

# CKY Parsing

LING 571 — Deep Processing Techniques for NLP

October 12, 2020

Shane Steinert-Threlkeld

# Announcements

- HW1: grades posted
  - In general, we will aim for Monday release of grades.
- Some notes:
  - Make sure dir structure of your submission is correct [generally, no nested directories]
  - Run `check_hwX.sh` before submitting!
  - Pay careful attention to format of output files; make sure there's exact match on toy examples
  - patas/dryas, etc: will regrade HW1 if that was an issue
  - Use full paths for python binaries to be safe

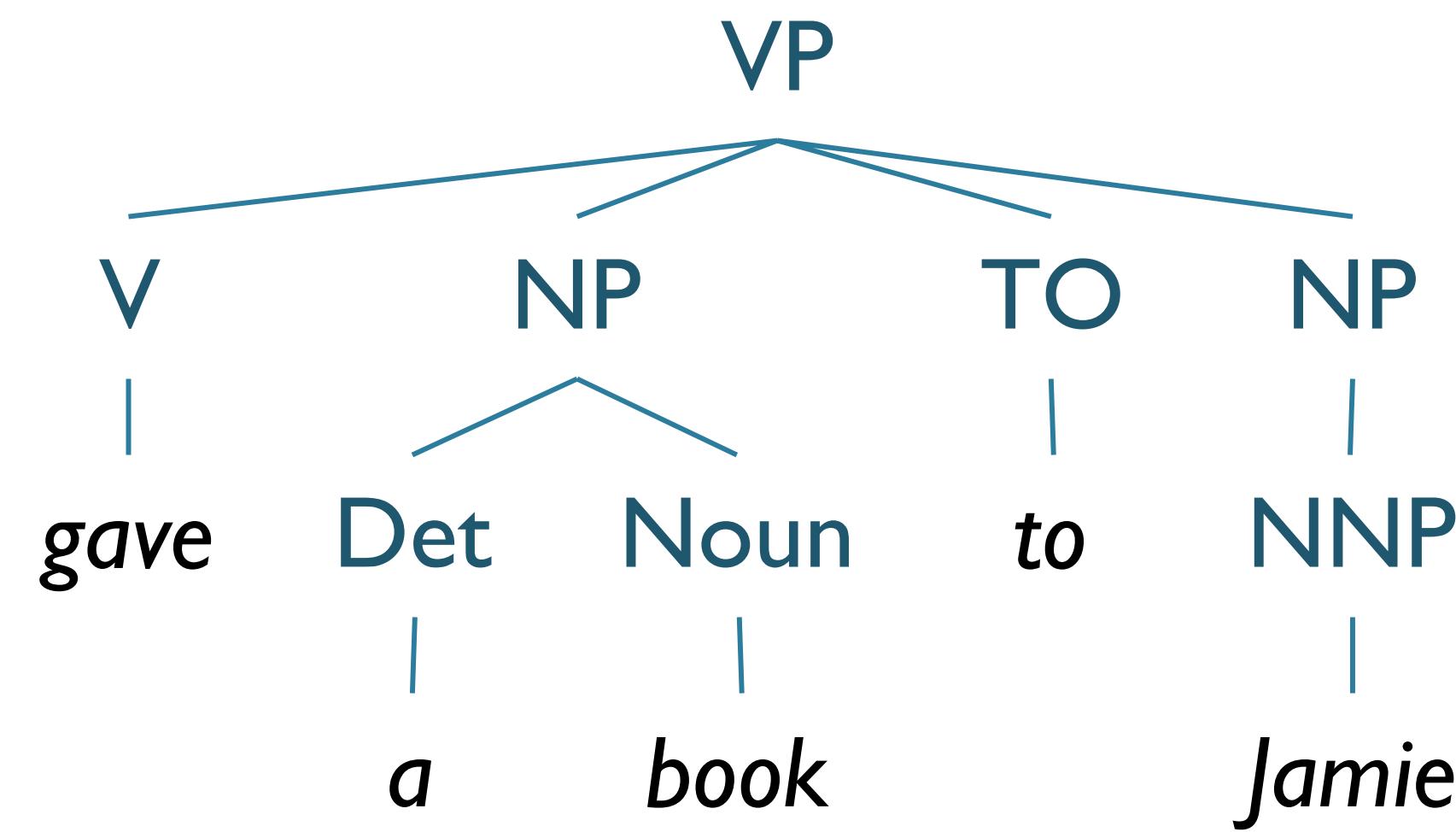
# Announcements: HW #2

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

# Variation in CNF: Binarization

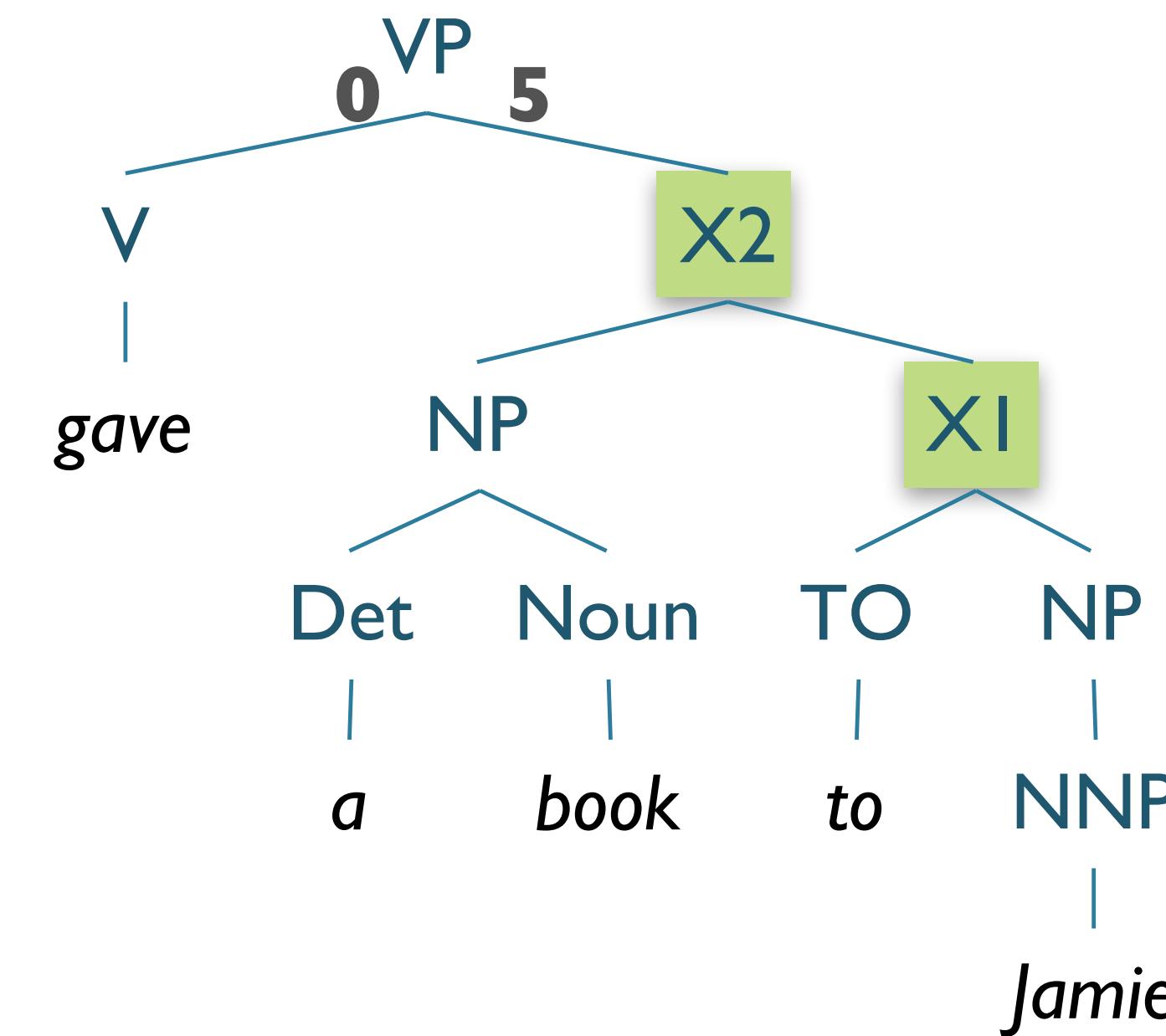
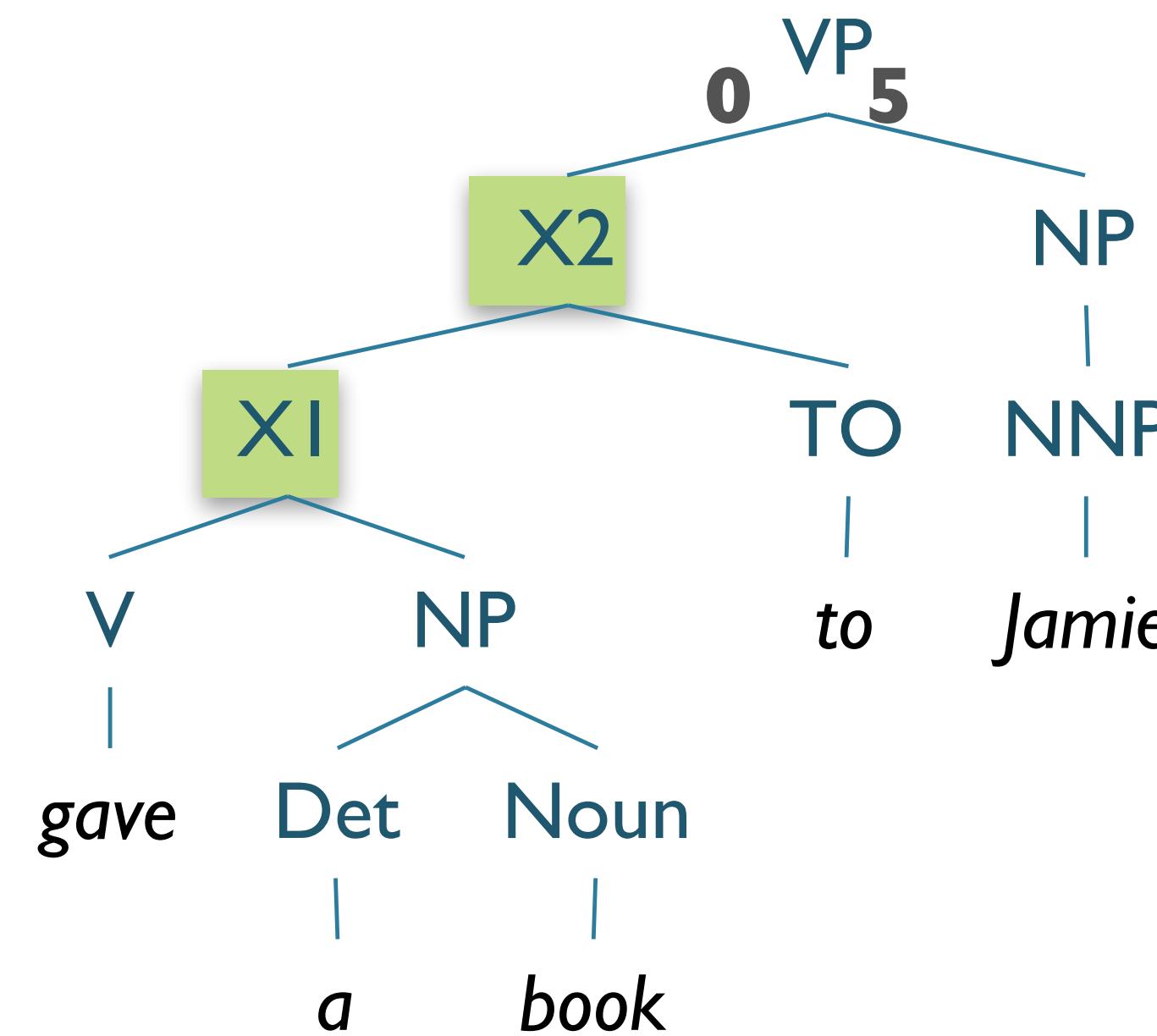
Original Rule

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



# Variation in CNF: Binarization

Original Rule	
$VP \rightarrow V \text{ } NP \text{ } TO \text{ } NP$	
Left to Right Reduction	Right to Left Reduction
$VP \rightarrow X1 \text{ } TO \text{ } NP$	$VP \rightarrow V \text{ } NP \text{ } X1$
$VP \rightarrow X2 \text{ } NP$	$VP \rightarrow V \text{ } X2$
$X1 \rightarrow V \text{ } NP$	$X1 \rightarrow TO \text{ } NP$
$X2 \rightarrow X1 \text{ } TO$	$X2 \rightarrow NP \text{ } X1$



# Indigenous Peoples' Day

- Seattle/Sealth/Si'ahl



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- For those of you taking 550:
  - The Lushootseed spelling [IPA] of Chief Seattle/Sealth/Si'ahl:
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  - siʔał ['siʔa:t]
- Duwamish — Dxʷdəwʔabš [dxʷdəwʔabʃ]



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- Duwamish — Dxʷdəwʔabš [dxʷdəwʔabʃ]
- IPA resources:
  - [https://en.wikipedia.org/wiki/International\\_Phonetic\\_Alphabet](https://en.wikipedia.org/wiki/International_Phonetic_Alphabet)
  - <http://web.mit.edu/6.mitx/www/24.900%20IPA/IPAapp.html>



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- Studying non-English languages gives more holistic insight for NLP tasks
  - Many interesting phenomena in non-Indo-European languages

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- Lushootseed exhibits debatable distinction between verbs and nouns [link to Glottolog page for more references]
  - ?uχw ti sbiaw  
**goes** that-which **is-a-coyote**  
“The/a coyote goes”
  - sbiaw ti ?uχw  
**is-a-coyote** that-which **goes**  
“The one who goes is a coyote”
  - (Translation distinction provided for clarity – semantically equivalent)

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“The one who goes is a coyote”  
*via Beck, 2013*
  - (Translation distinction provided for clarity – semantically equivalent)
- Lillooet Salish quantification has repercussions for e.g. English (Matthewson 2001)

# Indigenous Peoples' Day

- UW American Indian Studies Courses
  - (Sometimes including language courses, e.g. Southern Lushootseed)
  - Lushootseed resources: <https://tulalipluslushootseed.com/>

# Roadmap

- CKY Parsing Algorithm

- Dynamic programming structure

- Algorithm and example

- Analysis & Discussion

- Probabilistic CFGs

- Motivation: Ambiguity

- Augmenting CFGs with probabilities

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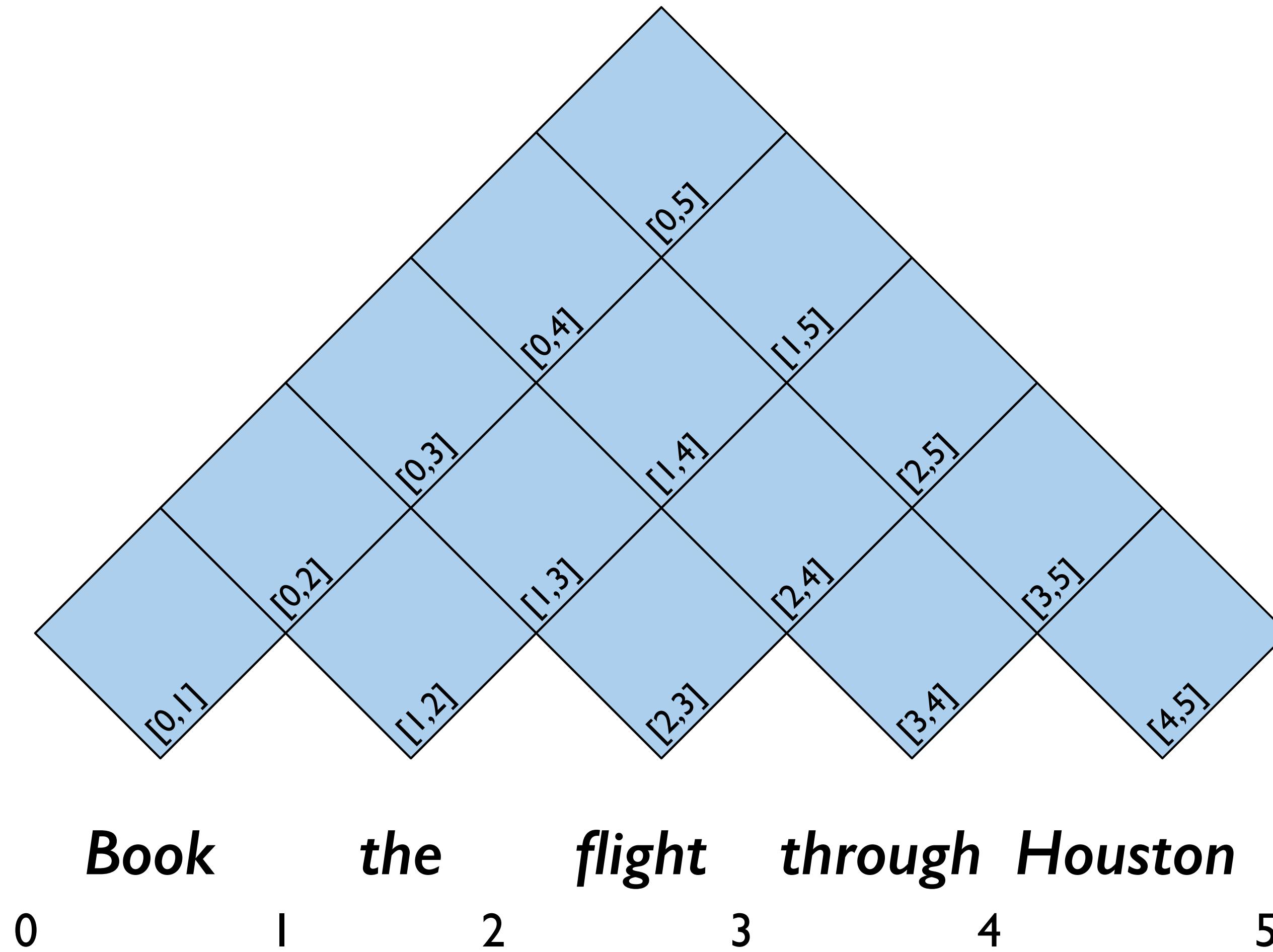
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- Each cell  $[i, j]$  contains SETS {} of non-terminals with derivations spanning  $i, j$ 
  - $[j - 1, j]$  contains pre-terminals
  - if  $[0, n]$  contains the start symbol, the sentence is **accepted**

# CKY Matrix

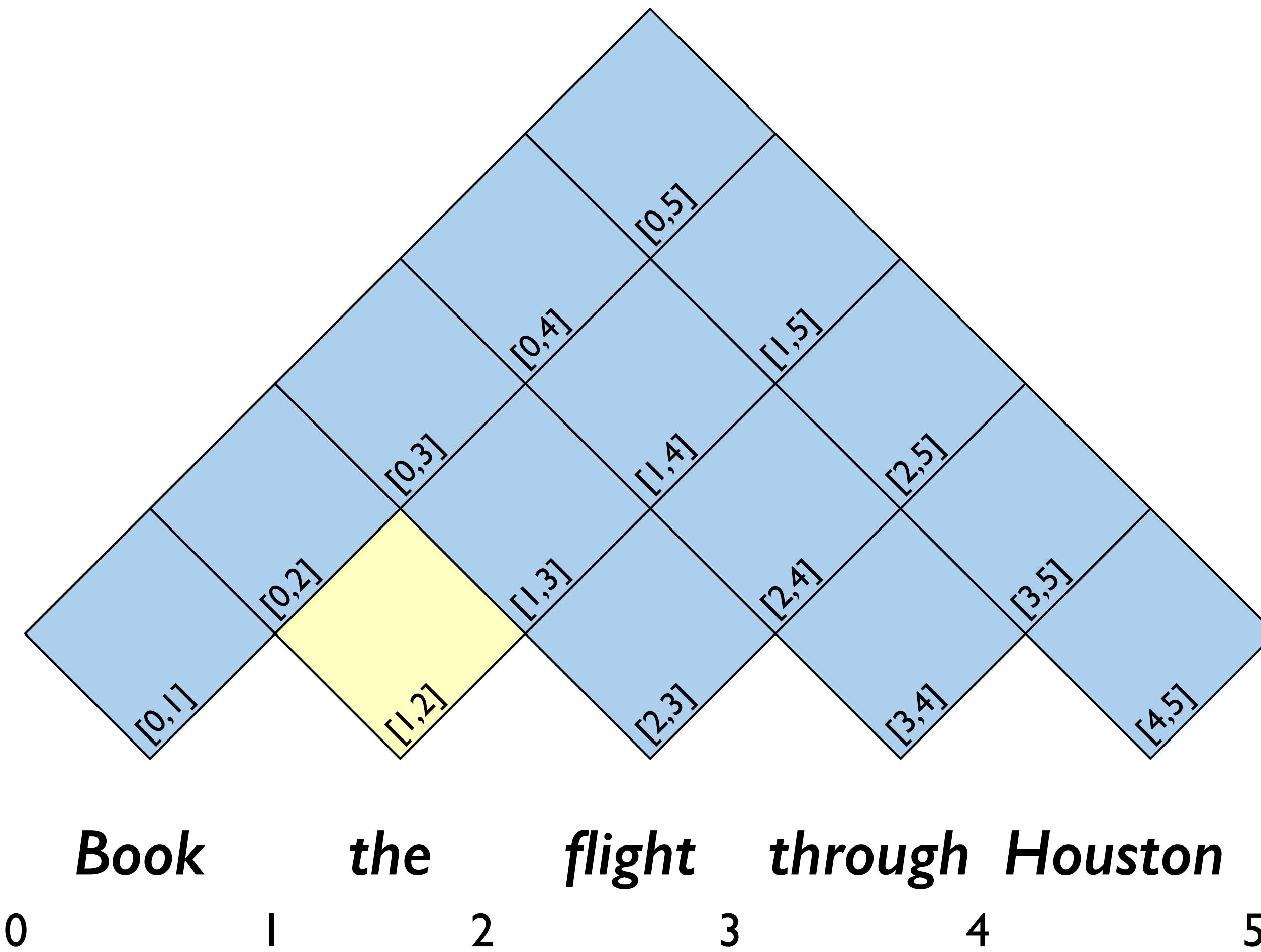
*Book      the      flight    through    Houston*

[0,1]	[0,2]	[0,3]	[0,4]	[0,5]
	[1,2]	[1,3]	[1,4]	[1,5]
		[2,3]	[2,4]	[2,5]
			[3,4]	[3,5]
				[4,5]

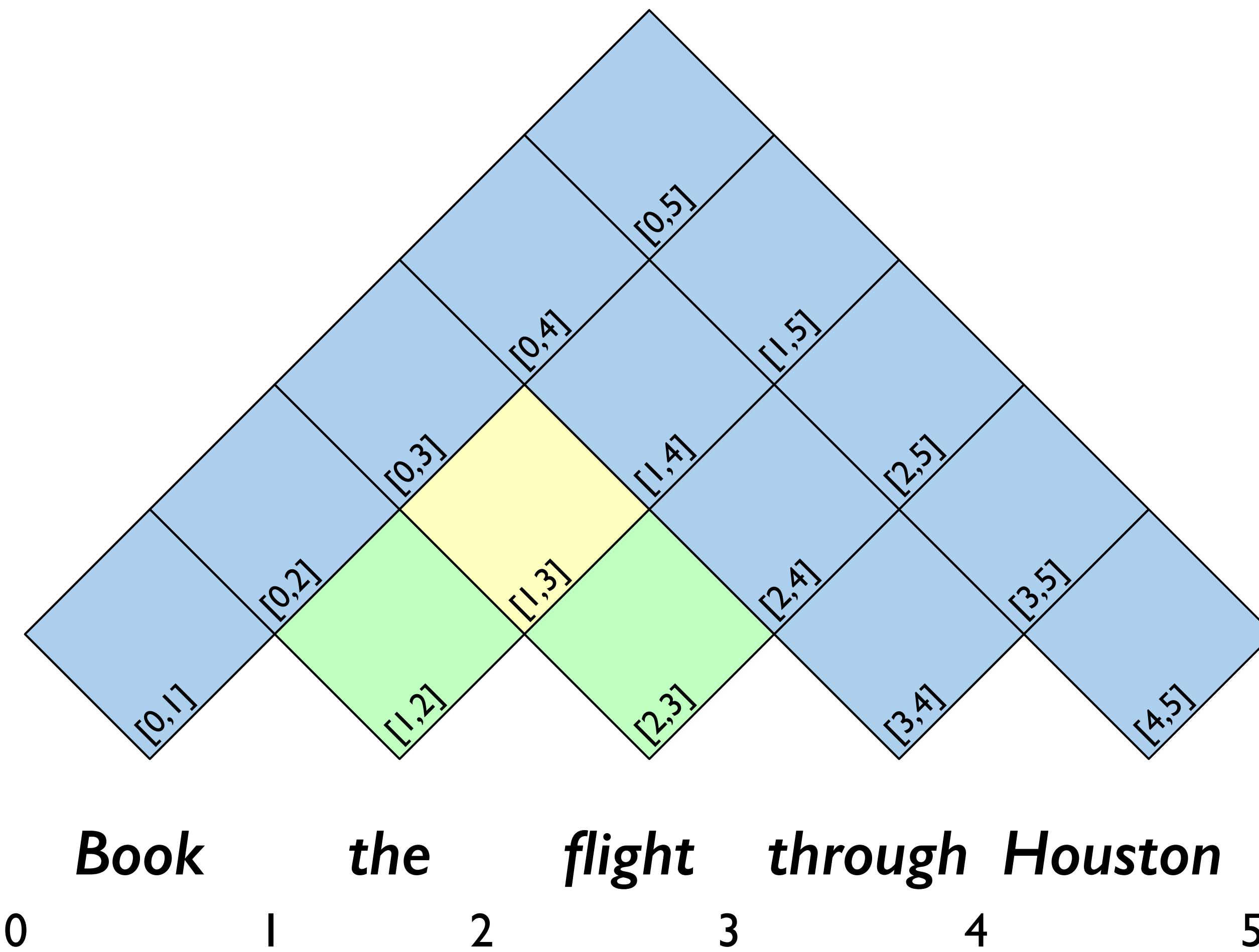
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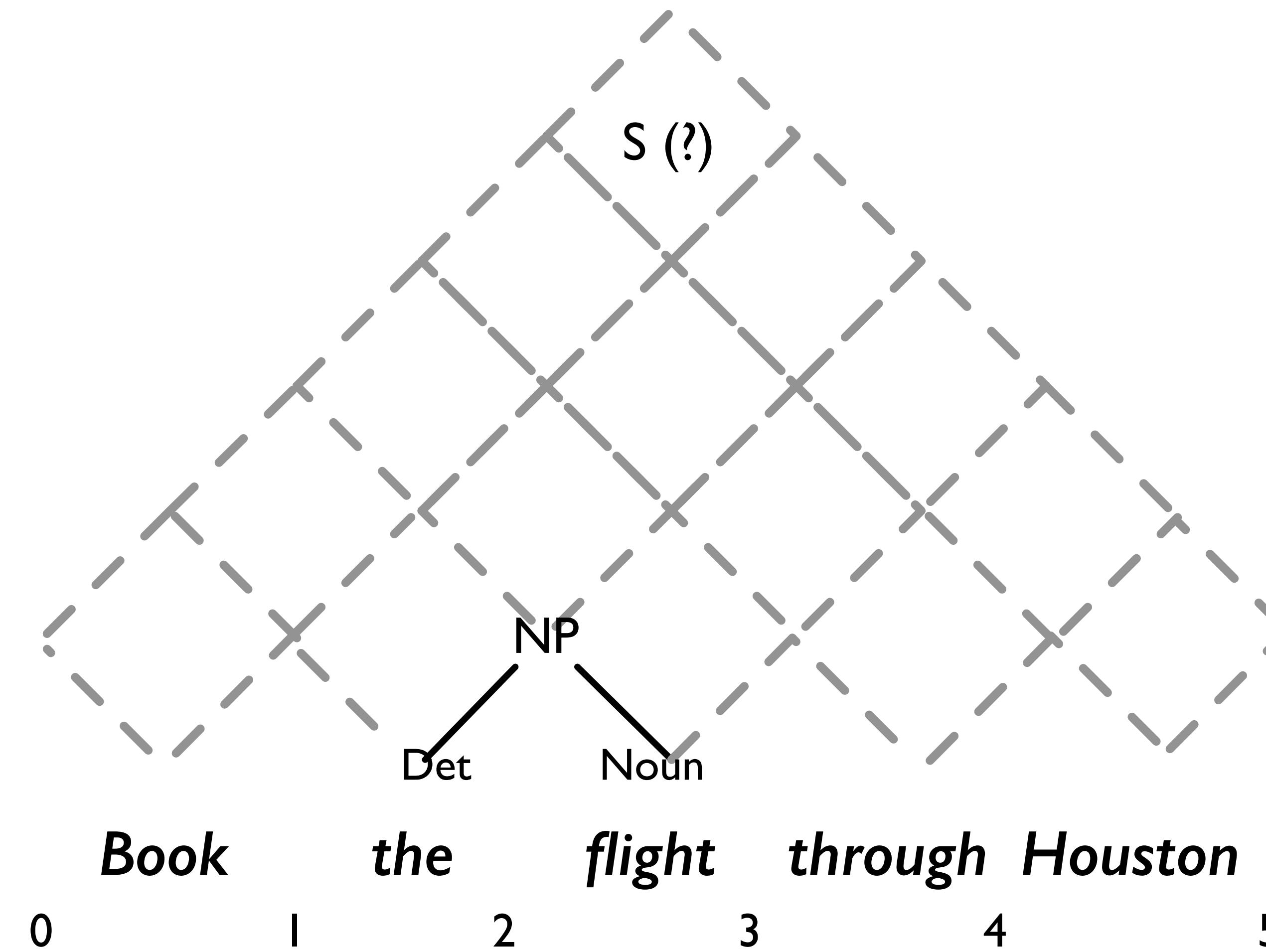
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# Dynamic Programming in CKY

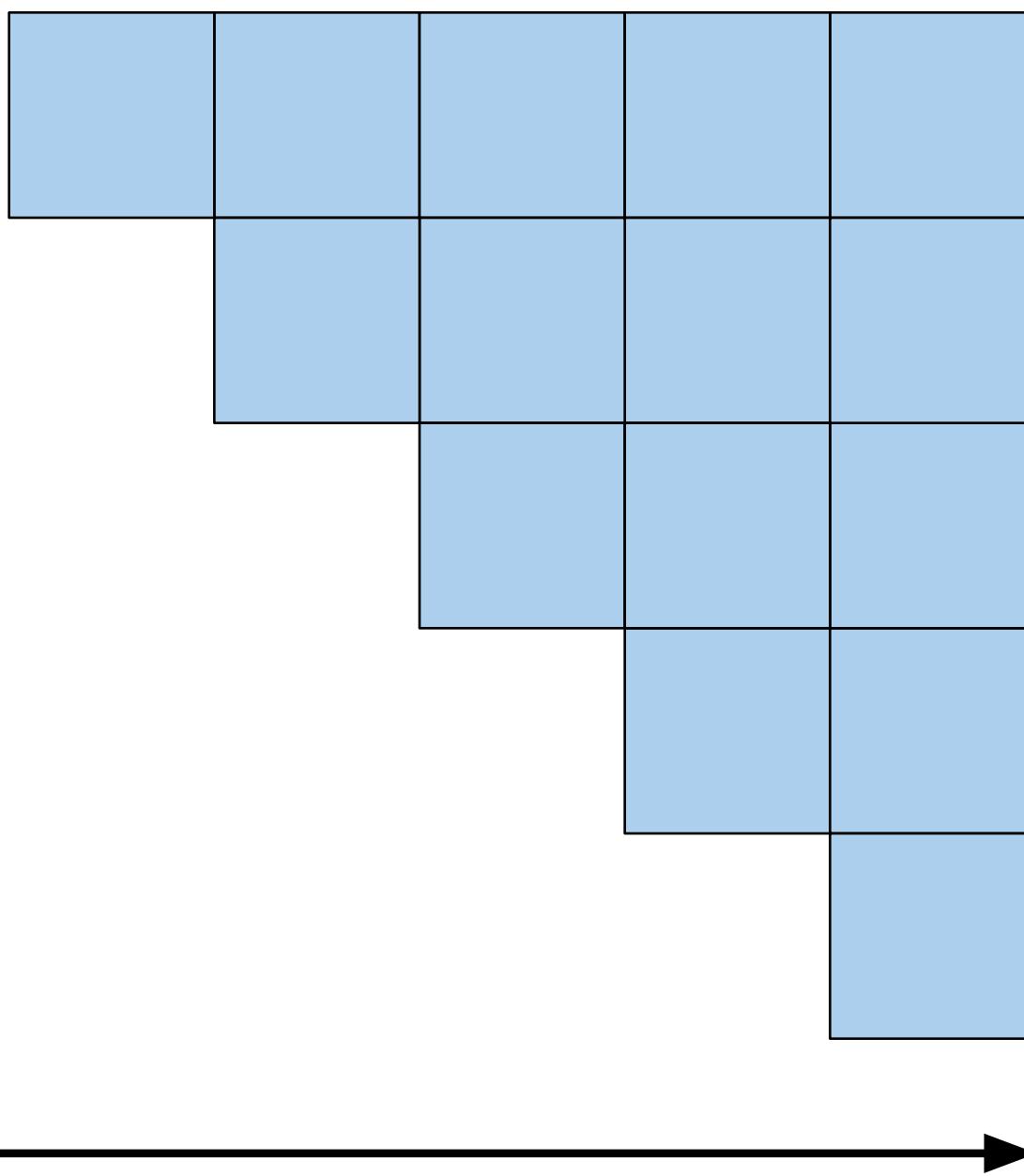
- Key idea:
  - for  $i < k < j$
  - ...and a parse spanning substring  $[ i, j ]$
  - There is a  $k$  such that there are parses spanning  $[ i, k ]$  and  $[ k, j ]$
  - We can construct parses for whole sentences by building from these partial parses
- So to have a rule  $A \rightarrow B C$  in  $[ i, j ]$ 
  - 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:

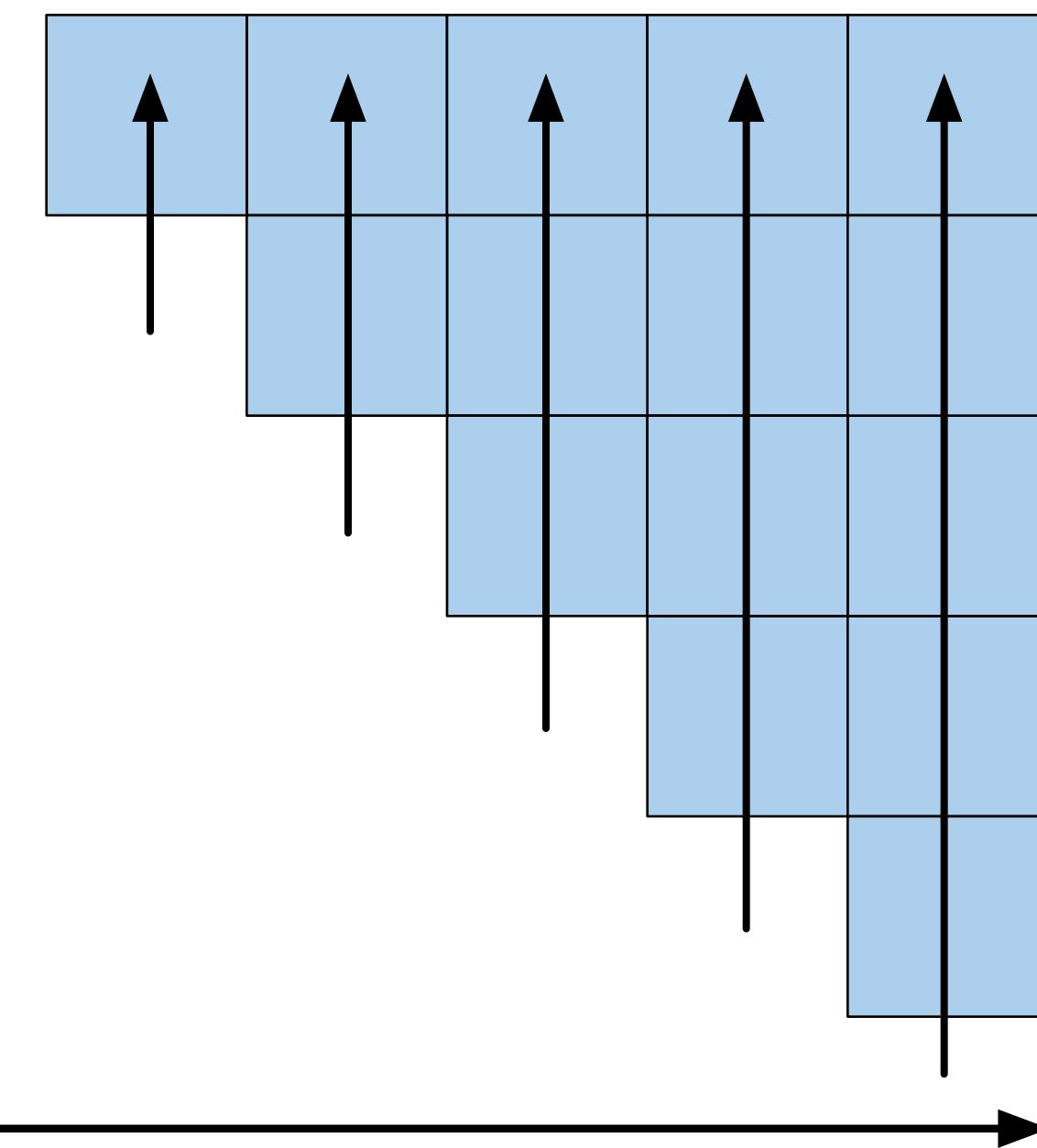
# CKY

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



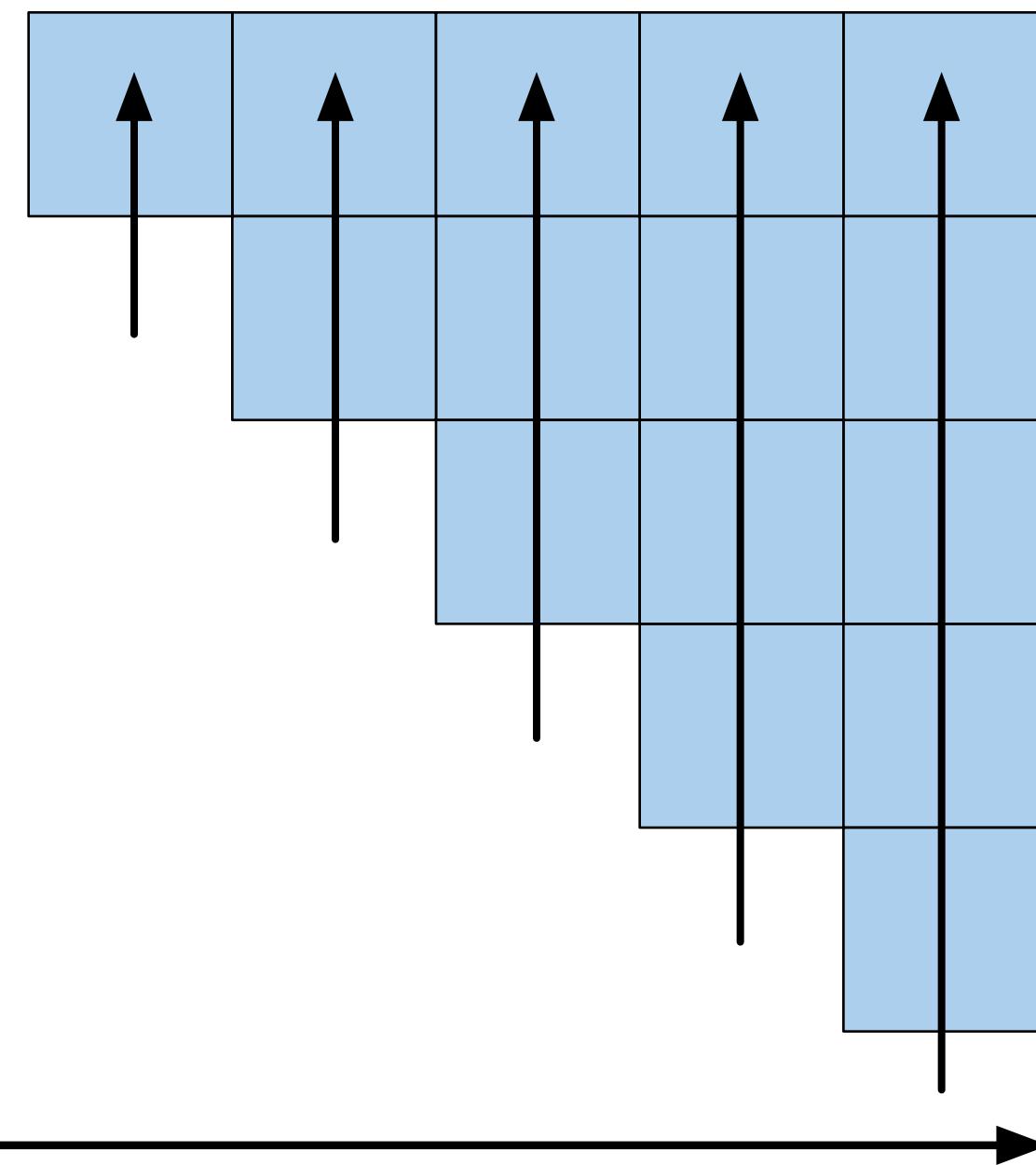
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- Table fills:
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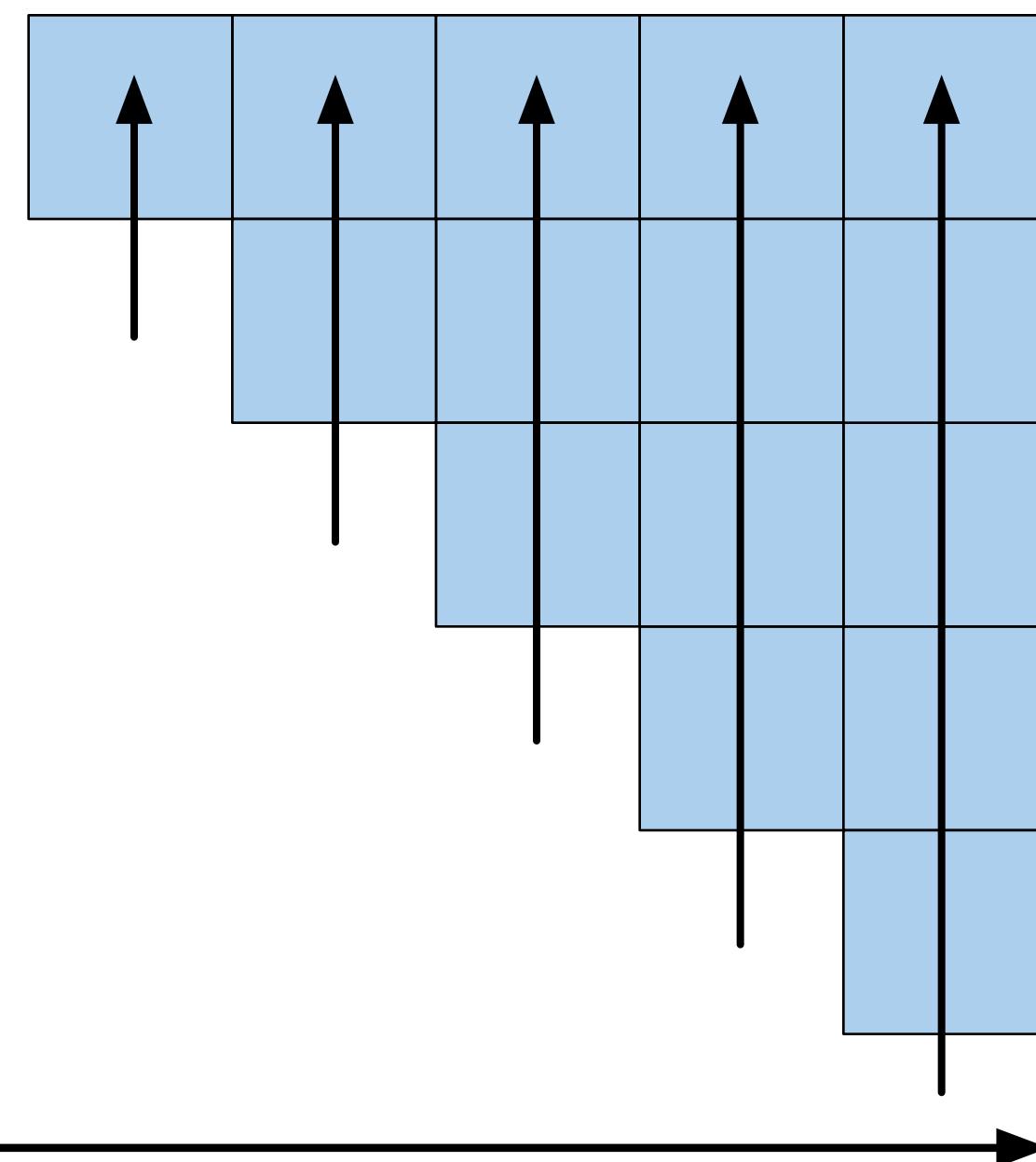
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- Why?



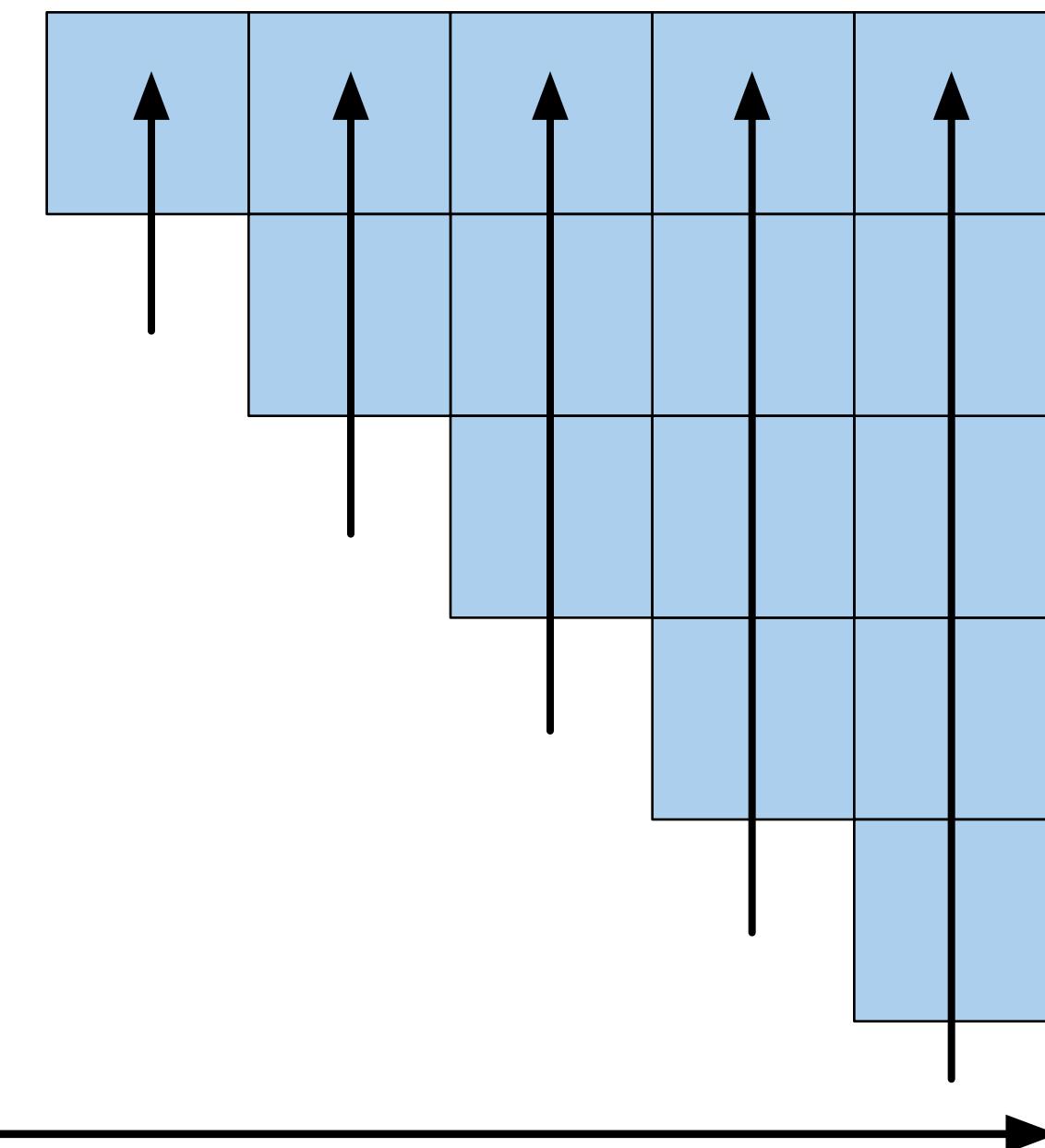
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  - To fill each cell, must have access to all sub-spans

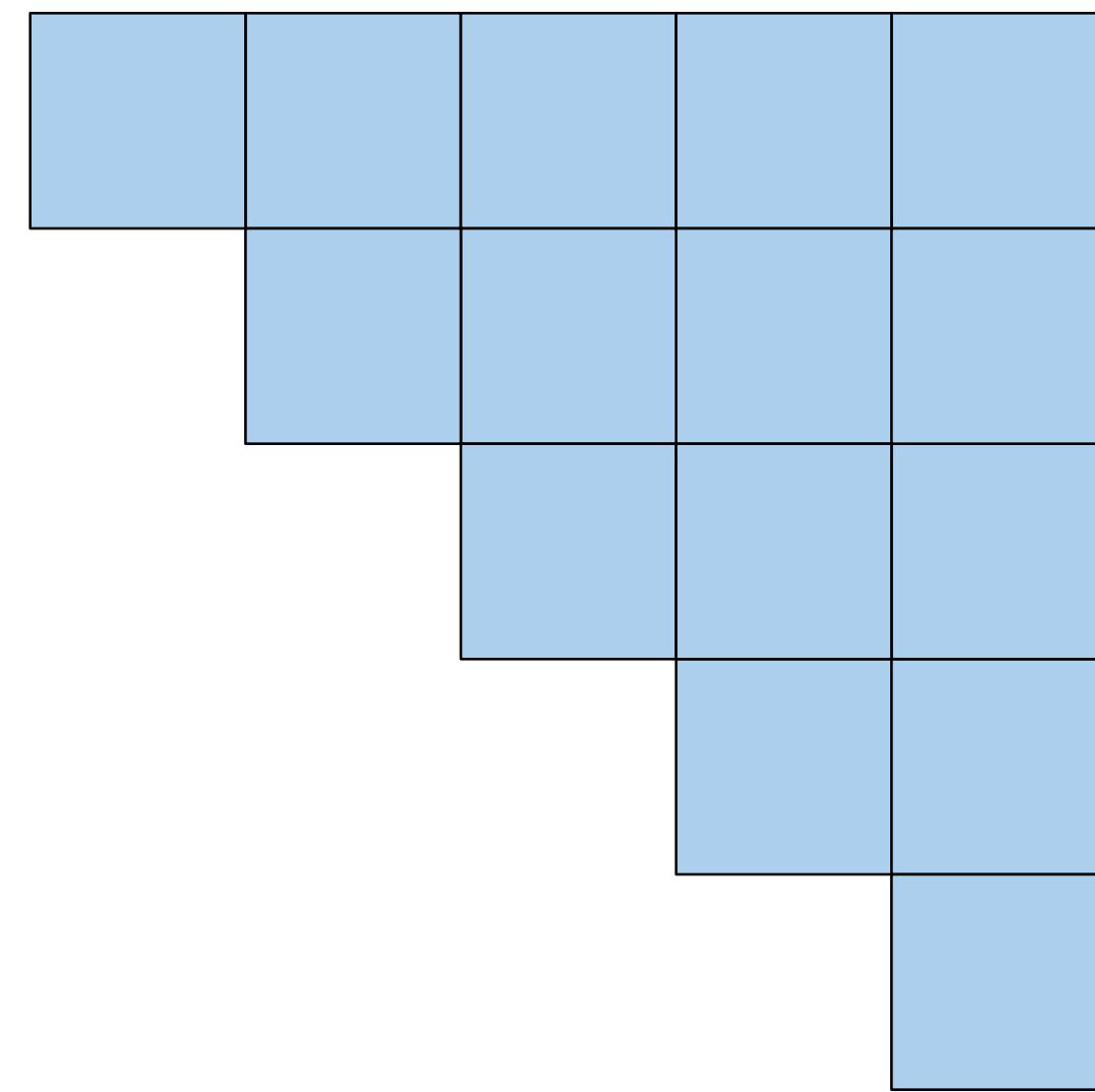


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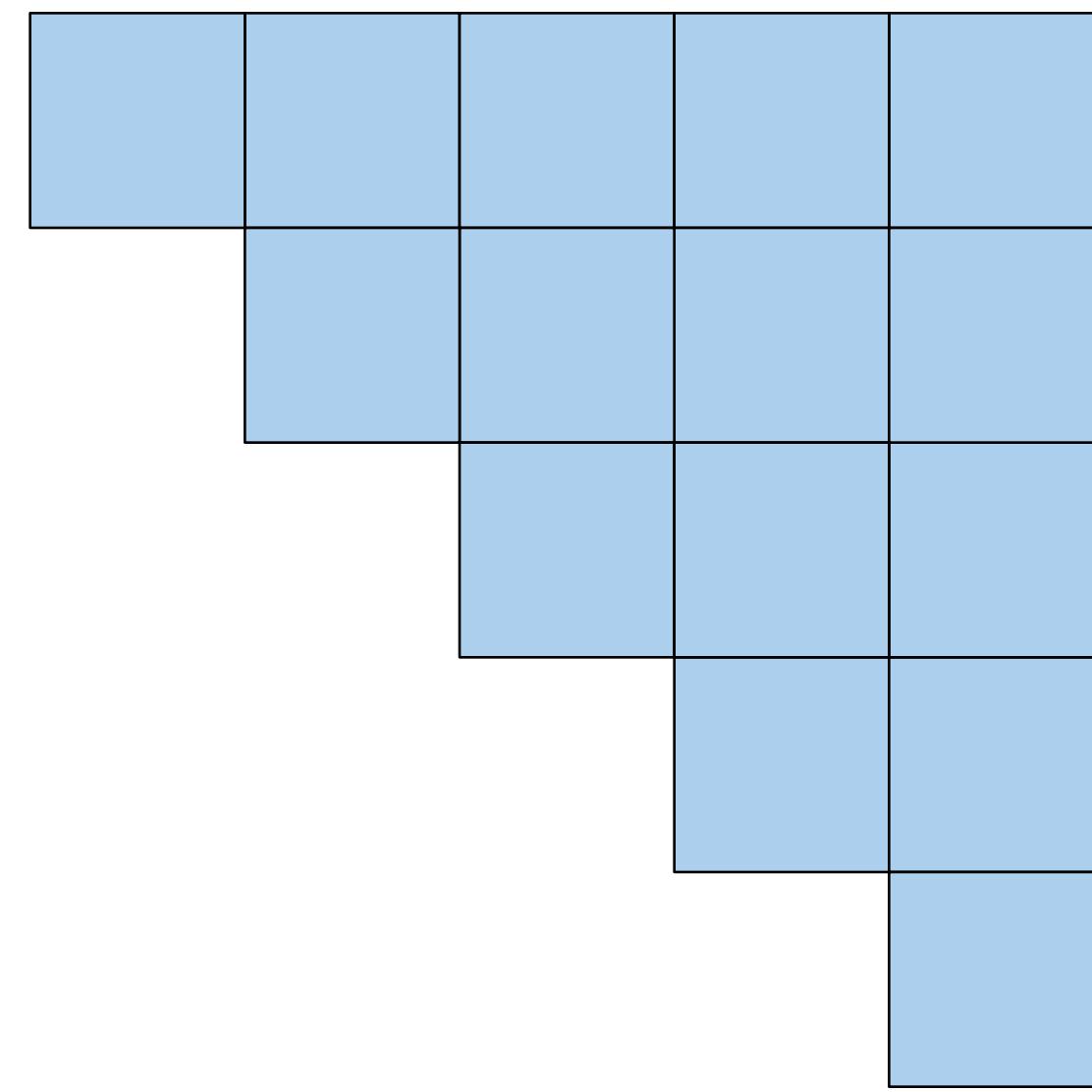


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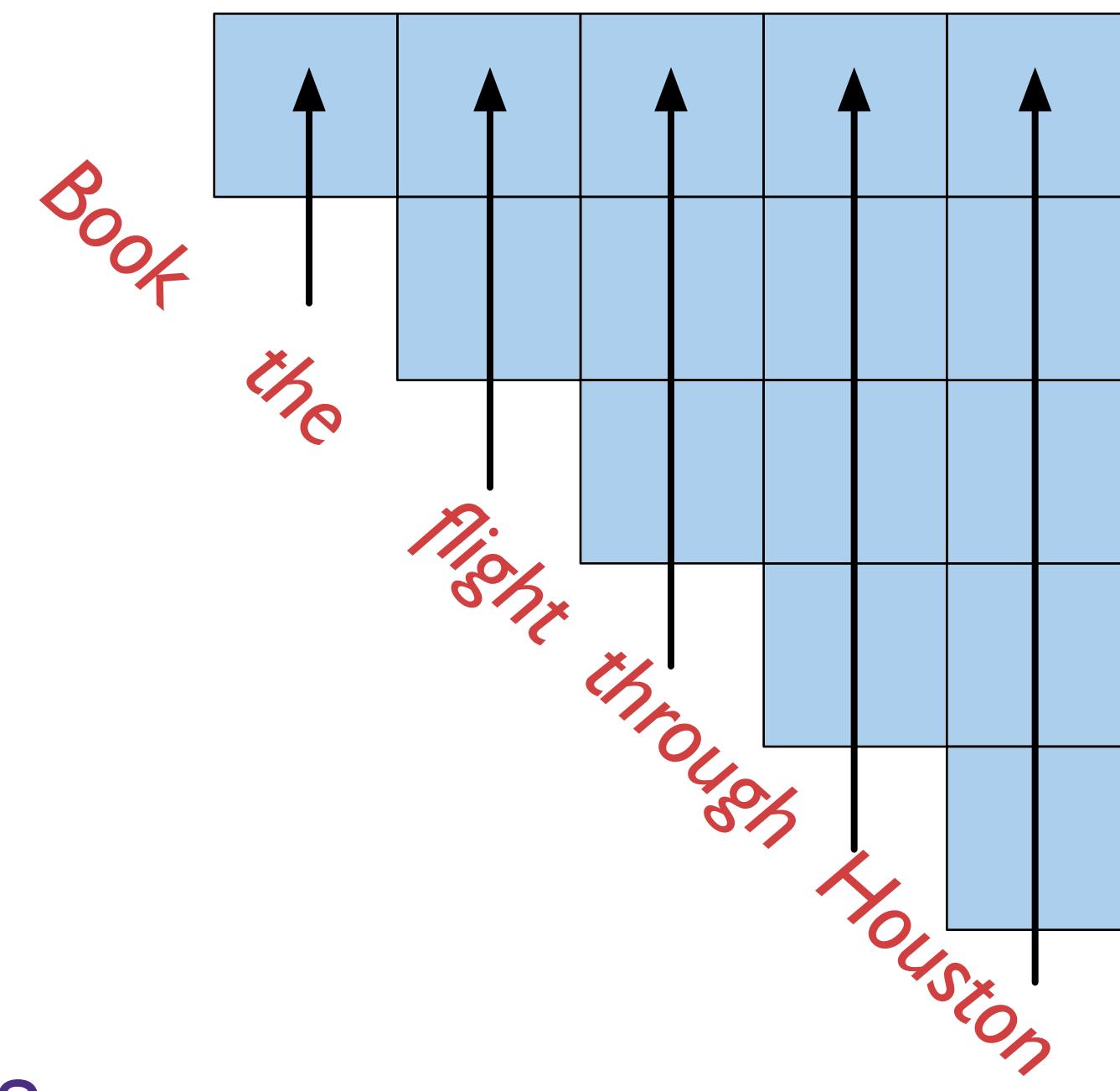
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# CKY Algorithm

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

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

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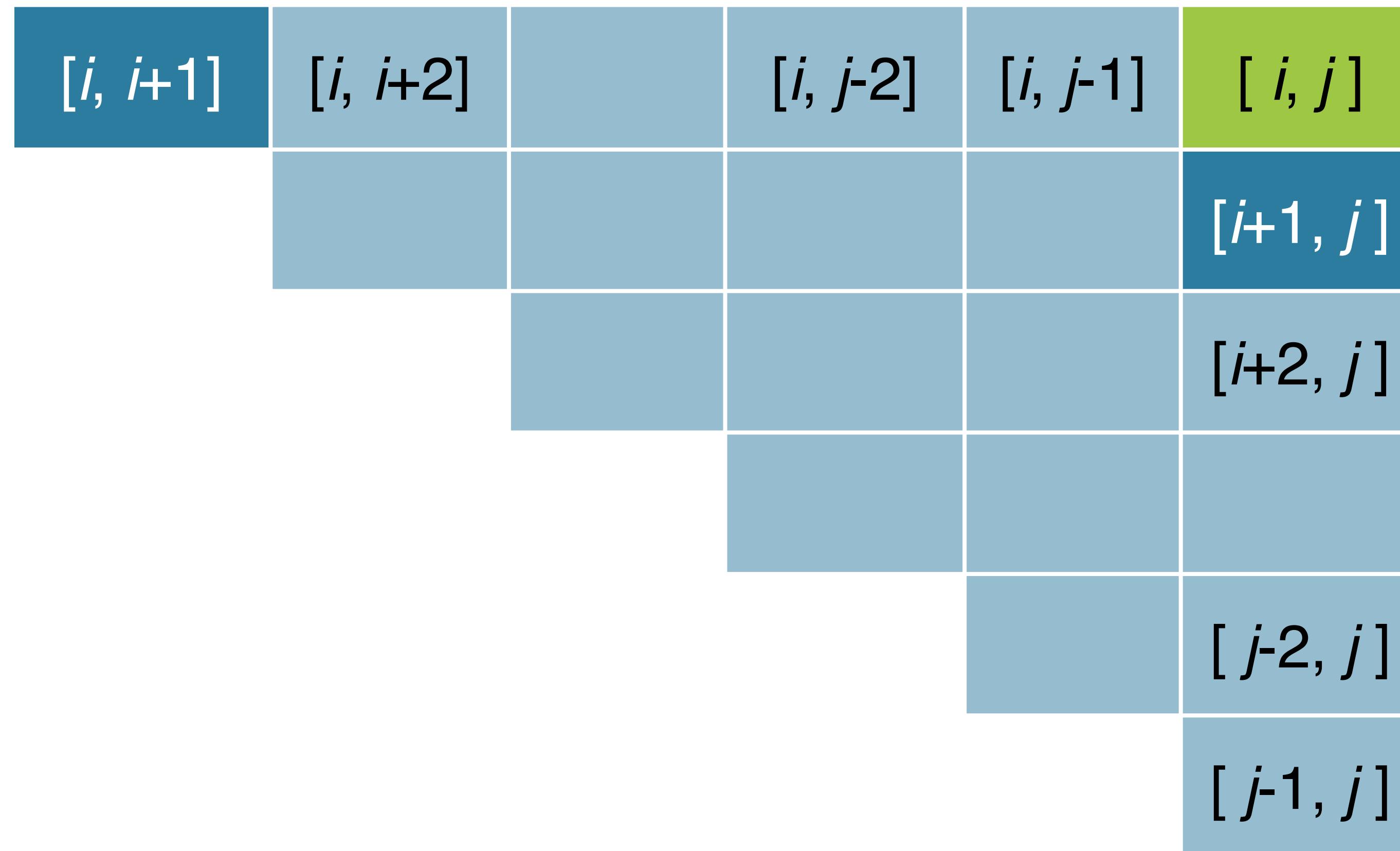
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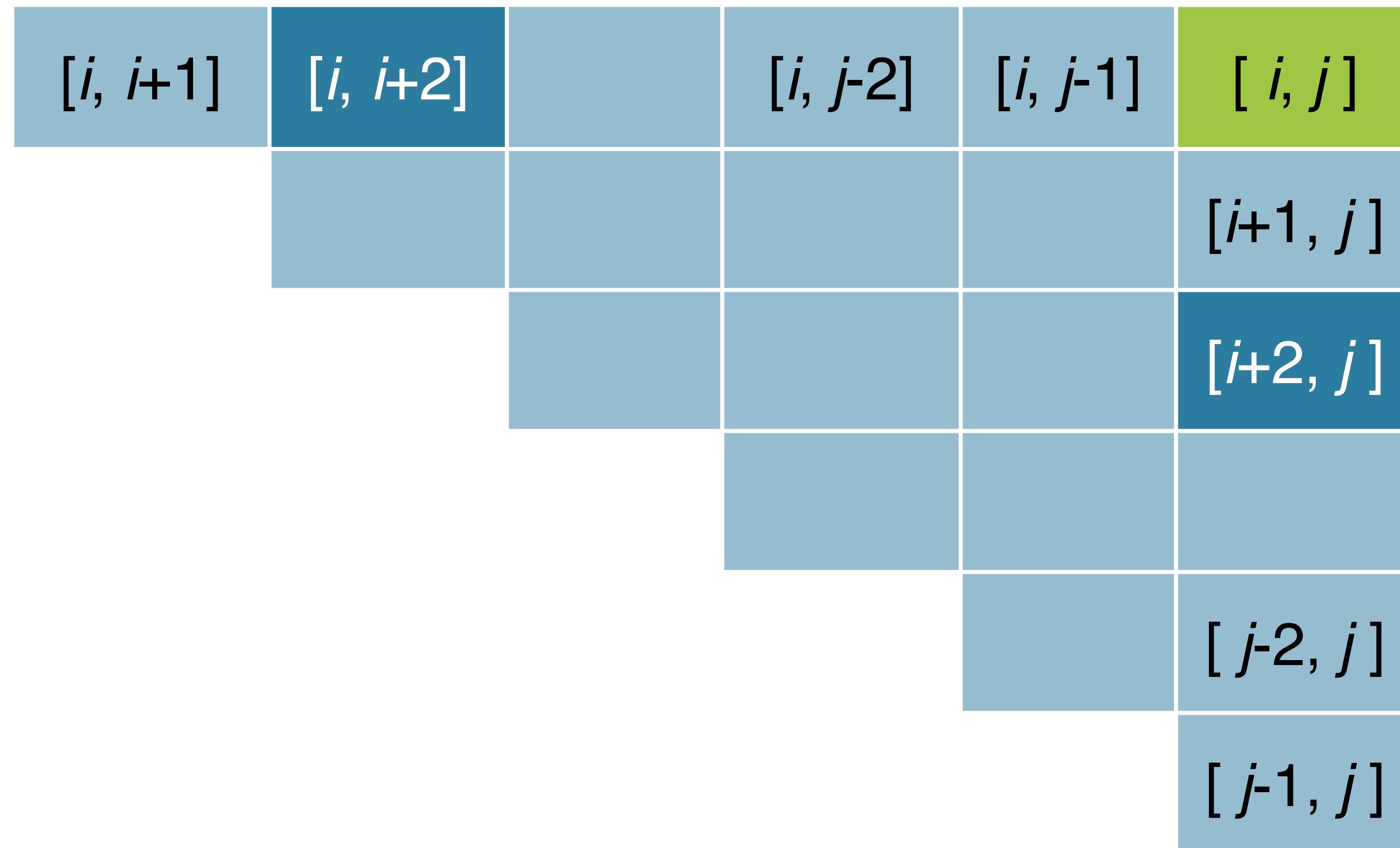
Filling the cell with set of applicable rules

