

# CKY Parsing

LING 571 — Deep Processing Techniques for NLP

October 7, 2019

Shane Steinert-Threlkeld

(h/t Ryan Georgi)

# Announcements

- HW1: grades posted
  - In general, we will aim for Monday release of grades.
- Distance students:
  - Let us know in chat if/when audio cuts out.
  - Trying one thing today; will try something more drastic if the issues persist.

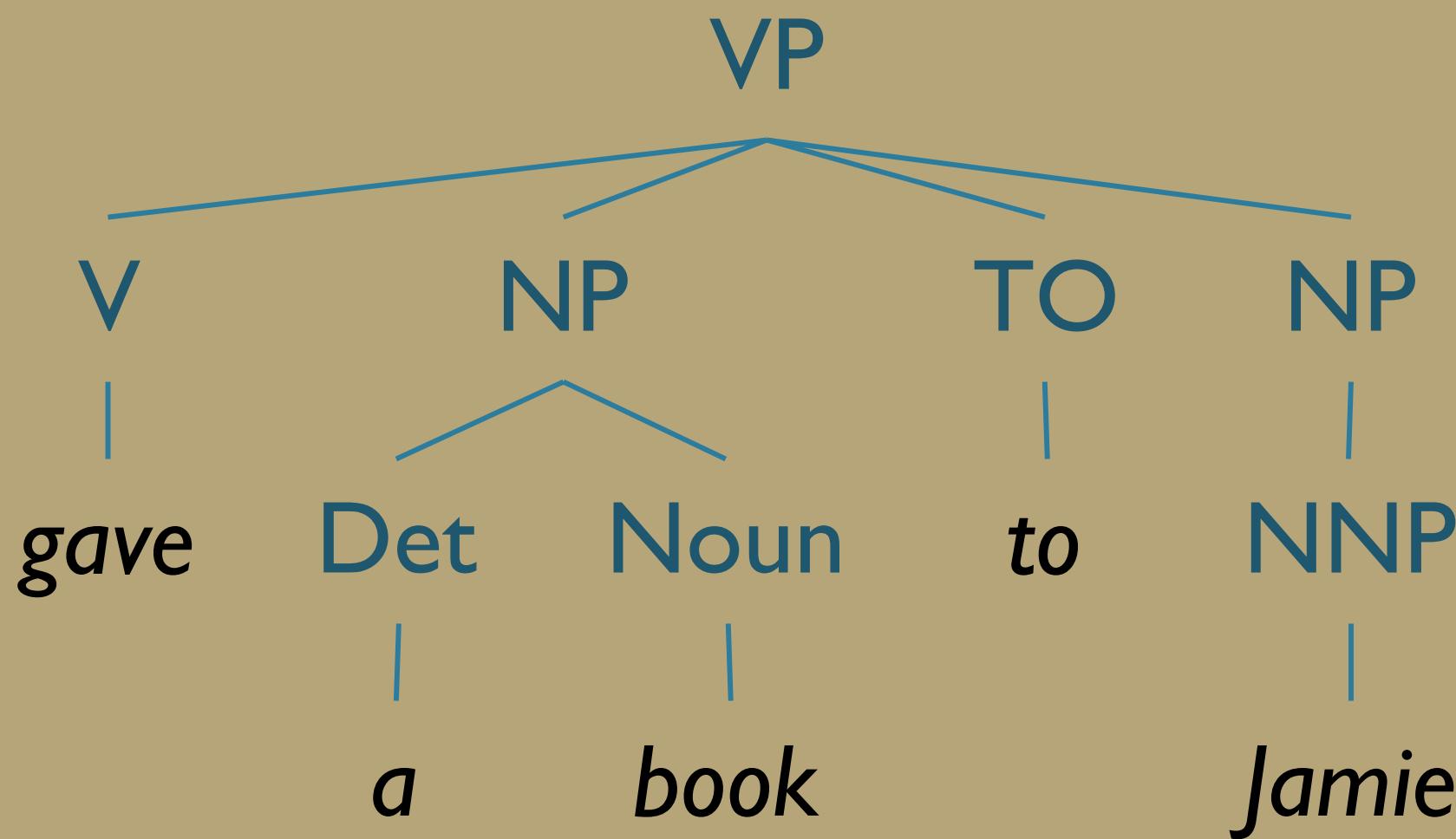
# Announcements: HW #2

- Due Wednesday, 11:00pm Pacific
- Grammar output format:
  1. Terminals quoted (single or double)
  2. One production per line
    - *Optionally*, RHS alternates with vertical bar/pipe character: |
  3. Start symbol is first nonterminal encountered in file

# Variation in CNF: Binarization

## Original Rule

$VP \rightarrow V \ NP \ TO \ NP$



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## Left to Right Reduction

$$VP \rightarrow X1 \ TO \ NP$$

$$X1 \rightarrow V \ NP$$

$$VP \rightarrow X2 \ NP$$

$$X2 \rightarrow X1 \ TO$$

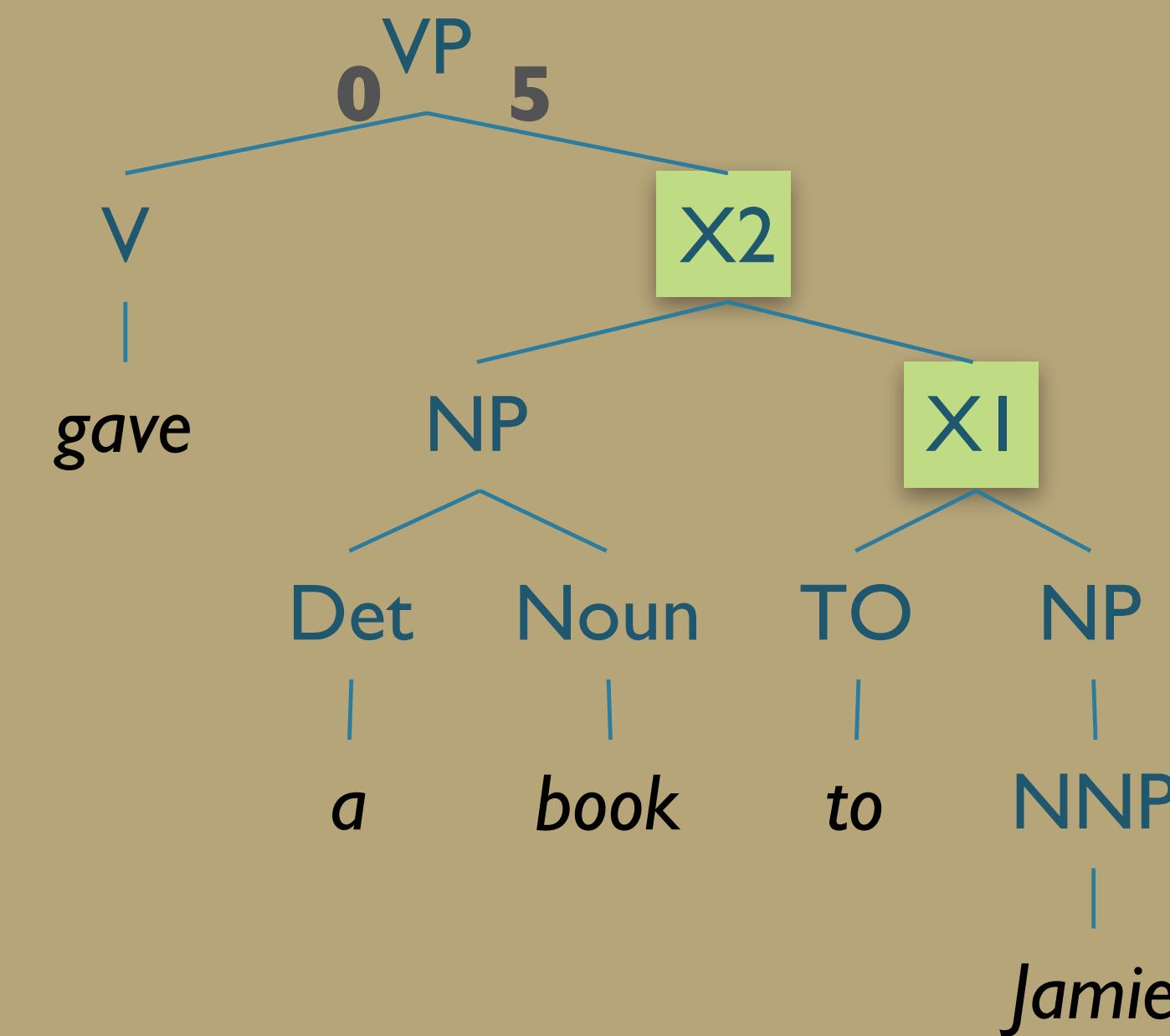
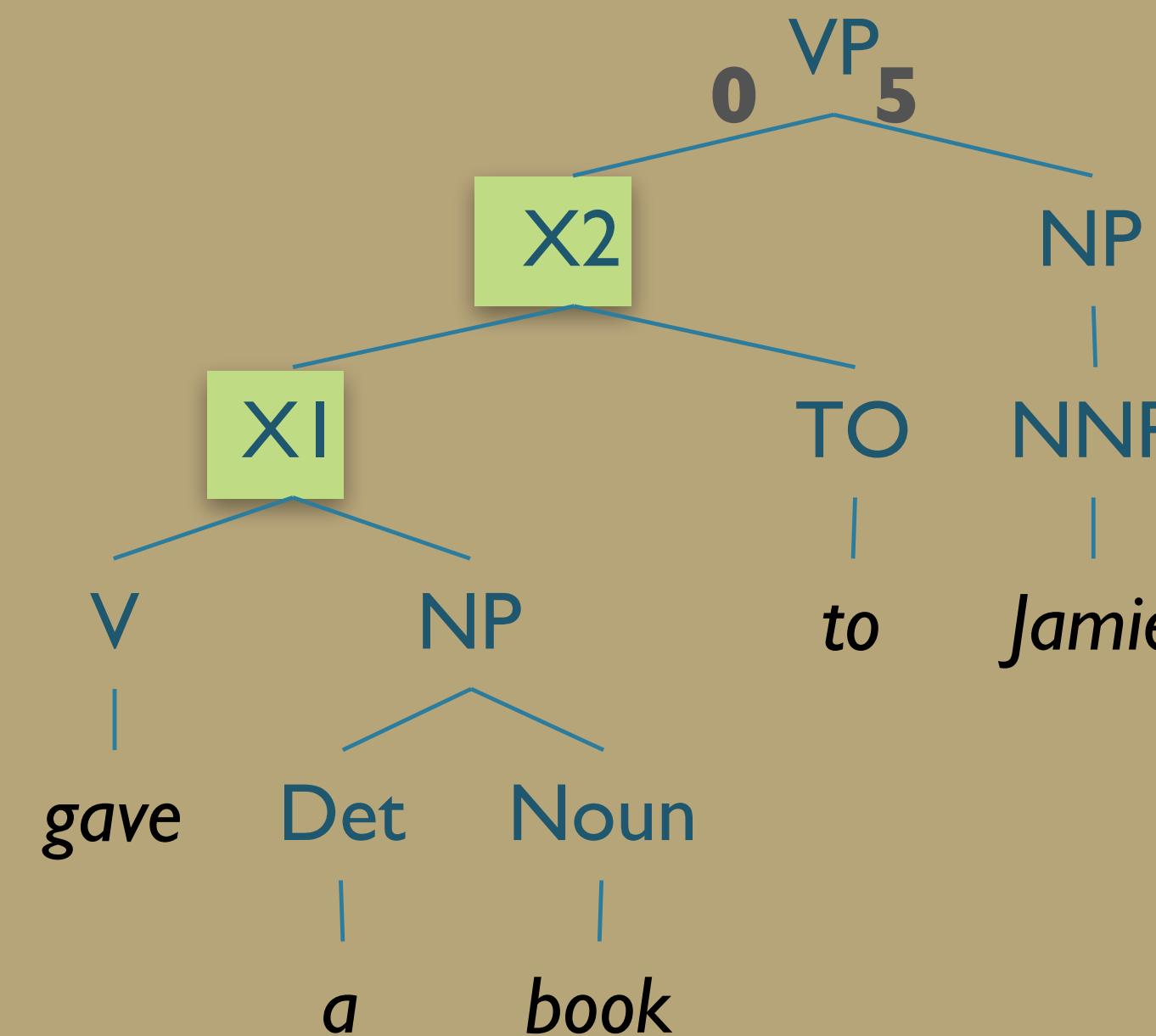
## Right to Left Reduction

$$VP \rightarrow V \ NP \ X1$$

$$X1 \rightarrow TO \ NP$$

$$VP \rightarrow V \ X2$$

$$X2 \rightarrow NP \ X1$$



# Roadmap

- CKY Parsing Algorithm
  - Dynamic programming structure
  - Algorithm and example
  - Analysis & Discussion
- Probabilistic CFGs
  - Motivation: Ambiguity
  - Augmenting CFGs with probabilities

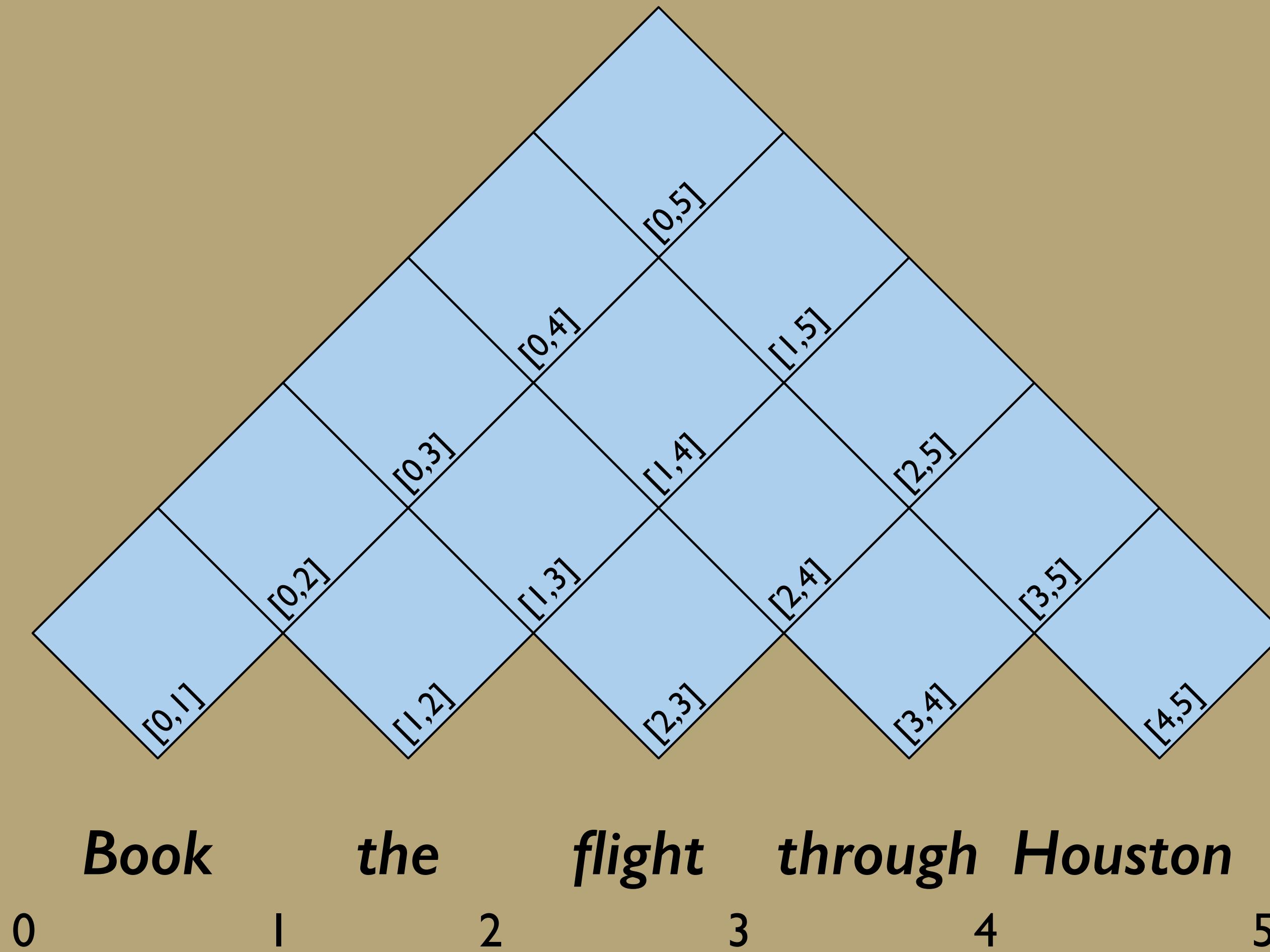
# CKY

- Given an input string  $S$  of length  $n$
- Build table  $(n + 1) \times (n + 1)$ 
  - Indexes correspond to inter-word positions
  - $_0$  Book  $_1$  that  $_2$  flight  $_3$
- 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***

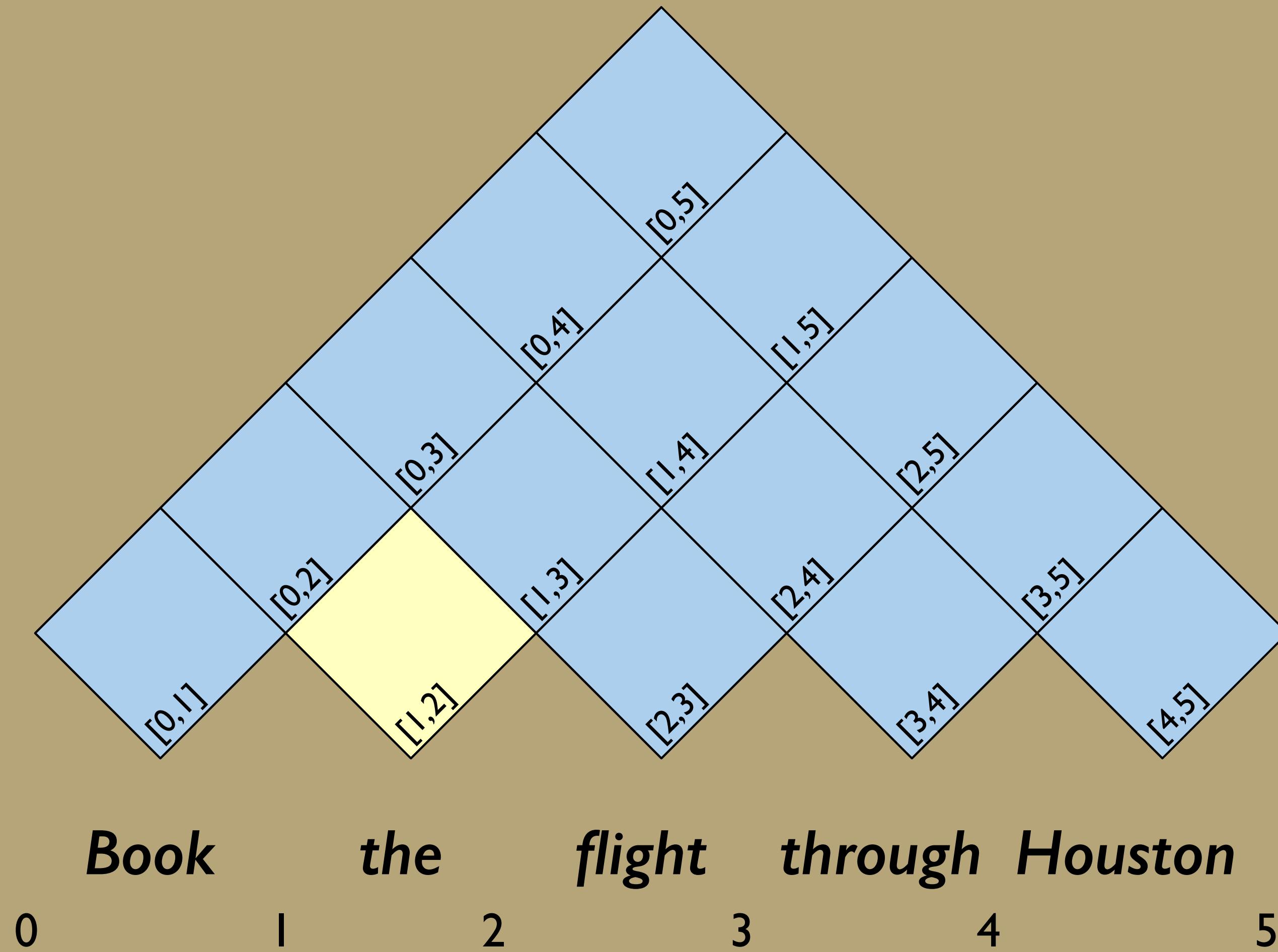
# CKY Matrix

<i>Book</i>	<i>the</i>	<i>flight</i>	<i>through</i>	<i>Houston</i>
[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]

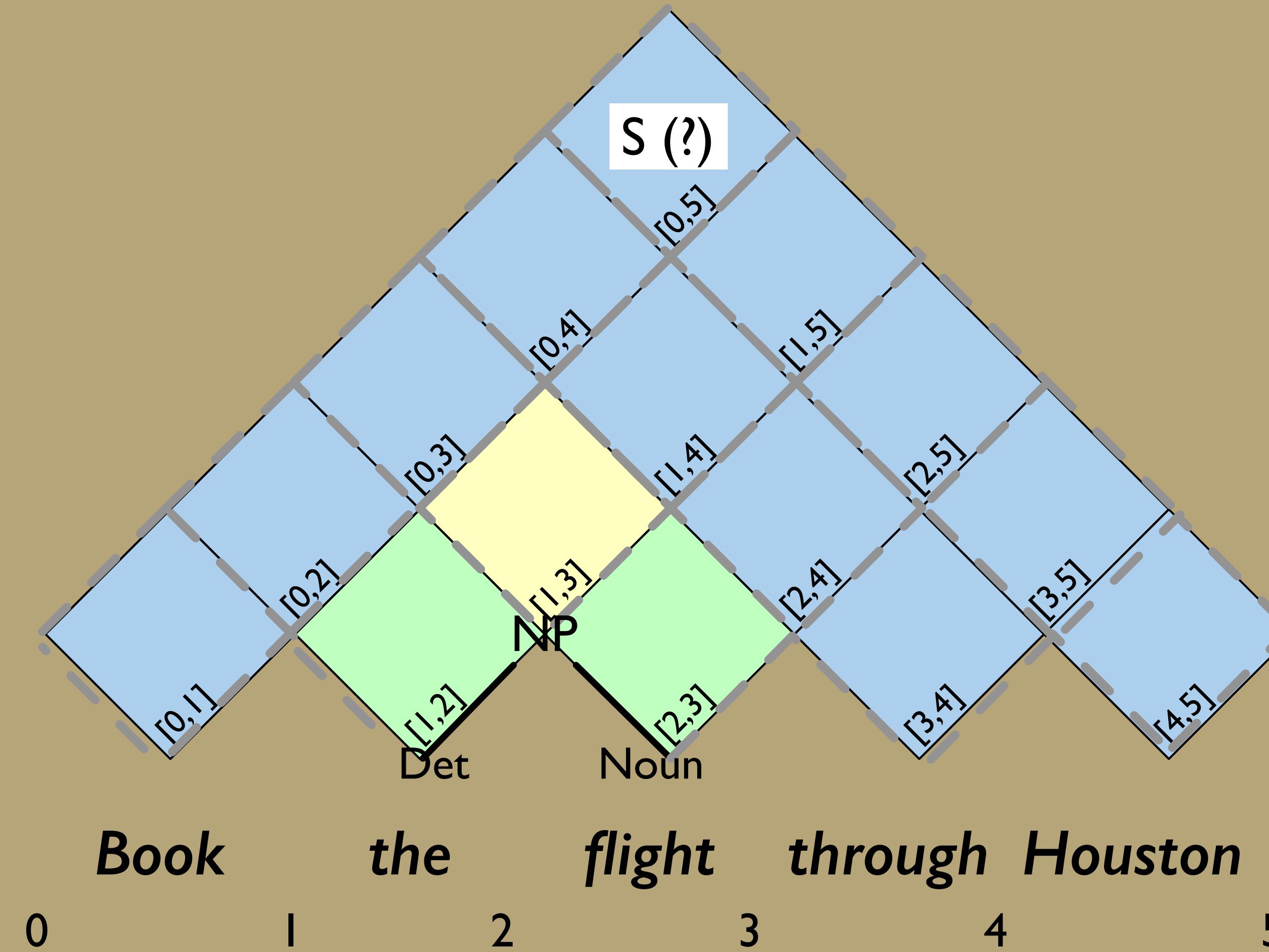
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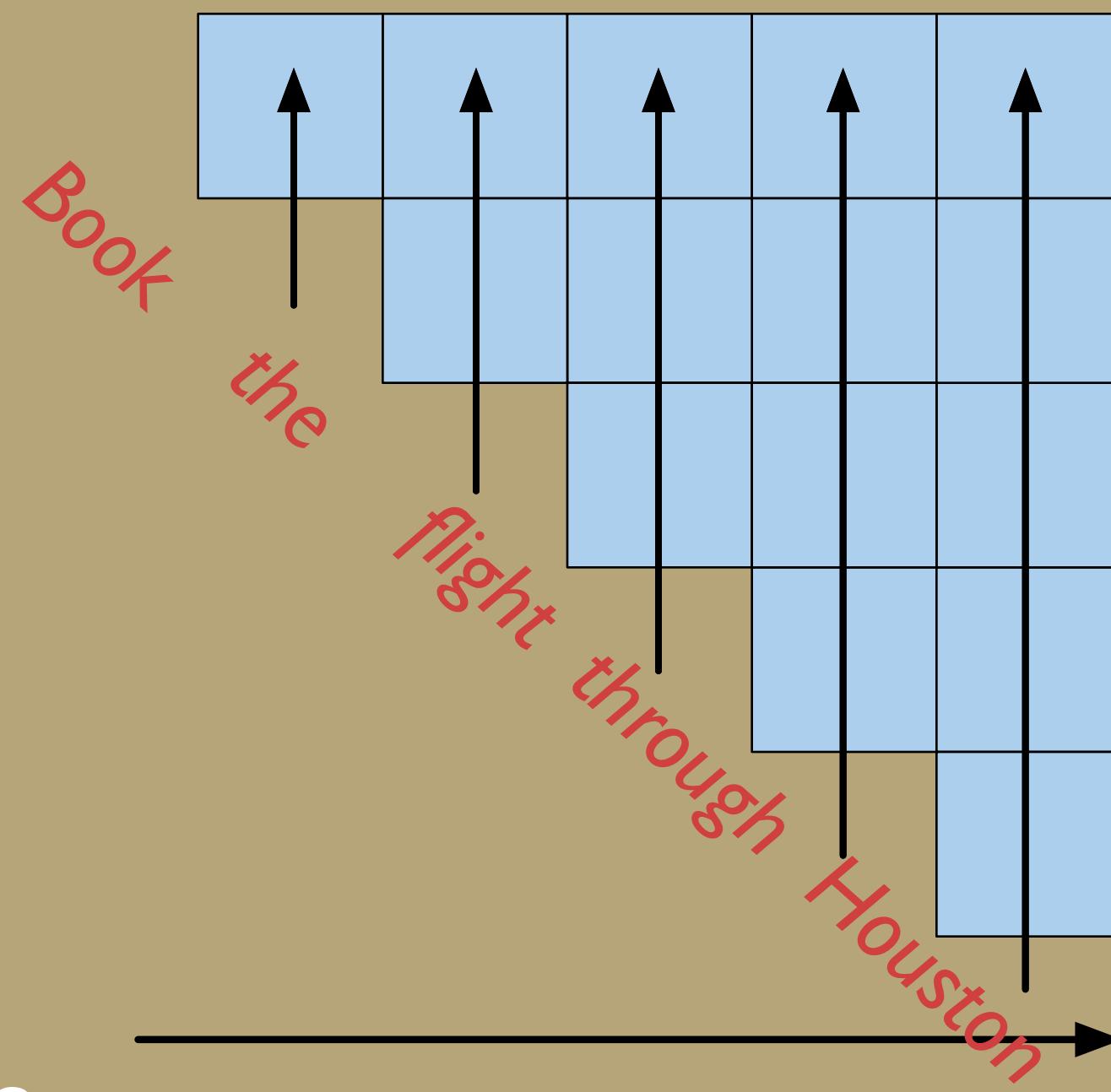


