

CKY Parsing

LING 571 — Deep Processing Techniques for NLP

October 11, 2021

Shane Steinert-Threlkeld

Announcements

- HW1 grades posted; will aim for Mondays in general
- 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

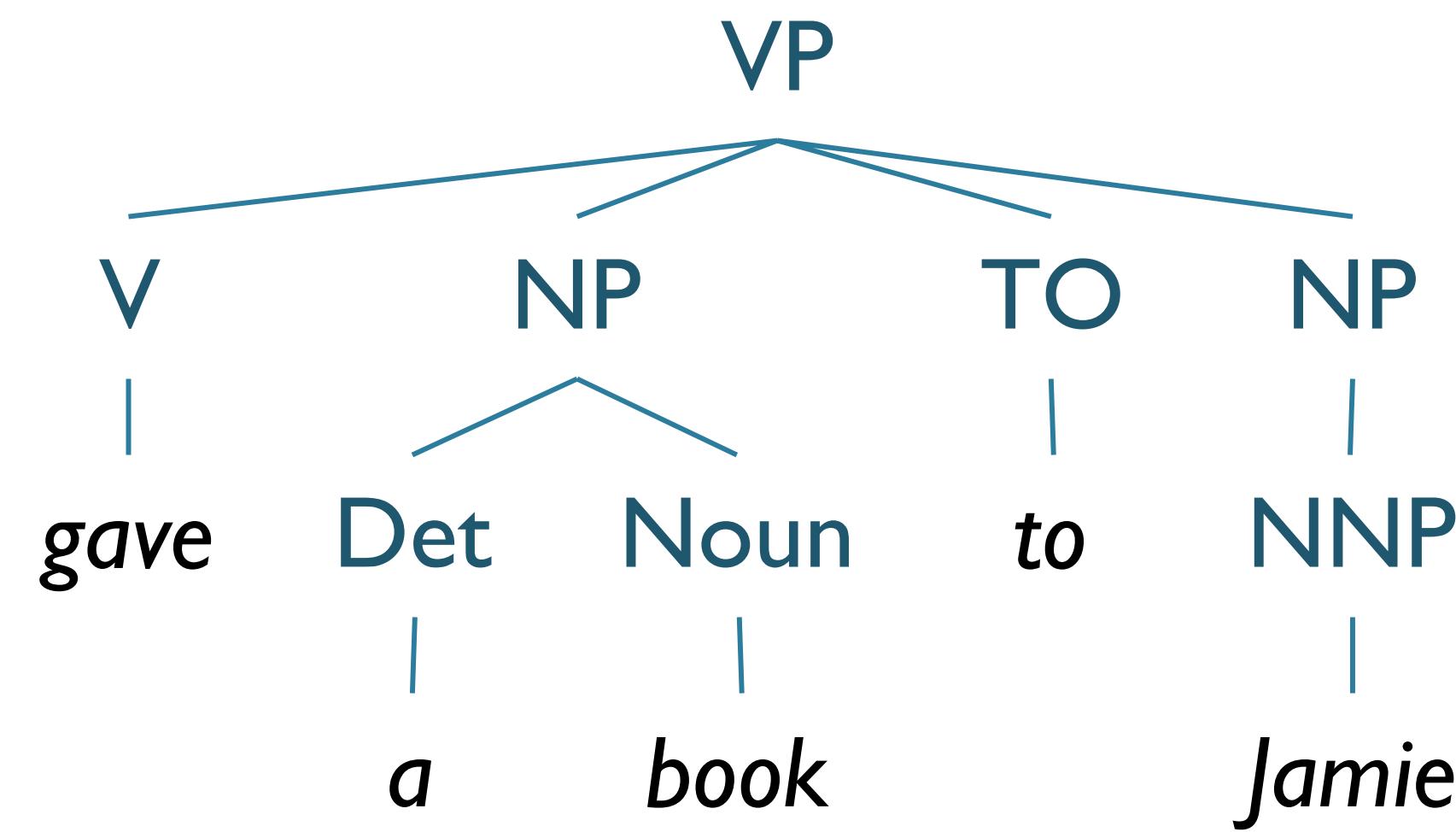
Announcements: HW #2

- Due Wednesday, 11:59pm 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
- Execute the conversion rules in the order that they are on the slides.
- Unit productions: any *non-unit* RHS that can be reached by a sequence of units. I updated the CNF slides to be clearer on this.

