CKY Parsing

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

Announcements

- HW1 grades posted
- 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!
- check_hwX.sh:
 - Unzips tar.gz file and checks its contents against submit-file-list
 - Best practice to do this before submitting!

Seattle/Sealth/Si'ahl



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 - si?at ['si?ax4]
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- IPA resources:
 - https://en.wikipedia.org/wiki/International_Phonetic_Alphabet
 - http://web.mit.edu/6.mitx/www/24.900%20IPA/IPAapp.html



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- <u>Lushootseed</u> exhibits debatable distinction between verbs and nouns [link to Glottolog page for more references]
 - ?uxw ti sbiaw
 goes that-which is-a-coyote
 "The/a coyote goes"
 - sbiaw ti ?uxw is-a-coyote that-which goes "The one who goes is a coyote"
 - (Translation distinction provided for clarity semantically equivalent)

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via Beck, 2013

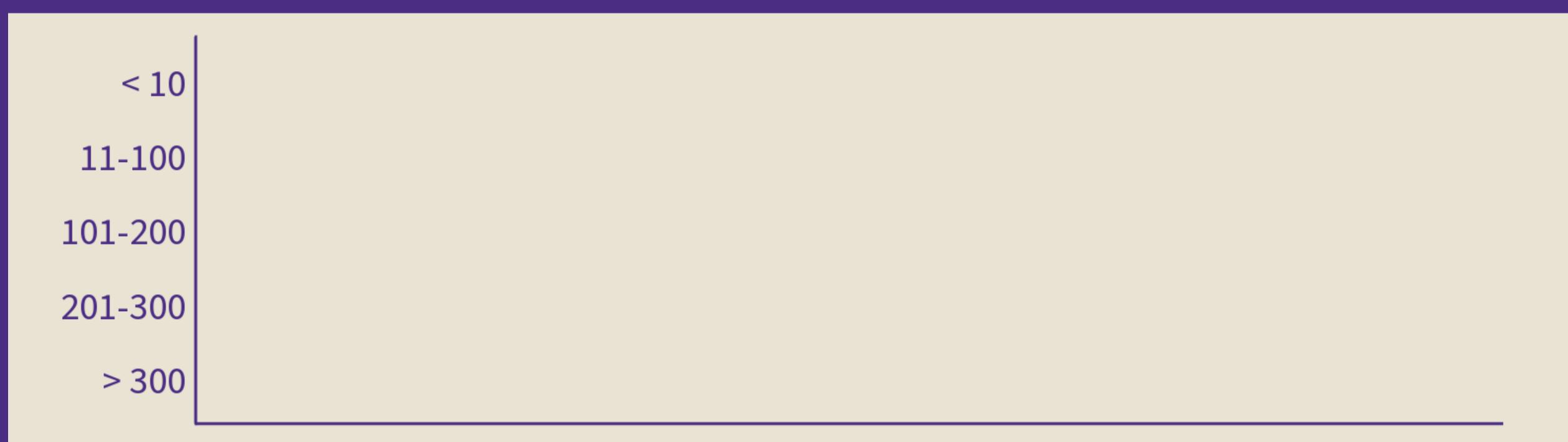
- sbiaw ti ?uxw
 is-a-coyote that-which goes
 "The one who goes is a coyote"
- (Translation distinction provided for clarity semantically equivalent)
- Lillooet Salish quantification has repercussions for e.g. English (Matthewson 2001)



Can you name any other languages indigenous to the Americas?



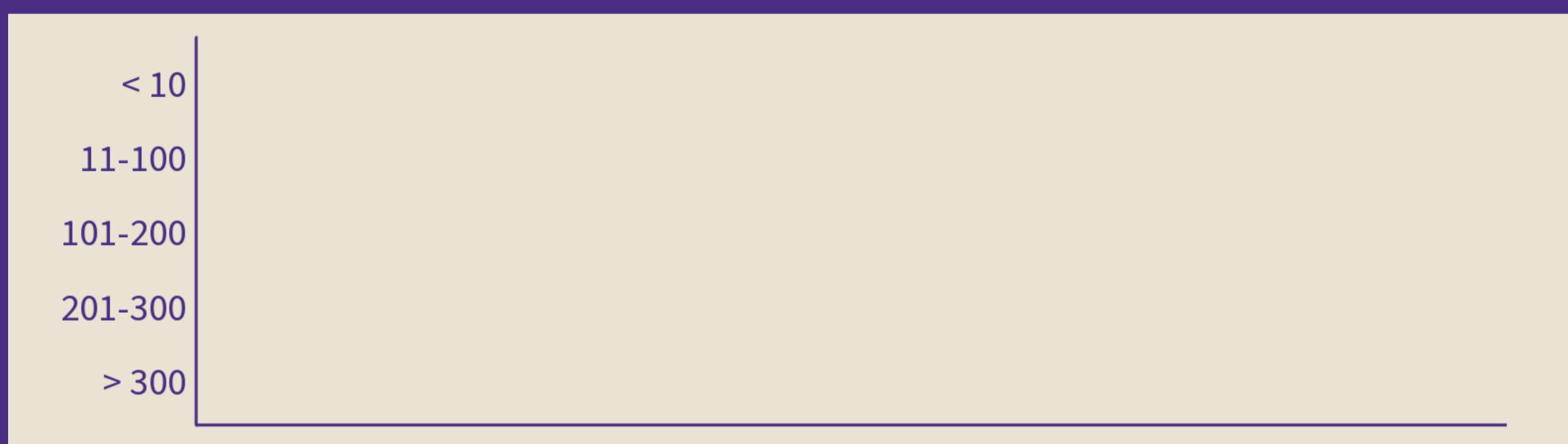
W How many indigenous languages do you think there are in the US today?



Total Results: 0



How many languages do you think were spoken in the now-US at the time Europeans arrived?

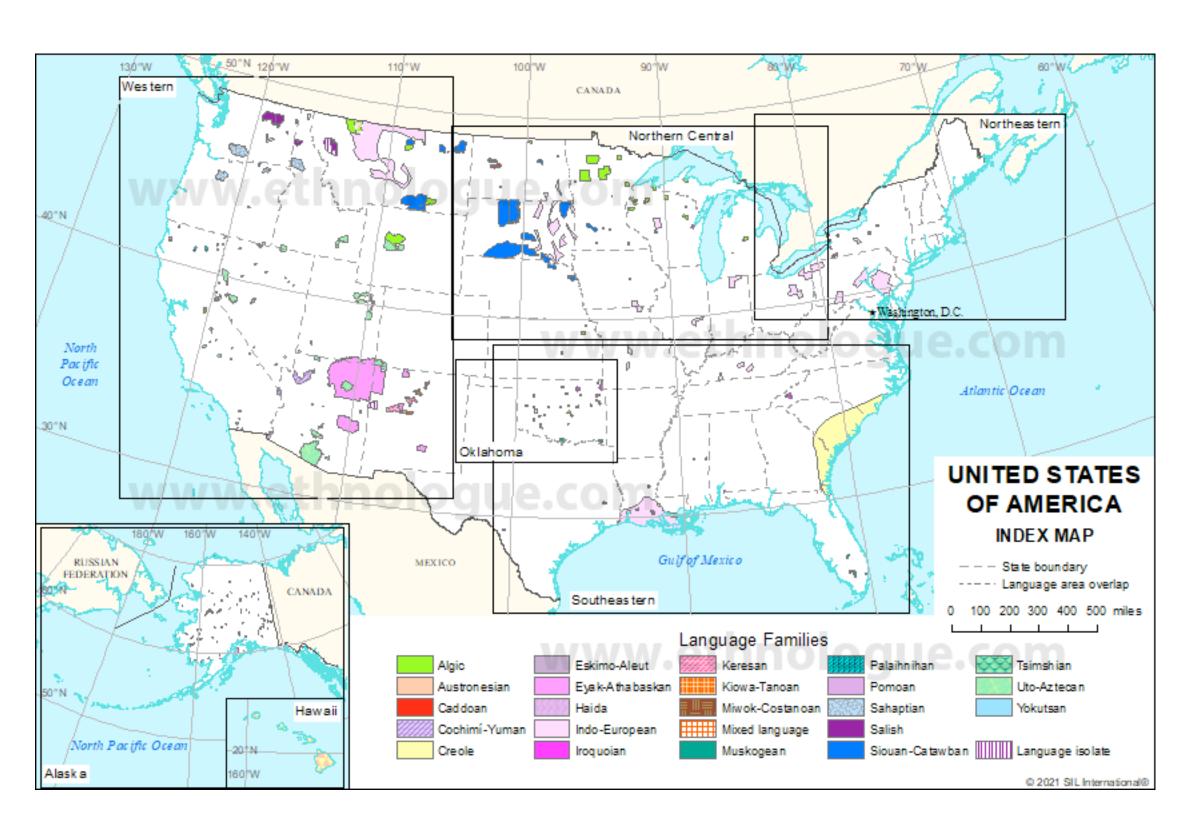


Total Results: 0



Languages in the U.S.

- Current estimate (Ethnologue): 238
 - 226 living, 12 extinct
 - 195 indigenous
- Navajo: ~170,000 speakers
 - Not in U.S. top 25 by pop size
- Many, many endangered; increased need for revitalization efforts



https://www.ethnologue.com/map/US_x_

Indigenous Peoples' Day: Resources

- UW American Indian Studies Courses
 - (Sometimes including language courses, e.g. Southern Lushootseed, Salish)
- Lushootseed resources: https://tulaliplushootseed.com/
- Computational Methods in the Study of Endangered Languages: https://computel-workshop.org/
- AmericasNLP: http://turing.iimas.unam.mx/americasnlp/index.html
 - 2021: https://aclanthology.org/volumes/2021.americasnlp-1/
 - 2022 shared task: https://github.com/AmericasNLP/americasnlp2022

Roadmap

- CKY Parsing Algorithm
 - Dynamic programming structure
 - Algorithm and example
 - **Analysis & Discussion**

- Next time: Probabilistic CFGs
 - Motivation: Ambiguity
 - Augmenting CFGs with probabilities

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- Build table $(n + 1) \times (n + 1)$

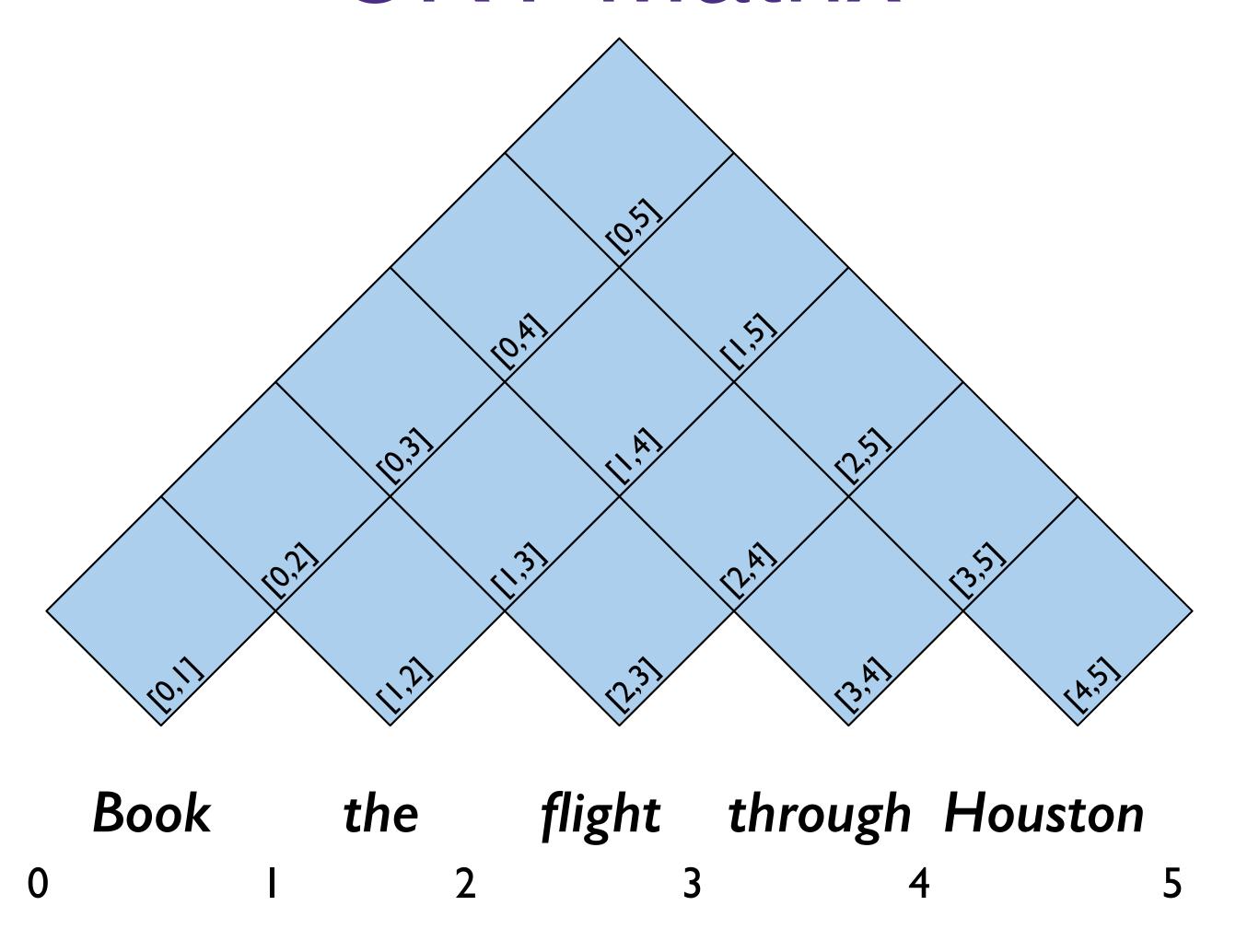
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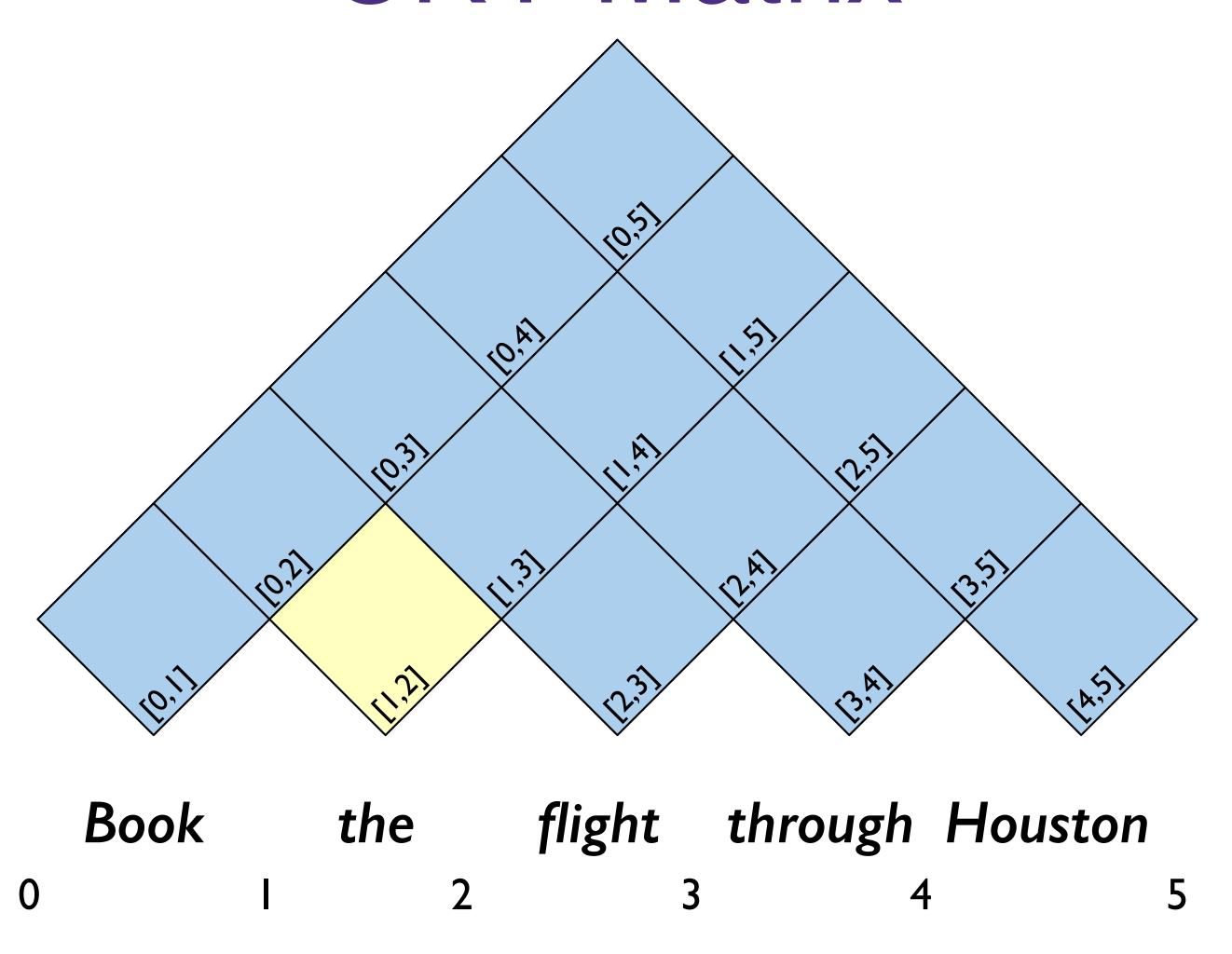
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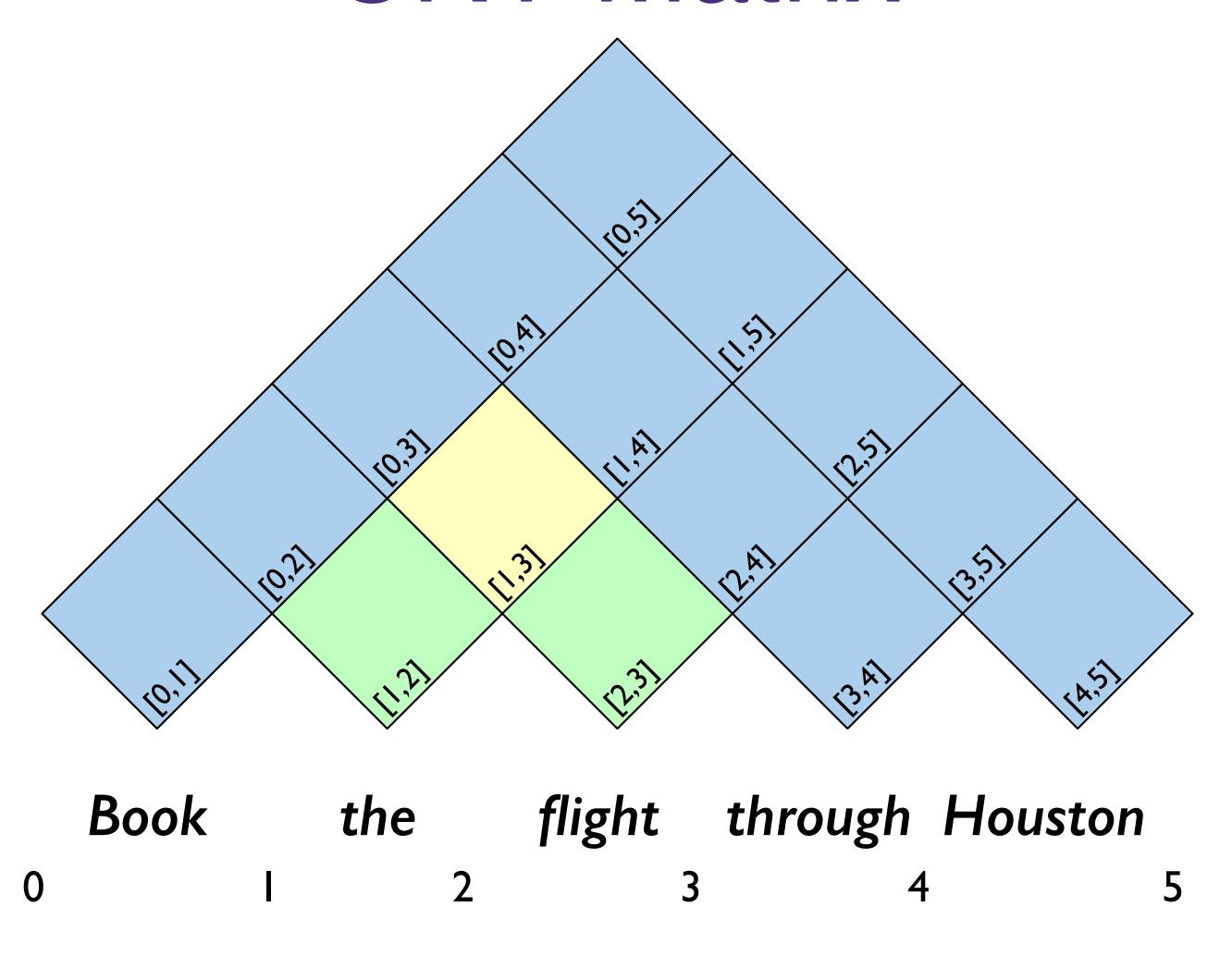
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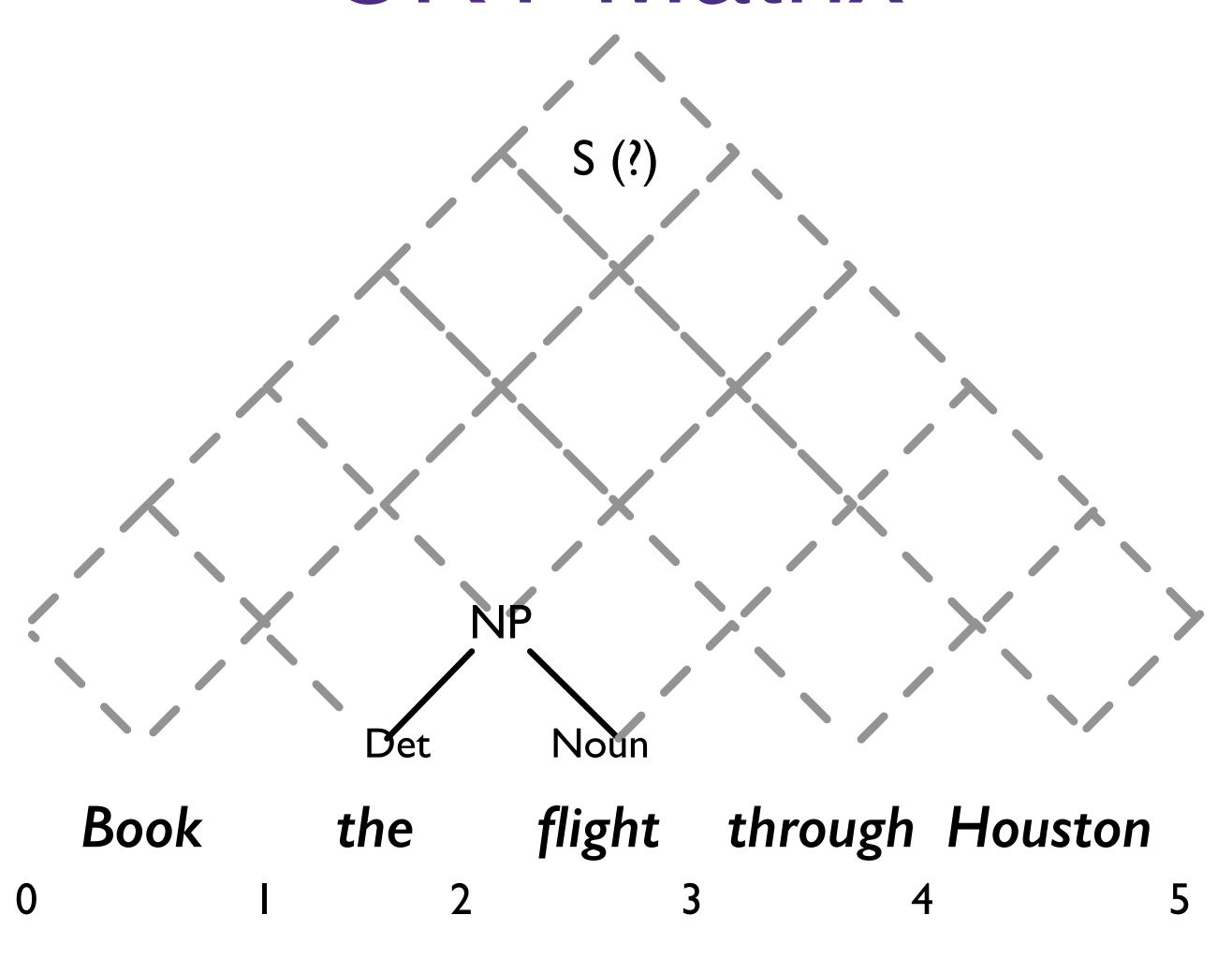
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- Each cell [i,j] contains SETS $\{\}$ of non-terminals with derivations spanning i,j
 - [j-1,j] contains pre-terminals
 - if [0, n] contains the start symbol, the sentence is *accepted*

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]







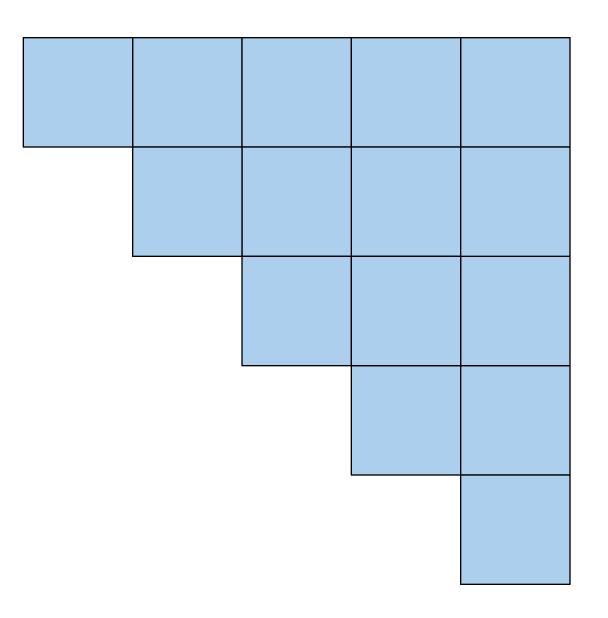


Dynamic Programming in CKY

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

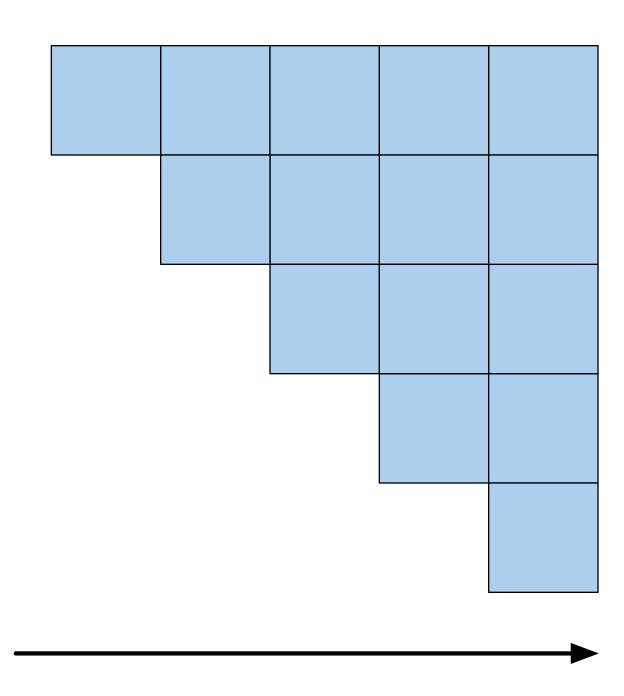


Table fills:



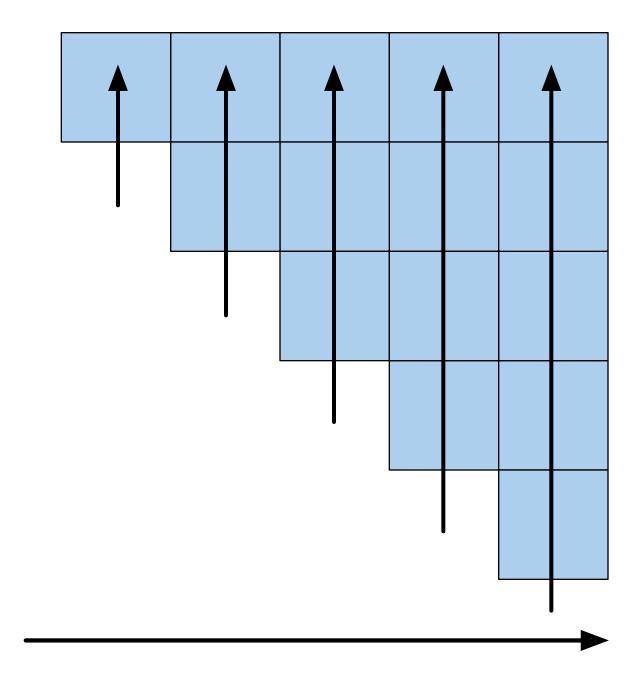


- Table fills:
 - Column-by-column, left-to-right



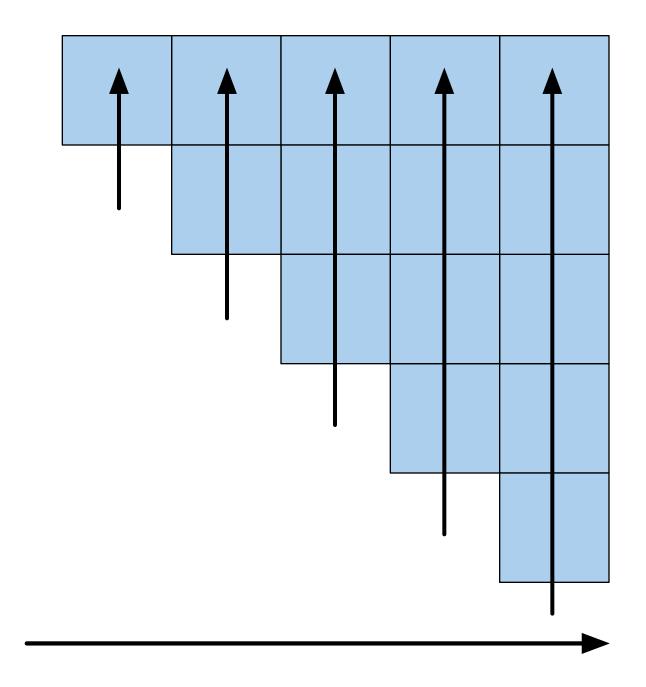


- Table fills:
 - Column-by-column, left-to-right
 - bottom-to-top

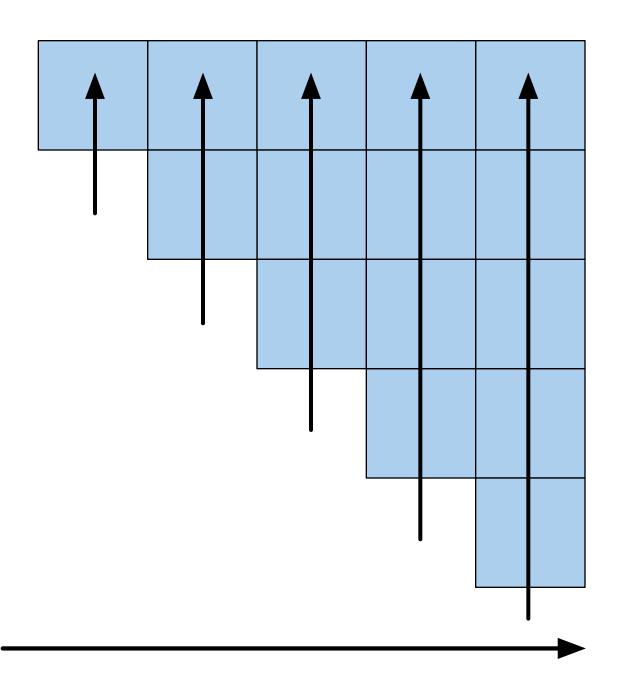




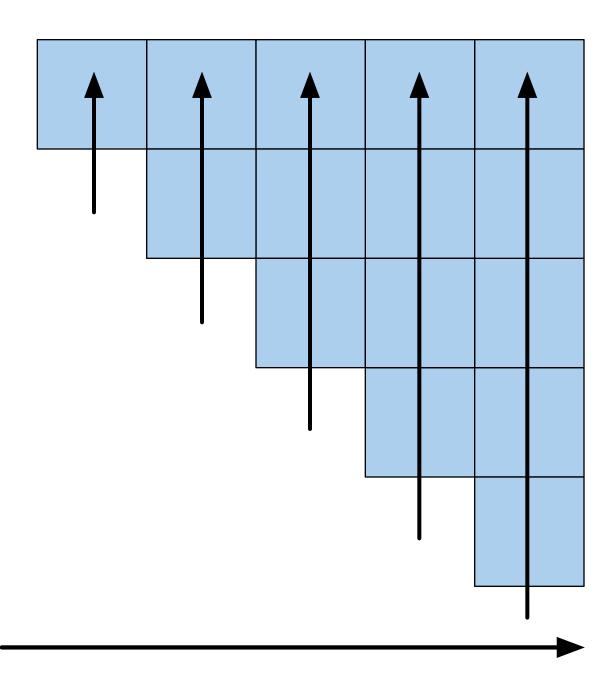
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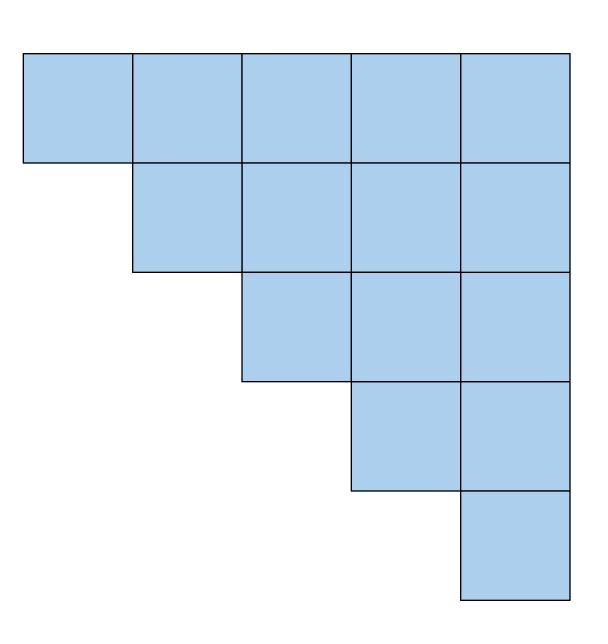


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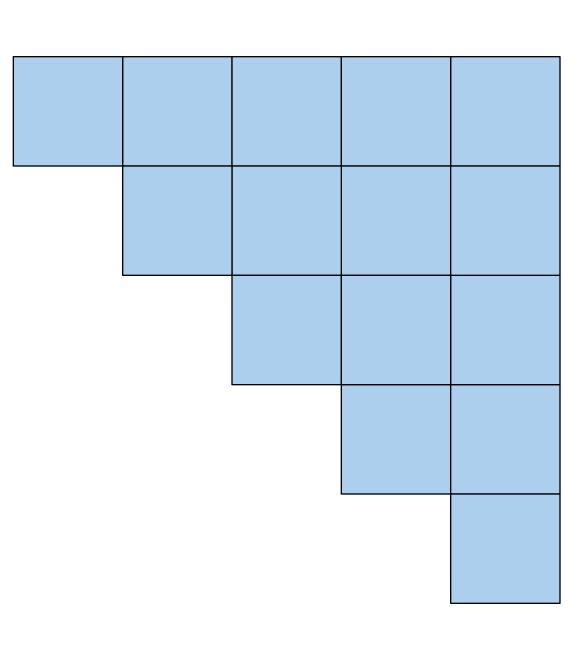
CKY

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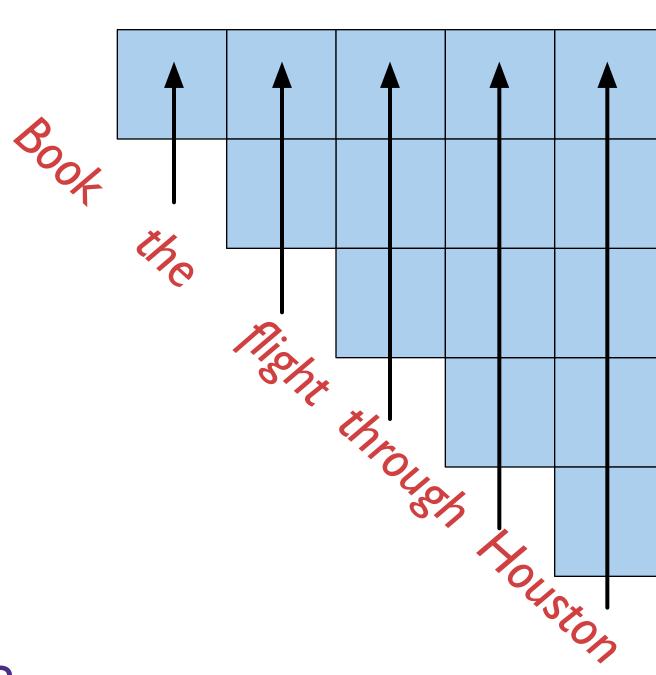
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function CKY-PARSE(words, grammar) returns table
for j \leftarrow from 1 to LENGTH(words) do
 table[\ j-1,\ j\ ] \leftarrow \{\ A\ |\ A \rightarrow words[\ j\ ] \in grammar\ \}
 for i \leftarrow from j-2 downto 0 do
 for k \leftarrow i+1 to j-1 do
 table[\ i,\ j\ ] \leftarrow table[\ i,\ j\ ] \cup
 \{A\ |\ A \rightarrow BC \in grammar\ B \in table[\ i,\ k\ ],\ C \in table[\ k,\ j\ ]\}
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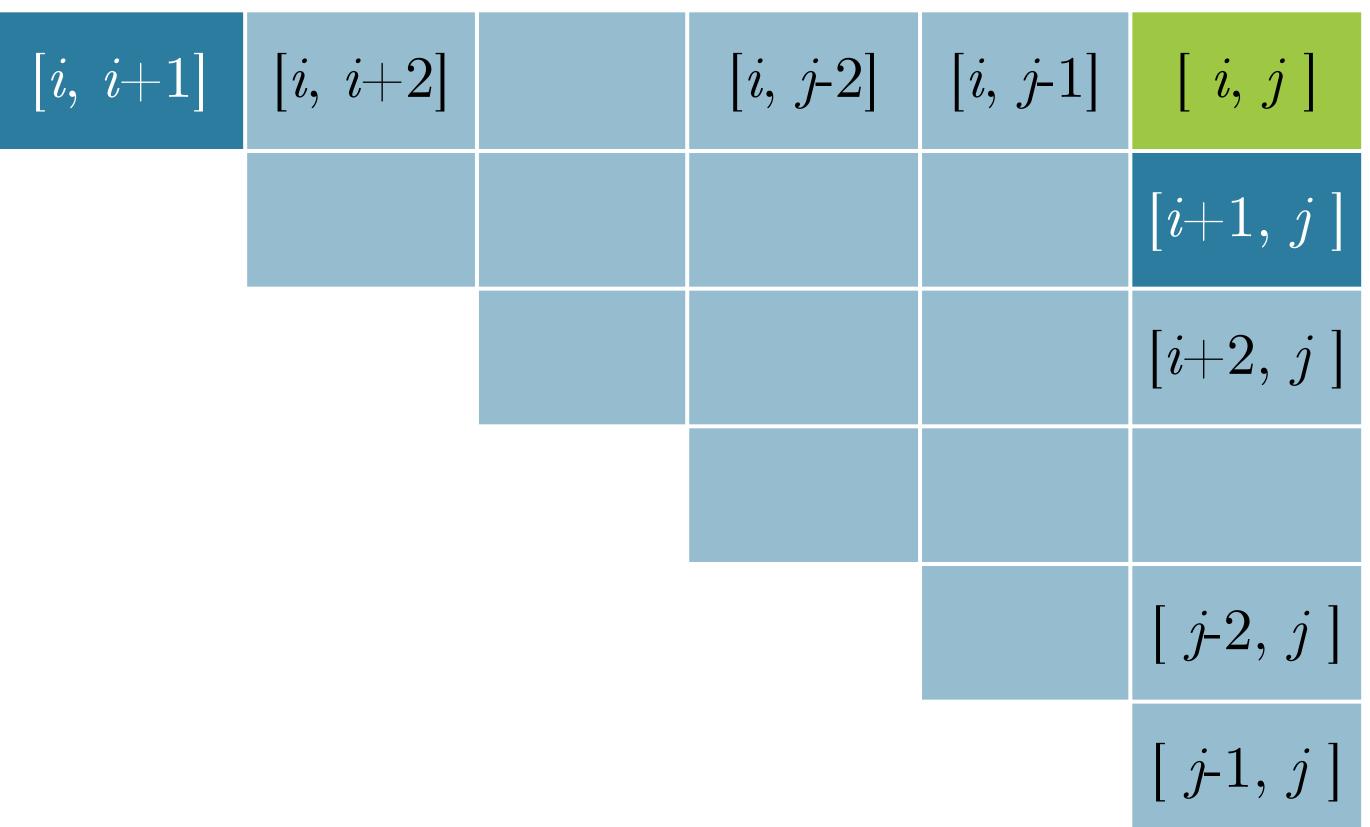
Left-to-right, bottom-to-top

