow VPP$ $VP \rightarrow VPP$	Preposition → from to or	7			[5,6]	
PP → Preposition NP	Verb → book include pre					



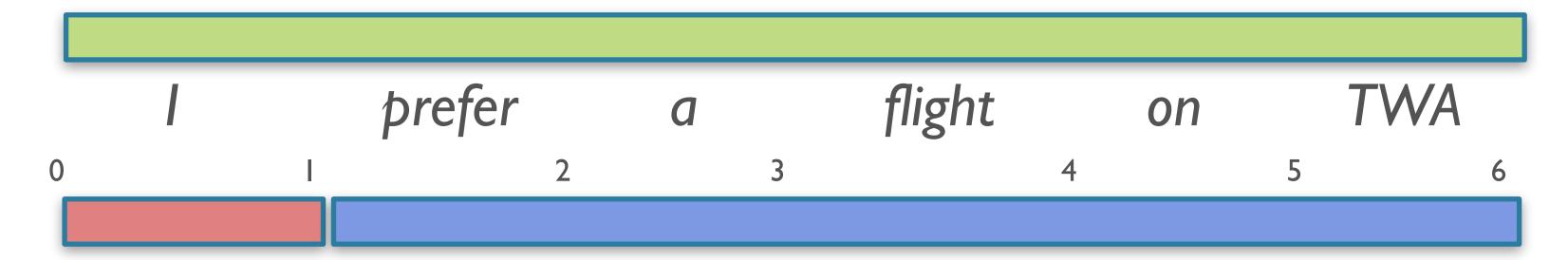
\mathcal{L}_1 Grammar $S \rightarrow NP VP$	NP, Pronoun	S		S		S
$S \rightarrow X1 VP$	[0,1]	[0,2]	[0,3]	[0,4]	[0,5]	[0,6]
$X1 \rightarrow Aux NP$		Verb, VP, S		VP, X2, S		VP, X2, S
S → book I include I prefer S → Verb NP						
$S \rightarrow Verb NP$ $S \rightarrow X2 PP$		[1,2]	[1,3]	[1,4]	[1,5]	[1,6]
$S \rightarrow XZ \cap Y$ $S \rightarrow Verb PP$			Det	NP		NP
$S \rightarrow VPPP$						
NP → I I she I me			[2,3]	[2,4]	[2,5]	[2,6]
NP → TWA Houston				Noun, Nom		Nom
NP → Det Nominal				radui, radii		
Nominal → book flight meal money				[3,4]	[3,5]	[3,6]
Nominal → Nominal Noun	Lexicon			L ' L		
Nominal → Nominal PP	Det → that this a				Prep	PP
VP → book I include I prefer	Noun → book flight meal	II monev			Γ 4 51	Γ <u>4</u>
VP → Verb NP	Pronoun → she me	Tillolicy			[4,5]	[4,6]
$VP \rightarrow X2 PP$	Proper-Noun → Houston	TWA				NNP, NP
X2 → Verb NP VP → Verb PP	Aux → does					FF 43
$VP \rightarrow VPP$ $VP \rightarrow VPP$	Preposition → from to or	n I near I through)			[5,6]
PP → Preposition NP	Verb → book include pre					