Variation in CNF: Binarization

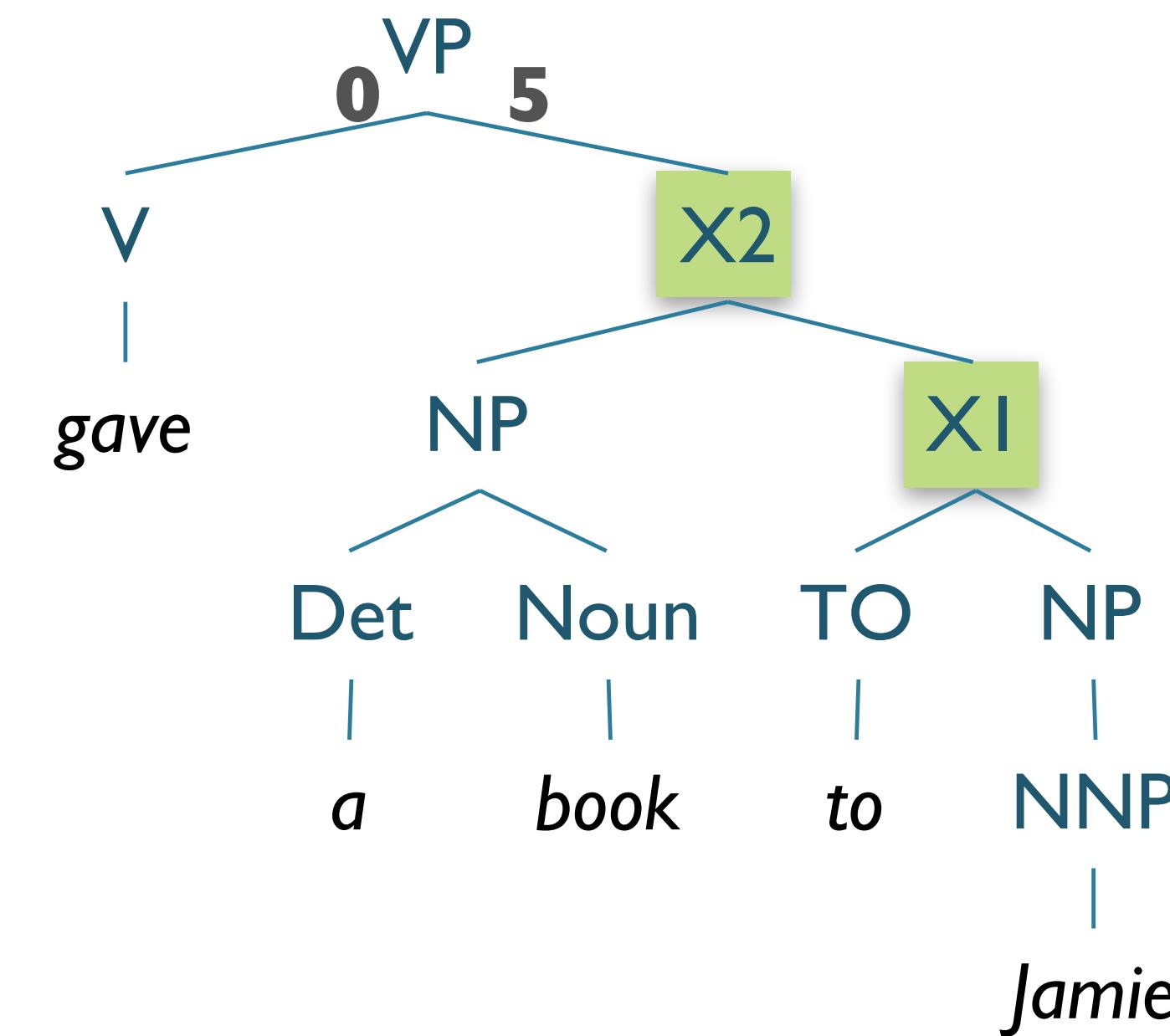
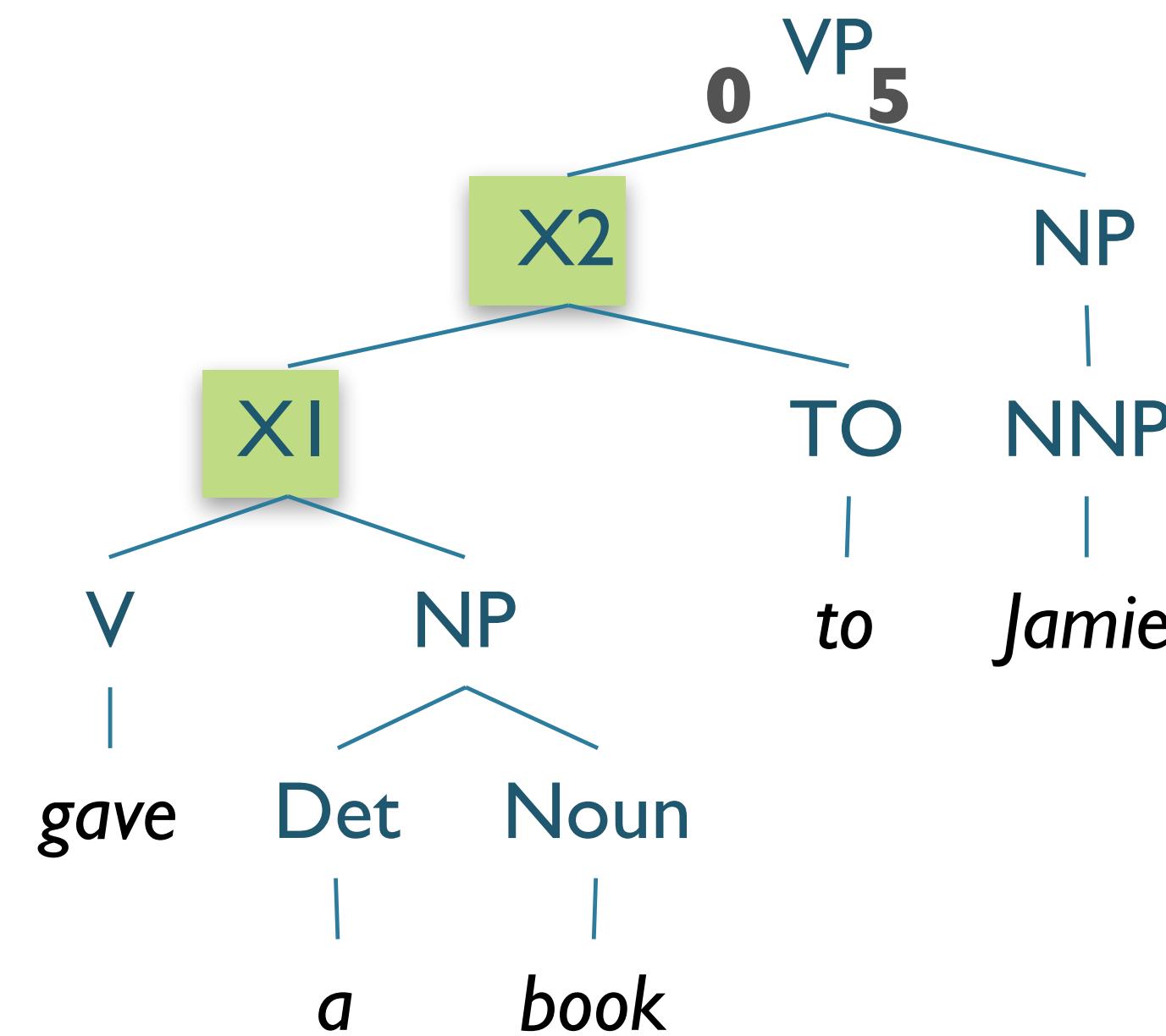
Original Rule

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



Variation in CNF: Binarization

Original Rule			
$VP \rightarrow V \ NP \ TO \ NP$			
Left to Right Reduction		Right to Left Reduction	
$VP \rightarrow X_1 \ TO \ NP$	$X_1 \rightarrow V \ NP$	$VP \rightarrow V \ NP \ X_1$	$X_1 \rightarrow TO \ NP$
$VP \rightarrow X_2 \ NP$	$X_2 \rightarrow X_1 \ TO$	$VP \rightarrow V \ X_2$	$X_2 \rightarrow NP \ X_1$



Indigenous Peoples' Day

- Seattle/Sealth/Si'ahl



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- The Lushootseed spelling [IPA] of Chief Seattle/Sealth/Si'ahl:
 - siʔat [siʔa:t]



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 - Source, with more Lushootseed: <https://historylink.org/File/8156>



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- IPA resources:
 - https://en.wikipedia.org/wiki/International_Phonetic_Alphabet
 - <http://web.mit.edu/6.mitx/www/24.900%20IPA/IPAapp.html>



Indigenous Peoples' Day

- 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]
 - **?učw** **ti** **sbiaw**
goes **that-which** **is-a-coyote**
“The/a coyote goes”
 - **sbiaw** **ti** **?učw**
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”
 - (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://tulalippluslushootseed.com/>

Roadmap

- CKY Parsing Algorithm

- Dynamic programming structure

- Algorithm and example

- Analysis & Discussion

- Next time: Probabilistic CFGs

- Motivation: Ambiguity

- Augmenting CFGs with probabilities

CKY

- Given an input string S of length n

CKY

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CKY

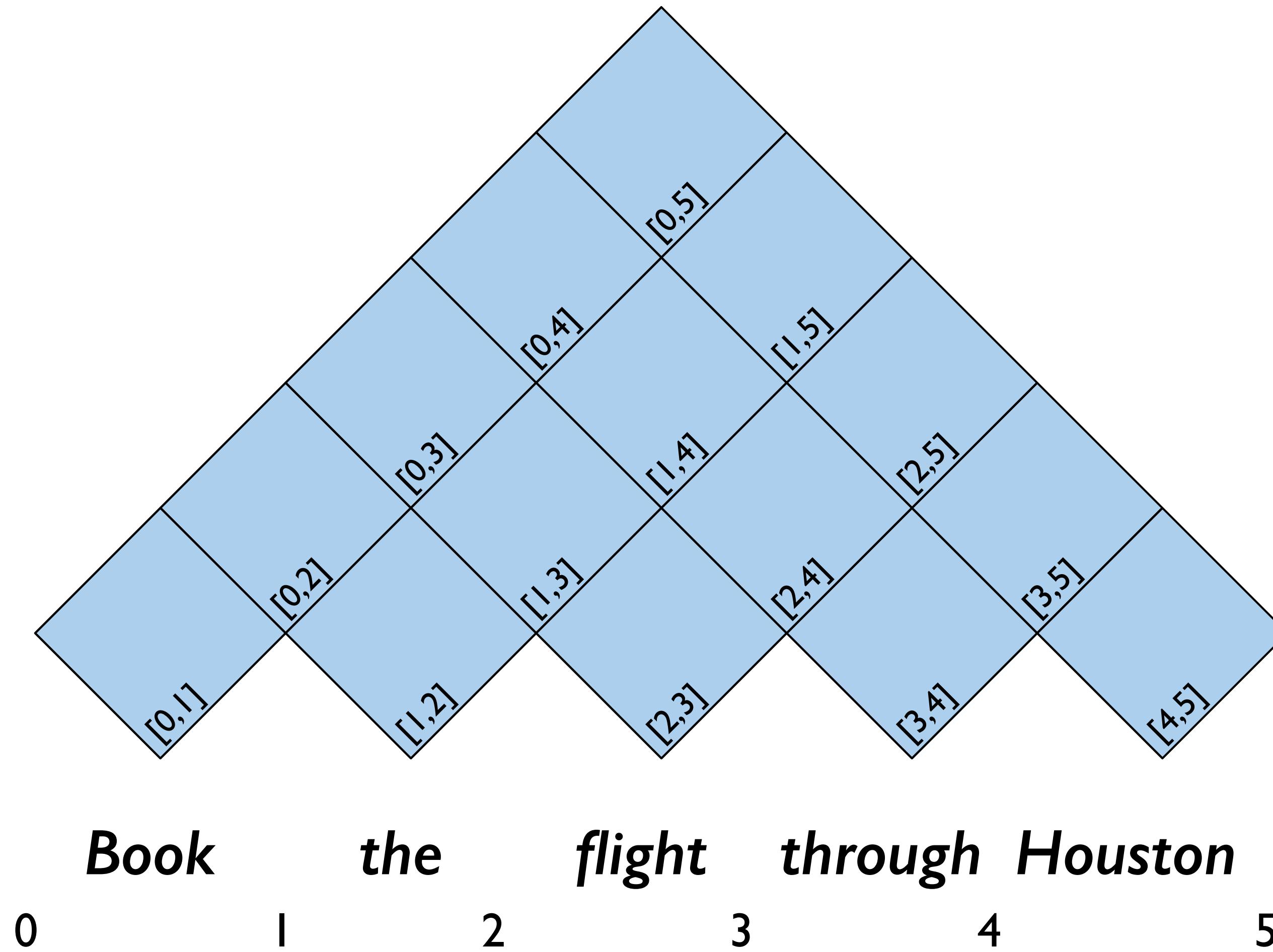
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- Each cell $[i, j]$ contains SETS { } of non-terminals with derivations spanning i, j
 - $[j - 1, j]$ contains pre-terminals
 - if $[0, n]$ contains the start symbol, the sentence is **accepted**