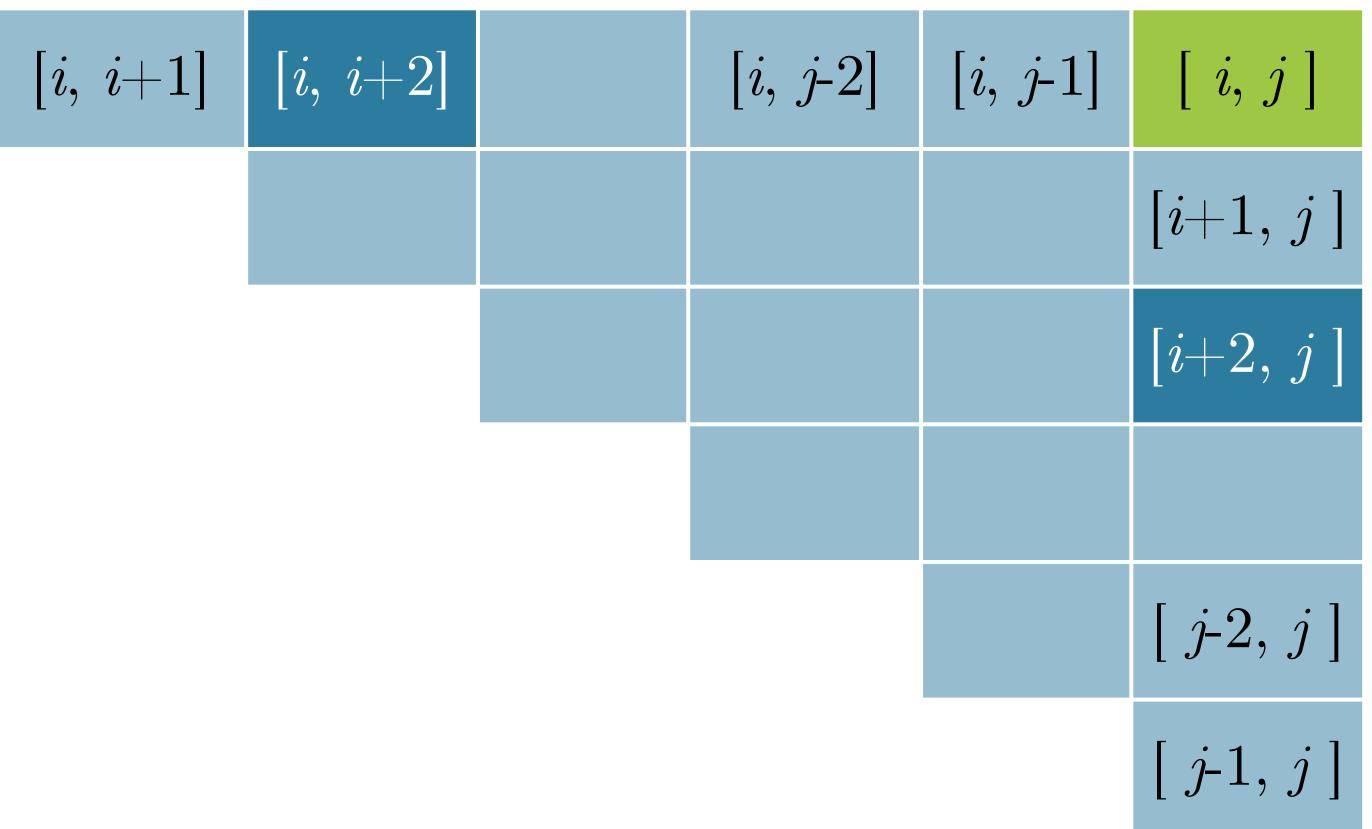
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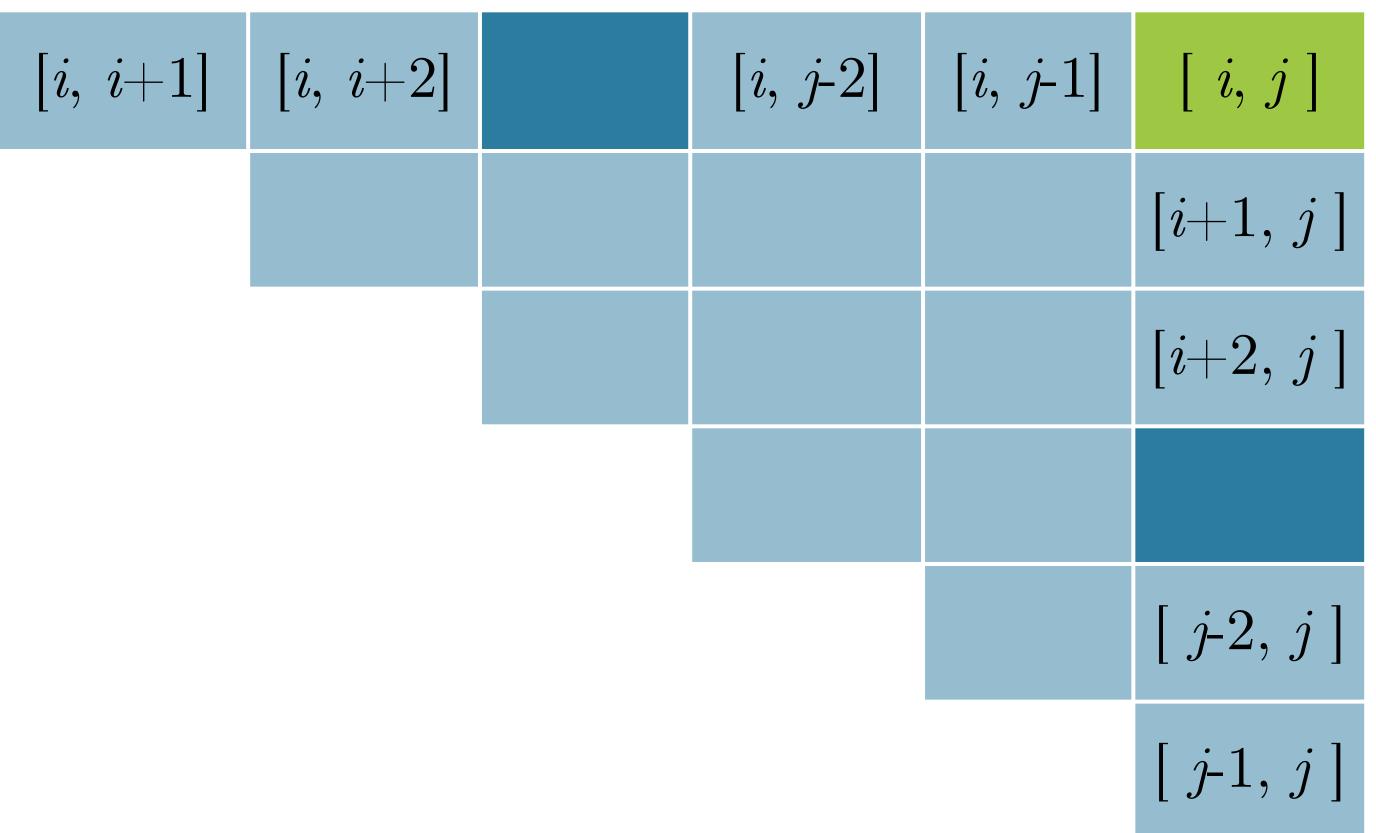
Left-to-right, bottom-to-top
Sliding k as the pivot for child nodes

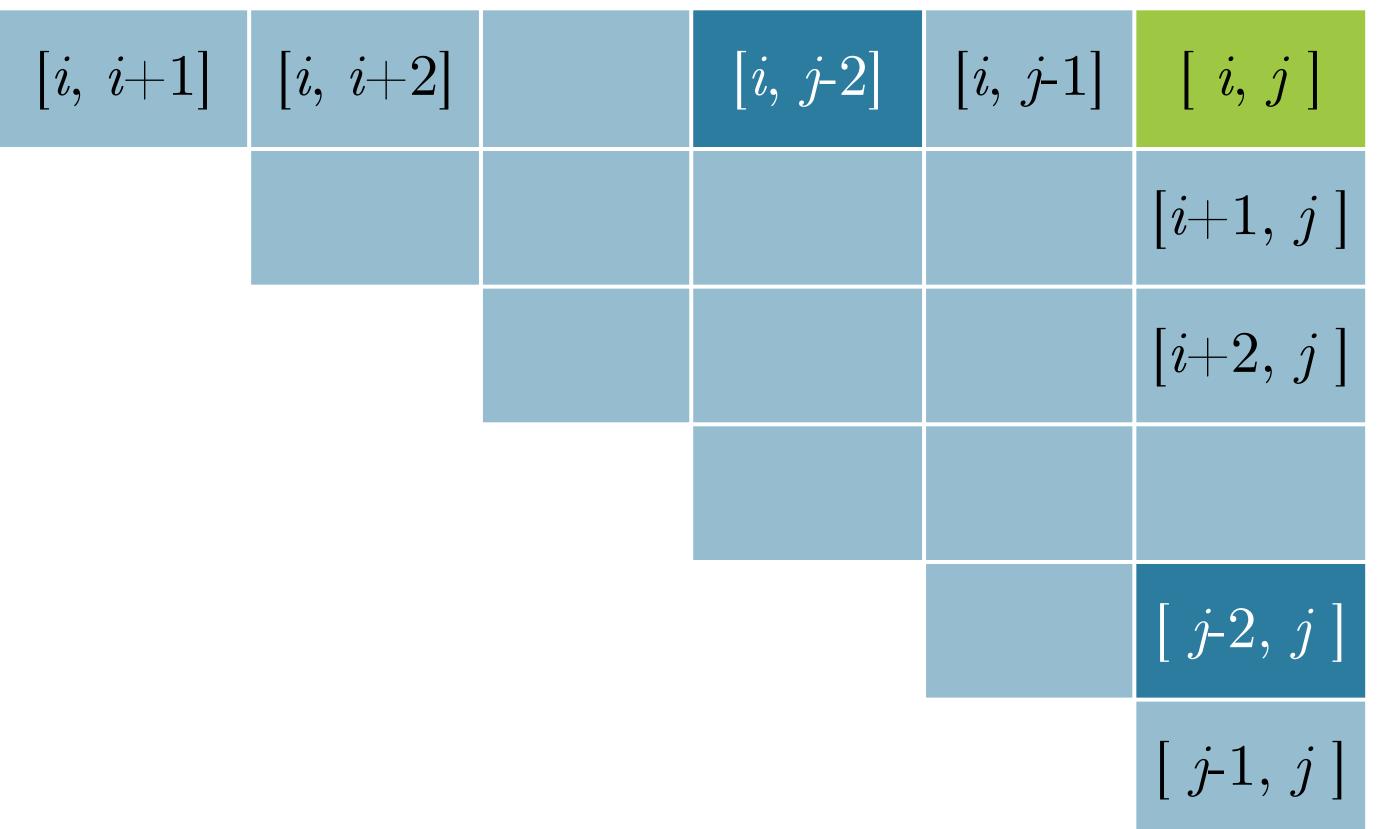
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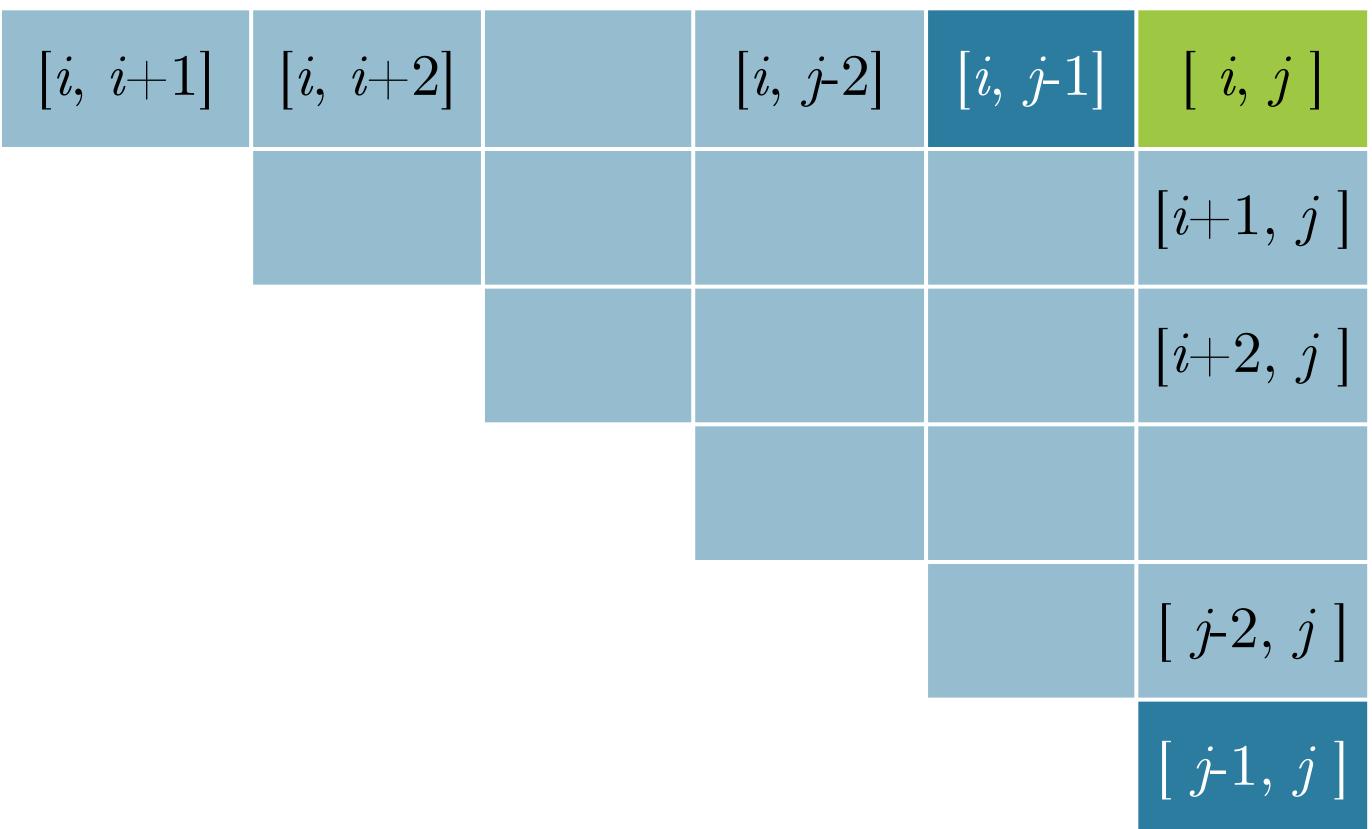
Left-to-right, bottom-to-top
Sliding k as the pivot for child nodes
Filling the cell with set of applicable rules

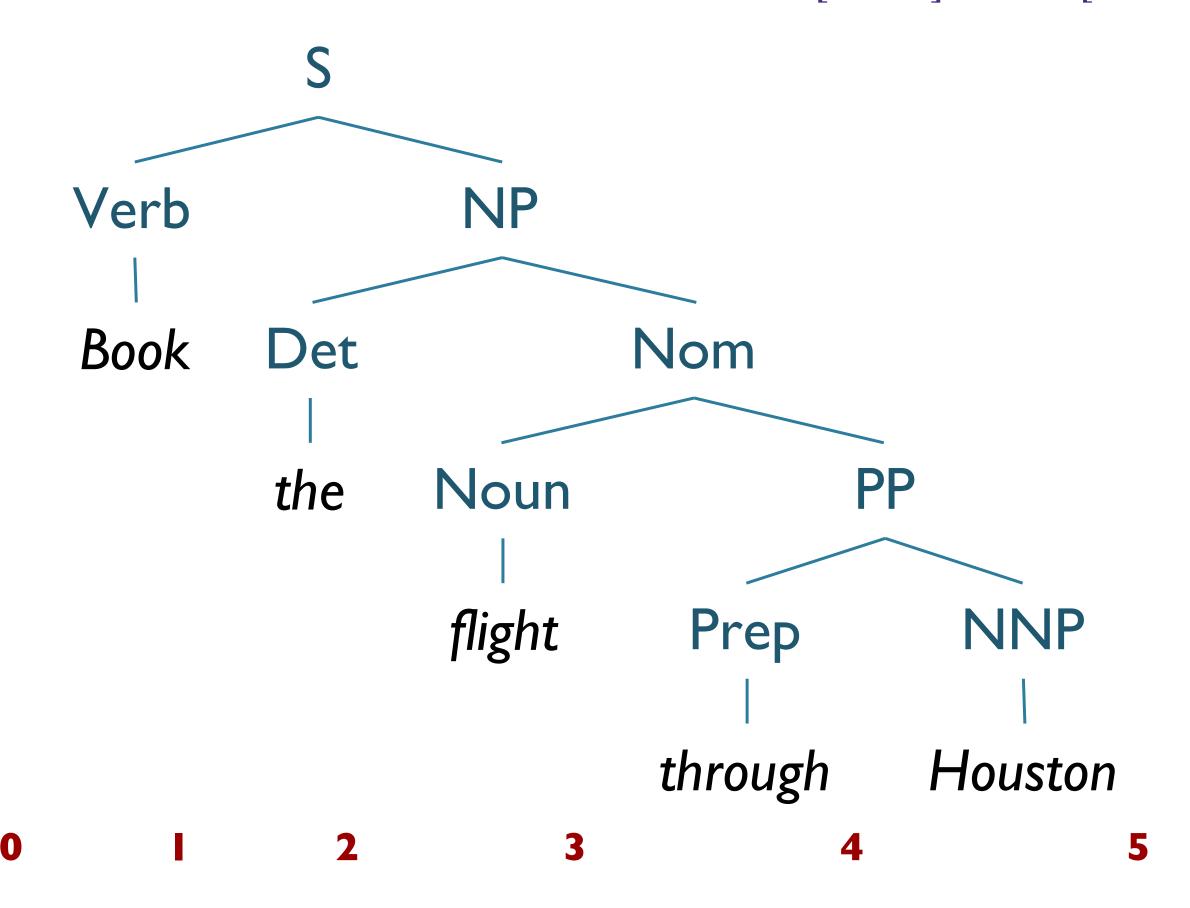


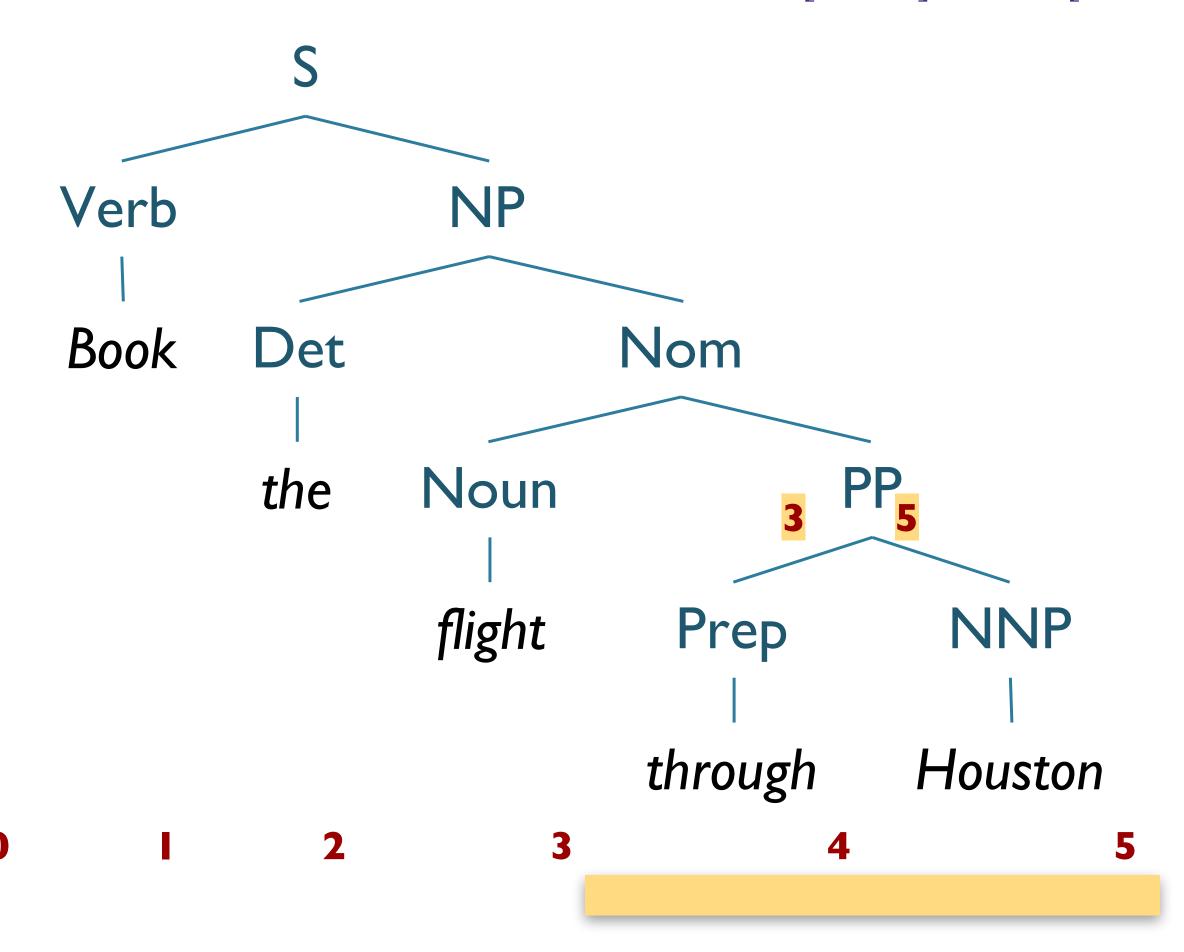


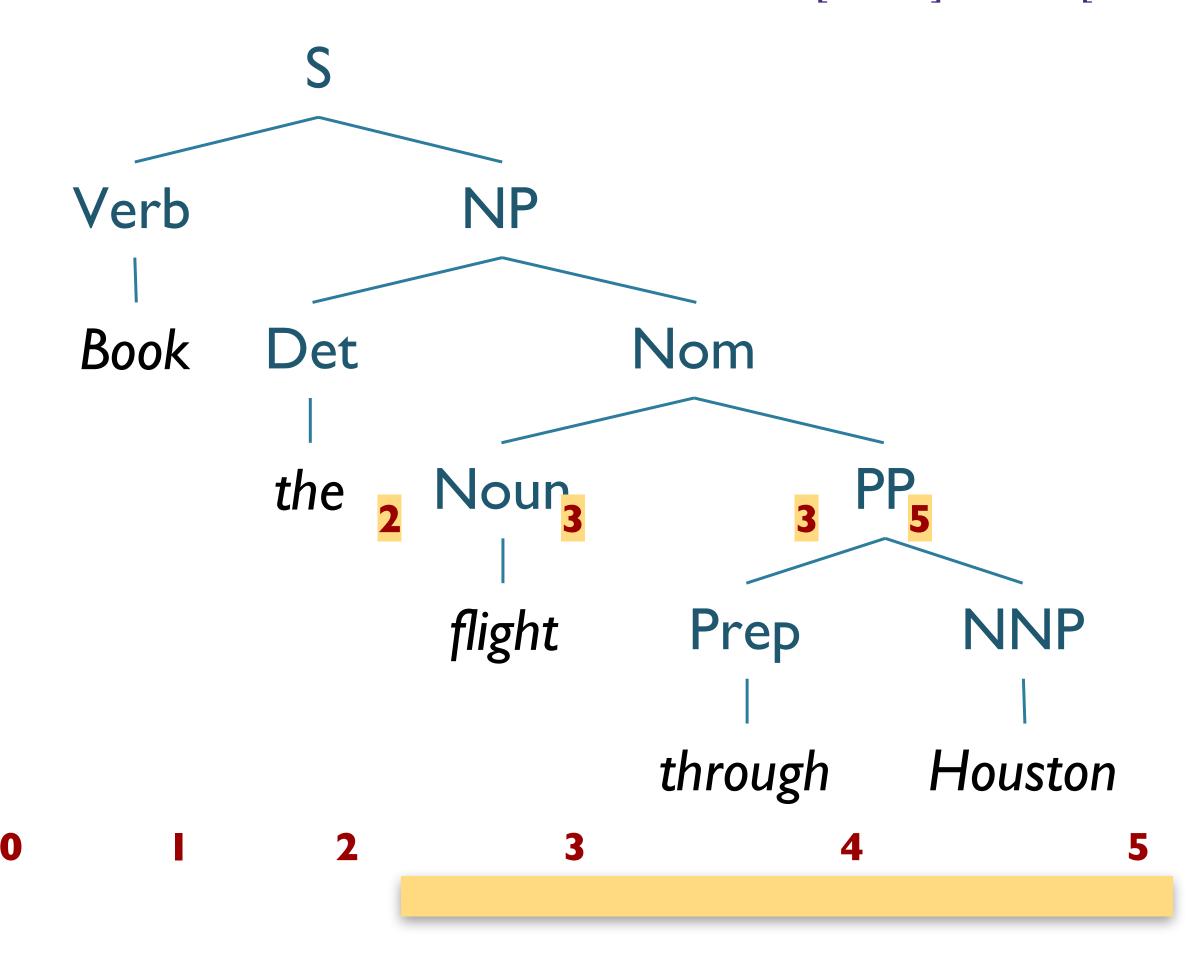


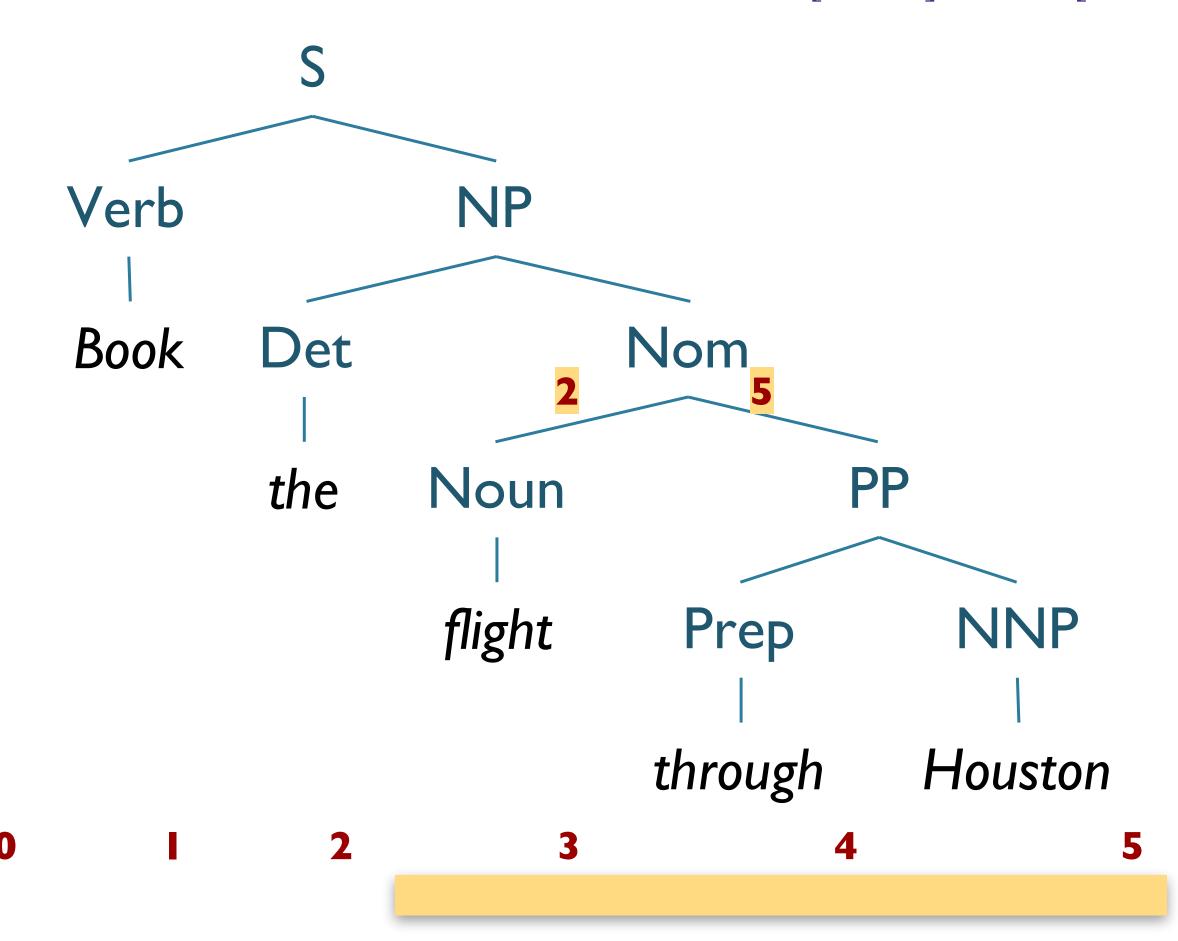


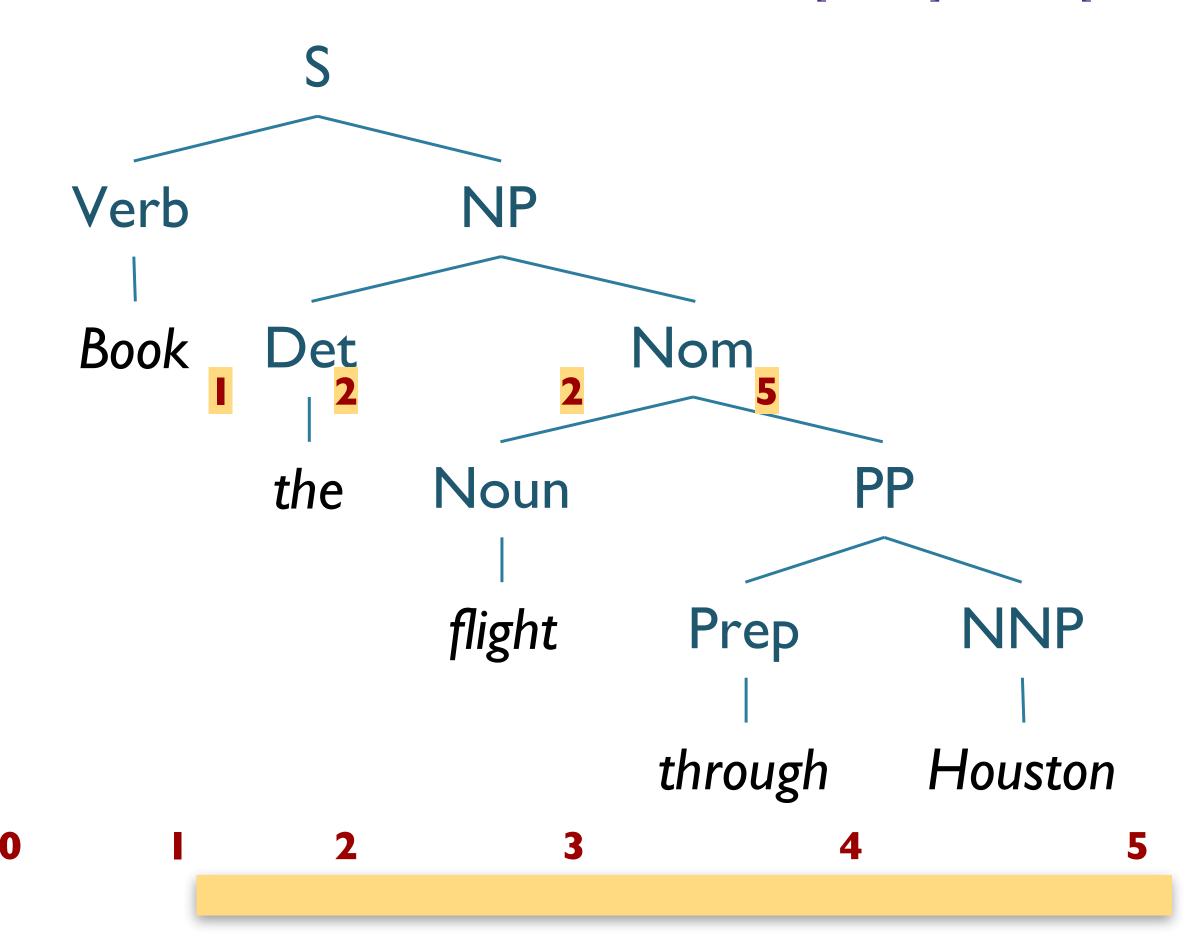


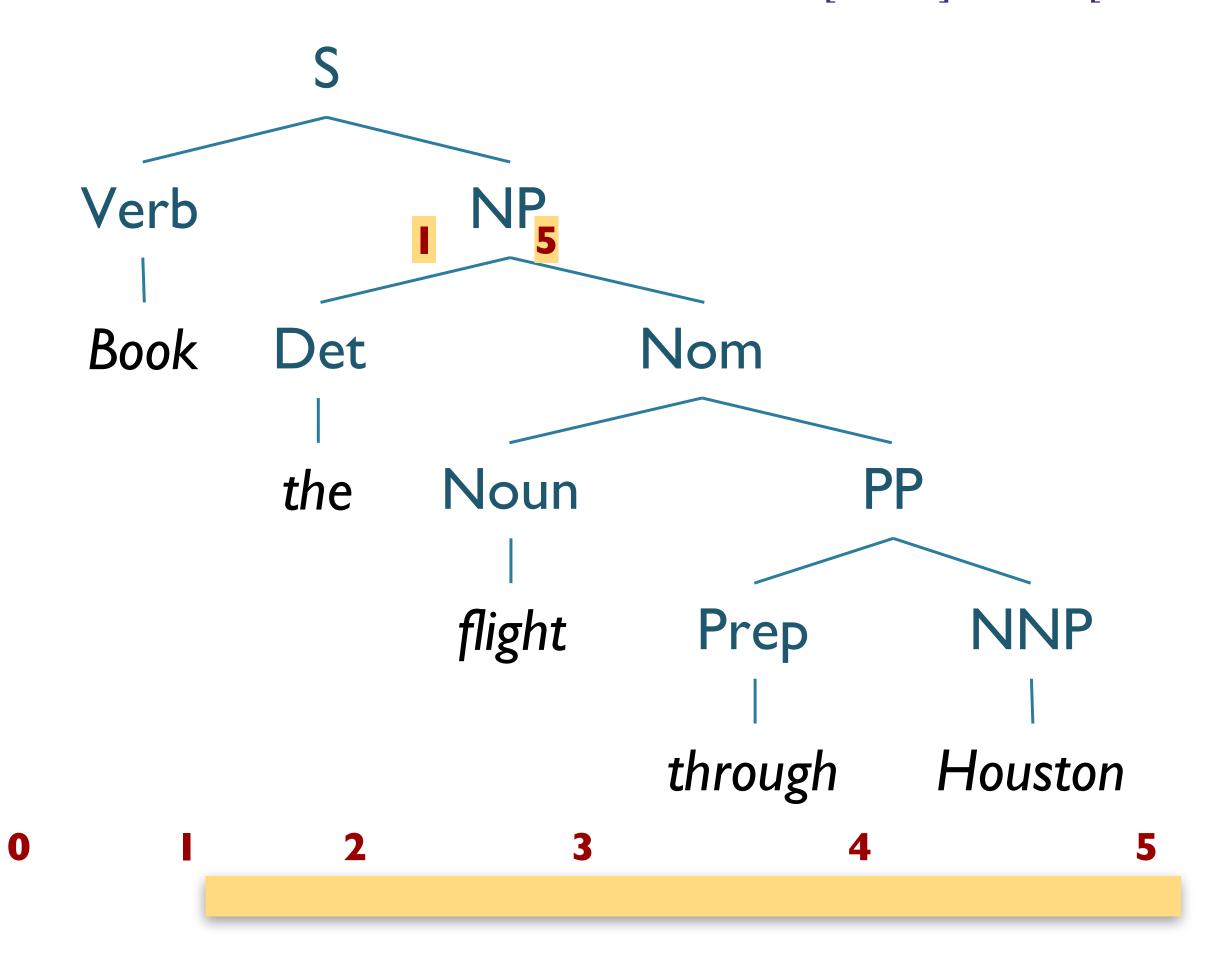


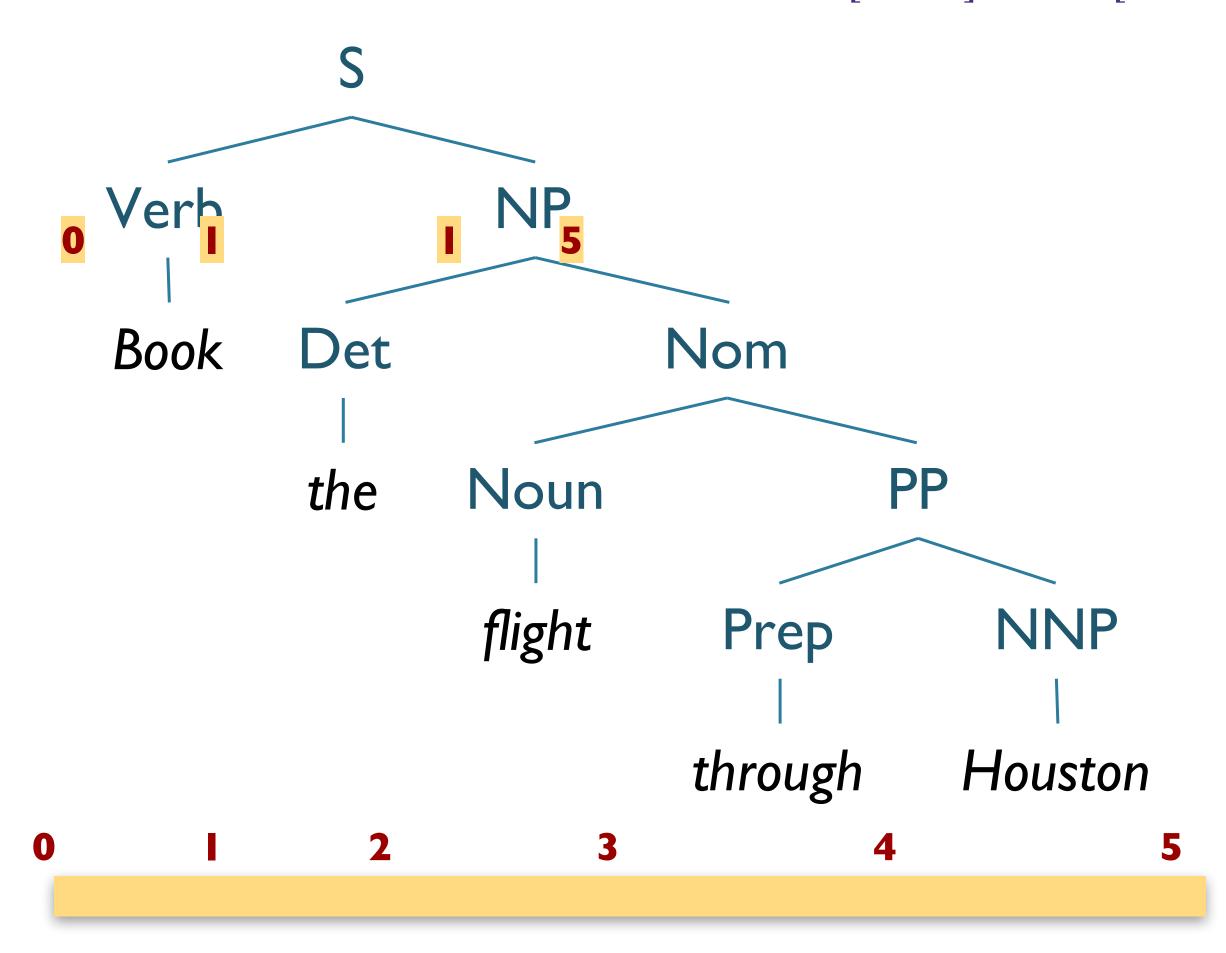


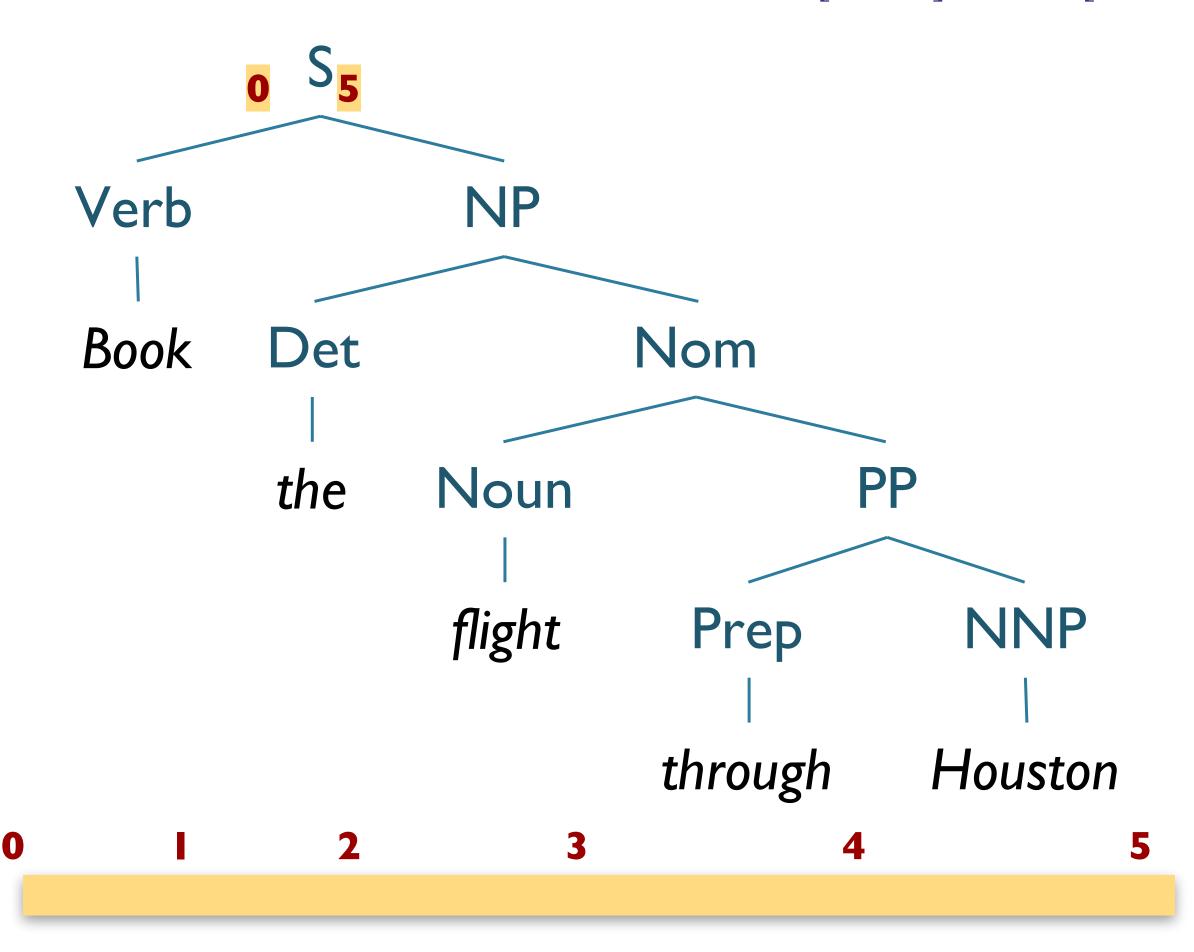


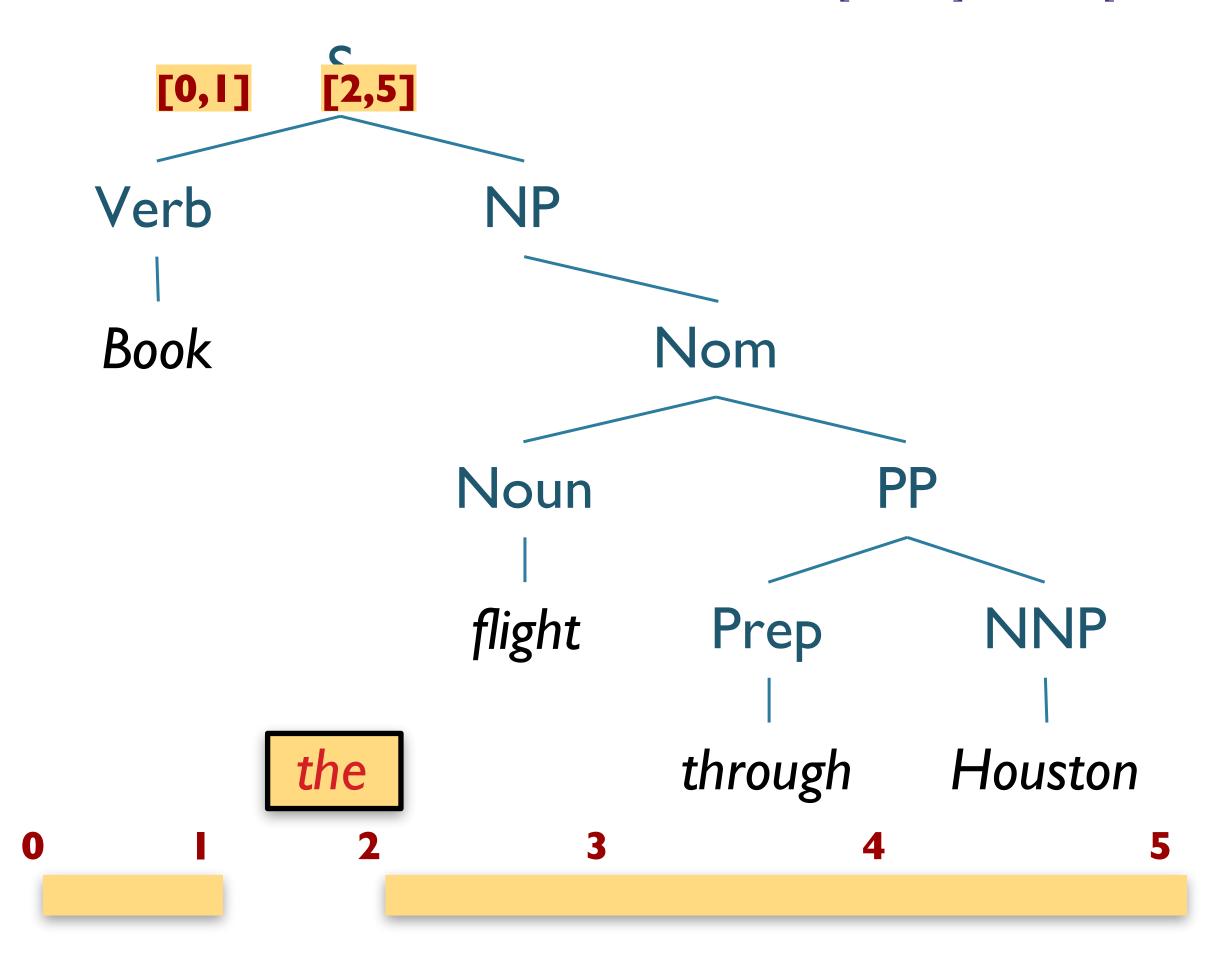


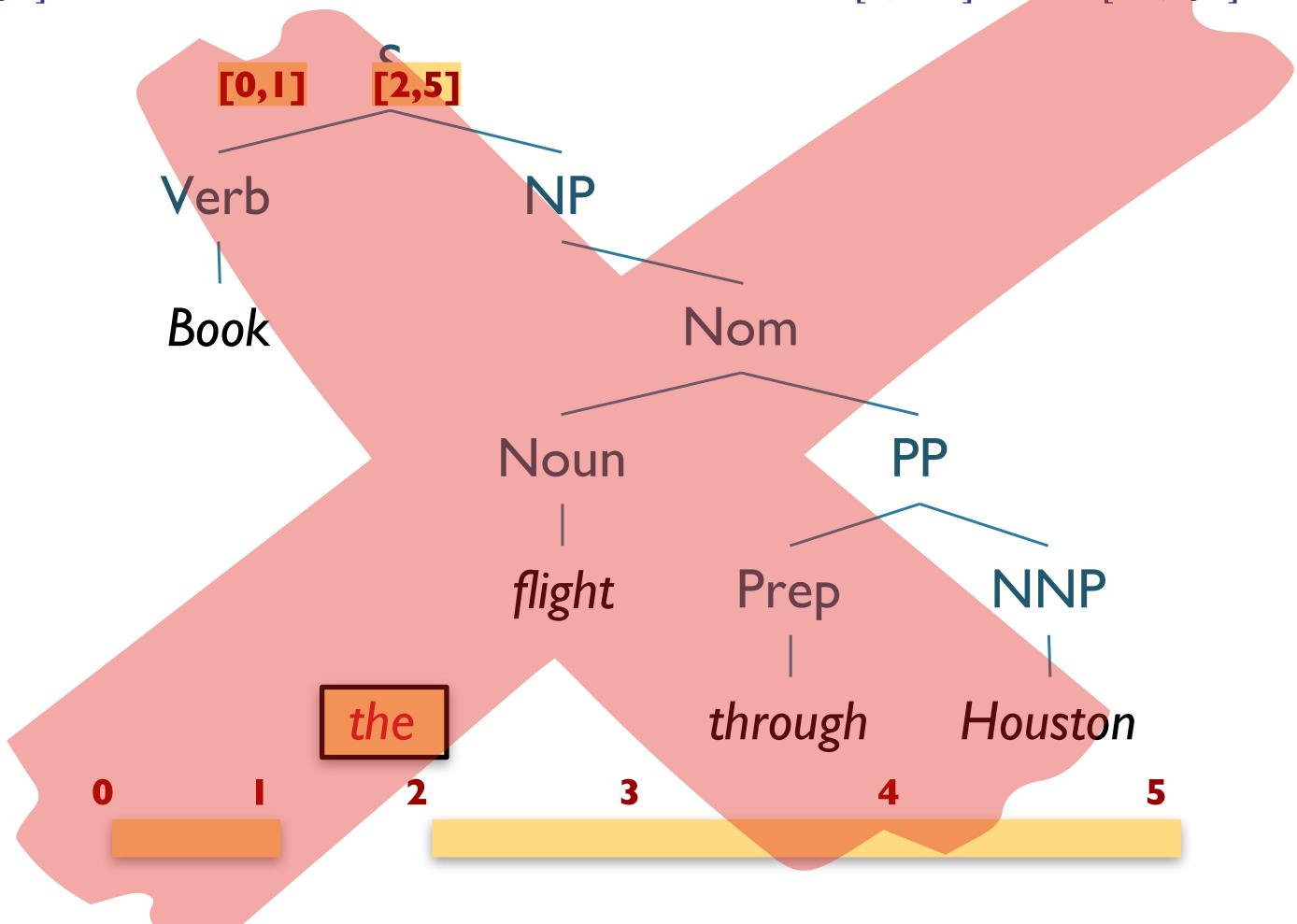












Would you say CKY is a top-down or a bottom-up parsing algorithm?