# Filling Cell $[i, j]$



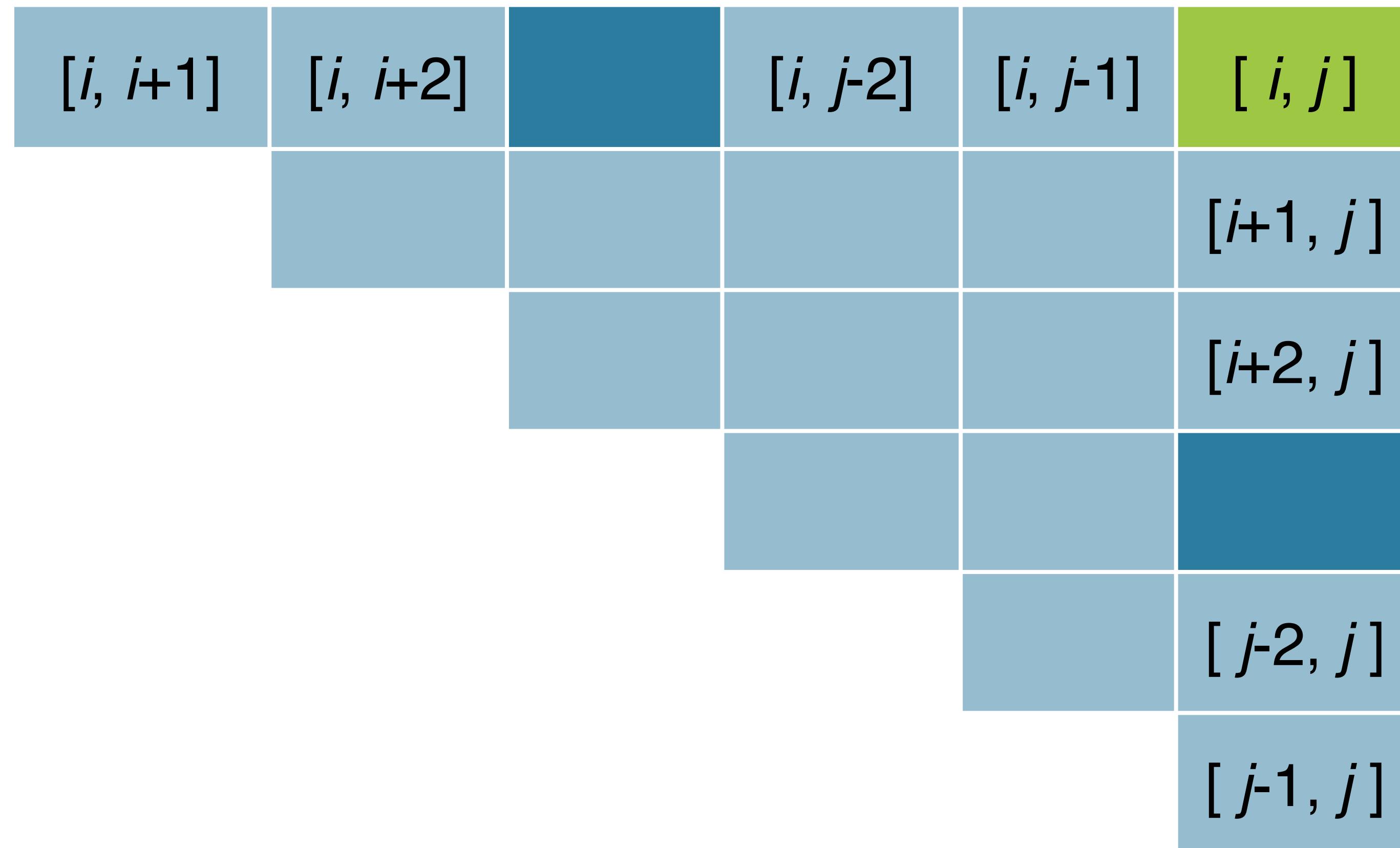
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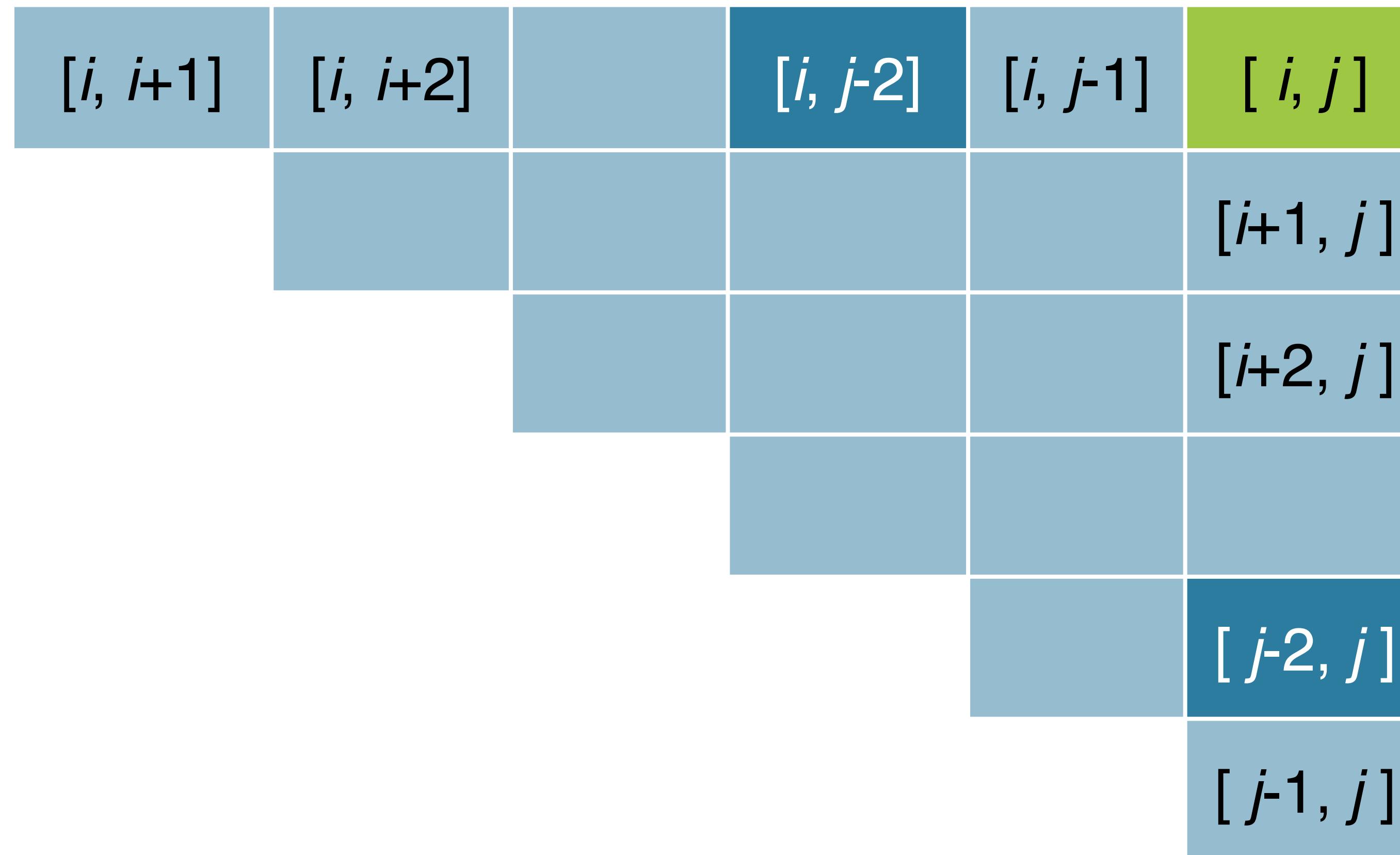
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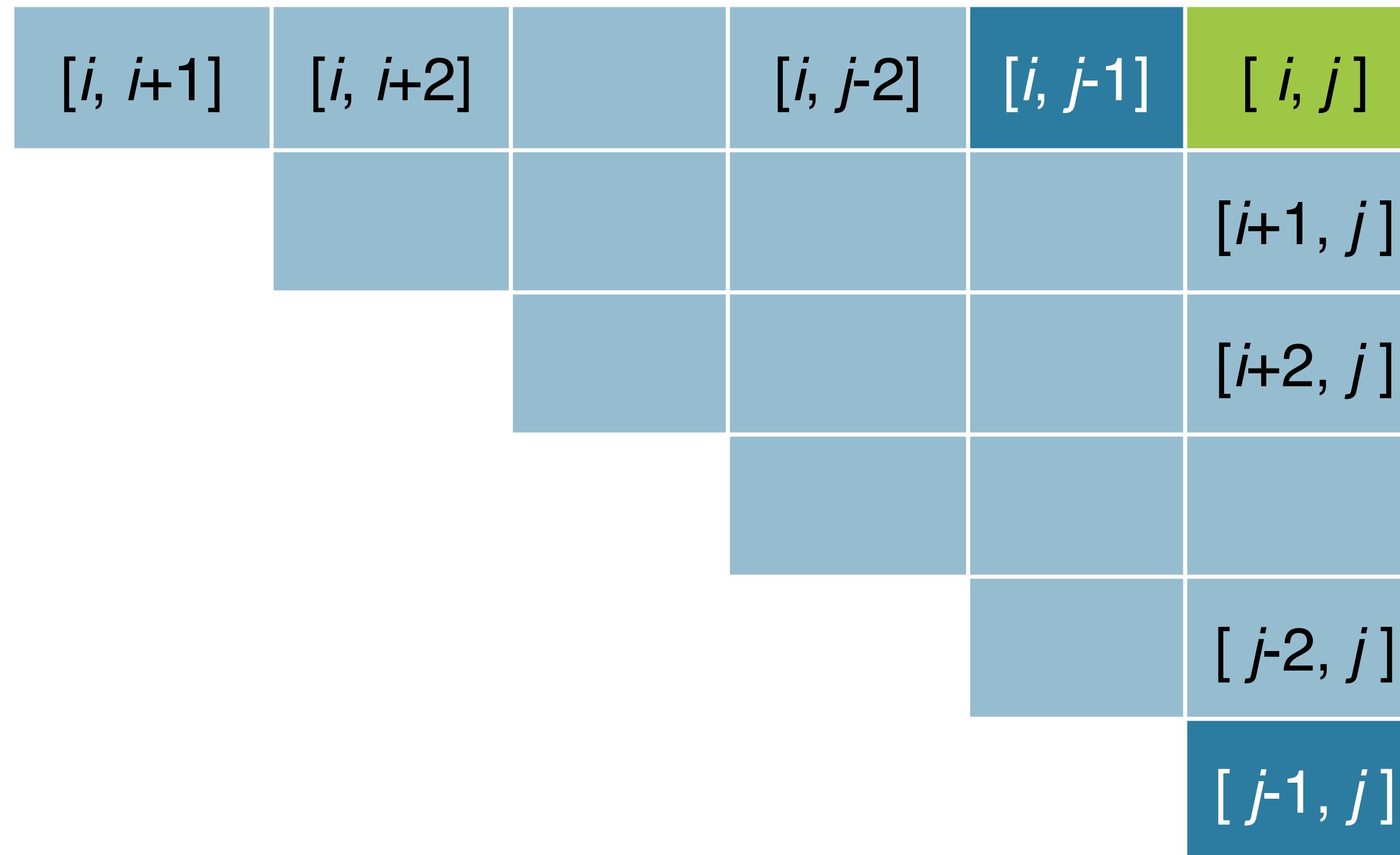
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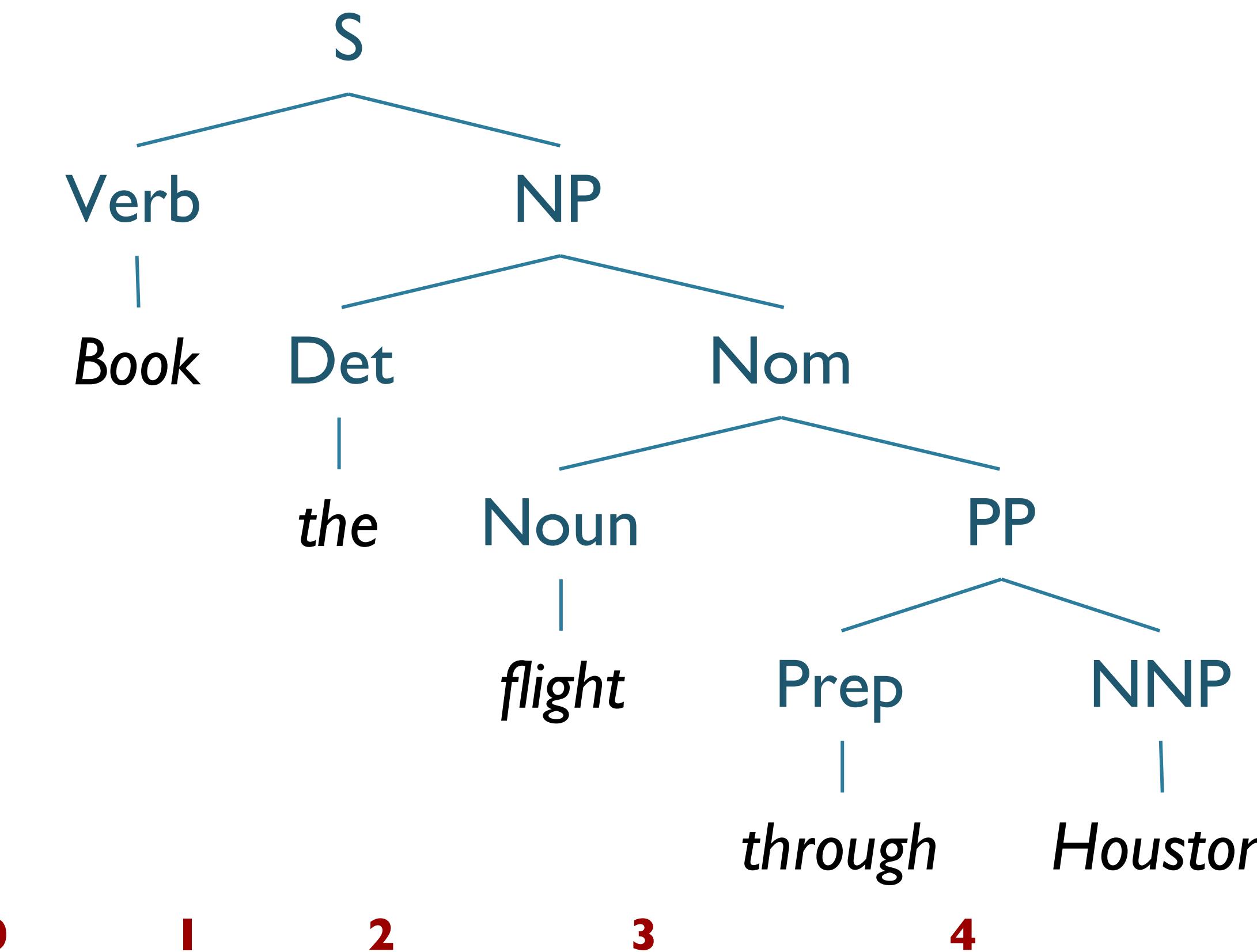
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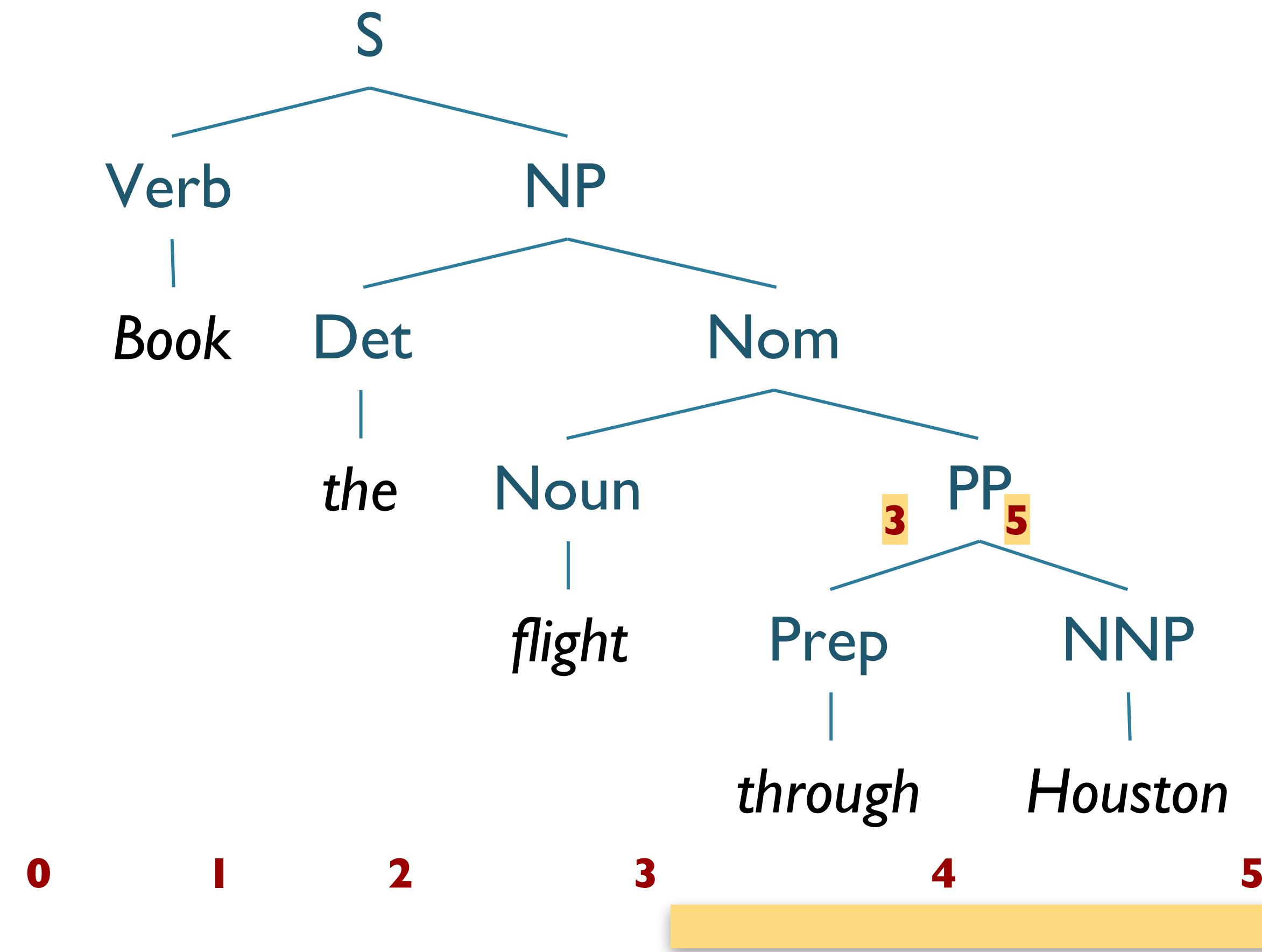
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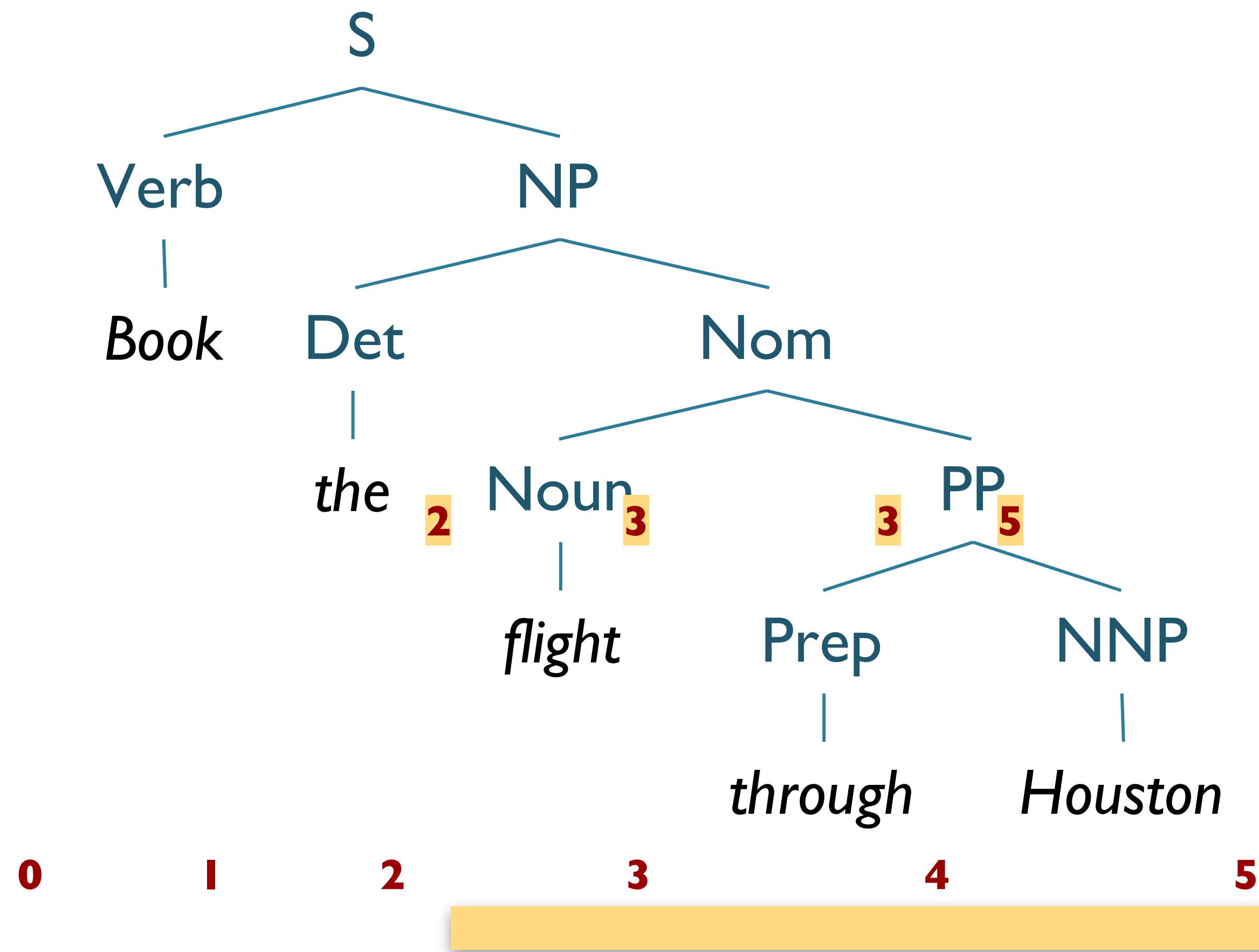
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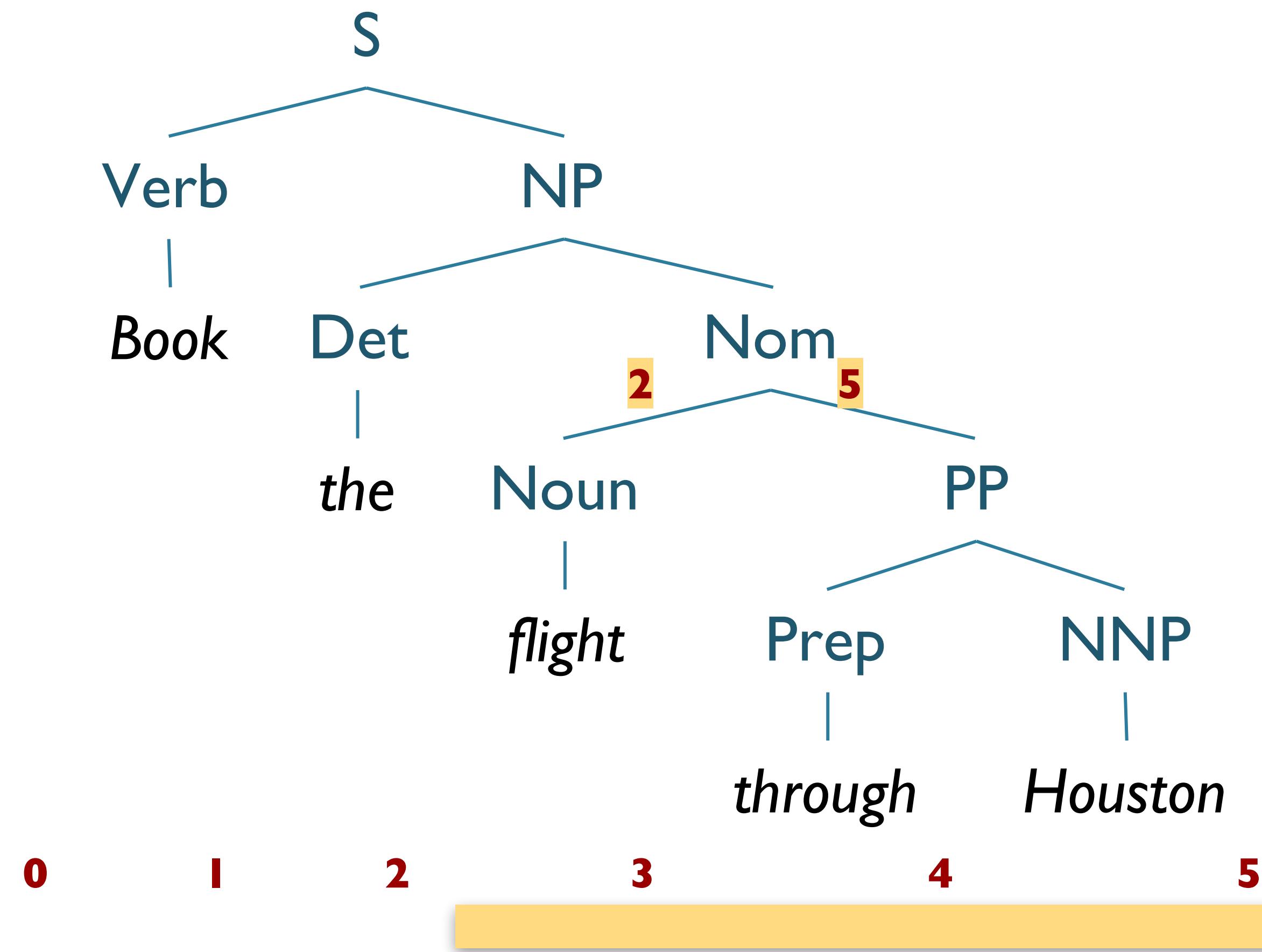
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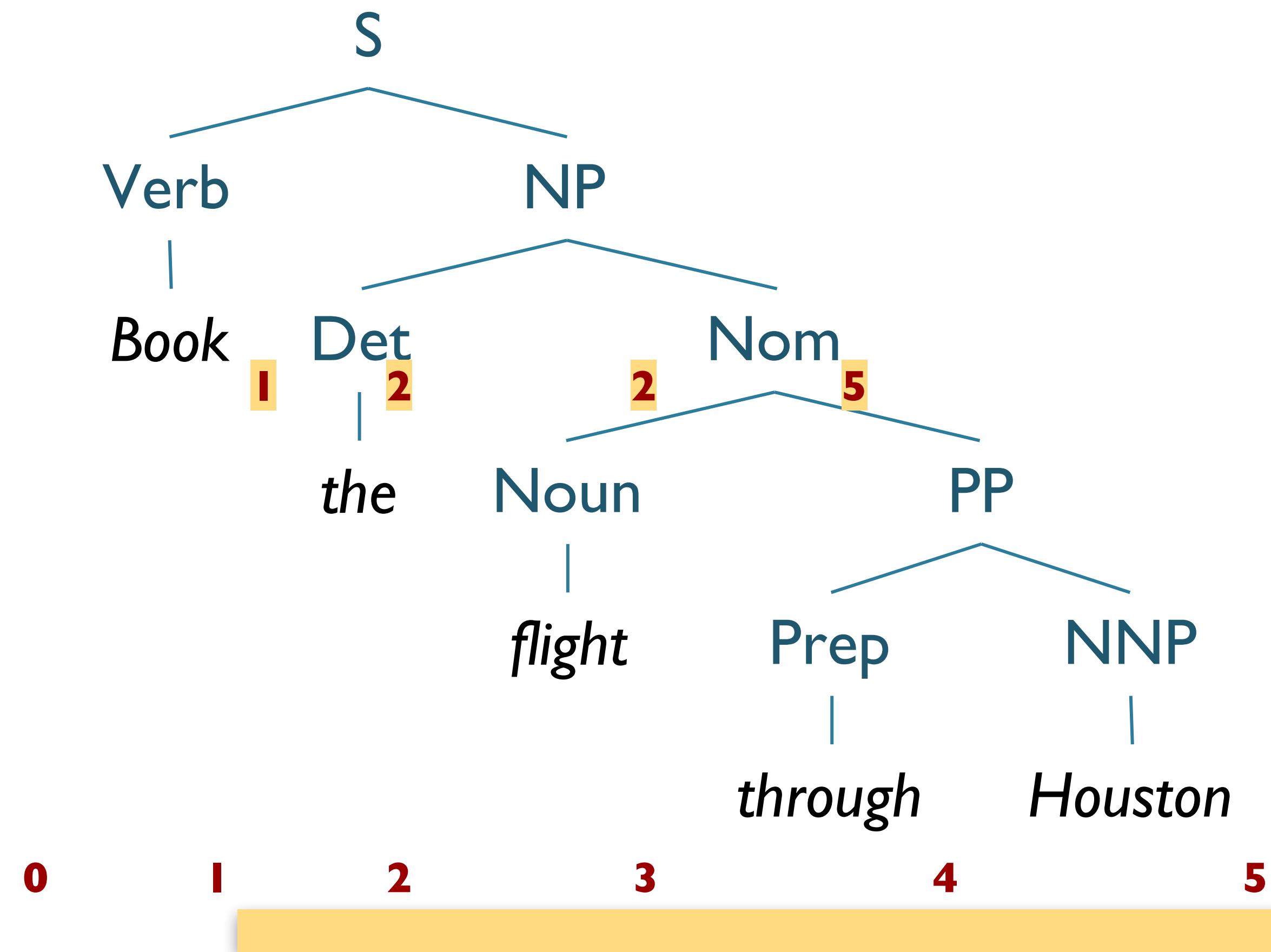
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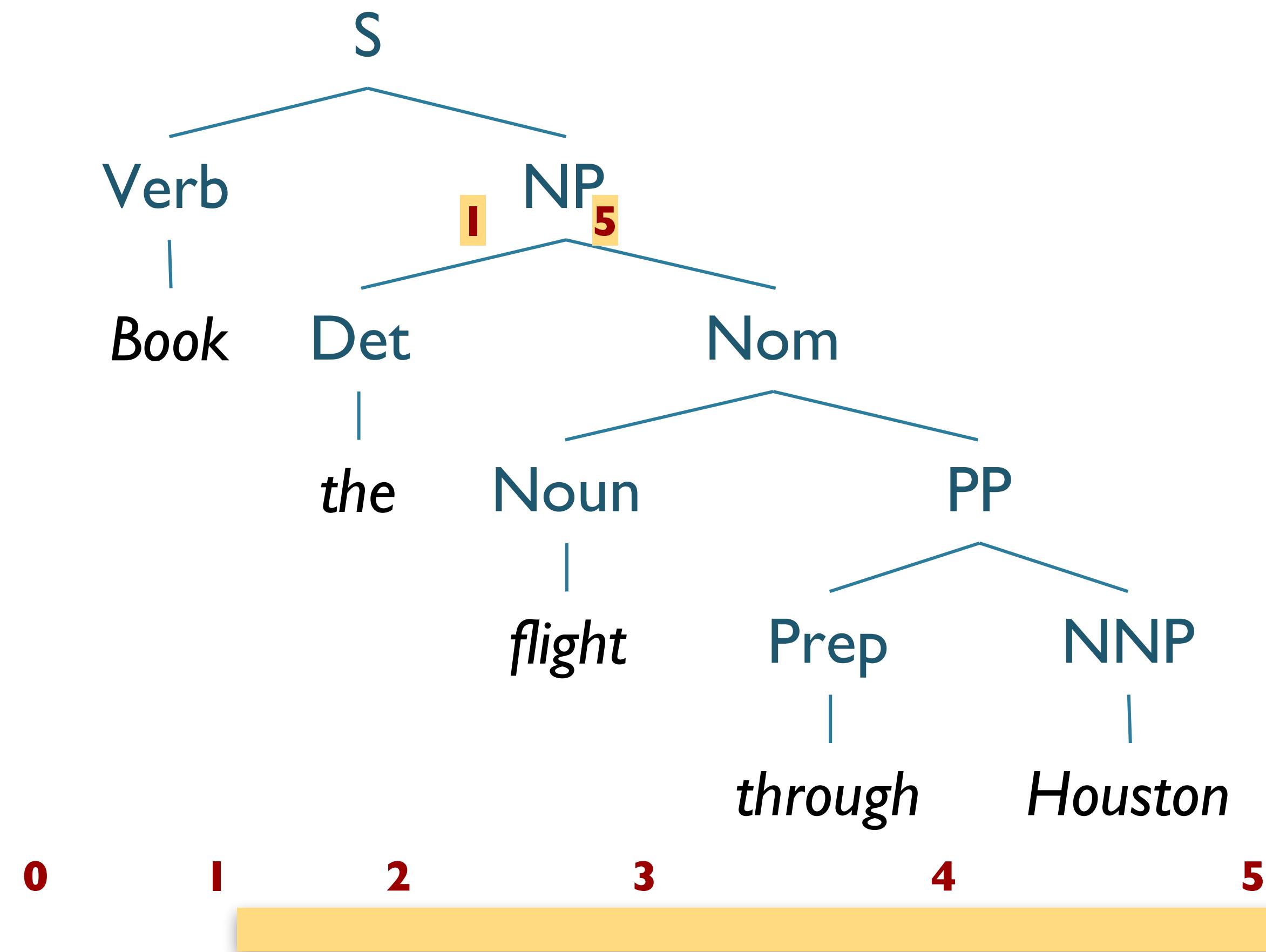
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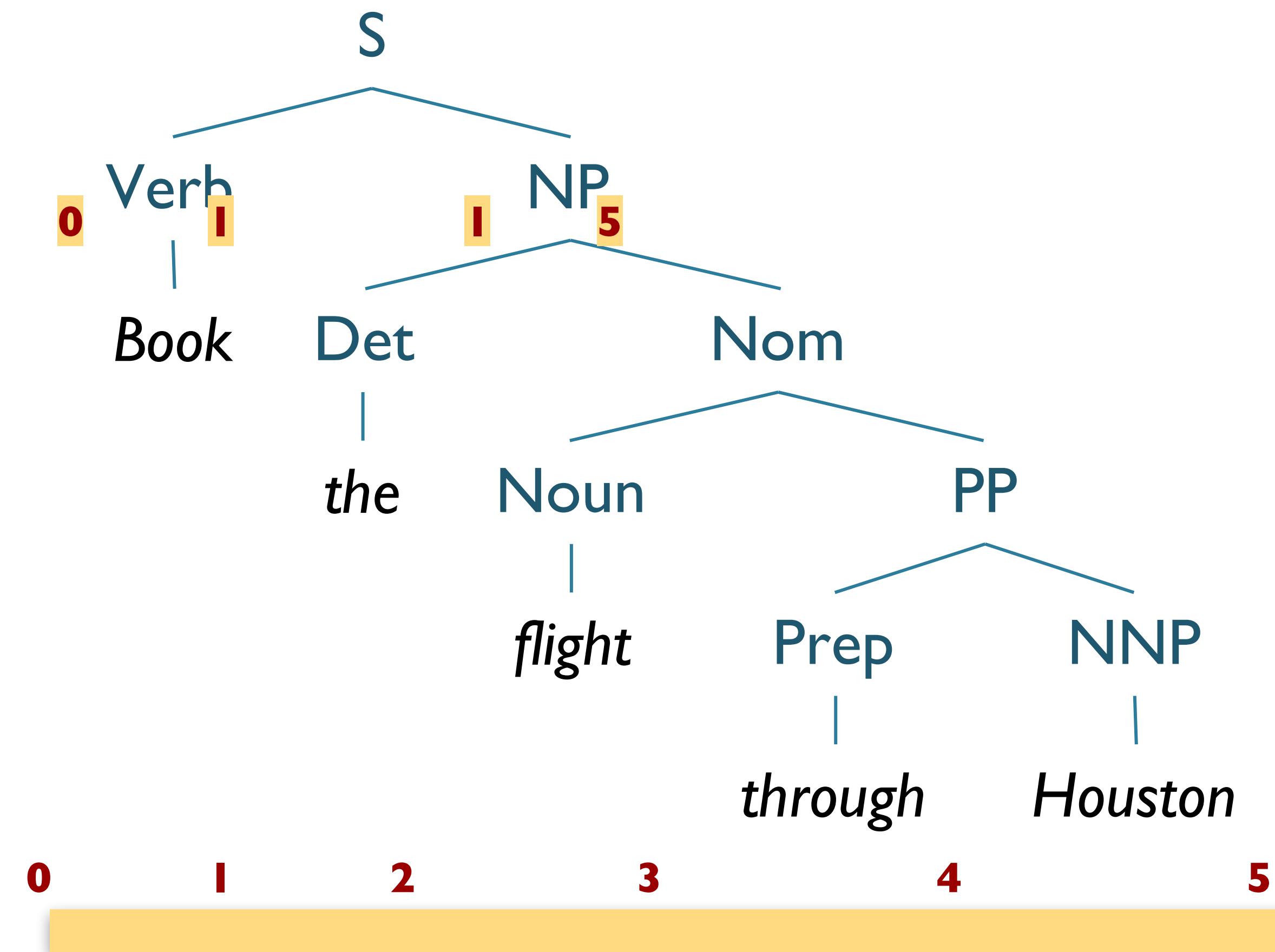
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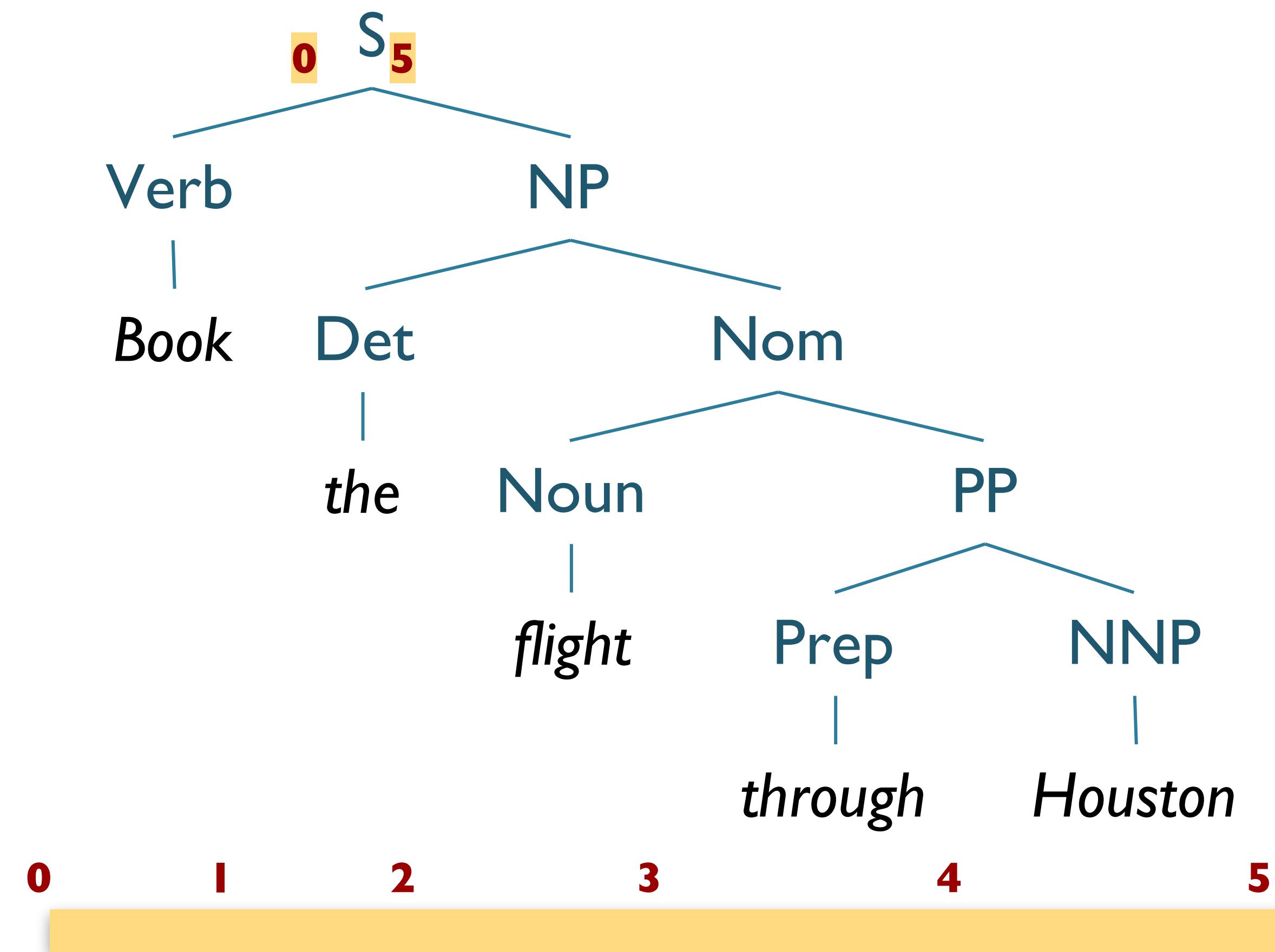
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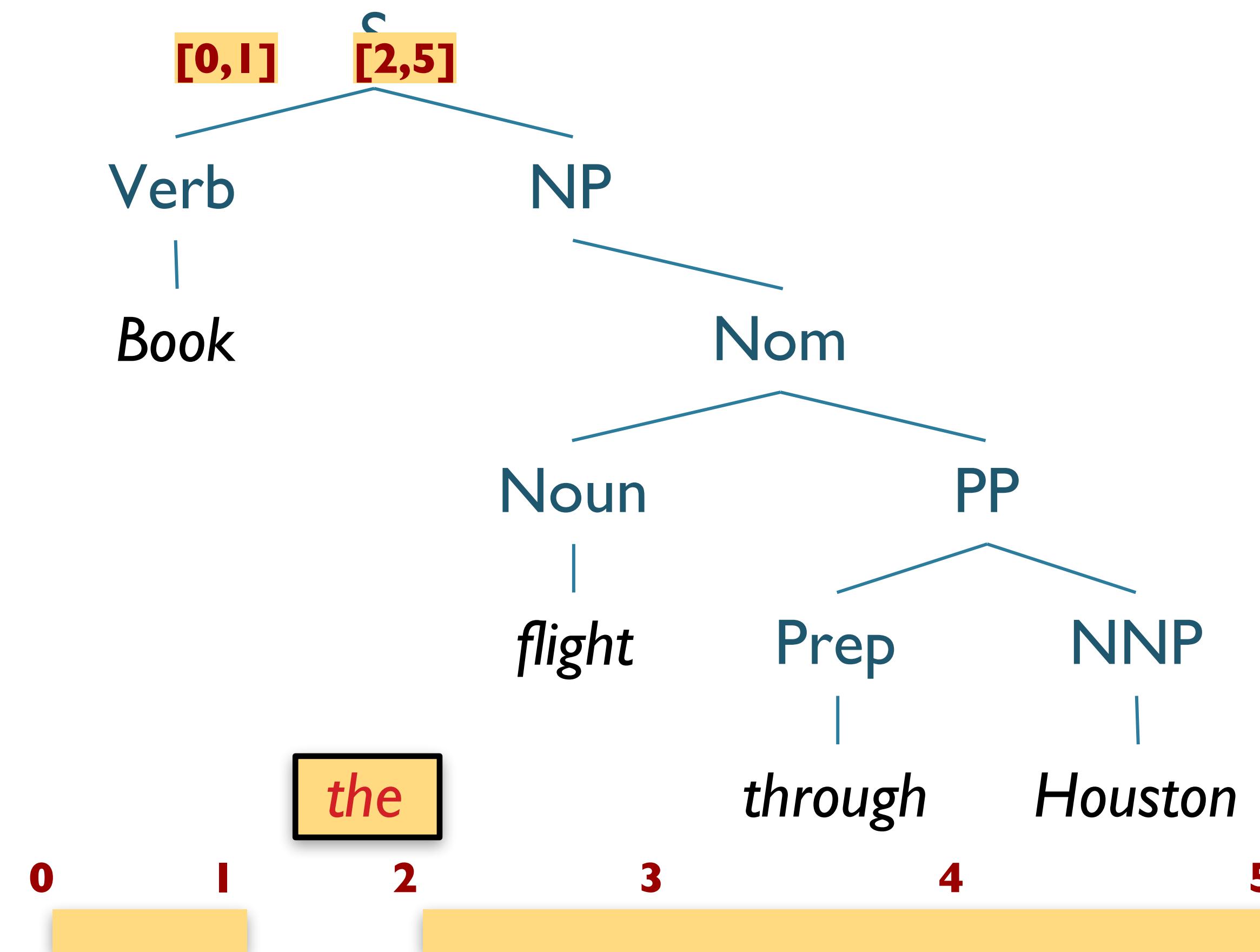
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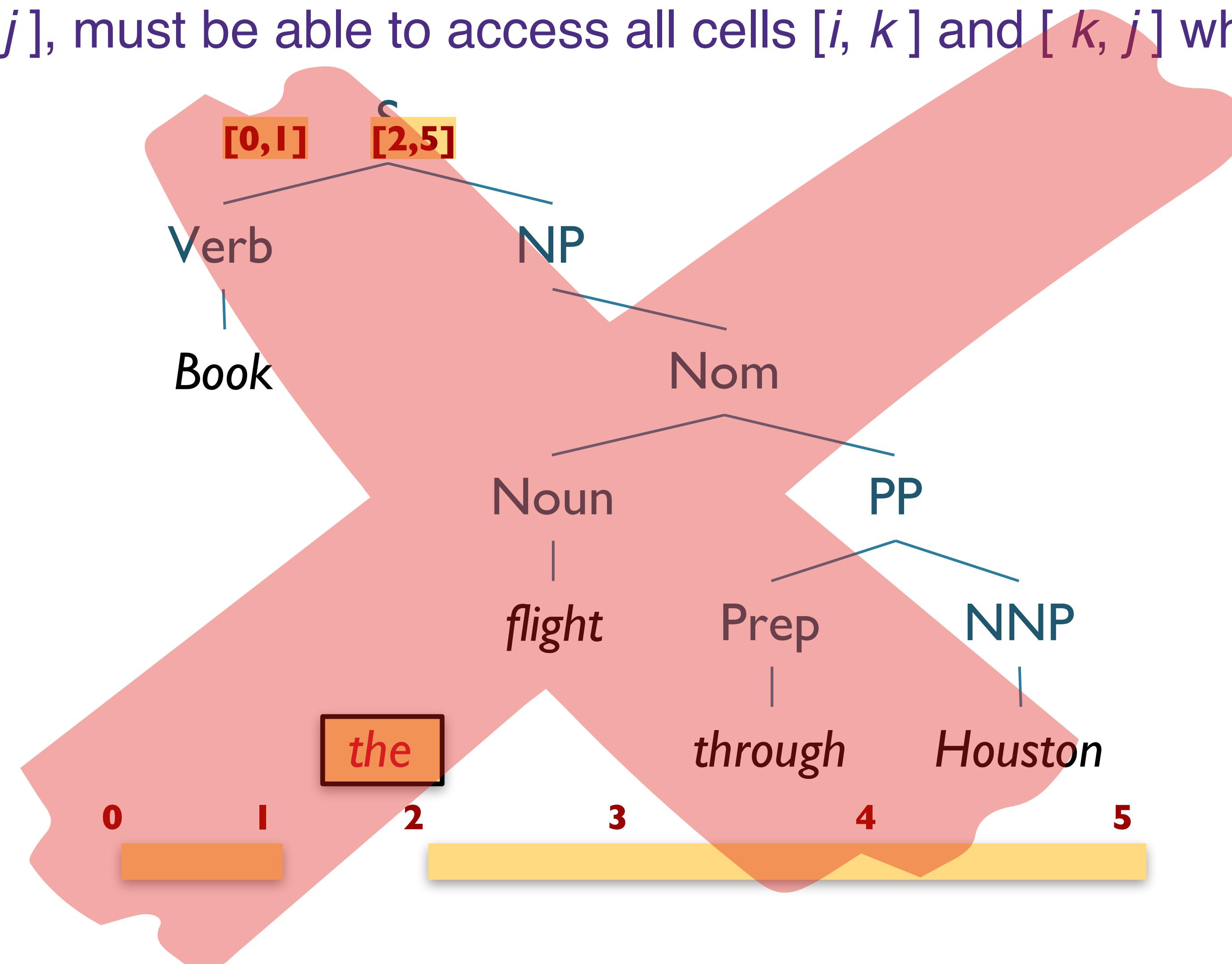
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# CKY Parsing Example