# Dynamic Programming in CKY

- 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  $A \rightarrow B \ C$  in  $[ i, j ]$ 
  - Must have  $B$  in  $[ i, k ]$  and  $C$  in  $[ k, j ]$  for some  $i < k < j$
  - CNF forces this for all  $j > i + 1$

# CKY

- Table fills:
  - Column-by-column, left-to-right
  - bottom-to-top
- Why?
  - To fill each cell, must have access to all sub-spans
    - For cell  $[i, j]$ , must be able to access all cells  $[i, k]$  and  $[k, j]$  where  $i < k < j$
  - Allows online sentence analysis
  - Works across input string as it arrives

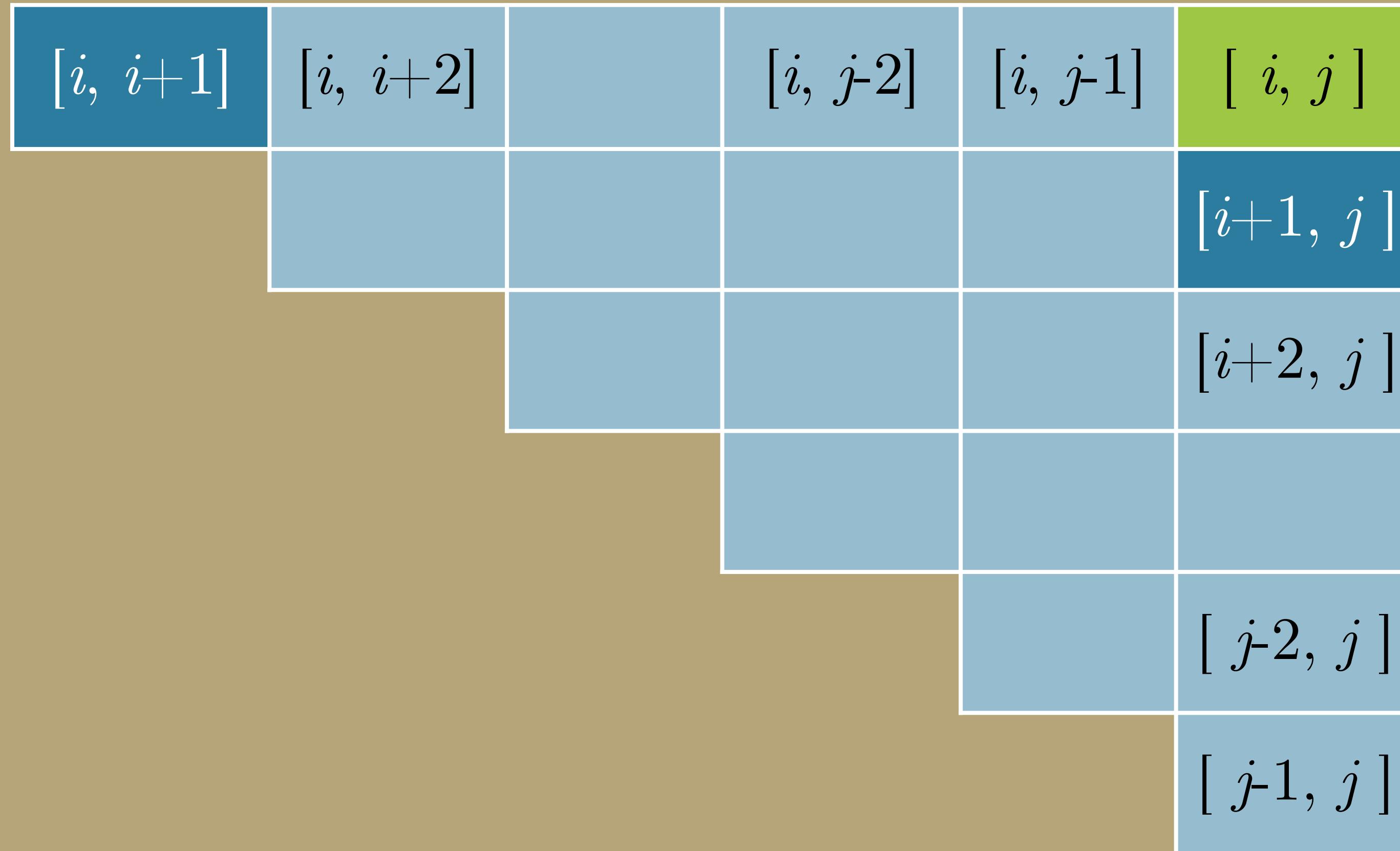


# CKY Algorithm

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

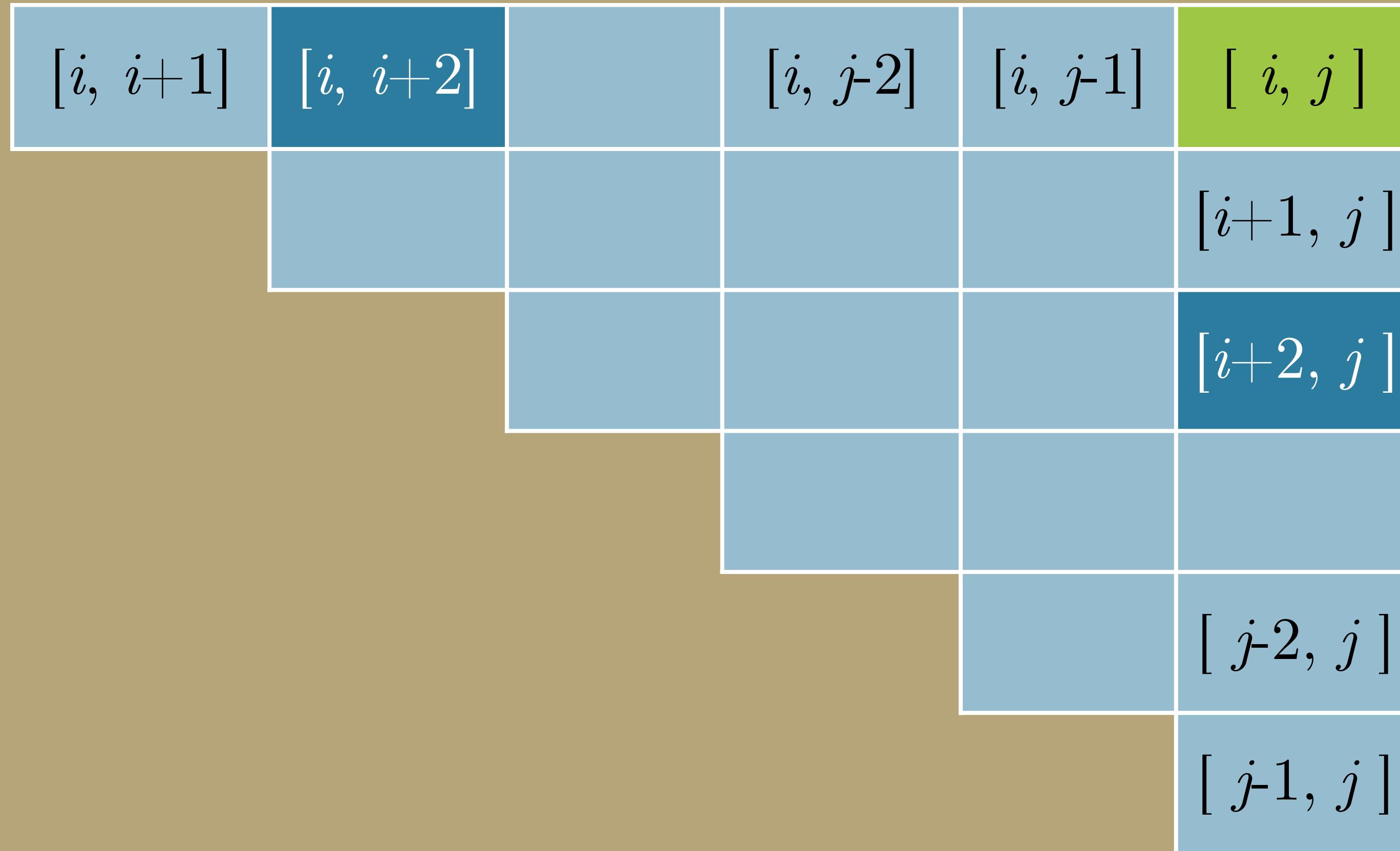
- Left-to-right, bottom-to-top
- Sliding  $k$  as the pivot for child nodes
- Filling the cell with set of applicable rules

# Filling Cell $[i, j]$



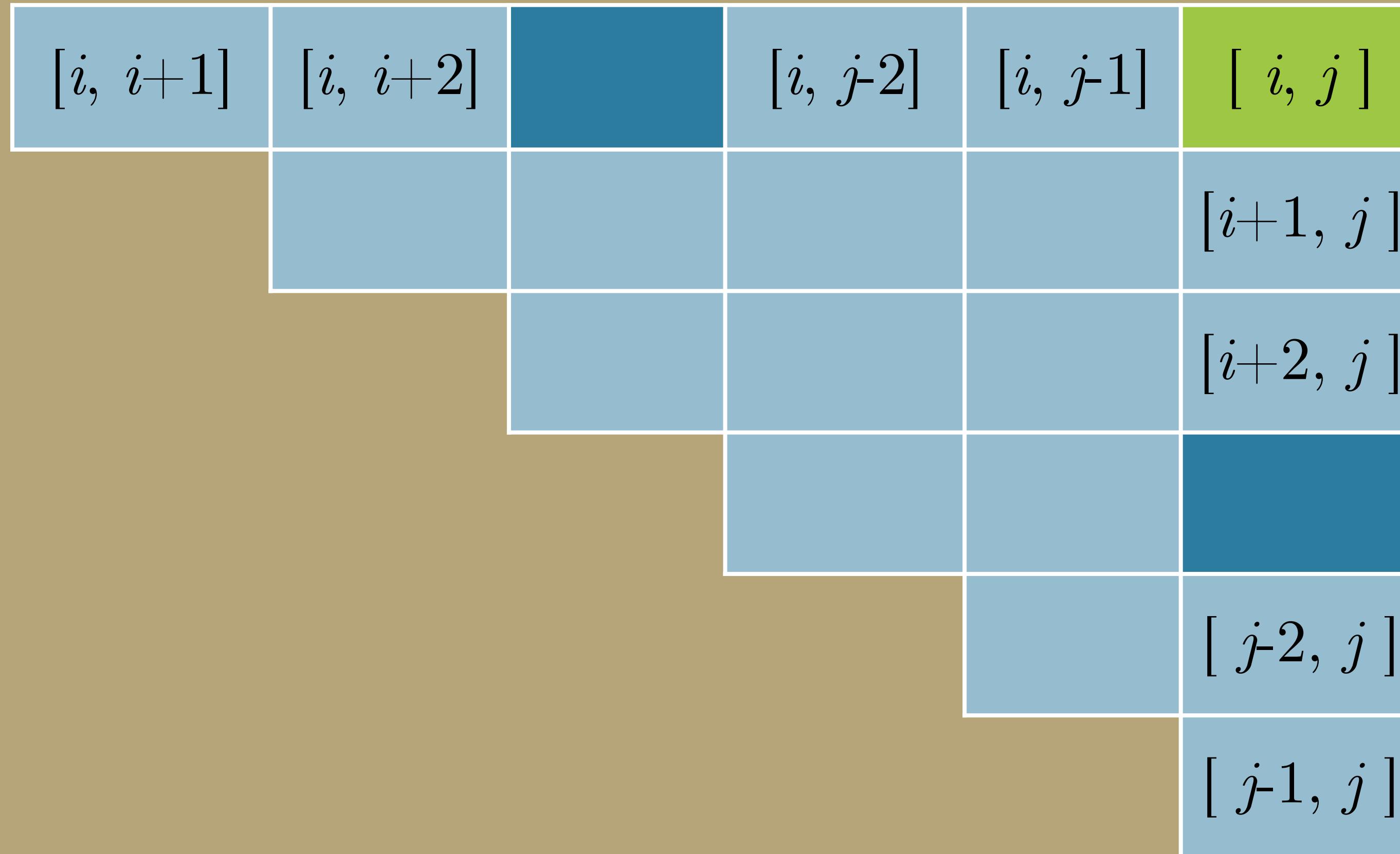
For cell  $[i, j]$ , find rule spanning cells  $[i, k]$  and  $[k, j]$  where  $i < k < j$

# Filling Cell $[i, j]$



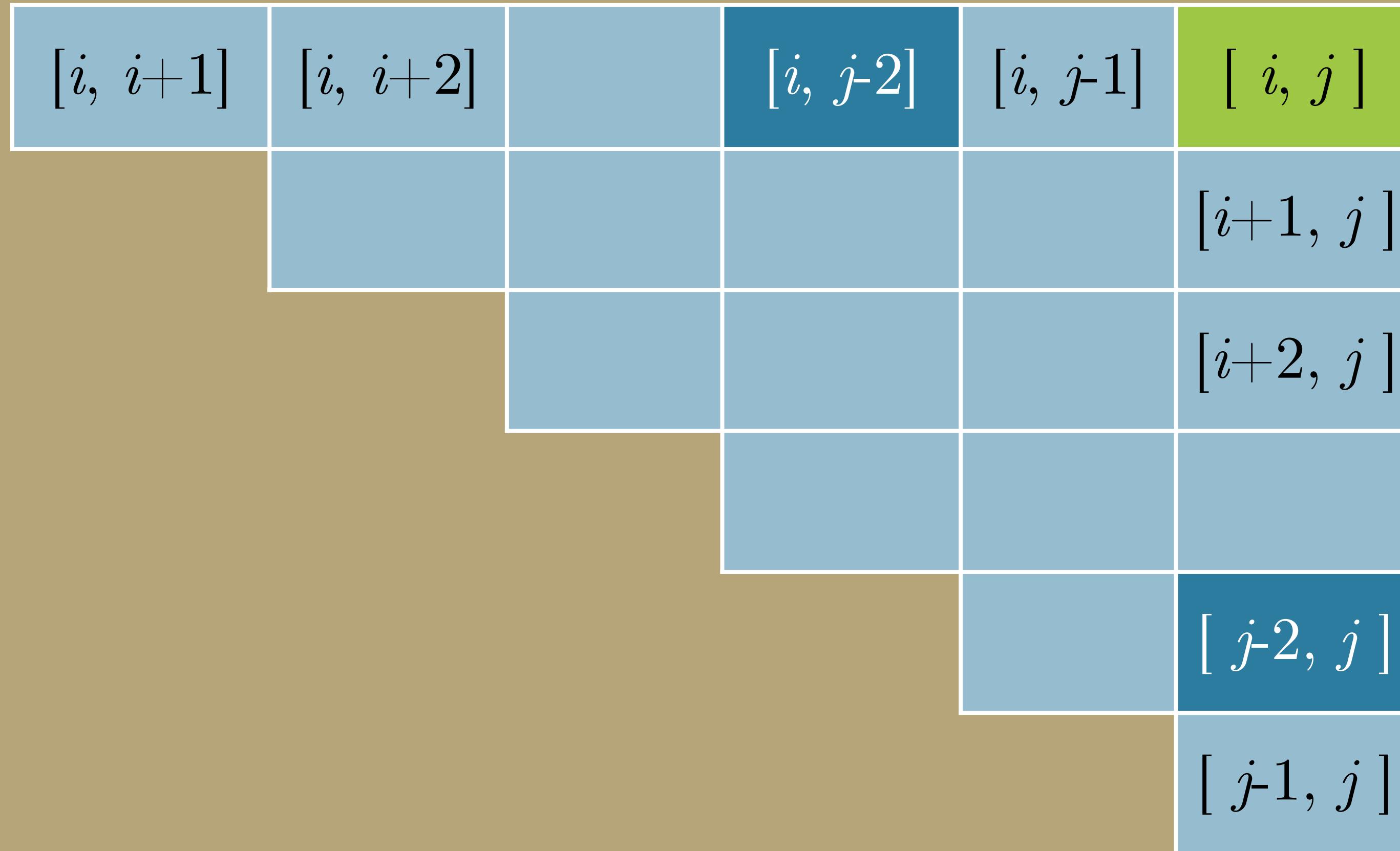
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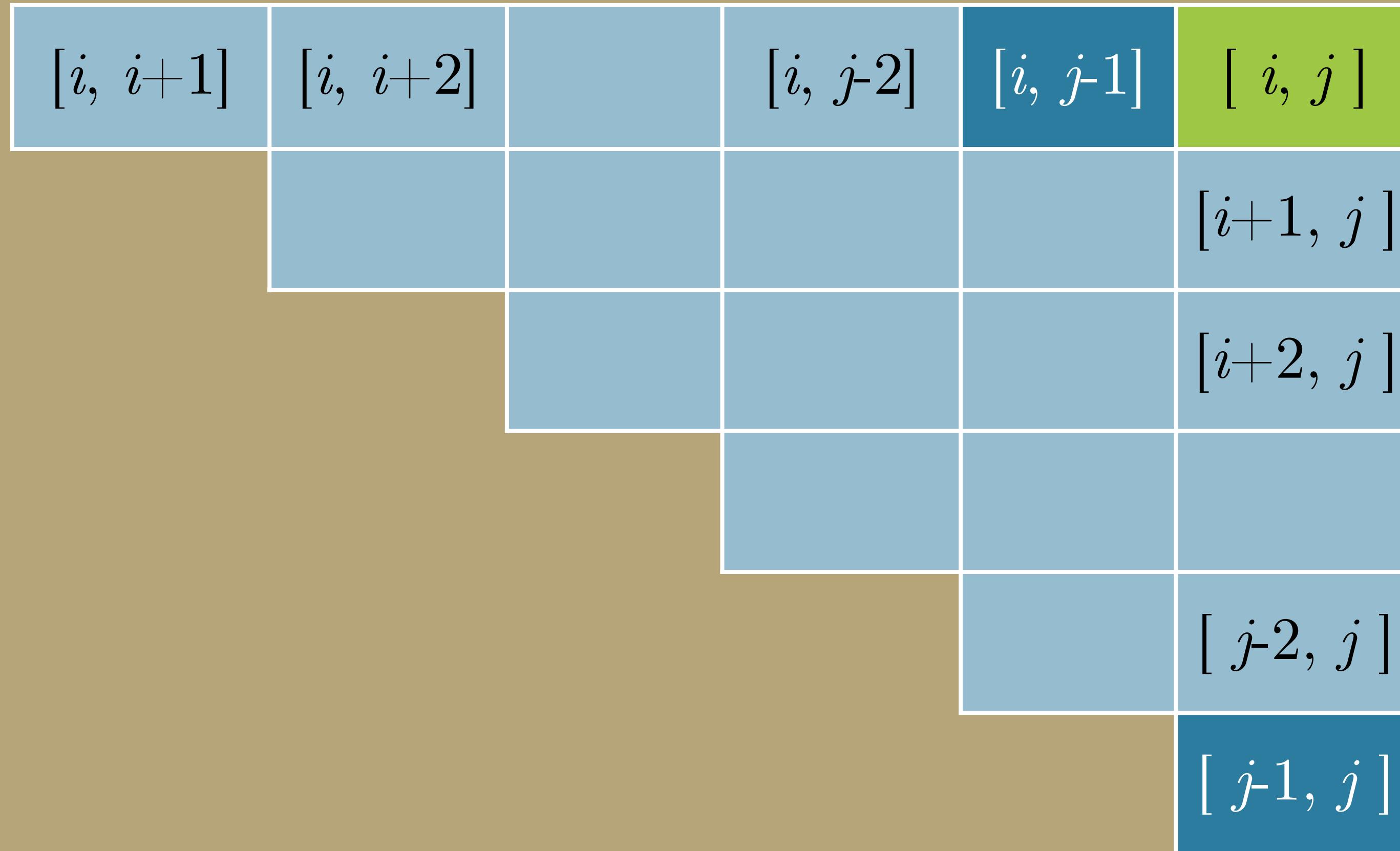
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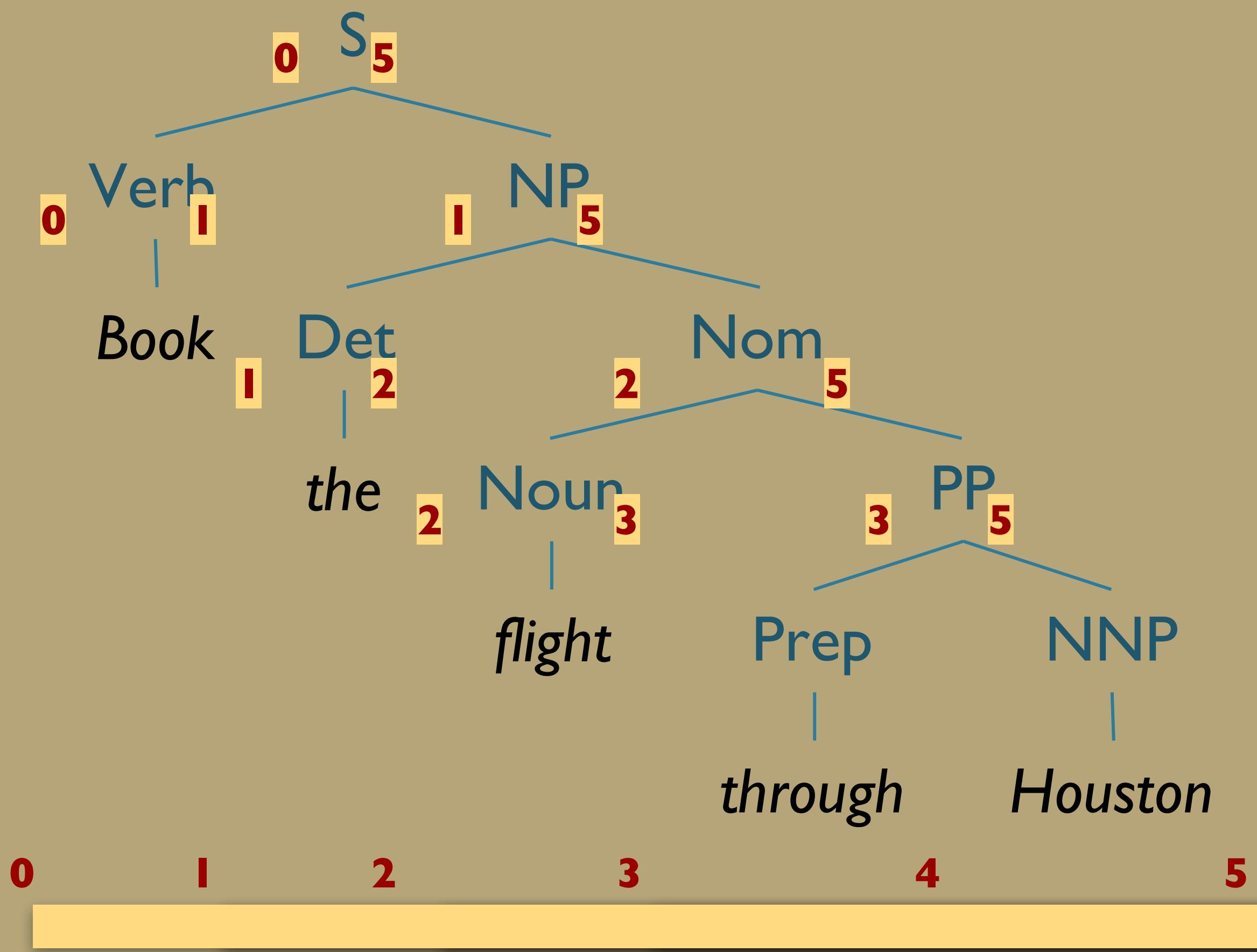
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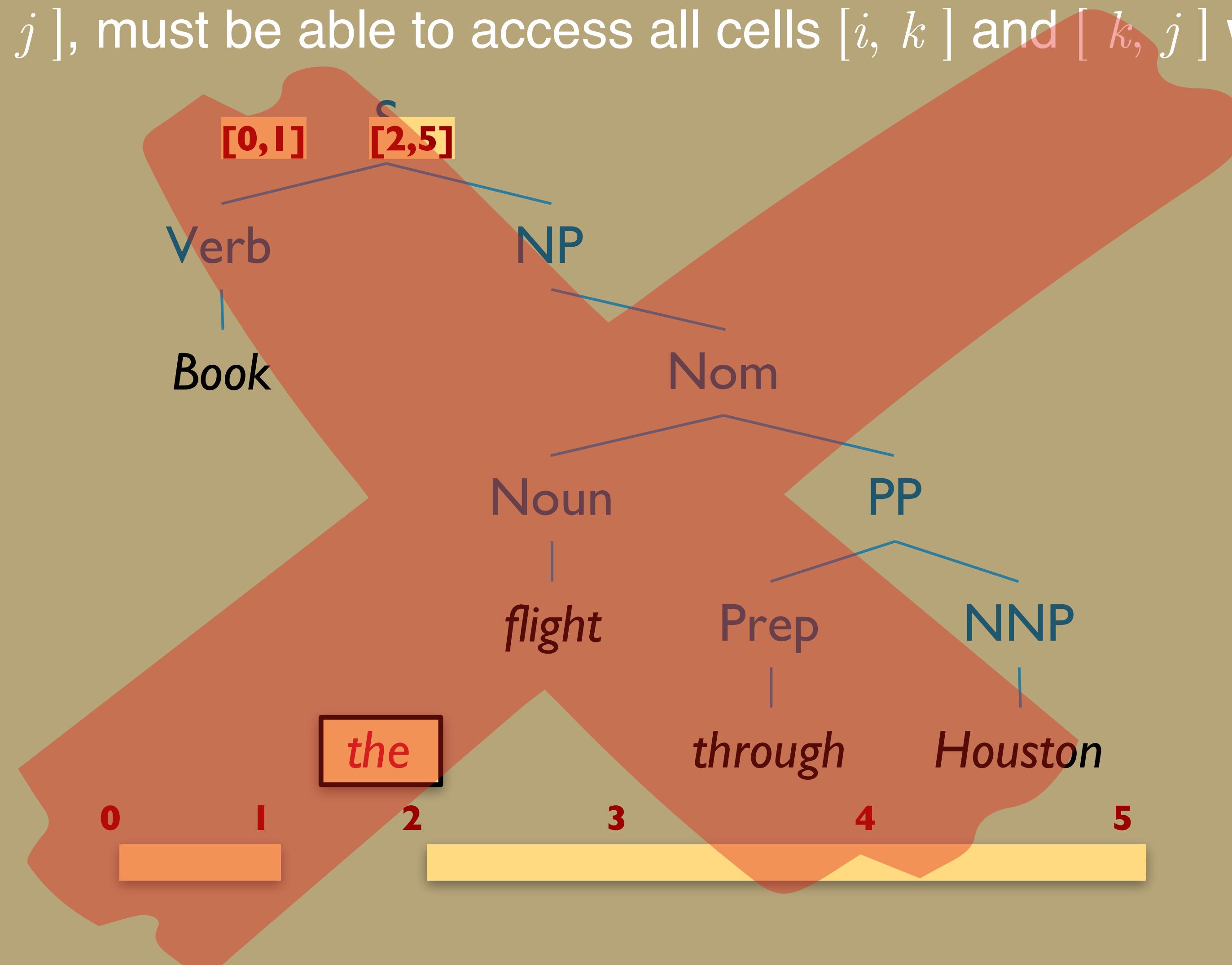
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# CKY Parsing Example