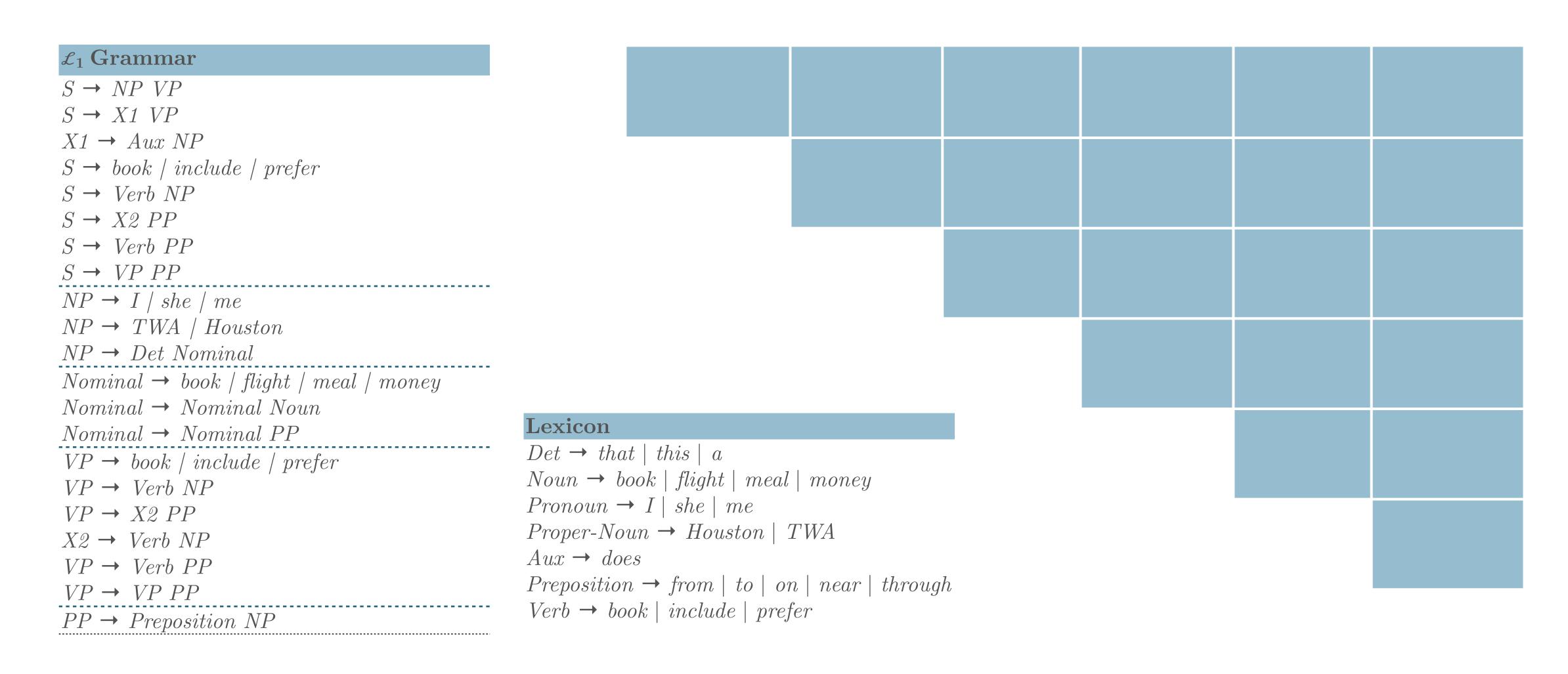
Top-down

Bottom-up

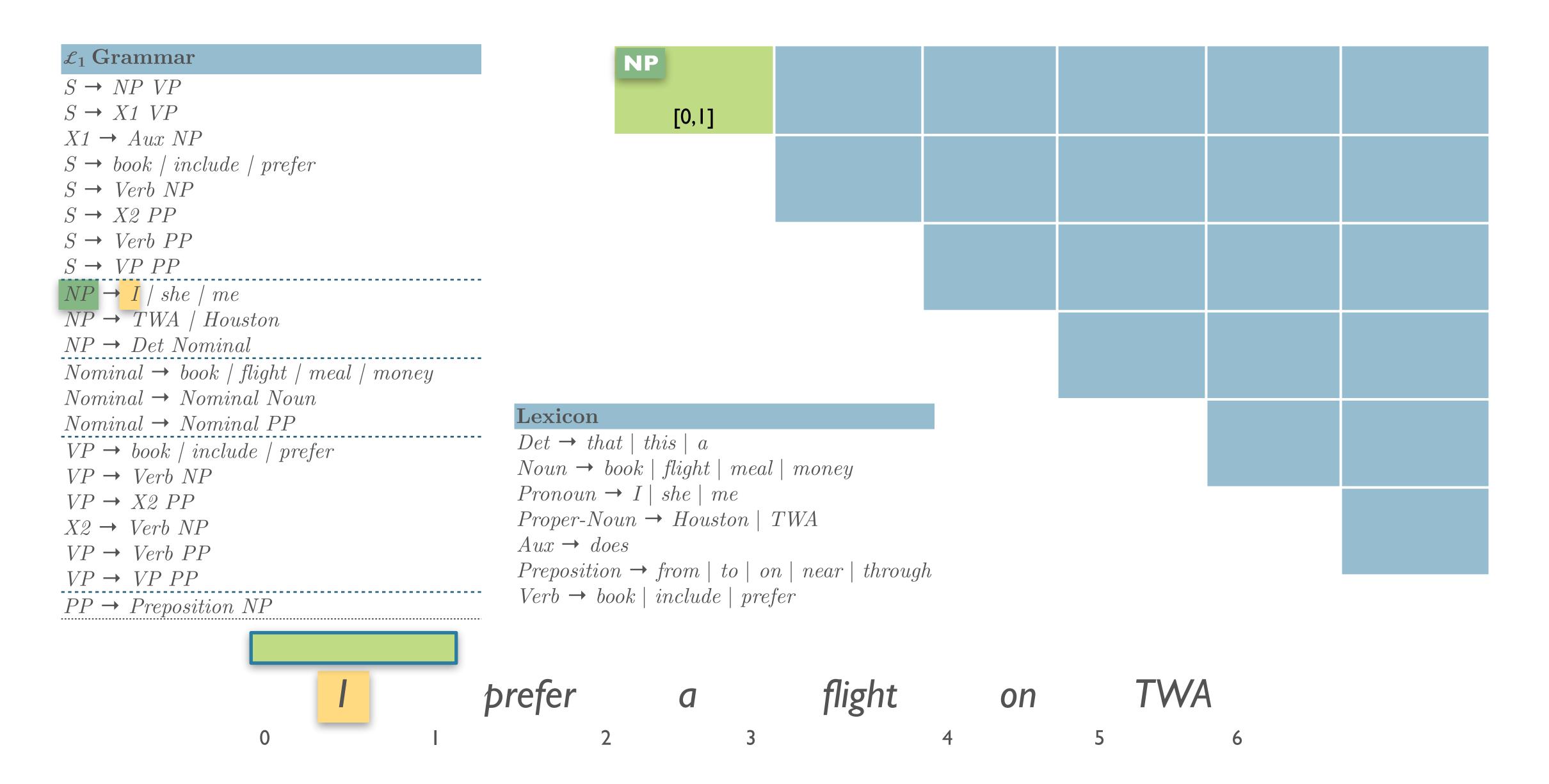
Total Results: 0

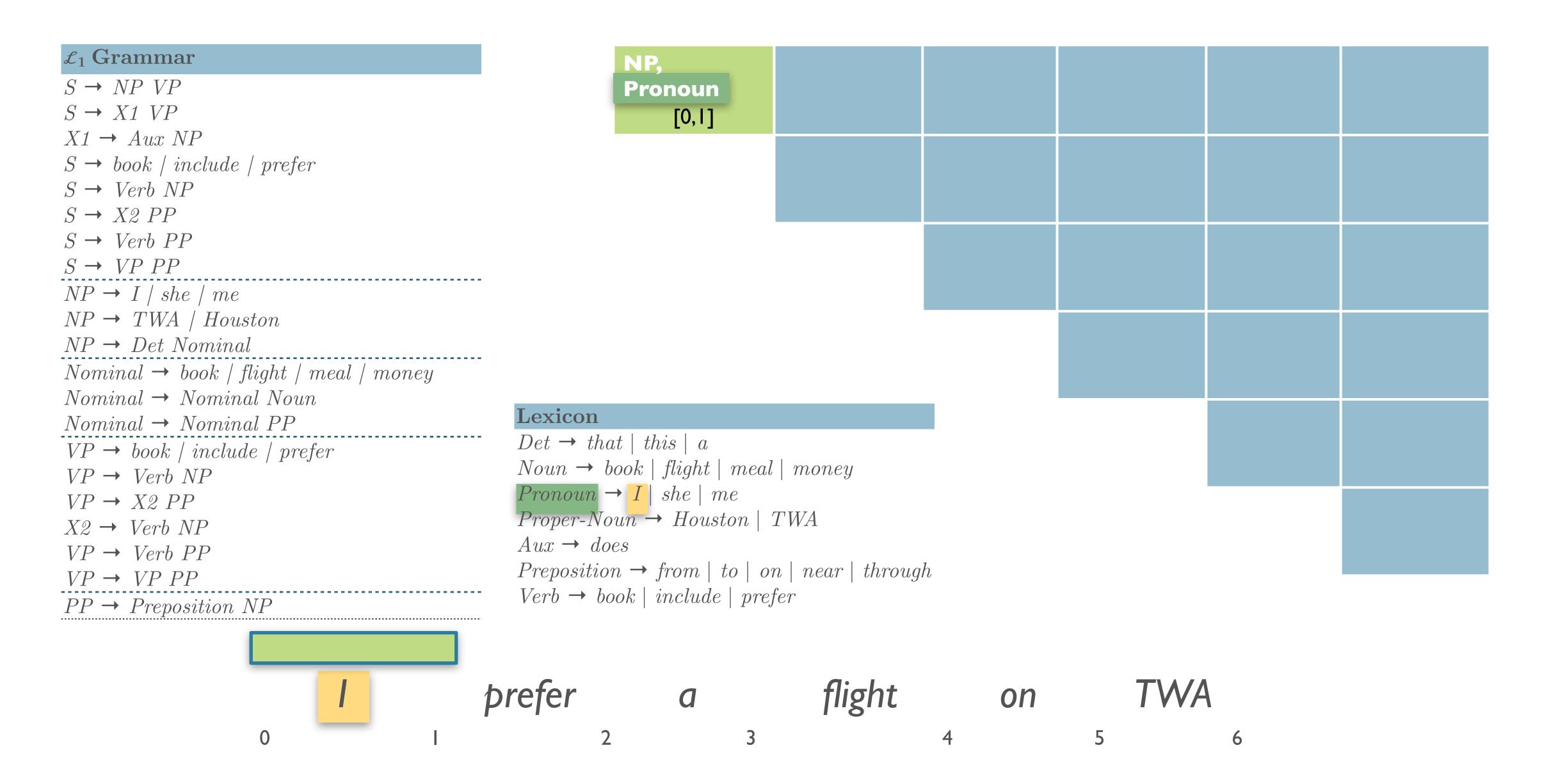


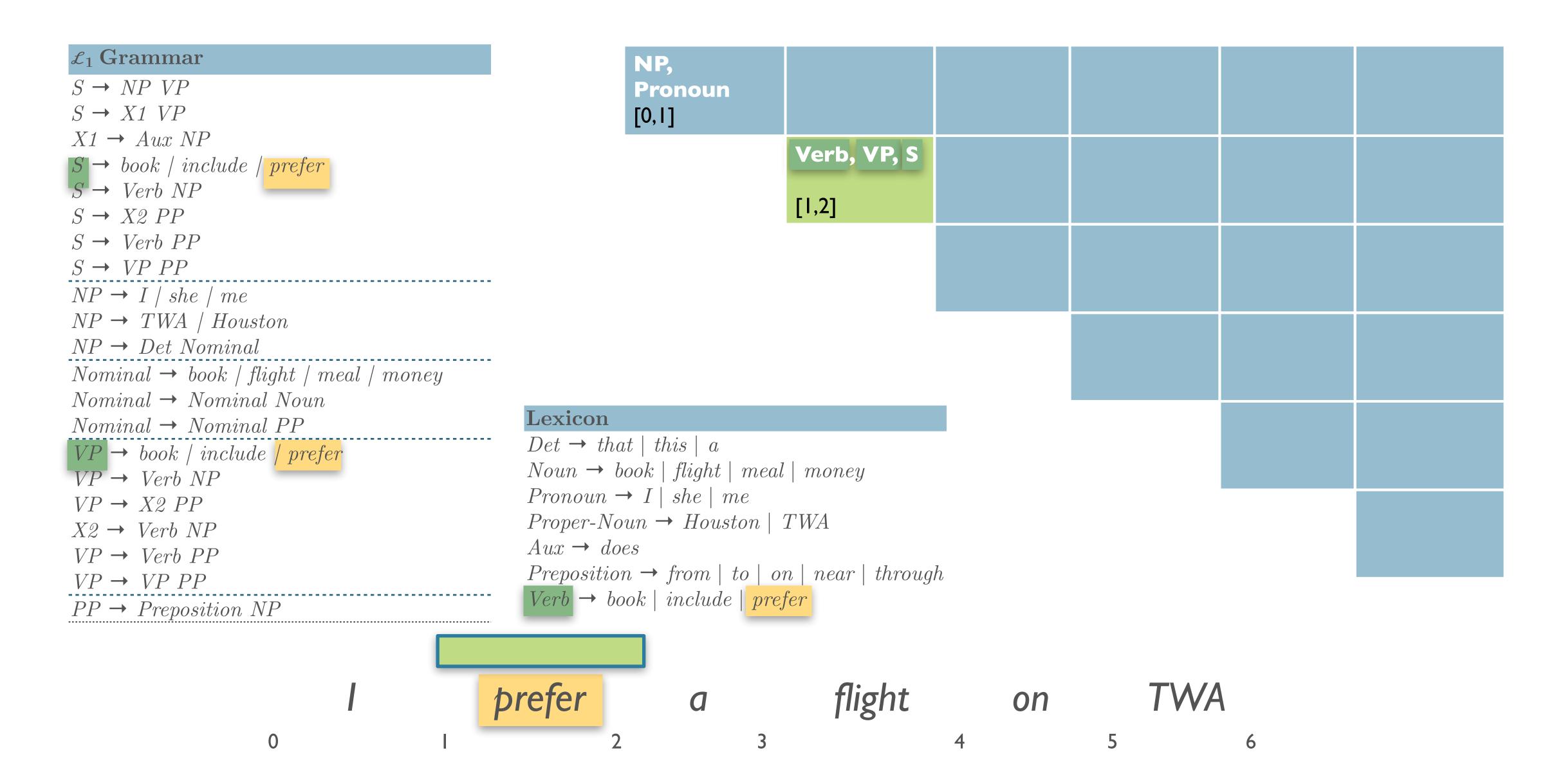
CKY Parsing Example

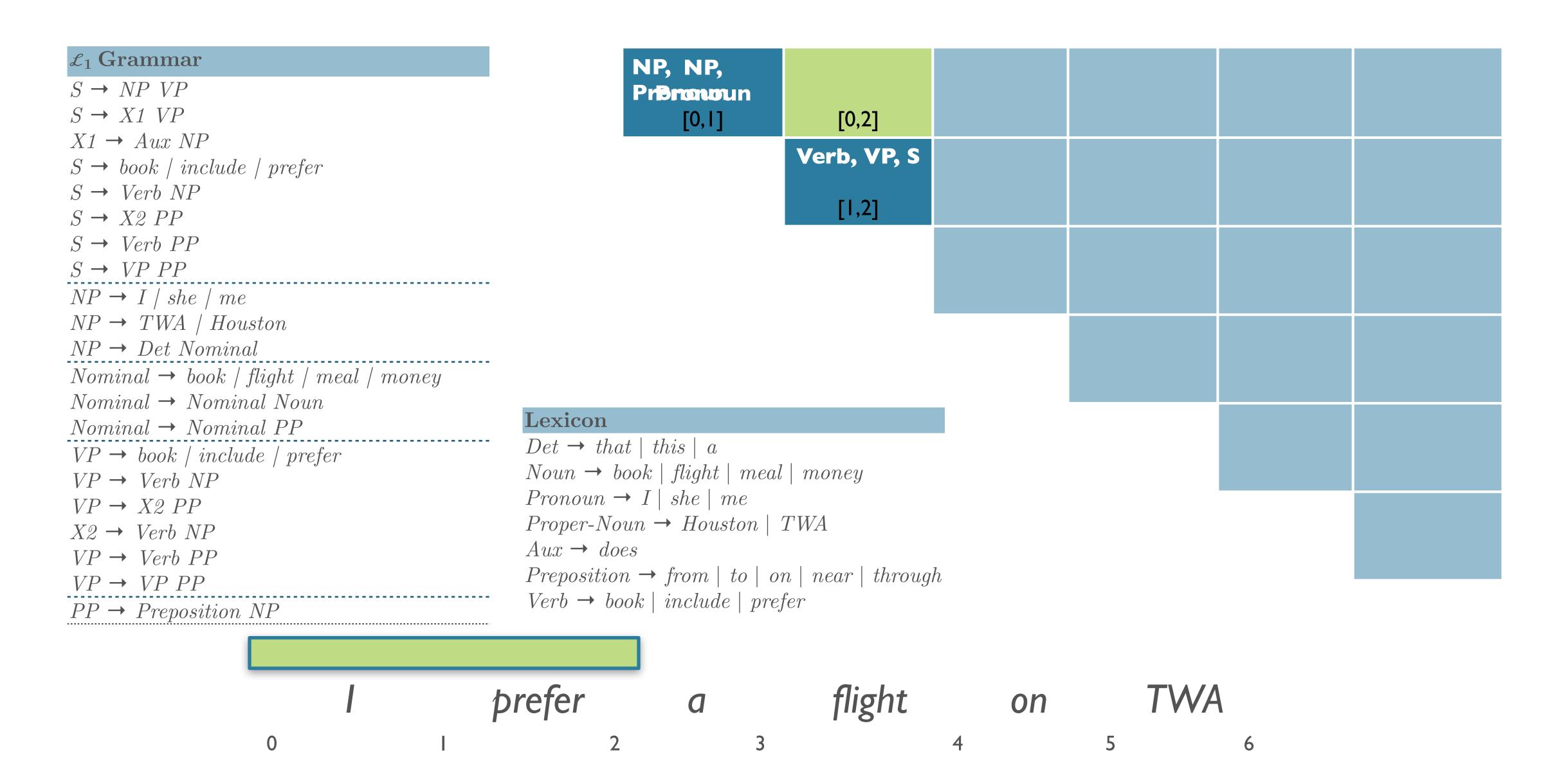


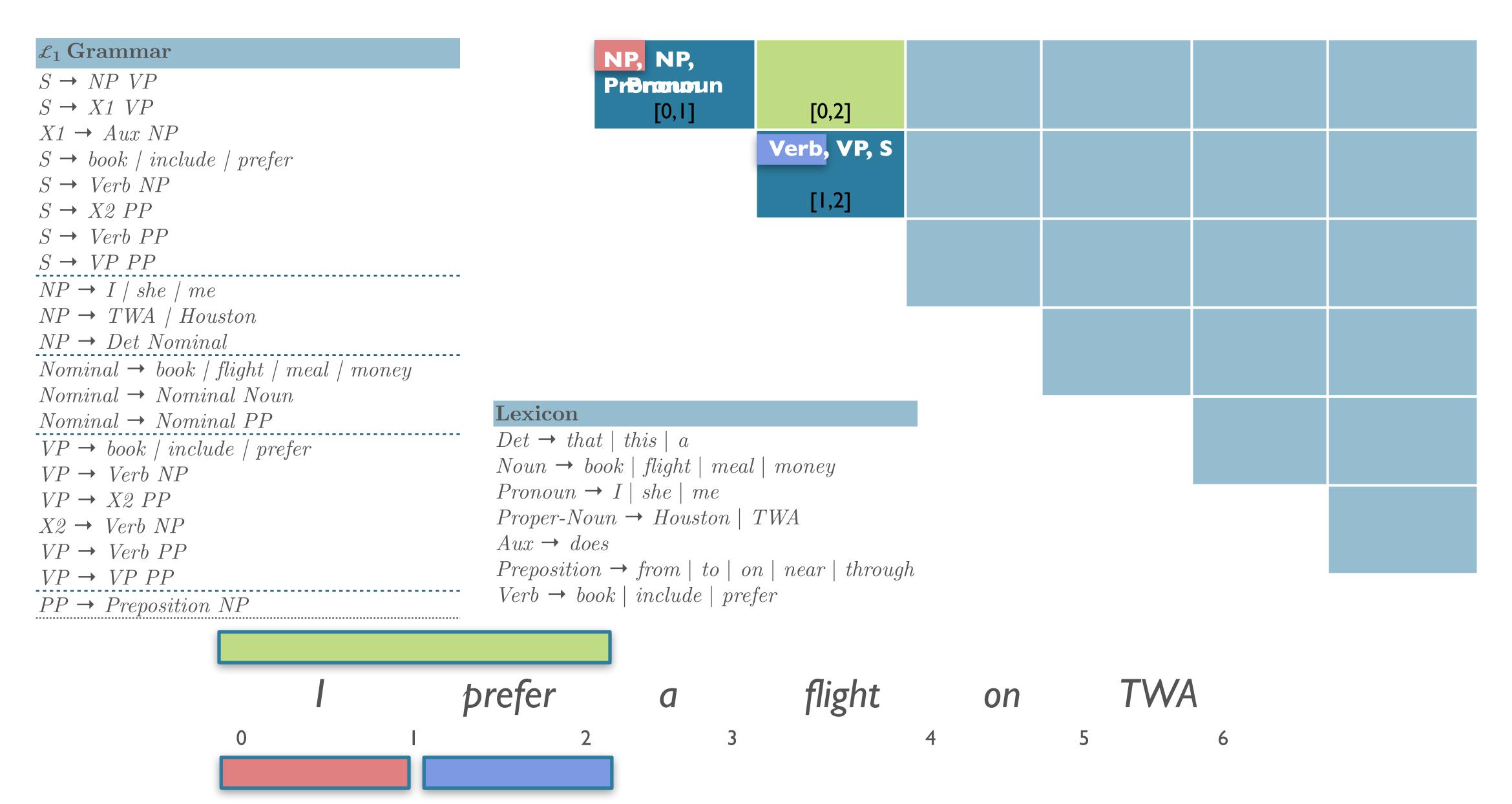


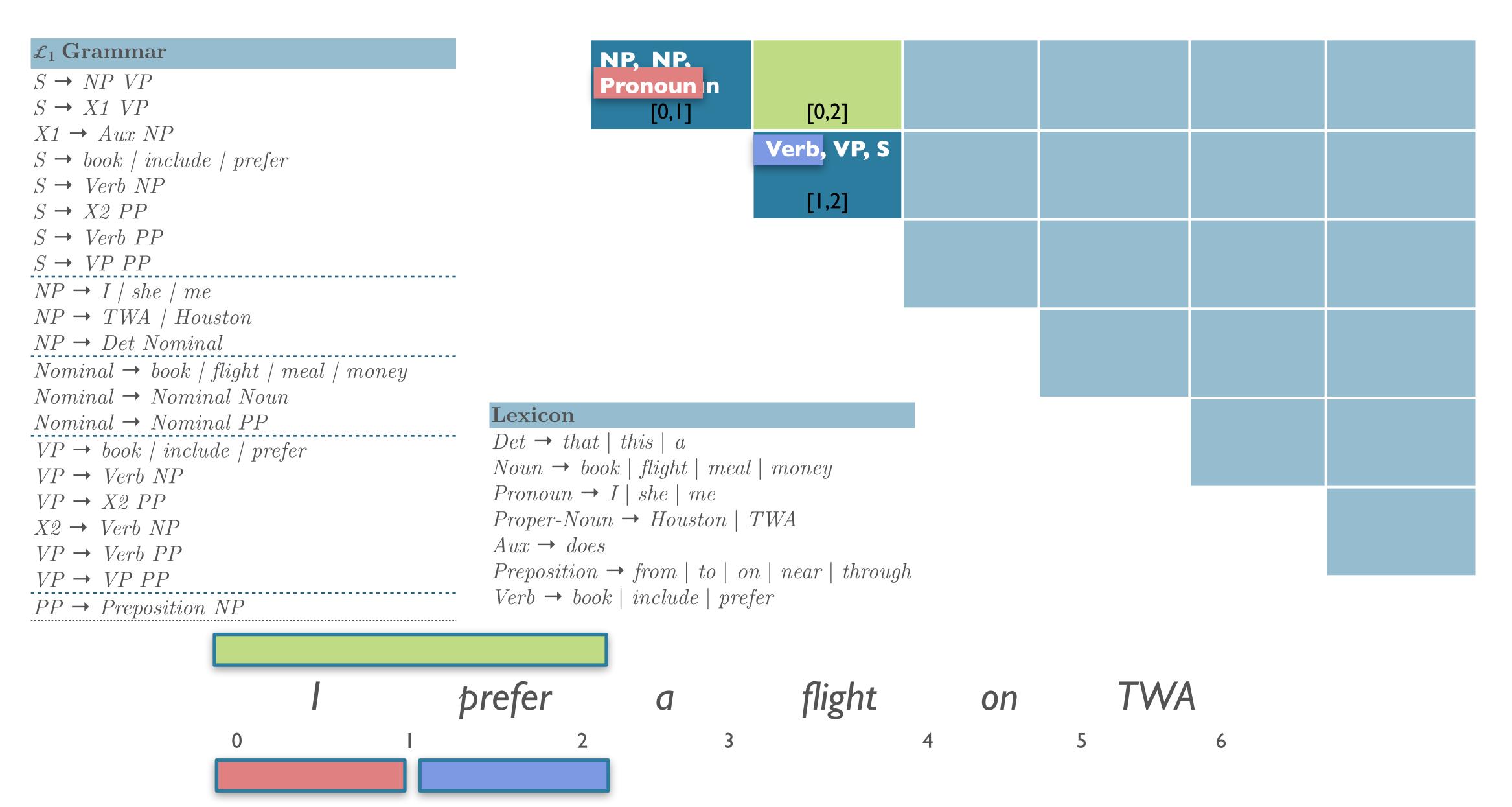


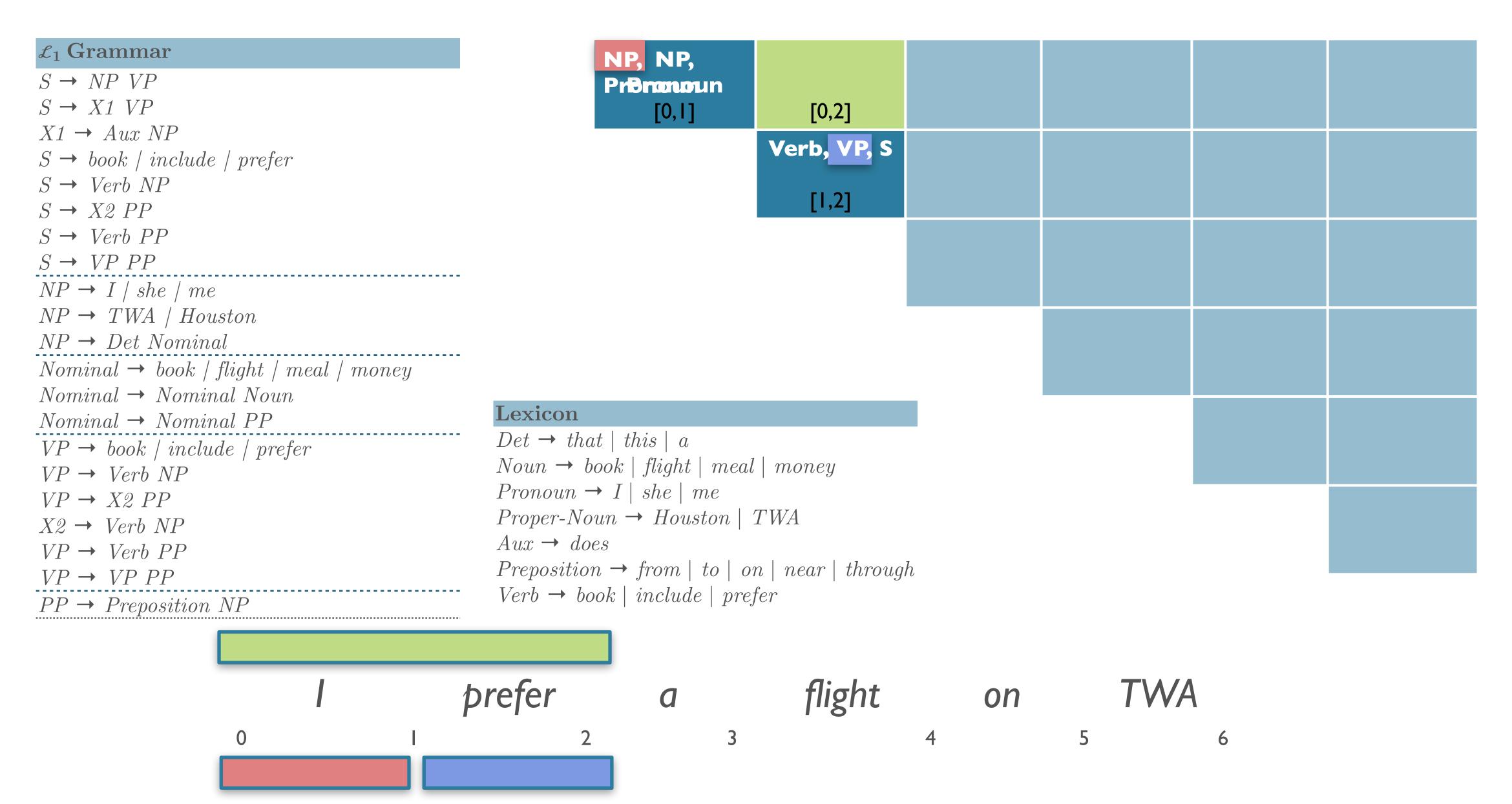


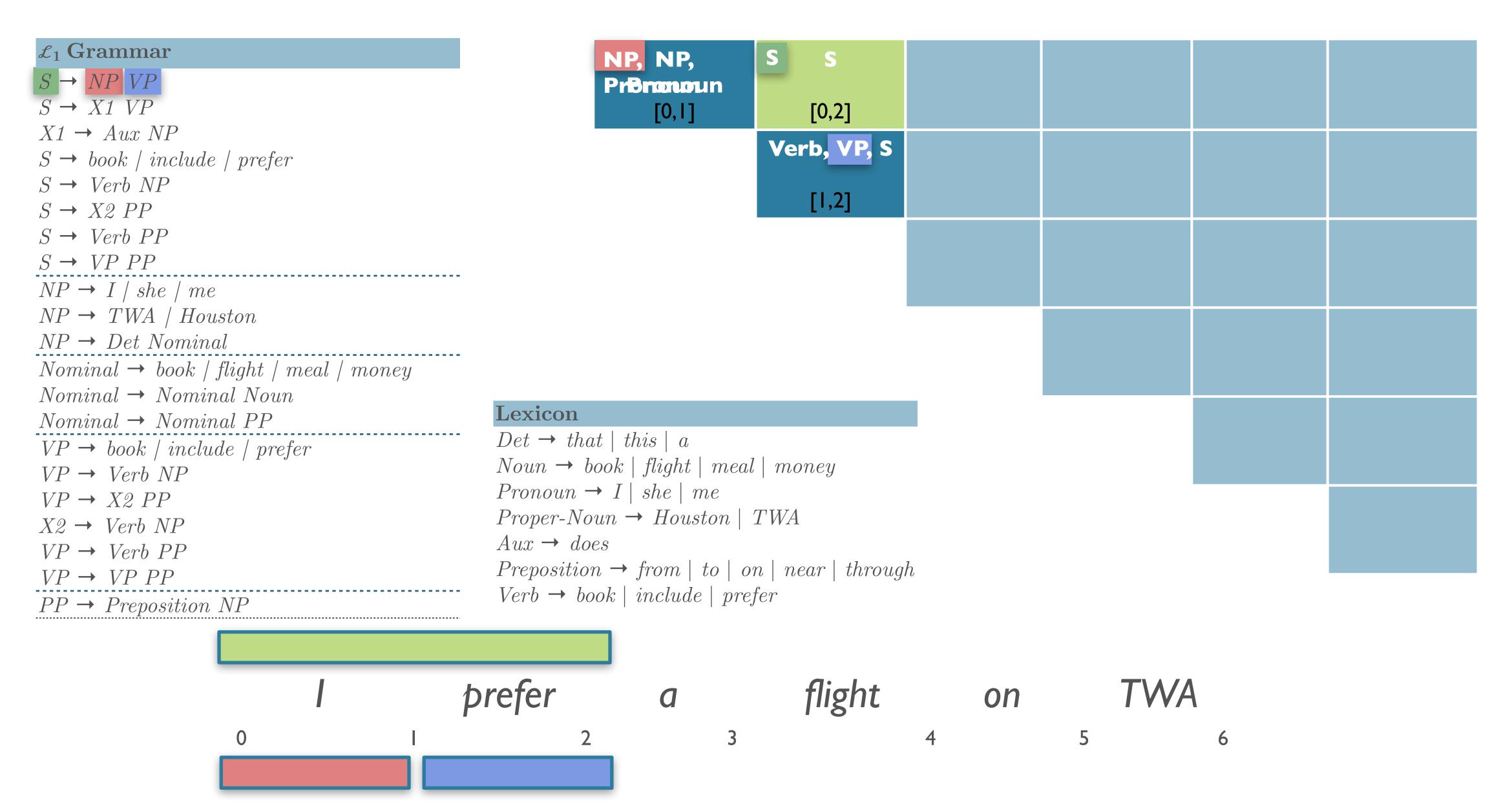


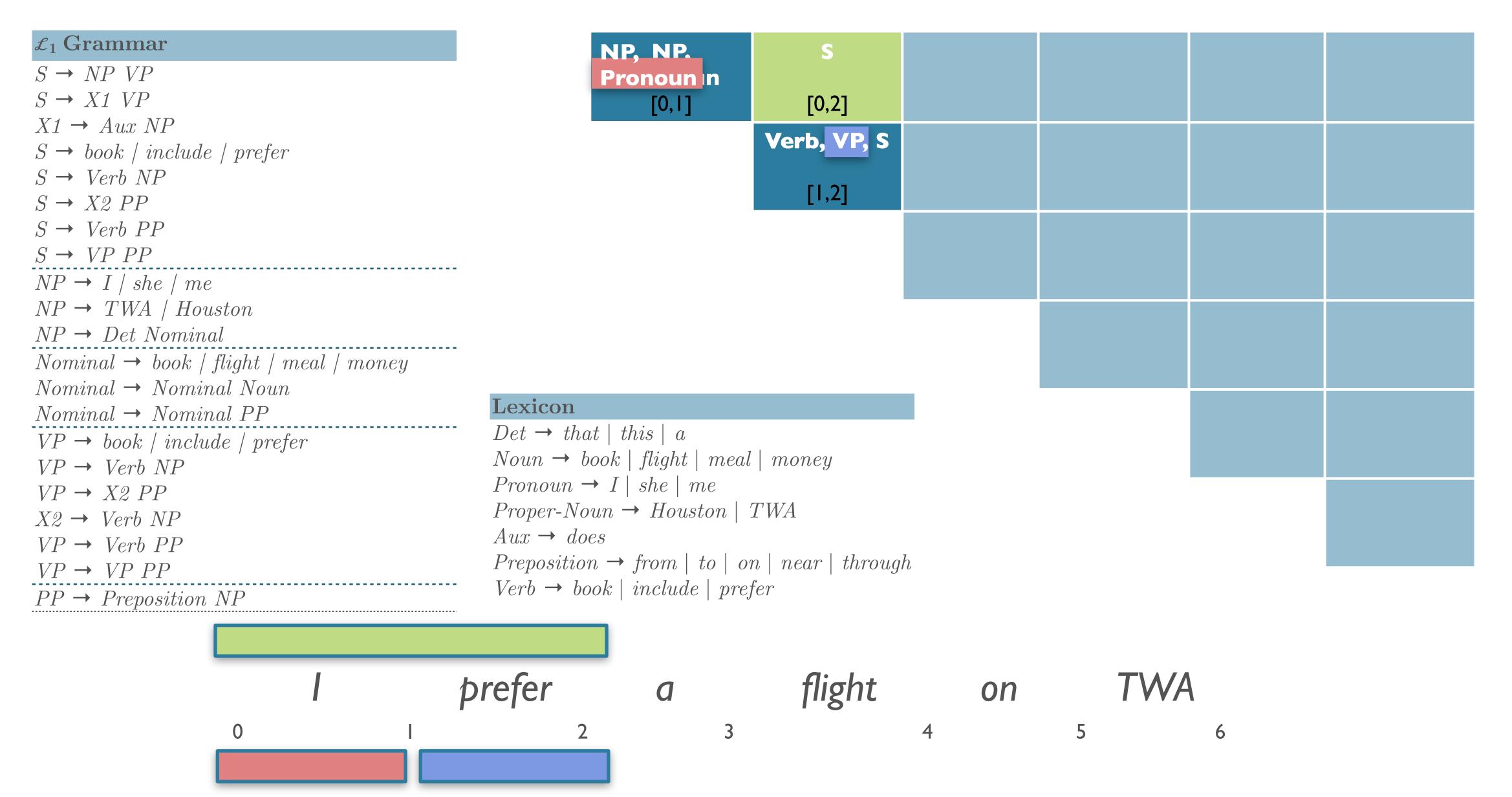


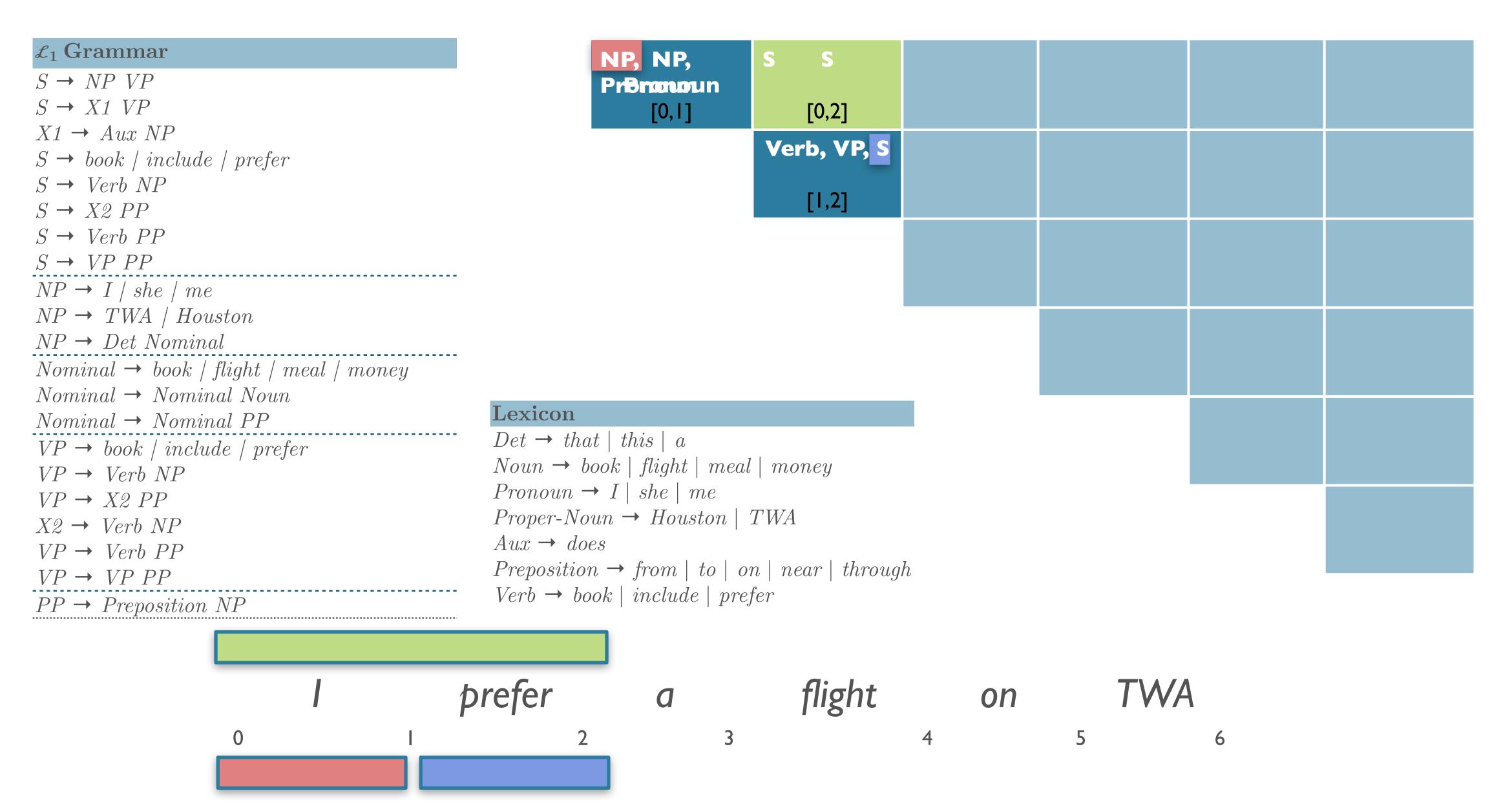




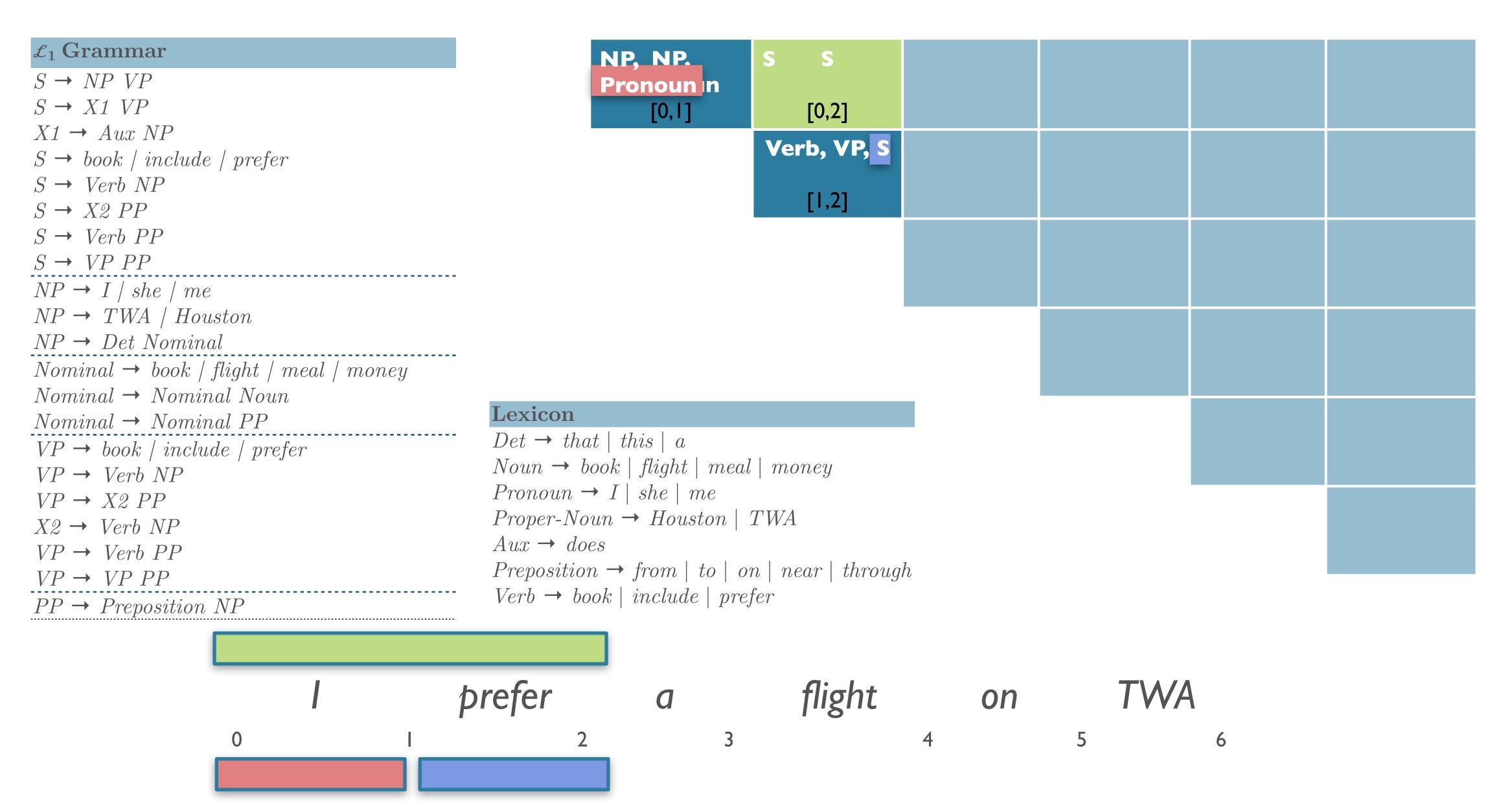


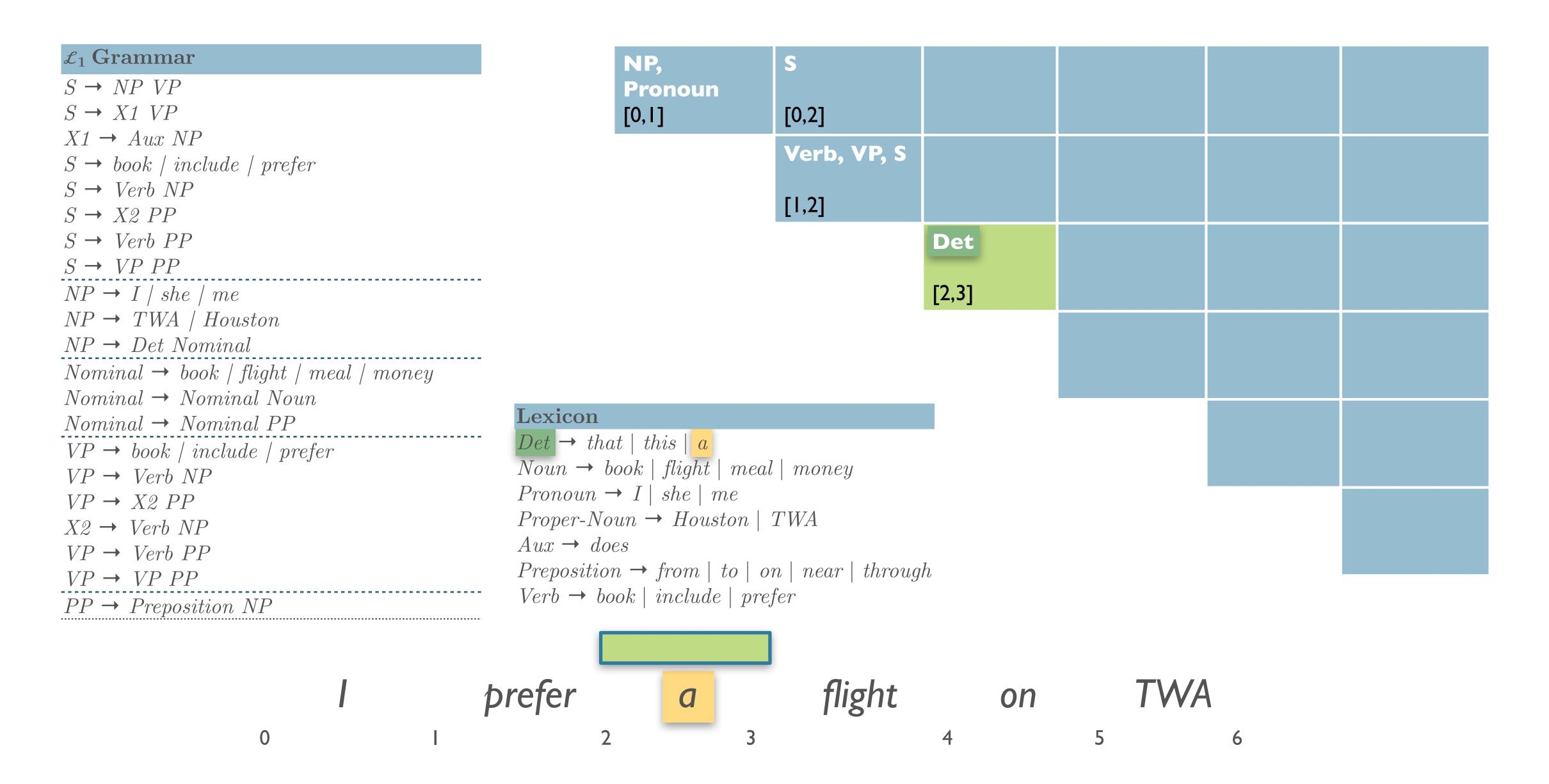


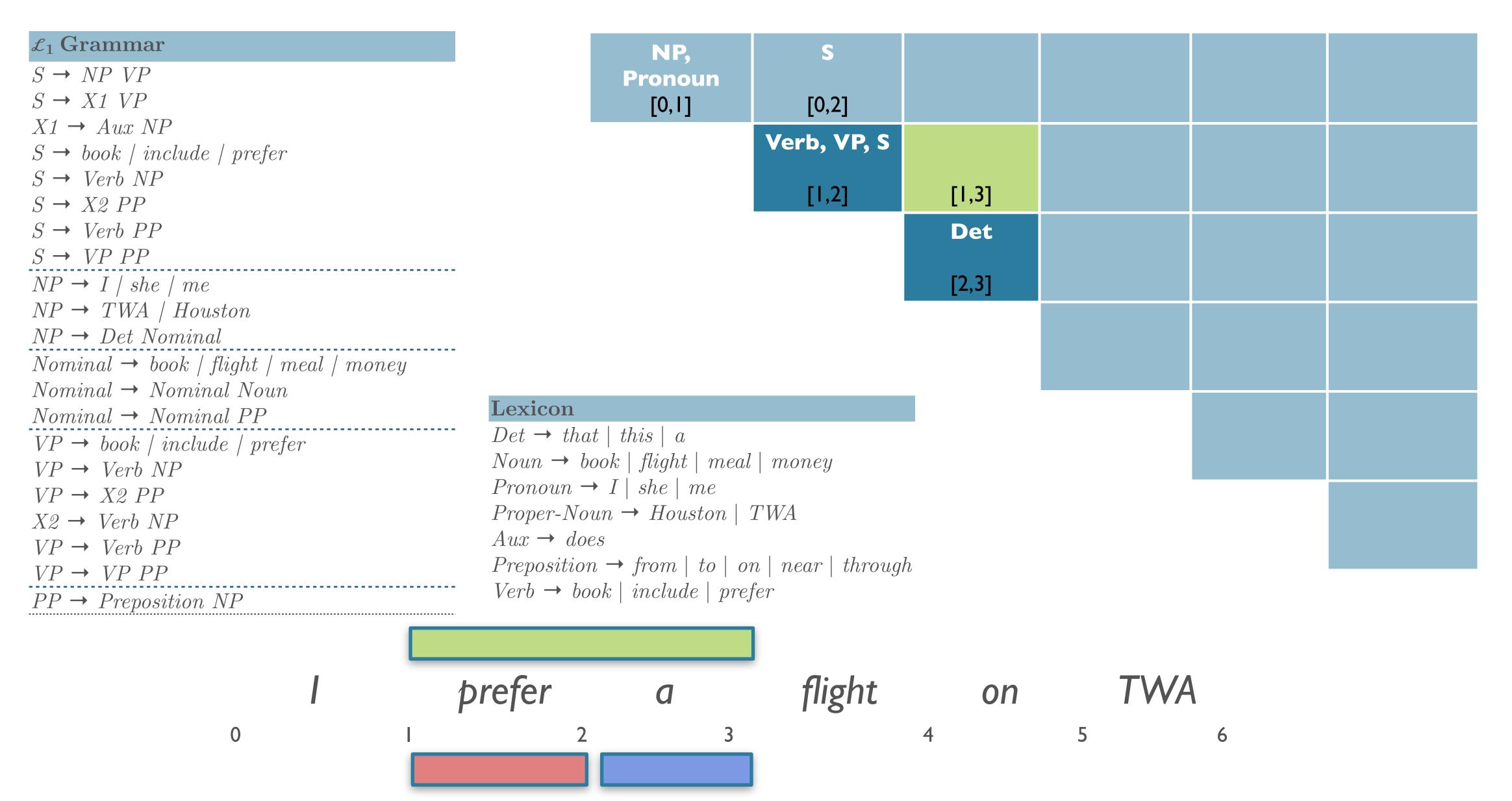


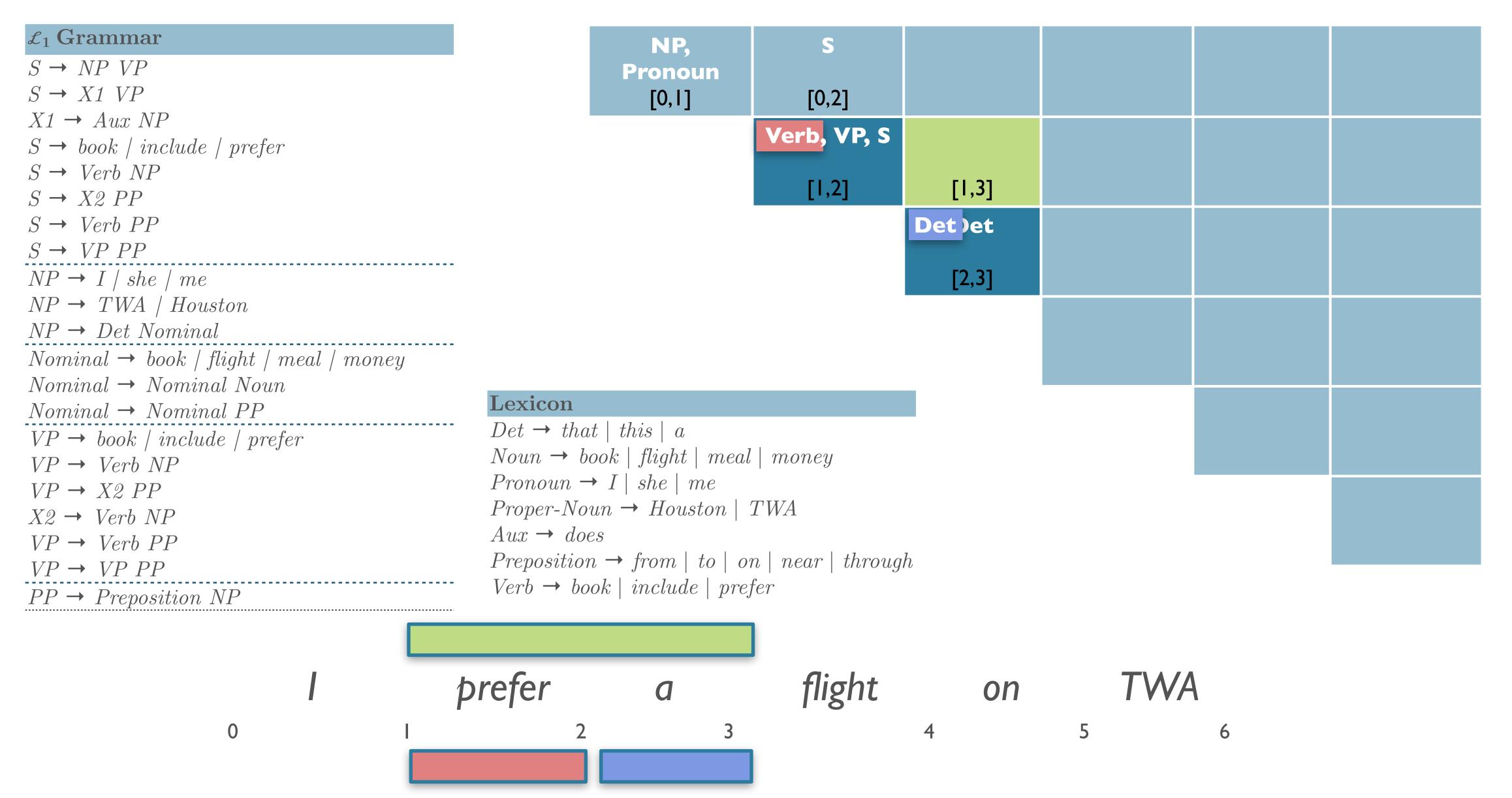


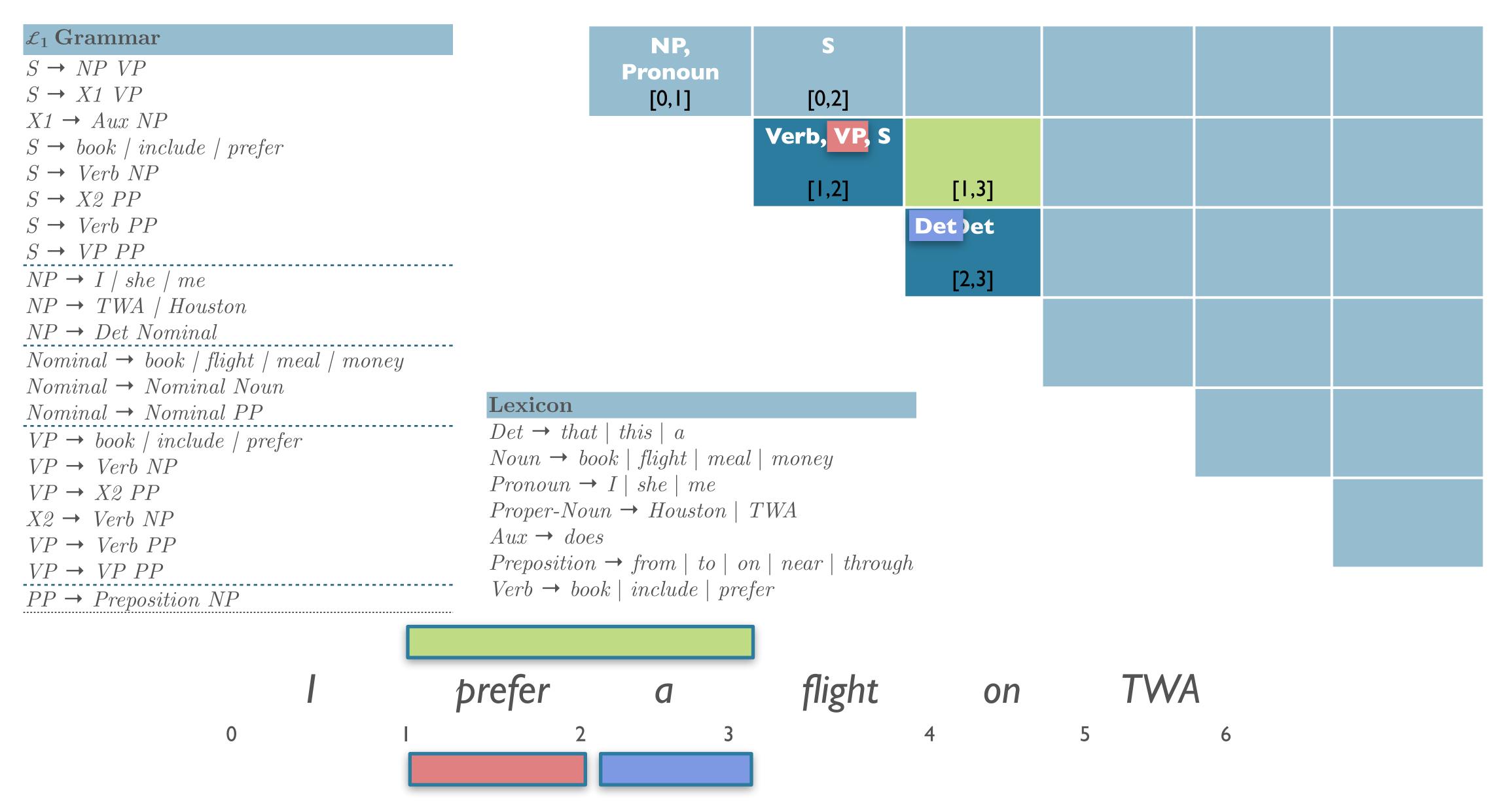
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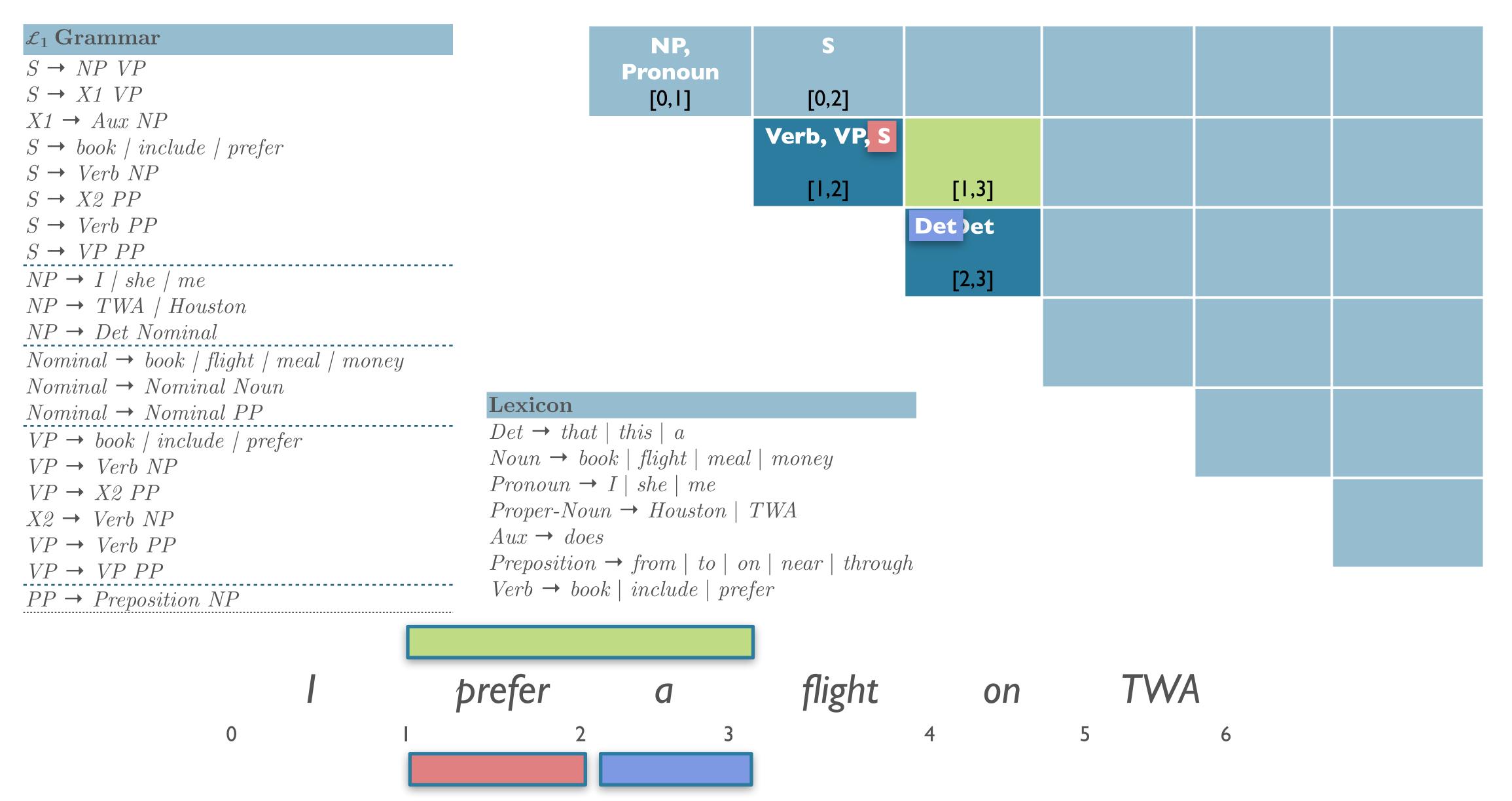