CKY Matrix

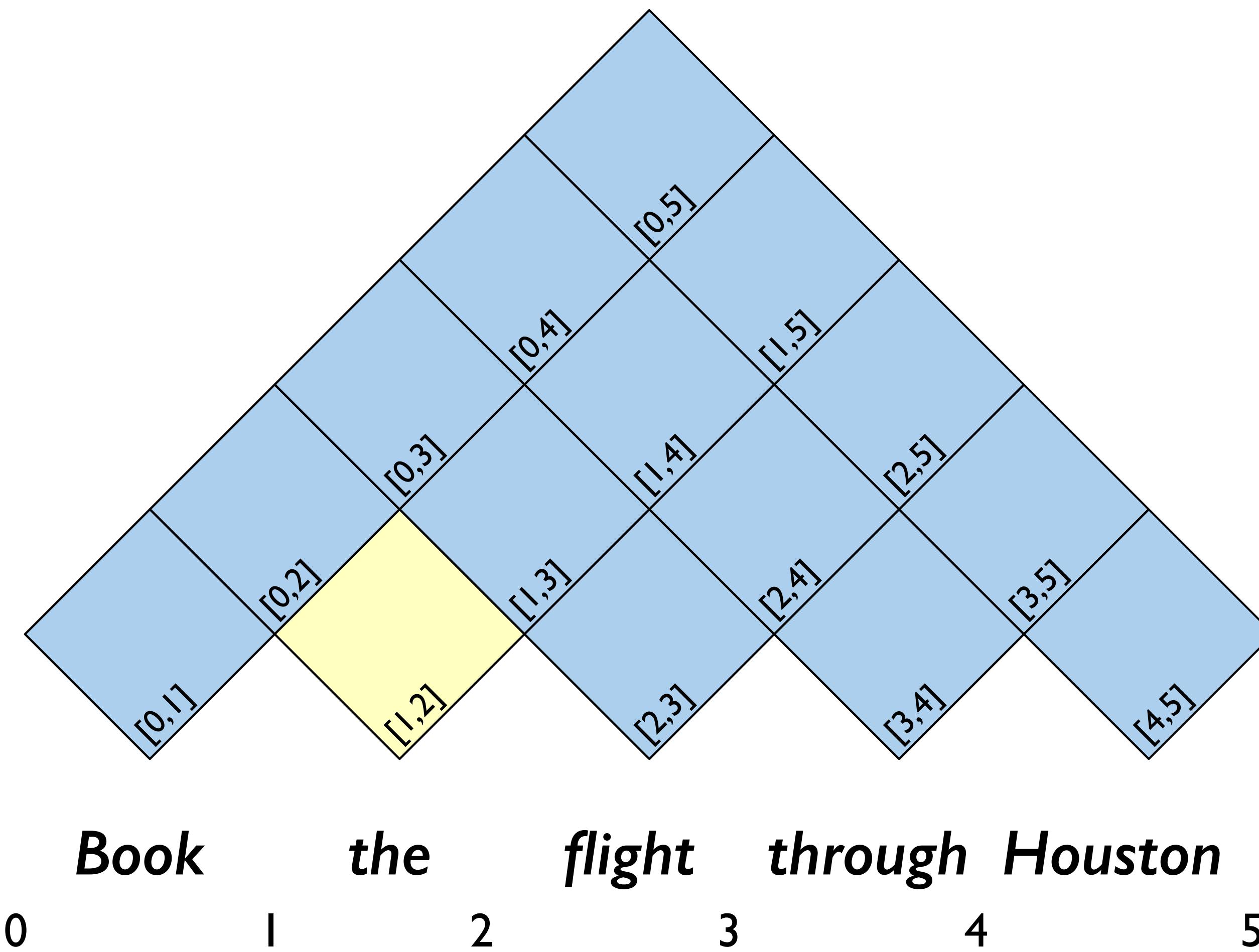
Book the flight through Houston

[0,1]	[0,2]	[0,3]	[0,4]	[0,5]
	[1,2]	[1,3]	[1,4]	[1,5]
		[2,3]	[2,4]	[2,5]
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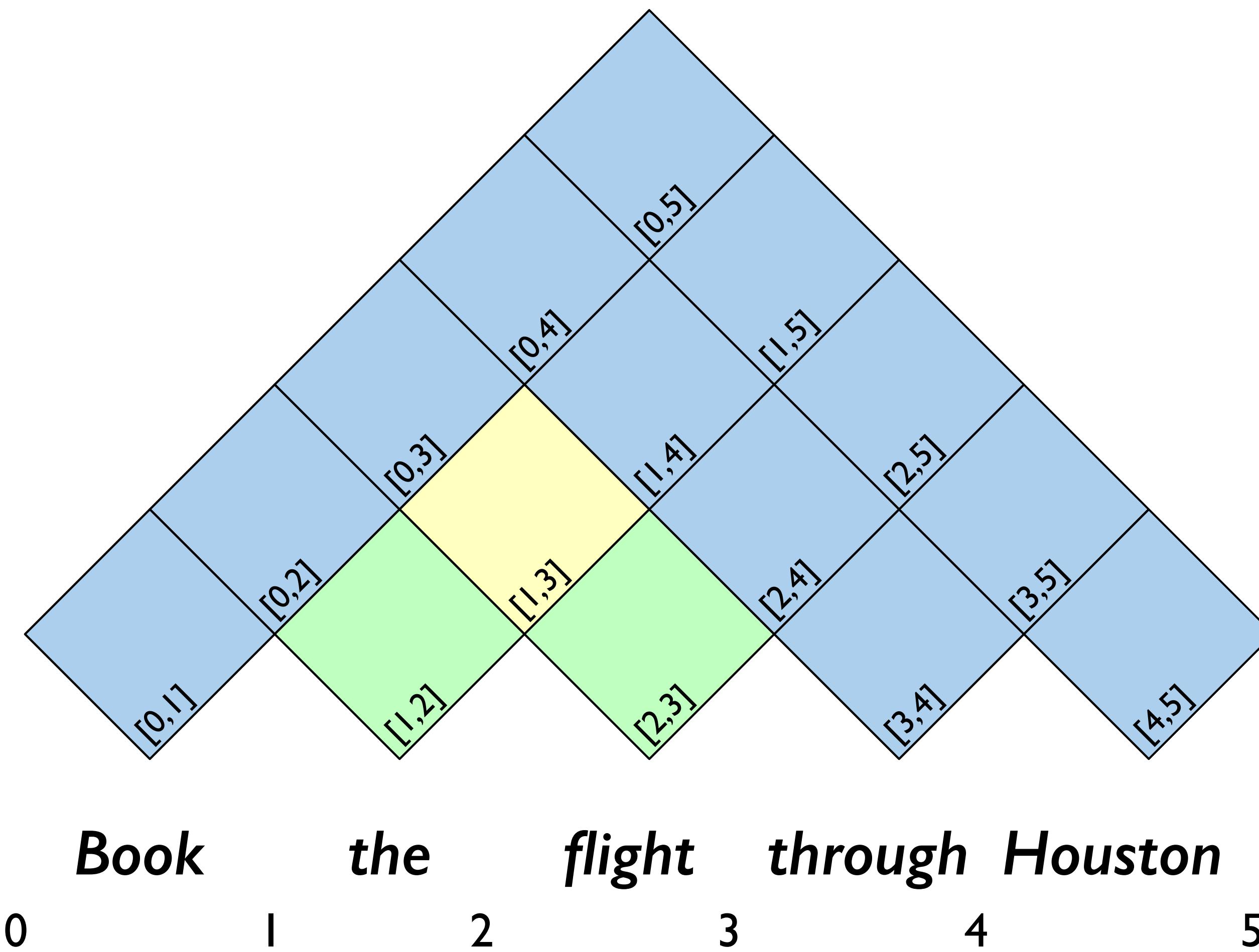