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

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

I prefer a flight on TWA

0 1 2 3 4 5 6

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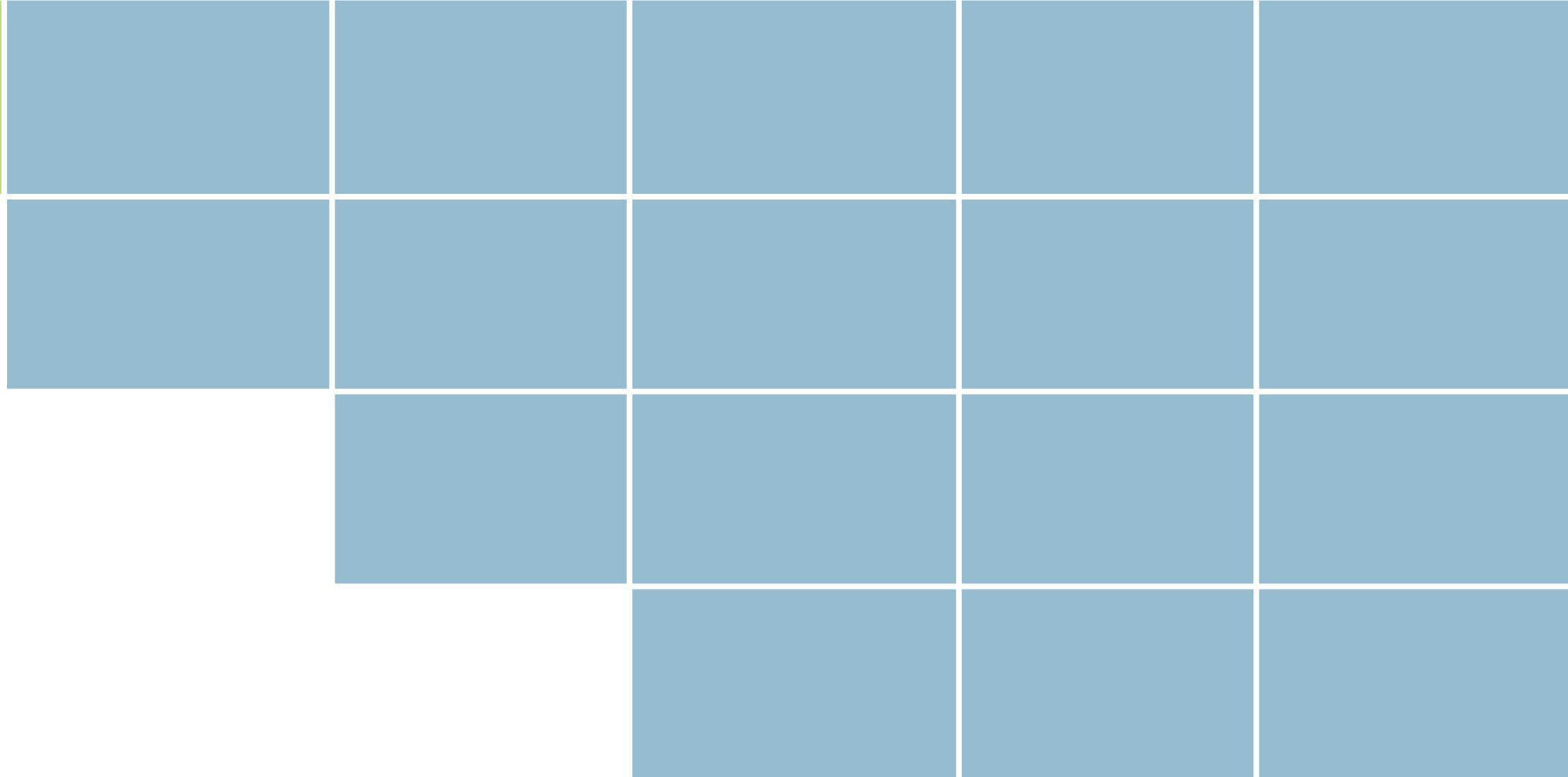
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### NP

[0, 1]



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$VP \rightarrow Verb NP$

$VP \rightarrow X2 PP$

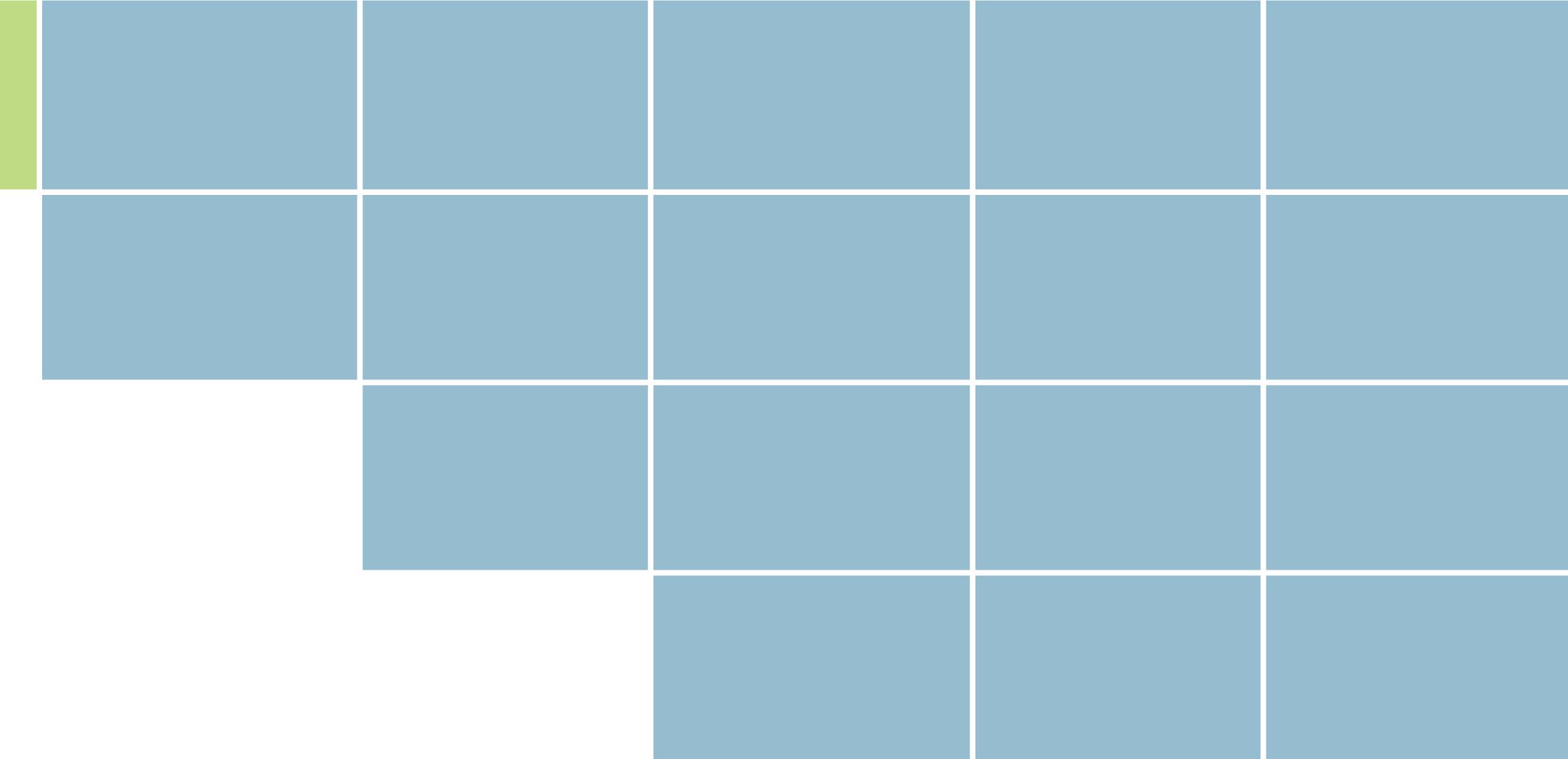
$X2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

$VP \rightarrow VP PP$

$PP \rightarrow Preposition NP$

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



### Lexicon

$Det \rightarrow that | this | a$

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

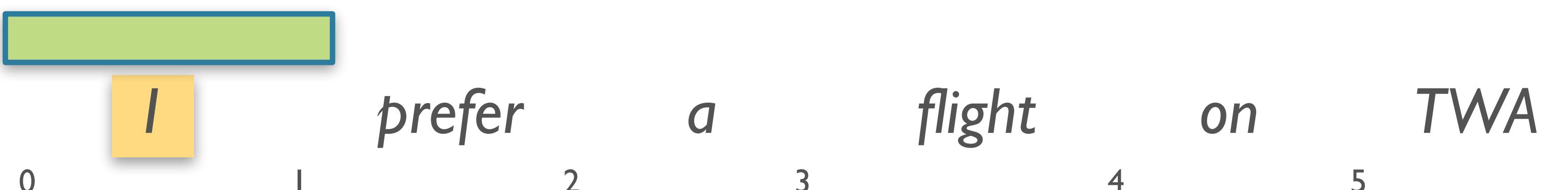
**Pronoun**  $\rightarrow I | she | me$

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

[0,2]

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

### 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, NP,  
ProNoun**  
[0,1]

[0,2]

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

### 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, NP,  
Pronoun**

[0,1]

[0,2]

**Verb, VP, S**

[1,2]

### Lexicon

$Det \rightarrow that | this | a$

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

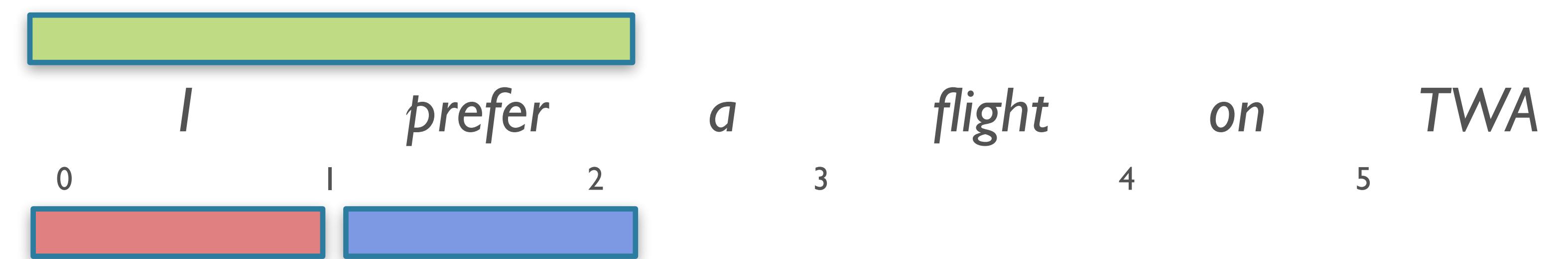
$Pronoun \rightarrow I | she | me$

$Proper-Noun \rightarrow Houston | TWA$

$Aux \rightarrow does$

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

$Verb \rightarrow book | include | prefer$



### $\mathcal{L}_1$ 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, NP,  
ProNoun**  
[0,1]

[0,2]

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

### 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

$S \rightarrow NP VP$   
 $S \rightarrow X_1 VP$   
 $X_1 \rightarrow Aux NP$   
 $S \rightarrow book | include | prefer$

$S \rightarrow Verb NP$   
 $S \rightarrow X_2 PP$   
 $S \rightarrow Verb PP$   
 $S \rightarrow VP PP$

$NP \rightarrow I | she | me$

$NP \rightarrow TWA | Houston$

$NP \rightarrow Det Nominal$

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

$Nominal \rightarrow Nominal Noun$

$Nominal \rightarrow Nominal PP$

$VP \rightarrow book | include | prefer$

$VP \rightarrow Verb NP$

$VP \rightarrow X_2 PP$

$X_2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

$VP \rightarrow VP PP$

$PP \rightarrow Preposition NP$

**NP, NP,  
PrPronoun**  
 $[0,1]$

**S S**

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

### 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, NP,  
Pronoun**

[0,1]

**S**

[0,2]

**Verb, VP, S**

[1,2]

### Lexicon

$Det \rightarrow that | this | a$

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

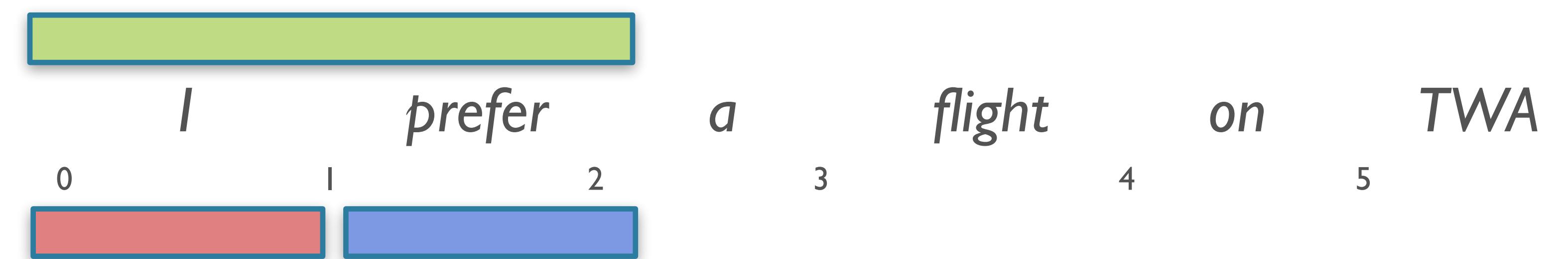
$Pronoun \rightarrow I | she | me$

$Proper-Noun \rightarrow Houston | TWA$

$Aux \rightarrow does$

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

$Verb \rightarrow book | include | prefer$



### L1 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, NP,  
ProNoun**  
 $[0,1]$

**S S**

$[0,2]$

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

### 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

$S \rightarrow NP VP$   
 $S \rightarrow X_1 VP$   
 $X_1 \rightarrow Aux NP$   
 $S \rightarrow book | include | prefer$   
 $S \rightarrow Verb NP$   
 $S \rightarrow X_2 PP$   
 $S \rightarrow Verb PP$   
 $S \rightarrow VP PP$