## $\mathcal{L}_1$ Grammar

$S \rightarrow NP\ VP$   
 $S \rightarrow X1\ VP$   
 $X1 \rightarrow Aux\ NP$   
 $S \rightarrow book\ / include\ / prefer$

$S \rightarrow Verb\ NP$   
 $S \rightarrow X2\ PP$   
 $S \rightarrow Verb\ PP$   
 $S \rightarrow VP\ PP$

$NP \rightarrow I\ / she\ / me$

$NP \rightarrow TWA\ / Houston$

$NP \rightarrow Det\ Nominal$

$Nominal \rightarrow book\ / flight\ / meal\ / money$

$Nominal \rightarrow Nominal\ Noun$

$Nominal \rightarrow Nominal\ PP$

$VP \rightarrow book\ / include\ / prefer$

$VP \rightarrow Verb\ NP$

$VP \rightarrow X2\ PP$

$X2 \rightarrow Verb\ NP$

$VP \rightarrow Verb\ PP$

$VP \rightarrow VP\ PP$

$PP \rightarrow Preposition\ NP$


**Lexicon**

$Det \rightarrow that\ | this\ | a$   
 $Noun \rightarrow book\ | flight\ | meal\ | money$   
 $Pronoun \rightarrow I\ | she\ | me$   
 $Proper-Noun \rightarrow Houston\ | TWA$   
 $Aux \rightarrow does$   
 $Preposition \rightarrow from\ | to\ | on\ | near\ | through$   
 $Verb \rightarrow book\ | include\ | prefer$

| prefer a flight on TWA  
0 1 2 3 4 5 6

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$S \rightarrow NP\ VP$   
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$VP \rightarrow book\ | include\ | prefer$

$VP \rightarrow Verb\ NP$

$VP \rightarrow X2\ PP$

$X2 \rightarrow Verb\ NP$

$VP \rightarrow Verb\ PP$

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## NP

[0, 1]


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I prefer a flight on TWA

0

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4

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**NP,  
Pronoun**

[0, 1]

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Timeline diagram showing tokens and their positions:

- 0:  $I$
- 1:  $prefer$
- 2:  $a$
- 3:  $flight$
- 4:  $on$
- 5:  $TWA$

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**NP,  
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[0,1]**

**Verb, VP, S**

[1,2]

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[0,1]

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**NP, Pronoun**  
[0,1]

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$PP \rightarrow Preposition NP$

| prefer a flight on TWA

0 | 1 2 3 4 5 6

<b>NP, Pronoun [0,1]</b>	<b>S [0,2]</b>			
	<b>Verb, VP, S [1,2]</b>			
		<b>Det [2,3]</b>		

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$Proper-Noun \rightarrow Houston | TWA$

$Aux \rightarrow does$

$Preposition \rightarrow from | to | on | near | through$

$Verb \rightarrow book | include | prefer$

### $\mathcal{L}_1$ Grammar

$S \rightarrow NP VP$   
 $S \rightarrow X1 VP$   
 $X1 \rightarrow Aux NP$   
 $S \rightarrow book / include / prefer$   
 $S \rightarrow Verb NP$

$S \rightarrow X2 PP$

$S \rightarrow Verb PP$

$S \rightarrow VP PP$

$NP \rightarrow I / she / me$

$NP \rightarrow TWA / Houston$

$NP \rightarrow Det Nominal$

$Nominal \rightarrow book / flight / meal / money$

$Nominal \rightarrow Nominal Noun$

$Nominal \rightarrow Nominal PP$

$VP \rightarrow book / include / prefer$

$VP \rightarrow Verb NP$

$VP \rightarrow X2 PP$

$X2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

$VP \rightarrow VP PP$

$PP \rightarrow Preposition NP$

<b>NP, Pronoun</b> [0,1]	<b>S</b> [0,2]			
		<b>Verb, VP, S</b> [1,2]	<b>[1,3]</b>	
			<b>Det</b> [2,3]	

### Lexicon

$Det \rightarrow that | this | a$

$Noun \rightarrow book | flight | meal | money$

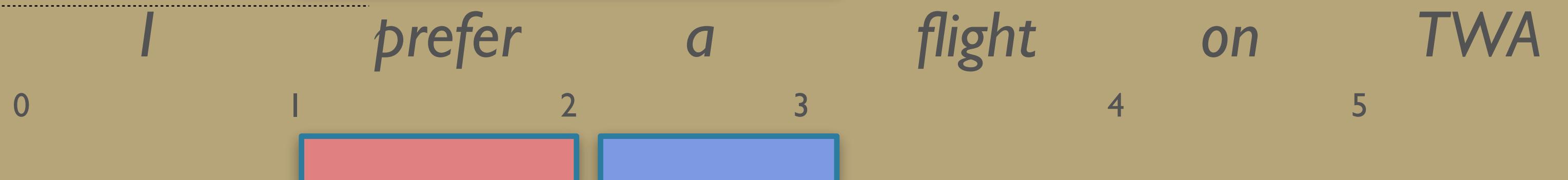
$Pronoun \rightarrow I | she | me$

$Proper-Noun \rightarrow Houston | TWA$

$Aux \rightarrow does$

$Preposition \rightarrow from | to | on | near | through$

$Verb \rightarrow book | include | prefer$



### $\mathcal{L}_1$ Grammar

$S \rightarrow NP VP$   
 $S \rightarrow X1 VP$   
 $X1 \rightarrow Aux NP$   
 $S \rightarrow book / include / prefer$   
 $S \rightarrow Verb NP$

$S \rightarrow X2 PP$

$S \rightarrow Verb PP$

$S \rightarrow VP PP$

$NP \rightarrow I / she / me$

$NP \rightarrow TWA / Houston$

$NP \rightarrow Det Nominal$

$Nominal \rightarrow book / flight / meal / money$

$Nominal \rightarrow Nominal Noun$

$Nominal \rightarrow Nominal PP$

$VP \rightarrow book / include / prefer$

$VP \rightarrow Verb NP$

$VP \rightarrow X2 PP$

$X2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

$VP \rightarrow VP PP$

$PP \rightarrow Preposition NP$

<b>NP, Pronoun</b> [0,1]	<b>S</b> [0,2]			
		<b>Verb, VP, S</b> [1,2]	[1,3]	
			<b>Det</b> [2,3]	

### Lexicon

$Det \rightarrow that | this | a$

$Noun \rightarrow book | flight | meal | money$

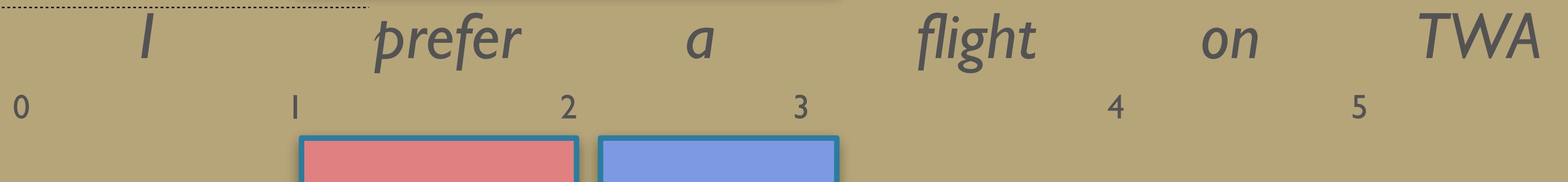
$Pronoun \rightarrow I | she | me$

$Proper-Noun \rightarrow Houston | TWA$

$Aux \rightarrow does$

$Preposition \rightarrow from | to | on | near | through$

$Verb \rightarrow book | include | prefer$



### $\mathcal{L}_1$ Grammar

$S \rightarrow NP VP$   
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 $X1 \rightarrow Aux NP$   
 $S \rightarrow book / include / prefer$   
 $S \rightarrow Verb NP$

$S \rightarrow X2 PP$

$S \rightarrow Verb PP$

$S \rightarrow VP PP$

$NP \rightarrow I / she / me$

$NP \rightarrow TWA / Houston$

$NP \rightarrow Det Nominal$

$Nominal \rightarrow book / flight / meal / money$

$Nominal \rightarrow Nominal Noun$

$Nominal \rightarrow Nominal PP$

$VP \rightarrow book / include / prefer$

$VP \rightarrow Verb NP$

$VP \rightarrow X2 PP$

$X2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

$VP \rightarrow VP PP$

$PP \rightarrow Preposition NP$

<b>NP, Pronoun</b> [0,1]	<b>S</b> [0,2]			
	<b>Verb, VP, S</b> [1,2]	[1,3]		
		<b>Det</b> [2,3]		

### Lexicon

$Det \rightarrow that | this | a$

$Noun \rightarrow book | flight | meal | money$

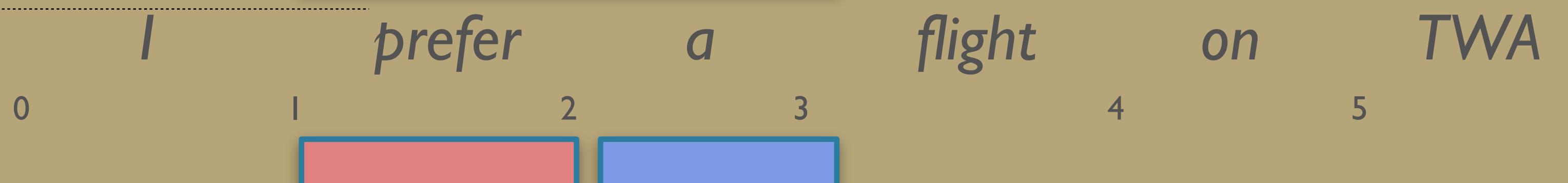
$Pronoun \rightarrow I | she | me$

$Proper-Noun \rightarrow Houston | TWA$

$Aux \rightarrow does$

$Preposition \rightarrow from | to | on | near | through$

$Verb \rightarrow book | include | prefer$



### $\mathcal{L}_1$ Grammar

$S \rightarrow NP VP$   
 $S \rightarrow X1 VP$   
 $X1 \rightarrow Aux NP$   
 $S \rightarrow book / include / prefer$   
 $S \rightarrow Verb NP$

$S \rightarrow X2 PP$

$S \rightarrow Verb PP$

$S \rightarrow VP PP$

$NP \rightarrow I / she / me$

$NP \rightarrow TWA / Houston$

$NP \rightarrow Det Nominal$

$Nominal \rightarrow book / flight / meal / money$

$Nominal \rightarrow Nominal Noun$

$Nominal \rightarrow Nominal PP$

$VP \rightarrow book / include / prefer$

$VP \rightarrow Verb NP$

$VP \rightarrow X2 PP$

$X2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

$VP \rightarrow VP PP$

$PP \rightarrow Preposition NP$

<b>NP, Pronoun</b> [0,1]	<b>S</b> [0,2]			
		<b>Verb, VP, S</b> [1,2]	[1,3]	
			<b>Det</b> [2,3]	

### Lexicon

$Det \rightarrow that | this | a$

$Noun \rightarrow book | flight | meal | money$

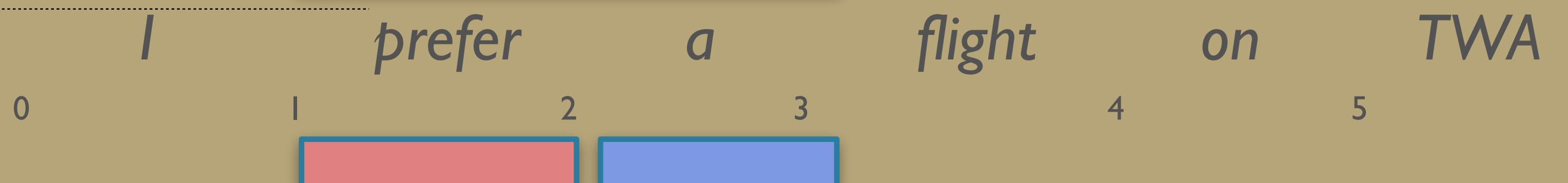
$Pronoun \rightarrow I | she | me$

$Proper-Noun \rightarrow Houston | TWA$

$Aux \rightarrow does$

$Preposition \rightarrow from | to | on | near | through$

$Verb \rightarrow book | include | prefer$



## $\mathcal{L}_1$ Grammar

$S \rightarrow NP VP$   
 $S \rightarrow X1 VP$   
 $X1 \rightarrow Aux NP$   
 $S \rightarrow book / include / prefer$   
 $S \rightarrow Verb NP$

$S \rightarrow X2 PP$   
 $S \rightarrow Verb PP$   
 $S \rightarrow VP PP$

$NP \rightarrow I / she / me$

$NP \rightarrow TWA / Houston$

$NP \rightarrow Det Nominal$

$Nominal \rightarrow book / flight / meal / money$

$Nominal \rightarrow Nominal Noun$

$Nominal \rightarrow Nominal PP$

$VP \rightarrow book / include / prefer$

$VP \rightarrow Verb NP$

$VP \rightarrow X2 PP$

$X2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

$VP \rightarrow VP PP$

$PP \rightarrow Preposition NP$

<b>NP, Pronoun</b> [0,1]	<b>S</b> [0,2]			
		<b>Verb, VP, S</b> [1,2]	<b>[1,3]</b>	
			<b>Det</b> [2,3]	

## Lexicon

$Det \rightarrow that | this | a$

$Noun \rightarrow book | flight | meal | money$

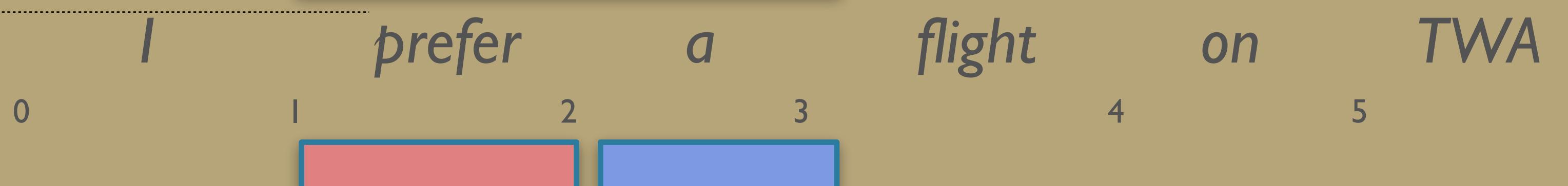
$Pronoun \rightarrow I | she | me$

$Proper-Noun \rightarrow Houston | TWA$

$Aux \rightarrow does$

$Preposition \rightarrow from | to | on | near | through$

$Verb \rightarrow book | include | prefer$



### $\mathcal{L}_1$ Grammar

$S \rightarrow NP VP$   
 $S \rightarrow X1 VP$   
 $X1 \rightarrow Aux NP$   
 $S \rightarrow book / include / prefer$   
 $S \rightarrow Verb NP$

$S \rightarrow X2 PP$

$S \rightarrow Verb PP$

$S \rightarrow VP PP$

$NP \rightarrow I / she / me$

$NP \rightarrow TWA / Houston$

$NP \rightarrow Det Nominal$

$Nominal \rightarrow book / flight / meal / money$

$Nominal \rightarrow Nominal Noun$

$Nominal \rightarrow Nominal PP$

$VP \rightarrow book / include / prefer$

$VP \rightarrow Verb NP$

$VP \rightarrow X2 PP$

$X2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

$VP \rightarrow VP PP$

$PP \rightarrow Preposition NI$

**NP,  
Pronoun**  
[0,1]

**S**

[0,2]

[0,3]

**Verb, VP, S**  
[1,2]

[1,3]

**Det**

[2,3]

### Lexicon

$Det \rightarrow that | this | a$

$Noun \rightarrow book | flight | meal | money$

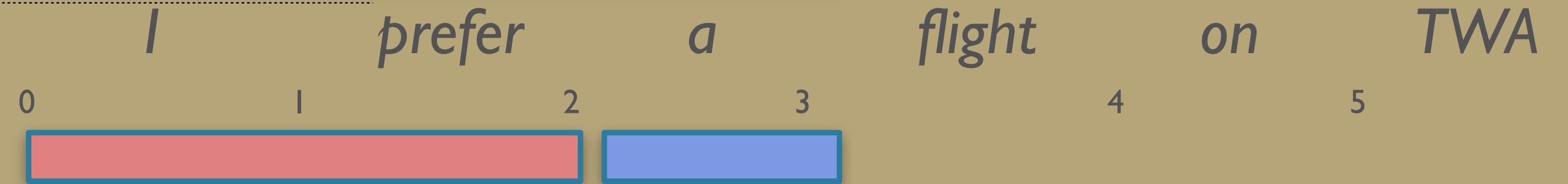
$Pronoun \rightarrow I | she | me$

$Proper-Noun \rightarrow Houston | TWA$

$Aux \rightarrow does$

$Preposition \rightarrow from | to | on | near | through$

$Verb \rightarrow book | include | prefer$



## $\mathcal{L}_1$ Grammar

$S \rightarrow NP\ VP$   
 $S \rightarrow X1\ VP$   
 $X1 \rightarrow Aux\ NP$   
 $S \rightarrow book\ / include\ / prefer$   
 $S \rightarrow Verb\ NP$

$S \rightarrow X2\ PP$

$S \rightarrow Verb\ PP$

$S \rightarrow VP\ PP$

$NP \rightarrow I\ / she\ / me$

$NP \rightarrow TWA\ / Houston$

$NP \rightarrow Det\ Nominal$

$Nominal \rightarrow book\ / flight\ / meal\ / money$

$Nominal \rightarrow Nominal\ Noun$

$Nominal \rightarrow Nominal\ PP$

$VP \rightarrow book\ / include\ / prefer$

$VP \rightarrow Verb\ NP$

$VP \rightarrow X2\ PP$

$X2 \rightarrow Verb\ NP$

$VP \rightarrow Verb\ PP$

$VP \rightarrow VP\ PP$

$PP \rightarrow Preposition\ Noun$

<b>NP, Pronoun</b> [0,1]	<b>S</b> [0,2]	[0,3]		
	<b>Verb, VP, S</b> [1,2]	[1,3]		
	<b>Det</b> [2,3]			

## Lexicon

$Det \rightarrow that\ | this\ | a$

$Noun \rightarrow book\ | flight\ | meal\ | money$

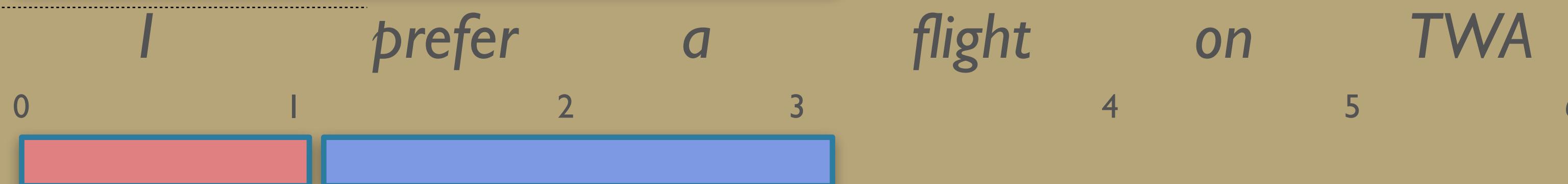
$Pronoun \rightarrow I\ | she\ | me$

$Proper-Noun \rightarrow Houston\ | TWA$

$Aux \rightarrow does$

$Preposition \rightarrow from\ | to\ | on\ | near\ | through$

$Verb \rightarrow book\ | include\ | prefer$



## $\mathcal{L}_1$ Grammar

$S \rightarrow NP VP$

$S \rightarrow X1 VP$

$X1 \rightarrow Aux NP$

$S \rightarrow book / include / prefer$

$S \rightarrow Verb NP$

$S \rightarrow X2 PP$

$S \rightarrow Verb PP$

$S \rightarrow VP PP$

$NP \rightarrow I / she / me$

$NP \rightarrow TWA / Houston$

$NP \rightarrow Det Nominal$

$Nominal \rightarrow book / flight / meal / money$

$Nominal \rightarrow Nominal Noun$

$Nominal \rightarrow Nominal PP$

$VP \rightarrow book / include / prefer$

$VP \rightarrow Verb NP$

$VP \rightarrow X2 PP$

$X2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

$VP \rightarrow VP PP$

$PP \rightarrow Preposition NP$

I prefer a flight on TWA

<b>NP, Pronoun [0,1]</b>	<b>S [0,2]</b>	<b>[0,3]</b>			
	<b>Verb, VP, S [1,2]</b>	<b>[1,3]</b>			
		<b>Det [2,3]</b>			
			<b>Noun, Nom [3,4]</b>		

## Lexicon

$Det \rightarrow that | this | a$

$Noun \rightarrow book | flight | meal | money$

$Pronoun \rightarrow I | she | me$

$Proper-Noun \rightarrow Houston | TWA$

$Aux \rightarrow does$

$Preposition \rightarrow from | to | on | near | through$

$Verb \rightarrow book | include | prefer$

## $\mathcal{L}_1$ Grammar

$S \rightarrow NP VP$   
 $S \rightarrow X1 VP$   
 $X1 \rightarrow Aux NP$   
 $S \rightarrow book / include / prefer$   
 $S \rightarrow Verb NP$

$S \rightarrow X2 PP$   
 $S \rightarrow Verb PP$   
 $S \rightarrow VP PP$

$NP \rightarrow I / she / me$

$NP \rightarrow TWA / Houston$

$NP \rightarrow Det Nominal$

$Nominal \rightarrow book / flight / meal / money$

$Nominal \rightarrow Nominal Noun$

$Nominal \rightarrow Nominal PP$

$VP \rightarrow book / include / prefer$

$VP \rightarrow Verb NP$

$VP \rightarrow X2 PP$

$X2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

$VP \rightarrow VP PP$

$PP \rightarrow Preposition NP$

<b>NP, Pronoun</b> [0,1]	<b>S</b> [0,2]	<b>[0,3]</b>		
	<b>Verb, VP, S</b> [1,2]	<b>[1,3]</b>		
		<b>Det</b> [2,3]	<b>[2,4]</b>	
			<b>Noun, Nom</b> [3,4]	