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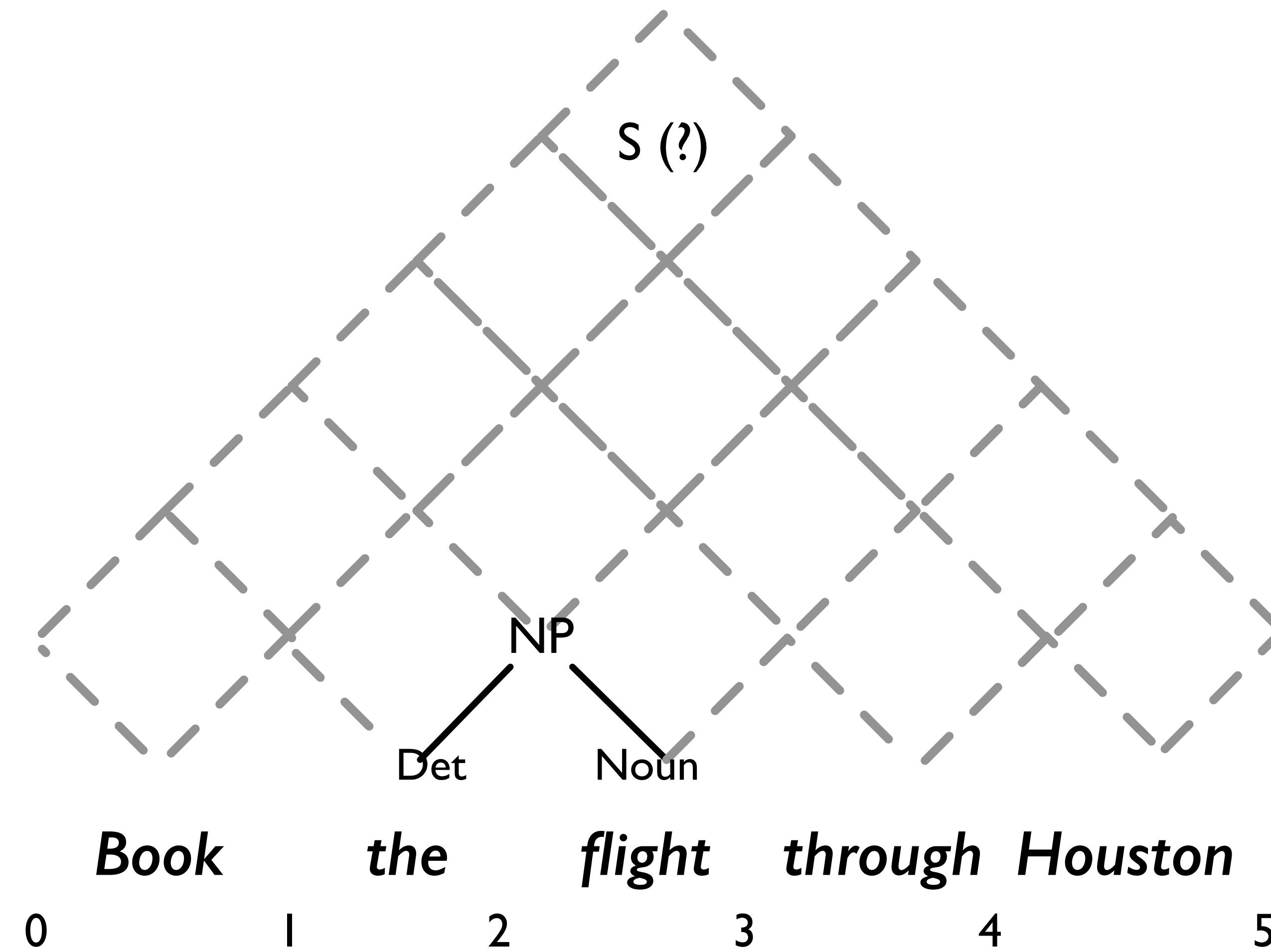
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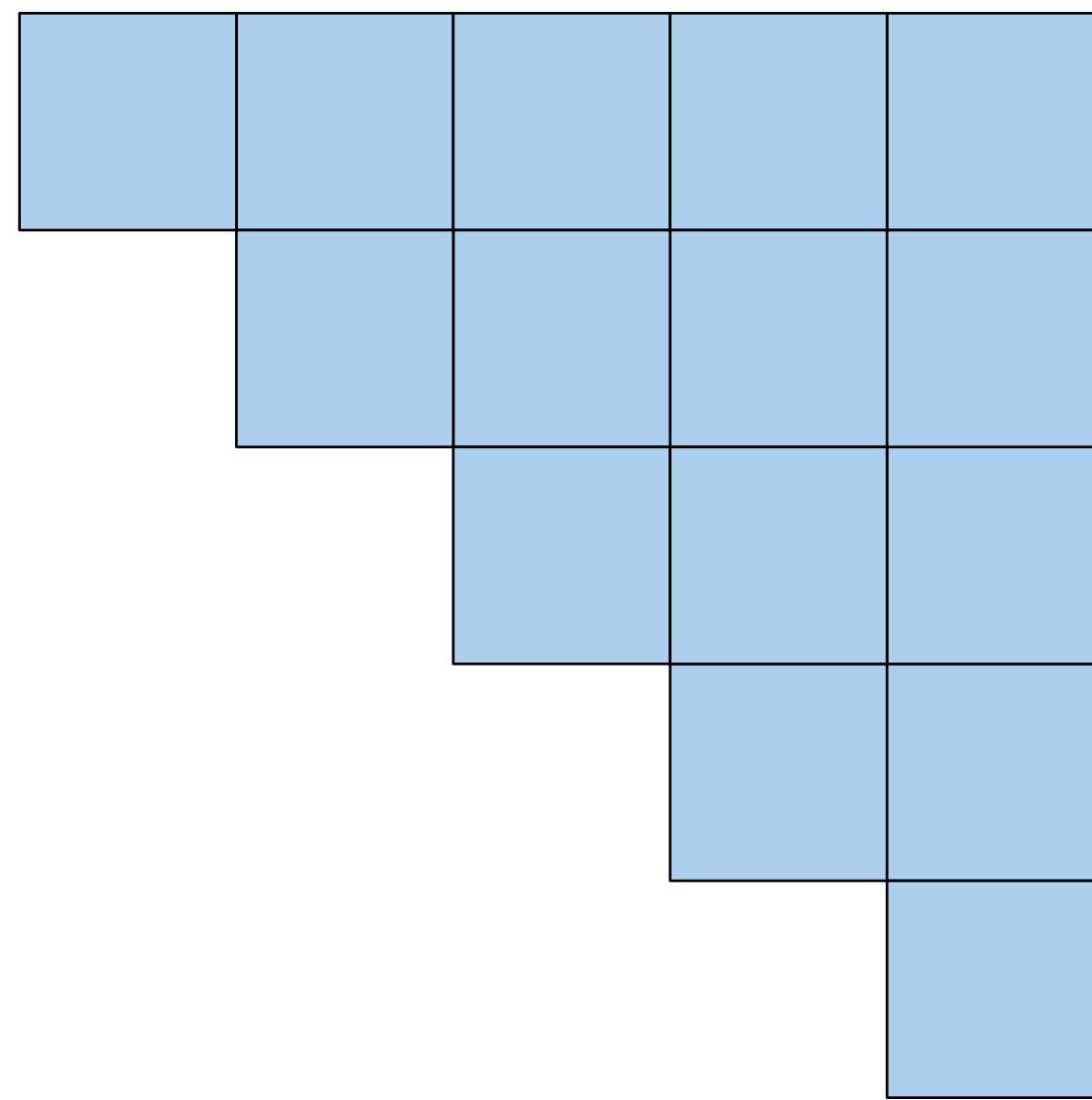
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Dynamic Programming in CKY