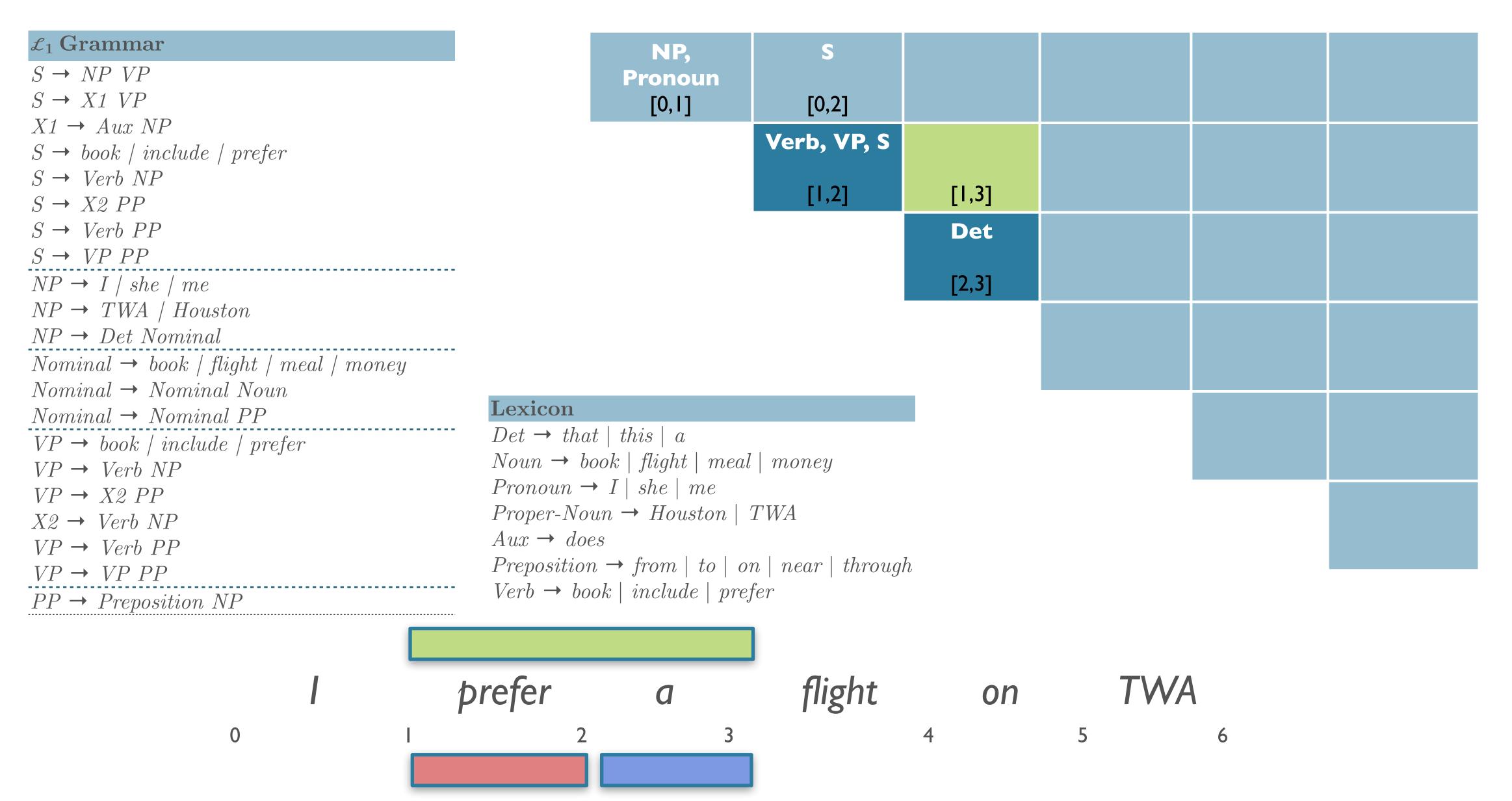


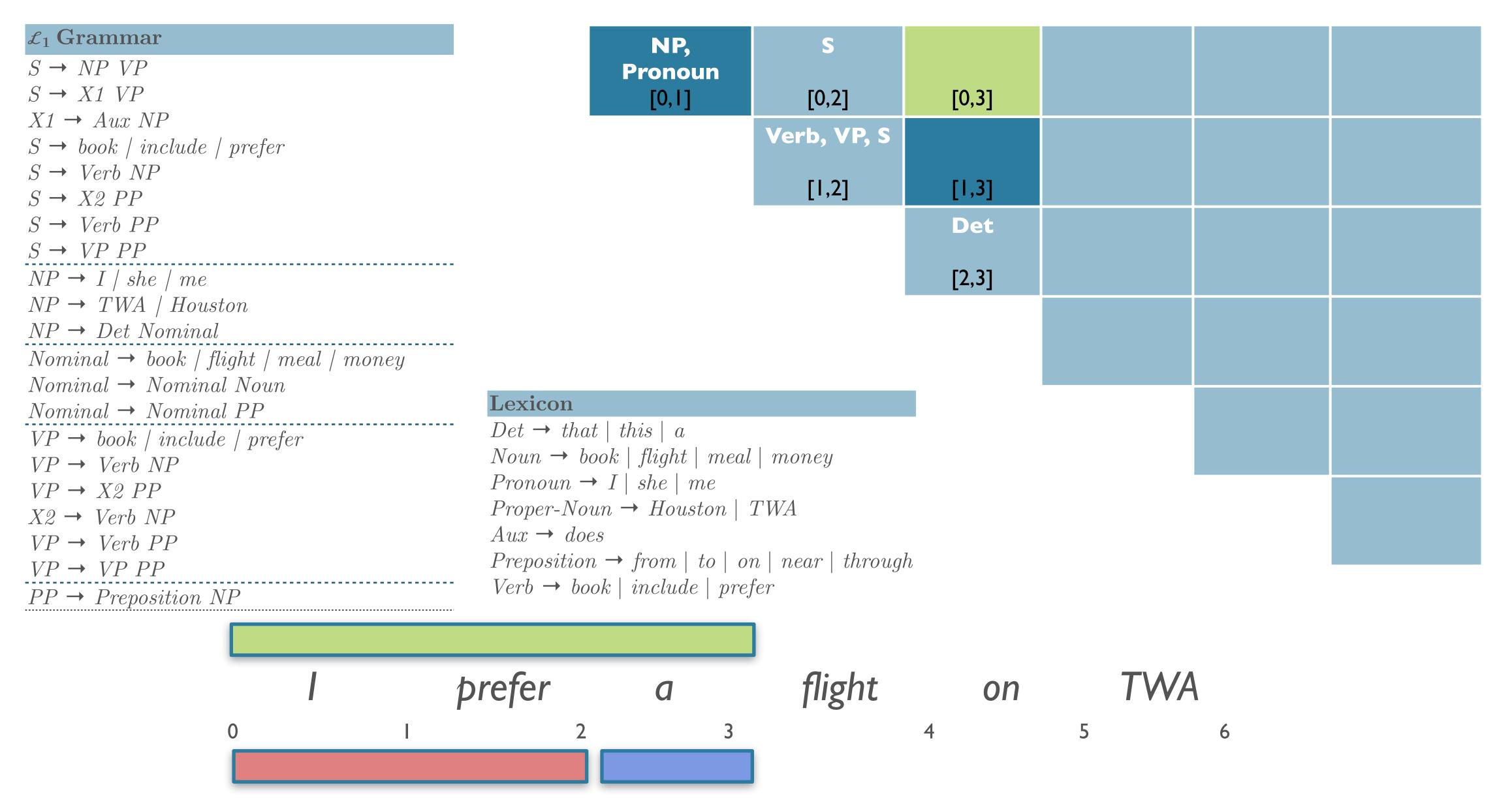


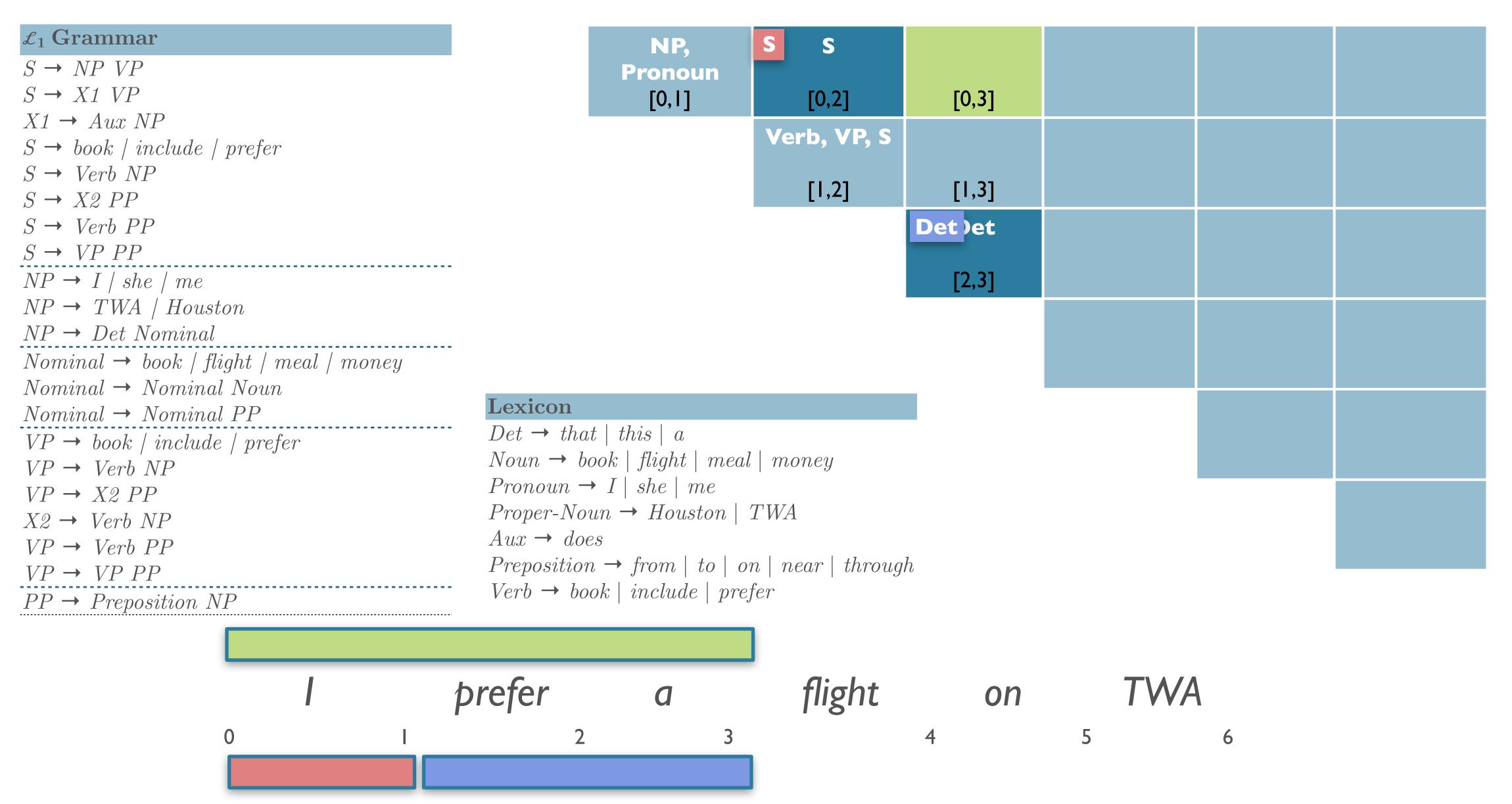


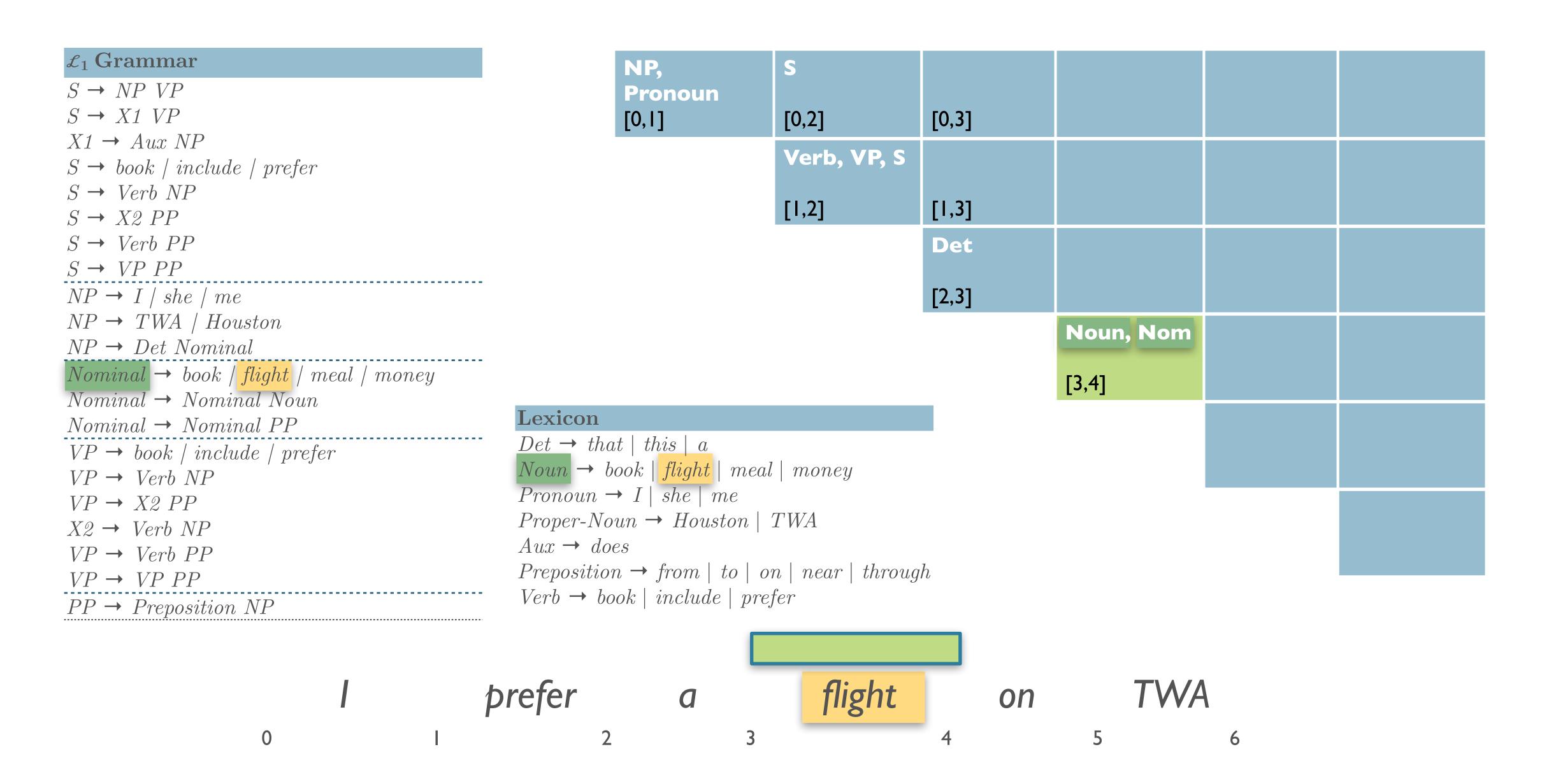


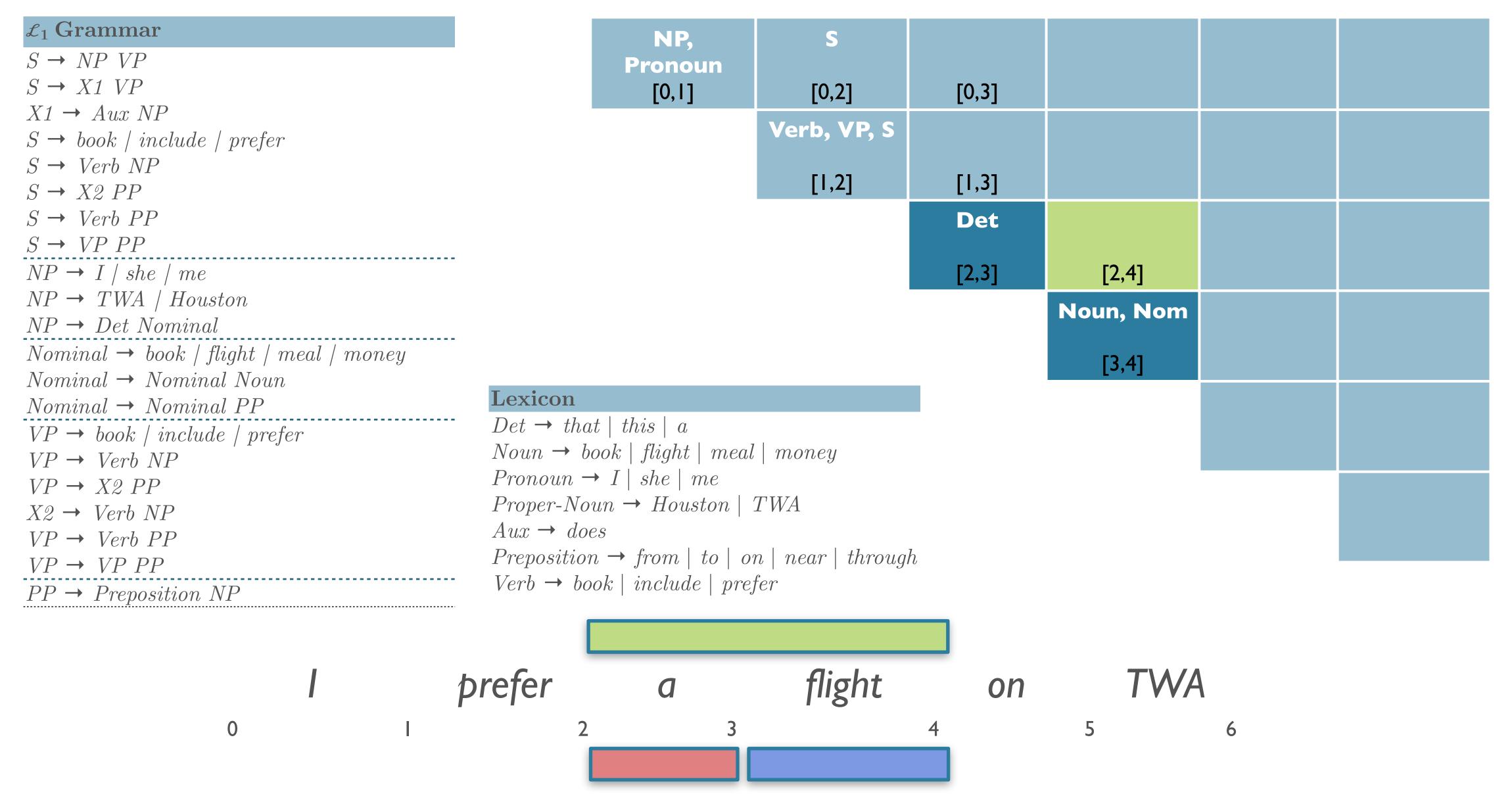


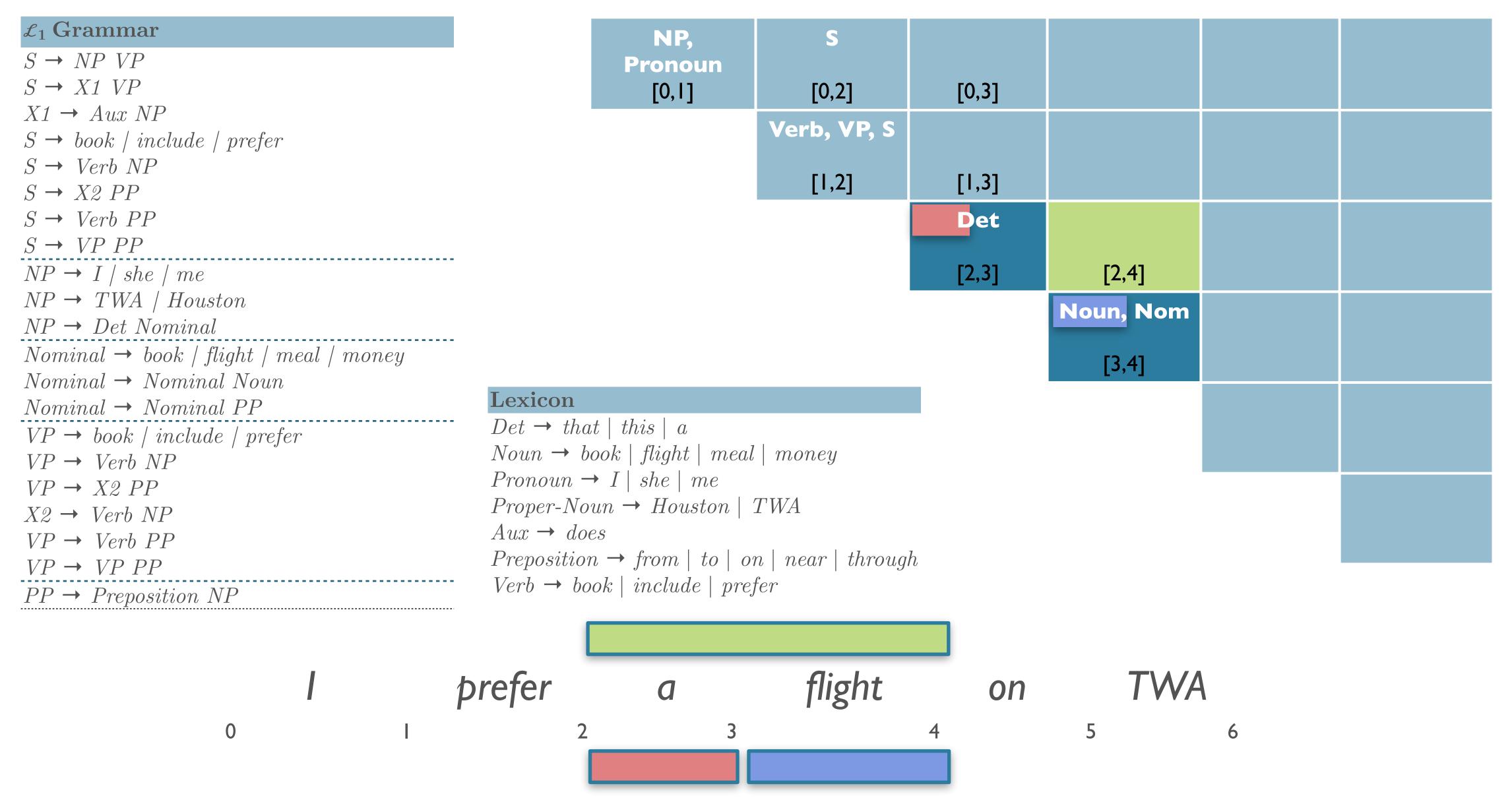


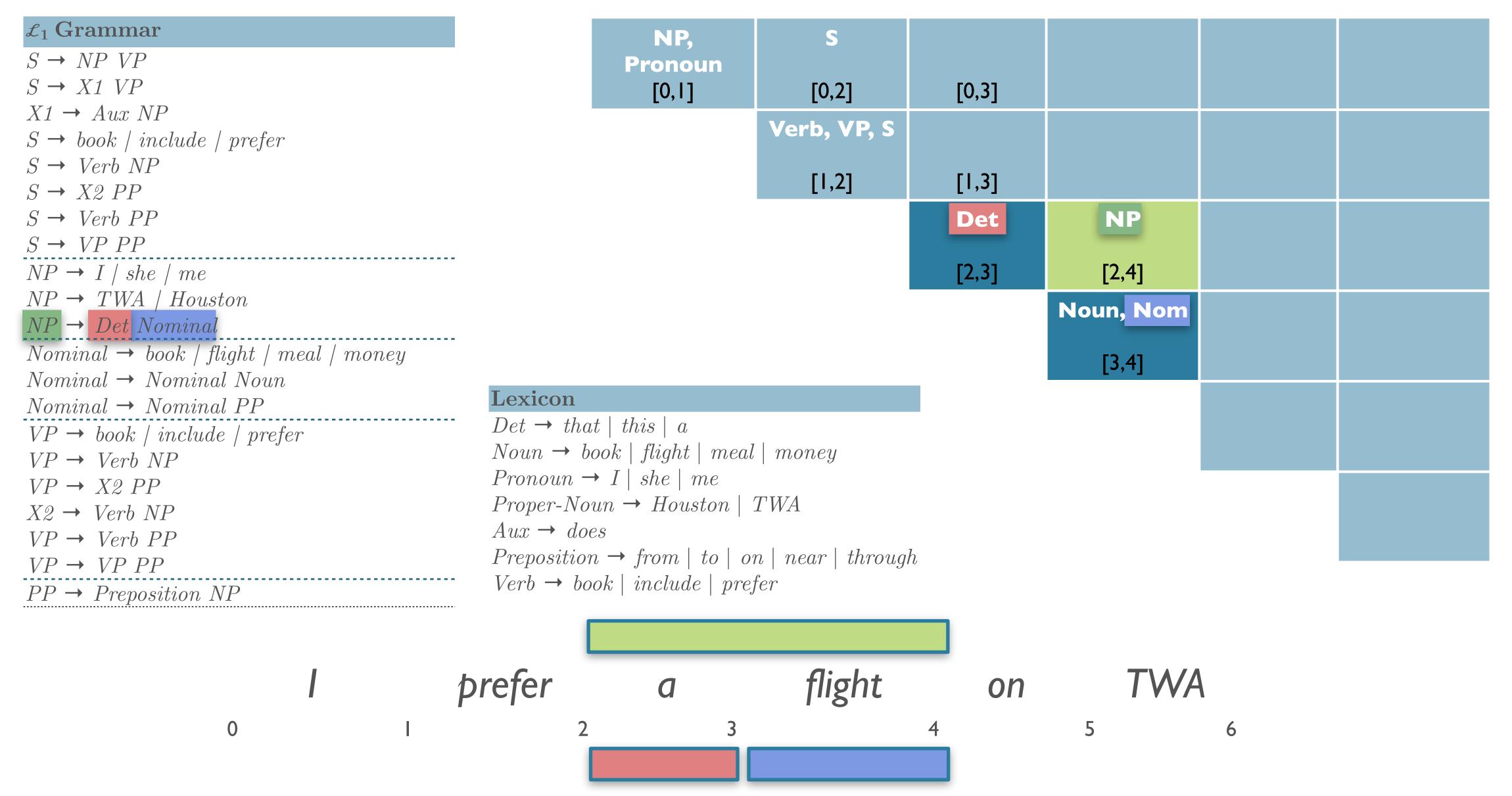


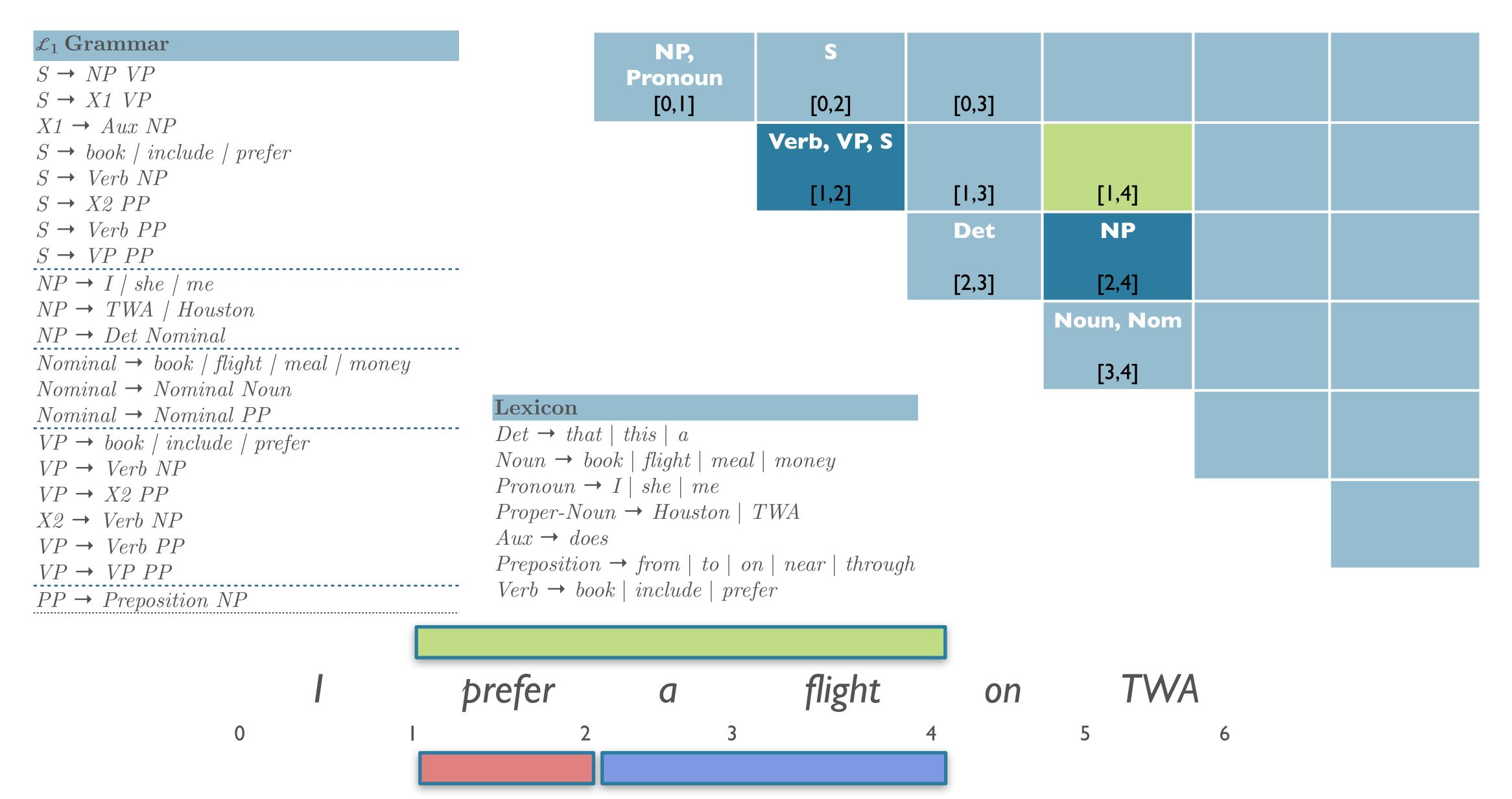


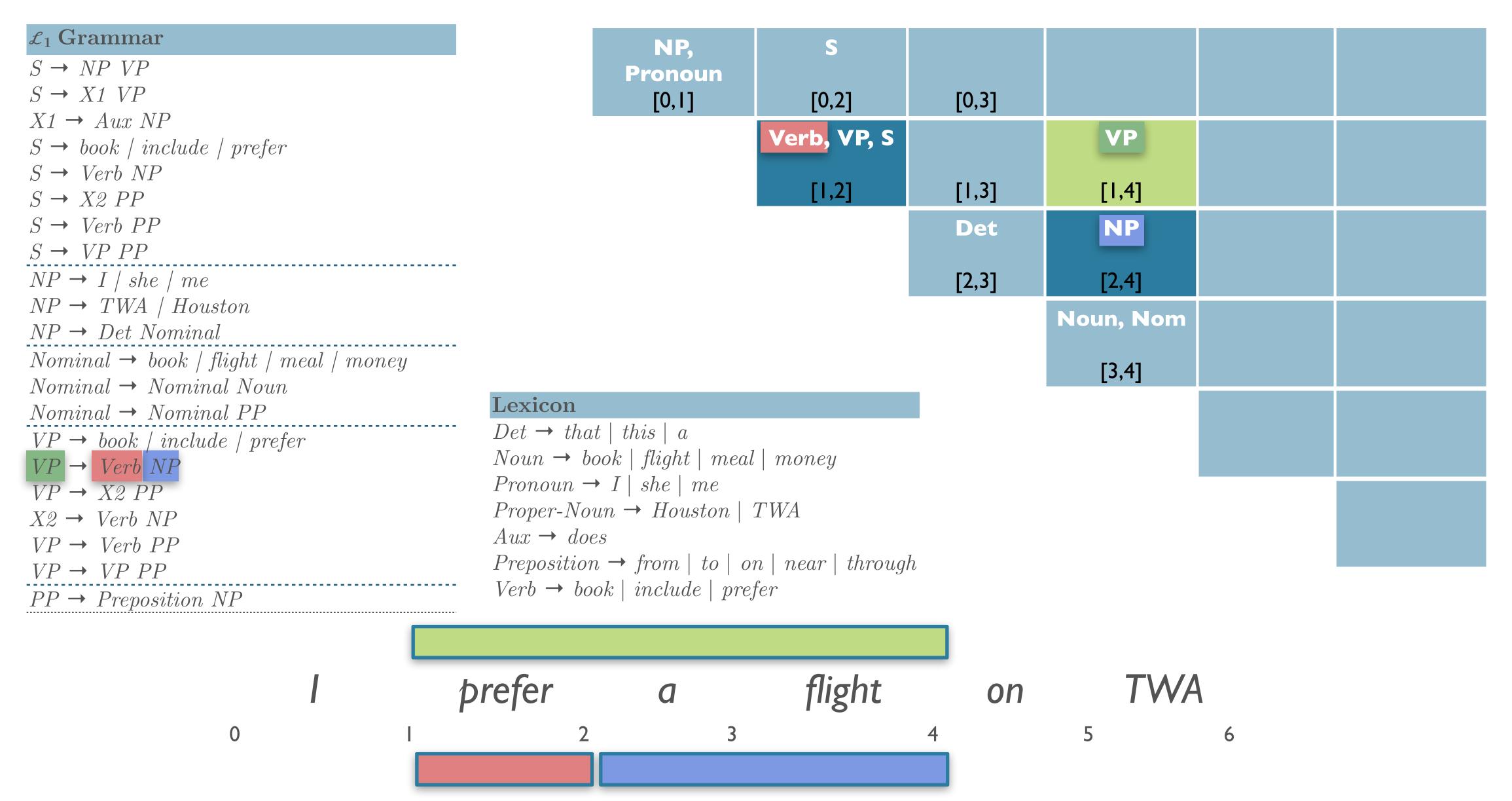


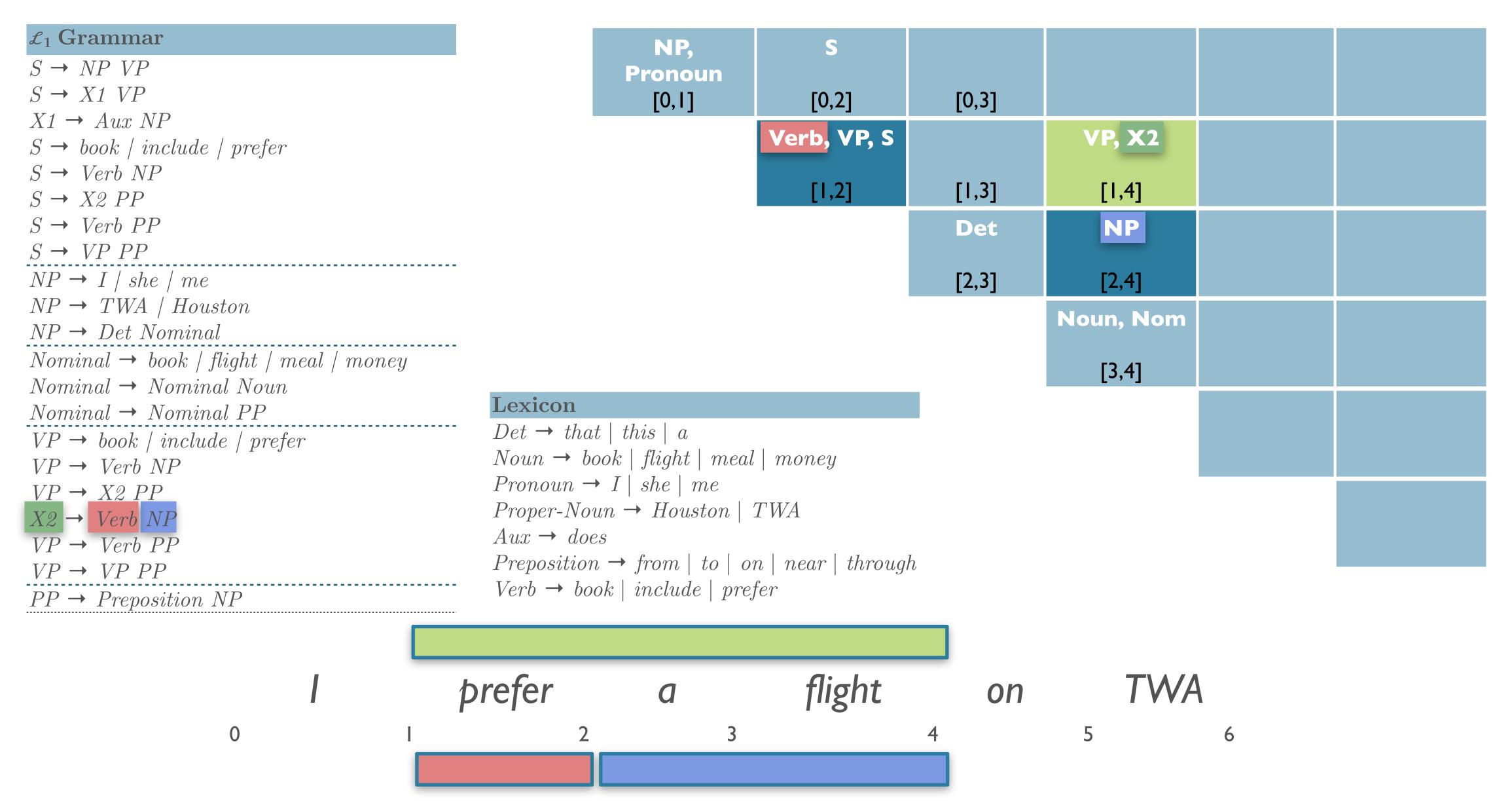


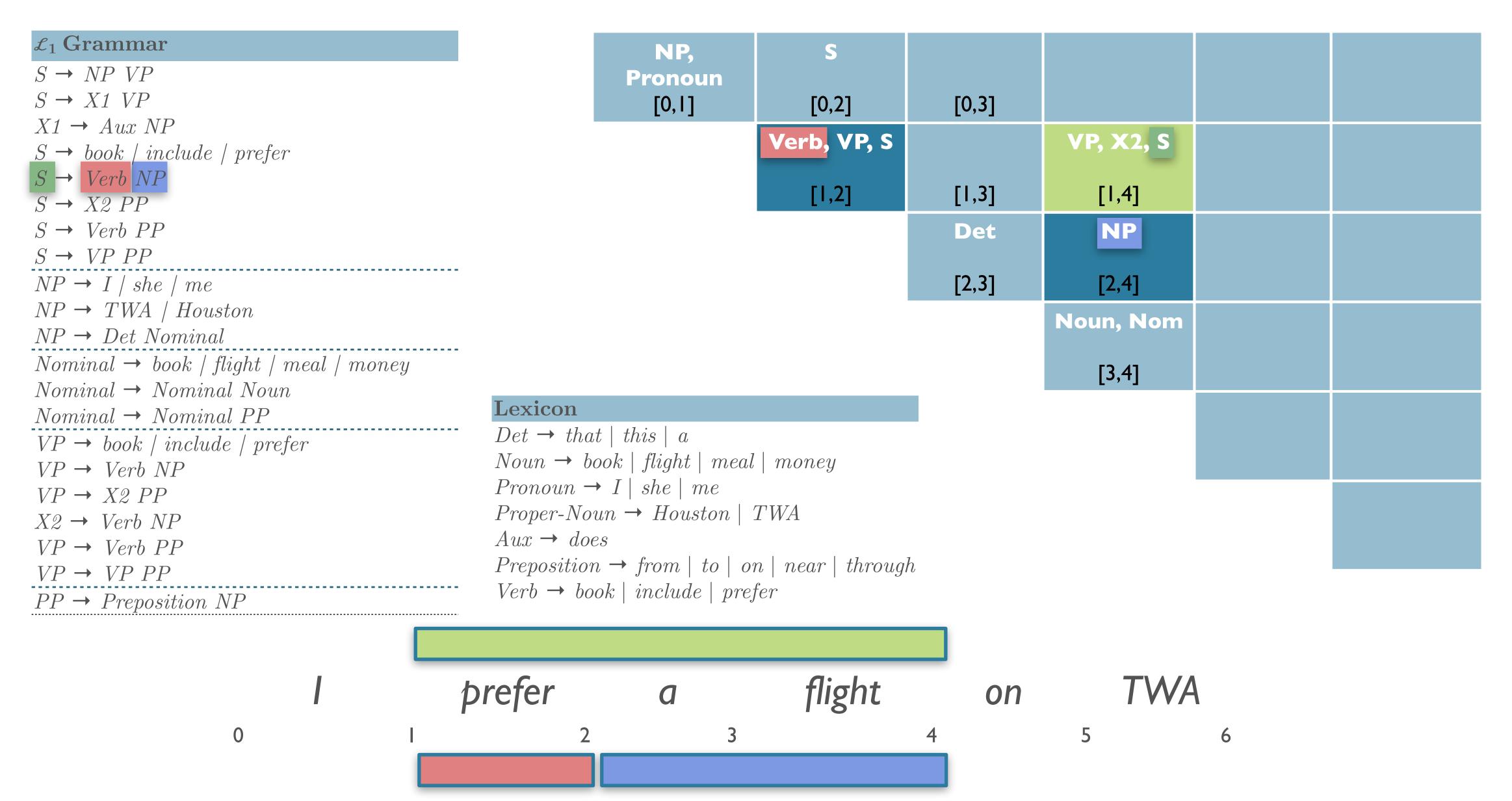


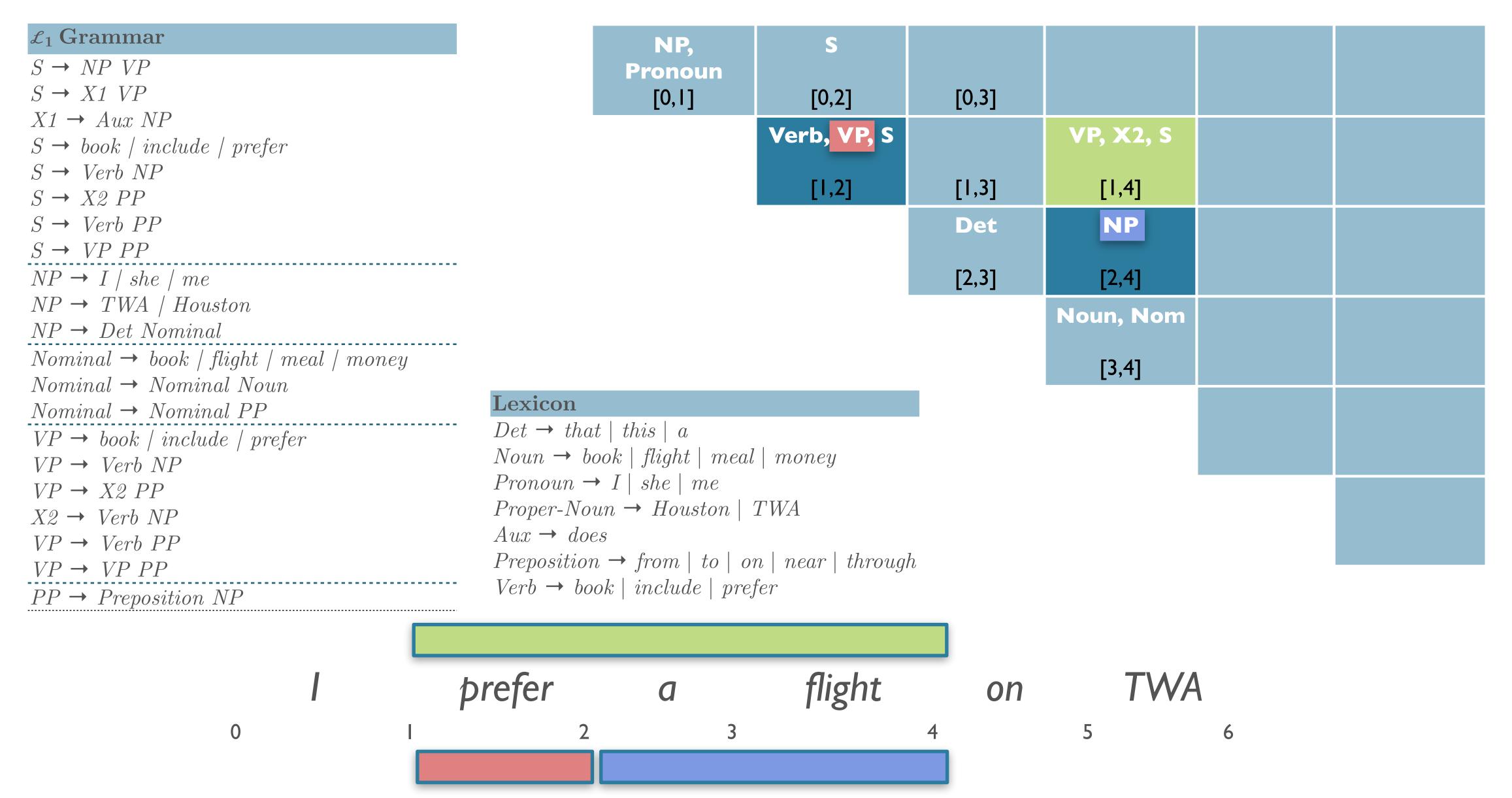


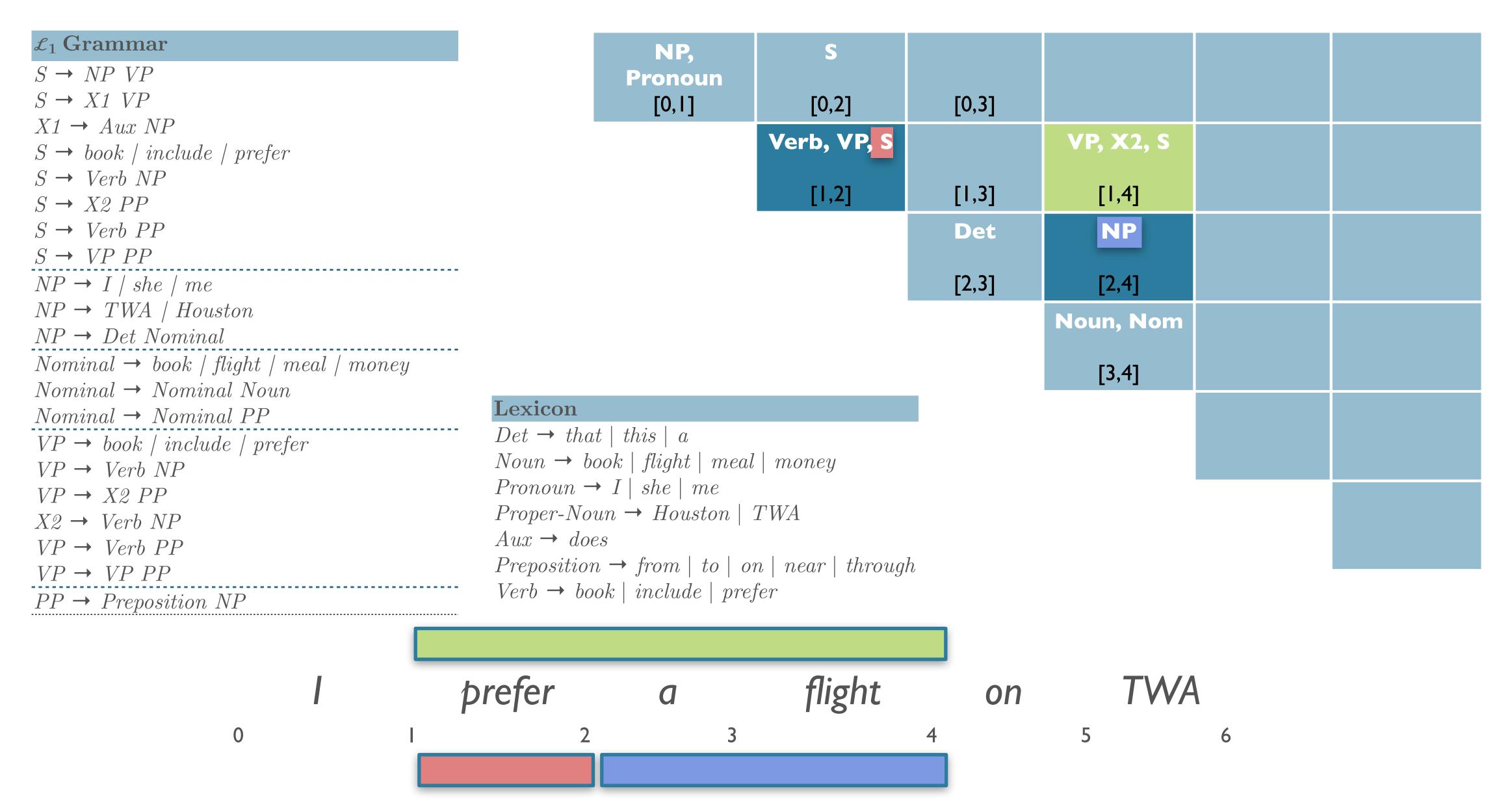


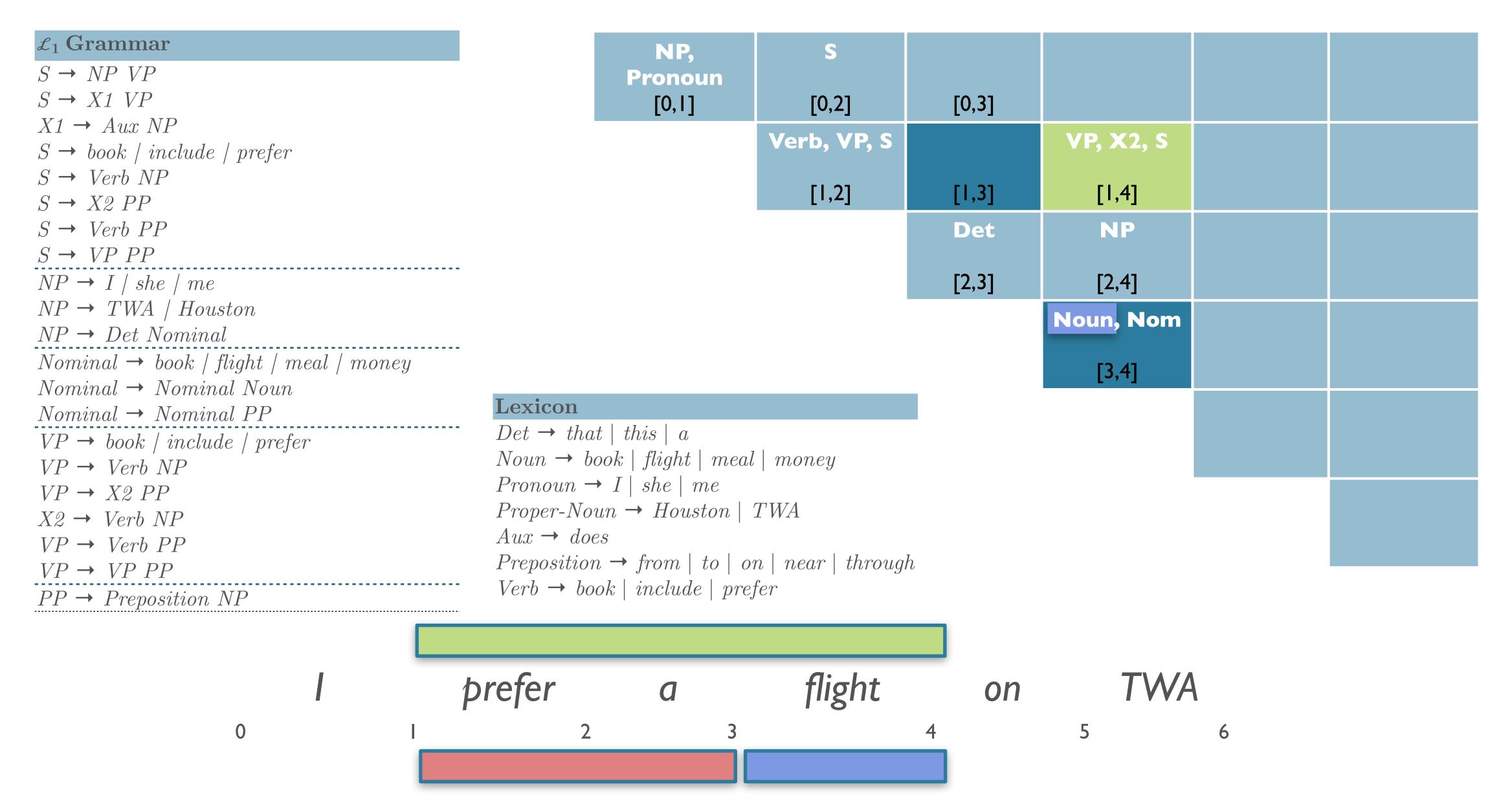


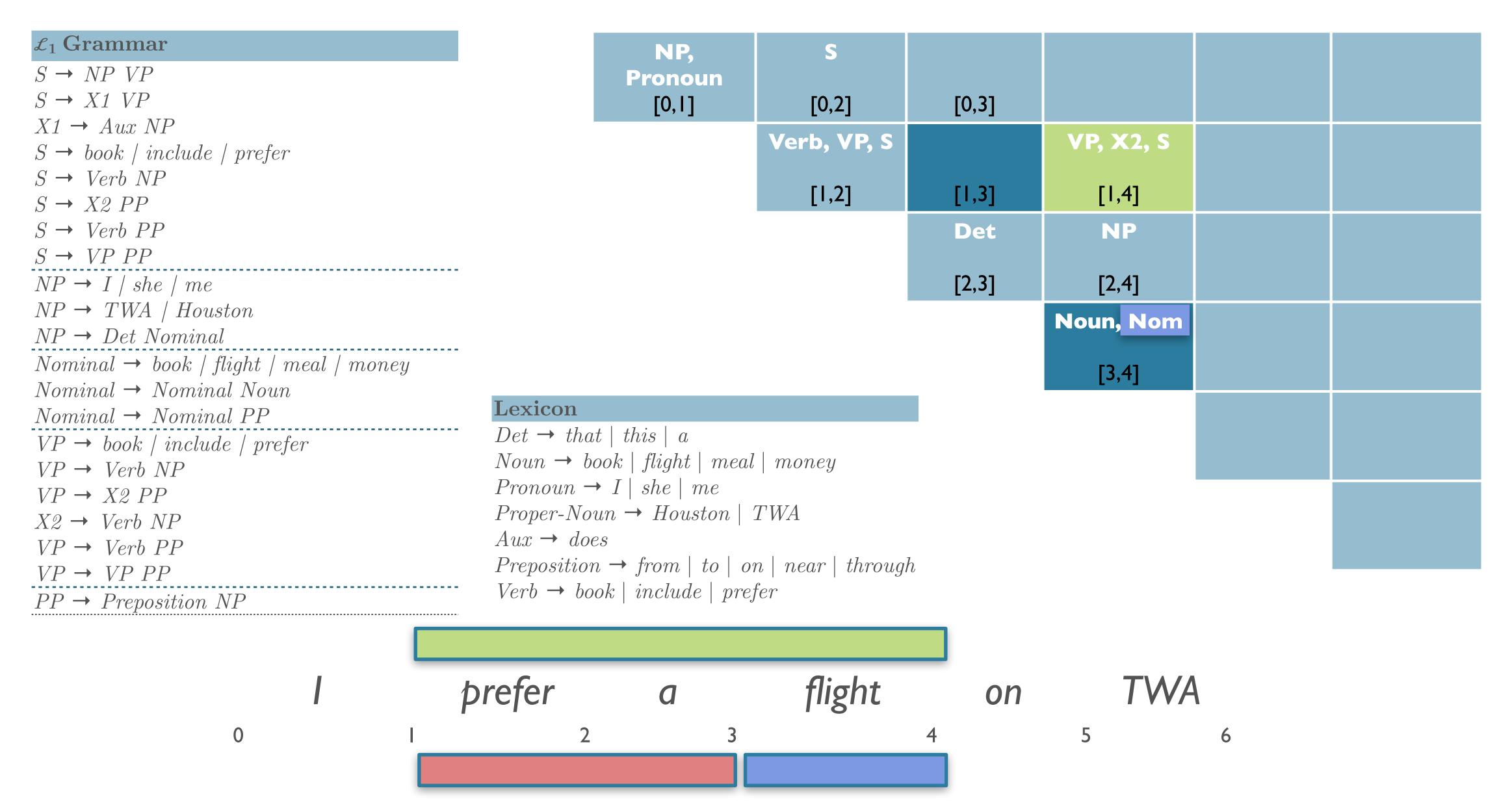


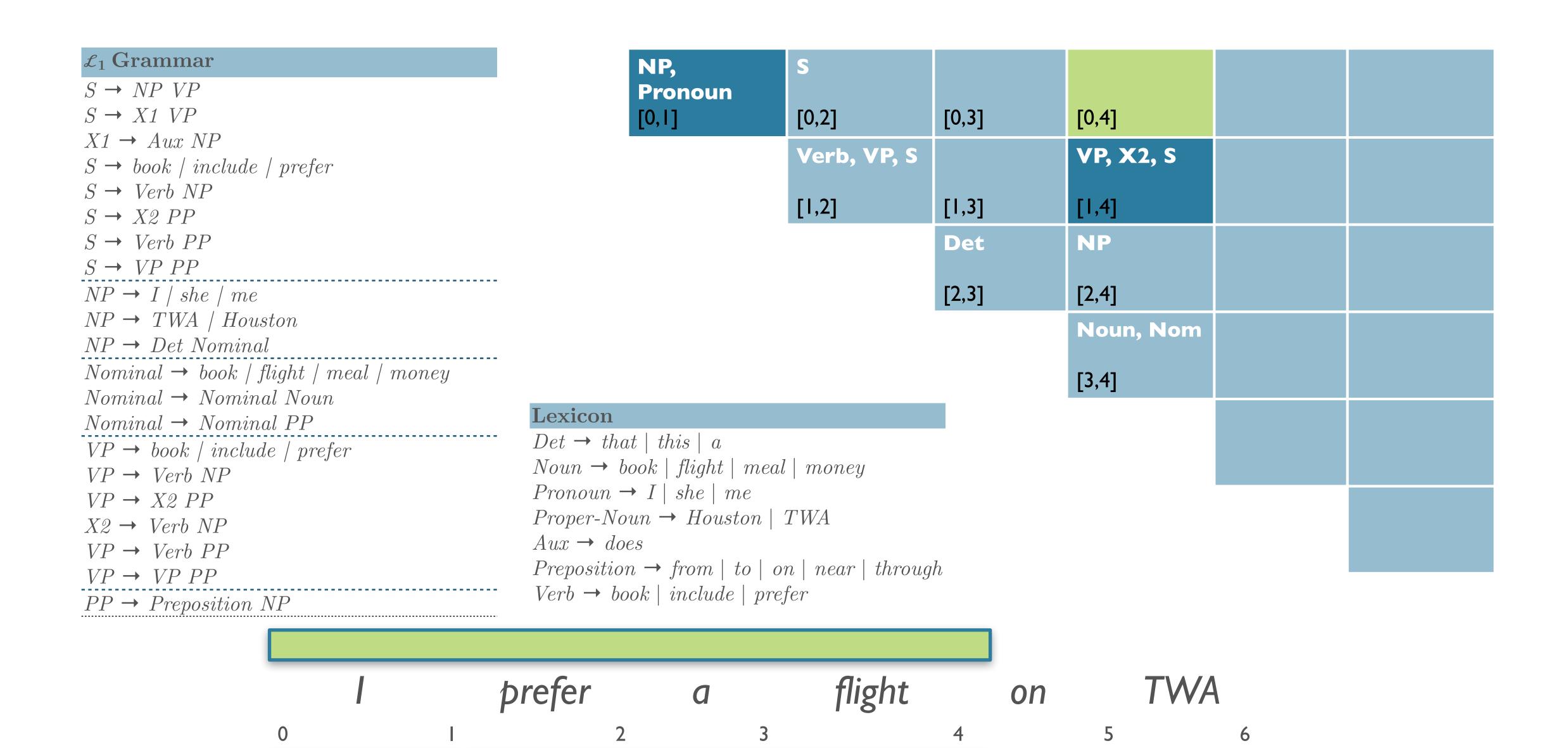


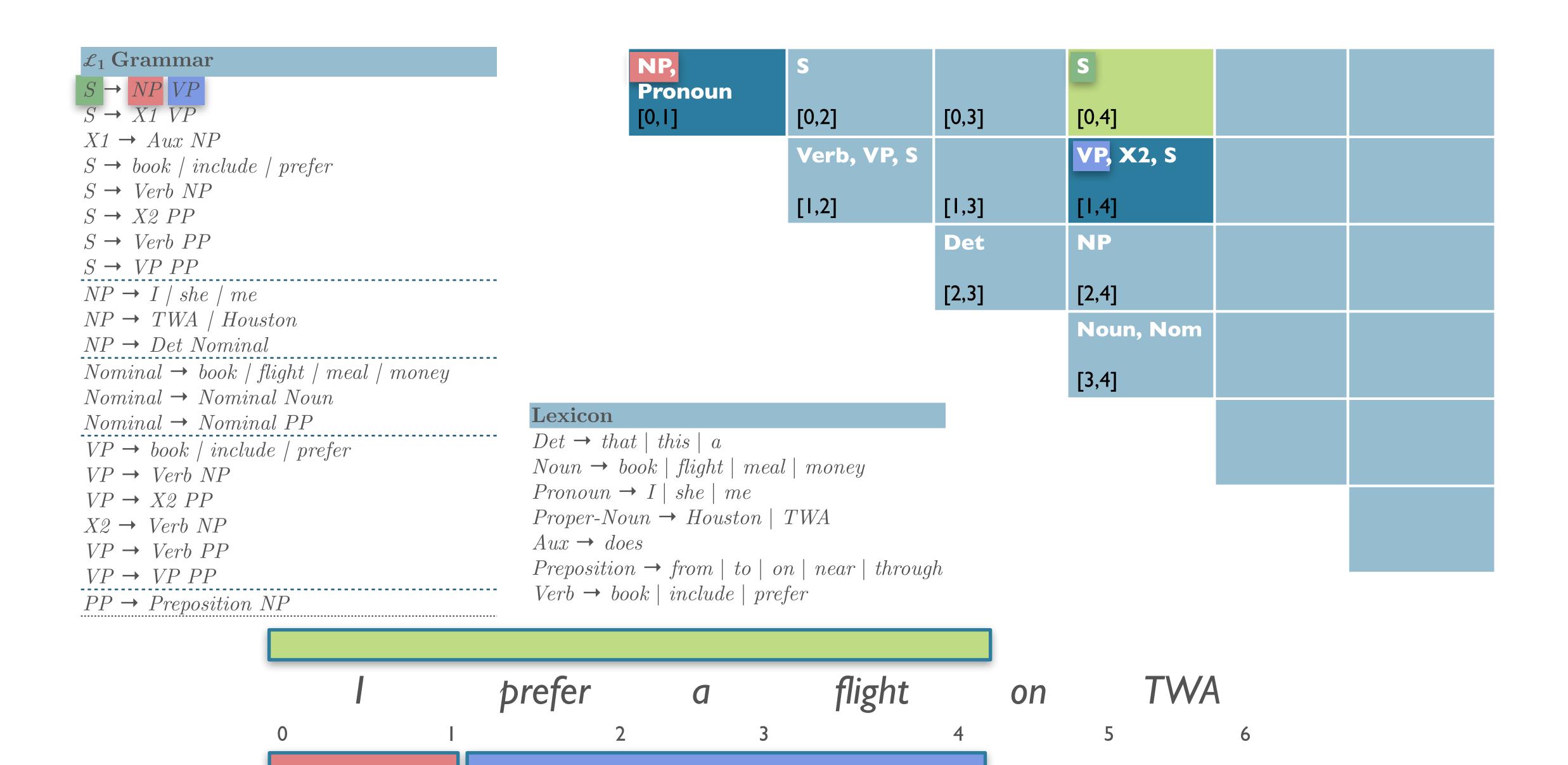


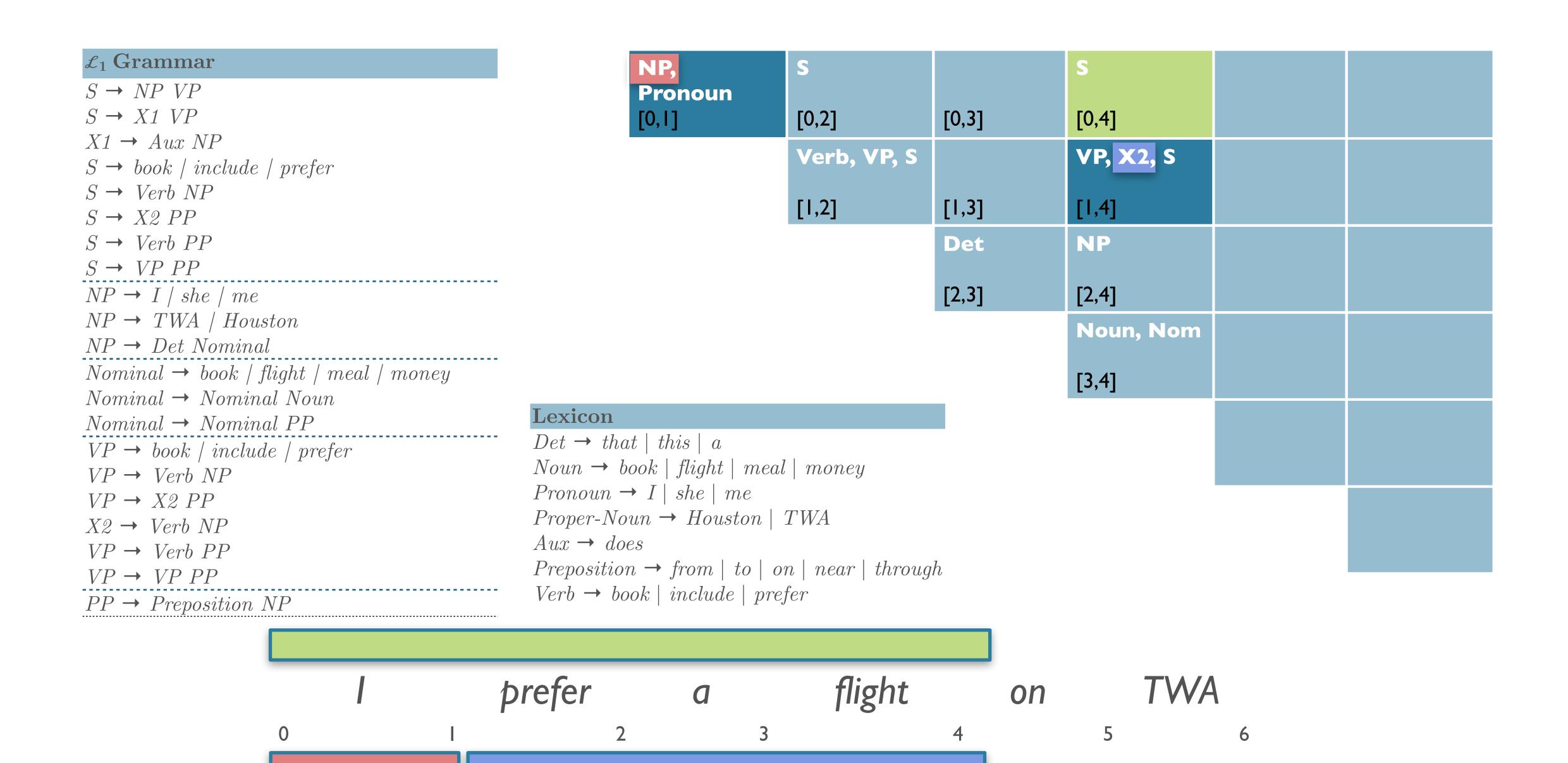


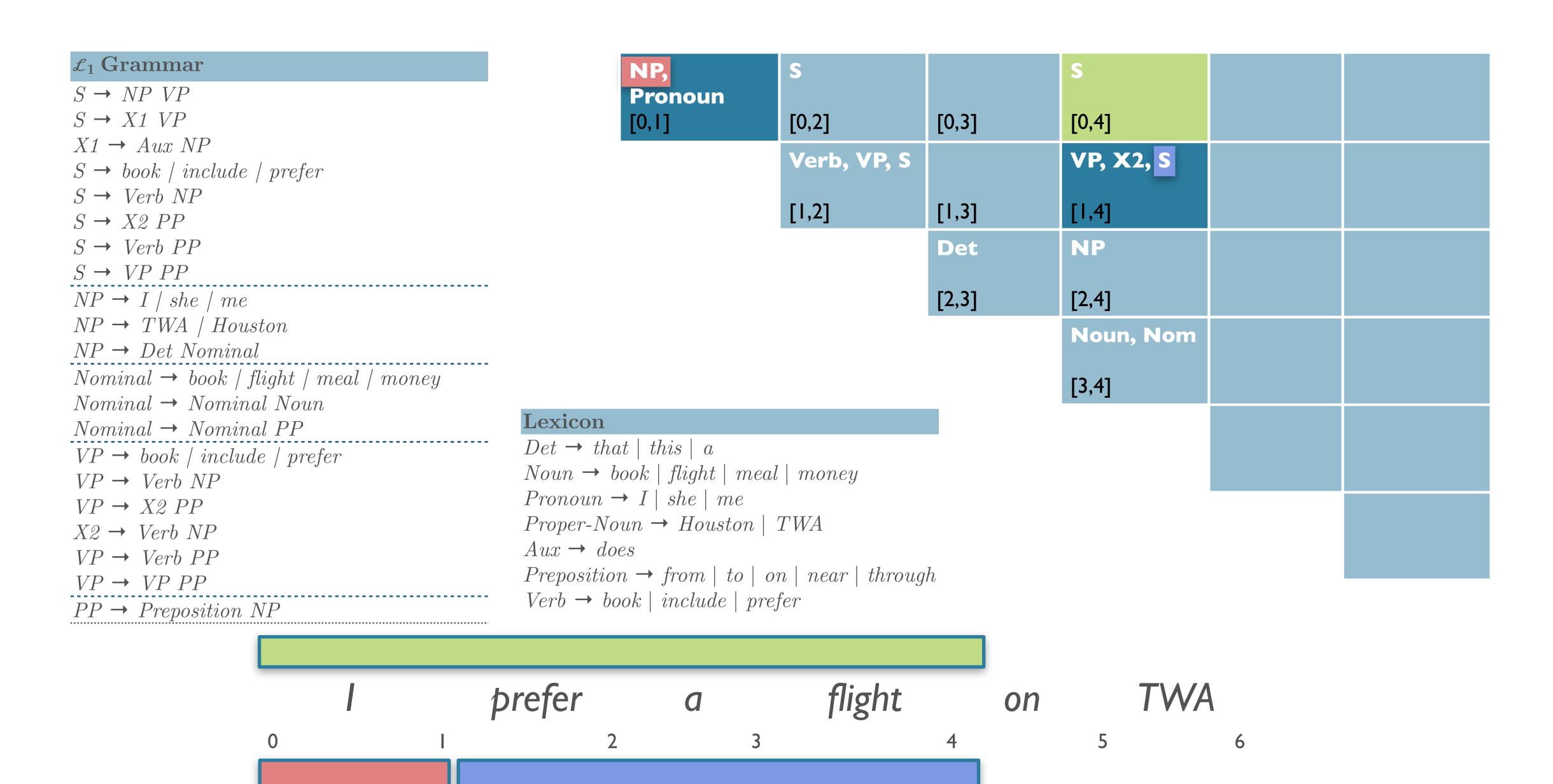


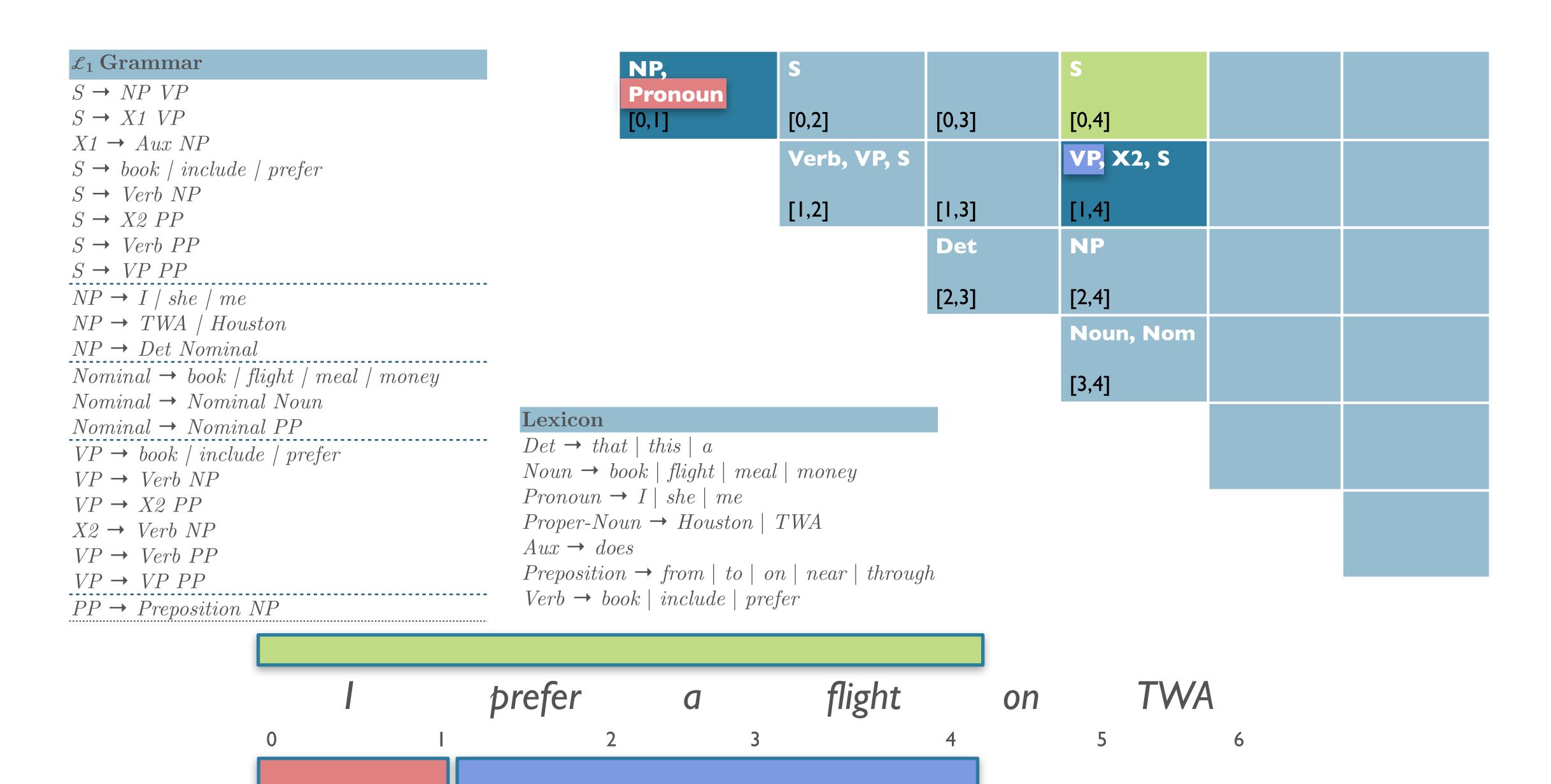


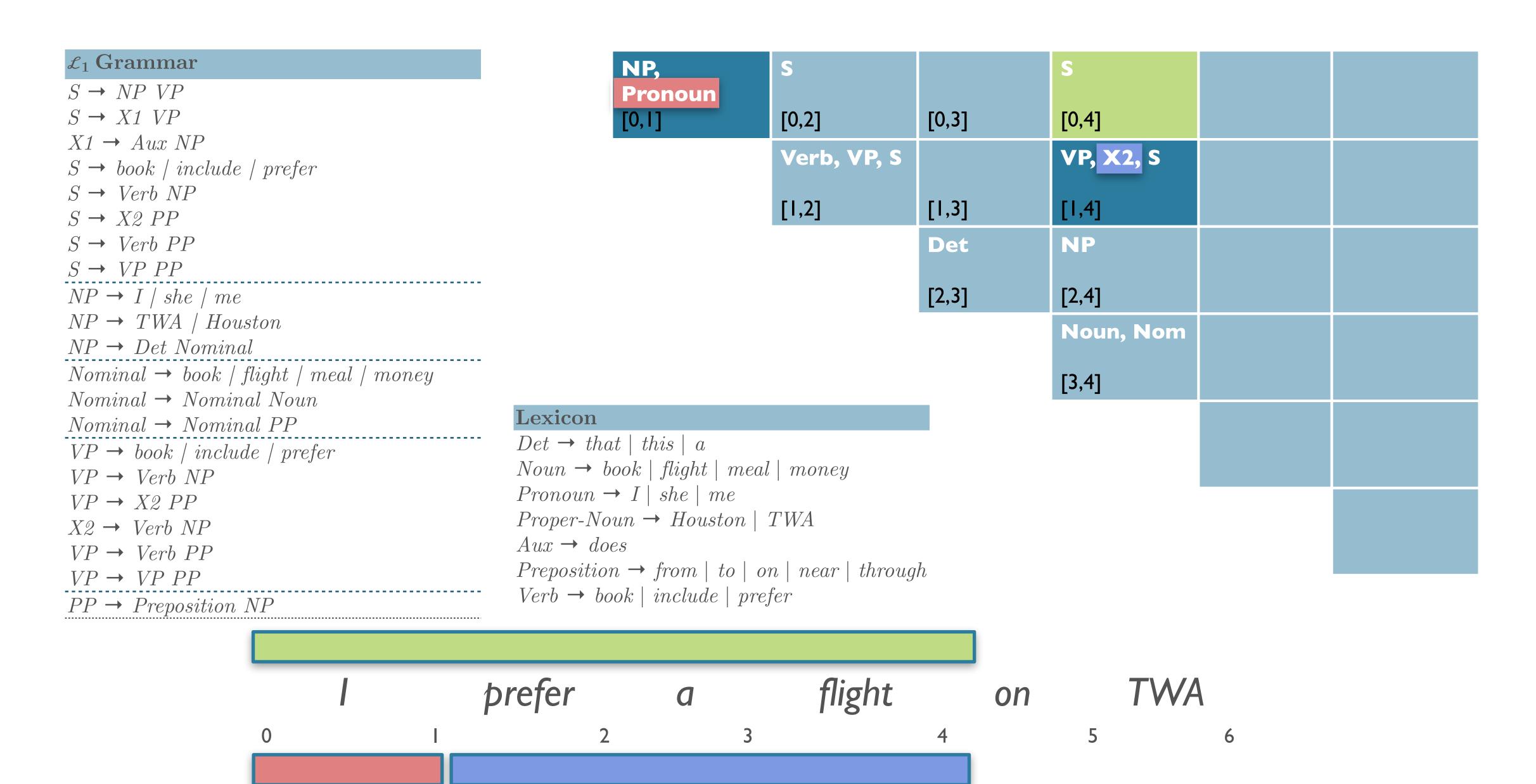


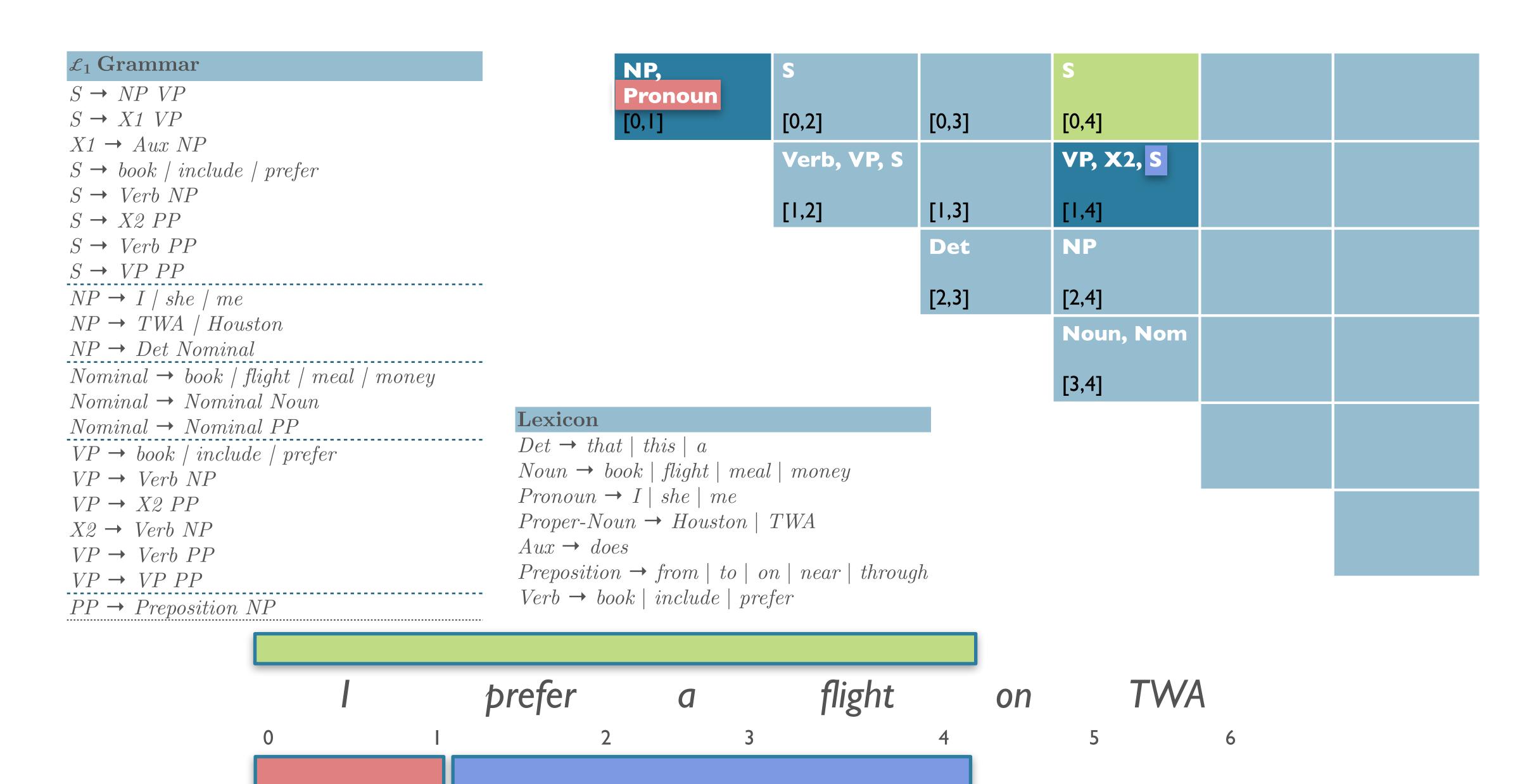


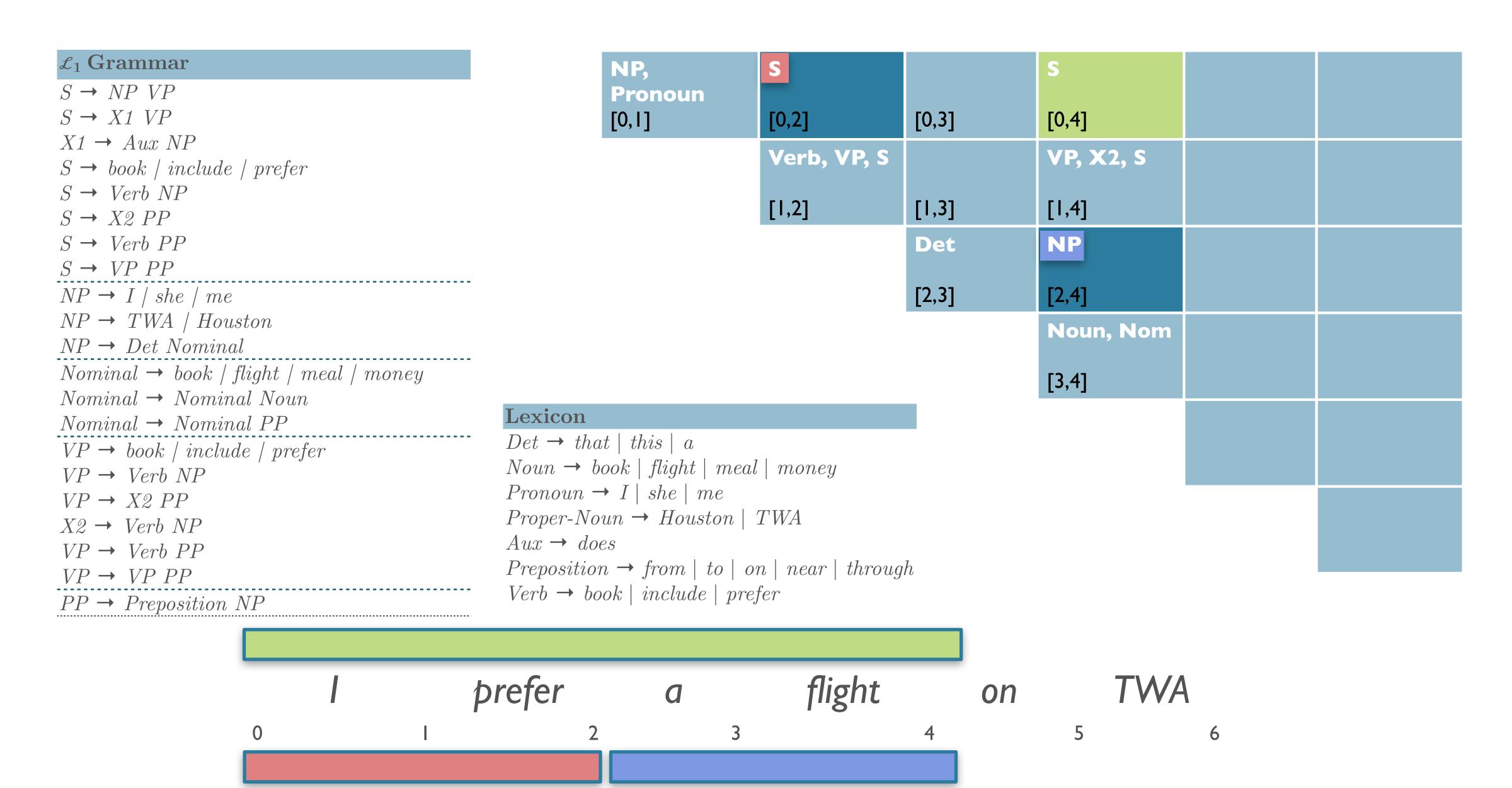




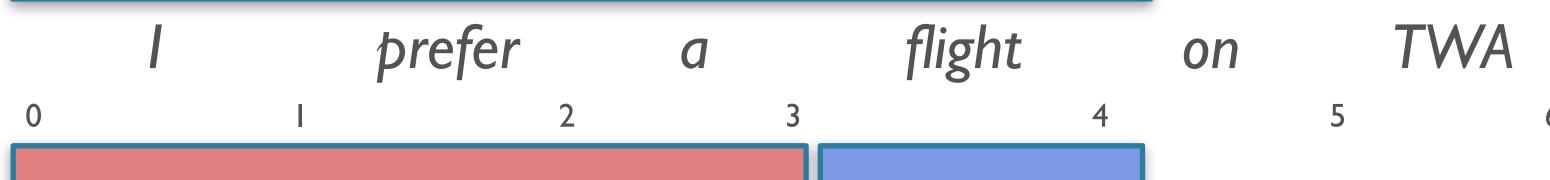








C_1 Grammar $C_2 \rightarrow NP \ VP$	NP, Pronoun	S		S	
$S \to X1 \ VP$	[0,1]	[0,2]	[0,3]	[0,4]	
$X1 \rightarrow Aux NP$ $S \rightarrow book / include / prefer$		Verb, VP, S		VP, X2, S	
$S \rightarrow Verb NP$ $S \rightarrow X2 PP$		[1,2]	[1,3]	[1,4]	
$S \rightarrow Verb PP$ $S \rightarrow VP PP$			Det	NP	
$NP \rightarrow I / she / me$			[2,3]	[2,4]	
$NP \rightarrow TWA \mid Houston$ $NP \rightarrow Det \ Nominal$			Noun, Nom		
Nominal → book / flight / meal / money Nominal → Nominal Noun				[3,4]	
$Nominal \rightarrow Nominal PP$	Lexicon				
$VP \rightarrow book / include / prefer$	$Det \rightarrow that \mid this \mid a$	7			
$VP \rightarrow Verb NP$	$Noun \rightarrow book \mid flight \mid meal$	$l \mid money$			
$VP \rightarrow X2 PP$	$Pronoun \rightarrow I \mid she \mid me$ $Pronoun \rightarrow Nove \rightarrow Hoveton \mid$				
$X2 \rightarrow Verb NP$	$Proper-Noun \rightarrow Houston \mid Array \rightarrow Arra$	1 VVA			
$VP \rightarrow Verb PP$	$Aux \rightarrow does$	17	7		
	$Preposition \rightarrow from \mid to \mid or$	$n \mid near \mid through$	n		
$VP \rightarrow VP PP$	$Verb \rightarrow book \mid include \mid pres$	C			



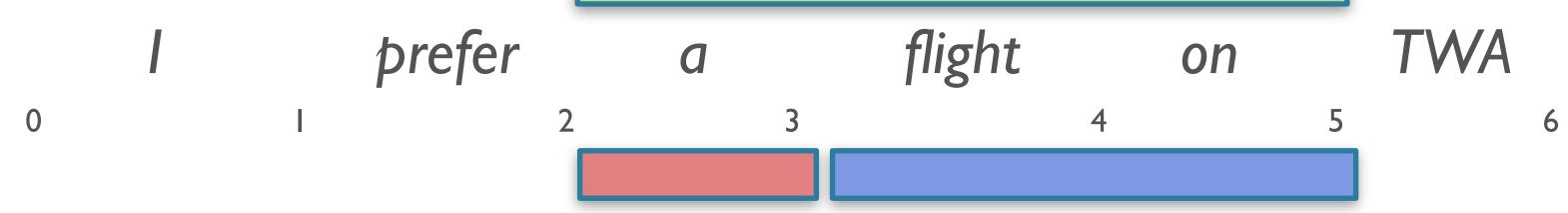
\mathcal{L}_1 Grammar	NP,	S		S		
$S \to NP VP$	Pronoun					
$S \rightarrow X1 \ VP$	[0,1]	[0,2]	[0,3]	[0,4]		
$X1 \rightarrow Aux NP$		Verb, VP, S		VP, X2, S		
$S \rightarrow book / include / prefer$		verb, vi, 5		\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\		
$S \rightarrow Verb NP$		ΓI 21	LI 31	ΓΙ Δ Ί		
$S \rightarrow X2 PP$		[1,2]	[1,3]	[1,4]		
$S \rightarrow Verb PP$			Det	NP		
$S \to VP PP$						
$NP \rightarrow I / she / me$			[2,3]	[2,4]		
$NP \rightarrow TWA / Houston$				Noun, Nom		
$NP \rightarrow Det\ Nominal$						
$Nominal \rightarrow book / flight / meal / money$				[3,4]		
$Nominal \rightarrow Nominal \ Noun$	T •		_	L-, .]		
$Nominal \rightarrow Nominal PP$	Lexicon				Prep	
$VP \rightarrow book / include / prefer$	$Det \rightarrow that \mid this \mid a$	7			- 4	