$NP \rightarrow I | she | me$

$NP \rightarrow TWA | Houston$

$NP \rightarrow Det Nominal$

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

$Nominal \rightarrow Nominal Noun$

$Nominal \rightarrow Nominal PP$

$VP \rightarrow book | include | prefer$

$VP \rightarrow Verb NP$

$VP \rightarrow X_2 PP$

$X_2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

$VP \rightarrow VP PP$

$PP \rightarrow Preposition NP$

**NP, NP,  
Pronoun**

[0,1]

**S S**

[0,2]

**Verb, VP, S**

[1,2]

### Lexicon

$Det \rightarrow that | this | a$

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

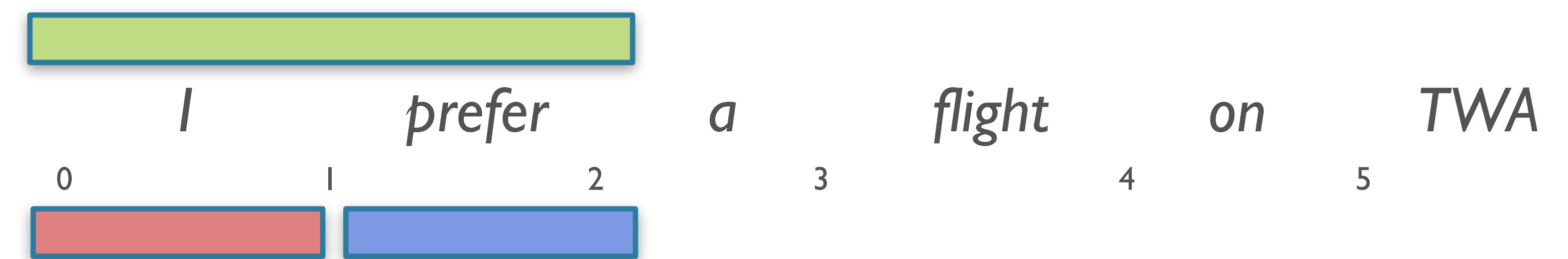
$Pronoun \rightarrow I | she | me$

$Proper-Noun \rightarrow Houston | TWA$

$Aux \rightarrow does$

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

$Verb \rightarrow book | include | prefer$



### L1 Grammar

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

$NP \rightarrow I | she | me$

$NP \rightarrow TWA | Houston$

$Nominal \rightarrow Det Nominal$

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

$Nominal \rightarrow Nominal Noun$

$Nominal \rightarrow Nominal PP$

$VP \rightarrow book | include | prefer$

$VP \rightarrow Verb NP$

$VP \rightarrow X2 PP$

$X2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

$VP \rightarrow VP PP$

$PP \rightarrow Preposition NP$

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

**S**  
 $[0,2]$

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

**Det**

$[2,3]$

### Lexicon

$Det \rightarrow that | this | a$

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

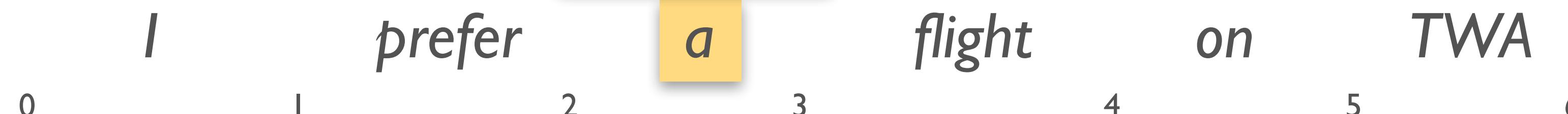
$Pronoun \rightarrow I | she | me$

$Proper-Noun \rightarrow Houston | TWA$

$Aux \rightarrow does$

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

$Verb \rightarrow book | include | prefer$



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

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

$NP \rightarrow I | she | me$

$NP \rightarrow TWA | Houston$

$NP \rightarrow Det Nominal$

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

$Nominal \rightarrow Nominal Noun$

$Nominal \rightarrow Nominal PP$

$VP \rightarrow book | include | prefer$

$VP \rightarrow Verb NP$

$VP \rightarrow X2 PP$

$X2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

$VP \rightarrow VP PP$

$PP \rightarrow Preposition NP$

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

**S**  
[0,2]

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

**[1,3]**  
**Det**  
[2,3]

### Lexicon

$Det \rightarrow that | this | a$

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

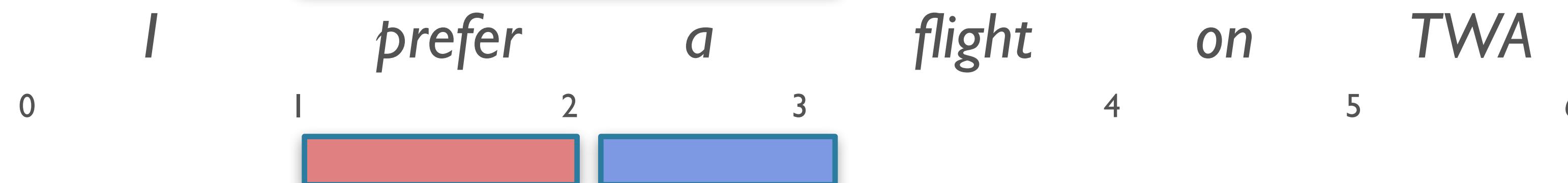
$Pronoun \rightarrow I | she | me$

$Proper-Noun \rightarrow Houston | TWA$

$Aux \rightarrow does$

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

$Verb \rightarrow book | include | prefer$



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

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

$NP \rightarrow I | she | me$

$NP \rightarrow TWA | Houston$

$NP \rightarrow Det Nominal$

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

$Nominal \rightarrow Nominal Noun$

$Nominal \rightarrow Nominal PP$

$VP \rightarrow book | include | prefer$

$VP \rightarrow Verb NP$

$VP \rightarrow X2 PP$

$X2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

$VP \rightarrow VP PP$

$PP \rightarrow Preposition NP$

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

**S**  
[0,2]

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

**Det**  
[1,3]  
**Det**  
[2,3]

### Lexicon

$Det \rightarrow that | this | a$

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

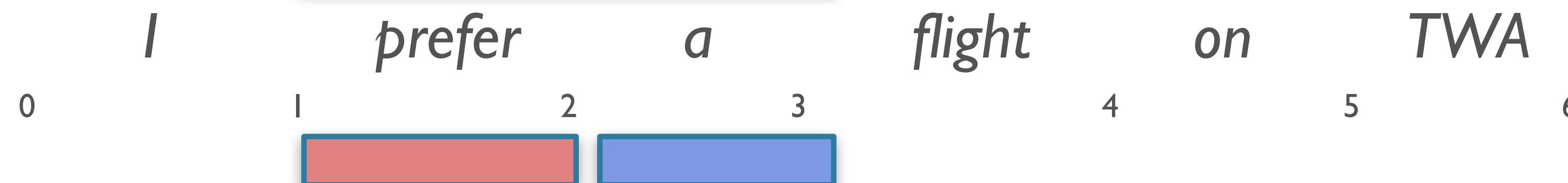
$Pronoun \rightarrow I | she | me$

$Proper-Noun \rightarrow Houston | TWA$

$Aux \rightarrow does$

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

$Verb \rightarrow book | include | prefer$



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

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

$NP \rightarrow I | she | me$

$NP \rightarrow TWA | Houston$

$NP \rightarrow Det Nominal$

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

$Nominal \rightarrow Nominal Noun$

$Nominal \rightarrow Nominal PP$

$VP \rightarrow book | include | prefer$

$VP \rightarrow Verb NP$

$VP \rightarrow X2 PP$

$X2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

$VP \rightarrow VP PP$

$PP \rightarrow Preposition NP$

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

**S**  
[0,2]

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

**Det**  
[1,3]  
[2,3]

### Lexicon

$Det \rightarrow that | this | a$

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

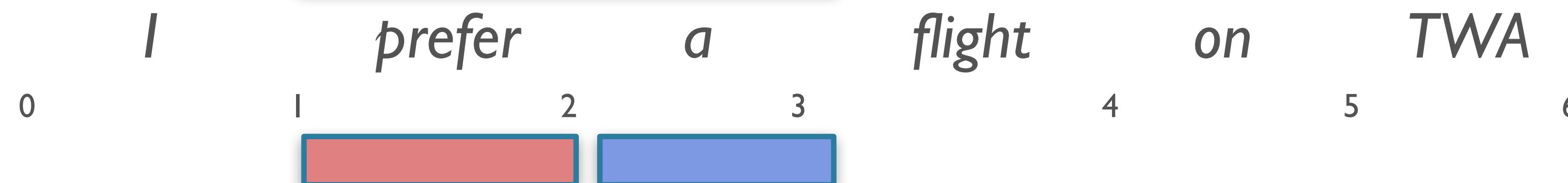
$Pronoun \rightarrow I | she | me$

$Proper-Noun \rightarrow Houston | TWA$

$Aux \rightarrow does$

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

$Verb \rightarrow book | include | prefer$



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

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

$NP \rightarrow I | she | me$

$NP \rightarrow TWA | Houston$

$NP \rightarrow Det Nominal$

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

$Nominal \rightarrow Nominal Noun$

$Nominal \rightarrow Nominal PP$

$VP \rightarrow book | include | prefer$

$VP \rightarrow Verb NP$

$VP \rightarrow X2 PP$

$X2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

$VP \rightarrow VP PP$

$PP \rightarrow Preposition NP$

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

**S**  
[0,2]

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

**[1,3]**  
**Det 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

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

$NP \rightarrow I | she | me$

$NP \rightarrow TWA | Houston$

$NP \rightarrow Det Nominal$

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

$Nominal \rightarrow Nominal Noun$

$Nominal \rightarrow Nominal PP$

$VP \rightarrow book | include | prefer$

$VP \rightarrow Verb NP$

$VP \rightarrow X2 PP$

$X2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

$VP \rightarrow VP PP$

$PP \rightarrow Preposition NP$

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

**S**  
[0,2]

**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

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

$NP \rightarrow I | she | me$

$NP \rightarrow TWA | Houston$

$NP \rightarrow Det Nominal$

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

$Nominal \rightarrow Nominal Noun$

$Nominal \rightarrow Nominal PP$

$VP \rightarrow book | include | prefer$

$VP \rightarrow Verb NP$

$VP \rightarrow X2 PP$

$X2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

$VP \rightarrow VP PP$

$PP \rightarrow Preposition NP$

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

**S**  
[0,2]

[0,3]

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

[1,3]

**Det**  
[2,3]

### Lexicon

$Det \rightarrow that | this | a$

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

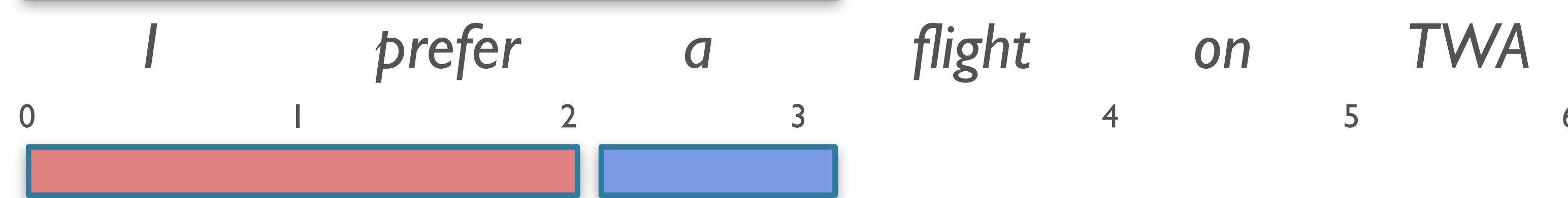
$Pronoun \rightarrow I | she | me$

$Proper-Noun \rightarrow Houston | TWA$

$Aux \rightarrow does$

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

$Verb \rightarrow book | include | prefer$



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

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

$NP \rightarrow I | she | me$

$NP \rightarrow TWA | Houston$

$NP \rightarrow Det Nominal$

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

$Nominal \rightarrow Nominal Noun$

$Nominal \rightarrow Nominal PP$

$VP \rightarrow book | include | prefer$

$VP \rightarrow Verb NP$

$VP \rightarrow X2 PP$

$X2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

$VP \rightarrow VP PP$

$PP \rightarrow Preposition NP$

NP, Pronoun [0,1]	S [0,2]	S [0,3]	Verb, VP, S [1,2]	Verb, VP, S [1,3]	Det [2,3]	Det [2,3]	Det [2,3]	Det [2,3]	Det [2,3]
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### Lexicon

$Det \rightarrow that | this | a$

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

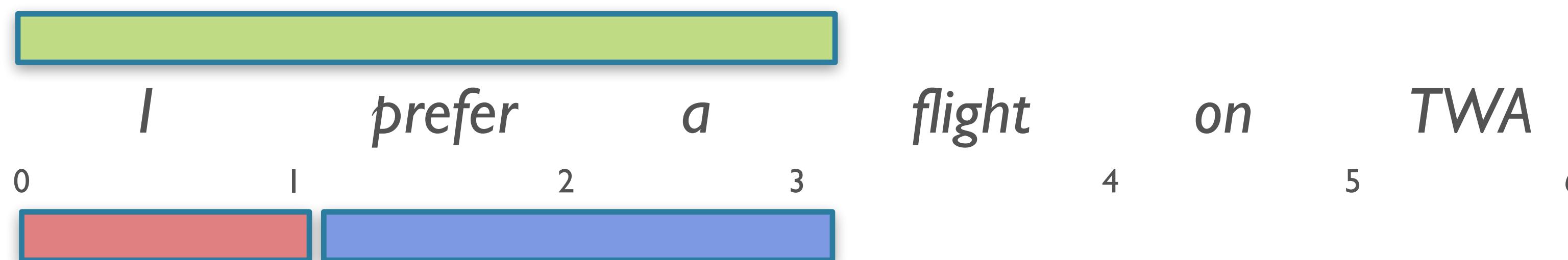
$Pronoun \rightarrow I | she | me$

$Proper-Noun \rightarrow Houston | TWA$

$Aux \rightarrow does$

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

$Verb \rightarrow book | include | prefer$



### L1 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**  
 $[0,2]$

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

**Det**  
 $[1,3]$

**[2,3]**

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

### Lexicon

$Det \rightarrow that | this | a$

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

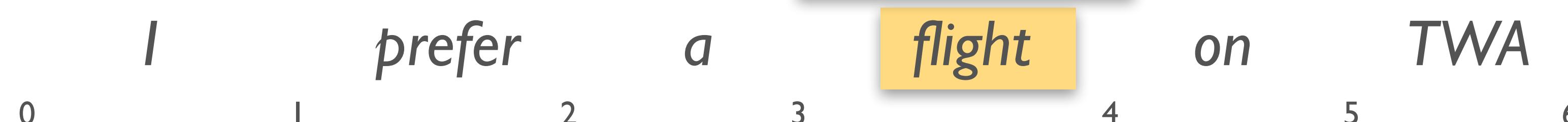
$Pronoun \rightarrow I | she | me$

$Proper-Noun \rightarrow Houston | TWA$

$Aux \rightarrow does$

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

$Verb \rightarrow book | include | prefer$



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

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

$NP \rightarrow I | she | me$

$NP \rightarrow TWA | Houston$

$NP \rightarrow Det Nominal$

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

$Nominal \rightarrow Nominal Noun$

$Nominal \rightarrow Nominal PP$

$VP \rightarrow book | include | prefer$

$VP \rightarrow Verb NP$

$VP \rightarrow X2 PP$

$X2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

$VP \rightarrow VP PP$

$PP \rightarrow Preposition NP$

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

### Lexicon

$Det \rightarrow that | this | a$

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

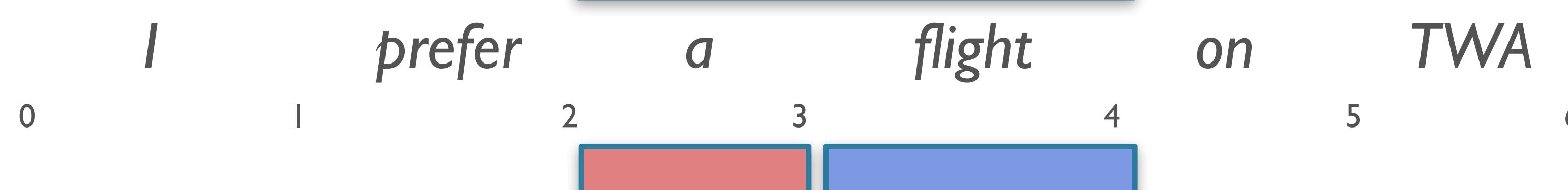
$Pronoun \rightarrow I | she | me$

$Proper-Noun \rightarrow Houston | TWA$

$Aux \rightarrow does$

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

$Verb \rightarrow book | include | prefer$



### $\mathcal{L}_1$ 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]	<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

$Det \rightarrow that | this | a$

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

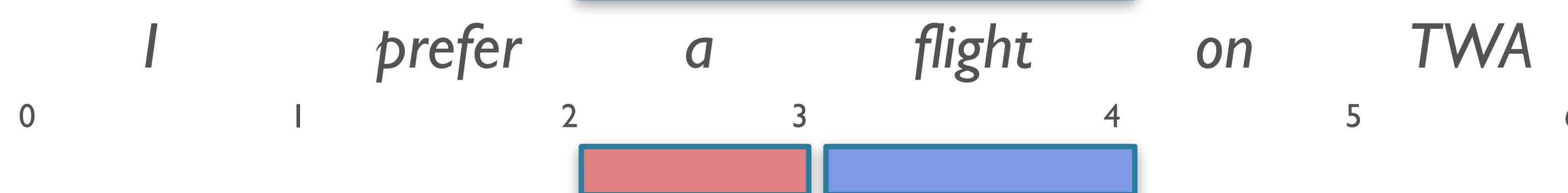
$Pronoun \rightarrow I | she | me$

$Proper-Noun \rightarrow Houston | TWA$

$Aux \rightarrow does$

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

$Verb \rightarrow book | include | prefer$



### $\mathcal{L}_1$ 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</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>NP</b> [2,4]
					<b>Noun, Nom</b> [3,4]

### Lexicon

$Det \rightarrow that | this | a$

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

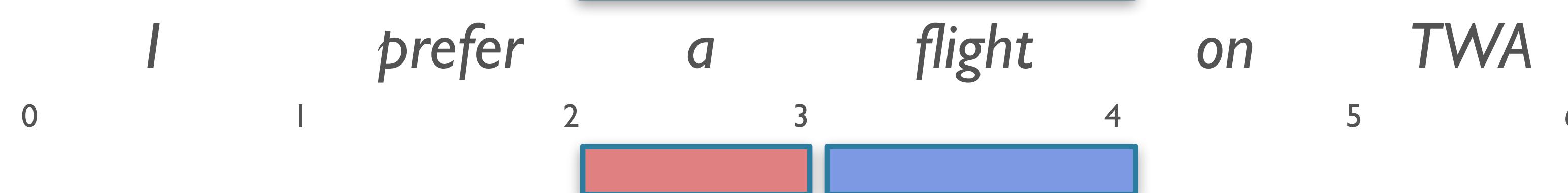
$Pronoun \rightarrow I | she | me$

$Proper-Noun \rightarrow Houston | TWA$

$Aux \rightarrow does$

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

$Verb \rightarrow book | include | prefer$



### $\mathcal{L}_1$ 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]	<b>[0,3]</b>			
		<b>Verb, VP, S</b> [1,2]			
			<b>[1,3]</b>	<b>[1,4]</b>	
			<b>Det</b>	<b>NP</b>	
				<b>[2,3]</b>	<b>[2,4]</b>
					<b>Noun, Nom</b> [3,4]

### Lexicon

$Det \rightarrow that | this | a$

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

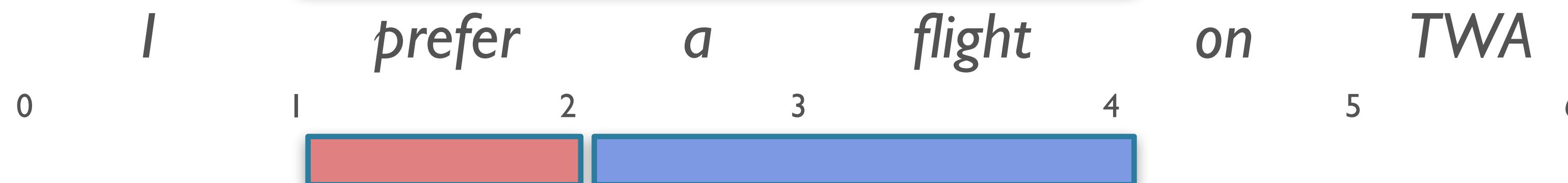
$Pronoun \rightarrow I | she | me$

$Proper-Noun \rightarrow Houston | TWA$

$Aux \rightarrow does$

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

$Verb \rightarrow book | include | prefer$



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

$S \rightarrow NP VP$   
 $S \rightarrow X_1 VP$   
 $X_1 \rightarrow Aux NP$   
 $S \rightarrow book | include | prefer$   
 $S \rightarrow Verb NP$   
 $S \rightarrow X_2 PP$   
 $S \rightarrow Verb PP$   
 $S \rightarrow VP PP$

$NP \rightarrow I | she | me$

$NP \rightarrow TWA | Houston$

$NP \rightarrow Det Nominal$

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

$Nominal \rightarrow Nominal Noun$

$Nominal \rightarrow Nominal PP$

$VP \rightarrow book | include | prefer$

$VP \rightarrow Verb NP$

$VP \rightarrow X_2 PP$

$X_2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

$VP \rightarrow VP PP$

$PP \rightarrow Preposition NP$

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

### Lexicon

$Det \rightarrow that | this | a$

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

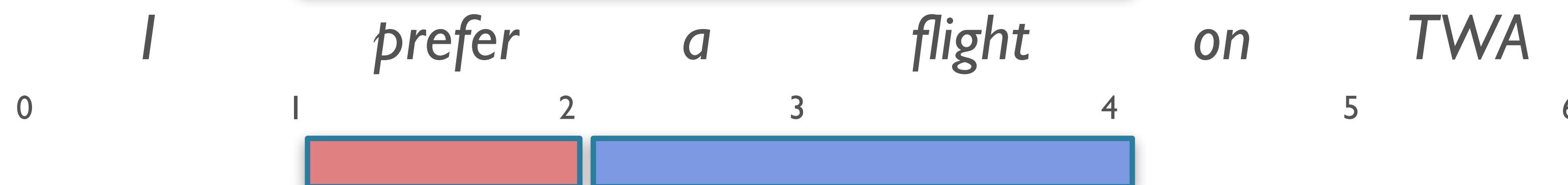
$Pronoun \rightarrow I | she | me$

$Proper-Noun \rightarrow Houston | TWA$

$Aux \rightarrow does$

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

$Verb \rightarrow book | include | prefer$



### $\mathcal{L}_1$ 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]	[0,3]			
			<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

$Det \rightarrow that | this | a$

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

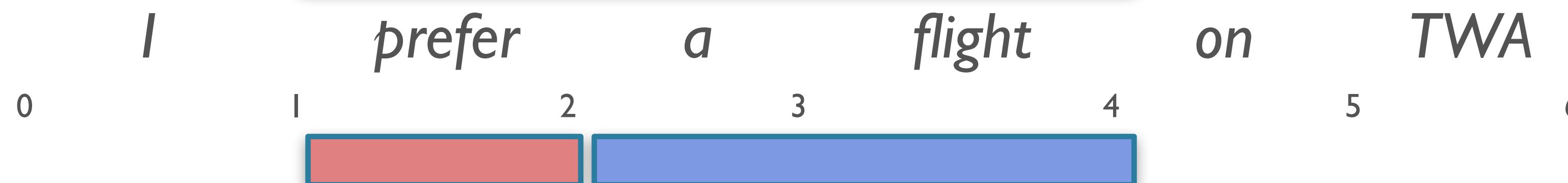
$Pronoun \rightarrow I | she | me$

$Proper-Noun \rightarrow Houston | TWA$

$Aux \rightarrow does$

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

$Verb \rightarrow book | include | prefer$



### $\mathcal{L}_1$ 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>	<b>NP</b>	
			[2,3]	[2,4]	
				<b>Noun, Nom</b> [3,4]	

### Lexicon

$Det \rightarrow that | this | a$

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

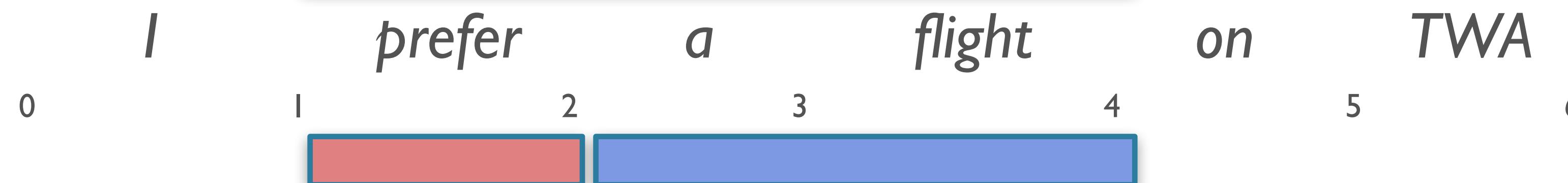
$Pronoun \rightarrow I | she | me$

$Proper-Noun \rightarrow Houston | TWA$

$Aux \rightarrow does$

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

$Verb \rightarrow book | include | prefer$



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

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

$NP \rightarrow I | she | me$

$NP \rightarrow TWA | Houston$

$NP \rightarrow Det Nominal$

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

$Nominal \rightarrow Nominal Noun$

$Nominal \rightarrow Nominal PP$

$VP \rightarrow book | include | prefer$

$VP \rightarrow Verb NP$

$VP \rightarrow X2 PP$

$X2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

$VP \rightarrow VP PP$

$PP \rightarrow Preposition NP$

<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]	
			<b>Det</b> [1,3]	<b>NP</b> [2,4]	
				<b>Noun, Nom</b> [3,4]	

### Lexicon

$Det \rightarrow that | this | a$

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

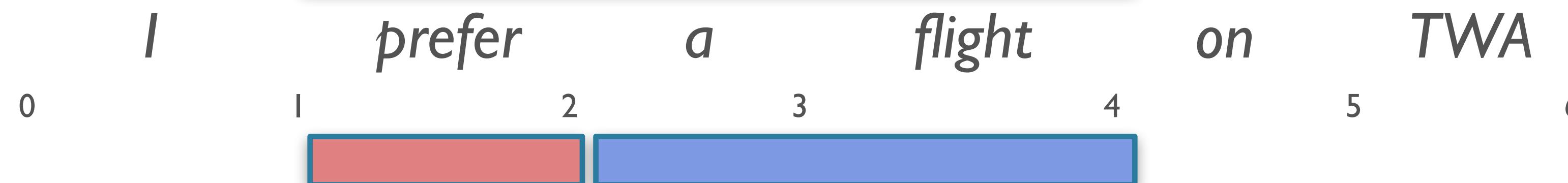
$Pronoun \rightarrow I | she | me$

$Proper-Noun \rightarrow Houston | TWA$

$Aux \rightarrow does$

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

$Verb \rightarrow book | include | prefer$



### $\mathcal{L}_1$ 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]	<b>[0,3]</b>			
		<b>Verb, VP, S</b> [1,2]	<b>[1,3]</b>	<b>VP, X2, S</b> [1,4]	
			<b>Det</b> [2,3]	<b>NP</b> [2,4]	
				<b>Noun, Nom</b> [3,4]	

### Lexicon

$Det \rightarrow that | this | a$

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

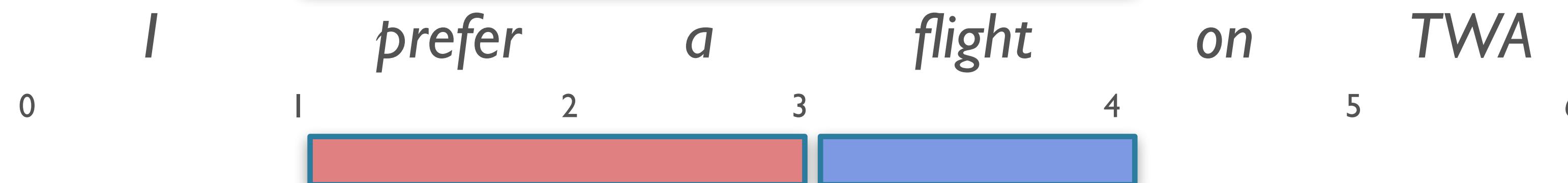
$Pronoun \rightarrow I | she | me$

$Proper-Noun \rightarrow Houston | TWA$

$Aux \rightarrow does$

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

$Verb \rightarrow book | include | prefer$



### $\mathcal{L}_1$ 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]	<b>[0,3]</b>			
		<b>Verb, VP, S</b> [1,2]	<b>[1,3]</b>	<b>VP, X2, S</b> [1,4]	
			<b>Det</b> [2,3]	<b>NP</b> [2,4]	
				<b>Noun, Nom</b> [3,4]	

### Lexicon

$Det \rightarrow that | this | a$

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

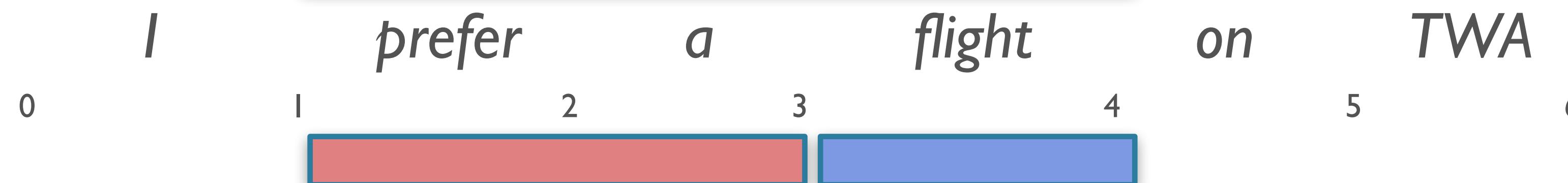
$Pronoun \rightarrow I | she | me$

$Proper-Noun \rightarrow Houston | TWA$

$Aux \rightarrow does$

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

$Verb \rightarrow book | include | prefer$



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

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

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

$NP \rightarrow I \mid she \mid me$

$NP \rightarrow TWA \mid Houston$

$NP \rightarrow Det Nominal$

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

$Nominal \rightarrow Nominal Noun$

$Nominal \rightarrow Nominal PP$

$VP \rightarrow book \mid include \mid prefer$

$VP \rightarrow Verb NP$

$VP \rightarrow X2 PP$

$X2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

$VP \rightarrow VP PP$

$PP \rightarrow Preposition NP$

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

<b>S</b>	$[0,2]$	$[0,3]$	<b>[0,4]</b>		
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**Verb, VP, S**  
 $[1,2]$

<b>Verb, VP, S</b>	$[1,2]$	$[1,3]$	<b>VP, X2, S</b>		
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**Det**  
 $[2,3]$

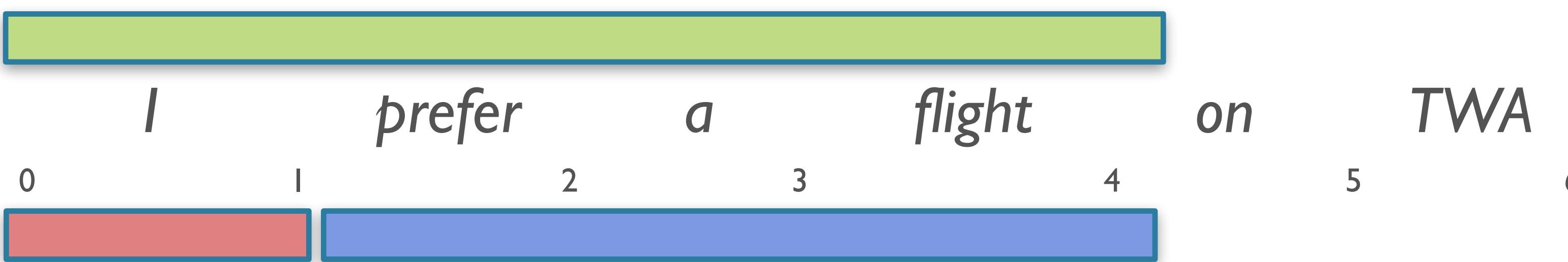
<b>Det</b>	$[2,3]$	<b>NP</b>		
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**Noun, Nom**  
 $[3,4]$