- 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 $j > i + 1$

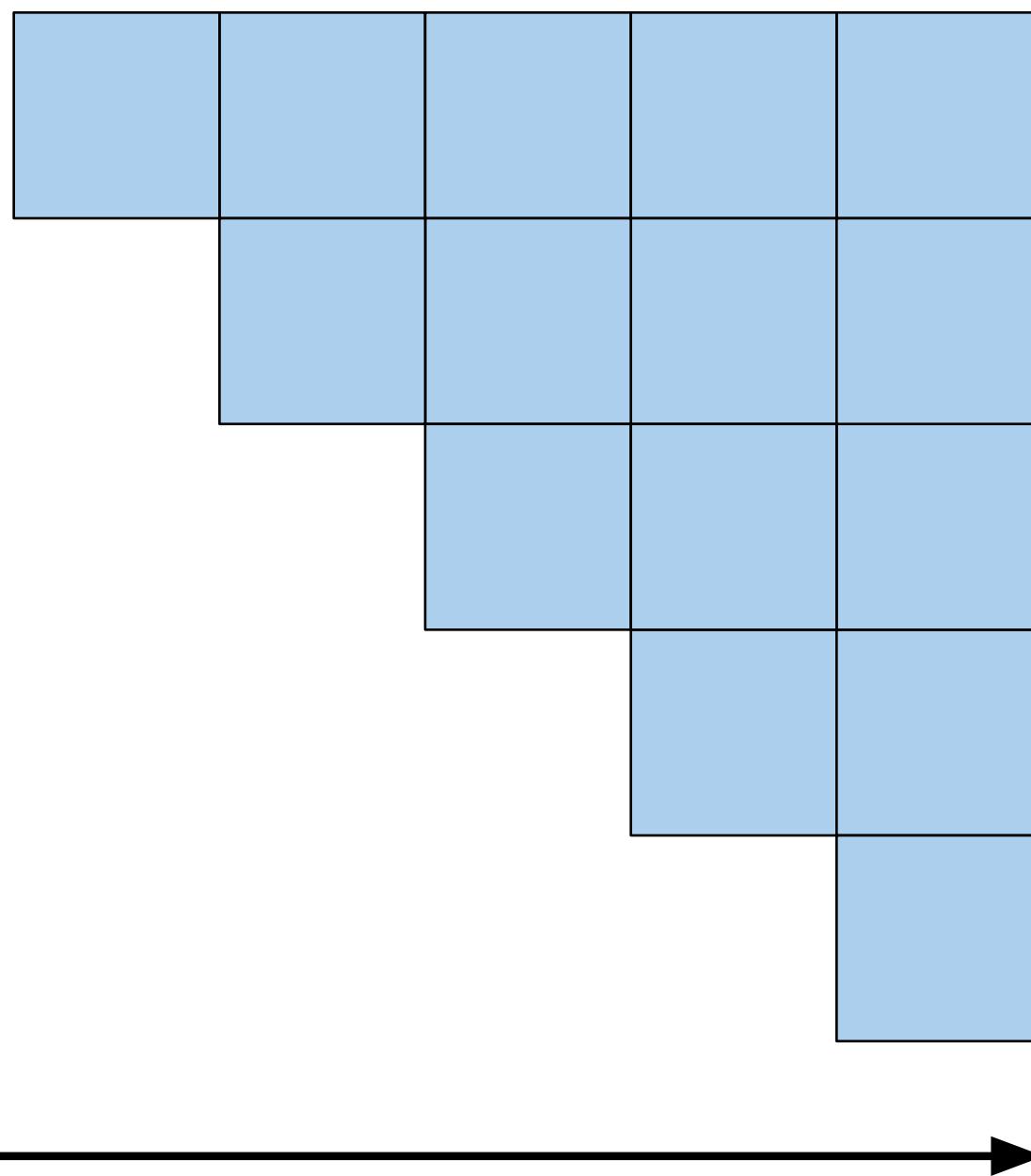
CKY



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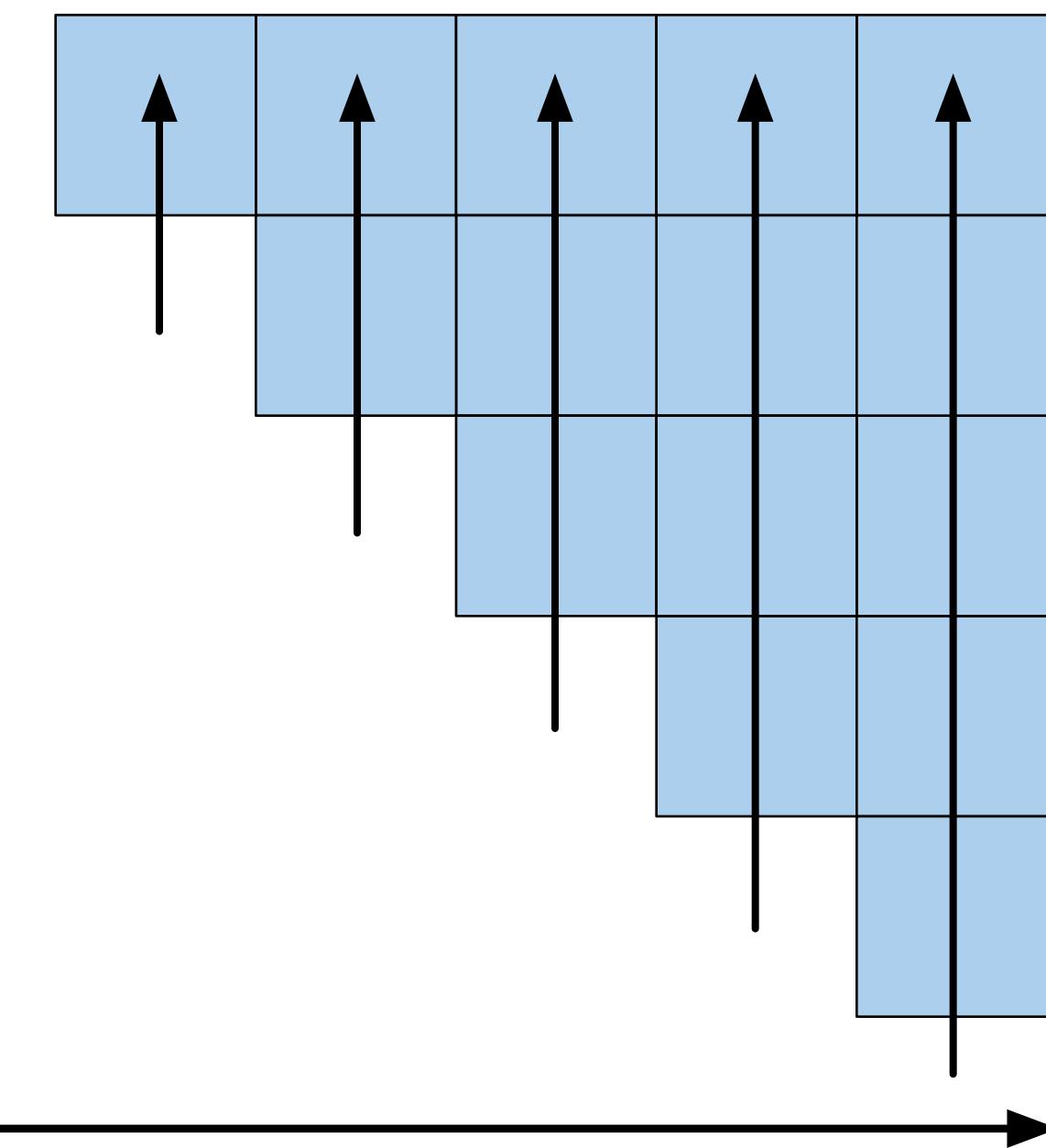
CKY