$VP \rightarrow Verb NP$	$Noun \rightarrow book \mid flight \mid mean$	$l \mid money$			[4,5]	
$VP \rightarrow X2 PP$	$Pronoun \rightarrow I \mid she \mid me$					
$X2 \rightarrow Verb NP$	$Proper-Noun \rightarrow Houston \mid$	TWA				
$VP \rightarrow Verb PP$	$Aux \rightarrow does$	1 1 17	7			
$VP \rightarrow VP PP$	$\begin{array}{ c c c c c c c c c c c c c c c c c c c$		ih			
$PP \rightarrow Preposition NP$	$Verb \rightarrow book \mid include \mid pre$	ter				



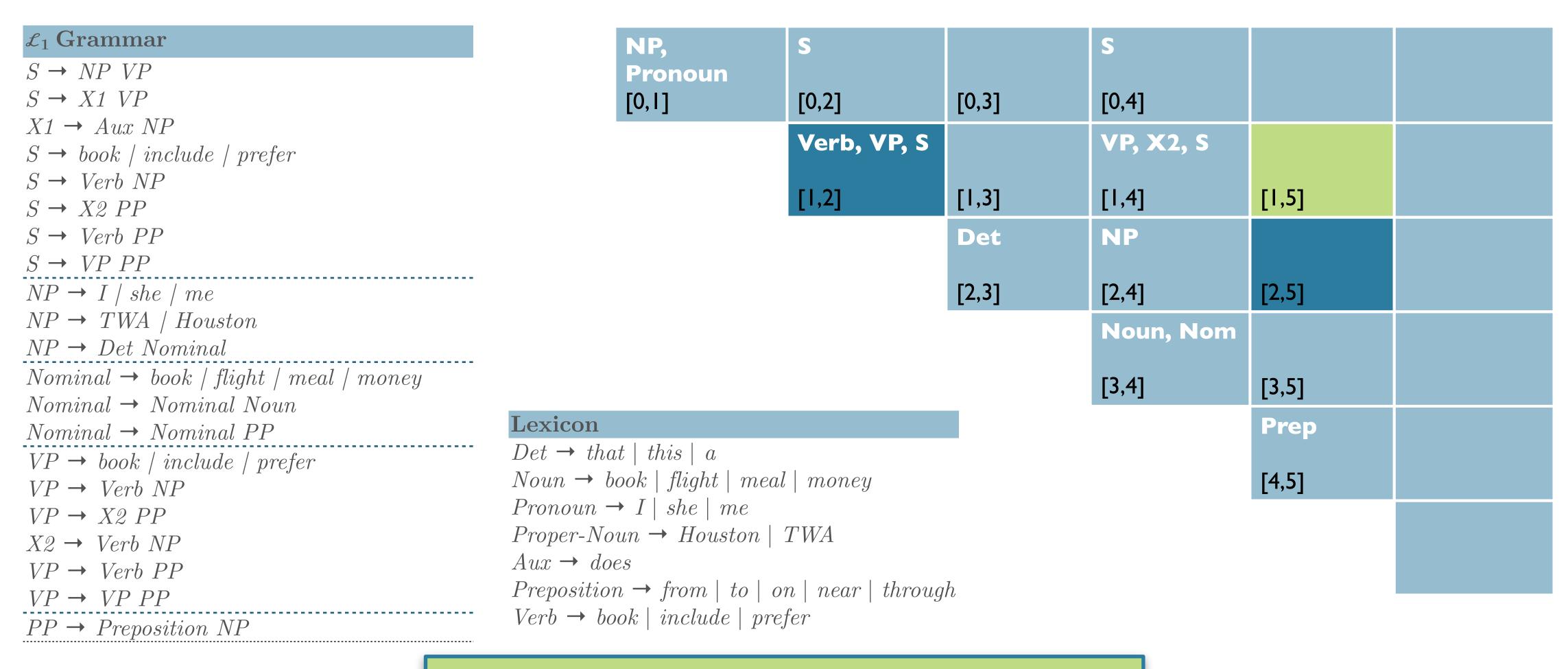
\mathcal{L}_1 Grammar $S \to NP \ VP$ $S \to X1 \ VP$	NP, Pronoun [0,1]	S [0,2]	[0,3]	S [0,4]		
$X1 \rightarrow Aux NP$ $S \rightarrow book / include / prefer$		Verb, VP, S		VP, X2, S		
$S \to Verb NP$ $S \to X2 PP$		[1,2]	[1,3]	[1,4]		
$S \rightarrow Verb PP$ $S \rightarrow VP PP$			Det	NP		
$NP \rightarrow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



\mathcal{L}_1 Grammar $S \to NP \ VP$ $S \to X1 \ VP$	NP, Pronoun [0,1]	S [0,2]	[0,3]	S [0,4]		
$X1 \rightarrow Aux \ NP$ $S \rightarrow book \ / \ include \ / \ prefer$ $S \rightarrow Verb \ NP$		Verb, VP, S		VP, X2, S		
$S \to X2 PP$ $S \to Verb PP$		[1,2]	[1,3] Det	[1,4] NP		
$S \rightarrow VP PP$ $NP \rightarrow I \mid she \mid me$ $NP \rightarrow TWA \mid Houston$			[2,3]	[2,4]	[2,5]	
$NP \rightarrow Det\ Nominal$ $Nominal \rightarrow book \ / \ flight \ / \ meal \ / \ money$				Noun, Nom [3,4]	[3,5]	
$Nominal \rightarrow Nominal \ Noun$ $Nominal \rightarrow Nominal \ PP$ $Nominal \rightarrow hook / implied a / profess$	Lexicon $Det \rightarrow that \mid this \mid a$			L / J	Prep	
$VP \rightarrow book \mid include \mid prefer$ $VP \rightarrow Verb \mid NP$ $VP \rightarrow X2 \mid PP$	$Noun \rightarrow book \mid flight \mid meal$ $Pronoun \rightarrow I \mid she \mid me$		[4,5]			
$X2 \rightarrow Verb \ NP$ $VP \rightarrow Verb \ PP$	$Proper-Noun \rightarrow Houston \mid$ $Aux \rightarrow does$ $Preposition \rightarrow from \mid to \mid o$					
$VP \rightarrow VP \ PP$ $PP \rightarrow Preposition \ NP$	$Verb \rightarrow book \mid include \mid pre$	•				

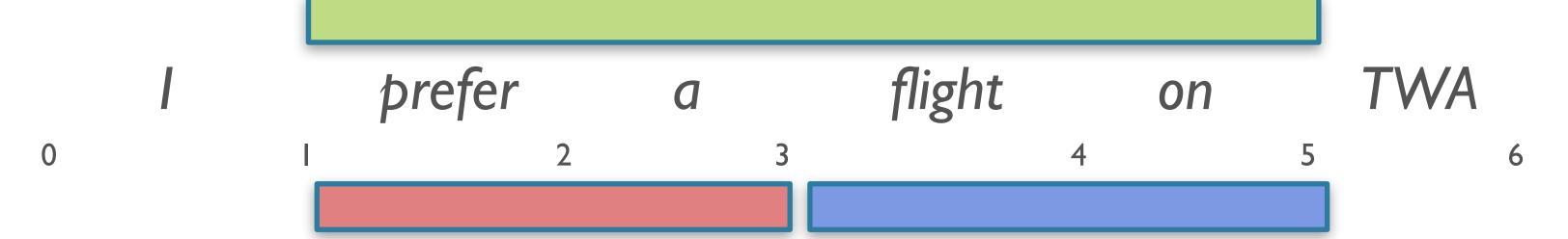


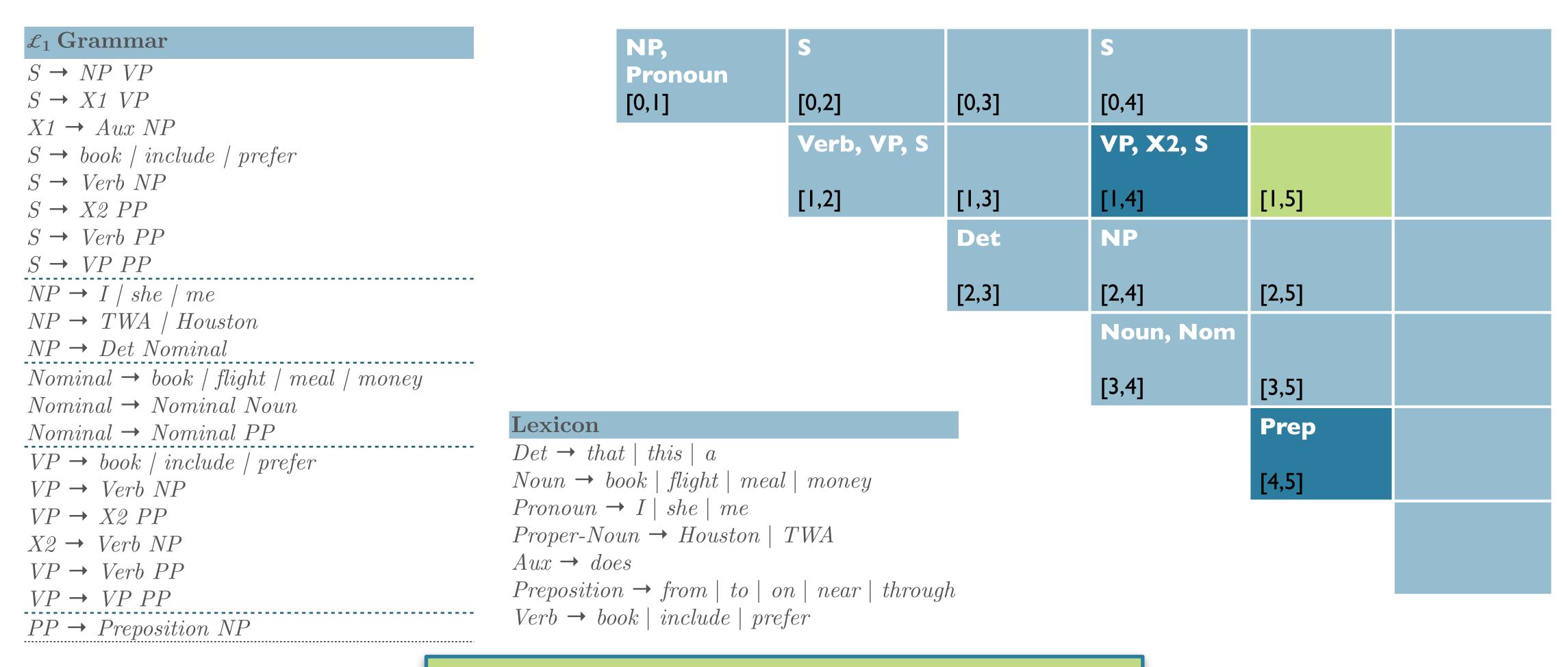
C_1 Grammar $C_2 \rightarrow NP \ VP$	NP, Pronoun	S		S		
$S \rightarrow X1 \ VP$	[0,1]	[0,2]	[0,3]	[0,4]		
$X1 \rightarrow Aux NP$			L / J			
$S \rightarrow book / include / prefer$		Verb, VP, S		VP, X2, S		
$S \rightarrow Verb NP$		[1,2]	L1 31	ΓΙ Δ Ί		
$S \rightarrow X2 PP$		[1,4]	[1,3]	[1,4]		
$S \rightarrow Verb PP$			Det	NP		
$S \rightarrow VP PP$	•					
$NP \rightarrow I / she / me$			[2,3]	[2,4]	[2,5]	
$NP \rightarrow TWA / Houston$				Noun, Nom		
$NP \rightarrow Det\ Nominal$	•					
$Nominal \rightarrow book / flight / meal / money$				[3,4]	[3,5]	
$Nominal \rightarrow Nominal Noun$ $Nominal \rightarrow Nominal DD$	Lexicon				Prep	
$Nominal \rightarrow Nominal PP$ $VP \rightarrow book / implied of markets$	$Det \rightarrow that \mid this \mid a$		•			
$VP \rightarrow book \mid include \mid prefer$ $VP \rightarrow Verb \mid NP$	$Noun \rightarrow book \mid flight \mid meal$	$\mid money$			[4,5]	