<b>Noun, Nom</b>	$[3,4]$		
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### Lexicon

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



### L1 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**

[1,4]

**Det**

[2,3]

**NP**

[2,4]

**Noun, Nom**

[3,4]

### Lexicon

$Det \rightarrow that | this | a$

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

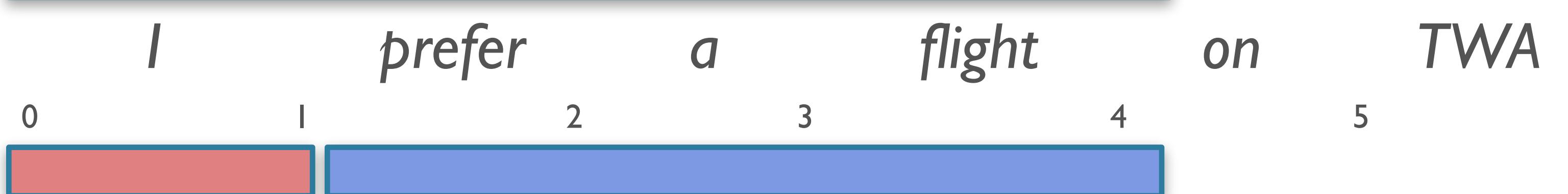
$Pronoun \rightarrow I | she | me$

$Proper-Noun \rightarrow Houston | TWA$

$Aux \rightarrow does$

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

$Verb \rightarrow book | include | prefer$



### L1 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]

<b>S</b>	[0,2]	[0,3]	<b>S</b>	

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

<b>Verb, VP, S</b>	[1,2]	<b>VP, X2, S</b>	

**Det**  
[2,3]

<b>Det</b>	[2,3]	<b>NP</b>	

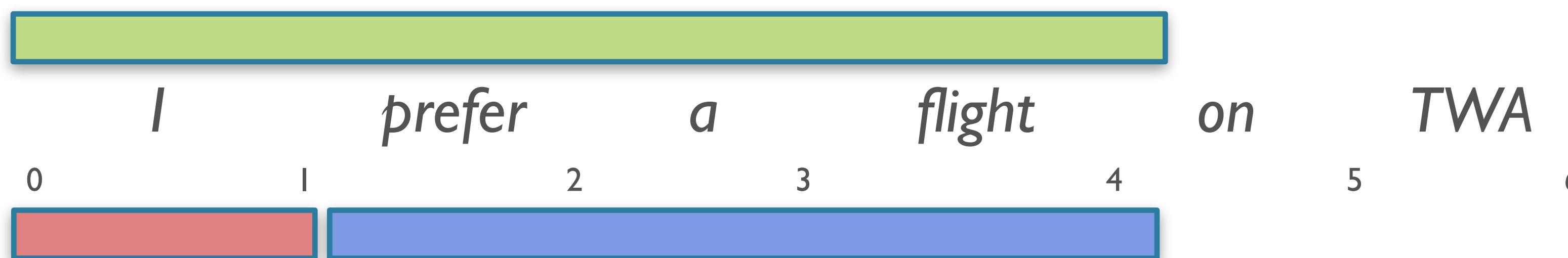
**NP**  
[2,4]

<b>NP</b>	[2,4]	<b>Noun, Nom</b>	

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

<b>Noun, Nom</b>	[3,4]		

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



### L1 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, VP, S**  
[1,3]

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

**Det**  
[2,3]

**NP**  
[2,4]

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

**Lexicon**

$Det \rightarrow that | this | a$

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

$Pronoun \rightarrow I | she | me$

$Proper-Noun \rightarrow Houston | TWA$

$Aux \rightarrow does$

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

$Verb \rightarrow book | include | prefer$

I prefer a flight on TWA

0 1 2 3 4 5 6



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

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

$S \rightarrow Verb PP$

$S \rightarrow VP PP$

$NP \rightarrow I | she | me$

$NP \rightarrow TWA | Houston$

$NP \rightarrow Det Nominal$

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

$Nominal \rightarrow Nominal Noun$

$Nominal \rightarrow Nominal PP$

$VP \rightarrow book | include | prefer$

$VP \rightarrow Verb NP$

$VP \rightarrow X2 PP$

$X2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

$VP \rightarrow VP PP$

$PP \rightarrow Preposition NP$

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

**S**  
[0,2]

**S**  
[0,3]

**S**  
[0,4]

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

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

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

**Det**

**NP**

[2,3]

[2,4]

**NP**

**Noun, Nom**

[3,4]

### Lexicon

$Det \rightarrow that | this | a$

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

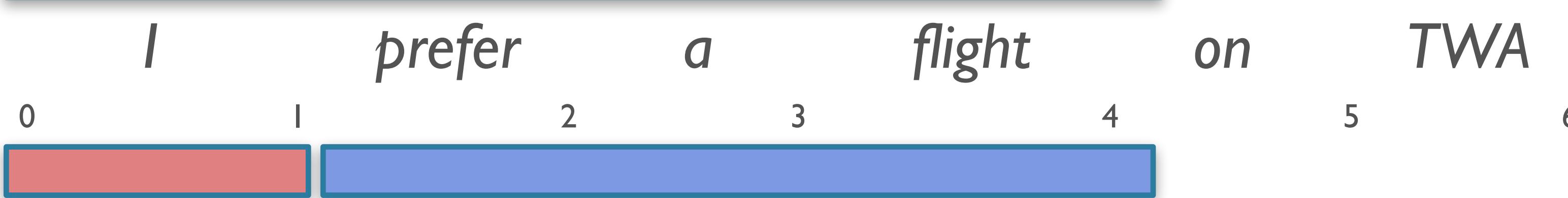
$Pronoun \rightarrow I | she | me$

$Proper-Noun \rightarrow Houston | TWA$

$Aux \rightarrow does$

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

$Verb \rightarrow book | include | prefer$

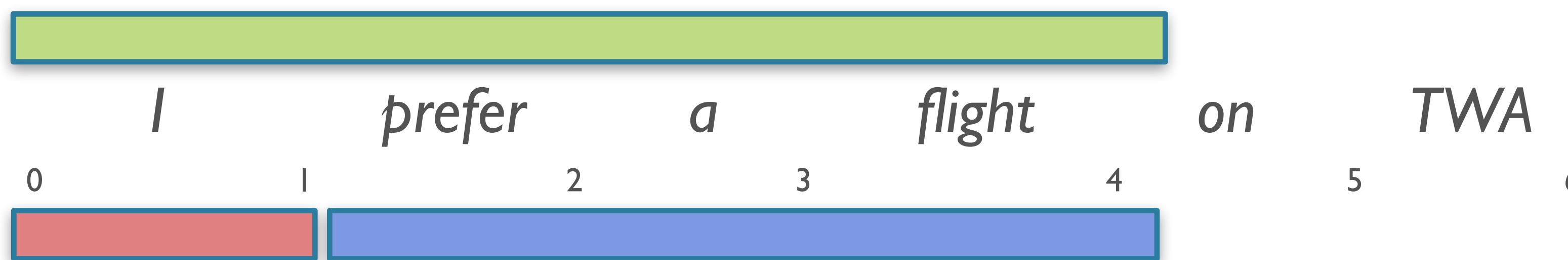


<b>L1 Grammar</b>	
$S \rightarrow NP\ VP$	
$S \rightarrow X1\ VP$	
$X1 \rightarrow Aux\ NP$	
$S \rightarrow book\ I\ include\ I\ prefer$	
$S \rightarrow Verb\ NP$	
$S \rightarrow X2\ PP$	
$S \rightarrow Verb\ PP$	
$S \rightarrow VP\ PP$	
<hr/>	
$NP \rightarrow I\ I\ she\ I\ me$	
$NP \rightarrow TWA\ I\ Houston$	
$NP \rightarrow Det\ Nominal$	
<hr/>	
$Nominal \rightarrow book\ I\ flight\ I\ meal\ I\ money$	
$Nominal \rightarrow Nominal\ Noun$	
$Nominal \rightarrow Nominal\ PP$	
<hr/>	
$VP \rightarrow book\ I\ include\ I\ prefer$	
$VP \rightarrow Verb\ NP$	
$VP \rightarrow X2\ PP$	
$X2 \rightarrow Verb\ NP$	
$VP \rightarrow Verb\ PP$	
$VP \rightarrow VP\ PP$	
<hr/>	
$PP \rightarrow Preposition\ NP$	

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

## Lexicon

*Det* → *that* | *this* | *a*  
*Noun* → *book* | *flight* | *meal* | *money*  
*Pronoun* → *I* | *she* | *me*  
*Proper-Noun* → *Houston* | *TWA*  
*Aux* → *does*  
*Preposition* → *from* | *to* | *on* | *near* | *through*  
*Verb* → *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]

[0,2]

[1,2]

[1,3]

[2,3]

[2,4]

[3,4]

**S**  
[0,3]

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

[1,3]

**Det**  
[2,3]

**NP**  
[2,4]

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

**S**  
[0,4]

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

**Det**  
[2,3]

**NP**  
[2,4]

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

### Lexicon

$Det \rightarrow that | this | a$

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

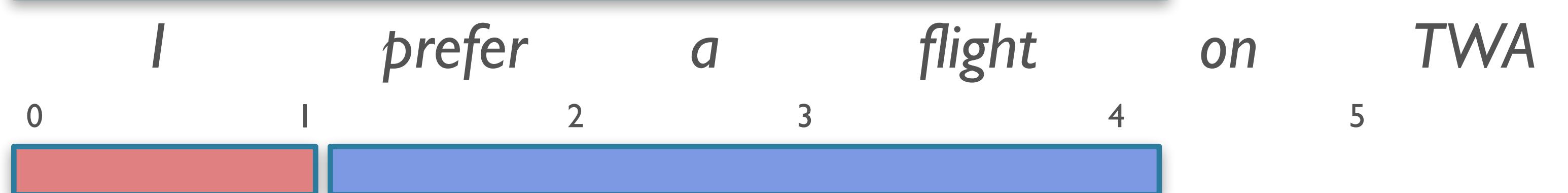
$Pronoun \rightarrow I | she | me$

$Proper-Noun \rightarrow Houston | TWA$

$Aux \rightarrow does$

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

$Verb \rightarrow book | include | prefer$



### L1 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**  
 $[0,1]$

$[0,2]$

$[0,3]$

$[0,4]$

$[1,2]$

$[1,3]$

$[1,4]$

$[2,3]$

$[2,4]$

$[3,4]$

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$[3,4]$

$[3,$

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

### Lexicon

$Det \rightarrow that | this | a$

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

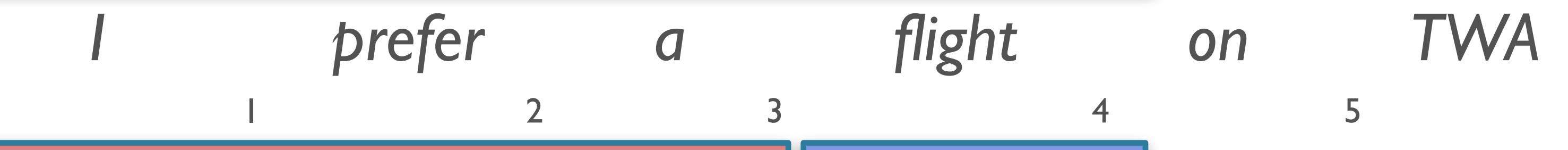
$Pronoun \rightarrow I | she | me$

$Proper-Noun \rightarrow Houston | TWA$

$Aux \rightarrow does$

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

$Verb \rightarrow book | include | prefer$



### L1 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, VP, S**  
 $[1,3]$

**Det**  
 $[1,4]$

**NP**  
 $[2,3]$

**NP**  
 $[2,4]$

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

**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 [1,4]		
		Det [2,3]		NP [2,4]	
				Noun, Nom [3,4]	Prep [3,5]
					Prep [4,5]

### Lexicon

$Det \rightarrow that | this | a$

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

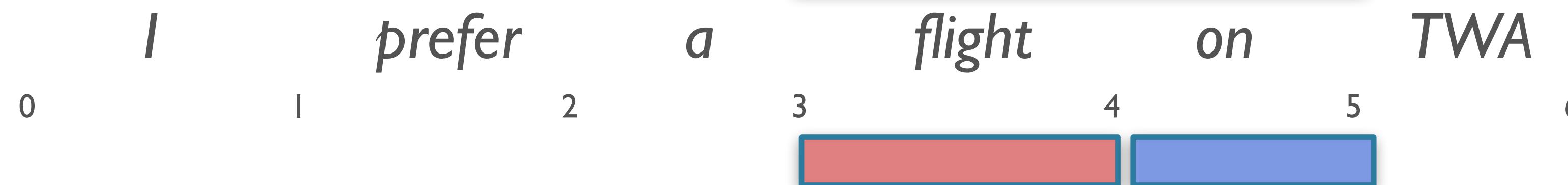
$Pronoun \rightarrow I | she | me$

$Proper-Noun \rightarrow Houston | TWA$

$Aux \rightarrow does$

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

$Verb \rightarrow book | include | prefer$



### $\mathcal{L}_1$ 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> [0,3]	<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</b> [2,5]	
				<b>Noun, Nom</b> [3,4]	[3,5]
				<b>Prep</b> [4,5]	

### Lexicon

$Det \rightarrow that | this | a$

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

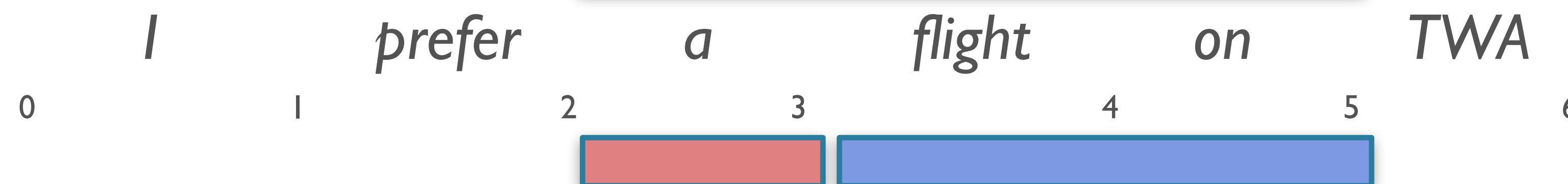
$Pronoun \rightarrow I | she | me$

$Proper-Noun \rightarrow Houston | TWA$

$Aux \rightarrow does$

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

$Verb \rightarrow book | include | prefer$



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

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

$S \rightarrow Verb PP$

$S \rightarrow VP PP$

$NP \rightarrow I | she | me$

$NP \rightarrow TWA | Houston$

$NP \rightarrow Det Nominal$

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

$Nominal \rightarrow Nominal Noun$

$Nominal \rightarrow Nominal PP$

$VP \rightarrow book | include | prefer$

$VP \rightarrow Verb NP$

$VP \rightarrow X2 PP$

$X2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

$VP \rightarrow VP PP$

$PP \rightarrow Preposition NP$

<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</b> [2,5]	
				<b>Noun, Nom</b> [3,4]	[3,5]
					<b>Prep</b> [4,5]

### Lexicon

$Det \rightarrow that | this | a$

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

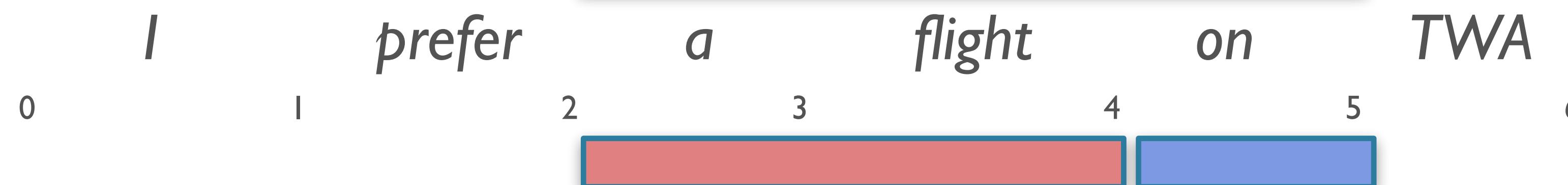
$Pronoun \rightarrow I | she | me$

$Proper-Noun \rightarrow Houston | TWA$

$Aux \rightarrow does$

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

$Verb \rightarrow book | include | prefer$



$\mathcal{L}_1$ Grammar	
$S \rightarrow NP VP$	
$S \rightarrow X_1 VP$	
$X_1 \rightarrow Aux NP$	
$S \rightarrow book \mid include \mid prefer$	
$S \rightarrow Verb NP$	
$S \rightarrow X_2 PP$	
$S \rightarrow Verb PP$	
$S \rightarrow VP PP$	
<hr/>	
$NP \rightarrow I \mid she \mid me$	
$NP \rightarrow TWA \mid Houston$	
$NP \rightarrow Det Nominal$	
<hr/>	
$Nominal \rightarrow book \mid flight \mid meal \mid money$	
$Nominal \rightarrow Nominal Noun$	
$Nominal \rightarrow Nominal PP$	
<hr/>	
$VP \rightarrow book \mid include \mid prefer$	
$VP \rightarrow Verb NP$	
$VP \rightarrow X_2 PP$	
$X_2 \rightarrow Verb NP$	
$VP \rightarrow Verb PP$	
$VP \rightarrow VP PP$	
<hr/>	
$PP \rightarrow Preposition NP$	

<b>NP, Pronoun</b> [0,1]	<b>S</b> [0,2]		<b>S</b> [0,3]			
	<b>Verb, VP, S</b> [1,2]			<b>VP, X2, S</b> [1,4]	[1,5]	
		<b>Det</b> [2,3]		<b>NP</b> [2,4]	<b>NP</b> [2,5]	
				<b>Noun, Nom</b> [3,4]	[3,5]	
					<b>Prep</b> [4,5]	
<i>at   this   a book   flight   meal   money</i>						

# Lexicon

*Det → that | this | a*

*Noun → book | flight | meal | money*

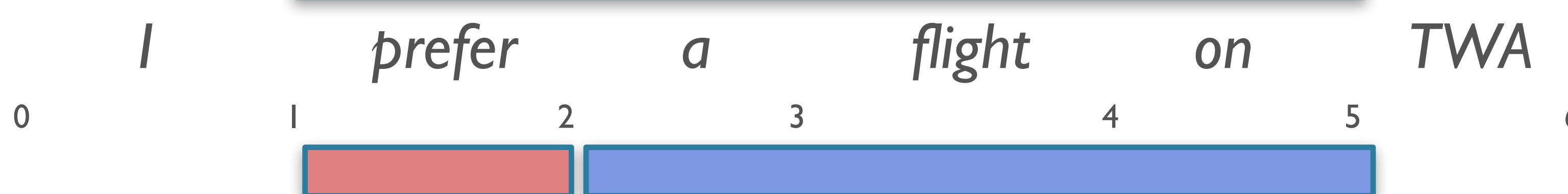
## *Pronoun → I | she | me*

# *Proper-Noun → Houston | TWA*

*Aux → does*

*Preposition → from | to | on | near | through*

**Verb → 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]

**[1,4]**  
[1,5]

**Det**  
[2,3]

**NP**  
[2,4]

[2,5]

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

**[3,5]**

**Prep**  
[4,5]

**Lexicon**

$Det \rightarrow that | this | a$

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

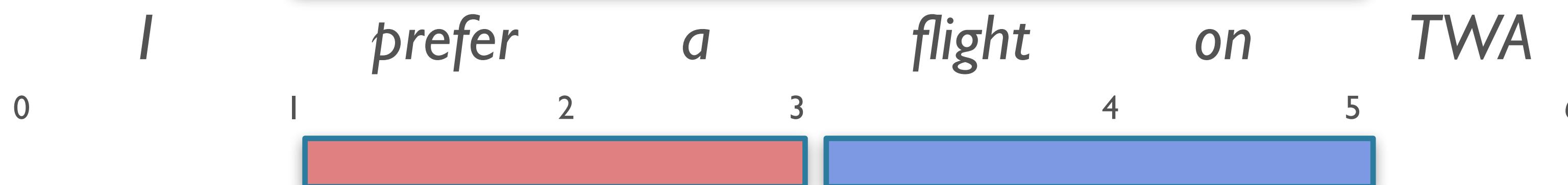
$Pronoun \rightarrow I | she | me$

$Proper-Noun \rightarrow Houston | TWA$

$Aux \rightarrow does$

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

$Verb \rightarrow book | include | prefer$



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

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

$S \rightarrow Verb PP$

$S \rightarrow VP PP$

$NP \rightarrow I | she | me$

$NP \rightarrow TWA | Houston$

$NP \rightarrow Det Nominal$

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

$Nominal \rightarrow Nominal Noun$

$Nominal \rightarrow Nominal PP$

$VP \rightarrow book | include | prefer$

$VP \rightarrow Verb NP$

$VP \rightarrow X2 PP$

$X2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

$VP \rightarrow VP PP$

$PP \rightarrow Preposition NP$

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

**S**  
[0,2]

**S**  
[0,3]

**S**  
[0,4]

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

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

**[1,4]**  
[1,5]

**Det**  
[2,3]

**NP**  
[2,4]

**[2,5]**

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

**[3,5]**

**Prep**  
[4,5]

### Lexicon

$Det \rightarrow that | this | a$

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

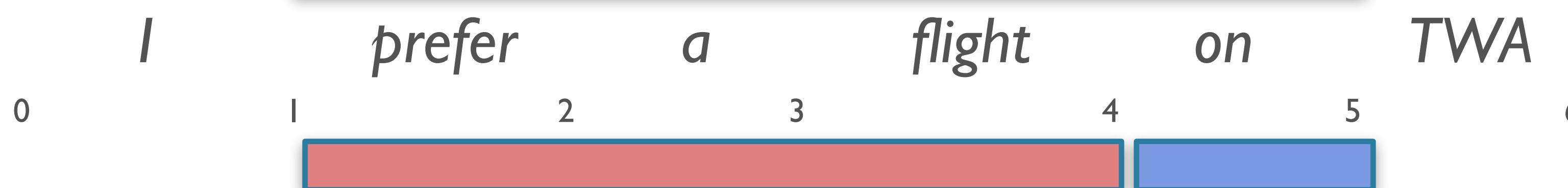
$Pronoun \rightarrow I | she | me$

$Proper-Noun \rightarrow Houston | TWA$

$Aux \rightarrow does$

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

$Verb \rightarrow book | include | prefer$



<b>L1 Grammar</b>	
$S \rightarrow NP\ VP$	
$S \rightarrow X1\ VP$	
$X1 \rightarrow Aux\ NP$	
$S \rightarrow book\ I\ include\ I\ prefer$	
$S \rightarrow Verb\ NP$	
$S \rightarrow X2\ PP$	
$S \rightarrow Verb\ PP$	
$S \rightarrow VP\ PP$	
<hr/>	
$NP \rightarrow I\ I\ she\ I\ me$	
$NP \rightarrow TWA\ I\ Houston$	
$NP \rightarrow Det\ Nominal$	
<hr/>	
$Nominal \rightarrow book\ I\ flight\ I\ meal\ I\ money$	
$Nominal \rightarrow Nominal\ Noun$	
$Nominal \rightarrow Nominal\ PP$	
<hr/>	
$VP \rightarrow book\ I\ include\ I\ prefer$	
$VP \rightarrow Verb\ NP$	
$VP \rightarrow X2\ PP$	
$X2 \rightarrow Verb\ NP$	
$VP \rightarrow Verb\ PP$	
$VP \rightarrow VP\ PP$	
<hr/>	
$PP \rightarrow Preposition\ NP$	

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

at | this | a  
book | flight | meal | money  
→ | | she | me

# Lexicon

*Det → that | this | a*

*Noun → book | flight | meal | money*

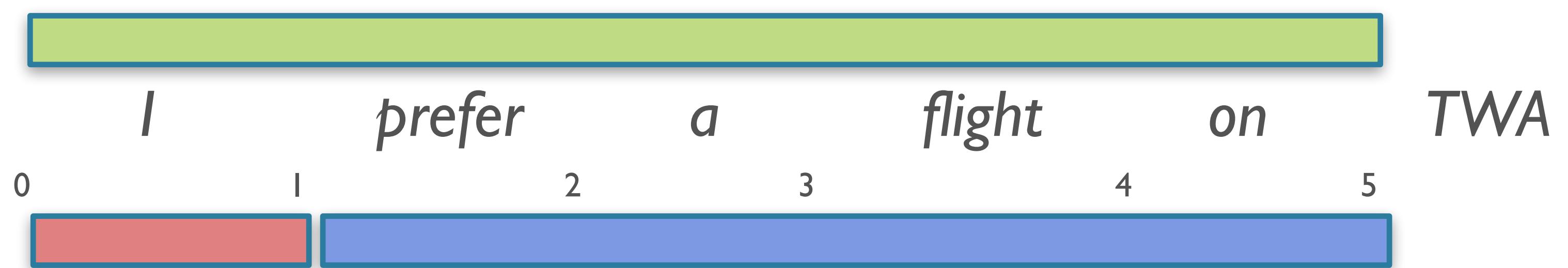
## Pronoun → I | she | me

# *Proper-Noun → Houston | TWA*

*Aux → does*

*Preposition → from | to | on | near | through*

*Verb → 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]

**Verb, VP, S**

[1,3]

**Verb, VP, S**

[1,4]

**Verb, VP, S**

[1,5]

**Det**

[2,3]

**Det**

**NP**

[2,4]

**NP**

[2,5]

**NP**

[3,4]

**Noun, Nom**

[3,5]

**Noun, Nom**

[3,5]

**Prep**

[4,5]

### Lexicon

$Det \rightarrow that | this | a$

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

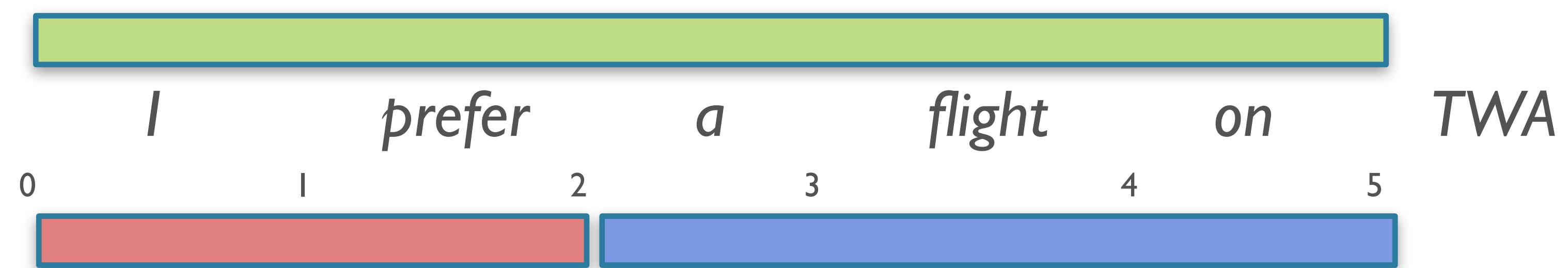
$Pronoun \rightarrow I | she | me$

$Proper-Noun \rightarrow Houston | TWA$

$Aux \rightarrow does$

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

$Verb \rightarrow book | include | prefer$



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

**Verb, VP, S**

[1,3]

**Verb, VP, S**

[1,4]

**Verb, VP, S**

[1,5]

**Det**

[2,3]

**Det**

[2,4]

**Det**

[2,5]

**NP**

[2,4]

**NP**

[2,5]

**Noun, Nom**

[3,4]

**Noun, Nom**

[3,4]

**Noun, Nom**

[3,5]

**Noun, Nom**

[3,5]

**Prep**

[4,5]

**Prep**

[4,5]

**Prep**

[4,5]

**Prep**

[4,5]

**Prep**

[4,5]

**Prep**

[4,5]

### Lexicon

$Det \rightarrow that | this | a$

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

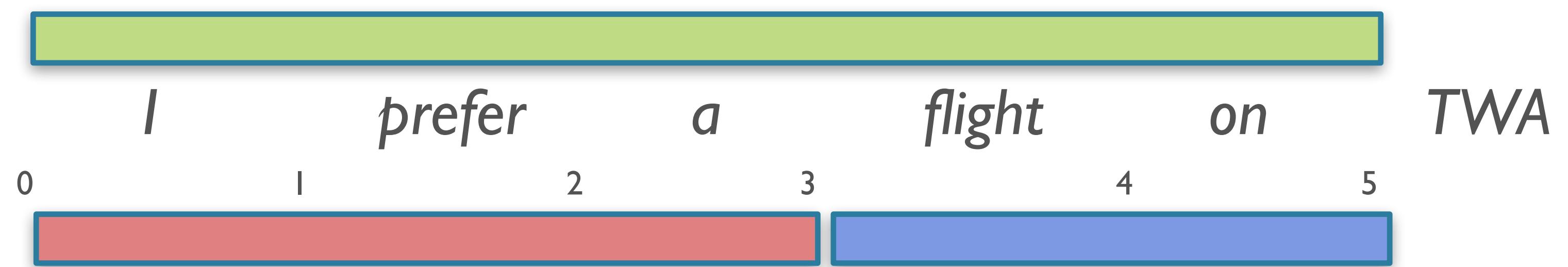
$Pronoun \rightarrow I | she | me$

$Proper-Noun \rightarrow Houston | TWA$

$Aux \rightarrow does$

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

$Verb \rightarrow book | include | prefer$



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

**[0,5]**

**Verb, VP, S**

[1,2]

**Verb, VP, S**

[1,3]

**Verb, VP, S**

[1,4]

**Verb, VP, S**

[1,5]

**VP, X2, S**

[1,6]

**VP, X2, S**

[1,7]

**VP, X2, S**

[1,8]

**VP, X2, S**

[1,9]

**VP, X2, S**

[1,10]

**VP, X2, S**

[1,11]

**VP, X2, S**

[1,12]

**VP, X2, S**

[1,13]

**VP, X2, S**

[1,14]

**VP, X2, S**

[1,15]

**VP, X2, S**

[1,16]

### Lexicon

$Det \rightarrow that | this | a$

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

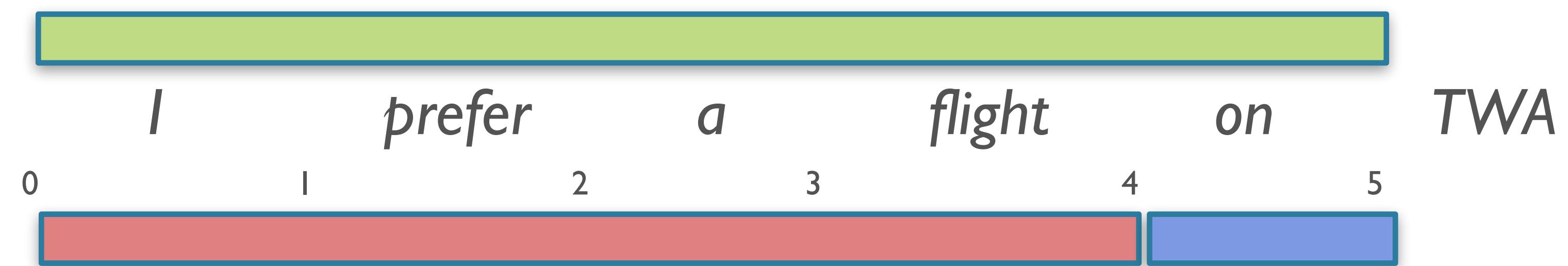
$Pronoun \rightarrow I | she | me$

$Proper-Noun \rightarrow Houston | TWA$

$Aux \rightarrow does$

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

$Verb \rightarrow book | include | prefer$



### L1 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]

[0,2]

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

[1,3]

**Det**  
[2,3]

[2,4]

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

[3,5]

**Prep**  
[4,5]

[5,6]