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



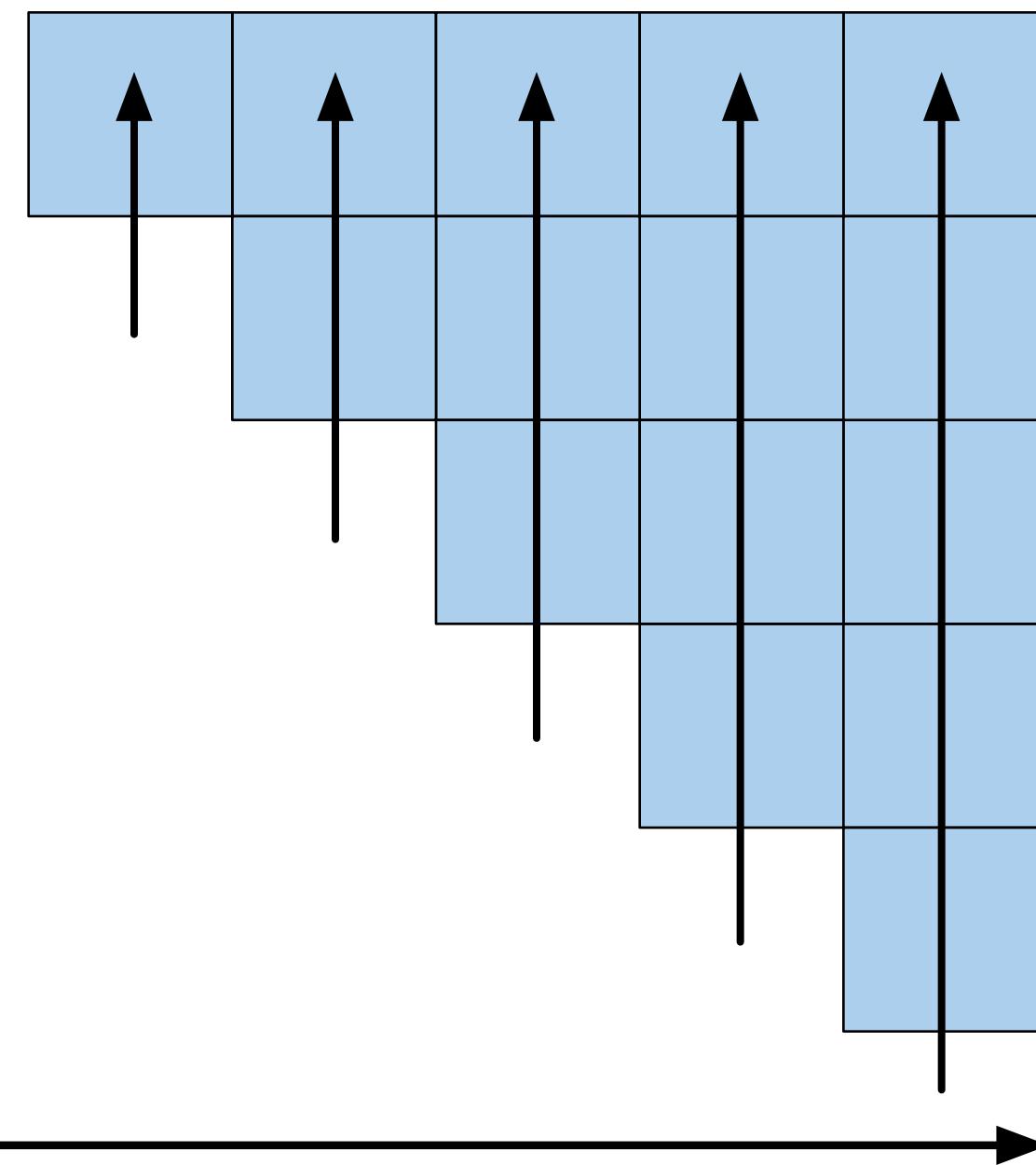
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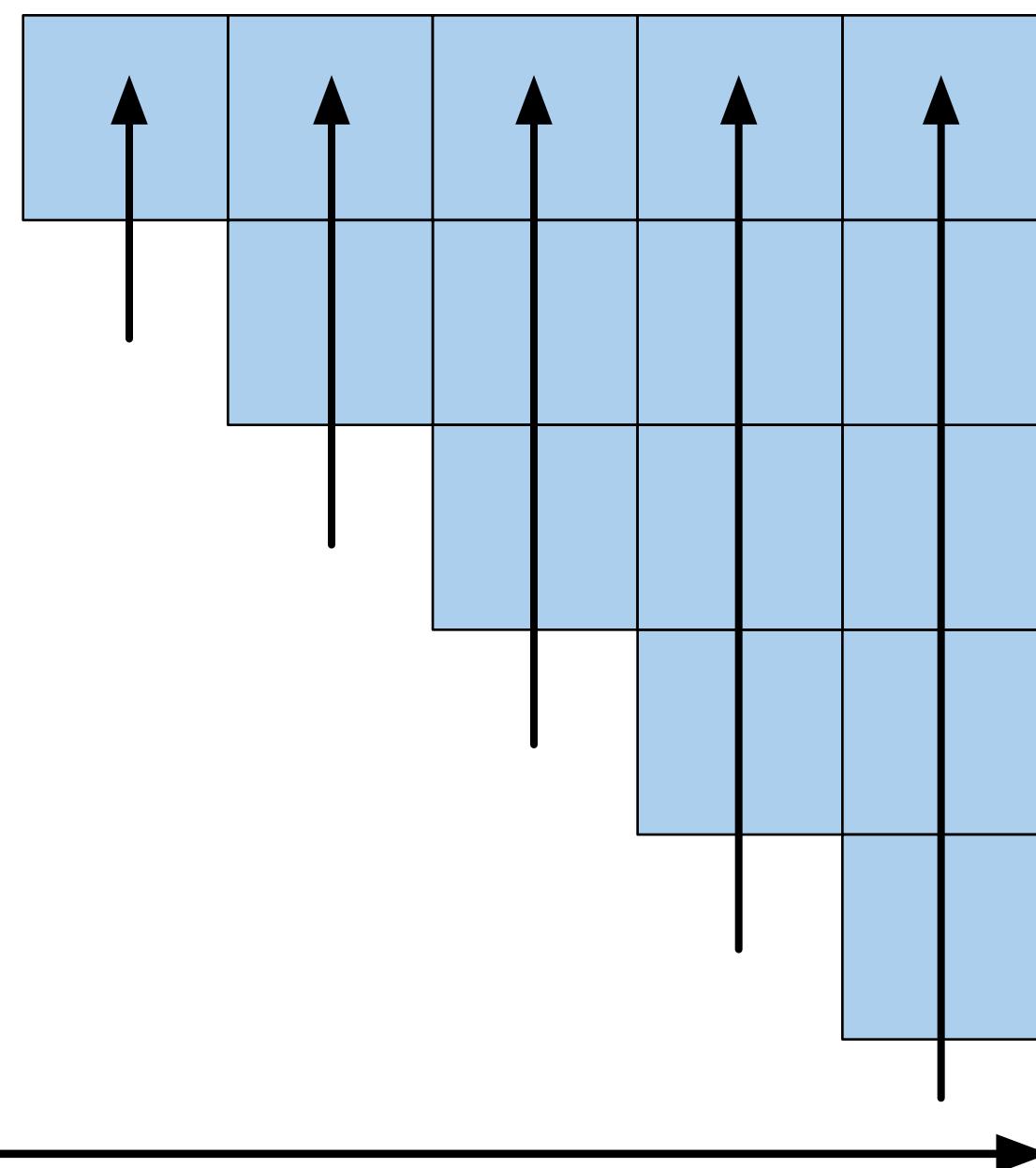
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- Why?