$VP \rightarrow X2 PP$	$Pronoun \rightarrow I \mid she \mid me$				L / J	
$X2 \rightarrow Verb NP$	$Proper-Noun \rightarrow Houston \mid :$	TWA				
$VP \rightarrow Verb PP$	$Aux \rightarrow does$					
$VP \rightarrow VP PP$	$Preposition \rightarrow from \mid to \mid or$	$n \mid near \mid through$	\tilde{n}			
$PP \rightarrow Preposition NP$	$Verb \rightarrow book \mid include \mid pres$	fer				
1	prefer a	flight	on	TWA		

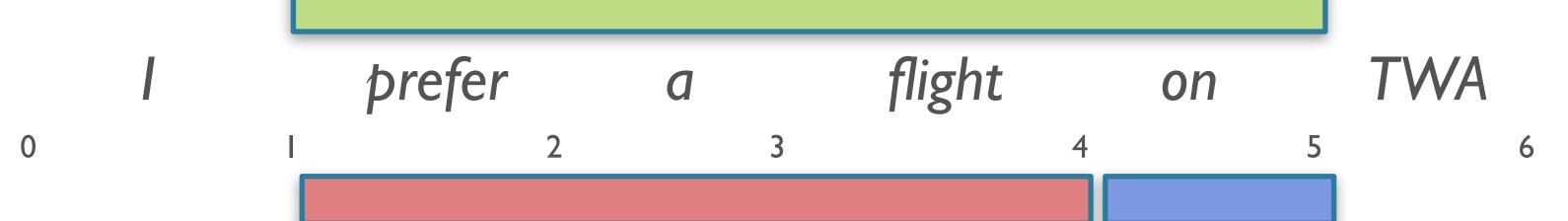




\mathcal{L}_1 Grammar	NP,	S		S		
$S \to NP VP$	Pronoun					
$S \rightarrow X1 \ VP$	[0,1]	[0,2]	[0,3]	[0,4]		
$X1 \rightarrow Aux NP$		Verb, VP, S		VP, X2, S		
$S \rightarrow book / include / prefer$		verb, vi, s		VI, AZ, 5		
$S \rightarrow Verb NP$		[L 2]	[] 3]	ΓΙ Δ Ί	F1 51	
$S \rightarrow X2 PP$		[1,2]	[1,3]	[1,4]	[1,5]	
$S \rightarrow Verb PP$			Det	NP		
$S \to VP PP$						
$NP \rightarrow I / she / me$			[2,3]	[2,4]	[2,5]	
$NP \rightarrow TWA / Houston$				Noun, Nom		
$NP \rightarrow Det\ Nominal$						
$Nominal \rightarrow book / flight / meal / money$				[3,4]	[3,5]	
$Nominal \rightarrow Nominal \ Noun$	•					
$Nominal \rightarrow Nominal PP$	Lexicon				Prep	
VI ' 0000 61606406 016161	$Det \rightarrow that \mid this \mid a$	7			- 4	
	$Noun \rightarrow book \mid flight \mid mean$	$k \mid money$			[4,5]	
VI , $\Lambda \gtrsim II$	$Pronoun \rightarrow I \mid she \mid me$					
ΛZ , $VCIOIVI$	$Proper-Noun \rightarrow Houston \mid$	TWA				
$VP \rightarrow Vero PP$	$Aux \rightarrow does$					
	$Preposition \rightarrow from \mid to \mid o$, ,	rh			
$PP \rightarrow Preposition NP$	$Verb \rightarrow book \mid include \mid pre$	ter				

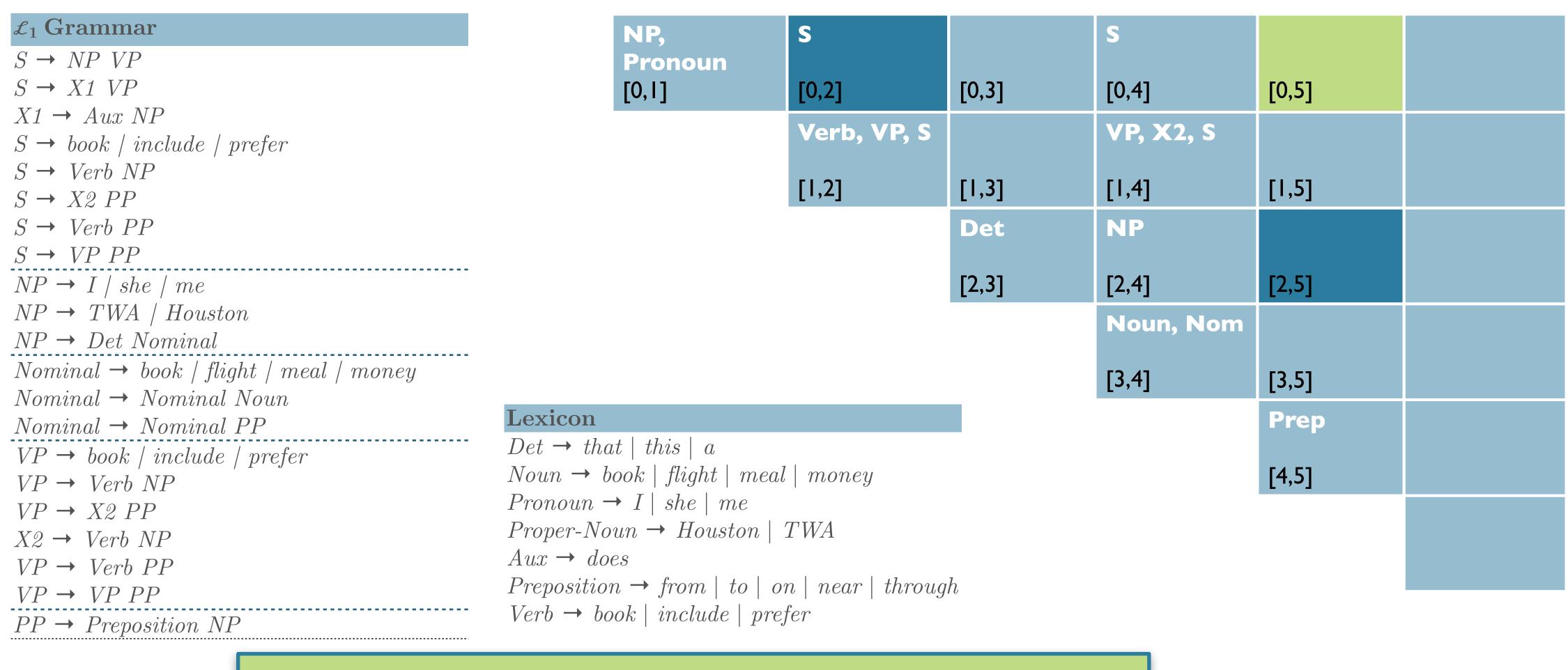


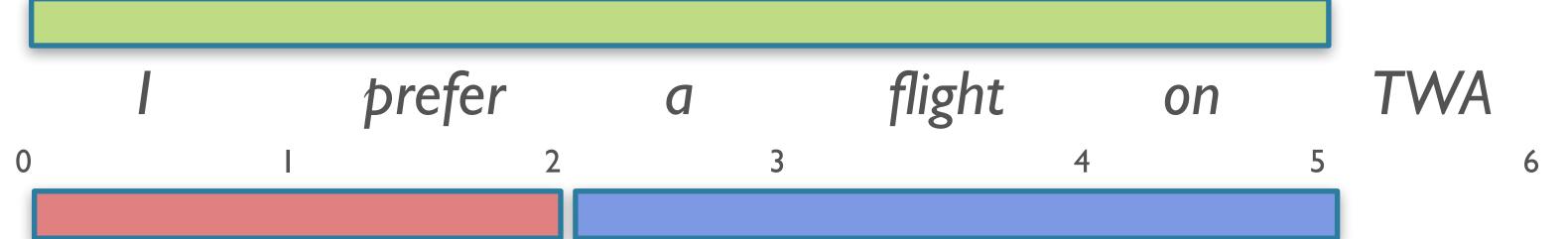




\mathcal{L}_1 Grammar	NP,	S		S		
$S \rightarrow NP VP$	Pronoun					
$S \rightarrow X1 \ VP$	[0,1]	[0,2]	[0,3]	[0,4]	[0,5]	
$X1 \rightarrow Aux NP$			L / J		L / J	
$S \rightarrow book / include / prefer$		Verb, VP, S		VP, X2, S		
$S \rightarrow Verb NP$		[] O]	[] 2]	F1 47	F1 F2	
$S \rightarrow X2 PP$		[1,2]	[1,3]	[1,4]	[1,5]	
$S \rightarrow Verb PP$			Det	NP		
$S \to VP PP$						
$NP \rightarrow I / she / me$			[2,3]	[2,4]	[2,5]	
$NP \rightarrow TWA / Houston$				Noun, Nom		
$NP \rightarrow Det\ Nominal$				rtoun, rtoin		
$Nominal \rightarrow book / flight / meal / money$				[3,4]	[3,5]	
$Nominal \rightarrow Nominal Noun$	T •					
$Nominal \rightarrow Nominal PP$	Lexicon				Prep	
$VP \rightarrow book / include / prefer$	$Det \rightarrow that \mid this \mid a$	7			F4 F3	
$VP \rightarrow Verb NP$	$Noun \rightarrow book \mid flight \mid mea$	$ul \mid money$			[4,5]	
$VP \rightarrow X2 PP$	$Pronoun \rightarrow I \mid she \mid me$	TT 1 1 7 A				
$X2 \rightarrow Verb NP$	$Proper-Noun \rightarrow Houston \mid$	IVVA				
$VP \rightarrow Verb PP$	$Aux \rightarrow does$.1.			
$VP \rightarrow VP PP$	$Preposition \rightarrow from \mid to \mid c$ $Vorb \rightarrow book \mid in all do \mid mn$		Tt			
$PP \rightarrow Preposition NP$	$Verb \rightarrow book \mid include \mid pre$	ejer.				