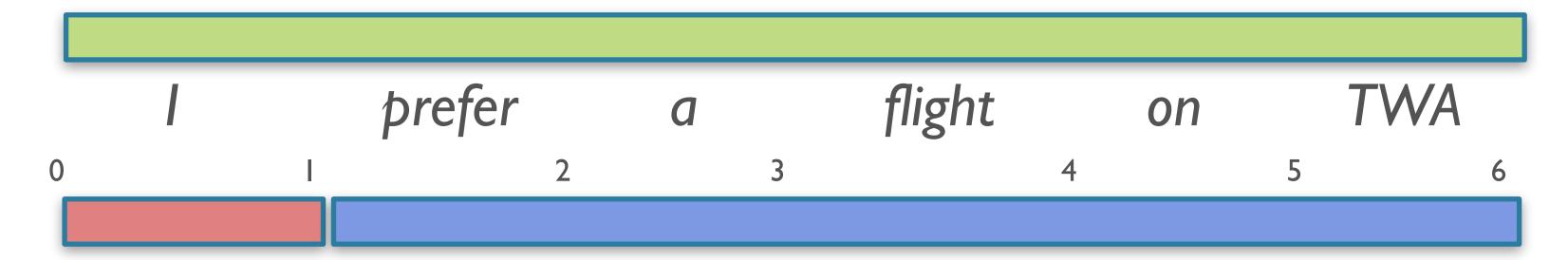
\mathcal{L}_1 Grammar $S \rightarrow NP VP$	NP, Pronoun	S		S		S
$S \rightarrow X1 VP$	[0,1]	[0,2]	[0,3]	[0,4]	[0,5]	[0,6]
$X1 \rightarrow Aux NP$		Verb, VP, S		VP, X2, S		VP, X2, S
S → book include prefer						, , , , , , , , , , , , , , , , , , , ,
$S \rightarrow Verb NP$ $S \rightarrow X2 PP$		[1,2]	[1,3]	[1,4]	[1,5]	[1,6]
$S \rightarrow Verb PP$			Det	NP		NP
$S \rightarrow VP PP$						
NP → I I she I me			[2,3]	[2,4]	[2,5]	[2,6]
NP → TWA I Houston				Noun, Nom		Nom
NP → Det Nominal				ivouii, ivoiii		
Nominal → book flight meal money				[3,4]	[3,5]	[3,6]
Nominal → Nominal Noun	Lexicon			L / J		PP
Nominal → Nominal PP	Det → that this a				Prep	
VP → book I include I prefer	Noun → book flight meal	II monev			[4,5]	[4,6]
$VP \rightarrow Verb NP$ $VP \rightarrow X2 PP$	Pronoun → II she I me				[', 9]	
$X2 \rightarrow X2 PP$ $X2 \rightarrow Verb NP$	Proper-Noun → Houston	TWA				NNP, NP
$VP \rightarrow Verb PP$	Aux → does					Γ 5 6 1
$VP \rightarrow VP PP$	Preposition → from to on near through					[5,6]
PP → Preposition NP	Verb → book include pre	efer				



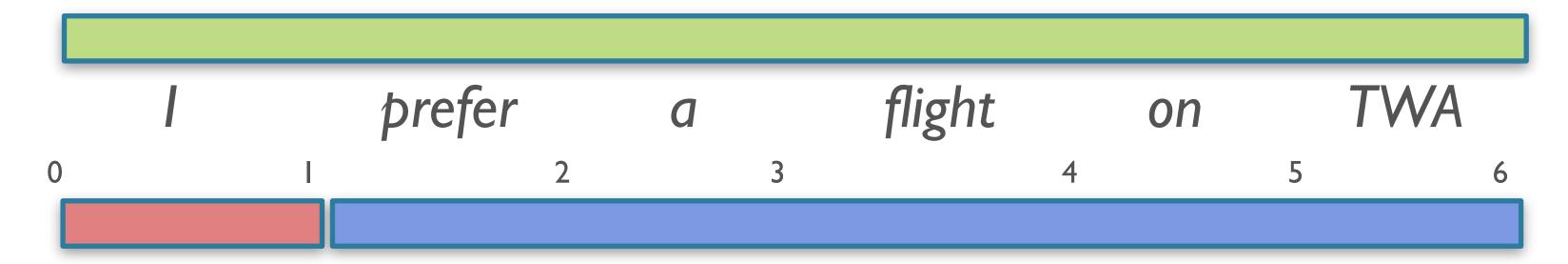
\mathcal{L}_1 Grammar $S \rightarrow NP VP$	NP, Pronoun	S		S		S
$S \rightarrow X1 VP$	[0,1]	[0,2]	[0,3]	[0,4]	[0,5]	[0,6]
$X1 \rightarrow Aux NP$		Verb, VP, S		VP, X2, S		VP, X2, S
S → book I include I prefer S → Verb NP						, , -
$S \rightarrow Verb NP$ $S \rightarrow X2 PP$		[1,2]	[1,3]	[1,4]	[1,5]	[1,6]
$S \rightarrow Verb PP$			Det	NP		NP
$S \rightarrow VP PP$						
NP → I I she I me			[2,3]	[2,4]	[2,5]	[2,6]
NP → TWA Houston				Noun, Nom		Nom
NP → Det Nominal						
Nominal → book flight meal money				[3,4]	[3,5]	[3,6]
Nominal → Nominal Noun Nominal → Nominal PP	Lexicon				Prep	PP
VP → book I include I prefer	Det → that this a					
VP → Verb NP	Noun → book flight mea	II money			[4,5]	[4,6]
$VP \rightarrow X2 PP$	Pronoun → she me					NNP, NP
X2 → Verb NP	Proper-Noun → Houston	TWA				
VP → Verb PP	Aux → does Proposition → from I to I or	al noarl through				[5,6]
$VP \rightarrow VP PP$	Preposition → from to or Verb → book include pre		I			
PP → Preposition NP	verb book i iliciade i pre	101				