**NNP, NP**

**Lexicon**

$Det \rightarrow that | this | a$

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

$Pronoun \rightarrow I | she | me$

$Proper-Noun \rightarrow Houston | TWA$

$Aux \rightarrow does$

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

$Verb \rightarrow book | include | prefer$



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

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

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

$NP \rightarrow I | she | me$

$NP \rightarrow TWA | Houston$

$NP \rightarrow Det Nominal$

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

$Nominal \rightarrow Nominal Noun$

$Nominal \rightarrow Nominal PP$

$VP \rightarrow book | include | prefer$

$VP \rightarrow Verb NP$

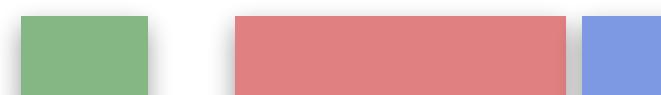
$VP \rightarrow X2 PP$

$X2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

$VP \rightarrow VP PP$

$PP \rightarrow Preposition NP$



$|$

*prefer*

*a*

*flight*

*on*

*TWA*

0

1

2

3

4

5

6

<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]	[1,5]
			<b>Det</b> [2,3]	<b>NP</b> [2,4]	
				<b>Noun, Nom</b> [3,4]	[3,5]
					<b>Prep</b> [4,5]

### Lexicon

$Det \rightarrow that | this | a$

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

$Pronoun \rightarrow I | she | me$

$Proper-Noun \rightarrow Houston | TWA$

$Aux \rightarrow does$

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

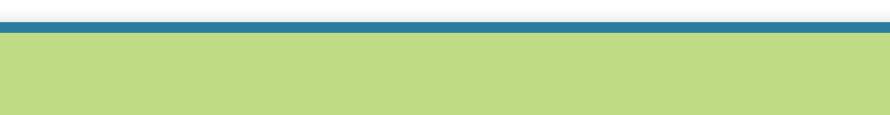
$Verb \rightarrow book | include | prefer$

**PP**

[4,6]

**NNP, NP**

[5,6]



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

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

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

$NP \rightarrow I | she | me$

$NP \rightarrow TWA | Houston$

$NP \rightarrow Det Nominal$

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

$Nominal \rightarrow Nominal Noun$

$Nominal \rightarrow Nominal PP$

$VP \rightarrow book | include | prefer$

$VP \rightarrow Verb NP$

$VP \rightarrow X2 PP$

$X2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

$VP \rightarrow VP PP$

$PP \rightarrow Preposition NP$

<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]		
			[2,5]		
			<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

$Det \rightarrow that | this | a$

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

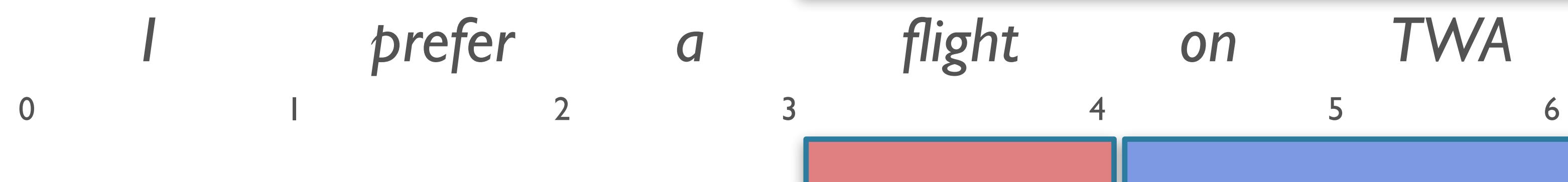
$Pronoun \rightarrow I | she | me$

$Proper-Noun \rightarrow Houston | TWA$

$Aux \rightarrow does$

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

$Verb \rightarrow book | include | prefer$



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

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

$S \rightarrow Verb PP$

$S \rightarrow VP PP$

$NP \rightarrow I | she | me$

$NP \rightarrow TWA | Houston$

$NP \rightarrow Det Nominal$

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

$Nominal \rightarrow Nominal Noun$

$Nominal \rightarrow Nominal PP$

$VP \rightarrow book | include | prefer$

$VP \rightarrow Verb NP$

$VP \rightarrow X2 PP$

$X2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

$VP \rightarrow VP PP$

$PP \rightarrow Preposition NP$

<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]		
			[2,5]		
			<b>Noun, Nom</b> [3,4]		<b>Nom</b> [3,6]
			[3,5]		
			<b>Prep</b> [4,5]		<b>PP</b> [4,6]

### Lexicon

$Det \rightarrow that | this | a$

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

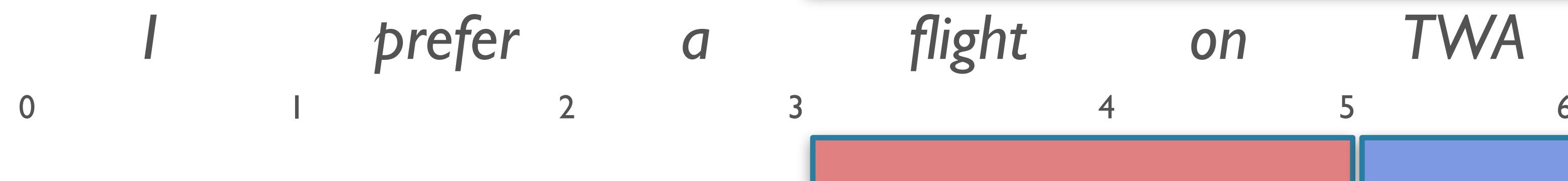
$Pronoun \rightarrow I | she | me$

$Proper-Noun \rightarrow Houston | TWA$

$Aux \rightarrow does$

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

$Verb \rightarrow book | include | prefer$



### $\mathcal{L}_1$ 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]	[1,5]	
		<b>Det</b> [2,3]	<b>NP</b> [2,4]	[2,5]	<b>NP</b> [2,6]
			<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]
<b>Lexicon</b>					
$Det \rightarrow that   this   a$ $Noun \rightarrow book   flight   meal   money$ $Pronoun \rightarrow I   she   me$ $Proper-Noun \rightarrow Houston   TWA$ $Aux \rightarrow does$ $Preposition \rightarrow from   to   on   near   through$ $Verb \rightarrow book   include   prefer$					



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

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

$S \rightarrow Verb PP$

$S \rightarrow VP PP$

$NP \rightarrow I | she | me$

$NP \rightarrow TWA | Houston$

$NP \rightarrow Det Nominal$

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

$Nominal \rightarrow Nominal Noun$

$Nominal \rightarrow Nominal PP$

$VP \rightarrow book | include | prefer$

$VP \rightarrow Verb NP$

$VP \rightarrow X2 PP$

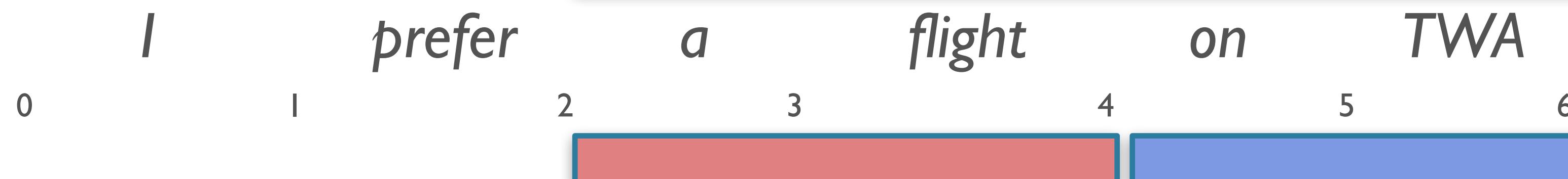
$X2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

$VP \rightarrow VP PP$

$PP \rightarrow Preposition NP$

<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]	[2,5]	<b>NP</b> [2,6]
			<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]
<b>Lexicon</b>					
$Det \rightarrow that   this   a$ $Noun \rightarrow book   flight   meal   money$ $Pronoun \rightarrow I   she   me$ $Proper-Noun \rightarrow Houston   TWA$ $Aux \rightarrow does$ $Preposition \rightarrow from   to   on   near   through$ $Verb \rightarrow book   include   prefer$					



### $\mathcal{L}_1$ 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]	[2,5]	<b>NP</b> [2,6]
			<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

$Det \rightarrow that | this | a$

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

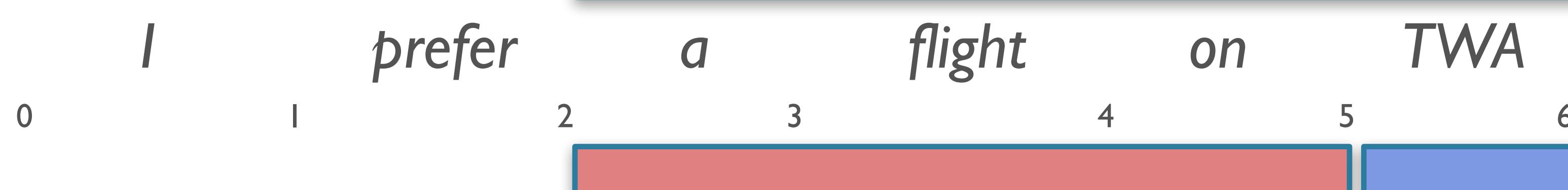
$Pronoun \rightarrow I | she | me$

$Proper-Noun \rightarrow Houston | TWA$

$Aux \rightarrow does$

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

$Verb \rightarrow book | include | prefer$



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

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

$S \rightarrow Verb PP$

$S \rightarrow VP PP$

$NP \rightarrow I | she | me$

$NP \rightarrow TWA | Houston$

$NP \rightarrow Det Nominal$

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

$Nominal \rightarrow Nominal Noun$

$Nominal \rightarrow Nominal PP$

$VP \rightarrow book | include | prefer$

$VP \rightarrow Verb NP$

$VP \rightarrow X2 PP$

$X2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

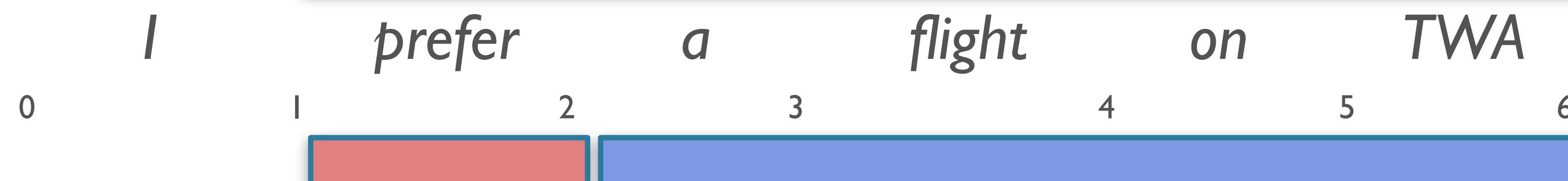
$VP \rightarrow VP PP$

$PP \rightarrow Preposition NP$

<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>Noun, Nom</b> [2,4]		
							<b>Prep</b> [2,5]	
								<b>PP</b> [2,6]
								<b>Nom</b> [3,6]
								<b>NNP, NP</b> [3,5]
								<b>[4,6]</b>
								<b>[5,6]</b>

**Lexicon**

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



### L1 Grammar

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

$NP \rightarrow I | she | me$

$NP \rightarrow TWA | Houston$

$NP \rightarrow Det Nominal$

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

$Nominal \rightarrow Nominal Noun$

$Nominal \rightarrow Nominal PP$

$VP \rightarrow book | include | prefer$

$VP \rightarrow Verb NP$

$VP \rightarrow X2 PP$

$X2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

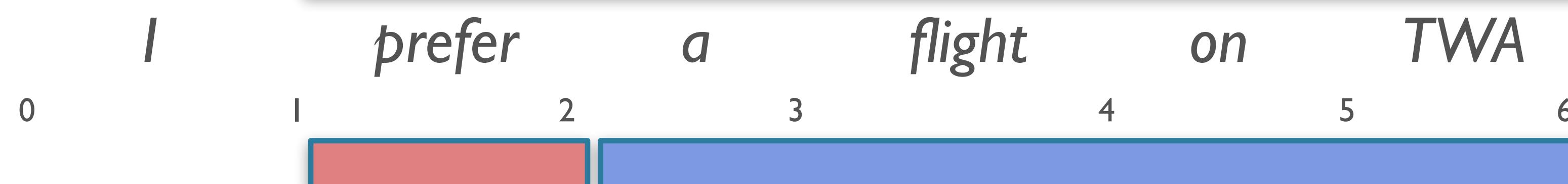
$VP \rightarrow VP PP$

$PP \rightarrow Preposition NP$

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

**Lexicon**

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



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

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

$NP \rightarrow I | she | me$

$NP \rightarrow TWA | Houston$

$NP \rightarrow Det Nominal$

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

$Nominal \rightarrow Nominal Noun$

$Nominal \rightarrow Nominal PP$

$VP \rightarrow book | include | prefer$

$VP \rightarrow Verb NP$

$VP \rightarrow X2 PP$

$X2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

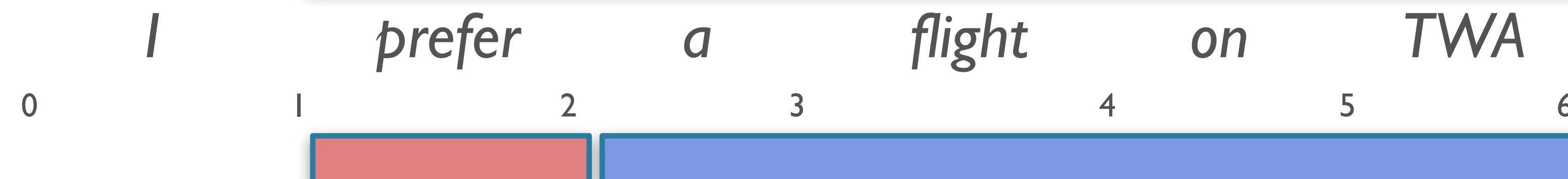
$VP \rightarrow VP PP$

$PP \rightarrow Preposition NP$

<b>NP, Pronoun</b> [0,1]	<b>S</b> [0,2]		<b>S</b> [0,3]		<b>S</b> [0,4]		<b>S</b> [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> [2,5]	<b>PP</b> [3,5]
								<b>NNP, NP</b> [4,5]
								<b>[5,6]</b>

**Lexicon**

$Det \rightarrow that | this | a$   
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 $Preposition \rightarrow from | to | on | near | through$   
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## $\mathcal{L}_1$ Grammar

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

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

$NP \rightarrow I | she | me$

$NP \rightarrow TWA | Houston$

$NP \rightarrow Det Nominal$

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

$Nominal \rightarrow Nominal Noun$

$Nominal \rightarrow Nominal PP$

$VP \rightarrow book | include | prefer$

$VP \rightarrow Verb NP$

$VP \rightarrow X2 PP$

$X2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

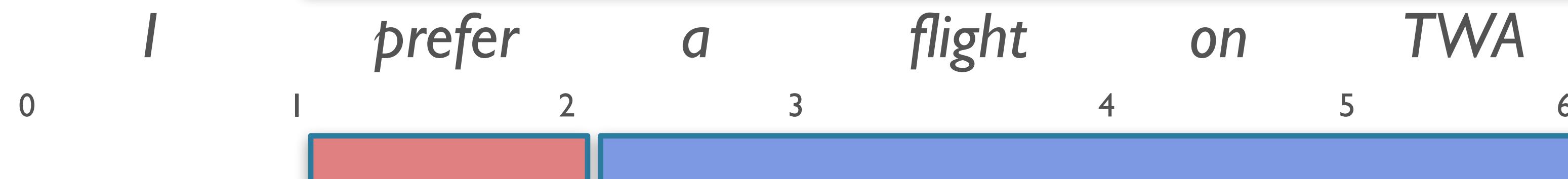
$VP \rightarrow VP PP$

$PP \rightarrow Preposition NP$

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

**Lexicon**

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

$NP \rightarrow I | she | me$

$NP \rightarrow TWA | Houston$

$NP \rightarrow Det Nominal$

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

$Nominal \rightarrow Nominal Noun$

$Nominal \rightarrow Nominal PP$

$VP \rightarrow book | include | prefer$

$VP \rightarrow Verb NP$

$VP \rightarrow X2 PP$

$X2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

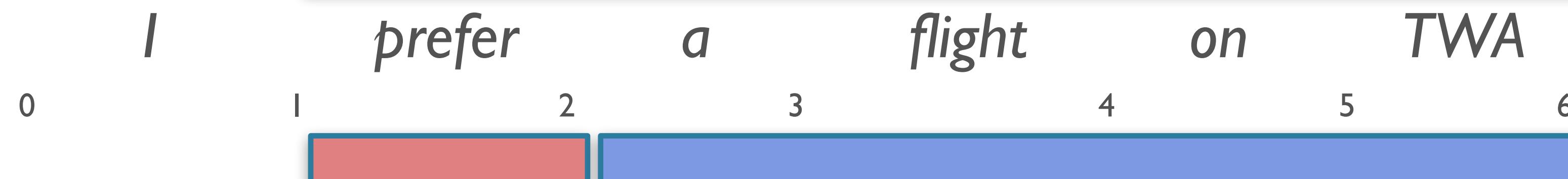
$VP \rightarrow VP PP$

$PP \rightarrow Preposition NP$

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

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 $S \rightarrow Verb PP$   
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$NP \rightarrow I | she | me$

$NP \rightarrow TWA | Houston$

$NP \rightarrow Det Nominal$

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

$Nominal \rightarrow Nominal Noun$

$Nominal \rightarrow Nominal PP$

$VP \rightarrow book | include | prefer$

$VP \rightarrow Verb NP$

$VP \rightarrow X2 PP$

$X2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

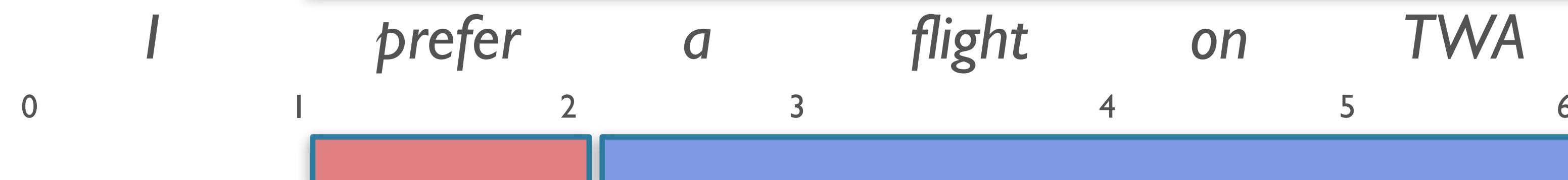
$VP \rightarrow VP PP$

$PP \rightarrow Preposition NP$

NP, Pronoun [0,1]	S [0,2]	[0,3]	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]
					NNP, NP [5,6]

**Lexicon**

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$S \rightarrow VP PP$

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$NP \rightarrow Det Nominal$

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

$Nominal \rightarrow Nominal Noun$

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$VP \rightarrow book | include | prefer$

$VP \rightarrow Verb NP$

$VP \rightarrow X2 PP$

$X2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

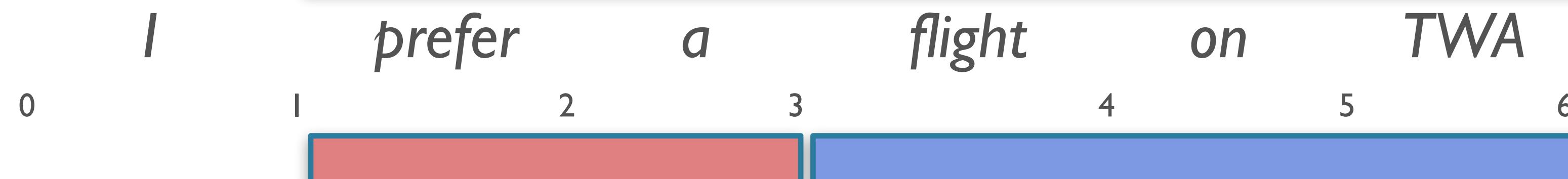
$VP \rightarrow VP PP$

$PP \rightarrow Preposition NP$

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

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

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

$S \rightarrow VP PP$

$NP \rightarrow I | she | me$

$NP \rightarrow TWA | Houston$

$NP \rightarrow Det Nominal$

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

$Nominal \rightarrow Nominal Noun$

$Nominal \rightarrow Nominal PP$

$VP \rightarrow book | include | prefer$

$VP \rightarrow Verb NP$

$VP \rightarrow X2 PP$

$X2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

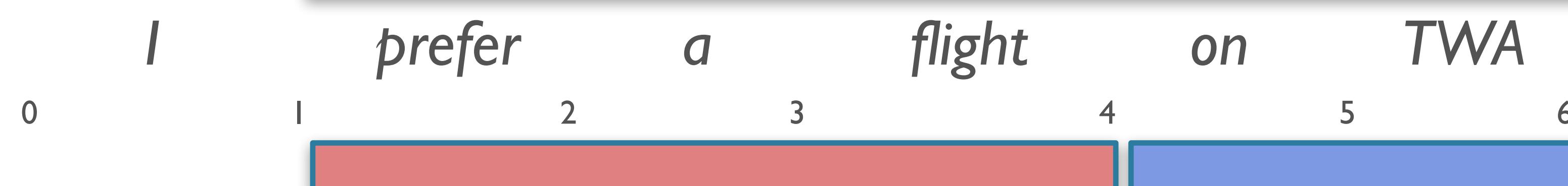
$VP \rightarrow VP PP$

$PP \rightarrow Preposition NP$

NP, Pronoun [0,1]	S [0,2]		S [0,4]		
		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]
					Prep [4,5]
					PP [4,6]
					NNP, NP [5,6]

**Lexicon**

$Det \rightarrow that | this | a$   
 $Noun \rightarrow book | flight | meal | money$   
 $Pronoun \rightarrow I | she | me$   
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## L1 Grammar

$S \rightarrow NP VP$   
 $S \rightarrow X1 VP$   
 $X1 \rightarrow Aux NP$   
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 $S \rightarrow X2 PP$

$S \rightarrow Verb PP$

$S \rightarrow VP PP$

$NP \rightarrow I | she | me$

$NP \rightarrow TWA | Houston$

$NP \rightarrow Det Nominal$

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

$Nominal \rightarrow Nominal Noun$

$Nominal \rightarrow Nominal PP$

$VP \rightarrow book | include | prefer$

$VP \rightarrow Verb NP$

$VP \rightarrow X2 PP$

$X2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

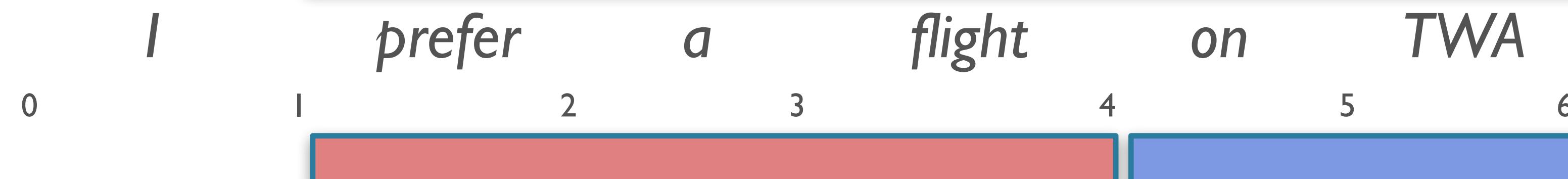
$VP \rightarrow VP PP$

$PP \rightarrow Preposition NP$

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]		
						[2,5]		NP [2,6]
								Nom [3,6]
								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

$S \rightarrow NP VP$   
 $S \rightarrow X1 VP$   
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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</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>NP</b> [1,6]
			<b>[2,3]</b>	<b>[2,4]</b>	<b>[2,5]</b>
				<b>Noun, Nom</b> [3,4]	
					<b>Nom</b> [3,6]
				<b>[3,5]</b>	
					<b>PP</b> [4,6]
				<b>[4,5]</b>	<b>NNP, NP</b> [5,6]

### Lexicon

$Det \rightarrow that | this | a$

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

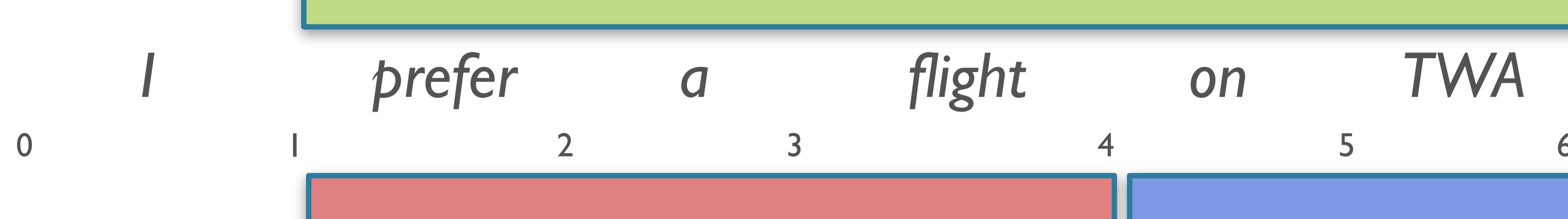
$Pronoun \rightarrow I | she | me$

$Proper-Noun \rightarrow Houston | TWA$

$Aux \rightarrow does$

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

$Verb \rightarrow book | include | prefer$



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

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

$S \rightarrow Verb PP$

$S \rightarrow VP PP$

$NP \rightarrow I | she | me$

$NP \rightarrow TWA | Houston$

$NP \rightarrow Det Nominal$

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

$Nominal \rightarrow Nominal Noun$

$Nominal \rightarrow Nominal PP$

$VP \rightarrow book | include | prefer$

$VP \rightarrow Verb NP$

$VP \rightarrow X2 PP$

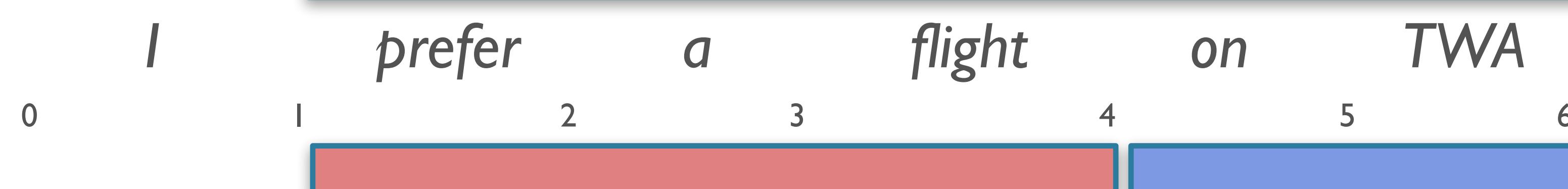
$X2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

$VP \rightarrow VP PP$

$PP \rightarrow Preposition NP$

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



### $\mathcal{L}_1$ 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 [1,4]</b>	<b>VP, X2, S [1,6]</b>
			<b>Det [1,3]</b>	<b>NP [1,5]</b>	<b>NP [2,6]</b>
				<b>[2,4]</b>	<b>[2,5]</b>
				<b>Noun, Nom [3,4]</b>	<b>Nom [3,6]</b>
					<b>Prep [4,5]</b>

### Lexicon

$Det \rightarrow that | this | a$

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

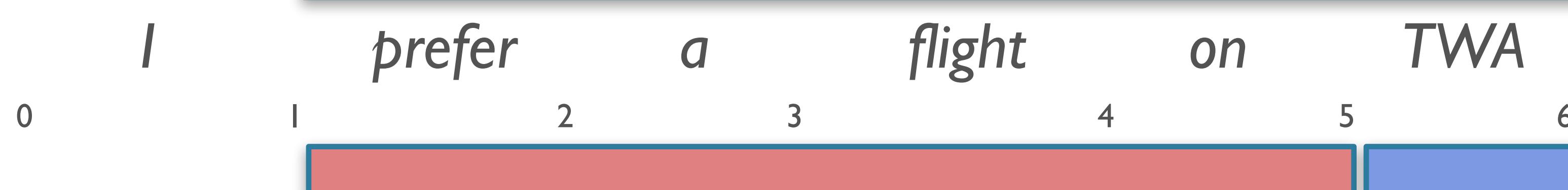
$Pronoun \rightarrow I | she | me$

$Proper-Noun \rightarrow Houston | TWA$

$Aux \rightarrow does$

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

$Verb \rightarrow book | include | prefer$

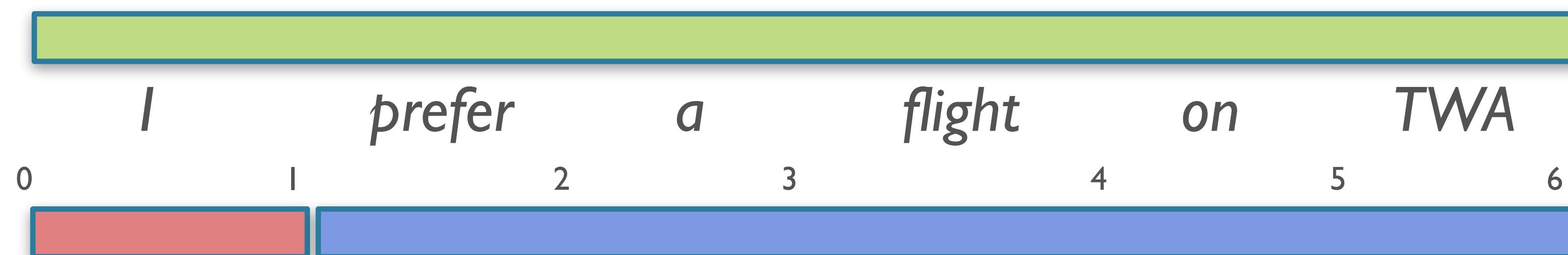


$\mathcal{L}_1$ Grammar
$S \rightarrow NP VP$
$S \rightarrow X1 VP$
$X1 \rightarrow Aux NP$
$S \rightarrow book   include   prefer$
$S \rightarrow Verb NP$
$S \rightarrow X2 PP$
$S \rightarrow Verb PP$
$S \rightarrow VP PP$
-----
$NP \rightarrow I   she   me$
$NP \rightarrow TWA   Houston$
$NP \rightarrow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

NP, Pronoun [0,1]	S [0,2]		S [0,3]		S [0,4]		[0,5]	[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]
								NNP, NP [5,6]

**Lexicon**

$Det \rightarrow that | this | a$   
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 $Aux \rightarrow does$   
 $Preposition \rightarrow from | to | on | near | through$   
 $Verb \rightarrow book | include | prefer$

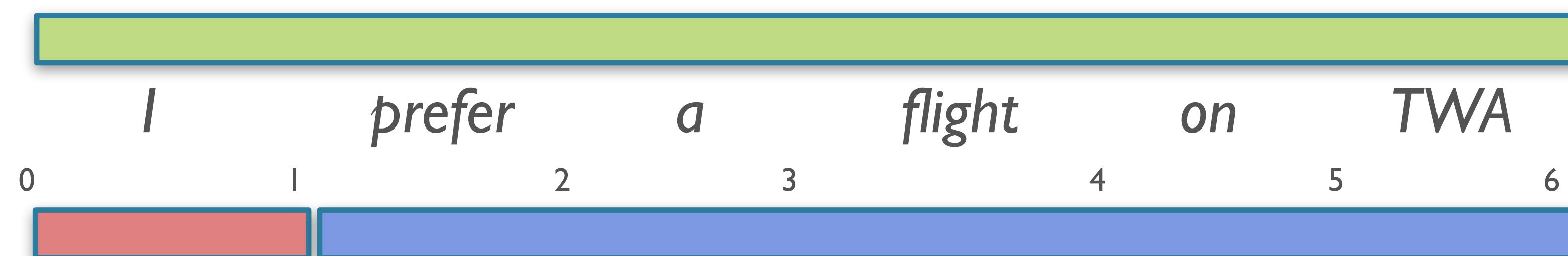


$\mathcal{L}_1$ Grammar
$S \rightarrow NP \mid VP$
$S \rightarrow X_1 \mid VP$
$X_1 \rightarrow Aux \mid NP$
$S \rightarrow book \mid I \mid include \mid prefer$
$S \rightarrow Verb \mid NP$
$S \rightarrow X_2 \mid PP$
$S \rightarrow Verb \mid PP$
$S \rightarrow VP \mid PP$
<hr/>
$NP \rightarrow I \mid she \mid me$
$NP \rightarrow TWA \mid Houston$
$NP \rightarrow Det \mid Nominal$
<hr/>
$Nominal \rightarrow book \mid flight \mid meal \mid money$
$Nominal \rightarrow Nominal \mid Noun$
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<hr/>
$VP \rightarrow book \mid include \mid prefer$
$VP \rightarrow Verb \mid NP$
$VP \rightarrow X_2 \mid PP$
$X_2 \rightarrow Verb \mid NP$
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$VP \rightarrow VP \mid PP$
<hr/>
$PP \rightarrow Preposition \mid NP$

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, X <sub>2</sub> , S [1,4]		VP, X <sub>2</sub> , S [1,6]
		Det [2,3]	NP [2,4]		NP [2,6]
			Noun, Nom [3,4]		Nom [3,6]
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**Lexicon**