## Lexicon

$Det \rightarrow that | this | a$

$Noun \rightarrow book | flight | meal | money$

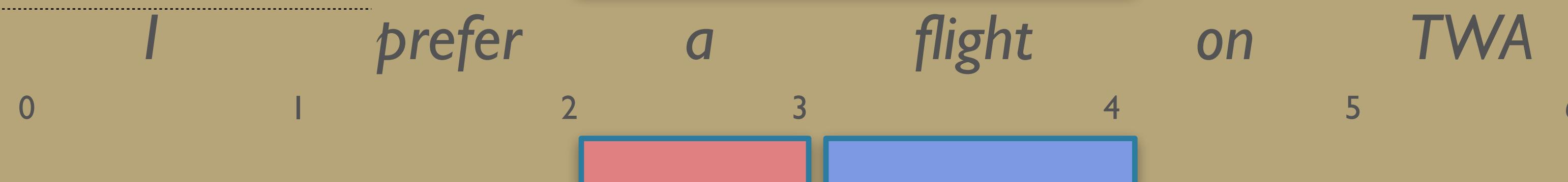
$Pronoun \rightarrow I | she | me$

$Proper-Noun \rightarrow Houston | TWA$

$Aux \rightarrow does$

$Preposition \rightarrow from | to | on | near | through$

$Verb \rightarrow book | include | prefer$



### $\mathcal{L}_1$ Grammar

$S \rightarrow NP VP$   
 $S \rightarrow X1 VP$   
 $X1 \rightarrow Aux NP$   
 $S \rightarrow book / include / prefer$   
 $S \rightarrow Verb NP$   
 $S \rightarrow X2 PP$   
 $S \rightarrow Verb PP$   
 $S \rightarrow VP PP$   


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 $NP \rightarrow I / she / me$   
 $NP \rightarrow TWA / Houston$   
 $NP \rightarrow Det Nominal$   


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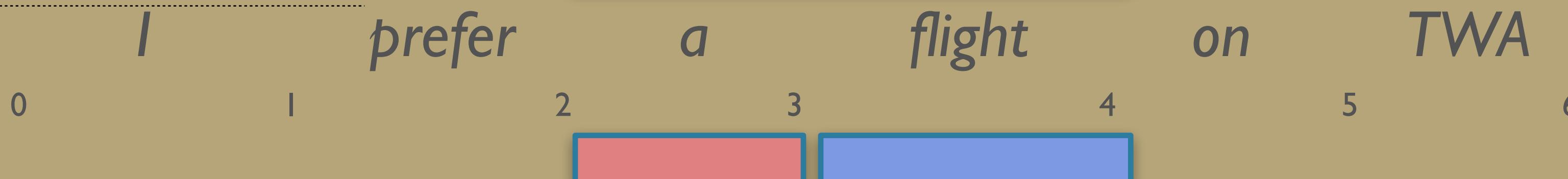
 $Nominal \rightarrow book / flight / meal / money$   
 $Nominal \rightarrow Nominal Noun$   
 $Nominal \rightarrow Nominal PP$   


---

 $VP \rightarrow book / include / prefer$   
 $VP \rightarrow Verb NP$   
 $VP \rightarrow X2 PP$   
 $X2 \rightarrow Verb NP$   
 $VP \rightarrow Verb PP$   
 $VP \rightarrow VP PP$   


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 $PP \rightarrow Preposition NP$



<b>NP, Pronoun</b> [0,1]	<b>S</b> [0,2]	<b>[0,3]</b>		
	<b>Verb, VP, S</b> [1,2]	<b>[1,3]</b>		
		<b>Det</b> [2,3]	<b>[2,4]</b>	
			<b>Noun, Nom</b> [3,4]	

### Lexicon

$Det \rightarrow that | this | a$   
 $Noun \rightarrow book | flight | meal | money$   
 $Pronoun \rightarrow I | she | me$   
 $Proper-Noun \rightarrow Houston | TWA$   
 $Aux \rightarrow does$   
 $Preposition \rightarrow from | to | on | near | through$   
 $Verb \rightarrow book | include | prefer$

### $\mathcal{L}_1$ Grammar

$S \rightarrow NP VP$

$S \rightarrow X1 VP$

$X1 \rightarrow Aux NP$

$S \rightarrow book / include / prefer$

$S \rightarrow Verb NP$

$S \rightarrow X2 PP$

$S \rightarrow Verb PP$

$S \rightarrow VP PP$

$NP \rightarrow I / she / me$

$NP \rightarrow TWA / Houston$

$NP \rightarrow Det Nominal$

$Nominal \rightarrow book / flight / meal / money$

$Nominal \rightarrow Nominal Noun$

$Nominal \rightarrow Nominal PP$

$VP \rightarrow book / include / prefer$

$VP \rightarrow Verb NP$

$VP \rightarrow X2 PP$

$X2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

$VP \rightarrow VP PP$

$PP \rightarrow Preposition NP$

<b>NP, Pronoun [0,1]</b>	<b>S [0,2]</b>	<b>[0,3]</b>		
	<b>Verb, VP, S [1,2]</b>	<b>[1,3]</b>		
		<b>Det [2,3]</b>	<b>NP [2,4]</b>	
			<b>Noun, Nom [3,4]</b>	

### Lexicon

$Det \rightarrow that | this | a$

$Noun \rightarrow book | flight | meal | money$

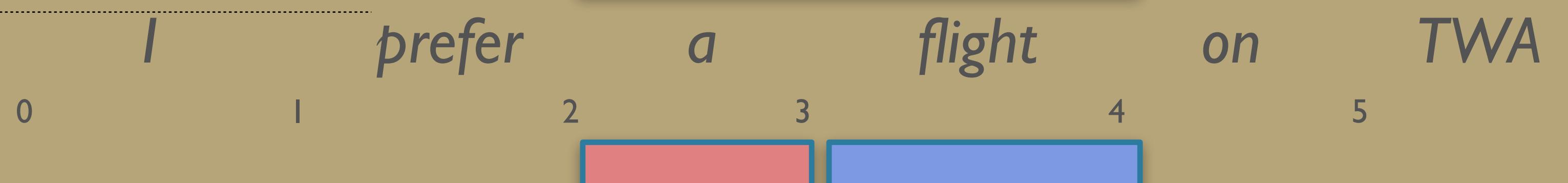
$Pronoun \rightarrow I | she | me$

$Proper-Noun \rightarrow Houston | TWA$

$Aux \rightarrow does$

$Preposition \rightarrow from | to | on | near | through$

$Verb \rightarrow book | include | prefer$



### $\mathcal{L}_1$ Grammar

$S \rightarrow NP VP$

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$S \rightarrow Verb NP$

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$S \rightarrow VP PP$

$NP \rightarrow I / she / me$

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$NP \rightarrow Det Nominal$

$Nominal \rightarrow book / flight / meal / money$

$Nominal \rightarrow Nominal Noun$

$Nominal \rightarrow Nominal PP$

$VP \rightarrow book / include / prefer$

$VP \rightarrow Verb NP$

$VP \rightarrow X2 PP$

$X2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

$VP \rightarrow VP PP$

$PP \rightarrow Preposition NP$

<b>NP, Pronoun</b> [0,1]	<b>S</b> [0,2]	[0,3]			
	<b>Verb, VP, S</b> [1,2]	[1,3]	[1,4]		
		<b>Det</b>	<b>NP</b>		
		[2,3]	[2,4]		
			<b>Noun, Nom</b> [3,4]		

### Lexicon

$Det \rightarrow that | this | a$

$Noun \rightarrow book | flight | meal | money$

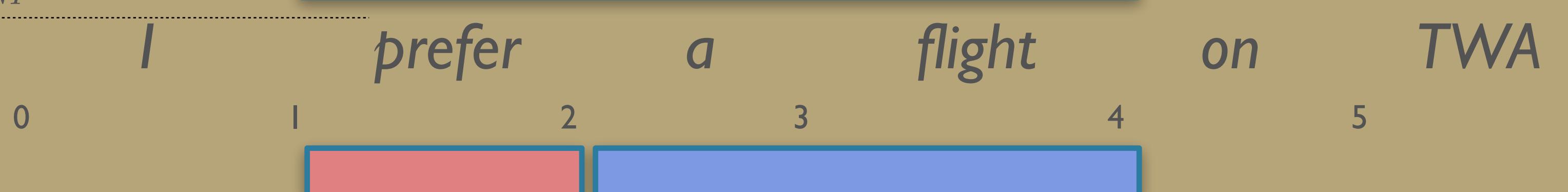
$Pronoun \rightarrow I | she | me$

$Proper-Noun \rightarrow Houston | TWA$

$Aux \rightarrow does$

$Preposition \rightarrow from | to | on | near | through$

$Verb \rightarrow book | include | prefer$



## $\mathcal{L}_1$ Grammar

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$S \rightarrow X1 VP$

$X1 \rightarrow Aux NP$

$S \rightarrow book / include / prefer$

$S \rightarrow Verb NP$

$S \rightarrow X2 PP$

$S \rightarrow Verb PP$

$S \rightarrow VP PP$

$NP \rightarrow I / she / me$

$NP \rightarrow TWA / Houston$

$NP \rightarrow Det Nominal$

$Nominal \rightarrow book / flight / meal / money$

$Nominal \rightarrow Nominal Noun$

$Nominal \rightarrow Nominal PP$

$VP \rightarrow book / include / prefer$

$VP \rightarrow Verb NP$

$VP \rightarrow X2 PP$

$X2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

$VP \rightarrow VP PP$

$PP \rightarrow Preposition NP$

NP, Pronoun [0,1]	S [0,2]	[0,3]	VP [1,4]		
	Verb, VP, S [1,2]	[1,3]			
		Det [2,3]	NP [2,4]		
			Noun, Nom [3,4]		

## Lexicon

$Det \rightarrow that | this | a$

$Noun \rightarrow book | flight | meal | money$

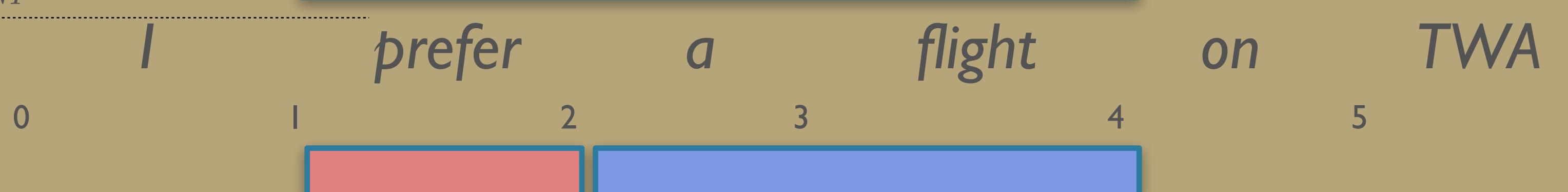
$Pronoun \rightarrow I | she | me$

$Proper-Noun \rightarrow Houston | TWA$

$Aux \rightarrow does$

$Preposition \rightarrow from | to | on | near | through$

$Verb \rightarrow book | include | prefer$



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$VP \rightarrow X2 PP$

$X2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

$VP \rightarrow VP PP$

$PP \rightarrow Preposition NP$

<b>NP, Pronoun</b> [0,1]	<b>S</b> [0,2]	<b>[0,3]</b>			
	<b>Verb, VP, S</b> [1,2]		<b>VP, X2</b> [1,4]		
		<b>[1,3]</b>			
			<b>Det</b>	<b>NP</b> [2,4]	
		<b>[2,3]</b>			
				<b>Noun, Nom</b> [3,4]	

## Lexicon

$Det \rightarrow that | this | a$

$Noun \rightarrow book | flight | meal | money$

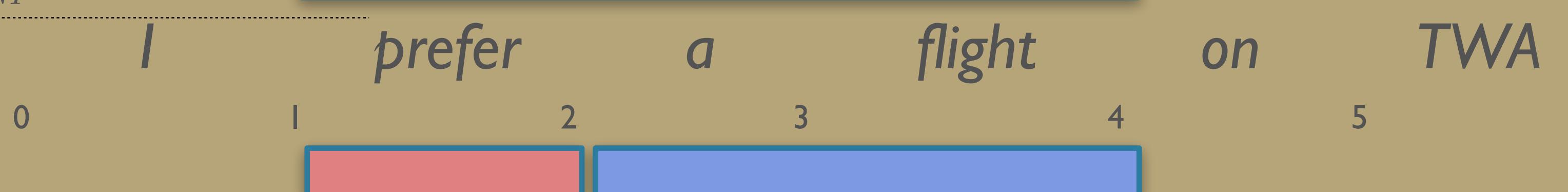
$Pronoun \rightarrow I | she | me$

$Proper-Noun \rightarrow Houston | TWA$

$Aux \rightarrow does$

$Preposition \rightarrow from | to | on | near | through$

$Verb \rightarrow book | include | prefer$



### $\mathcal{L}_1$ Grammar

$S \rightarrow NP VP$   
 $S \rightarrow X1 VP$   
 $X1 \rightarrow Aux NP$   
 $S \rightarrow book / include / prefer$   
 $S \rightarrow Verb NP$

$S \rightarrow X2 PP$

$S \rightarrow Verb PP$

$S \rightarrow VP PP$

$NP \rightarrow I / she / me$

$NP \rightarrow TWA / Houston$

$NP \rightarrow Det Nominal$

$Nominal \rightarrow book / flight / meal / money$

$Nominal \rightarrow Nominal Noun$

$Nominal \rightarrow Nominal PP$

$VP \rightarrow book / include / prefer$

$VP \rightarrow Verb NP$

$VP \rightarrow X2 PP$

$X2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

$VP \rightarrow VP PP$

$PP \rightarrow Preposition NP$

<b>NP, Pronoun</b> [0,1]	<b>S</b> [0,2]	[0,3]		
	<b>Verb, VP, S</b> [1,2]		<b>VP, X2, S</b> [1,4]	
		[1,3]	<b>Det</b> [2,3]	<b>NP</b> [2,4]
				<b>Noun, Nom</b> [3,4]

### Lexicon

$Det \rightarrow that | this | a$

$Noun \rightarrow book | flight | meal | money$

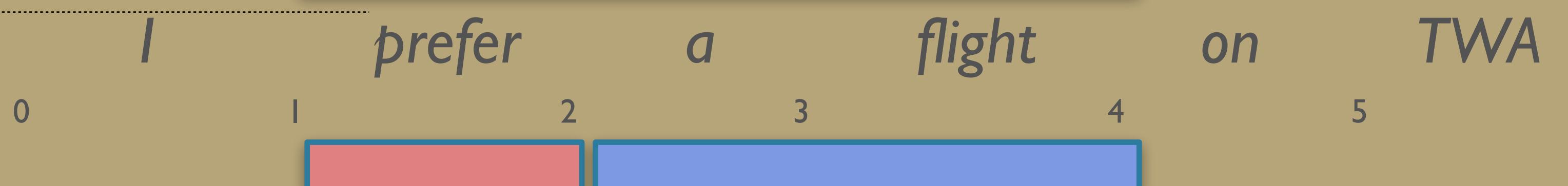
$Pronoun \rightarrow I | she | me$

$Proper-Noun \rightarrow Houston | TWA$

$Aux \rightarrow does$

$Preposition \rightarrow from | to | on | near | through$

$Verb \rightarrow book | include | prefer$



## $\mathcal{L}_1$ Grammar

$S \rightarrow NP VP$

$S \rightarrow X1 VP$

$X1 \rightarrow Aux NP$

$S \rightarrow book / include / prefer$

$S \rightarrow Verb NP$

$S \rightarrow X2 PP$

$S \rightarrow Verb PP$

$S \rightarrow VP PP$

$NP \rightarrow I / she / me$

$NP \rightarrow TWA / Houston$

$NP \rightarrow Det Nominal$

$Nominal \rightarrow book / flight / meal / money$

$Nominal \rightarrow Nominal Noun$

$Nominal \rightarrow Nominal PP$

$VP \rightarrow book / include / prefer$

$VP \rightarrow Verb NP$

$VP \rightarrow X2 PP$

$X2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

$VP \rightarrow VP PP$

$PP \rightarrow Preposition NP$

<b>NP, Pronoun</b> [0,1]	<b>S</b> [0,2]	[0,3]		
	<b>Verb, VP, S</b> [1,2]	[1,3]	<b>VP, X2, S</b> [1,4]	
		<b>Det</b> [2,3]	<b>NP</b> [2,4]	
			<b>Noun, Nom</b> [3,4]	

## Lexicon

$Det \rightarrow that | this | a$

$Noun \rightarrow book | flight | meal | money$

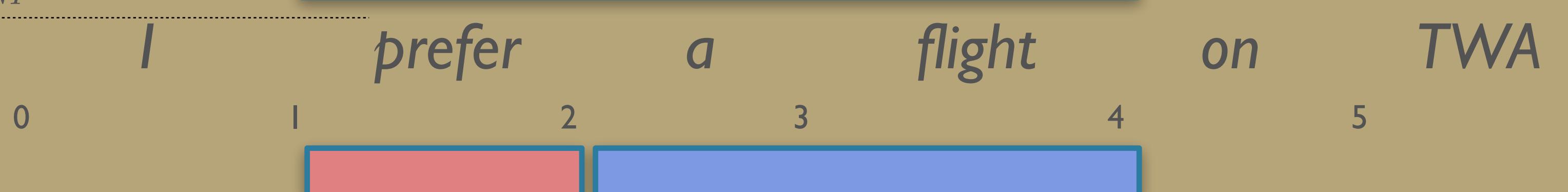
$Pronoun \rightarrow I | she | me$

$Proper-Noun \rightarrow Houston | TWA$

$Aux \rightarrow does$

$Preposition \rightarrow from | to | on | near | through$

$Verb \rightarrow book | include | prefer$



## $\mathcal{L}_1$ Grammar

$S \rightarrow NP VP$

$S \rightarrow X1 VP$

$X1 \rightarrow Aux NP$

$S \rightarrow book / include / prefer$

$S \rightarrow Verb NP$

$S \rightarrow X2 PP$

$S \rightarrow Verb PP$

$S \rightarrow VP PP$

$NP \rightarrow I / she / me$

$NP \rightarrow TWA / Houston$

$NP \rightarrow Det Nominal$

$Nominal \rightarrow book / flight / meal / money$

$Nominal \rightarrow Nominal Noun$

$Nominal \rightarrow Nominal PP$

$VP \rightarrow book / include / prefer$

$VP \rightarrow Verb NP$

$VP \rightarrow X2 PP$

$X2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

$VP \rightarrow VP PP$

$PP \rightarrow Preposition NP$

<b>NP, Pronoun</b> [0,1]	<b>S</b> [0,2]	[0,3]		
	<b>Verb, VP, S</b> [1,2]	[1,3]	<b>VP, X2, S</b> [1,4]	
		<b>Det</b> [2,3]	<b>NP</b> [2,4]	
			<b>Noun, Nom</b> [3,4]	

## Lexicon

$Det \rightarrow that | this | a$

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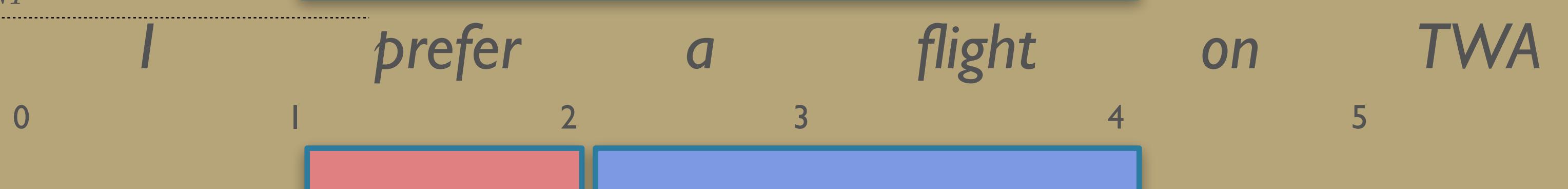
$Pronoun \rightarrow I | she | me$

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$Aux \rightarrow does$

$Preposition \rightarrow from | to | on | near | through$

$Verb \rightarrow book | include | prefer$



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$S \rightarrow Verb NP$

$S \rightarrow X2 PP$

$S \rightarrow Verb PP$

$S \rightarrow VP PP$

$NP \rightarrow I / she / me$

$NP \rightarrow TWA / Houston$

$NP \rightarrow Det Nominal$

$Nominal \rightarrow book / flight / meal / money$

$Nominal \rightarrow Nominal Noun$

$Nominal \rightarrow Nominal PP$

$VP \rightarrow book / include / prefer$

$VP \rightarrow Verb NP$

$VP \rightarrow X2 PP$

$X2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

$VP \rightarrow VP PP$

$PP \rightarrow Preposition NP$

<b>NP, Pronoun [0,1]</b>	<b>S [0,2]</b>	<b>[0,3]</b>			
	<b>Verb, VP, S [1,2]</b>	<b>[1,3]</b>	<b>VP, X2, S [1,4]</b>		
		<b>Det [2,3]</b>	<b>NP [2,4]</b>		
			<b>Noun, Nom [3,4]</b>		

## Lexicon

$Det \rightarrow that | this | a$

$Noun \rightarrow book | flight | meal | money$

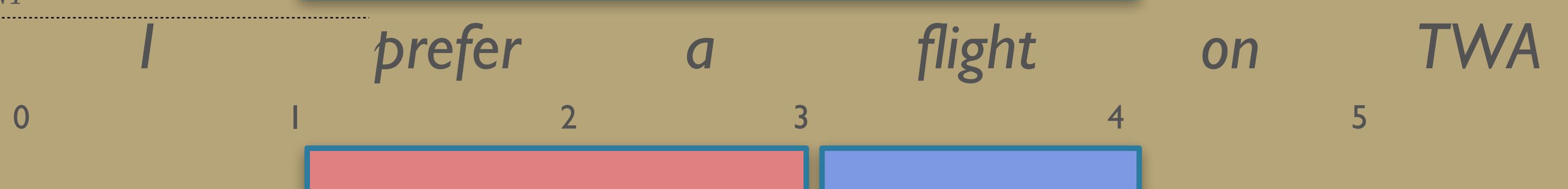
$Pronoun \rightarrow I | she | me$

$Proper-Noun \rightarrow Houston | TWA$

$Aux \rightarrow does$

$Preposition \rightarrow from | to | on | near | through$

$Verb \rightarrow book | include | prefer$



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$S \rightarrow NP VP$

$S \rightarrow X1 VP$

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$S \rightarrow book / include / prefer$

$S \rightarrow Verb NP$

$S \rightarrow X2 PP$

$S \rightarrow Verb PP$

$S \rightarrow VP PP$

$NP \rightarrow I / she / me$

$NP \rightarrow TWA / Houston$

$NP \rightarrow Det Nominal$

$Nominal \rightarrow book / flight / meal / money$

$Nominal \rightarrow Nominal Noun$

$Nominal \rightarrow Nominal PP$

$VP \rightarrow book / include / prefer$

$VP \rightarrow Verb NP$

$VP \rightarrow X2 PP$

$X2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

$VP \rightarrow VP PP$

$PP \rightarrow Preposition NP$

<b>NP, Pronoun [0,1]</b>	<b>S [0,2]</b>	<b>[0,3]</b>			
	<b>Verb, VP, S [1,2]</b>	<b>[1,3]</b>	<b>VP, X2, S [1,4]</b>		
		<b>Det [2,3]</b>	<b>NP [2,4]</b>		
			<b>Noun, Nom [3,4]</b>		

## Lexicon

$Det \rightarrow that | this | a$

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$Preposition \rightarrow from | to | on | near | through$

$Verb \rightarrow book | include | prefer$



### $\mathcal{L}_1$ Grammar

$S \rightarrow NP VP$

$S \rightarrow X1 VP$

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$S \rightarrow book / include / prefer$

$S \rightarrow Verb NP$

$S \rightarrow X2 PP$

$S \rightarrow Verb PP$

$S \rightarrow VP PP$

$NP \rightarrow I / she / me$

$NP \rightarrow TWA / Houston$

$NP \rightarrow Det Nominal$

$Nominal \rightarrow book / flight / meal / money$

$Nominal \rightarrow Nominal Noun$

$Nominal \rightarrow Nominal PP$

$VP \rightarrow book / include / prefer$

$VP \rightarrow Verb NP$

$VP \rightarrow X2 PP$

$X2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

$VP \rightarrow VP PP$

$PP \rightarrow Preposition N$

**NP,  
Pronoun**  
[0,1]

**S**

[0,2]

**Verb, VP, S**

[1,2]

[0,3]

[1,3]

**Det**

[2,3]

[0,4]

**VP, X2, S**

[1,4]

**NP**

[2,4]

**Noun, Nom**

[3,4]

### Lexicon

$Det \rightarrow that | this | a$

$Noun \rightarrow book | flight | meal | money$

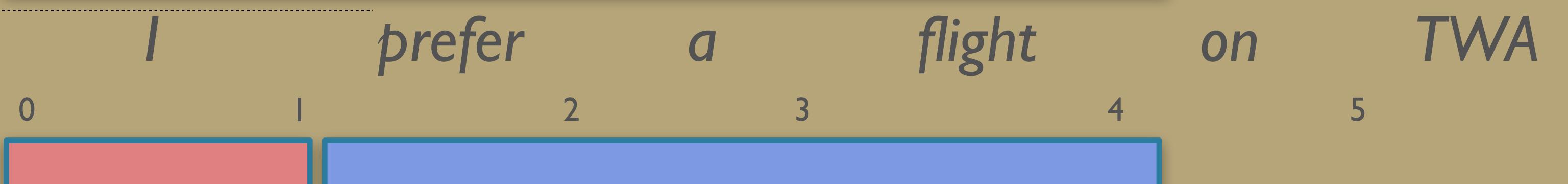
$Pronoun \rightarrow I | she | me$

$Proper-Noun \rightarrow Houston | TWA$

$Aux \rightarrow does$

$Preposition \rightarrow from | to | on | near | through$

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$S \rightarrow X1 VP$

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$S \rightarrow book / include / prefer$