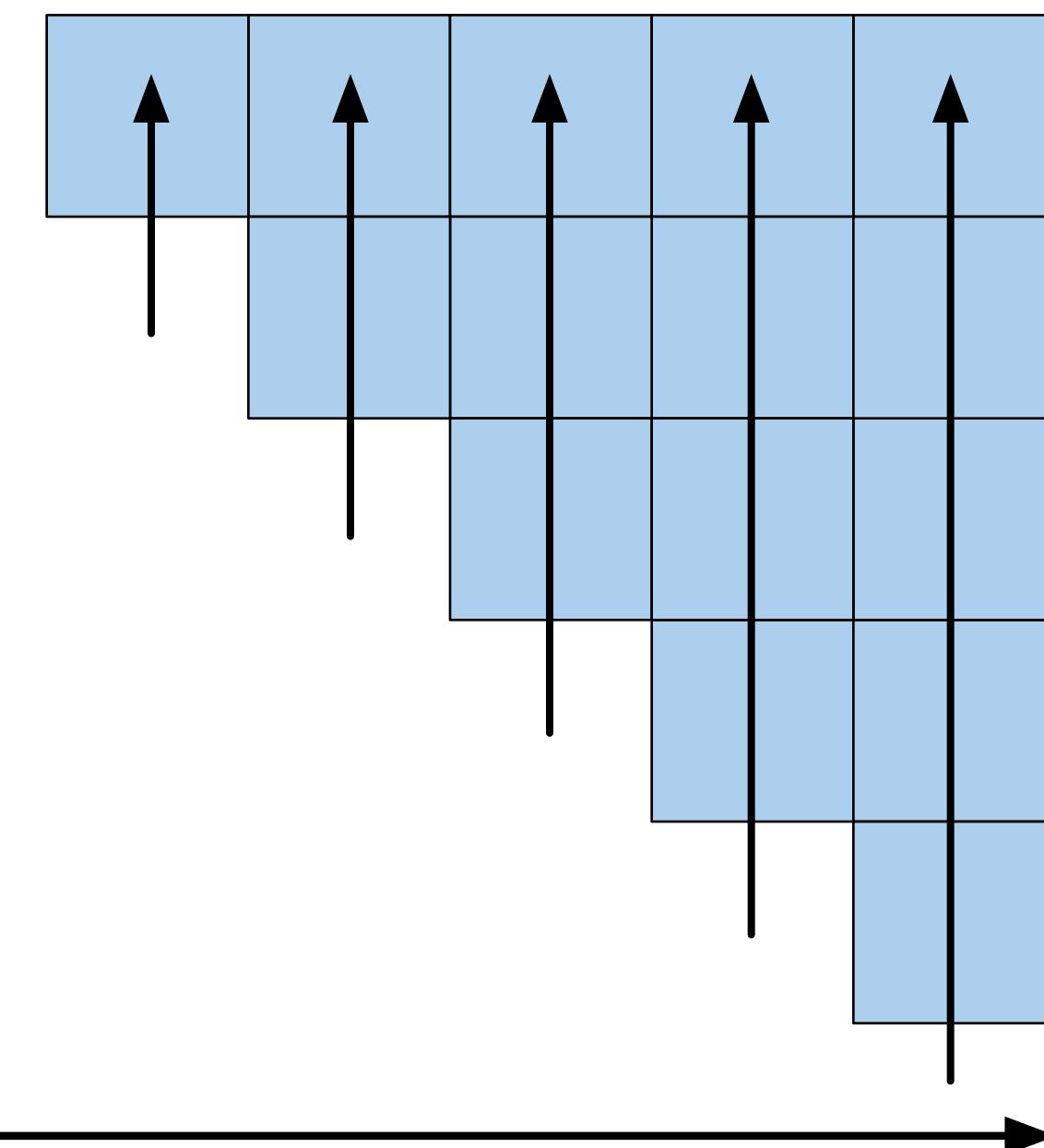
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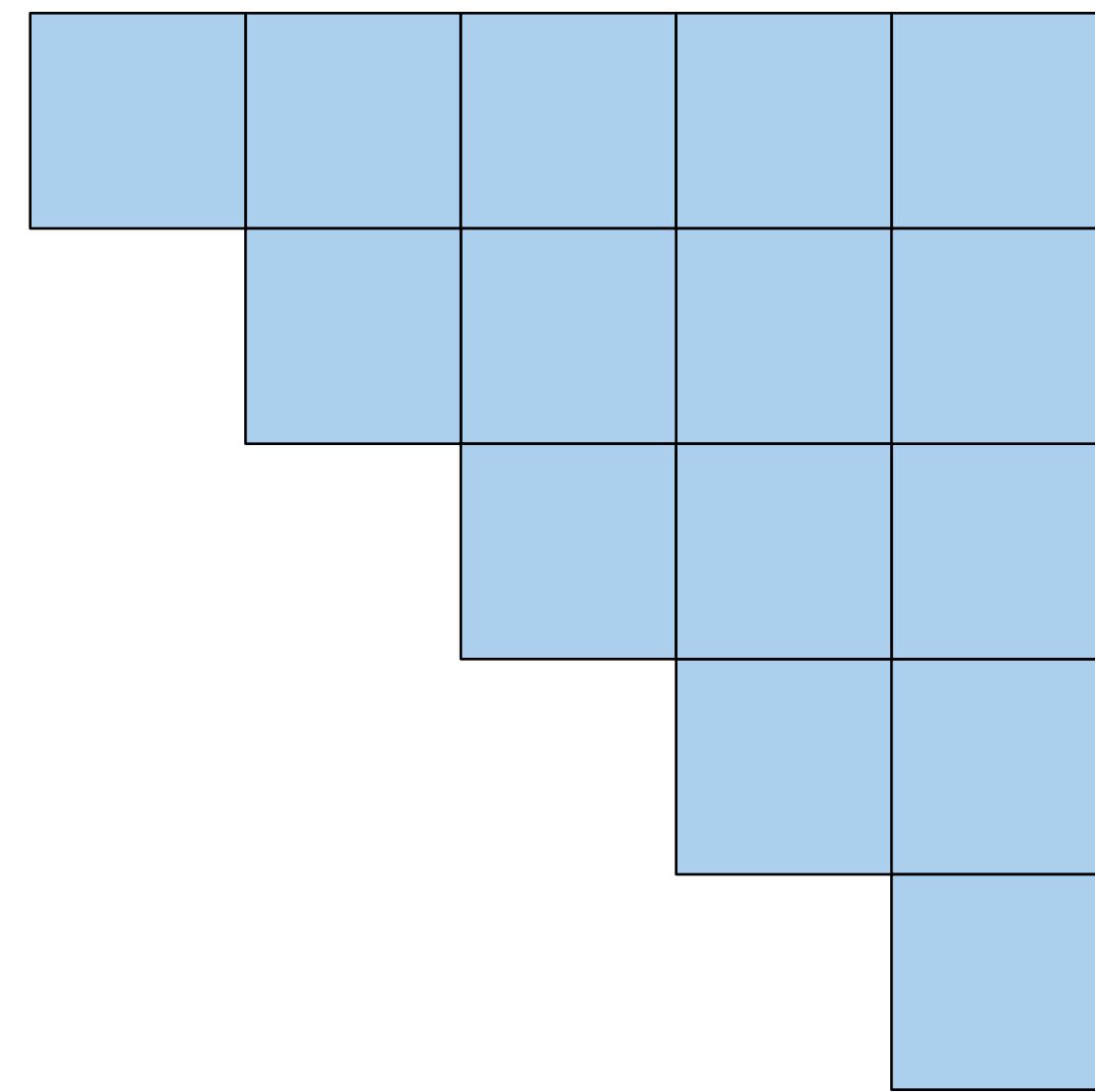