*Det → that | this | a*  
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*Preposition → from | to | on | near | through*  
*Verb → book | include | prefer*



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

$S \rightarrow NP VP$   
 $S \rightarrow X1 VP$   
 $X1 \rightarrow Aux NP$   
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$X2 \rightarrow Verb NP$

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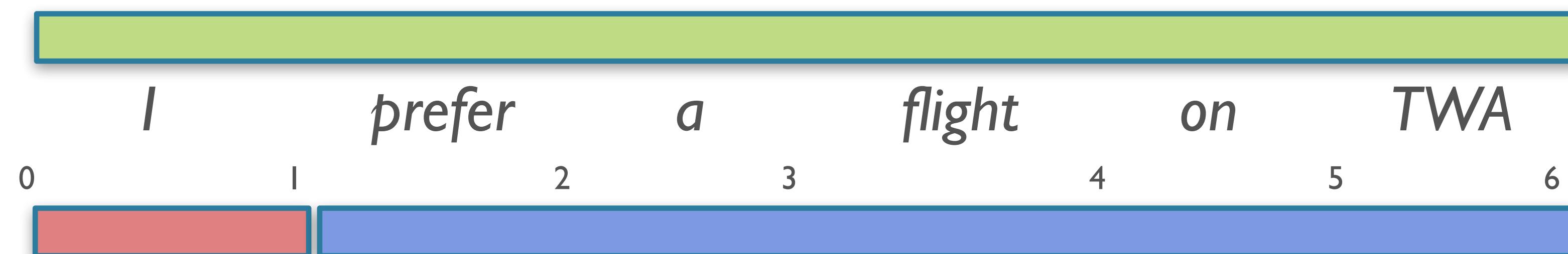
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NP, Pronoun [0,1]	S [0,2]	[0,3]	S [0,4]	[0,5]	S [0,6]
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		Det [2,3]	NP [2,4]		NP [2,6]
			Noun, Nom [3,4]		Nom [3,6]
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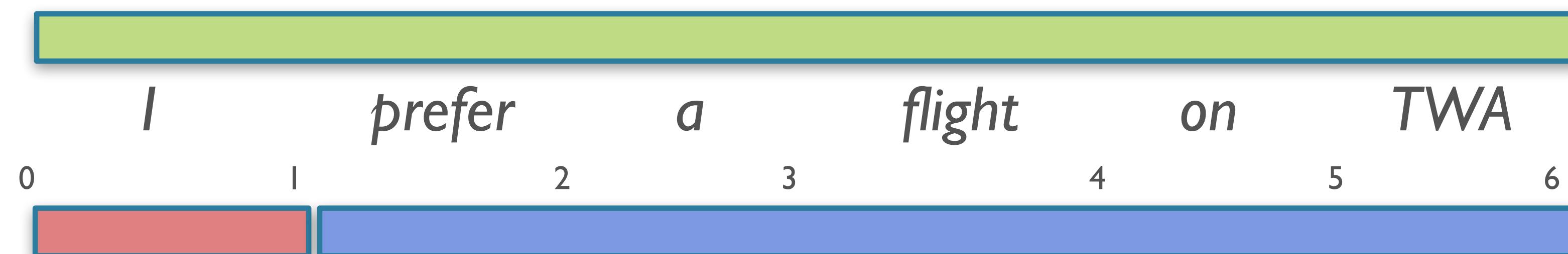
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NP, Pronoun [0,1]	S [0,2]		S [0,3]		S [0,4]		S [0,5]	S [0,6]
		Verb, VP, S [1,2]			VP, X2, S [1,3]			VP, X2, S [1,4]
				Det [2,3]		NP [2,4]		NP [2,5]
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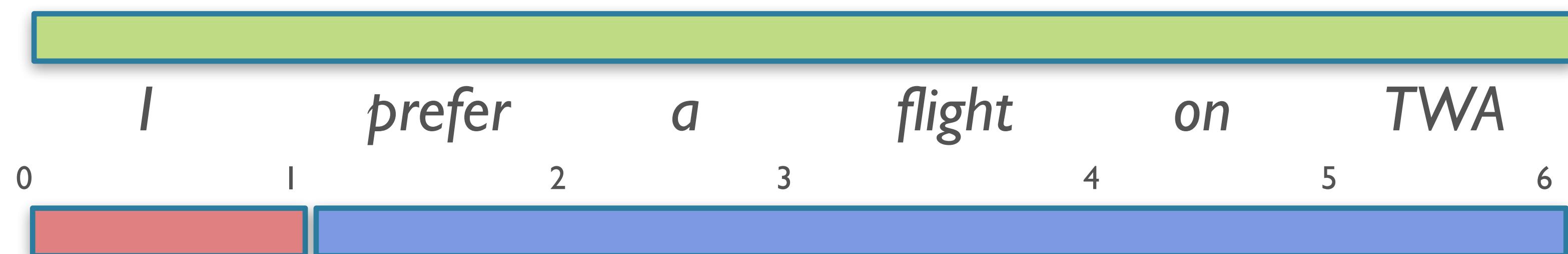
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NP, Pronoun [0,1]	S [0,2]		S [0,4]		S [0,6]
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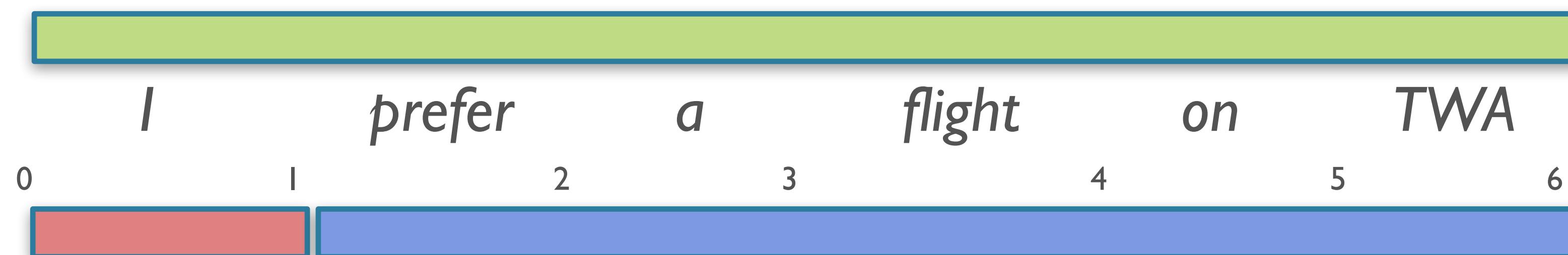
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$Proper-Noun \rightarrow Houston \mid TWA$

$Aux \rightarrow does$

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

$Verb \rightarrow book \mid include \mid prefer$



# 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** → **VP PP**

`bp_1 = BackPointer()`  
`bp_1.l_child = [VP, (1, 4)]`  
`bp_1.r_child = [PP, (4, 6)]`

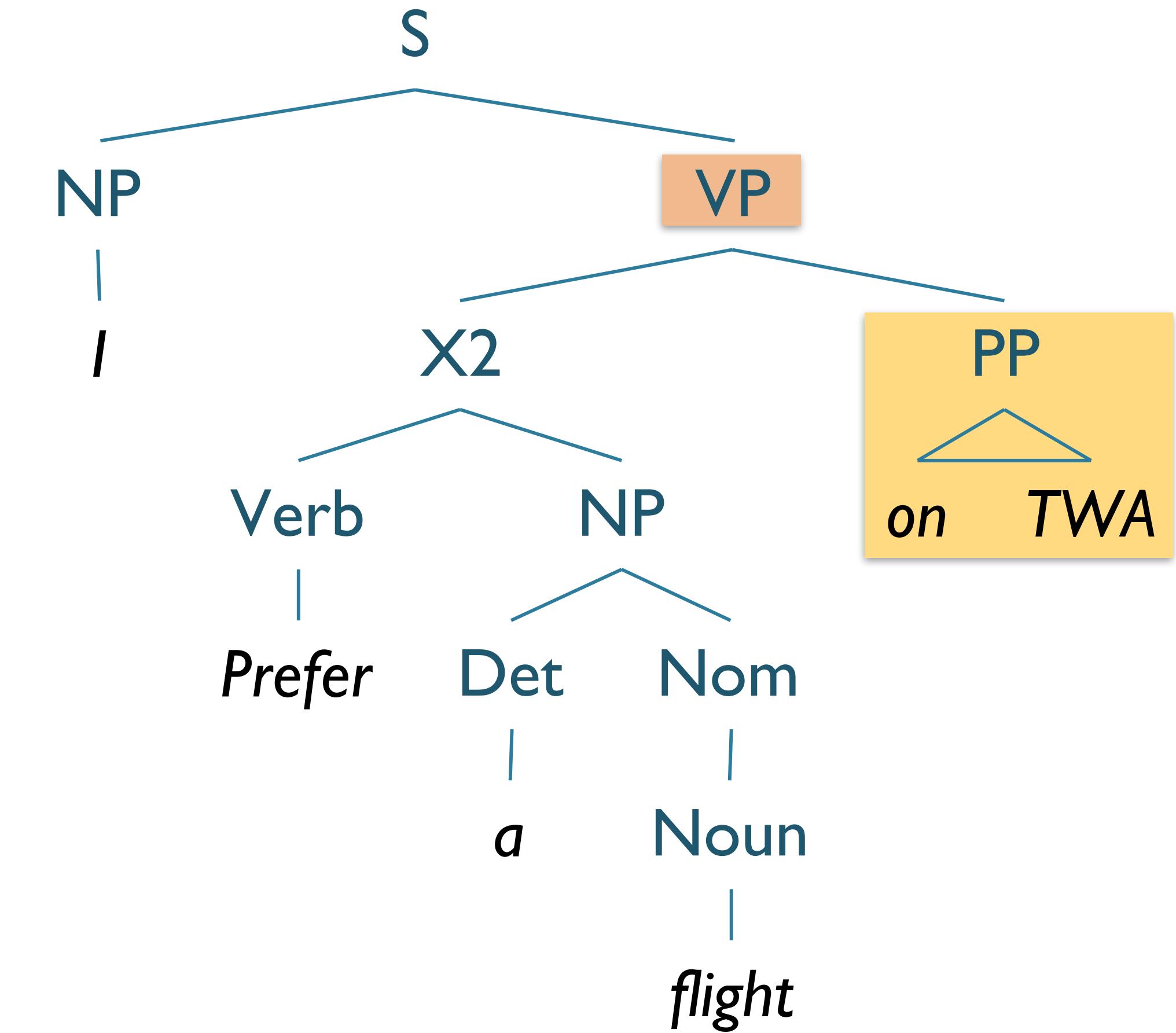
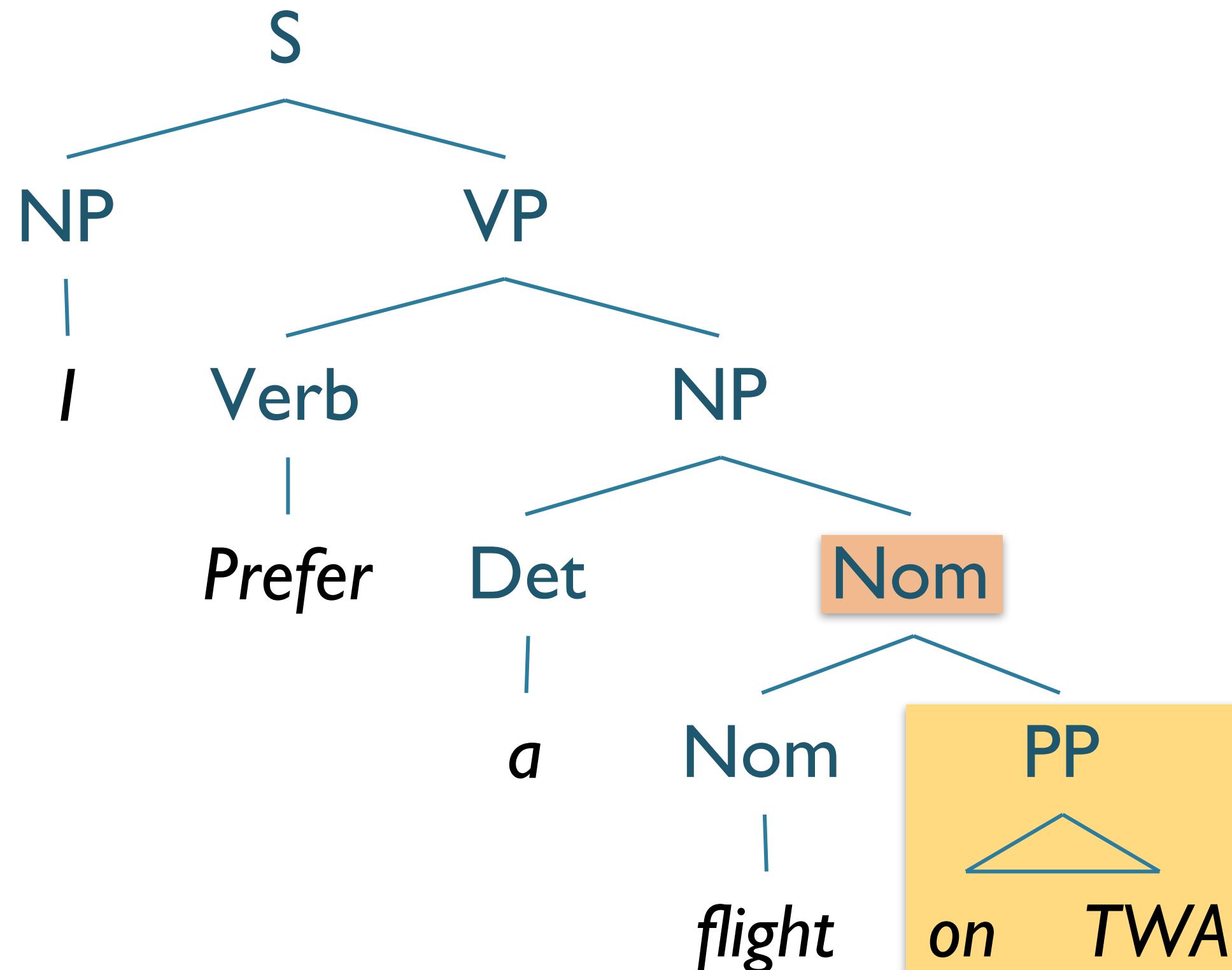
<b>NP, Pronoun</b> [0,1]	<b>S</b> [0,2]	[0,3]	<b>S</b> [0,4]	[0,5]	<b>VP</b>
	<b>Verb, VP, S</b> [1,2]	[1,3]	<b>VP, X2, S</b> [1,4]	[1,5]	<b>VP</b> [1,6]
		<b>Det</b> [2,3]	<b>NP</b> [2,4]	[2,5]	<b>NP</b> [2,6]
			<b>Noun, Nom</b> [3,4]	[3,5]	<b>Nom</b> [3,6]
				<b>Prep</b> [4,5]	<b>PP</b> [4,6]
		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

**VP** → **X2 PP**

`bp_2 = BackPointer()`  
`bp_2.l_child = [X2, (1, 4)]`  
`bp_2.r_child = [PP, (4, 6)]`

<b>NP, Pronoun</b> [0,1]	<b>S</b> [0,2]	[0,3]	<b>S</b> [0,4]	[0,5]	<b>VP</b>
	<b>Verb, VP, S</b> [1,2]	[1,3]	<b>VP, X2, S</b> [1,4]	[1,5]	<b>VP</b> [1,6]
		<b>Det</b> [2,3]	<b>NP</b> [2,4]	[2,5]	<b>NP</b> [2,6]
			<b>Noun, Nom</b> [3,4]	[3,5]	<b>Nom</b> [3,6]
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# 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 12, 2020

# 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**)

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$R$

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  $P(\beta | A)$

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---

$S$

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]	$Det \rightarrow that [.10]   a [.30]   the [.60]$
$S \rightarrow Aux NP VP$	[.15]	$Noun \rightarrow book [.10]   flight [.30]   meal [.15]   money [0.5]$
$S \rightarrow VP$	[.05]	$  flights [0.40]   dinner [.10]$
$NP \rightarrow Pronoun$	[.35]	$Verb \rightarrow book [.30]   include [.30]   prefer [.40]$
$NP \rightarrow Proper-Noun$	[.30]	$Pronoun \rightarrow I [.40]   she [.05]   me [.15]   you [.40]$
$NP \rightarrow Det Nominal$	[.20]	$Proper-Noun \rightarrow Houston [.60]   NWA [.40]$
$NP \rightarrow Nominal$	[.15]	$Aux \rightarrow does [.60]   can [.40]$
$Nominal \rightarrow Noun$	[.75]	$Preposition \rightarrow from [.30]   to [.30]   on [.20]   near [.15]$
$Nominal \rightarrow Nominal Noun$	[.20]	$  through [.05]$
$Nominal \rightarrow Nominal PP$	[.05]	
$VP \rightarrow Verb$	[.35]	
$VP \rightarrow Verb NP$	[.20]	
$VP \rightarrow Verb NP PP$	[.10]	
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# Example PCFG: Augmented $\mathcal{L}_1$

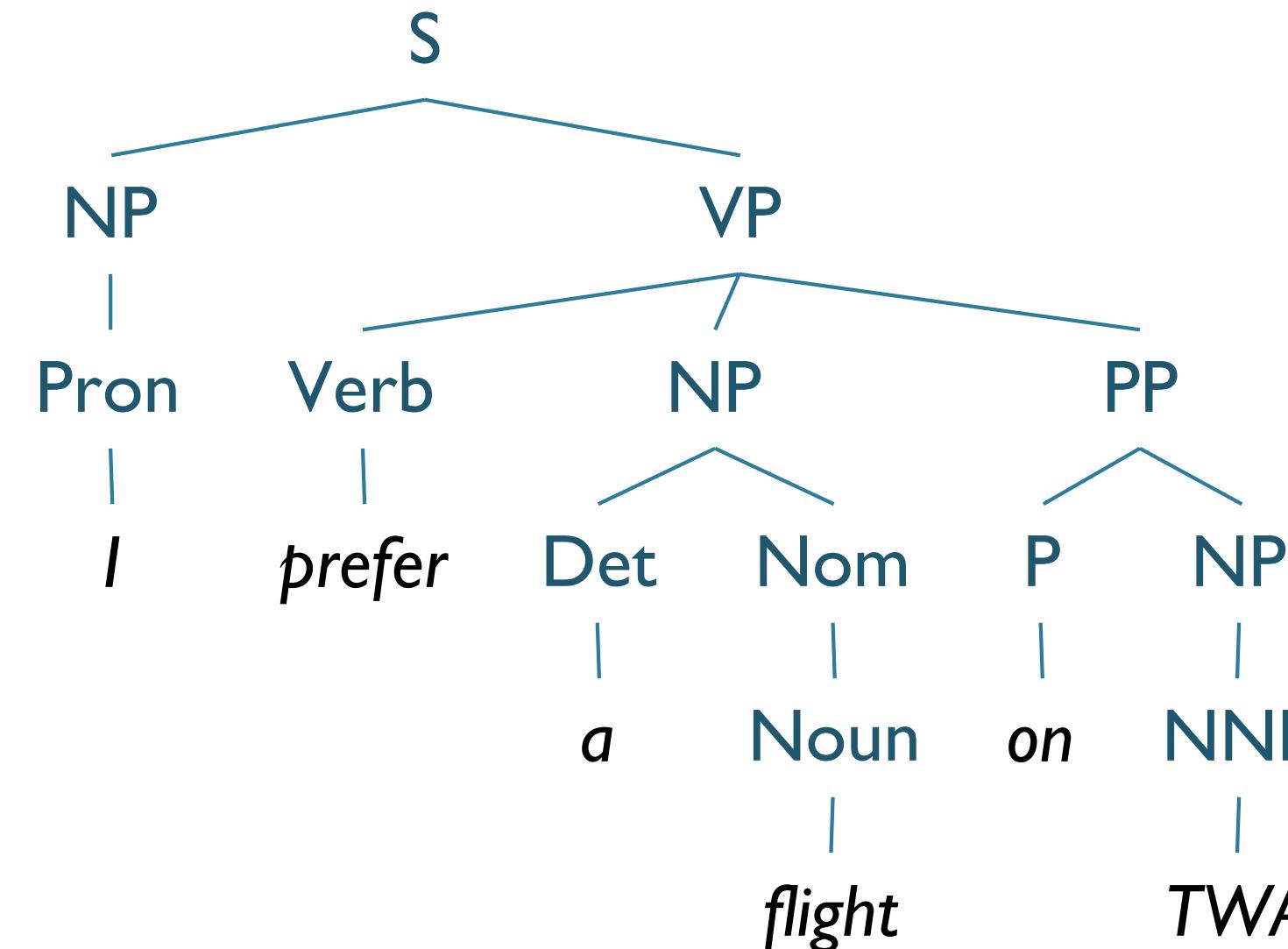
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# Disambiguation

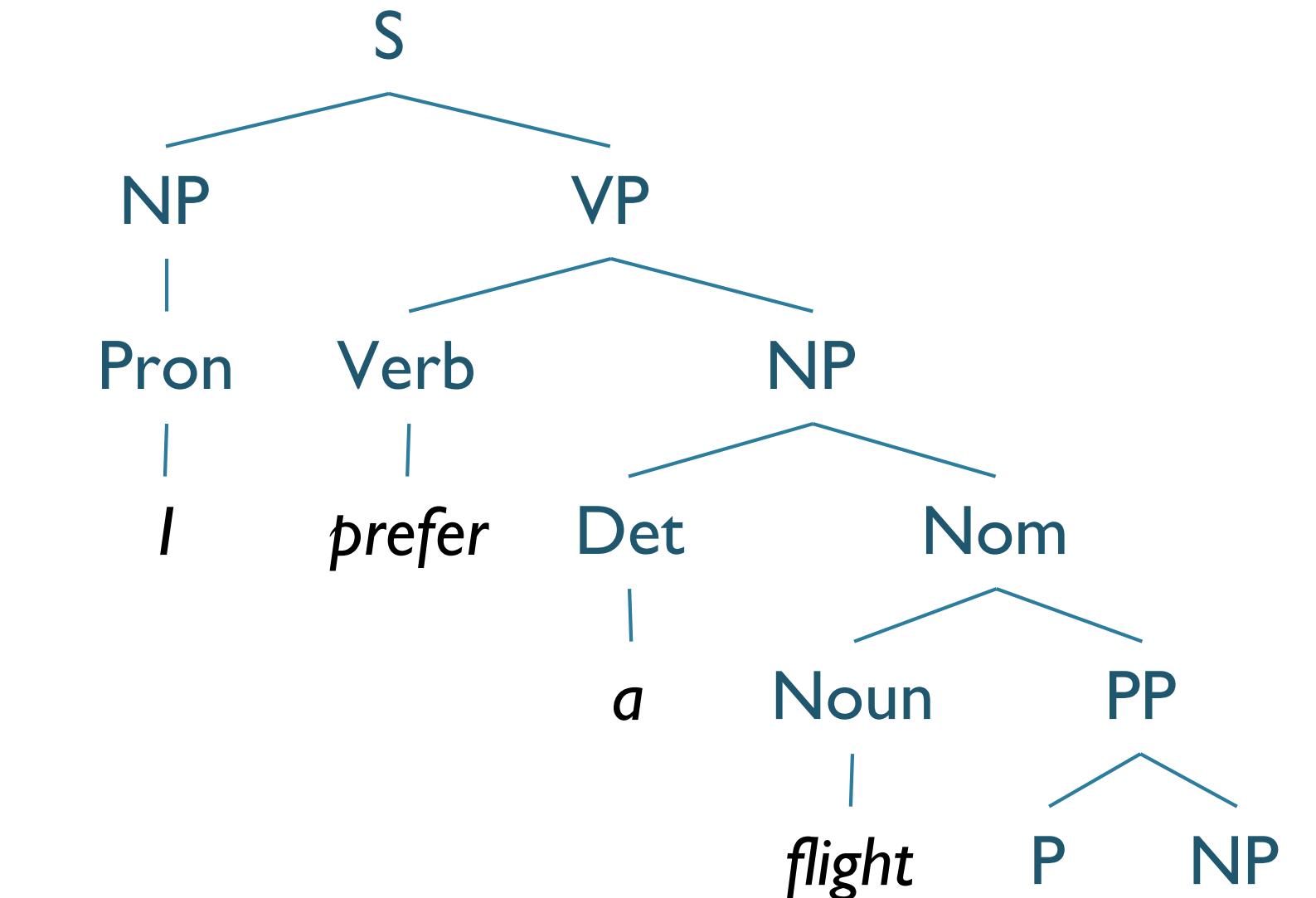
- A PCFG assigns probability to each parse tree  $T$  for input  $S$
- Probability of  $T$ : product of all rules used to derive  $T$

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

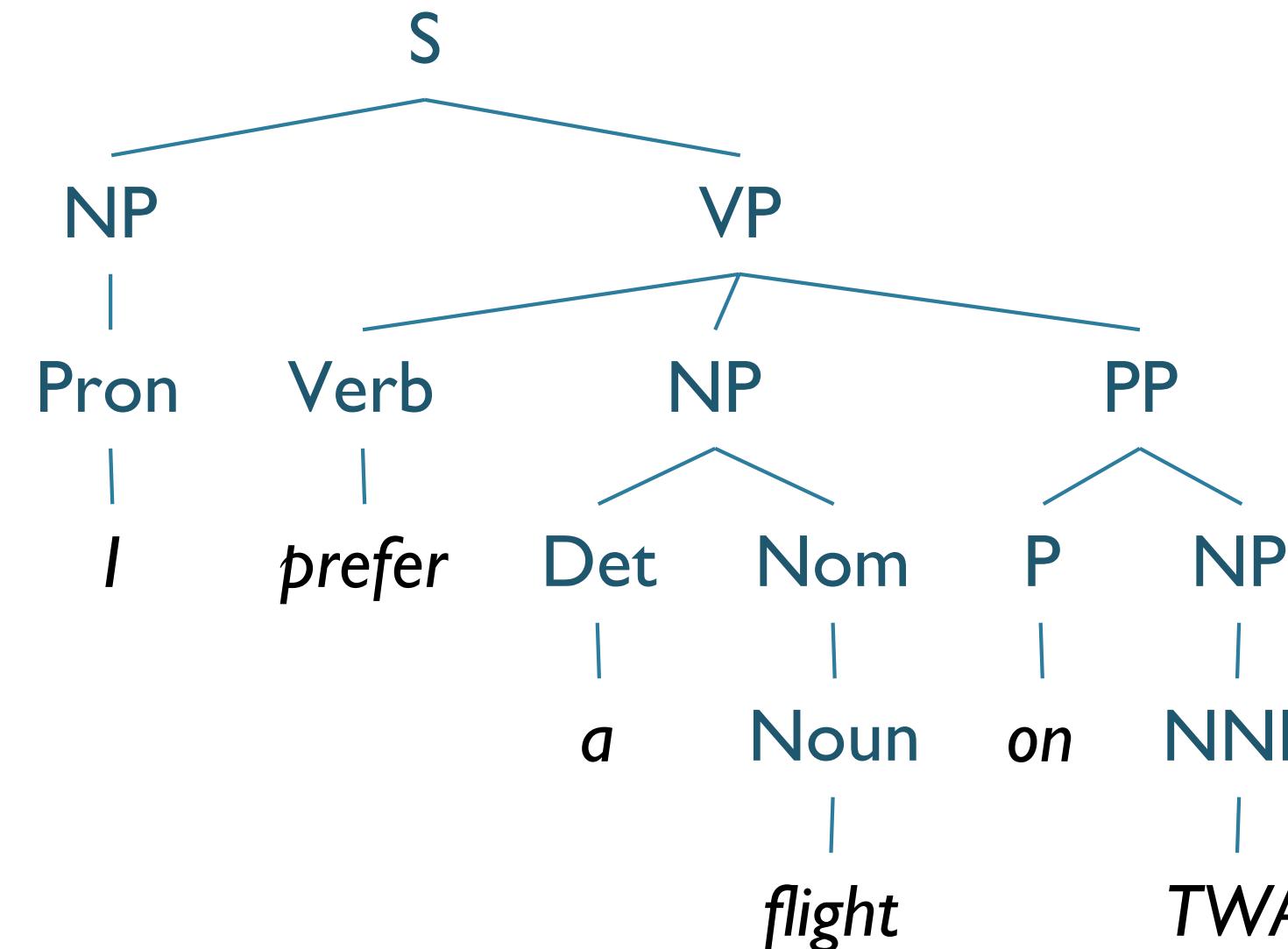
$$P(T, S) = P(T)P(S \mid T) = P(T)$$



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$V \rightarrow prefer$	[0.4]
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$Det \rightarrow a$	[0.3]
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$N \rightarrow flight$	[0.3]
$PP \rightarrow P NP$	[1.0]
$P \rightarrow on$	[0.2]
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$NNP \rightarrow NWA$	[0.4]

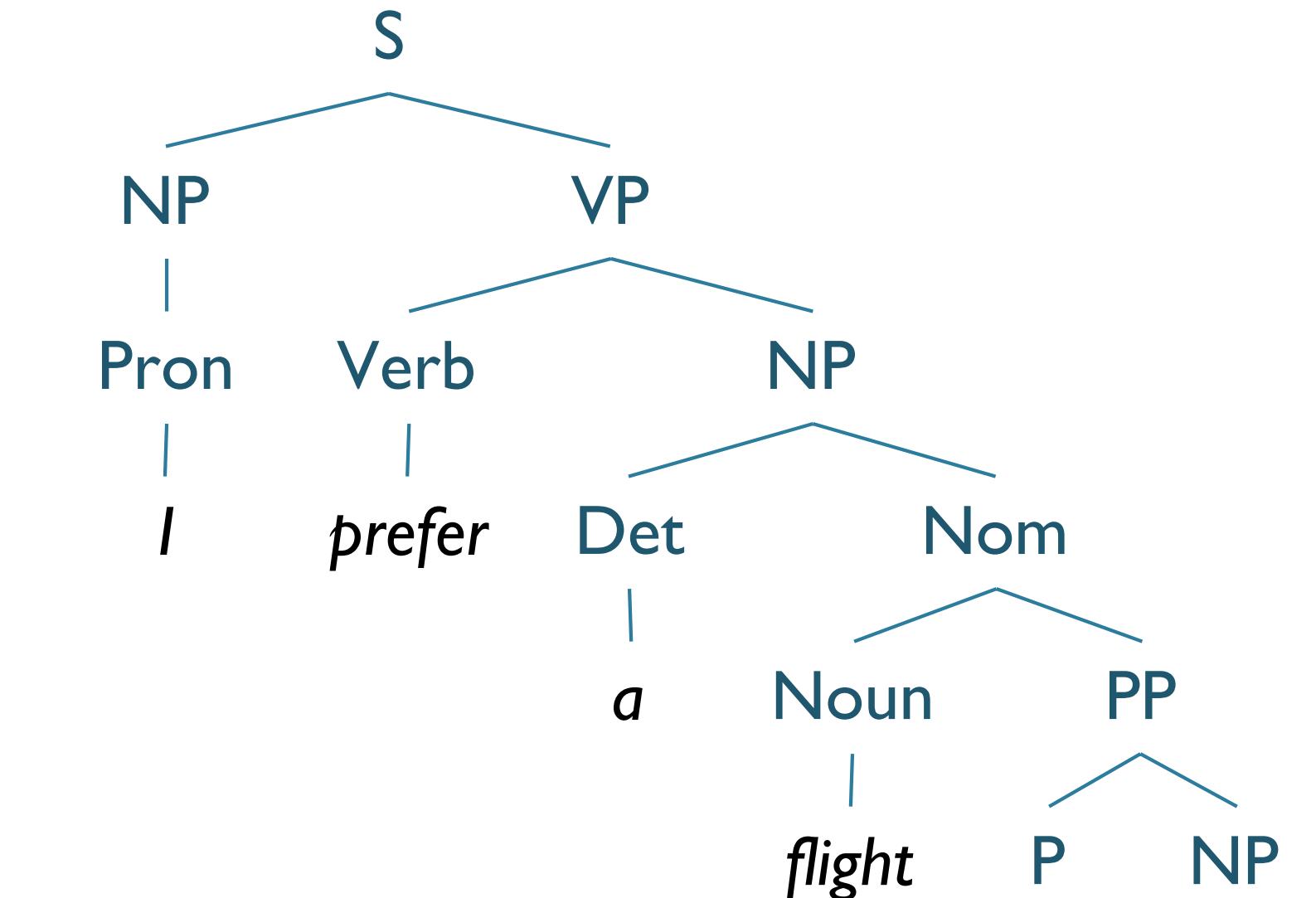


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$\sim 1.452 \times 10^{-6}$



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

# 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
```

# Unit Testing in Python

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```
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