\mathcal{L}_1 Grammar $S \rightarrow NP VP$	NP, Pronoun	S		S		S
$S \rightarrow X1 VP$	[0,1]	[0,2]	[0,3]	[0,4]	[0,5]	[0,6]
$X1 \rightarrow Aux NP$		Verb, VP, S		VP, X2, S		VP, X2, S
S → book I include I prefer						, , , , , , , , , , , , , , , , , , , ,
$S \rightarrow Verb NP$ $S \rightarrow X2 PP$		[1,2]	[1,3]	[1,4]	[1,5]	[1,6]
$S \rightarrow Verb PP$			Det	NP		NP
$S \rightarrow VPPP$						
NP → I I she I me			[2,3]	[2,4]	[2,5]	[2,6]
NP → TWA Houston				Noun, Nom		Nom
NP → Det Nominal						
Nominal → book flight meal money				[3,4]	[3,5]	[3,6]
Nominal → Nominal Noun	Lexicon				Prep	PP
Nominal → Nominal PP	Det → that this a				ПСР	
VP → book I include I prefer VP → Verb NP	Noun → book flight meal	II money			[4,5]	[4,6]
$VP \rightarrow X2 PP$	Pronoun → II she I me	-			-	NNP, NP
$X2 \rightarrow Verb NP$	Proper-Noun → Houston	TWA				MINIT, INI
VP → Verb PP	Aux → does					[5,6]
$VP \rightarrow VP PP$	Preposition → from to or		7			L / J
PP → Preposition NP	Verb → book include pre	eier				



\mathcal{L}_1 Grammar $S \rightarrow NP VP$	NP, Pronoun	S		S		S
$S \rightarrow X1 VP$	[0,1]	[0,2]	[0,3]	[0,4]	[0,5]	[0,6]
$X1 \rightarrow Aux NP$		Verb, VP, S		VP, X2, S		VP, X2, S
S → book include prefer				, , , , , , , , , , , , , , , , , , , ,		, , , , , , , , , , , , , , , , , , , ,
$S \rightarrow Verb NP$ $S \rightarrow X2 PP$		[1,2]	[1,3]	[1,4]	[1,5]	[1,6]
$S \rightarrow Verb PP$			Det	NP		NP
$S \rightarrow VP PP$						
NP → I she me			[2,3]	[2,4]	[2,5]	[2,6]
NP → TWA Houston				Noun, Nom		Nom
NP → Det Nominal						
Nominal → book flight meal money				[3,4]	[3,5]	[3,6]
Nominal → Nominal Noun	Lexicon				Prep	PP
Nominal → Nominal PP	Det → that this a				ПСР	
VP → book I include I prefer VP → Verb NP	Noun → book flight meal	II money			[4,5]	[4,6]
$VP \rightarrow X2 PP$	Pronoun → II she I me	-				NNP, NP
X2 → Verb NP	Proper-Noun → Houston	TWA				ididi, idi
VP → Verb PP	Aux → does					[5,6]
$VP \rightarrow VP PP$	Preposition → from to or		1			
PP → Preposition NP	Verb → book include pre	HEI				



Current CKY Algorithm

Limitations:

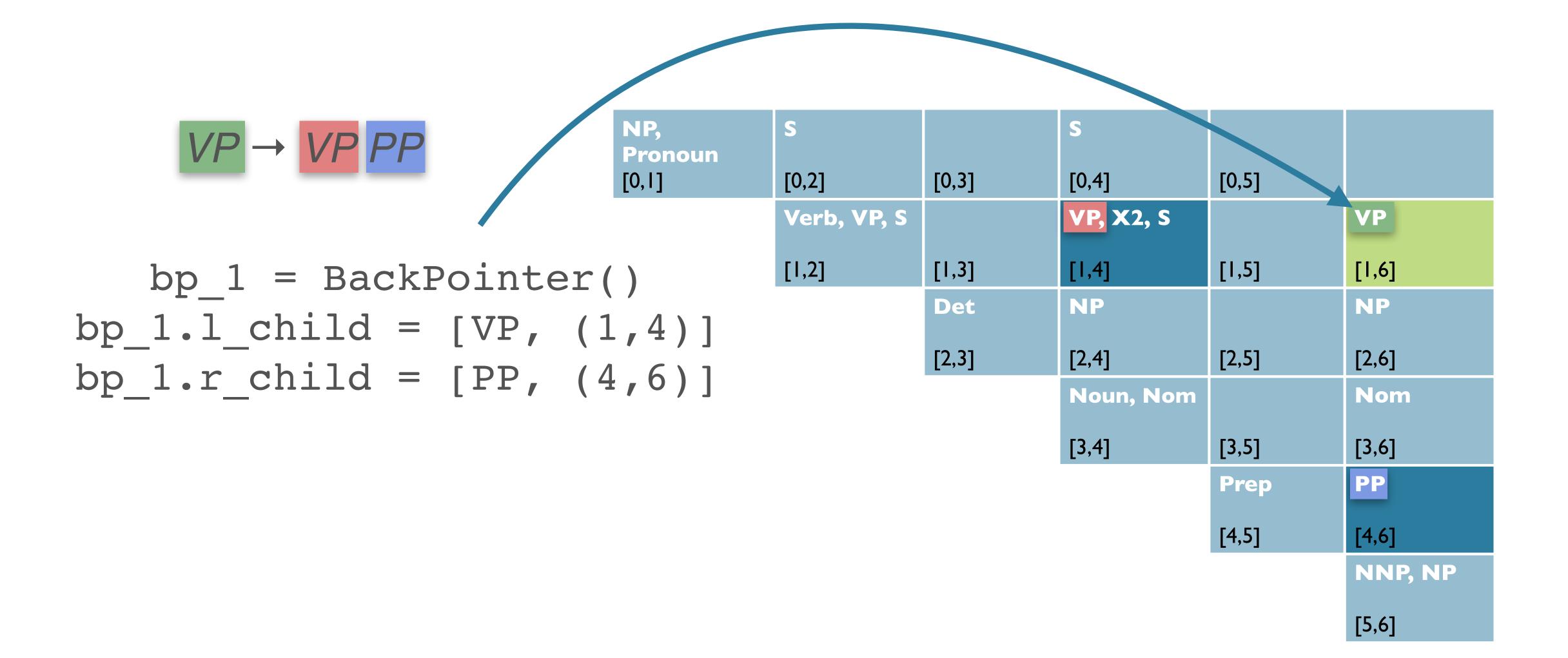
Only stores non-terminals in cell Not rules or cells corresponding to RHS Stores SETS of non-terminals Multiple rules with same LHS collide