$S \rightarrow Verb NP$

$S \rightarrow X2 PP$

$S \rightarrow Verb PP$

$S \rightarrow VP PP$

$NP \rightarrow I / she / me$

$NP \rightarrow TWA / Houston$

$NP \rightarrow Det Nominal$

$Nominal \rightarrow book / flight / meal / money$

$Nominal \rightarrow Nominal Noun$

$Nominal \rightarrow Nominal PP$

$VP \rightarrow book / include / prefer$

$VP \rightarrow Verb NP$

$VP \rightarrow X2 PP$

$X2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

$VP \rightarrow VP PP$

$PP \rightarrow Preposition N$

**NP,  
Pronoun  
[0,1]**

**S  
[0,2]**

**S  
[0,3]**

**S  
[0,4]**

**Verb, VP, S  
[1,2]**

**Verb, VP, S  
[1,3]**

**VP, X2, S  
[1,4]**

**Det  
[2,3]**

**NP  
[2,4]**

**Noun, Nom  
[3,4]**

**Lexicon**

$Det \rightarrow that | this | a$

$Noun \rightarrow book | flight | meal | money$

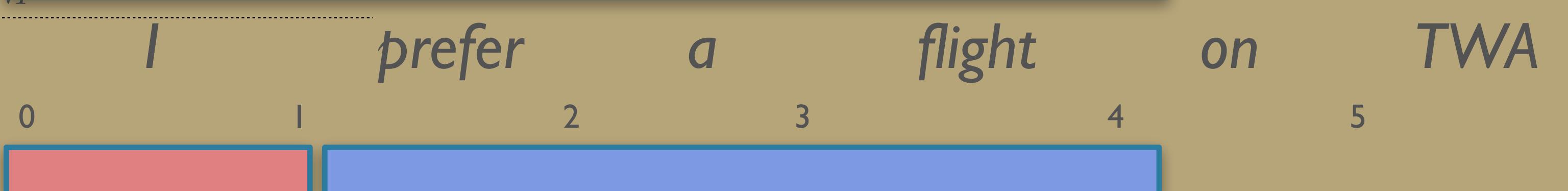
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$Preposition \rightarrow from | to | on | near | through$

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$S \rightarrow Verb NP$

$S \rightarrow X2 PP$

$S \rightarrow Verb PP$

$S \rightarrow VP PP$

$NP \rightarrow I / she / me$

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$Nominal \rightarrow Nominal PP$

$VP \rightarrow book / include / prefer$

$VP \rightarrow Verb NP$

$VP \rightarrow X2 PP$

$X2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

$VP \rightarrow VP PP$

$PP \rightarrow Preposition N$

<b>NP, Pronoun [0,1]</b>	<b>S</b> [0,2]		<b>S</b> [0,4]		
	<b>Verb, VP, S</b> [1,2]		<b>VP, X2, S</b> [1,4]		
		<b>Det</b> [1,3]	<b>NP</b> [2,4]		
			<b>Noun, Nom</b> [3,4]		

### Lexicon

$Det \rightarrow that | this | a$

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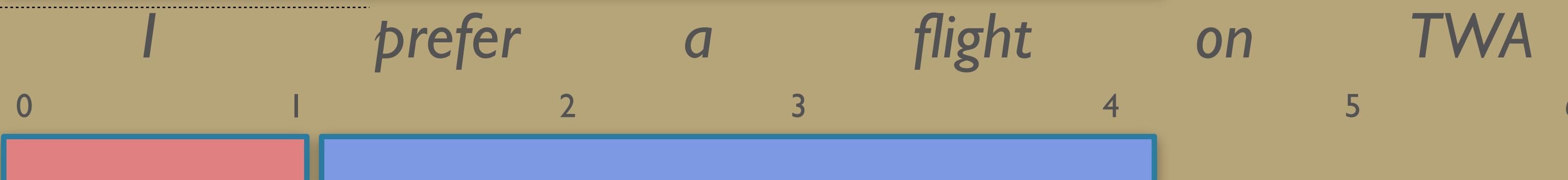
$Pronoun \rightarrow I | she | me$

$Proper-Noun \rightarrow Houston | TWA$

$Aux \rightarrow does$

$Preposition \rightarrow from | to | on | near | through$

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$VP \rightarrow Verb PP$

$VP \rightarrow VP PP$

$PP \rightarrow Preposition N$

<b>NP, Pronoun [0,1]</b>	<b>S</b> [0,2]		<b>S</b> [0,4]	
	<b>Verb, VP, S</b> [1,2]	[1,3]	<b>VP, X2, S</b> [1,4]	
	<b>Det</b> [2,3]	<b>NP</b> [2,4]		
		<b>Noun, Nom</b> [3,4]		

### Lexicon

$Det \rightarrow that | this | a$

$Noun \rightarrow book | flight | meal | money$

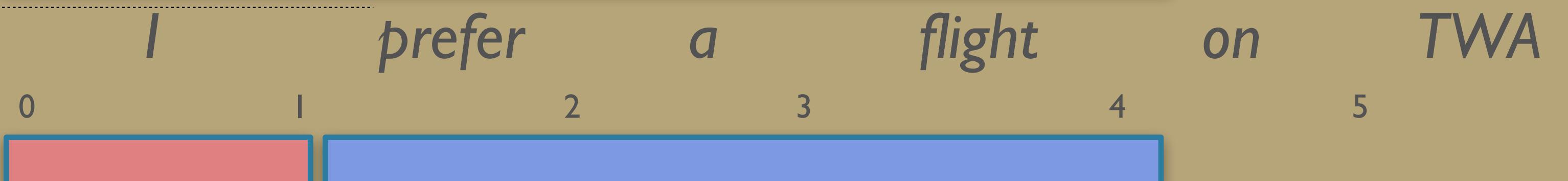
$Pronoun \rightarrow I | she | me$

$Proper-Noun \rightarrow Houston | TWA$

$Aux \rightarrow does$

$Preposition \rightarrow from | to | on | near | through$

$Verb \rightarrow book | include | prefer$



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$S \rightarrow X1 VP$

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$S \rightarrow book / include / prefer$

$S \rightarrow Verb NP$

$S \rightarrow X2 PP$

$S \rightarrow Verb PP$

$S \rightarrow VP PP$

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$NP \rightarrow Det Nominal$

$Nominal \rightarrow book / flight / meal / money$

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$Nominal \rightarrow Nominal PP$

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$VP \rightarrow Verb NP$

$VP \rightarrow X2 PP$

$X2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

$VP \rightarrow VP PP$

$PP \rightarrow Preposition N$

### NP, Pronoun

[0,1]

### S

[0,2]

### S

[0,3]

### S

[0,4]

### Verb, VP, S

[1,2]

### VP, X2, S

[1,4]

### Det

[2,3]

### NP

[2,4]

### Noun, Nom

[3,4]

### Lexicon

$Det \rightarrow that | this | a$

$Noun \rightarrow book | flight | meal | money$

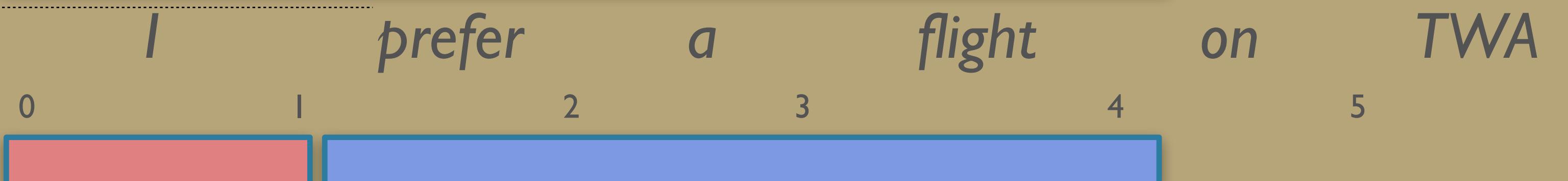
$Pronoun \rightarrow I | she | me$

$Proper-Noun \rightarrow Houston | TWA$

$Aux \rightarrow does$

$Preposition \rightarrow from | to | on | near | through$

$Verb \rightarrow book | include | prefer$



### $\mathcal{L}_1$ Grammar

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$S \rightarrow X1 VP$

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$S \rightarrow Verb NP$

$S \rightarrow X2 PP$

$S \rightarrow Verb PP$

$S \rightarrow VP PP$

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$NP \rightarrow Det Nominal$

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$Nominal \rightarrow Nominal PP$

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$VP \rightarrow Verb NP$

$VP \rightarrow X2 PP$

$X2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

$VP \rightarrow VP PP$

$PP \rightarrow Preposition N$

### NP, Pronoun

[0,1]

### S

[0,2]

### S

[0,3]

### S

[0,4]

### Verb, VP, S

[1,2]

### VP, X2, S

[1,4]

### Det

[2,3]

### NP

[2,4]

### Noun, Nom

[3,4]

### Lexicon

$Det \rightarrow that | this | a$

$Noun \rightarrow book | flight | meal | money$

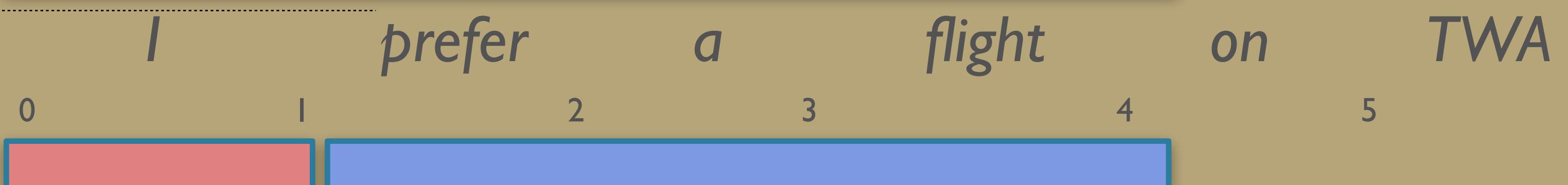
$Pronoun \rightarrow I | she | me$

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$Aux \rightarrow does$

$Preposition \rightarrow from | to | on | near | through$

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$X2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

$VP \rightarrow VP PP$

$PP \rightarrow Preposition N$

### NP, Pronoun

[0,1]

### S

[0,2]

### S

[0,3]

### S

[0,4]

### Verb, VP, S

[1,2]

### VP, X2, S

[1,4]

### Det

[2,3]

### NP

[2,4]

### Noun, Nom

[3,4]

### Lexicon

$Det \rightarrow that | this | a$

$Noun \rightarrow book | flight | meal | money$

$Pronoun \rightarrow I | she | me$

$Proper-Noun \rightarrow Houston | TWA$

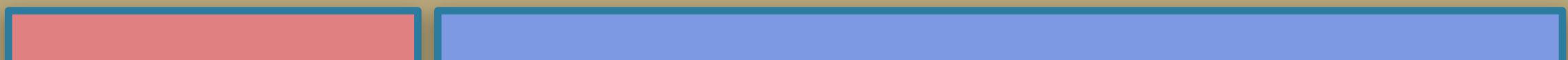
$Aux \rightarrow does$

$Preposition \rightarrow from | to | on | near | through$

$Verb \rightarrow book | include | prefer$

I prefer a flight on TWA

0 1 2 3 4 5 6



### $\mathcal{L}_1$ Grammar

$S \rightarrow NP VP$

$S \rightarrow X1 VP$

$X1 \rightarrow Aux NP$

$S \rightarrow book / include / prefer$

$S \rightarrow Verb NP$

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$S \rightarrow Verb PP$

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$VP \rightarrow Verb NP$

$VP \rightarrow X2 PP$

$X2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

$VP \rightarrow VP PP$

$PP \rightarrow Preposition N$

<b>NP, Pronoun [0,1]</b>	<b>S</b> [0,2]		<b>S</b> [0,4]	
	<b>Verb, VP, S</b> [1,2]	[1,3]	<b>VP, X2, S</b> [1,4]	
	<b>Det</b> [2,3]	<b>NP</b> [2,4]		
		<b>Noun, Nom</b> [3,4]		

### Lexicon

$Det \rightarrow that | this | a$

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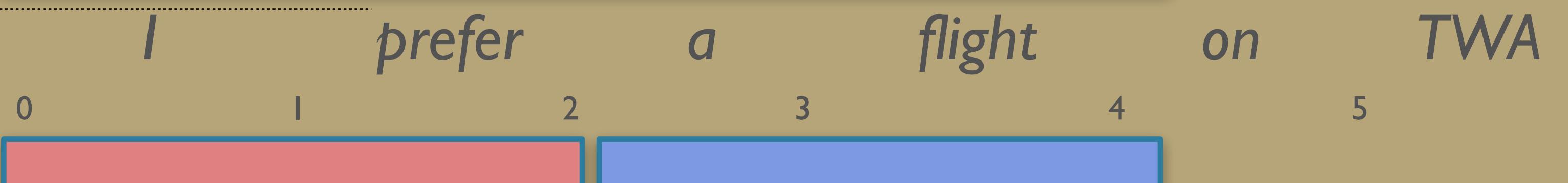
$Pronoun \rightarrow I | she | me$

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$Aux \rightarrow does$

$Preposition \rightarrow from | to | on | near | through$

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$S \rightarrow Verb PP$

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$NP \rightarrow Det Nominal$

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$Nominal \rightarrow Nominal PP$

$VP \rightarrow book / include / prefer$

$VP \rightarrow Verb NP$

$VP \rightarrow X2 PP$

$X2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

$VP \rightarrow VP PP$

$PP \rightarrow Preposition N$

NP, Pronoun [0,1]	S [0,2]	[0,3]	S [0,4]		
	<b>Verb, VP, S</b> [1,2]		<b>VP, X2, S</b> [1,4]		
		<b>Det</b> [1,3]	<b>NP</b> [1,4]		
			<b>Det</b> [2,3]	<b>NP</b> [2,4]	
				<b>Noun, Nom</b> [3,4]	

## Lexicon

$Det \rightarrow that | this | a$

$Noun \rightarrow book | flight | meal | money$

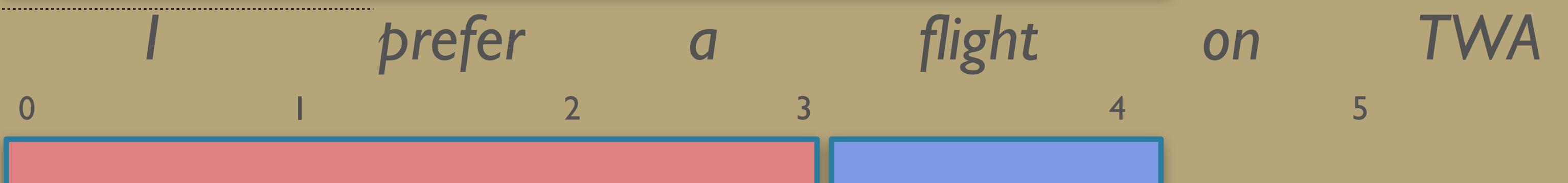
$Pronoun \rightarrow I | she | me$

$Proper-Noun \rightarrow Houston | TWA$

$Aux \rightarrow does$

$Preposition \rightarrow from | to | on | near | through$

$Verb \rightarrow book | include | prefer$



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$S \rightarrow NP VP$

$S \rightarrow X1 VP$

$X1 \rightarrow Aux NP$

$S \rightarrow book / include / prefer$

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$S \rightarrow X2 PP$

$S \rightarrow Verb PP$

$S \rightarrow VP PP$

$NP \rightarrow I / she / me$

$NP \rightarrow TWA / Houston$

$NP \rightarrow Det Nominal$

$Nominal \rightarrow book / flight / meal / money$

$Nominal \rightarrow Nominal Noun$

$Nominal \rightarrow Nominal PP$

$VP \rightarrow book / include / prefer$

$VP \rightarrow Verb NP$

$VP \rightarrow X2 PP$

$X2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

$VP \rightarrow VP PP$

$PP \rightarrow Preposition NP$



<b>NP, Pronoun [0,1]</b>	<b>S</b> [0,2]		<b>S</b> [0,4]		
	<b>Verb, VP, S [1,2]</b>		<b>VP, X2, S [1,4]</b>		
	<b>Det [2,3]</b>	<b>NP</b> [2,4]			
		<b>Noun, Nom [3,4]</b>			
		<b>Prep [4,5]</b>			

## Lexicon

$Det \rightarrow that | this | a$

$Noun \rightarrow book | flight | meal | money$

$Pronoun \rightarrow I | she | me$

$Proper-Noun \rightarrow Houston | TWA$

$Aux \rightarrow does$

$Preposition \rightarrow from | to | on | near | through$

$Verb \rightarrow book | include | prefer$

### $\mathcal{L}_1$ Grammar

$S \rightarrow NP VP$

$S \rightarrow X1 VP$

$X1 \rightarrow Aux NP$

$S \rightarrow book / include / prefer$

$S \rightarrow Verb NP$

$S \rightarrow X2 PP$

$S \rightarrow Verb PP$

$S \rightarrow VP PP$

$NP \rightarrow I / she / me$

$NP \rightarrow TWA / Houston$

$NP \rightarrow Det Nominal$

$Nominal \rightarrow book / flight / meal / money$

$Nominal \rightarrow Nominal Noun$

$Nominal \rightarrow Nominal PP$

$VP \rightarrow book / include / prefer$

$VP \rightarrow Verb NP$

$VP \rightarrow X2 PP$

$X2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

$VP \rightarrow VP PP$

$PP \rightarrow Preposition NP$

<b>NP, Pronoun [0,1]</b>	<b>S [0,2]</b>	<b>S [0,3]</b>	<b>S [0,4]</b>		
	<b>Verb, VP, S [1,2]</b>		<b>VP, X2, S [1,4]</b>		
		<b>Det [1,3]</b>	<b>NP [1,4]</b>		
			<b>[2,3]</b>	<b>[2,4]</b>	
				<b>Noun, Nom [3,4]</b>	<b>[3,5]</b>
					<b>Prep [4,5]</b>

### Lexicon

$Det \rightarrow that | this | a$

$Noun \rightarrow book | flight | meal | money$

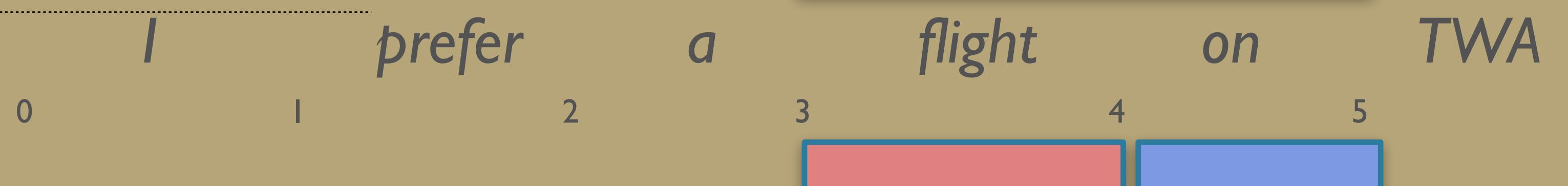
$Pronoun \rightarrow I | she | me$

$Proper-Noun \rightarrow Houston | TWA$

$Aux \rightarrow does$

$Preposition \rightarrow from | to | on | near | through$

$Verb \rightarrow book | include | prefer$



### $\mathcal{L}_1$ Grammar

$S \rightarrow NP VP$

$S \rightarrow X1 VP$

$X1 \rightarrow Aux NP$

$S \rightarrow book / include / prefer$

$S \rightarrow Verb NP$

$S \rightarrow X2 PP$

$S \rightarrow Verb PP$

$S \rightarrow VP PP$

$NP \rightarrow I / she / me$

$NP \rightarrow TWA / Houston$

$NP \rightarrow Det Nominal$

$Nominal \rightarrow book / flight / meal / money$

$Nominal \rightarrow Nominal Noun$

$Nominal \rightarrow Nominal PP$

$VP \rightarrow book / include / prefer$

$VP \rightarrow Verb NP$

$VP \rightarrow X2 PP$

$X2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

$VP \rightarrow VP PP$

$PP \rightarrow Preposition NP$

<b>NP, Pronoun</b> [0,1]	<b>S</b> [0,2]	<b>S</b> [0,3]	<b>S</b> [0,4]		
	<b>Verb, VP, S</b> [1,2]		<b>VP, X2, S</b> [1,4]		
		<b>Det</b> [2,3]	<b>NP</b> [2,4]	<b>NP, Nom</b> [3,4]	<b>Prep</b> [4,5]
				<b>[2,5]</b>	

### Lexicon

$Det \rightarrow that | this | a$

$Noun \rightarrow book | flight | meal | money$

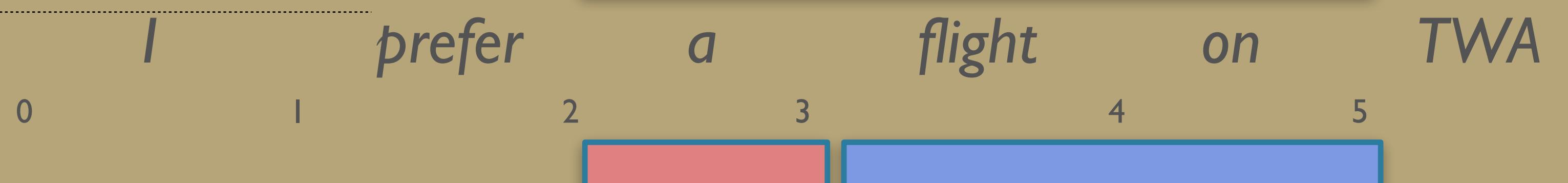
$Pronoun \rightarrow I | she | me$

$Proper-Noun \rightarrow Houston | TWA$

$Aux \rightarrow does$

$Preposition \rightarrow from | to | on | near | through$

$Verb \rightarrow book | include | prefer$



### $\mathcal{L}_1$ Grammar

$S \rightarrow NP VP$

$S \rightarrow X1 VP$

$X1 \rightarrow Aux NP$

$S \rightarrow book / include / prefer$

$S \rightarrow Verb NP$

$S \rightarrow X2 PP$

$S \rightarrow Verb PP$

$S \rightarrow VP PP$

$NP \rightarrow I / she / me$

$NP \rightarrow TWA / Houston$

$NP \rightarrow Det Nominal$

$Nominal \rightarrow book / flight / meal / money$

$Nominal \rightarrow Nominal Noun$

$Nominal \rightarrow Nominal PP$

$VP \rightarrow book / include / prefer$

$VP \rightarrow Verb NP$

$VP \rightarrow X2 PP$

$X2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

$VP \rightarrow VP PP$

$PP \rightarrow Preposition NP$

<b>NP, Pronoun</b> [0,1]	<b>S</b> [0,2]	<b>S</b> [0,3]	<b>S</b> [0,4]		
	<b>Verb, VP, S</b> [1,2]		<b>VP, X2, S</b> [1,4]		
		<b>Det</b> [1,3]	<b>NP</b> [2,4]	<b>Noun, Nom</b> [3,4]	<b>Prep</b> [3,5]
			<b>[2,3]</b>	<b>[2,5]</b>	<b>[4,5]</b>