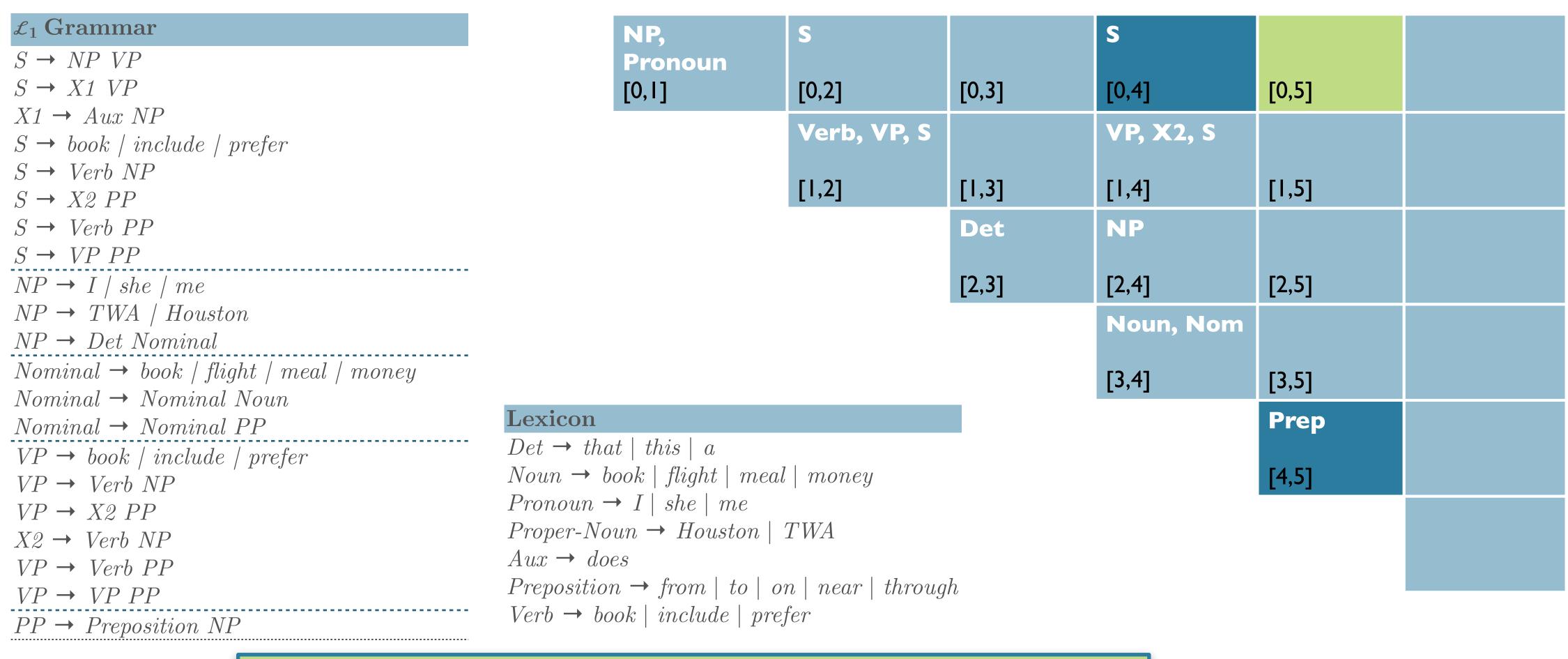


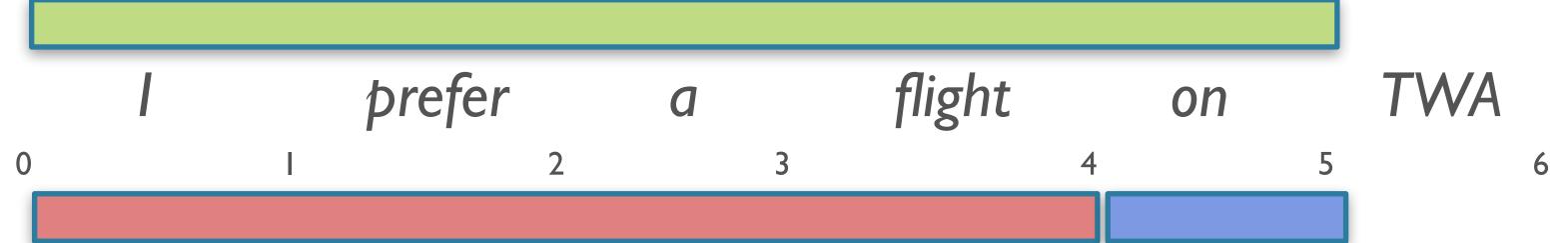




\mathcal{L}_1 Grammar	NP,	S		S		
$S \rightarrow NP VP$	Pronoun					
$S \rightarrow X1 \ VP$	[0,1]	[0,2]	[0,3]	[0,4]	[0,5]	
$X1 \rightarrow Aux NP$						
$S \rightarrow book / include / prefer$		Verb, VP, S		VP, X2, S		
$S \rightarrow Verb NP$		F1 21	F1 21	F1 47	F1 F3	
$S \rightarrow X2 PP$		[1,2]	[1,3]	[1,4]	[1,5]	
$S \rightarrow Verb PP$			Det	NP		
$S \rightarrow VP PP$						
$NP \rightarrow I / she / me$			[2,3]	[2,4]	[2,5]	
$NP \rightarrow TWA / Houston$				Noun, Nom		
$NP \rightarrow Det\ Nominal$				radin, radin		
$Nominal \rightarrow book / flight / meal / money$				[3,4]	[3,5]	
$Nominal \rightarrow Nominal \ Noun$	T •		_			
$Nominal \rightarrow Nominal PP$	Lexicon				Prep	
$VP \rightarrow book / include / prefer$	$Det \rightarrow that \mid this \mid a$	7. 1			_ ,	
$VP \rightarrow Verb NP$	$Noun \rightarrow book \mid flight \mid mea$	$al \mid money$			[4,5]	
$VP \rightarrow X2 PP$	$Pronoun \rightarrow I \mid she \mid me$					
$X2 \rightarrow Verb NP$	$Proper-Noun \rightarrow Houston \mid$	TWA				
$VP \rightarrow Verb PP$	$Aux \rightarrow does$	1 .7	7			
$VP \rightarrow VP PP$	$Preposition \rightarrow from \mid to \mid c$		gh			
$PP \rightarrow Preposition NP$	$Verb \rightarrow book \mid include \mid pro$	efer				



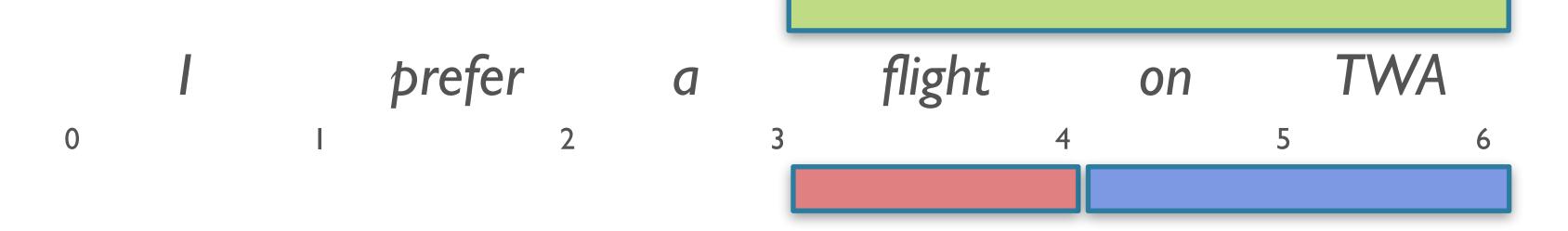




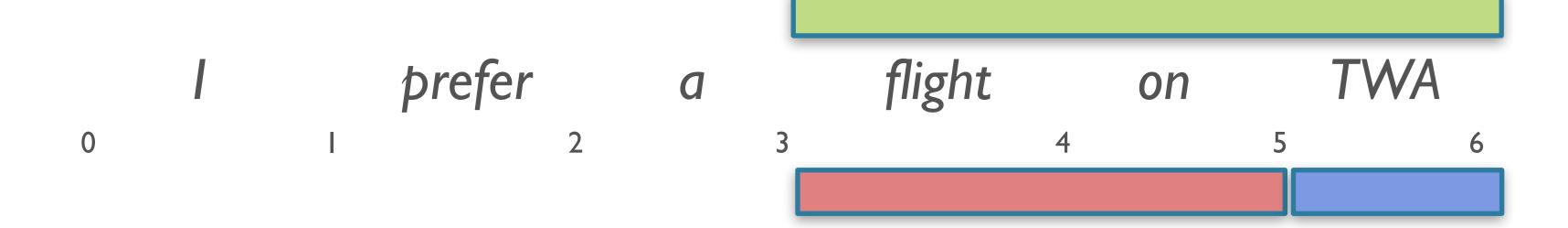
\mathcal{L}_1 Grammar $S \to NP \ VP$		NP, Pronoun	S		S		
$S \rightarrow X1 \ VP$		[0,1]	[0,2]	[0,3]	[0,4]	[0,5]	
$X1 \rightarrow Aux NP$			Verb, VP, S		VP, X2, S		
$S \rightarrow book \mid include \mid prefer$ $S \rightarrow Verb NP$							
$S \to X2 PP$			[1,2]	[1,3]	[1,4]	[1,5]	
$S \rightarrow Verb PP$				Det	NP		
$S \rightarrow VP PP$							
$NP \rightarrow I / she / me$				[2,3]	[2,4]	[2,5]	
$NP \rightarrow TWA \mid Houston$ $NP \rightarrow Det \ Nominal$					Noun, Nom		
$Nominal \rightarrow book / flight / meal / money$					FO. 47		
$Nominal \rightarrow Nominal \ Noun$					[3,4]	[3,5]	
$Nominal \rightarrow Nominal PP$	Lexicon					Prep	
$VP \rightarrow book \mid include \mid prefer$	$Det \rightarrow that$ $Norm \rightarrow ba$		a1 man an an			F4 F3	
$VP \rightarrow Verb NP$		$egin{array}{c c c} ok & flight & me \ I & she & me \ \end{array}$	at money			[4,5]	
$VP \rightarrow X2 PP$ $VO \rightarrow VV \rightarrow VP$		$n \rightarrow Houston$	TWA				NNP, NP
$X2 \rightarrow Verb \ NP$ $VP \rightarrow Verb \ PP$	$Aux \rightarrow does$						FF /3
$VP \rightarrow VP PP$	Preposition	\rightarrow from to	on near throug	gh			[5,6]
$PP \rightarrow Preposition NP$	$Verb \rightarrow boo$	$pk \mid include \mid pr$	refer				
	þrefer	a	flight	on	TWA		

\mathcal{L}_1 Grammar	NP,		S		S		
$S \to NP VP$		noun					
$S \to X1 \ VP$	[0,1]		[0,2]	[0,3]	[0,4]	[0,5]	
$X1 \to Aux NP$			Verb, VP, S		VP, X2, S		
$S \rightarrow book / include / prefer$, , , , , , , , , , , , , , , , , , , ,		
$S \rightarrow Verb NP$			[1,2]	[1,3]	[1,4]	[1,5]	
$S \rightarrow X2 PP$ $S \rightarrow Verb PP$			L / J				
$S \rightarrow VPP$				Det	NP		
$NP \rightarrow I / she / me$				[2,3]	[2,4]	[2,5]	
$NP \rightarrow TWA / Houston$				L / J			
$NP \rightarrow Det Nominal$					Noun, Nom		
$Nominal \rightarrow book \ / \ flight \ / \ meal \ / \ money$					[3,4]	[3,5]	
Nominal → Nominal Noun	-			_			
$Nominal \rightarrow Nominal PP$	Lexicon					Prep	PP
$VP \rightarrow book \mid include \mid prefer$	$Det \rightarrow that \mid this$	'	7			F 4 F 3	E 4 . 4 7
$VP \rightarrow Verb NP$	$Noun \rightarrow book \mid f$	-	$l \mid money$			[4,5]	[4,6]
$VP \rightarrow X2 PP$	$Pronoun \to I \mid s$ $Pronoun \to I \mid s$	·	TINA				NNP, NP
$X2 \rightarrow Verb NP$	$Proper-Noun \rightarrow Aux \rightarrow does$	$HOUSIOH \mid$	I VVA				
$VP \rightarrow Verb PP$		com to o	m maar throug	a.h			[5,6]
$VP \rightarrow VP PP$	$Preposition \rightarrow fr$ $Verb \rightarrow book \mid in$	·	·	116			
$PP \rightarrow Preposition NP$	vero , oook th	iciaac pre	JCI				
	refer		flight		n TWA		

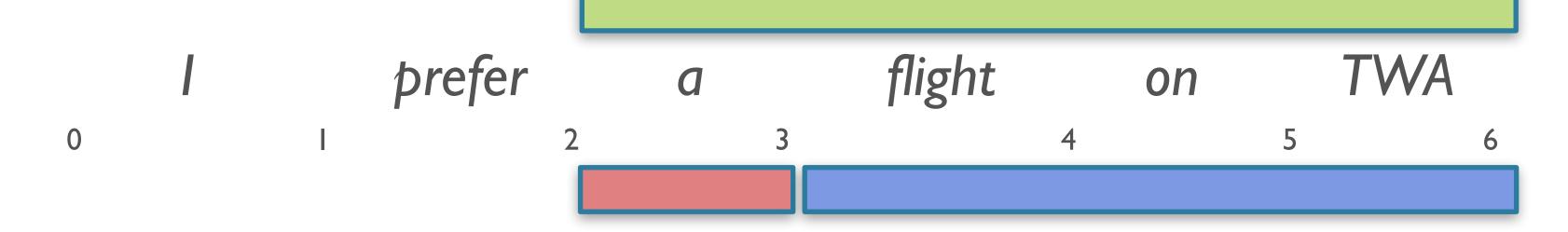
\mathcal{L}_1 Grammar	ND	C				
$S \rightarrow NP \ VP$	NP, Pronoun	S		S		
$S \rightarrow X1 \ VP$	[0,1]	[0,2]	[0,3]	[0,4]	[0,5]	
$X1 \rightarrow Aux NP$			L / J			
$S \rightarrow book / include / prefer$		Verb, VP, S		VP, X2, S		
$S \rightarrow Verb NP$		FL 21	F1 21	ΓΙ <i>Δ</i> Ί	F1 F3	
$S \to X2 PP$		[1,2]	[1,3]	[1,4]	[1,5]	
$S \rightarrow Verb PP$			Det	NP		
$S \to VP PP$						
$NP \rightarrow I / she / me$			[2,3]	[2,4]	[2,5]	
$NP \rightarrow TWA / Houston$				Noun, Nom		Nom
$NP \rightarrow Det\ Nominal$						
$Nominal \rightarrow book / flight / meal / money$				[3,4]	[3,5]	[3,6]
$Nominal \rightarrow Nominal Noun$	Lovicon					
$Nominal \rightarrow Nominal PP$	Lexicon $Det \rightarrow that \mid this \mid a$				Prep	PP
$VP \rightarrow book / include / prefer$	$Noun \rightarrow book \mid flight \mid mean$	l moneu			Γ Δ 51	Γ <u>4</u>
$VP \rightarrow Verb NP$	$Pronoun \rightarrow I \mid she \mid me$	$f \mid HOHCy$			[4,5]	[4,6]
$VP \rightarrow X2 PP$	$Proper-Noun \rightarrow Houston$	TWA				NNP, NP
$X2 \rightarrow Verb NP$	$Aux \rightarrow does$	1 //21				
$VP \rightarrow Verb PP$	$Preposition \rightarrow from \mid to \mid o$	h			[5,6]	
$VP \rightarrow VP PP$	$Verb \rightarrow book \mid include \mid pre$	-	• •			
$PP \rightarrow Preposition NP$		<i>J</i> - ·				



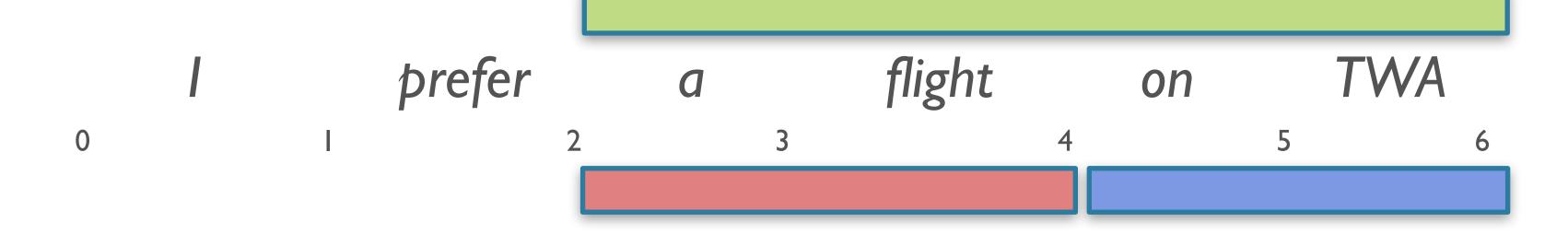
\mathcal{L}_1 Grammar	NP,	S		S		
$S \to NP VP$	Pronoun					
$S \rightarrow X1 \ VP$	[0,1]	[0,2]	[0,3]	[0,4]	[0,5]	
$X1 \rightarrow Aux NP$	_ _					
$S \rightarrow book / include / prefer$		Verb, VP, S		VP, X2, S		
$S \rightarrow Verb NP$		F1 21	FI 21	ΓΙ / 1	ri 51	
$S \to X2 PP$		[1,2]	[1,3]	[1,4]	[1,5]	
$S \rightarrow Verb PP$			Det	NP		
$S \to VP PP$						
$NP \rightarrow I / she / me$			[2,3]	[2,4]	[2,5]	
$NP \rightarrow TWA / Houston$				Noun, Nom		Nom
$NP \rightarrow Det\ Nominal$						
$Nominal \rightarrow book / flight / meal / money$				[3,4]	[3,5]	[3,6]
$Nominal \rightarrow Nominal \ Noun$	T			L / J		
$Nominal \rightarrow Nominal PP$	Lexicon Detailed this leads				Prep	PP
$VP \rightarrow book / include / prefer$	$Det \rightarrow that \mid this \mid a$	7 200 000 001			F4 F3	F4 23
$VP \rightarrow Verb NP$	$Noun \rightarrow book \mid flight \mid mean$	$l \mid money$			[4,5]	[4,6]
$VP \rightarrow X2 PP$	$Pronoun \rightarrow I \mid she \mid me$	TINA				NNP, NP
$X2 \rightarrow Verb NP$	$Proper-Noun \rightarrow Houston \mid Aux \rightarrow does$	1 VVA				
$VP \rightarrow Verb PP$		m moam thmough	.h			[5,6]
$VP \rightarrow VP PP$	$Preposition \rightarrow from \mid to \mid o$ $Vorb \rightarrow book \mid include \mid mre$		110			
$PP \rightarrow Preposition NP$	$Verb \rightarrow book \mid include \mid pre$	JET				



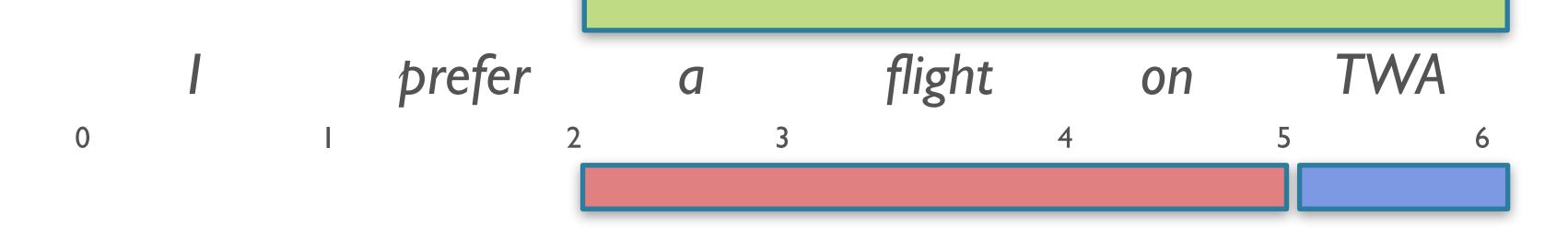
\mathcal{L}_1 Grammar	NP,	S		S		
$S \rightarrow NP VP$	Pronoun					
$S \rightarrow X1 \ VP$	[0,1]	[0,2]	[0,3]	[0,4]	[0,5]	
$X1 \rightarrow Aux NP$						
$S \rightarrow book / include / prefer$		Verb, VP, S		VP, X2, S		
$S \rightarrow Verb NP$		ΓΙ 21	[] 21	ΓΙ Δ 1	F1 51	
$S \to X2 PP$		[1,2]	[1,3]	[1,4]	[1,5]	
$S \rightarrow Verb PP$			Det	NP		NP
$S \rightarrow VP PP$						
$NP \rightarrow I / she / me$			[2,3]	[2,4]	[2,5]	[2,6]
$NP \rightarrow TWA \mid Houston$ $NP \rightarrow Det Nominal$				Noun, Nom		Nom
$Nominal \rightarrow book / flight / meal / money$				[3,4]	[3,5]	[3,6]
$Nominal \rightarrow Nominal Noun$	T•-			L / J		
$Nominal \rightarrow Nominal PP$	Lexicon				Prep	PP
$VP \rightarrow book / include / prefer$	$Det \rightarrow that \mid this \mid a$	7			F4 F3	F4 /3
$VP \rightarrow Verb NP$	$Noun \rightarrow book \mid flight \mid mea$	$l \mid money$			[4,5]	[4,6]
$VP \rightarrow X2 PP$	$Pronoun \rightarrow I \mid she \mid me$	TTIXZA				NNP, NP
$X2 \rightarrow Verb NP$	$Proper-Noun \rightarrow Houston \mid$	1 WA				
$VP \rightarrow Verb PP$	$Aux \rightarrow does$. L			[5,6]
$VP \rightarrow VP PP$	$Preposition \rightarrow from \mid to \mid c$		// <i>l</i>			
$PP \rightarrow Preposition NP$	$Verb \rightarrow book \mid include \mid pre$	ejer				



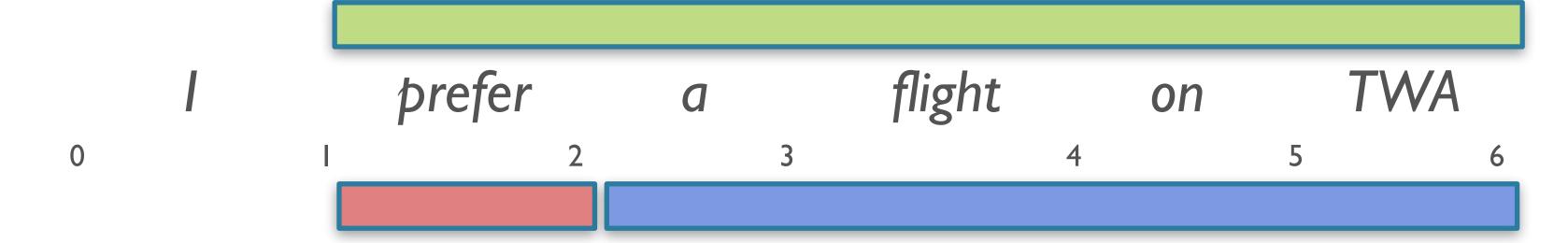
\mathcal{L}_1 Grammar	NID	C		C		
$S \to NP VP$	NP, Pronoun	S		S		
$S \rightarrow X1 \ VP$	[0,1]	[0,2]	[0,3]	[0,4]	[0,5]	
$X1 \rightarrow Aux NP$			L / J		L / J	
$S \rightarrow book / include / prefer$		Verb, VP, S		VP, X2, S		
$S \rightarrow Verb NP$		FL 27	F1 27	F1 47	F1 F3	
$S \rightarrow X2 PP$		[1,2]	[1,3]	[1,4]	[1,5]	
$S \rightarrow Verb PP$			Det	NP		NP
$S \to VP PP$						
$NP \rightarrow I / she / me$			[2,3]	[2,4]	[2,5]	[2,6]
$NP \rightarrow TWA / Houston$				Noun, Nom		Nom
$NP \rightarrow Det\ Nominal$						
$Nominal \rightarrow book / flight / meal / money$				[3,4]	[3,5]	[3,6]
$Nominal \rightarrow Nominal Noun$	T			L''/ J	_	
$Nominal \rightarrow Nominal PP$	Lexicon Detailed the second of the second o				Prep	PP
$VP \rightarrow book / include / prefer$	$Det \rightarrow that \mid this \mid a$ $Norm \rightarrow book \mid flight \mid mod$	1			F4 F3	F4 (7
$VP \rightarrow Verb NP$	$Noun \rightarrow book \mid flight \mid mean$	$x \mid money$			[4,5]	[4,6]
$VP \rightarrow X2 PP$	$Pronoun \rightarrow I \mid she \mid me$					NNP, NP
$X2 \rightarrow Verb NP$	$Proper-Noun \rightarrow Houston \mid Aux \rightarrow does$	1 VVA				
$VP \rightarrow Verb PP$		$m \mid m \circ ar \mid through$	a.h			[5,6]
$VP \rightarrow VP PP$	$Preposition \rightarrow from \mid to \mid o$ $Verb \rightarrow book \mid include \mid pre$	·	110			
$PP \rightarrow Preposition NP$	vero rodok priciale pre	J C 1				



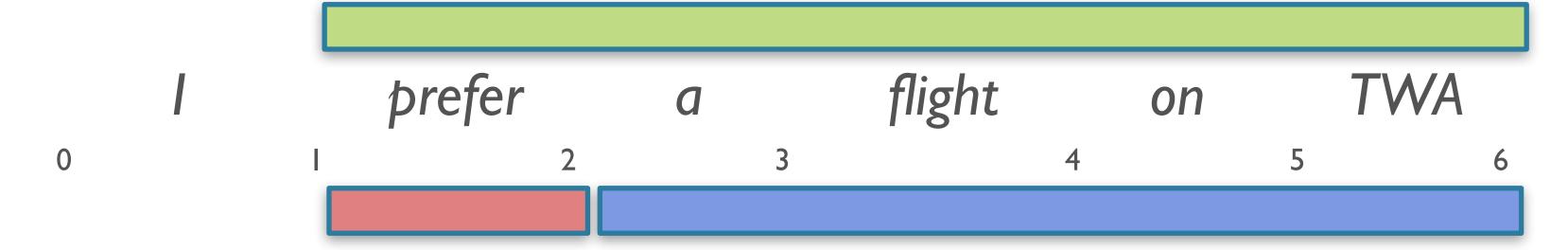
\mathcal{L}_1 Grammar $S \to NP \ VP$	NP,	S		S		
$S \rightarrow X1 \ VP$	Pronoun [0,1]	[0,2]	[0,3]	[0,4]	[0,5]	
$X1 \rightarrow Aux \ NP$ $S \rightarrow book \ / \ include \ / \ prefer$		Verb, VP, S		VP, X2, S		
$S \to Verb NP$ $S \to X2 PP$		[1,2]	[1,3]	[1,4]	[1,5]	
$S \rightarrow Verb PP$ $S \rightarrow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



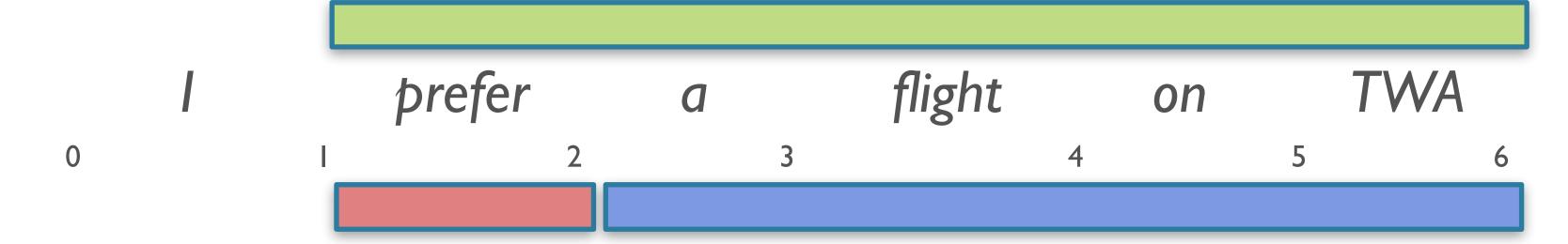
$\mathcal{L}_{1} \mathbf{Grammar}$ $S \to NP \ VP$ $S \to X1 \ VP$	NP, Pronoun [0,1]	S [0,2]	[0,3]	S [0,4]	[0,5]	
$X1 \rightarrow Aux NP$ $S \rightarrow book / include / prefer$		Verb, VP, S		VP, X2, S		
$S \rightarrow Verb NP$ $S \rightarrow X2 PP$		[1,2]	[1,3]	[1,4]	[1,5]	[1,6]
$S \rightarrow Verb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



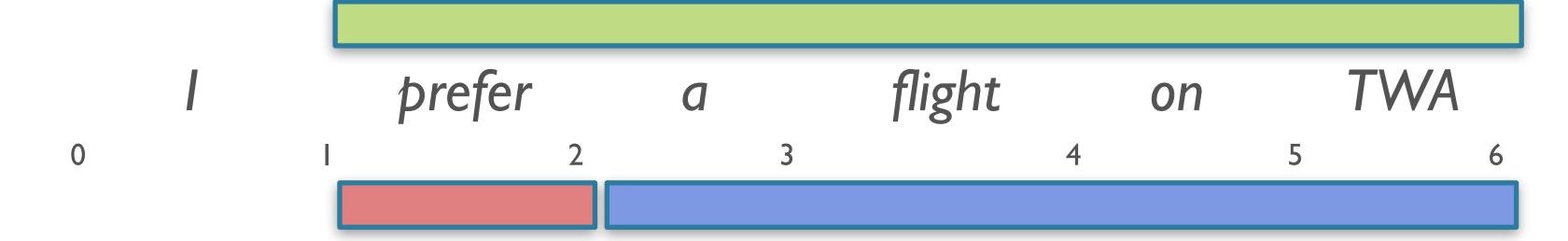
$\mathcal{L}_{1} \mathbf{Grammar}$ $S \to NP \ VP$ $C \to V1 \ VD$		NP, Pronoun	S		S		
$S \to X1 \ VP$		[0,1]	[0,2]	[0,3]	[0,4]	[0,5]	
$X1 \rightarrow Aux NP$ $S \rightarrow book / implied o / mmofor$			Verb, VP, S		VP, X2, S		VP
$S \rightarrow book \mid include \mid prefer$ $S \rightarrow Verb NP$							_
$S \to Vero NF$ $S \to X2 PP$			[1,2]	[1,3]	[1,4]	[1,5]	[1,6]
$S \to Verb PP$				Det	NP		NP
$S \to VP PP$							- N. C.
$NP \rightarrow I / she / me$				[2,3]	[2,4]	[2,5]	[2,6]
$NP \rightarrow TWA / Houston$				[_,_]		[_,_]	
$NP \rightarrow Det\ Nominal$					Noun, Nom		Nom
$Nominal \rightarrow book / flight / meal / money$					Γ2 <i>Α</i> 1	F2 F1	Γ2 4 1
$Nominal \rightarrow Nominal Noun$				_	[3,4]	[3,5]	[3,6]
$Nominal \rightarrow Nominal PP$	Lexicon					Prep	PP
$VP \rightarrow book / include / prefer$		$at \mid this \mid a$					
$\begin{array}{c ccccccccccccccccccccccccccccccccccc$		$book \mid flight \mid meal$	$l \mid money$			[4,5]	[4,6]
$VP \rightarrow X2 PP$		$\rightarrow I \mid she \mid me$					NNP, NP
$X2 \rightarrow Verb NP$	-	$un \rightarrow Houston \mid$	T'WA				
$VP \rightarrow Verb PP$	$Aux \rightarrow do$		1 1 7 7	,			[5,6]
$VP \rightarrow VP PP$		$n \rightarrow from \mid to \mid o$	·	l			
$PP \rightarrow Preposition NP$	$Verb \rightarrow bc$	$pok \mid include \mid pre$	ter				



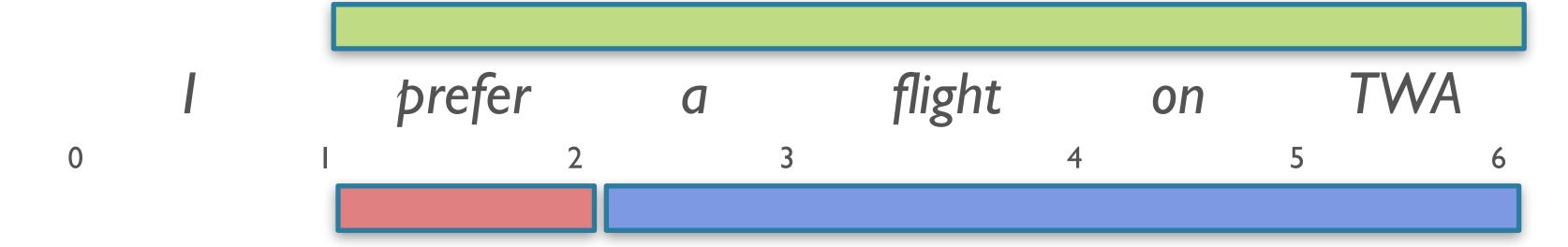
$\mathcal{L}_{1} \mathbf{Grammar}$ $S \to NP \ VP$ $S \to X1 \ VP$	NP, Pronoun [0,1]	S [0,2]	[0,3]	S [0,4]	[0,5]	
$X1 \rightarrow Aux NP$ $S \rightarrow book / include / prefer$ $S \rightarrow Verb NP$	L~,·]	Verb, VP, S		VP, X2, S		VP, X2
$S \to X2 PP$		[1,2]	[1,3]	[1,4]	[1,5]	[1,6]
$S \rightarrow Verb PP$ $S \rightarrow VP PP$			Det	NP		NP
$NP \rightarrow I / she / me$			[2,3]	[2,4]	[2,5]	[2,6]
$NP \rightarrow TWA \mid Houston$ $NP \rightarrow Det \ Nominal$				Noun, Nom		Nom
$Nominal \rightarrow book / flight / meal / money$				[3,4]	[3,5]	[3,6]
$Nominal \rightarrow Nominal \ Noun$ $Nominal \rightarrow Nominal \ PP$	$\begin{array}{c} \textbf{Lexicon} \\ Det \rightarrow that \mid this \mid a \end{array}$				Prep	PP
$VP \rightarrow book \mid include \mid prefer$ $VP \rightarrow Verb \mid NP$	$Noun \rightarrow book \mid flight \mid meat$	$l \mid money$			[4,5]	[4,6]
$VP \rightarrow X2 PP$ $X2 \rightarrow Verb NP$	$Pronoun \rightarrow I \mid she \mid me$ $Proper-Noun \rightarrow Houston \mid$	TWA				NNP, NP
$VP \rightarrow Verb PP$ $VP \rightarrow VP PP$	$Aux \rightarrow does$ $Preposition \rightarrow from \mid to \mid o$	$n \mid near \mid through$	h			[5,6]
$PP \rightarrow VPPP$ $PP \rightarrow Preposition NP$	$Verb \rightarrow book \mid include \mid pre$, ,				



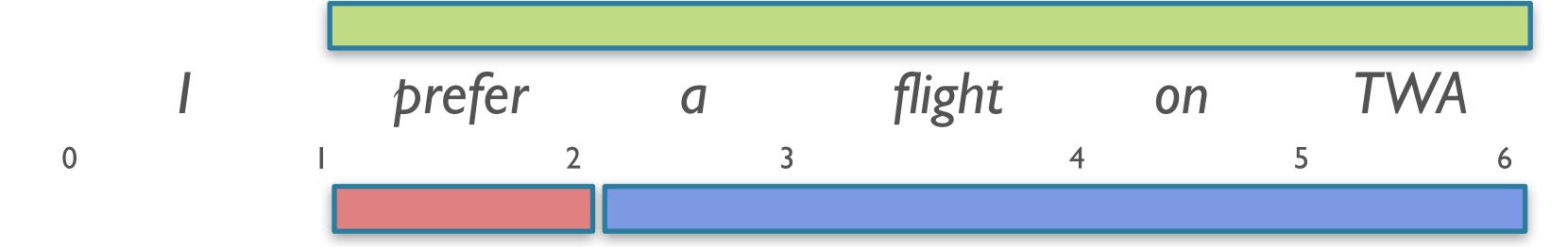
$\mathcal{L}_{1} \mathbf{Grammar}$ $S \to NP \ VP$ $S \to X1 \ VP$	NP, Pronoun [0,1]	S [0,2]	[0,3]	S [0,4]	[0,5]	
$X1 \rightarrow Aux NP$		Verb, VP, S		VP, X2, S	[-,-]	VP, X2, S
$S \rightarrow book / include / prefer$ $S \rightarrow Verb NP$ $S \rightarrow X2 PP$		[1,2]	[1,3]	[1,4]	[1,5]	[1,6]
$S \rightarrow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



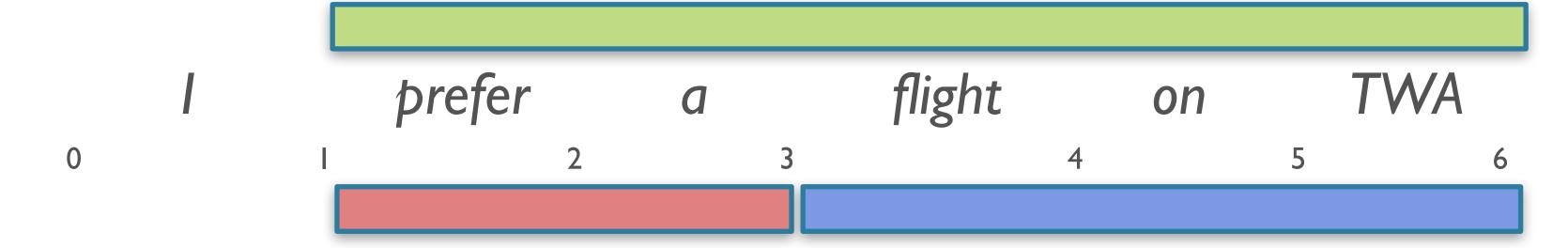
\mathcal{L}_1 Grammar $S \to NP \ VP$ $S \to X1 \ VP$	NP, Pronoun [0,1]	S [0,2]	[0,3]	S [0,4]	[0,5]	
$X1 \rightarrow Aux \ NP$ $S \rightarrow book \ / \ include \ / \ prefer$		Verb, VP, S		VP, X2, S		VP, X2, S
$S \rightarrow Verb NP$ $S \rightarrow X2 PP$		[1,2]	[1,3]	[1,4]	[1,5]	[1,6]
$S \rightarrow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



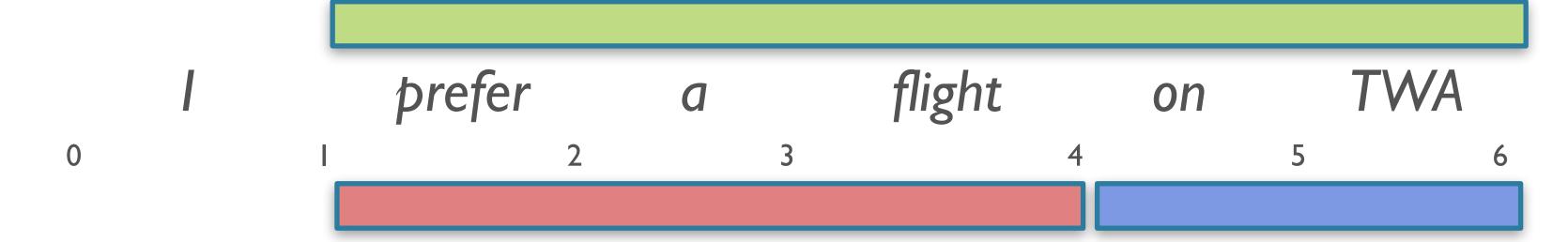
$\mathcal{L}_{1} \mathbf{Grammar}$ $S \to NP \ VP$ $S \to X1 \ VP$	NP, Pronoun [0,1]	S [0,2]	[0,3]	S [0,4]	[0,5]	
$X1 \rightarrow Aux NP$ $S \rightarrow book / include / prefer$		Verb, VP, S		VP, X2, S		VP, X2, S
$S \rightarrow Verb NP$ $S \rightarrow X2 PP$		[1,2]	[1,3]	[1,4]	[1,5]	[1,6]
$S \rightarrow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



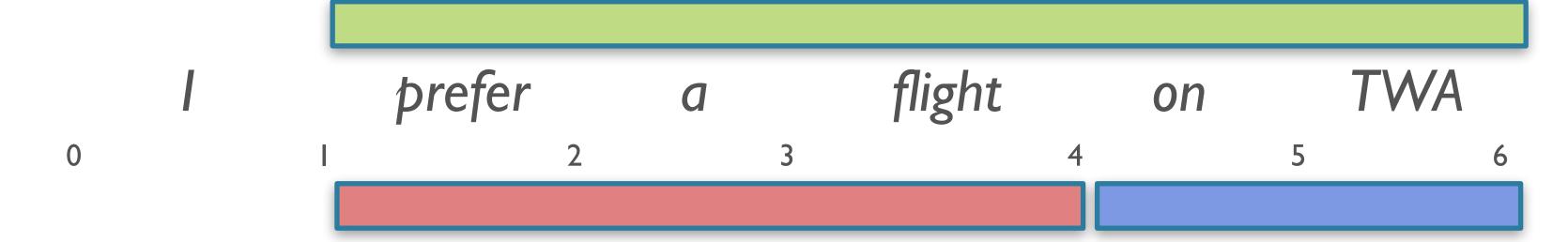
\mathcal{L}_1 Grammar	NP,	S		S		
$S \rightarrow NP VP$	Pronoun					
$S \rightarrow X1 \ VP$	[0,1]	[0,2]	[0,3]	[0,4]	[0,5]	
$X1 \rightarrow Aux NP$			L 7/ J		L · / · J	WD WO 6
$S \rightarrow book / include / prefer$		Verb, VP, S		VP, X2, S		VP, X2, S
$S \rightarrow Verb NP$		F1 07	.	- 1 4-		F1 47
$S \rightarrow X2 PP$		[1,2]	[1,3]	[1,4]	[1,5]	[1,6]
$S \rightarrow Verb PP$			Det	NP		NP
$S \rightarrow VP PP$						
$NP \rightarrow I / she / me$			[2,3]	[2,4]	[2,5]	[2,6]
$NP \rightarrow TWA / Houston$					2 7 2	
$NP \rightarrow Det Nominal$				Noun, Nom		Nom
$Nominal \rightarrow book / flight / meal / money$				F2 41	LO E1	F2 /1
$Nominal \rightarrow Nominal Noun$			_	[3,4]	[3,5]	[3,6]
$Nominal \rightarrow Nominal PP$	Lexicon				Prep	PP
$VP \rightarrow book / include / prefer$	$Det \rightarrow that \mid this \mid a$					
$VP \rightarrow Verb NP$	$Noun \rightarrow book \mid flight \mid mea$	$l \mid money$			[4,5]	[4,6]
$VP \rightarrow X2 PP$	$Pronoun \rightarrow I \mid she \mid me$					NNP, NP
$X2 \rightarrow Verb NP$	$Proper-Noun \rightarrow Houston$, , , , ,	
$VP \rightarrow Verb PP$	$Aux \rightarrow does$					[5 6]
$VP \rightarrow VP PP$	$Preposition \rightarrow from \mid to \mid c$	$on \mid near \mid through$	h			[5,6]
$PP \rightarrow Preposition NP$	$Verb \rightarrow book \mid include \mid pre$	efer				