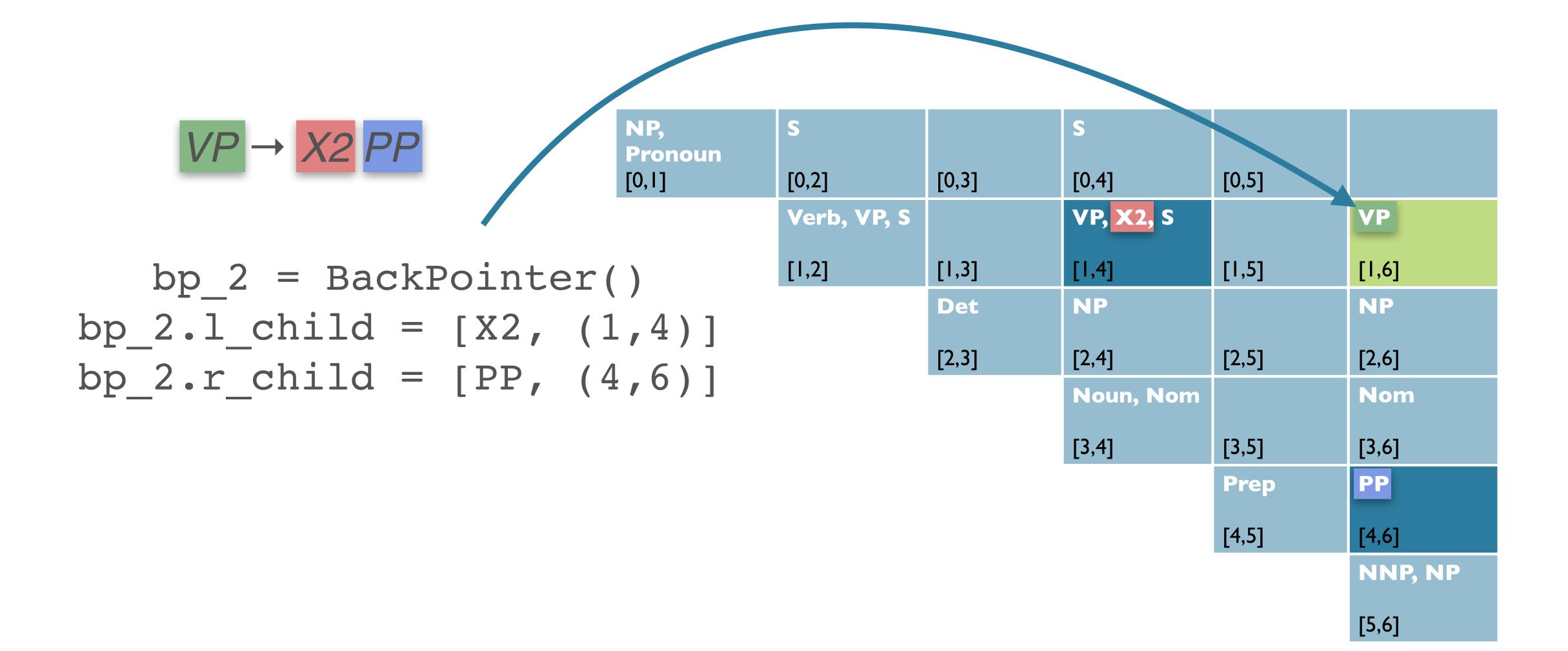
Currently only acceptance/recognition

CKY Parser

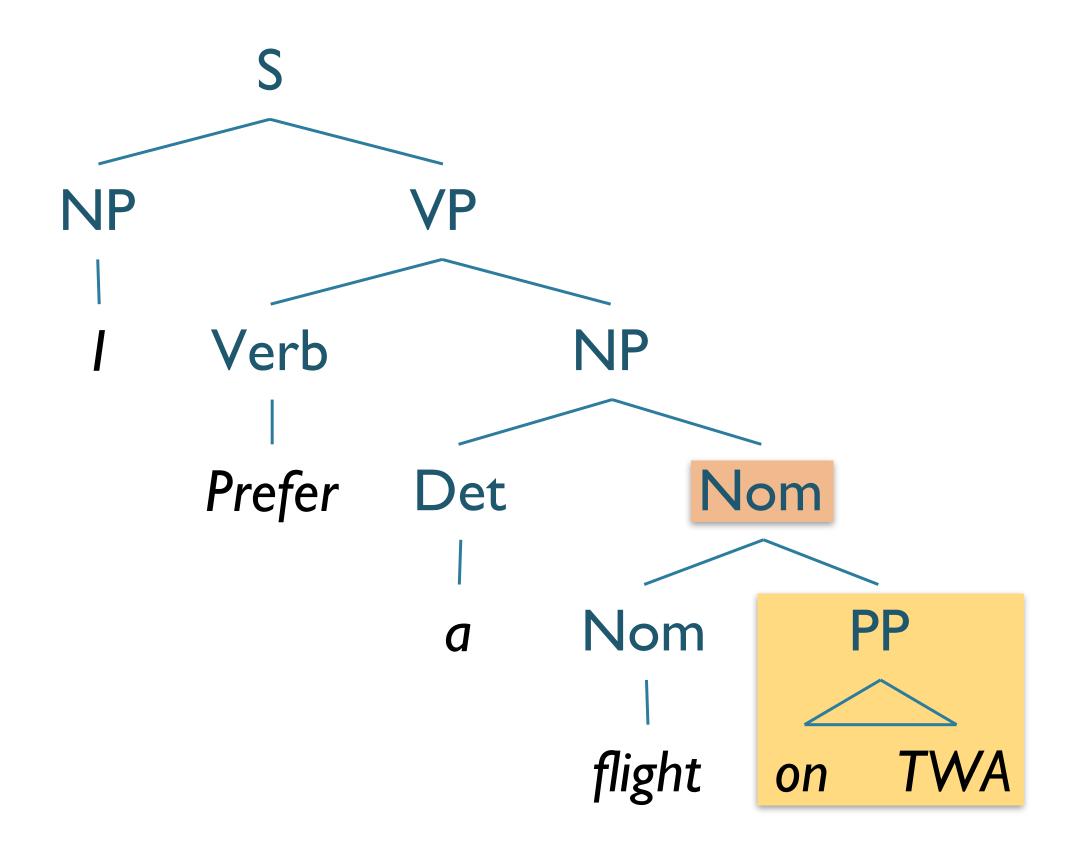
- Pair each nonterminal with back-pointer to cells from which it was derived
- Last step:
 - construct trees from back-pointers in [0, n]