### Lexicon

$Det \rightarrow that | this | a$

$Noun \rightarrow book | flight | meal | money$

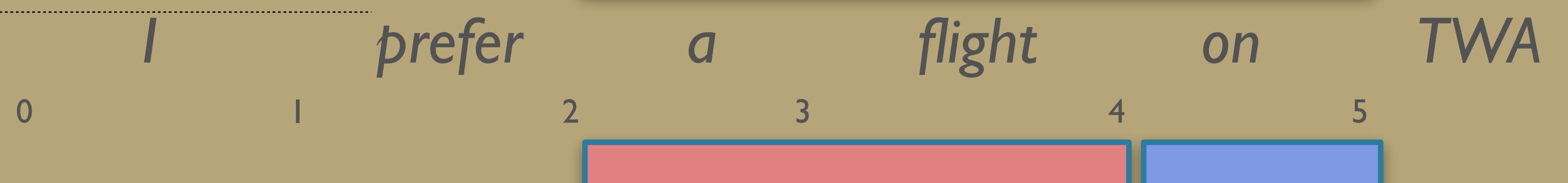
$Pronoun \rightarrow I | she | me$

$Proper-Noun \rightarrow Houston | TWA$

$Aux \rightarrow does$

$Preposition \rightarrow from | to | on | near | through$

$Verb \rightarrow book | include | prefer$



### $\mathcal{L}_1$ Grammar

$S \rightarrow NP VP$

$S \rightarrow X1 VP$

$X1 \rightarrow Aux NP$

$S \rightarrow book / include / prefer$

$S \rightarrow Verb NP$

$S \rightarrow X2 PP$

$S \rightarrow Verb PP$

$S \rightarrow VP PP$

$NP \rightarrow I / she / me$

$NP \rightarrow TWA / Houston$

$NP \rightarrow Det Nominal$

$Nominal \rightarrow book / flight / meal / money$

$Nominal \rightarrow Nominal Noun$

$Nominal \rightarrow Nominal PP$

$VP \rightarrow book / include / prefer$

$VP \rightarrow Verb NP$

$VP \rightarrow X2 PP$

$X2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

$VP \rightarrow VP PP$

$PP \rightarrow Preposition NP$

**NP,  
Pronoun**  
[0,1]

**S**  
[0,2]

**S**  
[0,3]

**S**  
[0,4]

**Verb, VP, S**  
[1,2]

**Verb**  
[1,3]

**VP, X2, S**  
[1,4]

**NP**  
[1,5]

**Det**  
[2,3]

**NP**  
[2,4]

**NP**  
[2,5]

**Noun, Nom**  
[3,4]

**Noun**  
[3,5]

**Prep**  
[4,5]

### Lexicon

$Det \rightarrow that | this | a$

$Noun \rightarrow book | flight | meal | money$

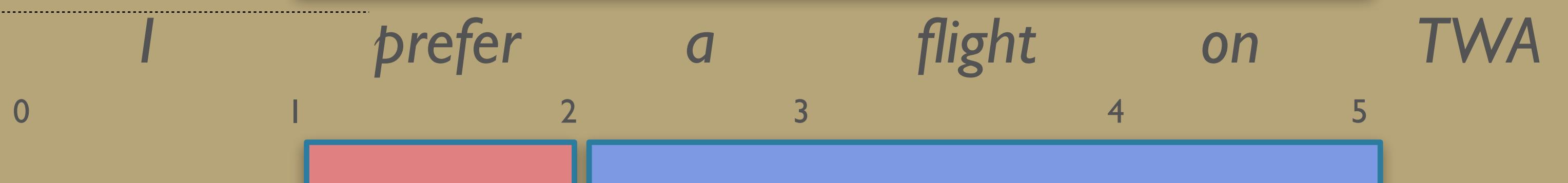
$Pronoun \rightarrow I | she | me$

$Proper-Noun \rightarrow Houston | TWA$

$Aux \rightarrow does$

$Preposition \rightarrow from | to | on | near | through$

$Verb \rightarrow book | include | prefer$



### $\mathcal{L}_1$ Grammar

$S \rightarrow NP VP$

$S \rightarrow X1 VP$

$X1 \rightarrow Aux NP$

$S \rightarrow book / include / prefer$

$S \rightarrow Verb NP$

$S \rightarrow X2 PP$

$S \rightarrow Verb PP$

$S \rightarrow VP PP$

$NP \rightarrow I / she / me$

$NP \rightarrow TWA / Houston$

$NP \rightarrow Det Nominal$

$Nominal \rightarrow book / flight / meal / money$

$Nominal \rightarrow Nominal Noun$

$Nominal \rightarrow Nominal PP$

$VP \rightarrow book / include / prefer$

$VP \rightarrow Verb NP$

$VP \rightarrow X2 PP$

$X2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

$VP \rightarrow VP PP$

$PP \rightarrow Preposition NP$

**NP,  
Pronoun**  
[0,1]

**S**  
[0,2]

**S**  
[0,3]

**S**  
[0,4]

**Verb, VP, S**  
[1,2]

**VP, X2, S**  
[1,3]

**VP, X2, S**  
[1,4]

**I, 5**  
[1,5]

**Det**  
[2,3]

**NP**  
[2,4]

**[2,5]**

**Noun, Nom**  
[3,4]

**[3,5]**

**Prep**  
[4,5]

### Lexicon

$Det \rightarrow that | this | a$

$Noun \rightarrow book | flight | meal | money$

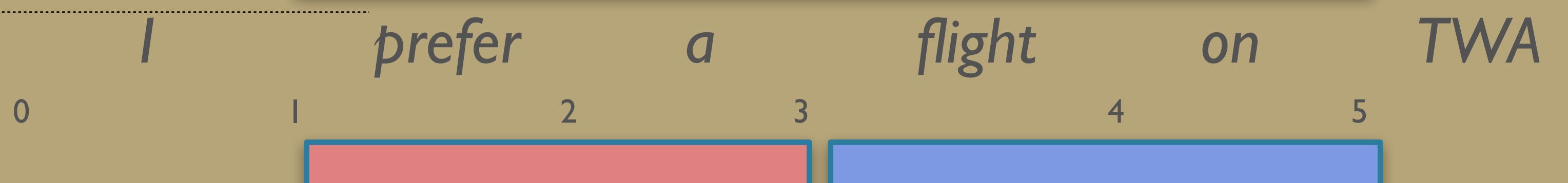
$Pronoun \rightarrow I | she | me$

$Proper-Noun \rightarrow Houston | TWA$

$Aux \rightarrow does$

$Preposition \rightarrow from | to | on | near | through$

$Verb \rightarrow book | include | prefer$



### $\mathcal{L}_1$ Grammar

$S \rightarrow NP VP$

$S \rightarrow X1 VP$

$X1 \rightarrow Aux NP$

$S \rightarrow book / include / prefer$

$S \rightarrow Verb NP$

$S \rightarrow X2 PP$

$S \rightarrow Verb PP$

$S \rightarrow VP PP$

$NP \rightarrow I / she / me$

$NP \rightarrow TWA / Houston$

$NP \rightarrow Det Nominal$

$Nominal \rightarrow book / flight / meal / money$

$Nominal \rightarrow Nominal Noun$

$Nominal \rightarrow Nominal PP$

$VP \rightarrow book / include / prefer$

$VP \rightarrow Verb NP$

$VP \rightarrow X2 PP$

$X2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

$VP \rightarrow VP PP$

$PP \rightarrow Preposition NP$

**NP,  
Pronoun**  
[0,1]

**S**  
[0,2]

**S**  
[0,3]

**S**  
[0,4]

**Verb, VP, S**  
[1,2]

**Verb**  
[1,3]

**VP, X2, S**  
[1,4]

**NP**  
[1,5]

**Det**  
[2,3]

**NP**  
[2,4]

**NP**  
[2,5]

**Noun, Nom**  
[3,4]

**Noun**  
[3,5]

**Prep**  
[4,5]

### Lexicon

$Det \rightarrow that | this | a$

$Noun \rightarrow book | flight | meal | money$

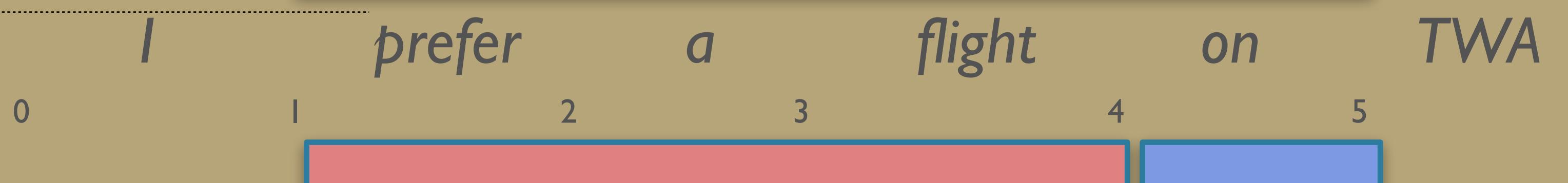
$Pronoun \rightarrow I | she | me$

$Proper-Noun \rightarrow Houston | TWA$

$Aux \rightarrow does$

$Preposition \rightarrow from | to | on | near | through$

$Verb \rightarrow book | include | prefer$



### $\mathcal{L}_1$ Grammar

$S \rightarrow NP VP$

$S \rightarrow X1 VP$

$X1 \rightarrow Aux NP$

$S \rightarrow book / include / prefer$

$S \rightarrow Verb NP$

$S \rightarrow X2 PP$

$S \rightarrow Verb PP$

$S \rightarrow VP PP$

$NP \rightarrow I / she / me$

$NP \rightarrow TWA / Houston$

$NP \rightarrow Det Nominal$

$Nominal \rightarrow book / flight / meal / money$

$Nominal \rightarrow Nominal Noun$

$Nominal \rightarrow Nominal PP$

$VP \rightarrow book / include / prefer$

$VP \rightarrow Verb NP$

$VP \rightarrow X2 PP$

$X2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

$VP \rightarrow VP PP$

$PP \rightarrow Preposition NP$

**NP,  
Pronoun**  
[0,1]

**S**  
[0,2]

**S**  
[0,3]

**S**  
[0,4]

**S**  
[0,5]

**Verb, VP, S**

[1,2]

[1,3]

**VP, X2, S**

[1,4]

[1,5]

**Det**

**NP**

[2,4]

[2,5]

**Noun, Nom**

[3,4]

[3,5]

**Prep**

[4,5]

### Lexicon

$Det \rightarrow that | this | a$

$Noun \rightarrow book | flight | meal | money$

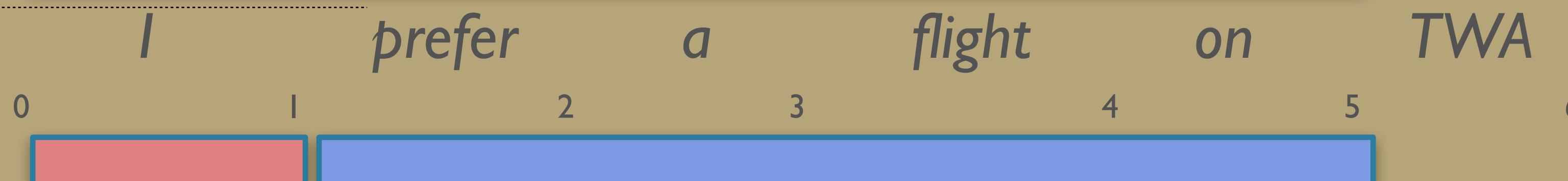
$Pronoun \rightarrow I | she | me$

$Proper-Noun \rightarrow Houston | TWA$

$Aux \rightarrow does$

$Preposition \rightarrow from | to | on | near | through$

$Verb \rightarrow book | include | prefer$



### $\mathcal{L}_1$ Grammar

$S \rightarrow NP VP$

$S \rightarrow X1 VP$

$X1 \rightarrow Aux NP$

$S \rightarrow book / include / prefer$

$S \rightarrow Verb NP$

$S \rightarrow X2 PP$

$S \rightarrow Verb PP$

$S \rightarrow VP PP$

$NP \rightarrow I / she / me$

$NP \rightarrow TWA / Houston$

$NP \rightarrow Det Nominal$

$Nominal \rightarrow book / flight / meal / money$

$Nominal \rightarrow Nominal Noun$

$Nominal \rightarrow Nominal PP$

$VP \rightarrow book / include / prefer$

$VP \rightarrow Verb NP$

$VP \rightarrow X2 PP$

$X2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

$VP \rightarrow VP PP$

$PP \rightarrow Preposition NP$

**NP,  
Pronoun**  
[0,1]

**S**

[0,2]  
[0,3]

[0,4]

[0,5]

**Verb, VP, S**

[1,2]

[1,3]

[1,4]

[1,5]

**Det**

[2,3]

[2,4]

[2,5]

**Noun, Nom**

[3,4]

[3,5]

**Prep**

[4,5]

### Lexicon

$Det \rightarrow that | this | a$

$Noun \rightarrow book | flight | meal | money$

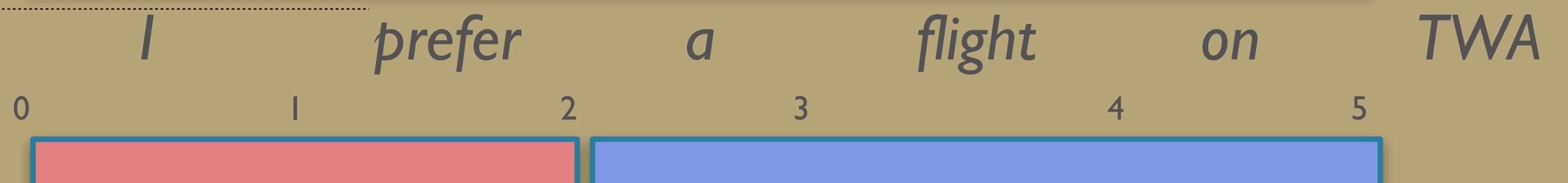
$Pronoun \rightarrow I | she | me$

$Proper-Noun \rightarrow Houston | TWA$

$Aux \rightarrow does$

$Preposition \rightarrow from | to | on | near | through$

$Verb \rightarrow book | include | prefer$



### $\mathcal{L}_1$ Grammar

$S \rightarrow NP VP$

$S \rightarrow X1 VP$

$X1 \rightarrow Aux NP$

$S \rightarrow book / include / prefer$

$S \rightarrow Verb NP$

$S \rightarrow X2 PP$

$S \rightarrow Verb PP$

$S \rightarrow VP PP$

$NP \rightarrow I / she / me$

$NP \rightarrow TWA / Houston$

$NP \rightarrow Det Nominal$

$Nominal \rightarrow book / flight / meal / money$

$Nominal \rightarrow Nominal Noun$

$Nominal \rightarrow Nominal PP$

$VP \rightarrow book / include / prefer$

$VP \rightarrow Verb NP$

$VP \rightarrow X2 PP$

$X2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

$VP \rightarrow VP PP$

$PP \rightarrow Preposition NP$

<b>NP, Pronoun</b> [0,1]	<b>S</b> [0,2]		<b>S</b> [0,4]		
	<b>Verb, VP, S</b> [1,2]		<b>VP, X2, S</b> [1,4]		
		<b>Det</b> [1,3]	<b>NP</b> [1,5]		
			<b>Noun, Nom</b> [2,4]		
			<b>[3,4]</b>	<b>[3,5]</b>	
				<b>Prep</b> [4,5]	

### Lexicon

$Det \rightarrow that | this | a$

$Noun \rightarrow book | flight | meal | money$

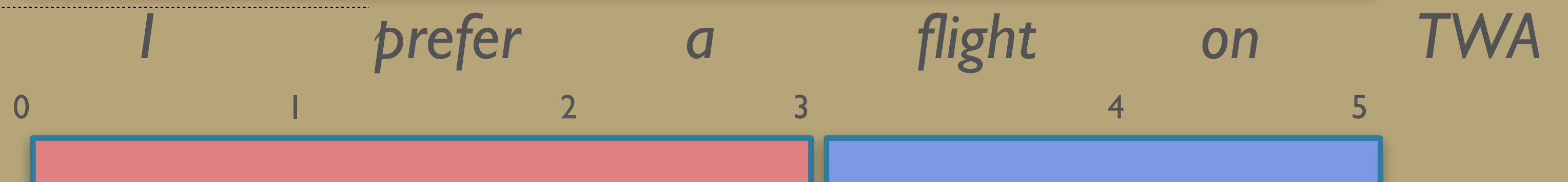
$Pronoun \rightarrow I | she | me$

$Proper-Noun \rightarrow Houston | TWA$

$Aux \rightarrow does$

$Preposition \rightarrow from | to | on | near | through$

$Verb \rightarrow book | include | prefer$



### $\mathcal{L}_1$ Grammar

$S \rightarrow NP VP$

$S \rightarrow X1 VP$

$X1 \rightarrow Aux NP$

$S \rightarrow book / include / prefer$

$S \rightarrow Verb NP$

$S \rightarrow X2 PP$

$S \rightarrow Verb PP$

$S \rightarrow VP PP$

$NP \rightarrow I / she / me$

$NP \rightarrow TWA / Houston$

$NP \rightarrow Det Nominal$

$Nominal \rightarrow book / flight / meal / money$

$Nominal \rightarrow Nominal Noun$

$Nominal \rightarrow Nominal PP$

$VP \rightarrow book / include / prefer$

$VP \rightarrow Verb NP$

$VP \rightarrow X2 PP$

$X2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

$VP \rightarrow VP PP$

$PP \rightarrow Preposition NP$

**NP,  
Pronoun**  
[0,1]

**S**  
[0,2]

**S**  
[0,3]

**S**  
[0,4]

**[0,5]**

**Verb, VP, S**  
[1,2]

**[1,3]**

**VP, X2, S**  
[1,4]

**[1,5]**

**Det**  
[2,3]

**NP**  
[2,4]

**[2,5]**

**Noun, Nom**  
[3,4]

**[3,5]**

**Prep**  
[4,5]

### Lexicon

$Det \rightarrow that | this | a$

$Noun \rightarrow book | flight | meal | money$

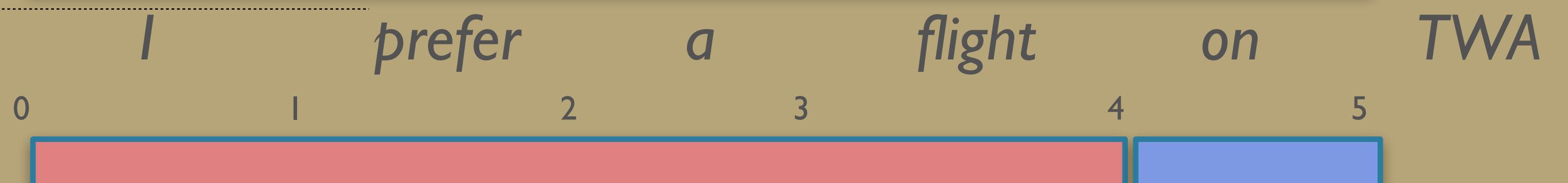
$Pronoun \rightarrow I | she | me$

$Proper-Noun \rightarrow Houston | TWA$

$Aux \rightarrow does$

$Preposition \rightarrow from | to | on | near | through$

$Verb \rightarrow book | include | prefer$



### $\mathcal{L}_1$ Grammar

$S \rightarrow NP VP$

$S \rightarrow X1 VP$

$X1 \rightarrow Aux NP$

$S \rightarrow book / include / prefer$

$S \rightarrow Verb NP$

$S \rightarrow X2 PP$

$S \rightarrow Verb PP$

$S \rightarrow VP PP$

$NP \rightarrow I / she / me$

$NP \rightarrow TWA / Houston$

$NP \rightarrow Det Nominal$

$Nominal \rightarrow book / flight / meal / money$

$Nominal \rightarrow Nominal Noun$

$Nominal \rightarrow Nominal PP$

$VP \rightarrow book / include / prefer$

$VP \rightarrow Verb NP$

$VP \rightarrow X2 PP$

$X2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

$VP \rightarrow VP PP$

$PP \rightarrow Preposition NP$



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

### Lexicon

$Det \rightarrow that | this | a$

$Noun \rightarrow book | flight | meal | money$

$Pronoun \rightarrow I | she | me$

$Proper-Noun \rightarrow Houston | TWA$

$Aux \rightarrow does$

$Preposition \rightarrow from | to | on | near | through$

$Verb \rightarrow book | include | prefer$

### $\mathcal{L}_1$ Grammar

$S \rightarrow NP VP$

$S \rightarrow X1 VP$

$X1 \rightarrow Aux NP$

$S \rightarrow book / include / prefer$

$S \rightarrow Verb NP$

$S \rightarrow X2 PP$

$S \rightarrow Verb PP$

$S \rightarrow VP PP$

$NP \rightarrow I / she / me$

$NP \rightarrow TWA / Houston$

$NP \rightarrow Det Nominal$

$Nominal \rightarrow book / flight / meal / money$

$Nominal \rightarrow Nominal Noun$

$Nominal \rightarrow Nominal PP$

$VP \rightarrow book / include / prefer$

$VP \rightarrow Verb NP$

$VP \rightarrow X2 PP$

$X2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

$VP \rightarrow VP PP$

$PP \rightarrow Preposition NP$

**NP,  
Pronoun**  
[0,1]

**S**  
[0,2]

**S**  
[0,3]

**S**  
[0,4]

[0,5]

**Verb, VP, S**  
[1,2]

[1,3]

**VP, X2, S**  
[1,4]

[1,5]

**Det**  
[2,3]

**NP**  
[2,4]

[2,5]

**Noun, Nom**  
[3,4]

[3,5]

**Prep**  
[4,5]

**PP**  
[4,6]

**NNP, NP**  
[5,6]

### Lexicon

$Det \rightarrow that | this | a$

$Noun \rightarrow book | flight | meal | money$

$Pronoun \rightarrow I | she | me$

$Proper-Noun \rightarrow Houston | TWA$

$Aux \rightarrow does$

$Preposition \rightarrow from | to | on | near | through$

$Verb \rightarrow book | include | prefer$



### $\mathcal{L}_1$ Grammar

$S \rightarrow NP VP$

$S \rightarrow X1 VP$

$X1 \rightarrow Aux NP$

$S \rightarrow book / include / prefer$

$S \rightarrow Verb NP$

$S \rightarrow X2 PP$

$S \rightarrow Verb PP$

$S \rightarrow VP PP$

$NP \rightarrow I / she / me$

$NP \rightarrow TWA / Houston$

$NP \rightarrow Det Nominal$

$Nominal \rightarrow book / flight / meal / money$

$Nominal \rightarrow Nominal Noun$

$Nominal \rightarrow Nominal PP$

$VP \rightarrow book / include / prefer$

$VP \rightarrow Verb NP$

$VP \rightarrow X2 PP$

$X2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

$VP \rightarrow VP PP$

$PP \rightarrow Preposition NP$

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

### Lexicon

$Det \rightarrow that | this | a$

$Noun \rightarrow book | flight | meal | money$

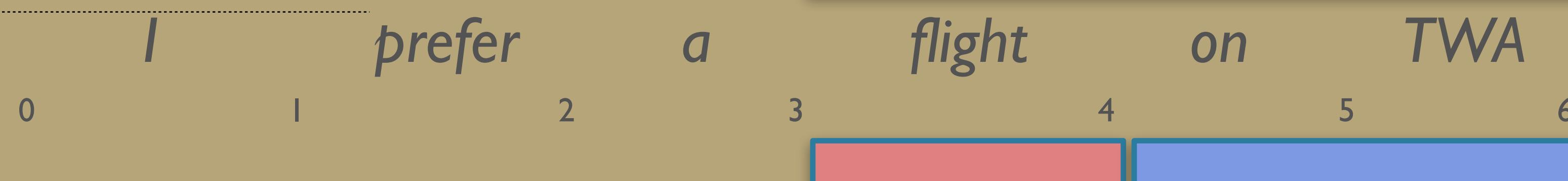
$Pronoun \rightarrow I | she | me$

$Proper-Noun \rightarrow Houston | TWA$

$Aux \rightarrow does$

$Preposition \rightarrow from | to | on | near | through$

$Verb \rightarrow book | include | prefer$



### $\mathcal{L}_1$ Grammar

$S \rightarrow NP VP$

$S \rightarrow X1 VP$

$X1 \rightarrow Aux NP$

$S \rightarrow book / include / prefer$

$S \rightarrow Verb NP$

$S \rightarrow X2 PP$

$S \rightarrow Verb PP$

$S \rightarrow VP PP$

$NP \rightarrow I / she / me$

$NP \rightarrow TWA / Houston$

$NP \rightarrow Det Nominal$

$Nominal \rightarrow book / flight / meal / money$

$Nominal \rightarrow Nominal Noun$

$Nominal \rightarrow Nominal PP$

$VP \rightarrow book / include / prefer$

$VP \rightarrow Verb NP$

$VP \rightarrow X2 PP$

$X2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

$VP \rightarrow VP PP$

$PP \rightarrow Preposition NP$

**NP,  
Pronoun**  
[0,1]

**S**  
[0,2]

**S**  
[0,3]

**S**  
[0,4]

**VP, X2, S**  
[0,5]

**Verb, VP, S**  
[1,2]

**Det**  
[1,3]

**NP**  
[1,4]

**NP**  
[1,5]

**Det**  
[2,3]

**Noun, Nom**  
[2,4]

**Nom**  
[2,5]

**Noun, Nom**  
[3,4]

**NP**  
[3,5]

**Prep**  
[3,6]

**PP**  
[4,5]

**NNP, NP**  
[4,6]

**NNP, NP**  
[5,6]

### Lexicon

$Det \rightarrow that | this | a$

$Noun \rightarrow book | flight | meal | money$

$Pronoun \rightarrow I | she | me$

$Proper-Noun \rightarrow Houston | TWA$

$Aux \rightarrow does$

$Preposition \rightarrow from | to | on | near | through$

$Verb \rightarrow book | include | prefer$



### $\mathcal{L}_1$ Grammar

$S \rightarrow NP VP$

$S \rightarrow X1 VP$

$X1 \rightarrow Aux NP$

$S \rightarrow book / include / prefer$

$S \rightarrow Verb NP$

$S \rightarrow X2 PP$

$S \rightarrow Verb PP$

$S \rightarrow VP PP$

$NP \rightarrow I / she / me$

$NP \rightarrow TWA / Houston$

$NP \rightarrow Det Nominal$

$Nominal \rightarrow book / flight / meal / money$

$Nominal \rightarrow Nominal Noun$

$Nominal \rightarrow Nominal PP$

$VP \rightarrow book / include / prefer$

$VP \rightarrow Verb NP$

$VP \rightarrow X2 PP$

$X2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

$VP \rightarrow VP PP$

$PP \rightarrow Preposition NP$

**NP,  
Pronoun**  
[0,1]

**S**  
[0,2]

**S**  
[0,3]

**S**  
[0,4]

[0,5]

**Verb, VP, S**  
[1,2]

**VP, X2, S**  
[1,3]

**VP, X2, S**  
[1,4]

[1,5]

**Det**  
[2,3]

**NP**  
[2,4]

**NP**  
[2,5]

**NP**  
[2,6]

**Noun, Nom**  
[3,4]

[3,5]

**Nom**  
[3,6]

**Prep**  
[4,5]

**PP**  
[4,6]

**NNP, NP**  
[5,6]

### Lexicon

$Det \rightarrow that | this | a$

$Noun \rightarrow book | flight | meal | money$

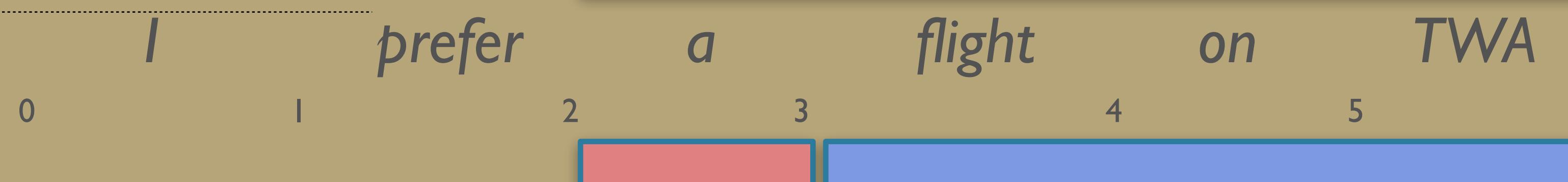
$Pronoun \rightarrow I | she | me$

$Proper-Noun \rightarrow Houston | TWA$

$Aux \rightarrow does$

$Preposition \rightarrow from | to | on | near | through$

$Verb \rightarrow book | include | prefer$



### $\mathcal{L}_1$ Grammar

$S \rightarrow NP VP$

$S \rightarrow X1 VP$

$X1 \rightarrow Aux NP$

$S \rightarrow book / include / prefer$

$S \rightarrow Verb NP$

$S \rightarrow X2 PP$

$S \rightarrow Verb PP$

$S \rightarrow VP PP$

$NP \rightarrow I / she / me$

$NP \rightarrow TWA / Houston$

$NP \rightarrow Det Nominal$

$Nominal \rightarrow book / flight / meal / money$

$Nominal \rightarrow Nominal Noun$

$Nominal \rightarrow Nominal PP$

$VP \rightarrow book / include / prefer$

$VP \rightarrow Verb NP$

$VP \rightarrow X2 PP$

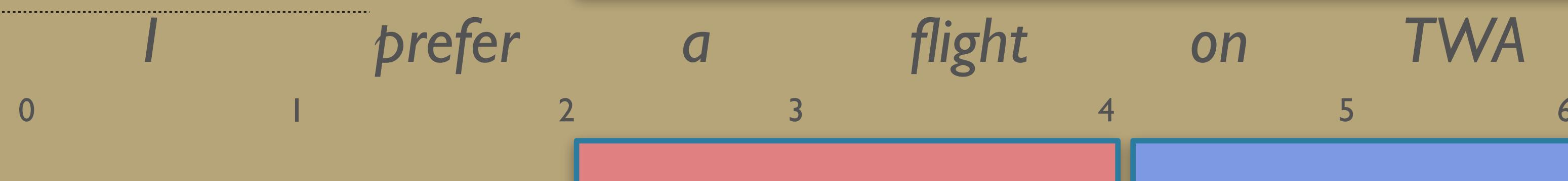
$X2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