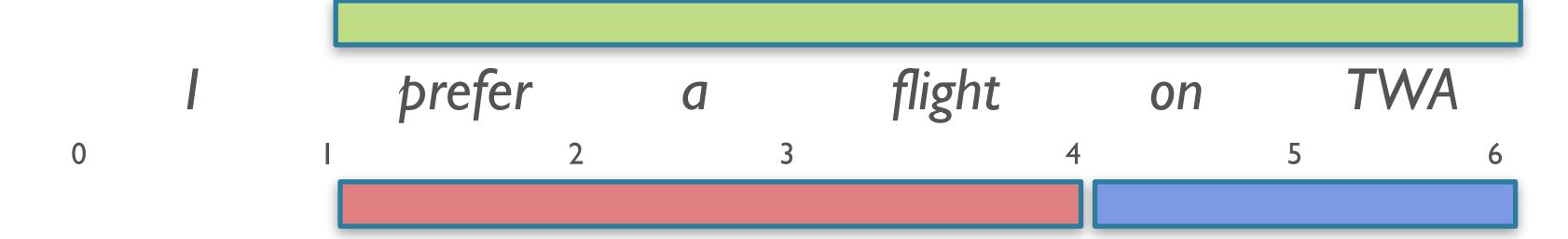
\mathcal{L}_1 Grammar $S \to NP \ VP$ $S \to X1 \ VP$	NP, Pronoun [0,1]	S [0,2]	[0,3]	S [0,4]	[0,5]	
$X1 \rightarrow Aux \ NP$ $S \rightarrow book \ / \ include \ / \ prefer$		Verb, VP, S		VP, X2, S		VP, X2, S
$S \rightarrow Verb NP$ $S \rightarrow X2 PP$		[1,2]	[1,3]	[1,4]	[1,5]	[1,6]
$S \rightarrow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



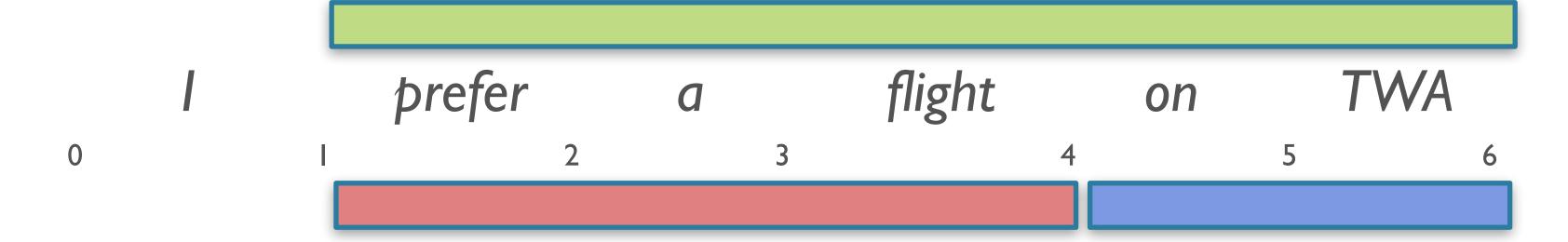
$\mathcal{L}_{1} \mathbf{Grammar}$ $S \to NP \ VP$ $S \to X1 \ VP$	NP, Pronoun [0,1]	S [0,2]	[0,3]	S [0,4]	[0,5]	
$X1 \rightarrow Aux NP$ $C \rightarrow b \circ de / im else de / manform$		Verb, VP, S		VP, X2, S		VP, X2, S
$S \rightarrow book \mid include \mid prefer$ $S \rightarrow Verb NP$ $S \rightarrow X2 PP$		[1,2]	[1,3]	[1,4]	[1,5]	[1,6]
$S \rightarrow Verb PP$			Det	NP		NP
$S \to VP PP$ $NP \to I / she / me$			[2,3]	[2,4]	[2,5]	[2,6]
$NP \rightarrow TWA \mid Houston$ $NP \rightarrow Det \ Nominal$				Noun, Nom		Nom
$Nominal \rightarrow book \mid flight \mid meal \mid money$ $Nominal \rightarrow Nominal Noun$				[3,4]	[3,5]	[3,6]
$Nominal \rightarrow Nominal PP$	Lexicon				Prep	PP
$VP \rightarrow book \mid include \mid prefer$ $VP \rightarrow Verb \mid NP$	$Det \rightarrow that \mid this \mid a$ $Noun \rightarrow book \mid flight \mid meal$	$l \mid money$			[4,5]	[4,6]
$VP \rightarrow X2 PP$	$Pronoun \rightarrow I \mid she \mid me$ $Proper-Noun \rightarrow Houston \mid$	TWA				NNP, NP
$X2 \rightarrow Verb \ NP$ $VP \rightarrow Verb \ PP$ $VP \rightarrow VP \ PP$	$Aux \rightarrow does$ $Preposition \rightarrow from \mid to \mid or$		h			[5,6]
$PP \rightarrow Preposition NP$	$Verb \rightarrow book \mid include \mid pres$	fer				



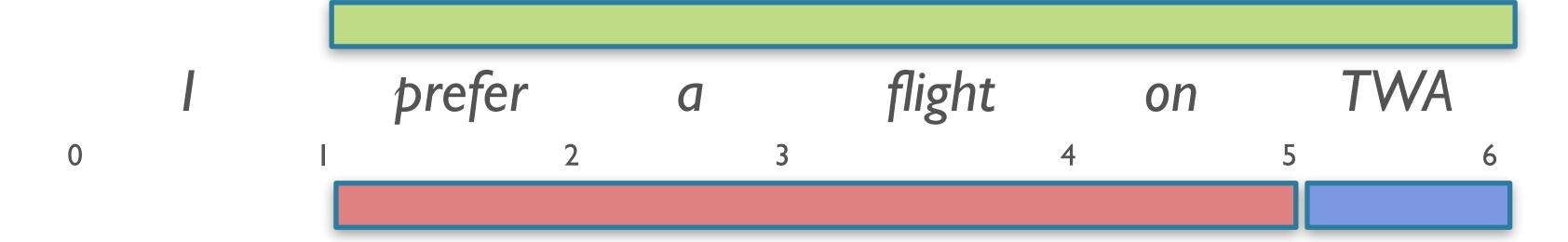
\mathcal{L}_1 Grammar $S \to NP \ VP$ $S \to X1 \ VP$	NP, Pronoun [0,1]	S [0,2]	[0,3]	S [0,4]	[0,5]	
$X1 \rightarrow Aux NP$ $S \rightarrow book / include / prefer$		Verb, VP, S		VP, X2, S		VP, X2, S
$S \rightarrow Verb NP$ $S \rightarrow X2 PP$		[1,2]	[1,3]	[1,4]	[1,5]	[1,6]
$S \rightarrow Verb PP$			Det	NP		NP
$S \rightarrow VP PP$ $NP \rightarrow I / she / me$			[2,3]	[2,4]	[2,5]	[2,6]
$NP \rightarrow TWA \mid Houston$ $NP \rightarrow Det \ Nominal$				Noun, Nom		Nom
$Nominal \rightarrow book / flight / meal / money$ $Nominal \rightarrow Nominal Noun$				[3,4]	[3,5]	[3,6]
$Nominal \rightarrow Nominal PP$	Lexicon				Prep	PP
$VP \rightarrow book \mid include \mid prefer$ $VP \rightarrow Verb NP$	$Det \rightarrow that \mid this \mid a$ $Noun \rightarrow book \mid flight \mid meal \mid money$				[4,5]	[4,6]
$\begin{array}{c} VP \rightarrow X2 PP \\ VO \rightarrow Voob ND \end{array}$	$Pronoun \rightarrow I \mid she \mid me$ $Proper-Noun \rightarrow Houston \mid$	TWA				NNP, NP
$X2 \rightarrow Verb \ NP$ $VP \rightarrow Verb \ PP$ $VP \rightarrow VP \ PP$	$Aux \rightarrow does$ $Preposition \rightarrow from \mid to \mid or$		h			[5,6]
$PP \rightarrow Preposition NP$	$Verb \rightarrow book \mid include \mid pres$	fer				



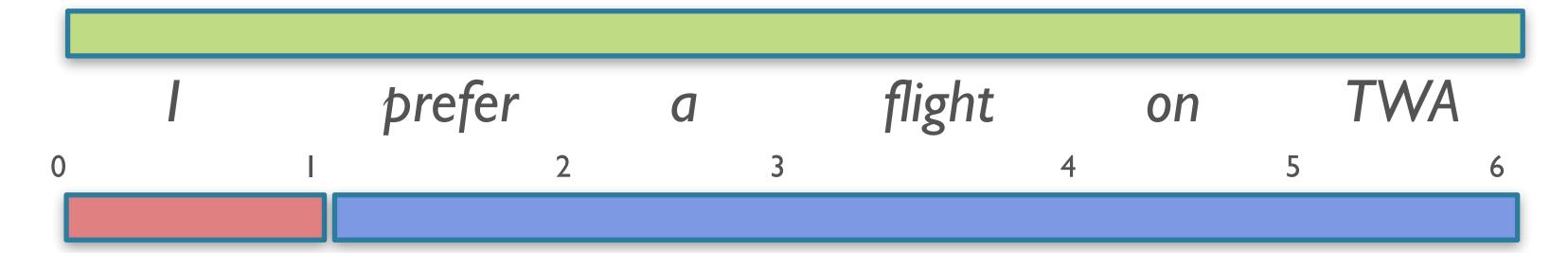
\mathcal{L}_1 Grammar	NID	C		C		
$S \rightarrow NP \ VP$	NP, Pronoun			S		
$S \rightarrow X1 \ VP$	[0,1]	[0,2]	[0,3]	[0,4]	[0,5]	
$X1 \rightarrow Aux NP$			L / J	VP, X2, S	• * •	VD V2 C
$S \rightarrow book / include / prefer$		Verb, VP, S		VP, A2,		VP, X2, S
$S \rightarrow Verb NP$		[1,2]	LI 31	[1,4]	[1,5]	[1,6]
$S \rightarrow X2 PP$		[1,4]	[1,3]	[1,7]	[1,5]	[1,0]
$S \rightarrow Verb PP$			Det	NP		NP
$S \to VP PP$						
$NP \rightarrow I / she / me$			[2,3]	[2,4]	[2,5]	[2,6]
$NP \rightarrow TWA / Houston$				Noun, Nom		Nom
$NP \rightarrow Det\ Nominal$				radan, radin		
$Nominal \rightarrow book / flight / meal / money$				[3,4]	[3,5]	[3,6]
$Nominal \rightarrow Nominal \ Noun$	т •			[5, 1]		
$Nominal \rightarrow Nominal PP$	Lexicon				Prep	PP
$VP \rightarrow book / include / prefer$	$Det \rightarrow that \mid this \mid a$	- 1				
$VP \rightarrow Verb NP$	$Noun \rightarrow book \mid flight \mid mean$	$l \mid money$			[4,5]	[4,6]
$VP \rightarrow X2 PP$	$Pronoun \rightarrow I \mid she \mid me$				NNP, NP	
$X2 \rightarrow Verb NP$	$Proper-Noun \rightarrow Houston \mid$					
$VP \rightarrow Verb PP$	$Aux \rightarrow does$	7			[5,6]	
$VP \rightarrow VP PP$	$Preposition \rightarrow from \mid to \mid o$	h			L	
$PP \rightarrow Preposition NP$	$Verb \rightarrow book \mid include \mid pre$	ter				



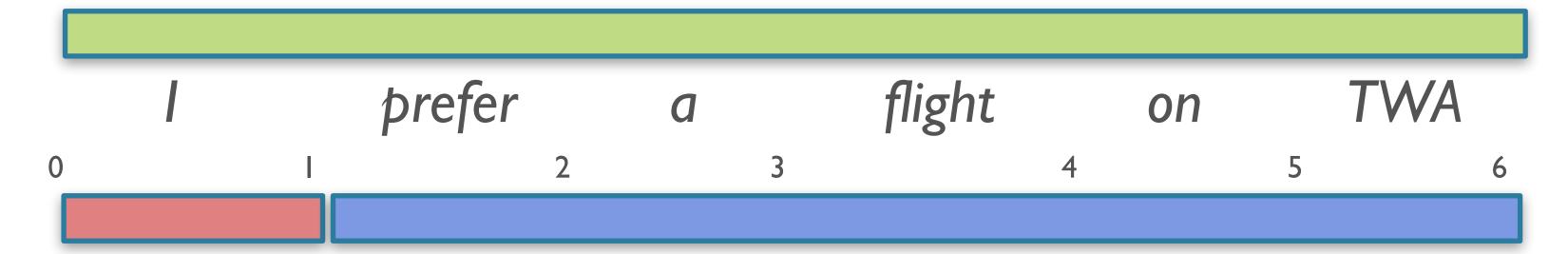
$X1 \rightarrow Aux \ NP$ $S \rightarrow book \mid include \mid prefer$ $S \rightarrow Verb \ NP$ $S \rightarrow Verb \ NP$ $S \rightarrow Verb \ PP$ $S \rightarrow VP \ PP$	$\mathcal{L}_{1} \mathbf{Grammar}$ $S \to NP \ VP$ $S \to X1 \ VP$	NP, Pronoun [0,1]	S [0,2]	[0,3]	S [0,4]	[0,5]	
$S \rightarrow X2\ PP$ $S \rightarrow Verb\ PP$ $S \rightarrow VP\ PP$ $NP \rightarrow I\ \ she\ \ me$ $NP \rightarrow TWA\ \ Houston$ $NP \rightarrow Det\ Nominal$ $Nominal \rightarrow book\ \ flight\ \ meal\ \ money$ $Nominal \rightarrow Nominal\ Noun$ $Nominal \rightarrow Nominal\ Noun$ $Nominal \rightarrow Nominal\ PP$		[Lovol			VP, X2, S
$S \rightarrow VP \ PP$ $NP \rightarrow I \ \ she \ \ me$ $NP \rightarrow TWA \ \ Houston$ $NP \rightarrow Det \ Nominal$ $Nominal \rightarrow book \ \ flight \ \ meal \ \ money$ $Nominal \rightarrow Nominal \ Noun$ $Nominal \rightarrow Nominal \ Noun$ $Nominal \rightarrow Nominal \ P$ $Prep$ $Prep$ $Prep$ $Prep$			[1,2]	[1,3]	[1,4]	[1,5]	[1,6]
$NP ightharpoonup TWA \ / \ Houston \ NP ightharpoonup Det \ Nominal ightharpoonup book \ / \ flight \ / \ meal \ / \ money \ Nominal ightharpoonup Nominal \ Nominal \ Nominal \ Nominal \ Nominal \ Prep$ Lexicon Prep Pre				Det	NP		NP
$ \begin{array}{c ccccccccccccccccccccccccccccccccccc$	•			[2,3]		[2,5]	[2,6]
Nominal o Nominal Noun $Nominal o Nominal PP$ $Nominal o Nominal PP$ $Dot o that thick a$	$NP \rightarrow Det\ Nominal$				Noun, Nom		Nom
$Nominal \ PP$					[3,4]	[3,5]	[3,6]
$VP \rightarrow 000K + thetaer$	$Nominal \rightarrow Nominal PP$					Prep	PP
$VP \rightarrow Verb NP$ $[4,5]$ $Promoum \rightarrow I \mid aba \mid ma$	$VP \rightarrow Verb NP$	$Noun \rightarrow book \mid flight \mid meal \mid money$				[4,5]	[4,6]
$VP \rightarrow X2 \ PP$ $X2 \rightarrow Verb \ NP$ $Proper-Noun \rightarrow Houston \mid TWA$, =, =	$Pronoun \rightarrow I \mid she \mid me$ $Proper-Noun \rightarrow Houston \mid TWA$					NNP, NP
$VP \rightarrow Verb \ PP$ $VP \rightarrow VP \ PP$ $Preposition \ NP$ $Verb \rightarrow book \mid include \mid prefer$ $Verb \rightarrow book \mid include \mid prefer$ $Verb \rightarrow book \mid include \mid prefer$		$Preposition \rightarrow from \mid to \mid or$			[5,6]		



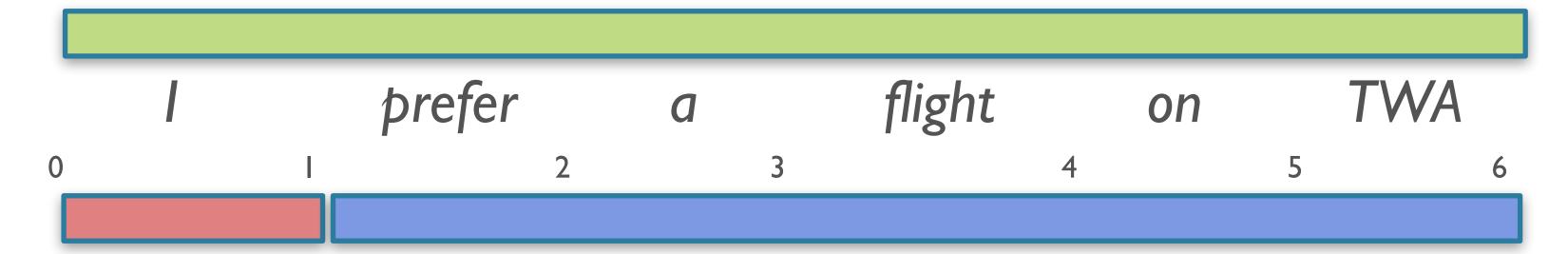
\mathcal{L}_1 Grammar	NP,	S		S		
$S \rightarrow NP VP$	Pronoun					
$S \rightarrow X1 \ VP$	[0,1]	[0,2]	[0,3]	[0,4]	[0,5]	[0,6]
$X1 \rightarrow Aux NP$		Verb, VP, S		VP, X2, S		VP, X2, S
$S \rightarrow book / include / prefer$		verb, vr, s		VP, AZ, S		VP, AZ, 3
$S \rightarrow Verb NP$		ΓI 21	LI 31	ΓΙ <i>Δ</i> 1	F1 51	ΓΙ 61
$S \rightarrow X2 PP$		[1,2]	[1,3]	[1,4]	[1,5]	[1,6]
$S \rightarrow Verb PP$			Det	NP		NP
$S \to VP PP$						
$NP \rightarrow I / she / me$			[2,3]	[2,4]	[2,5]	[2,6]
$NP \rightarrow TWA / Houston$				Noun, Nom		Nom
$NP \rightarrow Det\ Nominal$				140411, 140111		
$Nominal \rightarrow book / flight / meal / money$				[3,4]	[3,5]	[3,6]
$Nominal \rightarrow Nominal \ Noun$	T			[5, 1]		
$Nominal \rightarrow Nominal PP$	Lexicon				Prep	PP
$VP \rightarrow book / include / prefer$	$Det \rightarrow that \mid this \mid a$	v 1			_ ,	
$VP \rightarrow Verb NP$	$Noun \rightarrow book \mid flight \mid meal$	$l \mid money$			[4,5]	[4,6]
$VP \rightarrow X2 PP$	$Pronoun \rightarrow I \mid she \mid me$					NNP, NP
$X2 \rightarrow Verb NP$	$Proper-Noun \rightarrow Houston \mid$	T'WA				
$VP \rightarrow Verb PP$	$Aux \rightarrow does$			[5,6]		
$VP \rightarrow VP PP$	$Preposition \rightarrow from \mid to \mid o$		h			L
$PP \rightarrow Preposition NP$	$Verb \rightarrow book \mid include \mid pre$	ter				



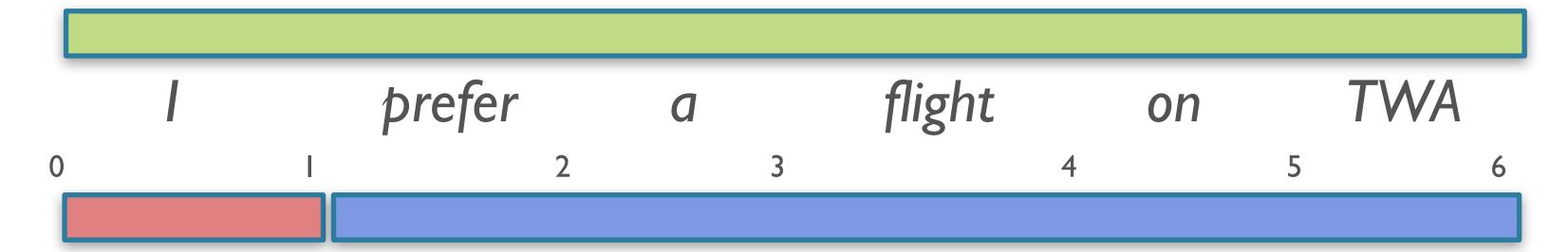
\mathcal{L}_1 Grammar $S \rightarrow NP VP$	NP, Pronoun	S		S		S
$S \to NP VP$ $S \to X1 VP$	[0,1]	[0,2]	[0,3]	[0,4]	[0,5]	[0,6]
$X1 \rightarrow Aux NP$		Verb, VP, S		VP, X2, S		VP, X2, S
$S \rightarrow book / include / prefer$, verb, vr, o		, , , , , , ,		7, 7, 7, 7
$S \to Verb NP$		[1,2]	[1,3]	[1,4]	[1,5]	[1,6]
$S \to X2 PP$		L · , ~ J			[1,5]	
$S \to Verb PP$			Det	NP		NP
$S \to VP PP$						
$NP \rightarrow I / she / me$			[2,3]	[2,4]	[2,5]	[2,6]
$NP \rightarrow TWA / Houston$				Noun, Nom		Nom
$NP \rightarrow Det\ Nominal$						
$Nominal \rightarrow book / flight / meal / money$				[3,4]	[3,5]	[3,6]
$Nominal \rightarrow Nominal \ Noun$	T •			Layan		
$Nominal \rightarrow Nominal PP$	Lexicon				Prep	PP
$VP \rightarrow book / include / prefer$	$Det \rightarrow that \mid this \mid a$, I			- 4	- 4 4-
$VP \rightarrow Verb NP$	$Noun \rightarrow book \mid flight \mid meal$	money			[4,5]	[4,6]
$VP \rightarrow X2 PP$	$Pronoun \rightarrow I \mid she \mid me$				NNP, NP	
$X2 \rightarrow Verb NP$	$Proper-Noun \rightarrow Houston \mid$	TWA				
$VP \rightarrow Verb PP$	$Aux \rightarrow does$	7			[5,6]	
$VP \rightarrow VP PP$	$Preposition \rightarrow from \mid to \mid o$	h			L / J	
$PP \rightarrow Preposition NP$	$Verb \rightarrow book \mid include \mid pre$	ter				



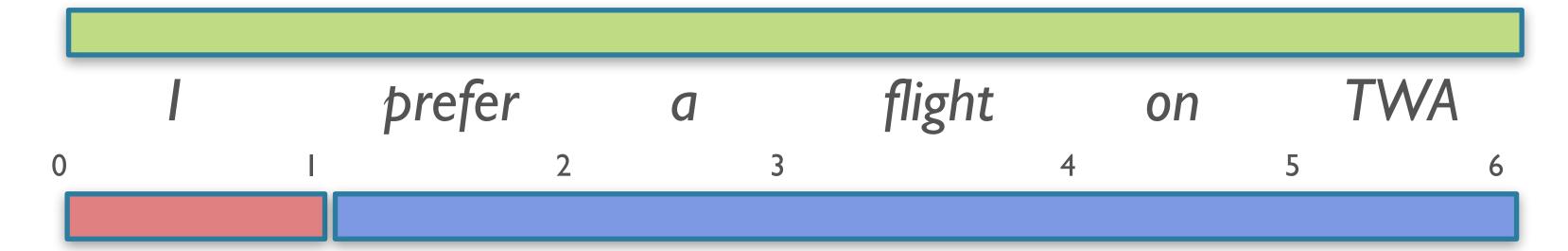
$\mathcal{L}_1 \mathbf{Grammar}$ $S \to NP \ VP$ $C \to V1 \ VD$	NP, Pronoun	S		S		S
$S \to X1 \ VP$	[0,1]	[0,2]	[0,3]	[0,4]	[0,5]	[0,6]
$X1 \to Aux NP$ $C \to book / implied of maniform$		Verb, VP, S		VP, X2, S		VP, X2, S
$S \rightarrow book / include / prefer$ $S \rightarrow Vomb ND$						
$S \to Verb NP$ $S \to X2 PP$		[1,2]	[1,3]	[1,4]	[1,5]	[1,6]
$S \rightarrow AZPP$ $S \rightarrow Verb PP$			Det	NP		NP
$S \to VP PP$			Det			NP
$NP \rightarrow I / she / me$			[2,3]	[2,4]	[2,5]	[2,6]
$NP \rightarrow TWA / Houston$			[2,5]		[2,5]	
$NP \rightarrow Det\ Nominal$				Noun, Nom		Nom
$Nominal \rightarrow book / flight / meal / money$				FO 47	F2 F3	F2 43
$Nominal \rightarrow Nominal \ Noun$				[3,4]	[3,5]	[3,6]
$Nominal \rightarrow Nominal PP$	Lexicon				Prep	PP
$VP \rightarrow book / include / prefer$	$Det \rightarrow that \mid this \mid a$					
$VP \rightarrow Verb NP$	$Noun \rightarrow book \mid flight \mid meat$	$l \mid money$			[4,5]	[4,6]
$VP \rightarrow X2 PP$	$Pronoun \rightarrow I \mid she \mid me$					NNP, NP
$X2 \rightarrow Verb NP$	Proper-Noun → Houston TWA					
$VP \rightarrow Verb PP$	$Aux \rightarrow does$					[5,6]
$VP \rightarrow VP PP$	$Preposition \rightarrow from \mid to \mid on \mid near \mid through$					
$PP \rightarrow Preposition NP$	$Verb \rightarrow book \mid include \mid pre$	fer				



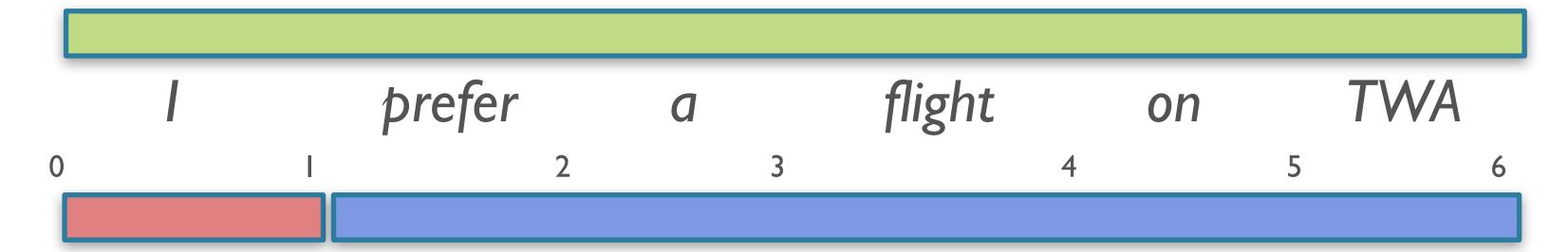
\mathcal{L}_1 Grammar $S \to NP VP$	NP, Pronoun	S		S		S
$S \rightarrow X1 \ VP$	[0,1]	[0,2]	[0,3]	[0,4]	[0,5]	[0,6]
$X1 \rightarrow Aux NP$		Verb, VP, S		VP, X2, S		VP, X2, S
$S \rightarrow book / include / prefer$		v c, v , o				VI, 202, S
$S \rightarrow Verb NP$		[1,2]	[1,3]	[1,4]	[1,5]	[1,6]
$S \to X2 PP$ $S \to Varib PP$		L / J			L / J	
$S \rightarrow Verb PP$ $S \rightarrow VP PP$			Det	NP		NP
$NP \rightarrow I / she / me$			[2,3]	[2,4]	[2,5]	[2,6]
$NP \rightarrow TWA / Houston$			[2,5]		[2,5]	
$NP \rightarrow Det\ Nominal$				Noun, Nom		Nom
$Nominal \rightarrow book / flight / meal / money$				L3 <i>\</i> 1	L3 21	Γ2 4 1
$Nominal \rightarrow Nominal Noun$				[3,4]	[3,5]	[3,6]
$Nominal \rightarrow Nominal PP$	Lexicon				Prep	PP
$VP \rightarrow book / include / prefer$	$Det \rightarrow that \mid this \mid a$	r 1			- 4	- 4 4-
$VP \rightarrow Verb NP$	$Noun \rightarrow book \mid flight \mid meal$	money			[4,5]	[4,6]
$VP \rightarrow X2 PP$	$Pronoun \rightarrow I \mid she \mid me$					NNP, NP
$X2 \rightarrow Verb NP$	$Proper-Noun \rightarrow Houston \mid Aux \rightarrow does$	1 VVA				
$VP \rightarrow Verb PP$		n near through)			[5,6]
$VP \rightarrow VP PP$	$Preposition \rightarrow from \mid to \mid or$ $Verb \rightarrow book \mid include \mid pres$		b			
$PP \rightarrow Preposition NP$	vero , ooon memme pre	101				



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



\mathcal{L}_1 Grammar $S \to NP \ VP$	NP, Pronoun	S		S		S
$S \rightarrow X1 \ VP$	[0,1]	[0,2]	[0,3]	[0,4]	[0,5]	[0,6]
$X1 \rightarrow Aux \ NP$ $S \rightarrow book \ / \ include \ / \ prefer$		Verb, VP, S		VP, X2, S		VP, X2, S
$S \rightarrow Verb NP$		F1 21	FI 21	ΓΙ <i>Δ</i> Ί	F1 E1	Γ1 / 1
$S \rightarrow X2 PP$		[1,2]	[1,3]	[1,4]	[1,5]	[1,6]
$S \rightarrow Verb PP$			Det	NP		NP
$S \to VP PP$			FO 01	FO 47	FO F1	FO 43
$NP \rightarrow I / she / me$			[2,3]	[2,4]	[2,5]	[2,6]
$NP \rightarrow TWA / Houston$				Noun, Nom		Nom
$NP \rightarrow Det\ Nominal$						
Nominal → book / flight / meal / money				[3,4]	[3,5]	[3,6]
$Nominal \rightarrow Nominal Noun$	Lexicon				Prep	PP
$Nominal \rightarrow Nominal PP$	$Det \rightarrow that \mid this \mid a$				riep	
$VP \rightarrow book \mid include \mid prefer$ $VP \rightarrow Verb \mid NP$	$Noun \rightarrow book \mid flight \mid meal$	money			[4,5]	[4,6]
$VP \rightarrow X2 PP$	$Pronoun \rightarrow I \mid she \mid me$				L / · 1	
$X2 \rightarrow Verb NP$	$Proper-Noun \rightarrow Houston$	TWA				NNP, NP
$VP \rightarrow Verb PP$	$Aux \rightarrow does$					FF / 1
$VP \rightarrow VP PP$	$Preposition \rightarrow from \mid to \mid o$	$n \mid near \mid through$	l			[5,6]
$PP \rightarrow Preposition NP$	$Verb \rightarrow book \mid include \mid pres$	fer				



Current CKY Algorithm

Limitations:

Only stores non-terminals in cell

Not rules or cells corresponding to RHS

Stores SETS of non-terminals

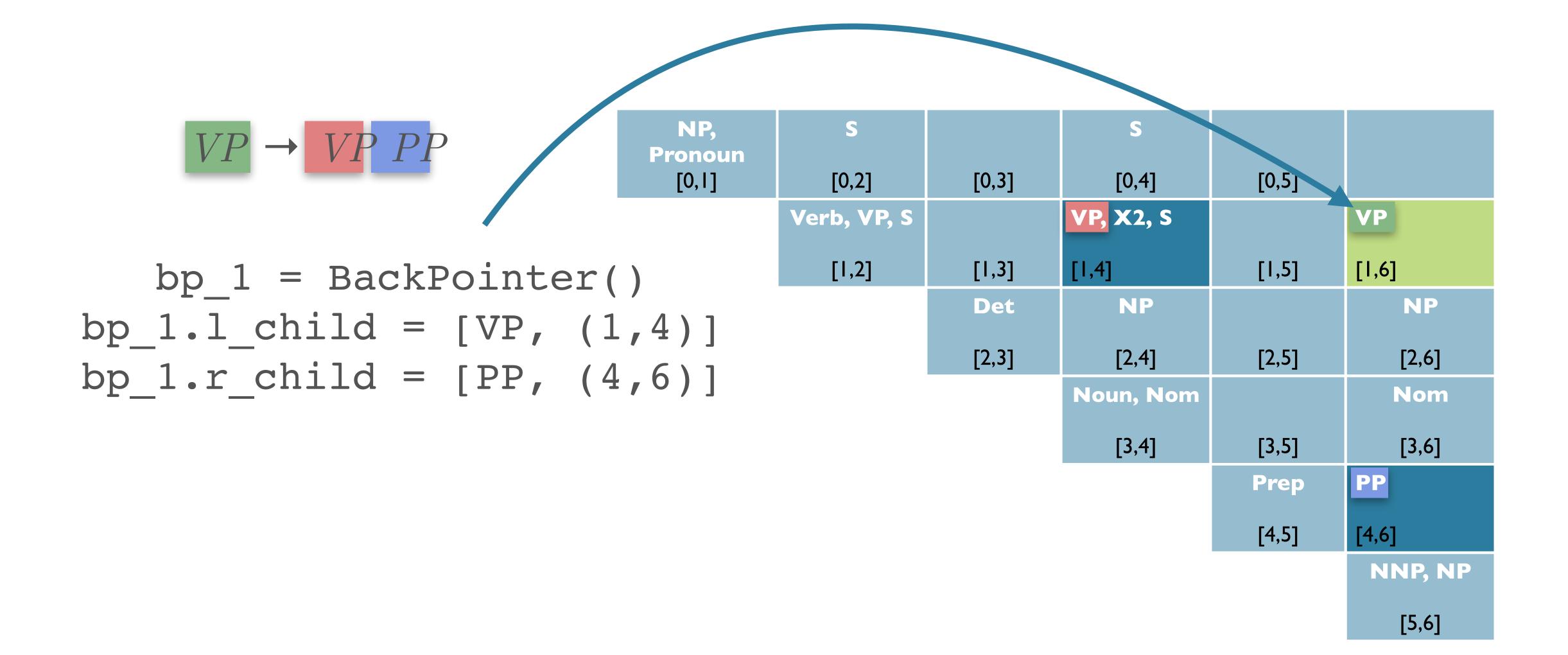
Multiple rules with same LHS collide

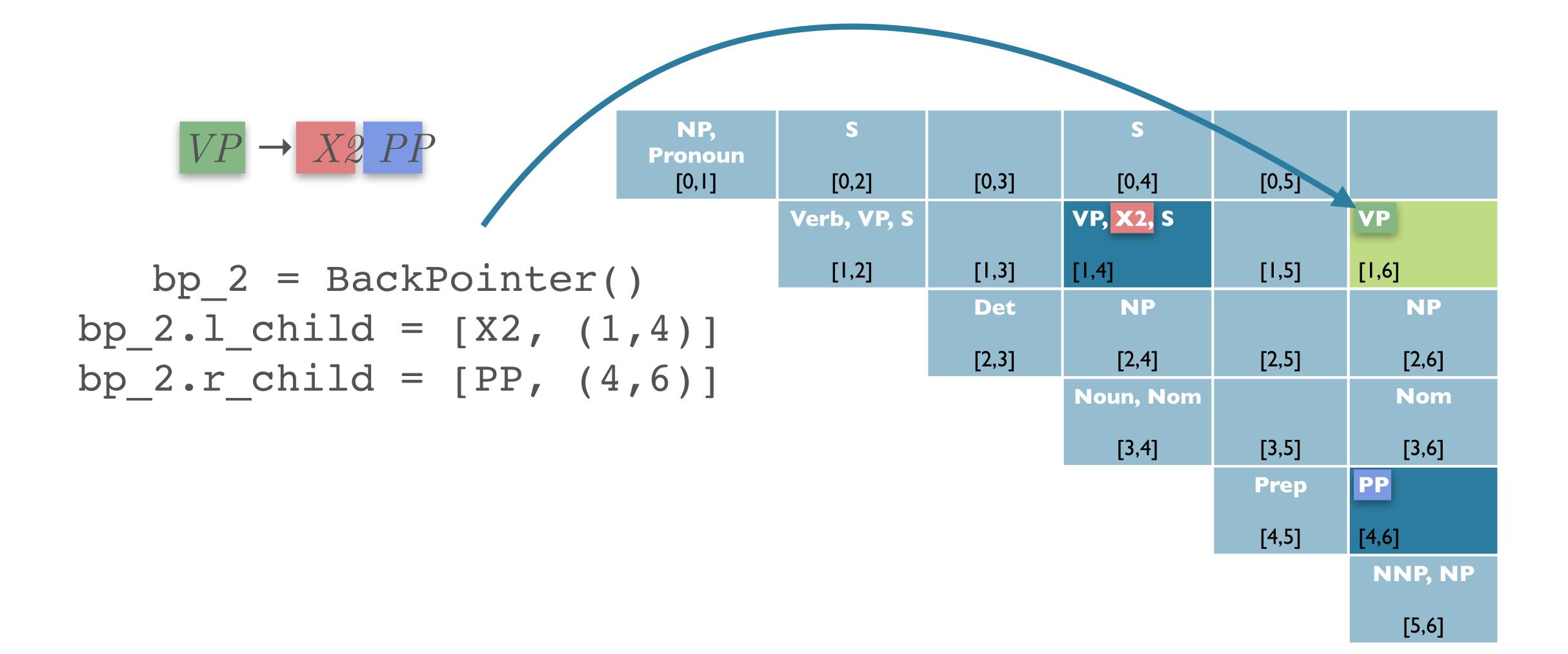
Currently only acceptance/recognition

CKY Parser

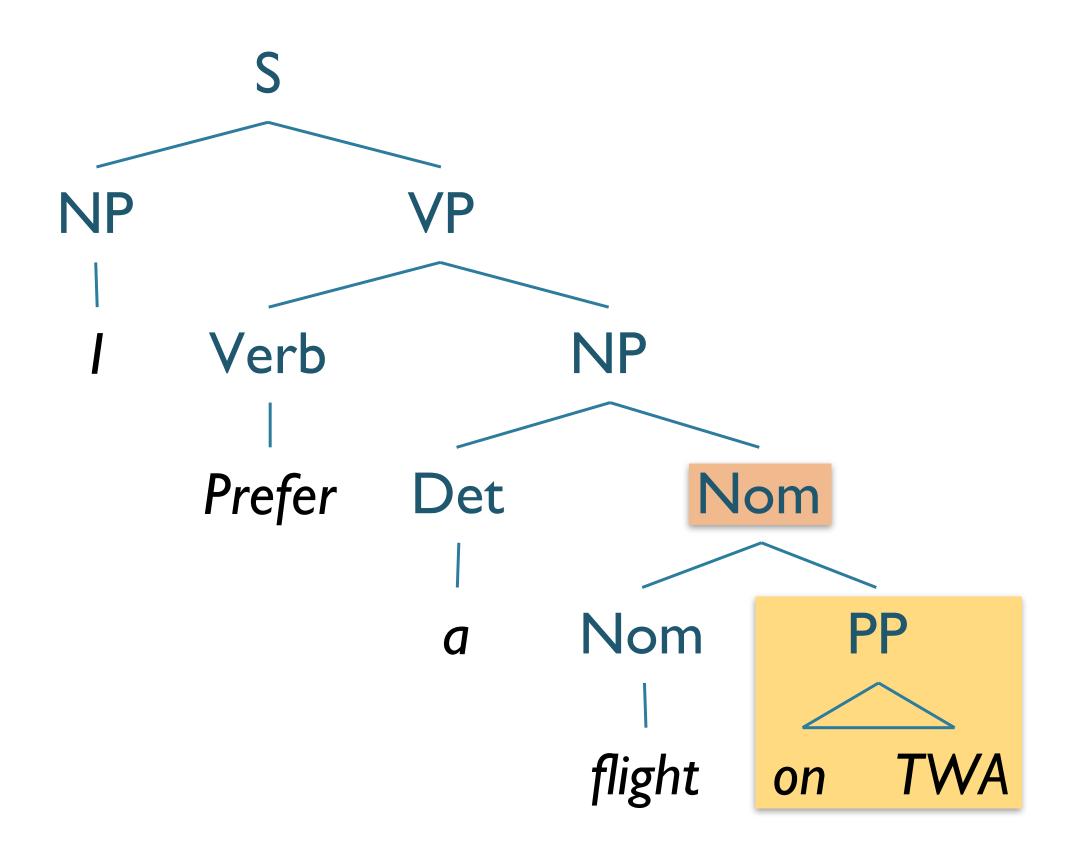
- Pair each nonterminal with back-pointer to cells from which it was derived
- Last step:
 - construct trees from back-pointers in [0, n]

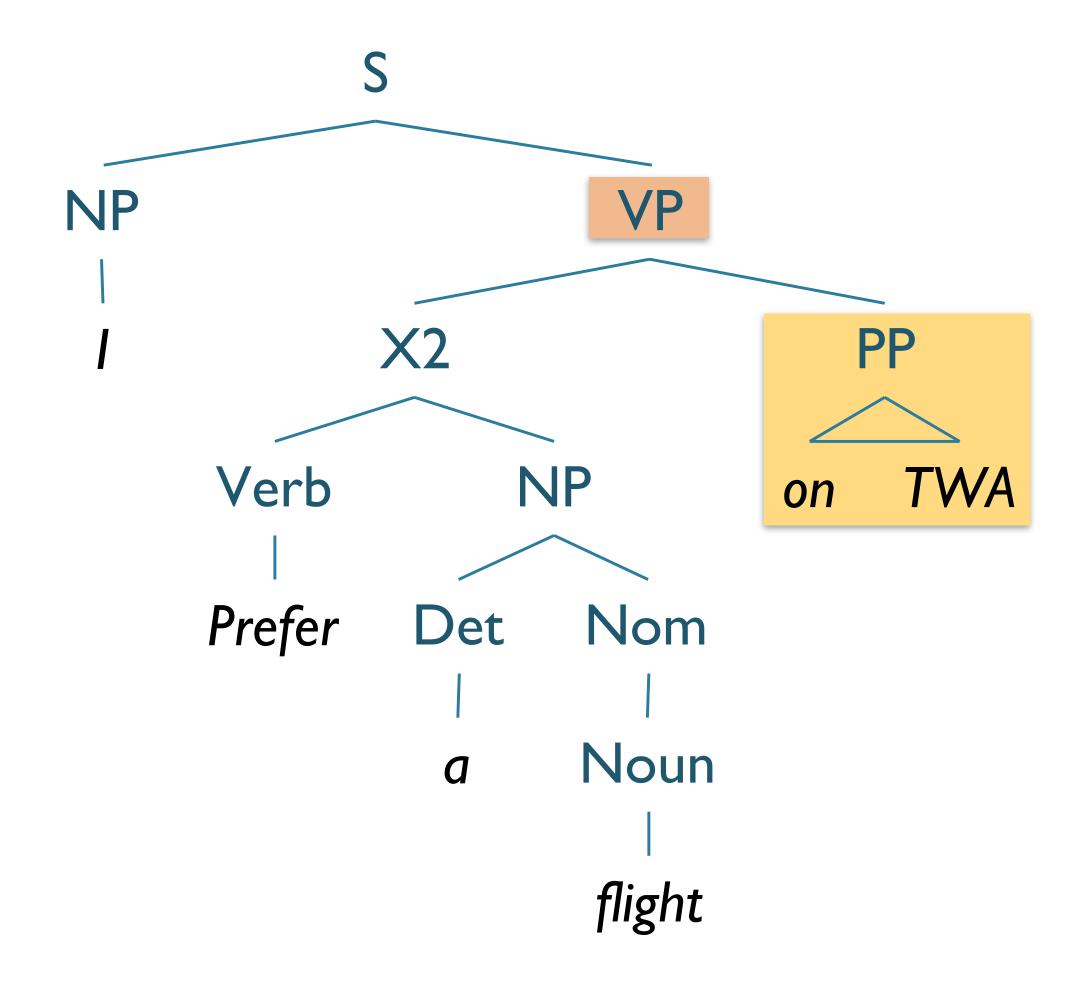
NP, Pronoun	S		S		
[0,1]	[0,2]	[0,3]	[0,4]	[0,5]	
	Verb, VP, S		VP, X2, S		VP
	[1,2]	[1,3]	[1,4]	[1,5]	[1,6]
		Det	NP		NP
		[2,3]	[2,4]	[2,5]	[2,6]
			Noun, Nom		Nom
			[3,4]	[3,5]	[3,6]
				Prep	PP
				[4,5]	[4,6]
					NNP, NP
					[5,6]





Resulting Parses





CKY Discussion

Running time:

 $O(n^3)$ where n is the length of the input string lnner 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