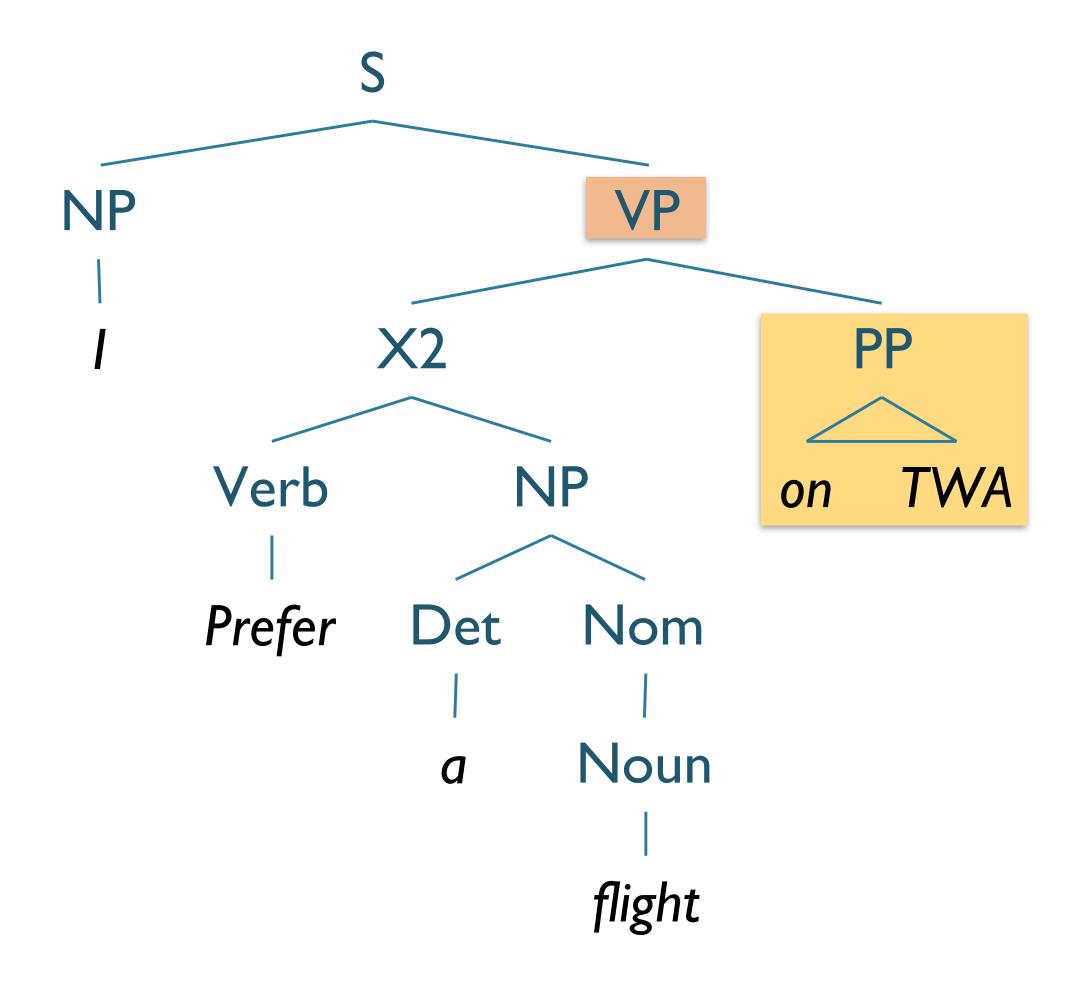
NP,	S		S		
Pronoun [0,1]	[0,2]	[0,3]	[0,4]	[0,5]	
	Verb, VP, S		VP, X2, S		VP
	[1,2]	[1,3]	[1,4]	[1,5]	[1,6]
		Det	NP		NP
		[2,3]	[2,4]	[2,5]	[2,6]
			Noun, Nom		Nom
			[3,4]	[3,5]	[3,6]
				Prep	PP
				[4,5]	[4,6]
					NNP, NP
					[5,6]





Resulting Parses





CKY Discussion

Running time:

 $O(n^3)$ where *n* is the length of the input string Inner loop grows as square of # of non-terminals

Expressiveness:

As implemented, requires CNF

Weak equivalence to original grammar

Doesn't capture full original structure

Back-conversion?

Can do binarization, terminal conversion

Unit productions requires change in CKY