$VP \rightarrow VP PP$

$PP \rightarrow Preposition NP$

<b>NP, Pronoun [0,1]</b>	<b>S</b> [0,2]		<b>S</b> [0,4]		
	<b>Verb, VP, S [1,2]</b>		<b>VP, X2, S [1,4]</b>		
	<b>Det [2,3]</b>	<b>NP [2,4]</b>			<b>NP [2,6]</b>
		<b>Noun, Nom [3,4]</b>			<b>Nom [3,6]</b>
			<b>Prep [4,5]</b>	<b>PP [4,6]</b>	<b>NNP, NP [5,6]</b>
	<b>Lexicon</b> <i>Det</i> → that   this   a <i>Noun</i> → book   flight   meal   money <i>Pronoun</i> → I   she   me <i>Proper-Noun</i> → Houston   TWA <i>Aux</i> → does <i>Preposition</i> → from   to   on   near   through <i>Verb</i> → book   include   prefer				



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$S \rightarrow Verb PP$

$S \rightarrow VP PP$

$NP \rightarrow I / she / me$

$NP \rightarrow TWA / Houston$

$NP \rightarrow Det Nominal$

$Nominal \rightarrow book / flight / meal / money$

$Nominal \rightarrow Nominal Noun$

$Nominal \rightarrow Nominal PP$

$VP \rightarrow book / include / prefer$

$VP \rightarrow Verb NP$

$VP \rightarrow X2 PP$

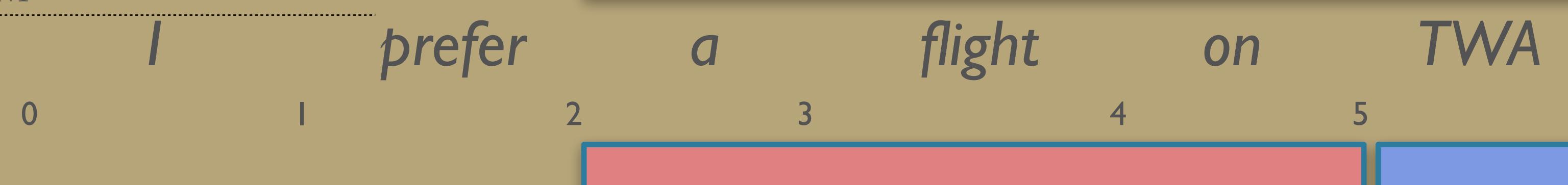
$X2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

$VP \rightarrow VP PP$

$PP \rightarrow Preposition NP$

<b>NP, Pronoun [0,1]</b>	<b>S</b> [0,2]		<b>S</b> [0,4]		
	<b>Verb, VP, S [1,2]</b>		<b>VP, X2, S [1,4]</b>		
		<b>Det [1,3]</b>	<b>NP [1,5]</b>		
		<b>[2,3]</b>	<b>[2,4]</b>	<b>[2,5]</b>	<b>NP [2,6]</b>
			<b>Noun, Nom [3,4]</b>		<b>Nom [3,6]</b>
			<b>[3,5]</b>		
				<b>Prep [4,5]</b>	<b>PP [4,6]</b>
					<b>NNP, NP [5,6]</b>
<b>Lexicon</b>					
<i>Det</i> $\rightarrow$ that   this   a					
<i>Noun</i> $\rightarrow$ book   flight   meal   money					
<i>Pronoun</i> $\rightarrow$ I   she   me					
<i>Proper-Noun</i> $\rightarrow$ Houston   TWA					
<i>Aux</i> $\rightarrow$ does					
<i>Preposition</i> $\rightarrow$ from   to   on   near   through					
<i>Verb</i> $\rightarrow$ book   include   prefer					



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$S \rightarrow VP PP$

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$NP \rightarrow TWA / Houston$

$NP \rightarrow Det Nominal$

$Nominal \rightarrow book / flight / meal / money$

$Nominal \rightarrow Nominal Noun$

$Nominal \rightarrow Nominal PP$

$VP \rightarrow book / include / prefer$

$VP \rightarrow Verb NP$

$VP \rightarrow X2 PP$

$X2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

$VP \rightarrow VP PP$

$PP \rightarrow Preposition NP$

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

**Lexicon**

$Det \rightarrow that | this | a$

$Noun \rightarrow book | flight | meal | money$

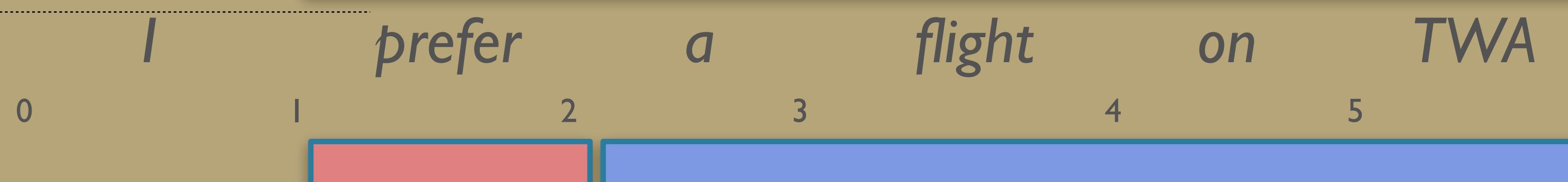
$Pronoun \rightarrow I | she | me$

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$S \rightarrow Verb PP$

$S \rightarrow VP PP$

$NP \rightarrow I / she / me$

$NP \rightarrow TWA / Houston$

$NP \rightarrow Det Nominal$

$Nominal \rightarrow book / flight / meal / money$

$Nominal \rightarrow Nominal Noun$

$Nominal \rightarrow Nominal PP$

$VP \rightarrow book / include / prefer$

$VP \rightarrow Verb NP$

$VP \rightarrow X2 PP$

$X2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

$VP \rightarrow VP PP$

$PP \rightarrow Preposition NP$

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

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$VP \rightarrow VP PP$

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

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$Noun \rightarrow book | flight | meal | money$

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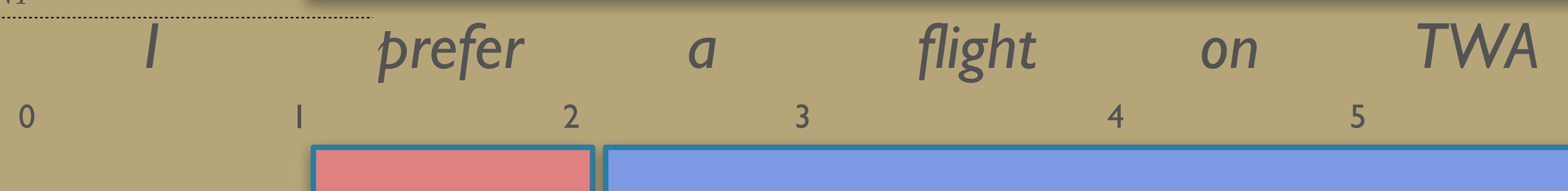
$Proper-Noun \rightarrow Houston | TWA$

$Aux \rightarrow does$

$Preposition \rightarrow from | to | on | near | through$

$Verb \rightarrow book | include | prefer$

$PP \rightarrow Preposition NP$



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$VP \rightarrow VP PP$

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NP, Pronoun [0,1]	S [0,2]		S [0,3]		S [0,4]		[0,5]	
		<b>Verb, VP, S</b> [1,2]			<b>VP, X2, S</b> [1,3]			<b>VP, X2, S</b> [1,6]
				<b>Det</b> [2,3]		<b>NP</b> [2,4]		<b>NP</b> [2,6]
						<b>Noun, Nom</b> [3,4]		<b>Nom</b> [3,6]
							<b>Prep</b> [3,5]	<b>PP</b> [4,6]
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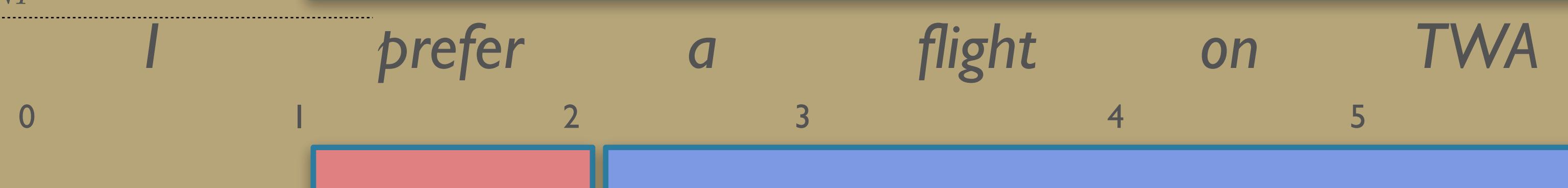
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<b>NP, Pronoun</b> [0,1]	<b>S</b> [0,2]		<b>S</b> [0,4]		
	<b>Verb, VP, S</b> [1,2]		<b>VP, X2, S</b> [1,3]		<b>VP, X2, S</b> [1,6]
		<b>Det</b> [2,3]	<b>NP</b> [2,4]		<b>NP</b> [2,6]
			<b>Noun, Nom</b> [3,4]		<b>Nom</b> [3,6]
				<b>Prep</b> [4,5]	<b>PP</b> [4,6]
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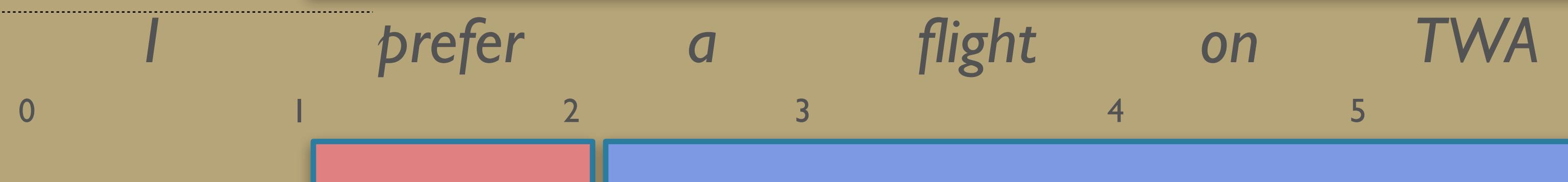
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$VP \rightarrow Verb PP$

$VP \rightarrow VP PP$

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

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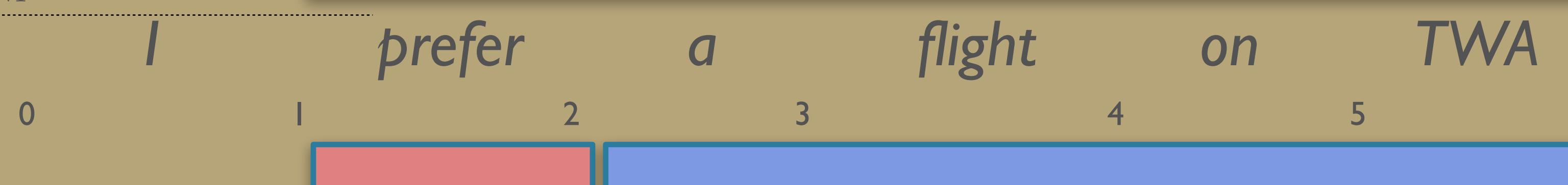
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NP, Pronoun [0,1]	S [0,2]		S [0,3]		S [0,4]		[0,5]	
		Verb, VP, S [1,2]		VP, X2, S [1,3]		VP, X2, S [1,4]		VP, X2, S [1,6]
				Det [2,3]		NP [2,4]		NP [2,6]
						Noun, Nom [3,4]		Nom [3,6]
							Prep [3,5]	PP [4,6]
								NNP, NP [5,6]

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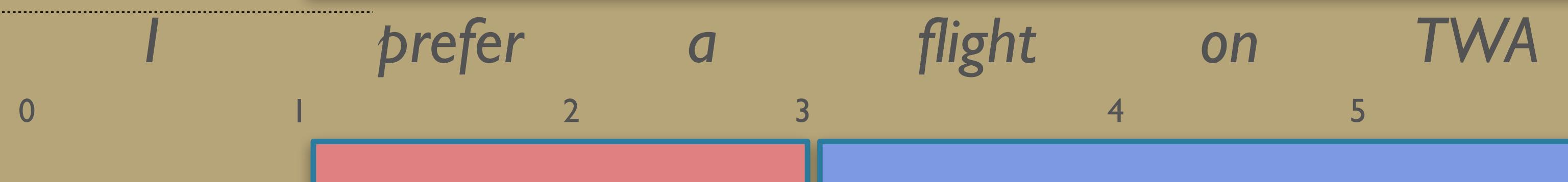
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NP, Pronoun [0,1]	S [0,2]		S [0,4]		
	<b>Verb, VP, S</b> [1,2]		<b>VP, X2, S</b> [1,4]		<b>VP, X2, S</b> [1,6]
		<b>Det</b> [2,3]	<b>NP</b> [2,4]		<b>NP</b> [2,6]
			<b>Noun, Nom</b> [3,4]		<b>Nom</b> [3,6]
				<b>Prep</b> [4,5]	<b>PP</b> [4,6]

### Lexicon

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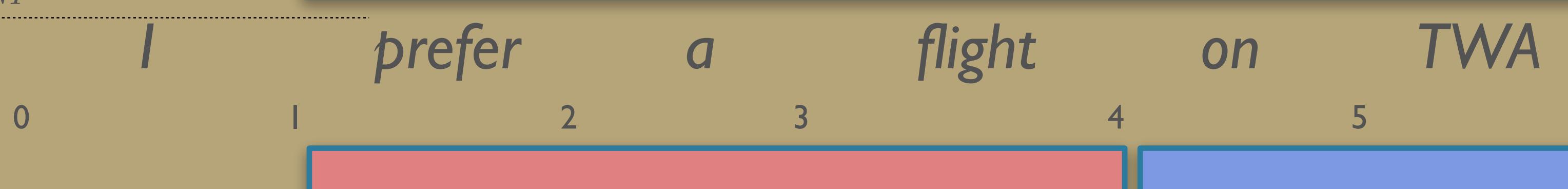
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$X2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

$VP \rightarrow VP PP$

$PP \rightarrow Preposition NP$

NP, Pronoun [0,1]	S [0,2]		S [0,4]		
	<b>Verb, VP, S</b> [1,2]		<b>VP, X2, S</b> [1,4]		<b>VP, X2, S</b> [1,6]
		<b>Det</b> [2,3]	<b>NP</b> [2,4]		<b>NP</b> [2,6]
			<b>Noun, Nom</b> [3,4]		<b>Nom</b> [3,6]
				<b>Prep</b> [4,5]	<b>PP</b> [4,6]
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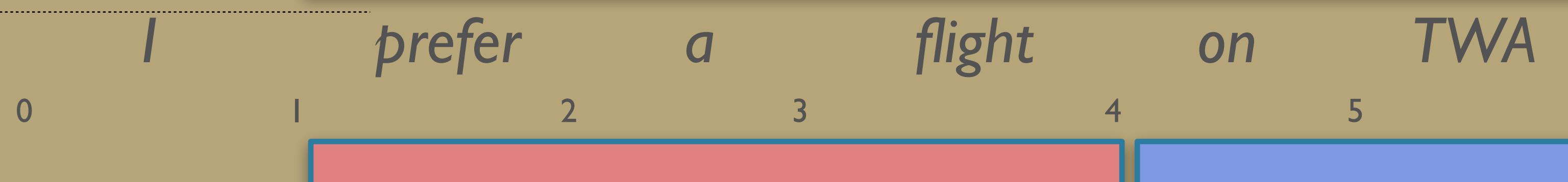
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$X2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

$VP \rightarrow VP PP$

$PP \rightarrow Preposition NP$

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

### Lexicon

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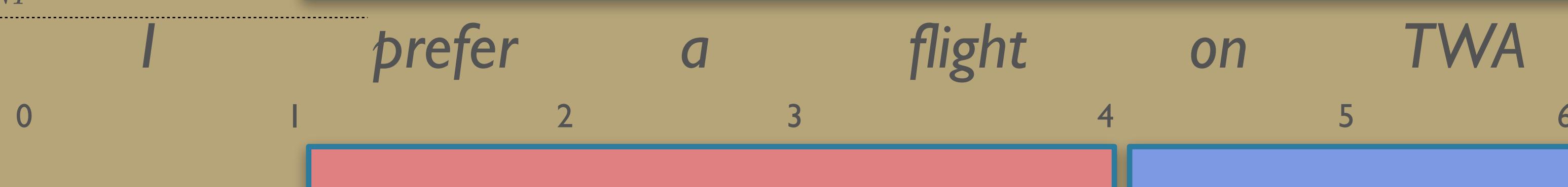
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$VP \rightarrow VP PP$

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

**Lexicon**

$Det \rightarrow that | this | a$

$Noun \rightarrow book | flight | meal | money$

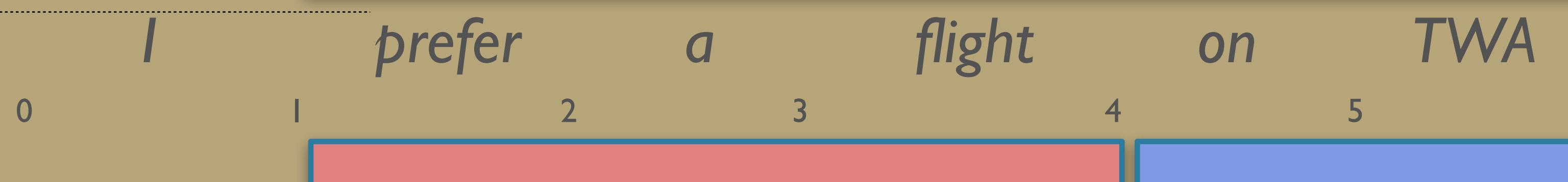
$Pronoun \rightarrow I | she | me$

$Proper-Noun \rightarrow Houston | TWA$

$Aux \rightarrow does$

$Preposition \rightarrow from | to | on | near | through$

$Verb \rightarrow book | include | prefer$



### $\mathcal{L}_1$ Grammar

$S \rightarrow NP VP$

$S \rightarrow X1 VP$

$X1 \rightarrow Aux NP$

$S \rightarrow book / include / prefer$

$S \rightarrow Verb NP$

$S \rightarrow X2 PP$

$S \rightarrow Verb PP$

$S \rightarrow VP PP$

$NP \rightarrow I / she / me$

$NP \rightarrow TWA / Houston$

$NP \rightarrow Det Nominal$

$Nominal \rightarrow book / flight / meal / money$

$Nominal \rightarrow Nominal Noun$

$Nominal \rightarrow Nominal PP$

$VP \rightarrow book / include / prefer$

$VP \rightarrow Verb NP$

$VP \rightarrow X2 PP$

$X2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

$VP \rightarrow VP PP$

$PP \rightarrow Preposition NP$

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

**Lexicon**

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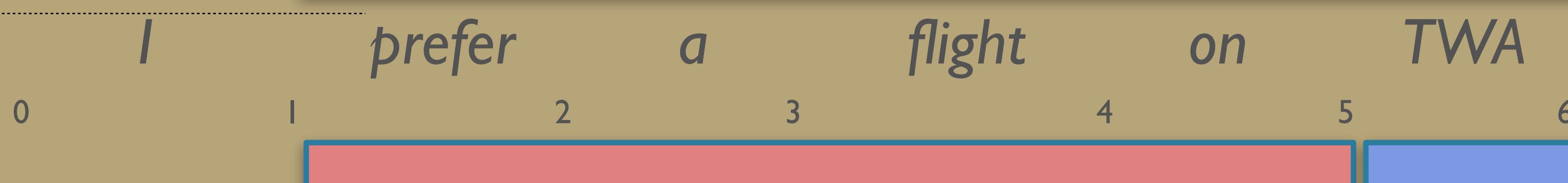
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$NP \rightarrow TWA / Houston$

$NP \rightarrow Det Nominal$

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$Nominal \rightarrow Nominal PP$

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$VP \rightarrow X2 PP$

$X2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

$VP \rightarrow VP PP$

$PP \rightarrow Preposition NP$

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

**Lexicon**

$Det \rightarrow that | this | a$

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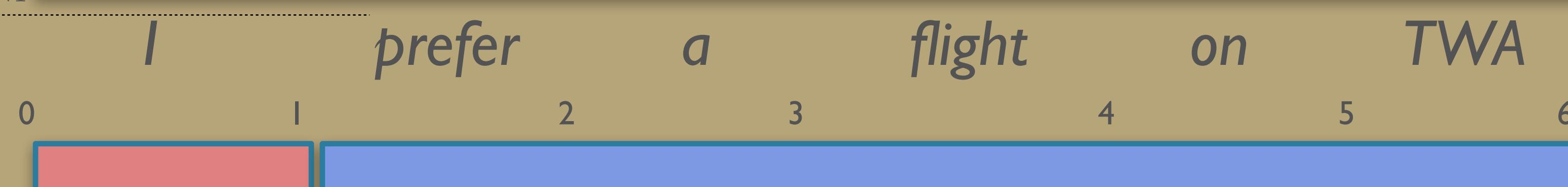
$Pronoun \rightarrow I | she | me$

$Proper-Noun \rightarrow Houston | TWA$

$Aux \rightarrow does$

$Preposition \rightarrow from | to | on | near | through$

$Verb \rightarrow book | include | prefer$



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$S \rightarrow VP PP$

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$NP \rightarrow Det Nominal$

$Nominal \rightarrow book / flight / meal / money$

$Nominal \rightarrow Nominal Noun$

$Nominal \rightarrow Nominal PP$

$VP \rightarrow book / include / prefer$

$VP \rightarrow Verb NP$

$VP \rightarrow X2 PP$

$X2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

$VP \rightarrow VP PP$

$PP \rightarrow Preposition NP$

**NP,  
Pronoun**  
[0,1]

**S**

**S**

**S**

**S**

[0,2]

[0,3]

[0,4]

[0,6]

**Verb, VP, S**  
[1,2]

**Verb, VP, S**  
[1,3]

**Verb, VP, S**  
[1,4]

**Verb, VP, S**  
[1,6]

**Det**

**NP**

**NP**

**NP**

[2,3]

[2,4]

[2,5]

[2,6]

**Noun, Nom**  
[3,4]

**Noun, Nom**  
[3,4]

**Noun, Nom**  
[3,5]

**Nom**

**Prep**

**Prep**

**Prep**

**PP**

[4,5]

[4,5]

[4,5]

[4,6]

**NNP, NP**  
[5,6]

**NNP, NP**  
[5,6]

**NNP, NP**  
[5,6]

**NNP, NP**  
[5,6]

**Lexicon**

$Det \rightarrow that | this | a$

$Noun \rightarrow book | flight | meal | money$

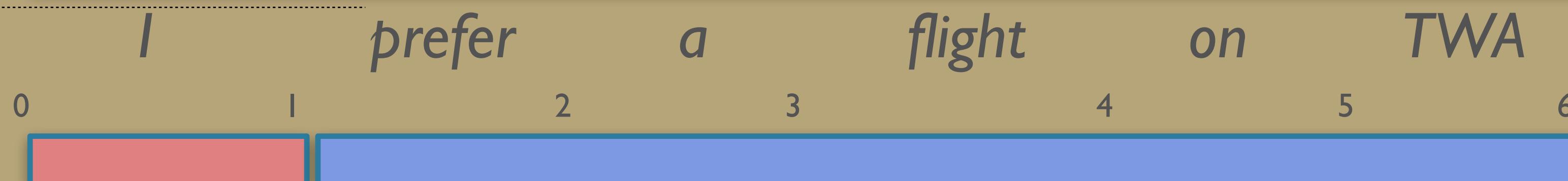
$Pronoun \rightarrow I | she | me$

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$VP \rightarrow Verb PP$

$VP \rightarrow VP PP$

$PP \rightarrow Preposition NP$

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

$X2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

$VP \rightarrow VP PP$

$PP \rightarrow Preposition NP$

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

### Lexicon

$Det \rightarrow that | this | a$

$Noun \rightarrow book | flight | meal | money$

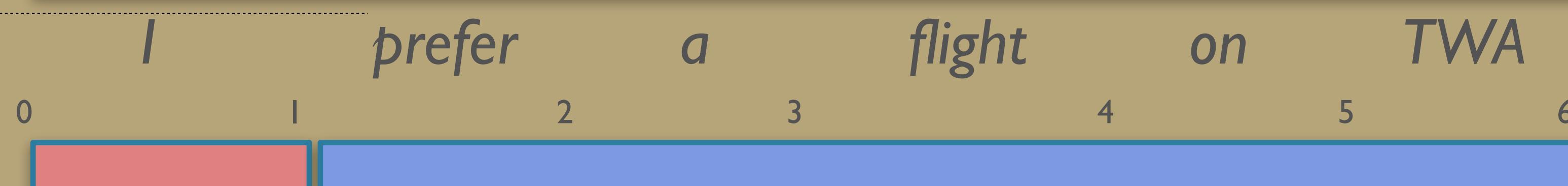
$Pronoun \rightarrow I | she | me$

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$Preposition \rightarrow from | to | on | near | through$

$Verb \rightarrow book | include | prefer$



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$S \rightarrow Verb NP$

$S \rightarrow X2 PP$

$S \rightarrow Verb PP$

$S \rightarrow VP PP$

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$NP \rightarrow TWA / Houston$

$NP \rightarrow Det Nominal$

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$VP \rightarrow X2 PP$

$X2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

$VP \rightarrow VP PP$

$PP \rightarrow Preposition NP$

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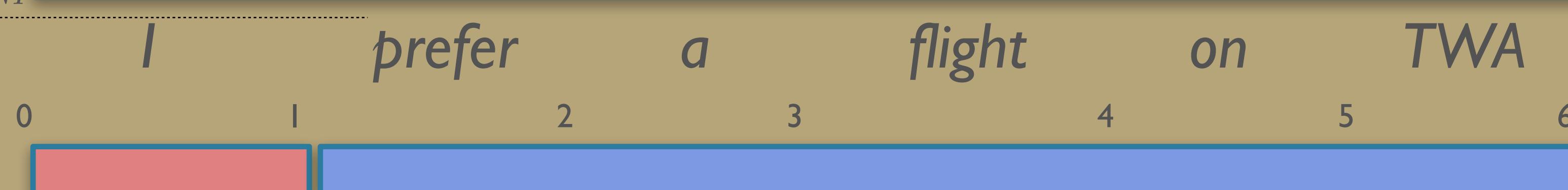
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NP, Pronoun [0,1]	S [0,2]		S [0,3]		S [0,4]		S [0,5]	S [0,6]
		Verb, VP, S [1,2]			VP, X2, S [1,3]			VP, X2, S [1,4]
				Det [2,3]		NP [2,4]		NP [1,5]
						Noun, Nom [3,4]		Nom [3,5]
							Prep [4,5]	PP [4,6]
								NNP, NP [5,6]

**Lexicon**

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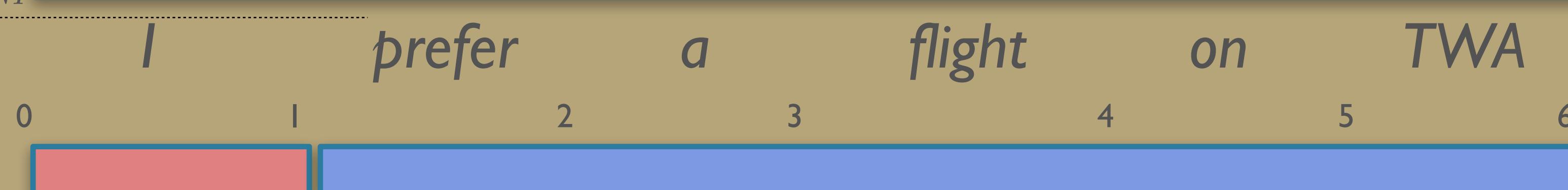
$Pronoun \rightarrow I | she | me$

$Proper-Noun \rightarrow Houston | TWA$

$Aux \rightarrow does$

$Preposition \rightarrow from | to | on | near | through$

$Verb \rightarrow book | include | prefer$



# 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 ]

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

$VP \rightarrow VP \mid PP$

$bp\_1 = \text{BackPointer}()$   
 $bp\_1.l\_child = [VP, (1, 4)]$   
 $bp\_1.r\_child = [PP, (4, 6)]$

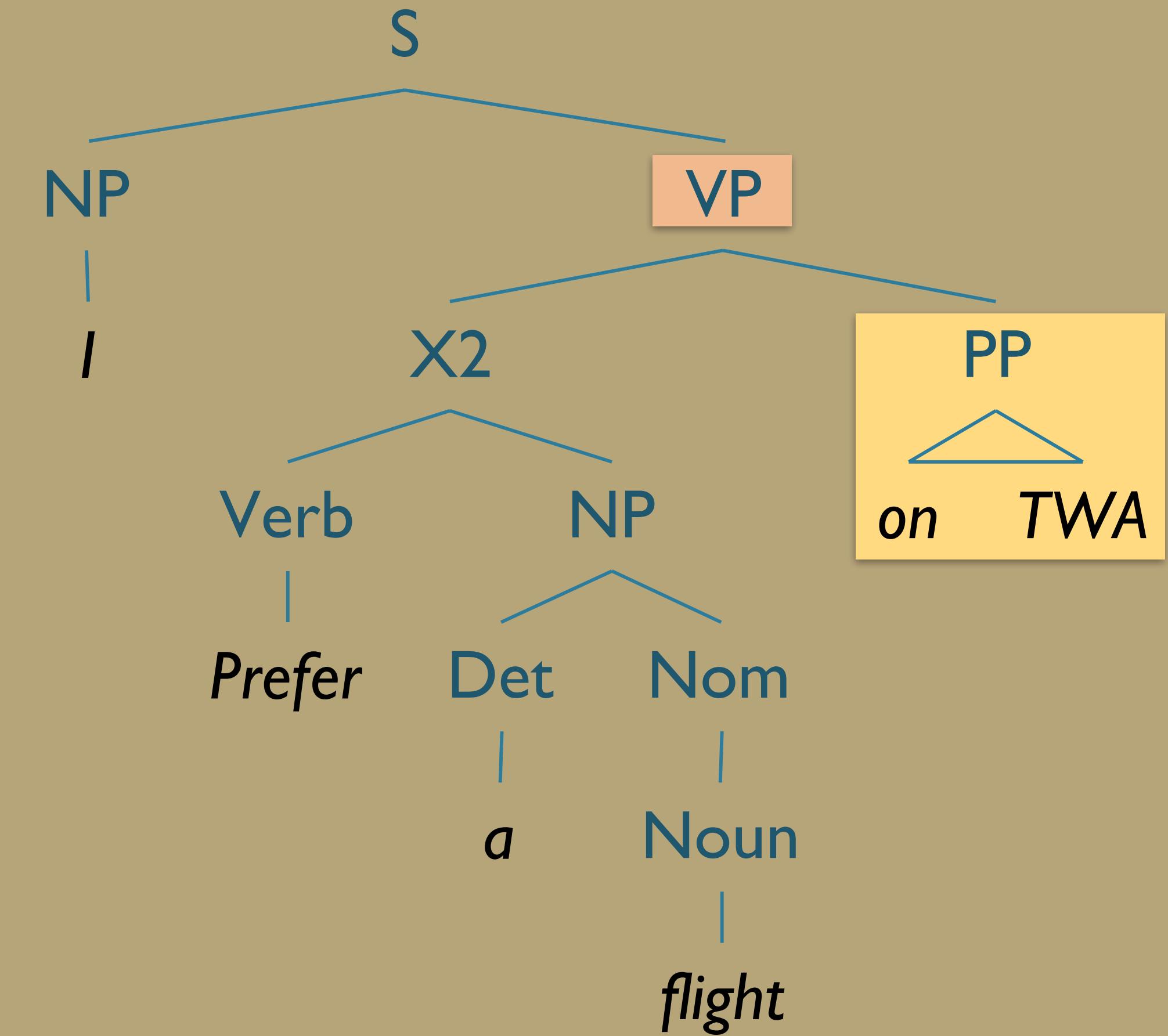
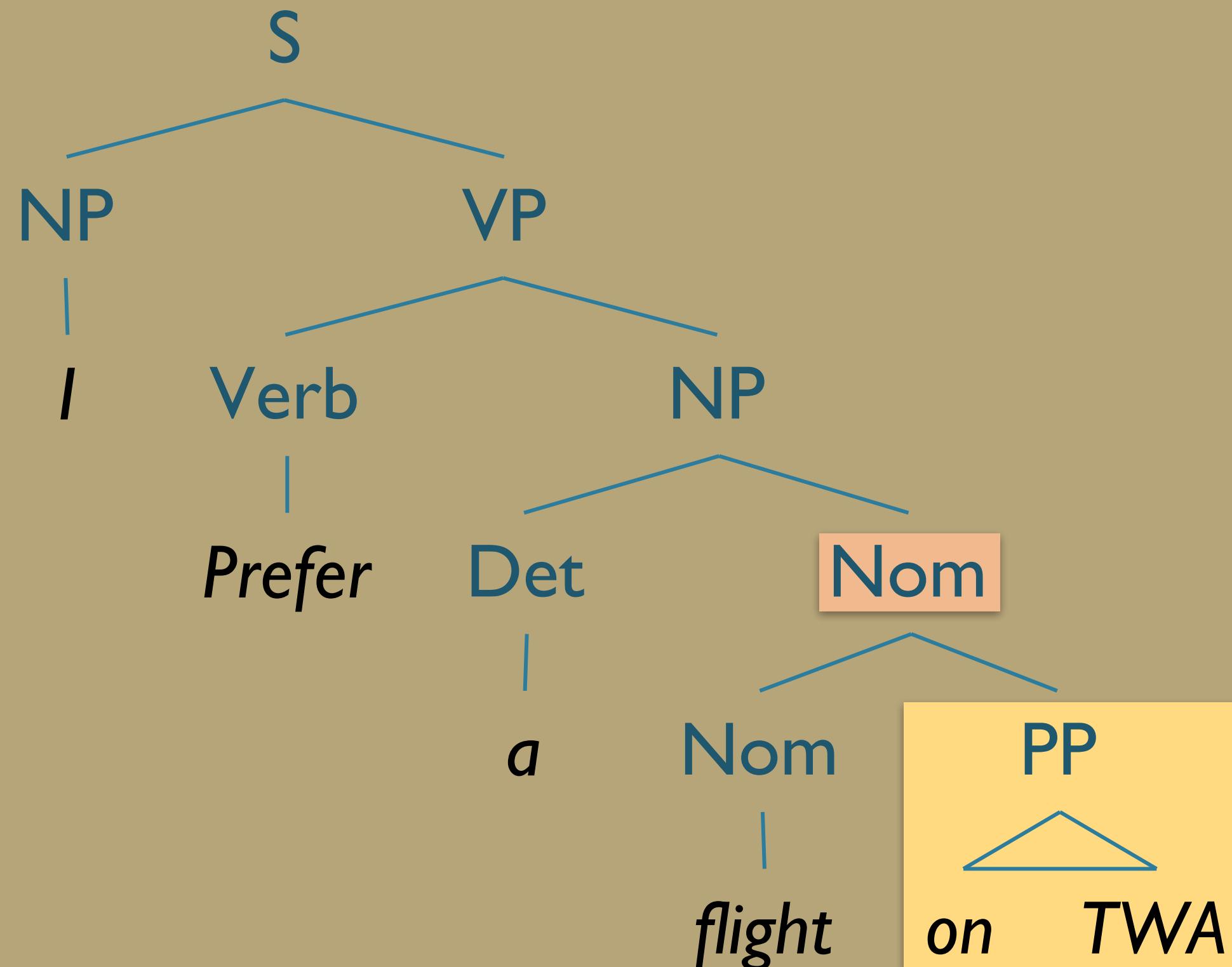
NP, Pronoun [0,1]	S [0,2]	[0,3]	S [0,4]	[0,5]
	Verb, VP, S [1,2]		VP, X2, S [1,4]	VP [1,6]
		Det [2,3]	NP [2,4]	NP [2,6]
			Noun, Nom [3,4]	Nom [3,6]
			Prep [4,5]	PP [4,6]
				NNP, NP [5,6]

$VP \rightarrow X2 \mid PP$

$bp\_2 = \text{BackPointer}()$   
 $bp\_2.l\_child = [X2, (1, 4)]$   
 $bp\_2.r\_child = [PP, (4, 6)]$

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

# 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

# Parsing: PCFGs

Ling 571  
Deep Processing Techniques for NLP  
October 7, 2019

# Probabilistic Context-free Grammars: Roadmap

- Motivation: Ambiguity
- Approach:
  - Definition
  - Disambiguation
  - Parsing
  - Evaluation
  - Enhancements

# Motivation

- What about ambiguity?
- Current algorithm can *represent* it
- ...can't resolve it.

# Probabilistic Parsing

- Provides strategy for solving disambiguation problem
  - Compute the probability of all analyses
  - Select the most probable
- Employed in language modeling for speech recognition
  - N-gram grammars predict words, constrain search
  - Also, constrain generation, translation

# PCFGs: Formal Definition

$N$

a set of **non-terminal symbols** (or **variables**)

---

$\Sigma$

a set of **terminal symbols** (disjoint from  $N$ )

---

$R$

a set of rules of productions, each of the form  $A \rightarrow \beta[p]$ , where  $A$  is a non-terminal where  
 $A$  is a non-terminal,  $\beta$  is a string of symbols from the infinite set of strings  $(\Sigma \cup N)^*$  and  $p$   
is a number between 0 and 1 expressing  $P(\beta|A)$

---

$S$

a designated **start symbol**

# PCFGs

- Augment each production with probability that LHS will be expanded as RHS
  - $P(A \rightarrow \beta)$
  - $P(A \rightarrow \beta | A)$
  - $P(\beta | A)$
  - $P(RHS | LHS)$
- NB: the first is often used; but the latter are what's really meant.

# PCFGs

- Sum over all possible expansions is 1

$$\sum_{\beta} P(A \rightarrow \beta) = 1$$

- A PCFG is *consistent* if sum of probabilities of all sentences in language is 1
- Recursive rules often yield inconsistent grammars ([Booth & Thompson, 1973](#))

# Example PCFG: Augmented $\mathcal{L}_1$

Grammar		Lexicon
$S \rightarrow NP\ VP$	[.80]	$Det \rightarrow that [.10] \mid a [.30] \mid the [.60]$
$S \rightarrow Aux\ NP\ VP$	[.15]	$Noun \rightarrow book [.10] \mid flight [.30] \mid meal [.15] \mid money [0.5]$
$S \rightarrow VP$	[.05]	$\mid flights [0.40] \mid dinner [.10]$
$NP \rightarrow Pronoun$	[.35]	$Verb \rightarrow book [.30] \mid include [.30] \mid prefer [.40]$
$NP \rightarrow Proper-Noun$	[.30]	$Pronoun \rightarrow I [.40] \mid she [.05] \mid me [.15] \mid you [.40]$
$NP \rightarrow Det\ Nominal$	[.20]	$Proper-Noun \rightarrow Houston [.60] \mid NWA [.40]$
$NP \rightarrow Nominal$	[.15]	$Aux \rightarrow does [.60] \mid can [.40]$
$Nominal \rightarrow Noun$	[.75]	$Preposition \rightarrow from [.30] \mid to [.30] \mid on [.20] \mid near [.15]$
$Nominal \rightarrow Nominal\ Noun$	[.20]	$\mid through [.05]$
$Nominal \rightarrow Nominal\ PP$	[.05]	
$VP \rightarrow Verb$	[.35]	
$VP \rightarrow Verb\ NP$	[.20]	
$VP \rightarrow Verb\ NP\ PP$	[.10]	
$VP \rightarrow Verb\ PP$	[.15]	
$VP \rightarrow Verb\ NP\ NP$	[.05]	
$VP \rightarrow VP\ PP$	[.15]	
$PP \rightarrow Preposition\ NP$	[1.0]	

# Example PCFG: Augmented $\mathcal{L}_1$

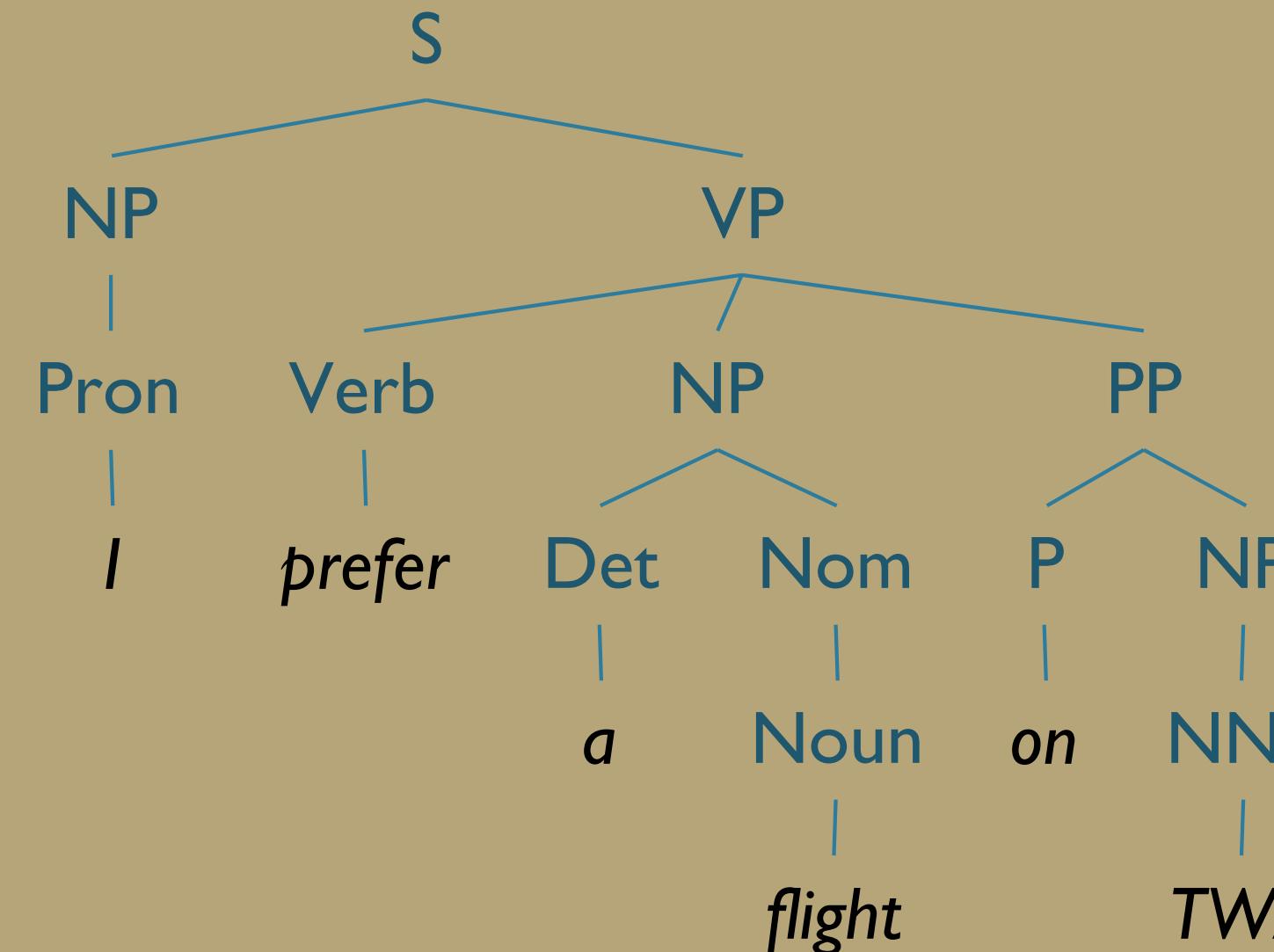
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$NP \rightarrow Proper-Noun$	[.30]	$Pronoun \rightarrow I [.40] \mid she [.05] \mid me [.15] \mid you [.40]$
$NP \rightarrow Det\ Nominal$	[.20]	$Proper-Noun \rightarrow Houston [.60] \mid NWA [.40]$
$NP \rightarrow Nominal$	[.15]	$Aux \rightarrow does [.60] \mid can [.40]$
$Nominal \rightarrow Noun$	[.75]	$Preposition \rightarrow from [.30] \mid to [.30] \mid on [.20] \mid near [.15]$
$Nominal \rightarrow Nominal\ Noun$	[.20]	$\mid through [.05]$
$Nominal \rightarrow Nominal\ PP$	[.05]	
$VP \rightarrow Verb$	[.35]	
$VP \rightarrow Verb\ NP$	[.20]	
$VP \rightarrow Verb\ NP\ PP$	[.10]	
$VP \rightarrow Verb\ PP$	[.15]	
$VP \rightarrow Verb\ NP\ NP$	[.05]	
$VP \rightarrow VP\ PP$	[.15]	
$PP \rightarrow Preposition\ NP$	[1.0]	

# Disambiguation

- A PCFG assigns probability to each parse tree  $T$  for input  $S$
- Probability of  $T$ : product of all rules used to derive  $T$

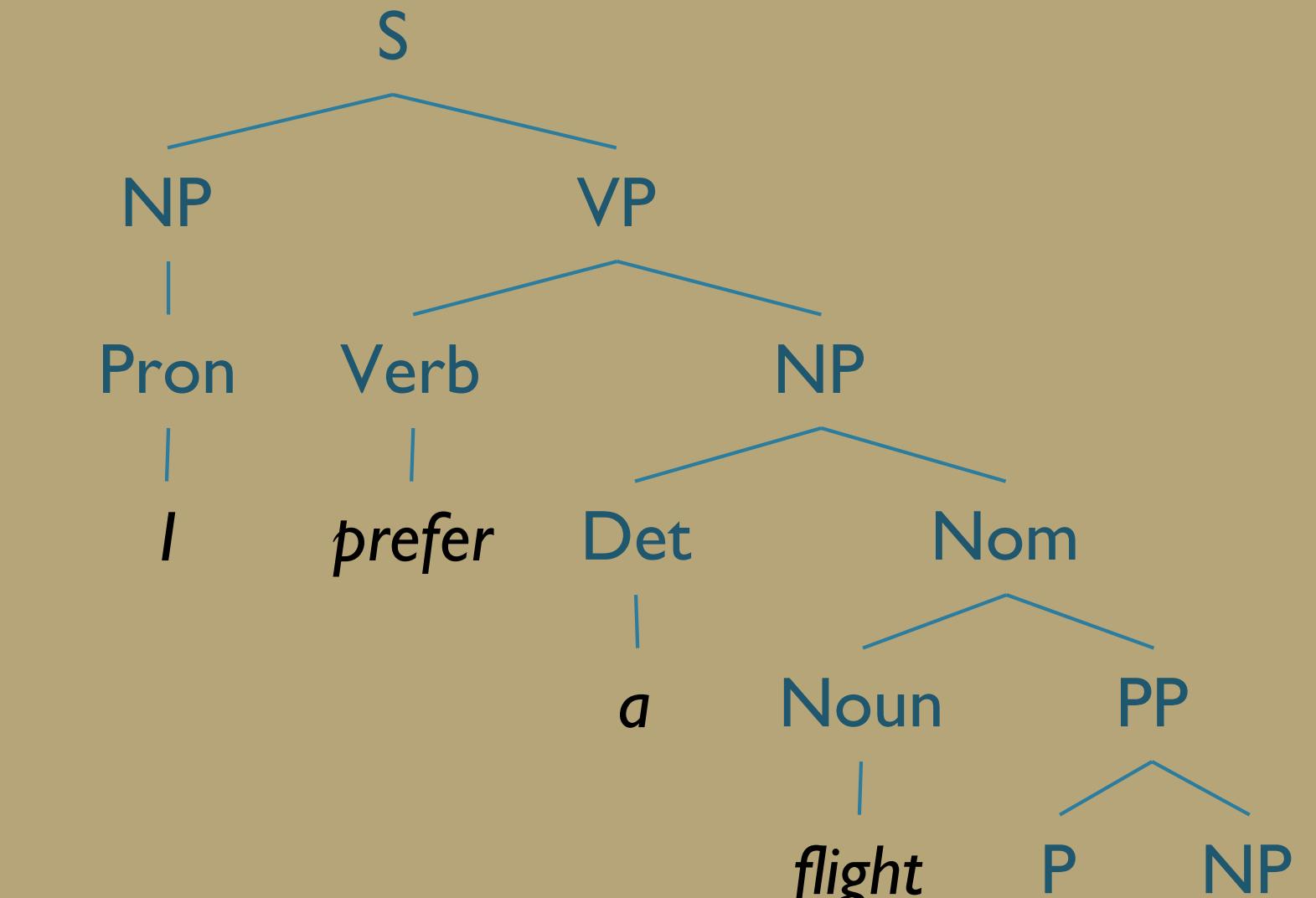
$$P(T, S) = \prod_{i=1}^n P(RHS_i \mid LHS_i)$$

$$P(T, S) = P(T)P(S \mid T) = P(T)$$



$S \rightarrow NP VP$	[0.8]
$NP \rightarrow Pron$	[0.35]
$Pron \rightarrow I$	[0.4]
$VP \rightarrow V NP PP$	[0.1]
$V \rightarrow prefer$	[0.4]
$NP \rightarrow Det Nom$	[0.2]
$Det \rightarrow a$	[0.3]
$Nom \rightarrow N$	[0.75]
$N \rightarrow flight$	[0.3]
$PP \rightarrow P NP$	[1.0]
$P \rightarrow on$	[0.2]
$NP \rightarrow NNP$	[0.3]
$NNP \rightarrow NWA$	[0.4]

$\sim 1.452 \times 10^{-6}$



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$Pron \rightarrow I$	[0.4]
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$Nom \rightarrow Nom PP$	[0.05]
$Nom \rightarrow N$	[0.75]
$N \rightarrow flight$	[0.3]
$PP \rightarrow P NP$	[1.0]
$P \rightarrow on$	[0.2]
$NP \rightarrow NNP$	[0.3]
$NNP \rightarrow NWA$	[0.4]

$\sim 1.452 \times 10^{-7}$

# Parsing Problem for PCFGs

- Select  $T$  such that (*s.t.*)

$$\hat{T}(S) = \operatorname{argmax}_{T \text{ s.t. } S=\text{yield}(T)} P(T)$$

- String of words  $S$  is *yield* of parse tree
- Select the tree  $\hat{T}$  that maximizes the probability of the parse

# Unit Testing

# Unit Testing

- Strategy of testing individual pieces of code in isolation
- Helps ensure:
  - Basic functionality in isolation
  - Complex functionality when individual components are combined
- In many industry jobs, you can't commit code without unit tests!

# Unit Testing in Python

- Many good tutorials on the web [[here's one](#)]
- In a nutshell:

```
from unittest import TestCase

class longTests(TestCase):
    def test_three(self):
        length_3_rule = parse_productions('A -> B C D')
        target_rules = parse_productions('''A -> B _X0_
                                         _X0_ -> C D''')
        self.assertEqual(set(target_rules),
                        set(fix_long_rules(length_3_rule)))
```

# Unit Testing in Python

- “nose” is a test running framework that will detect all `test_*` method functions

```
python3 -m nose hw2.py
```

```
AssertionError: Items in the first set but not the second:
```

```
    A -> B _X0_
        _X0_ -> C D
```

```
Items in the second set but not the first:
```

```
    A -> B C
```

---

```
Ran 12 tests in 0.040s
```

```
FAILED (failures=1)
```

# Unit Testing

- Good practice:
  - Save input that crashes your program for a unit test