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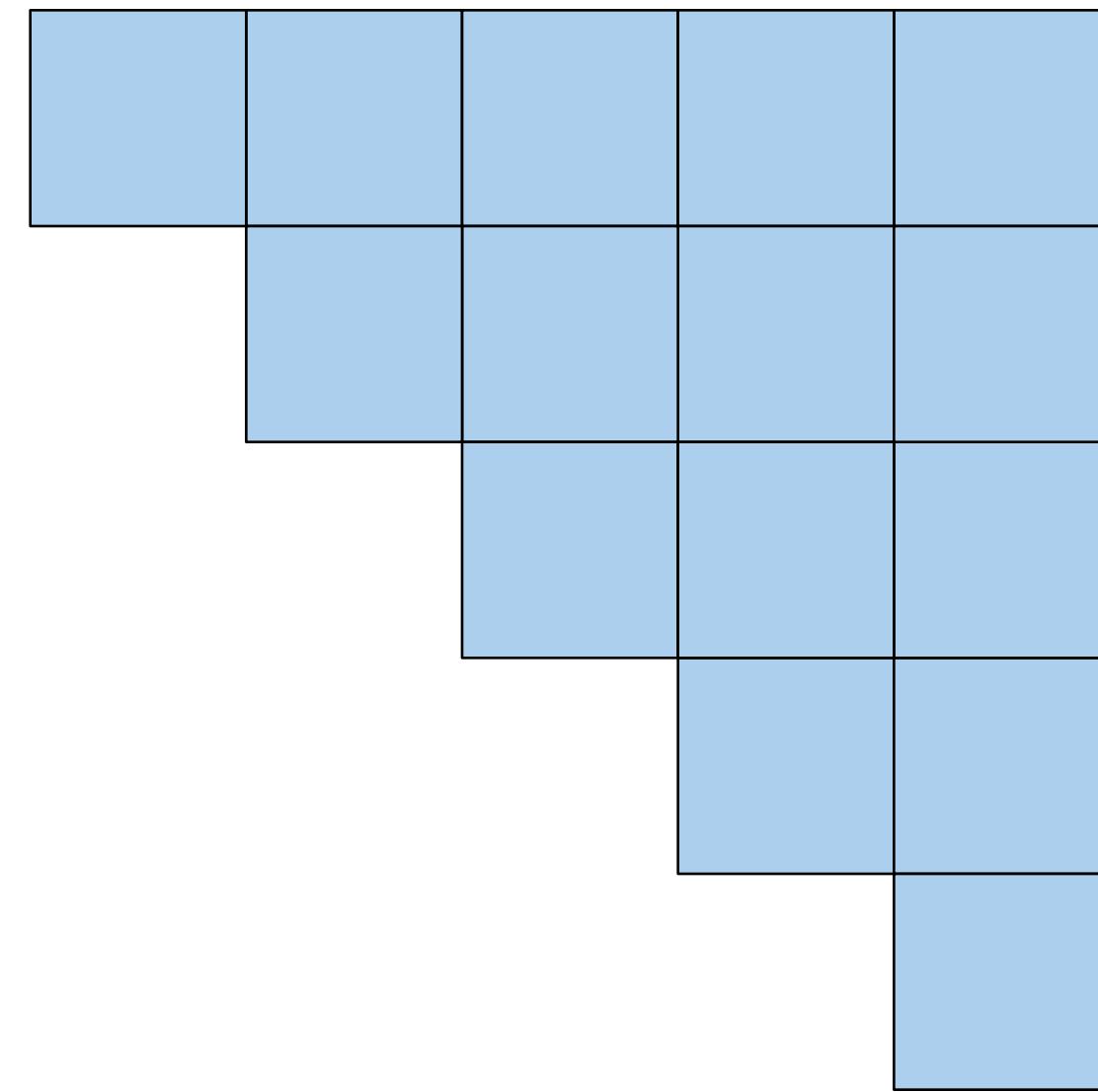


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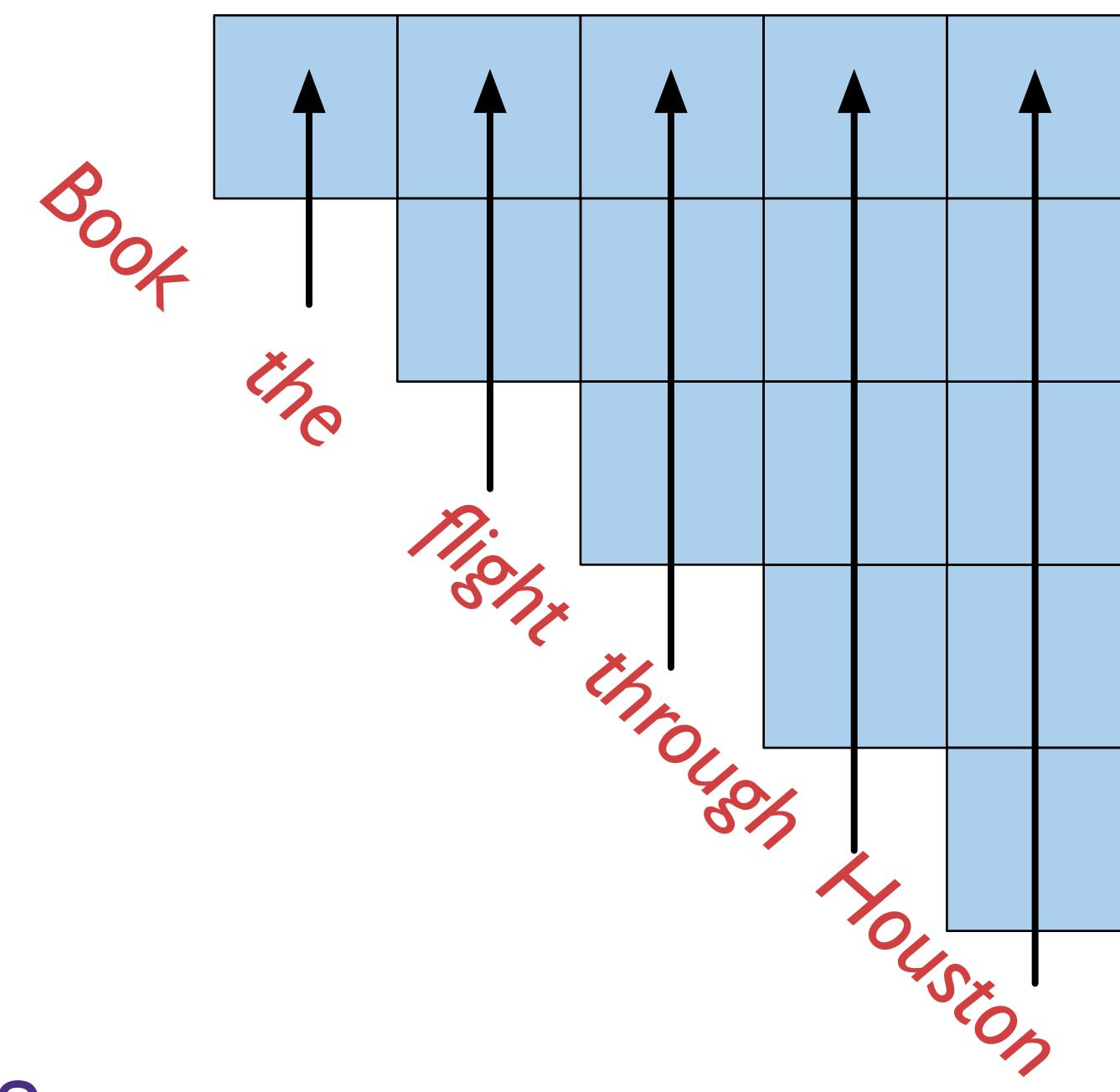
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CKY Algorithm

```
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 ]  $\cup$ 
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Left-to-right, bottom-to-top
Sliding *k* as the pivot for child nodes

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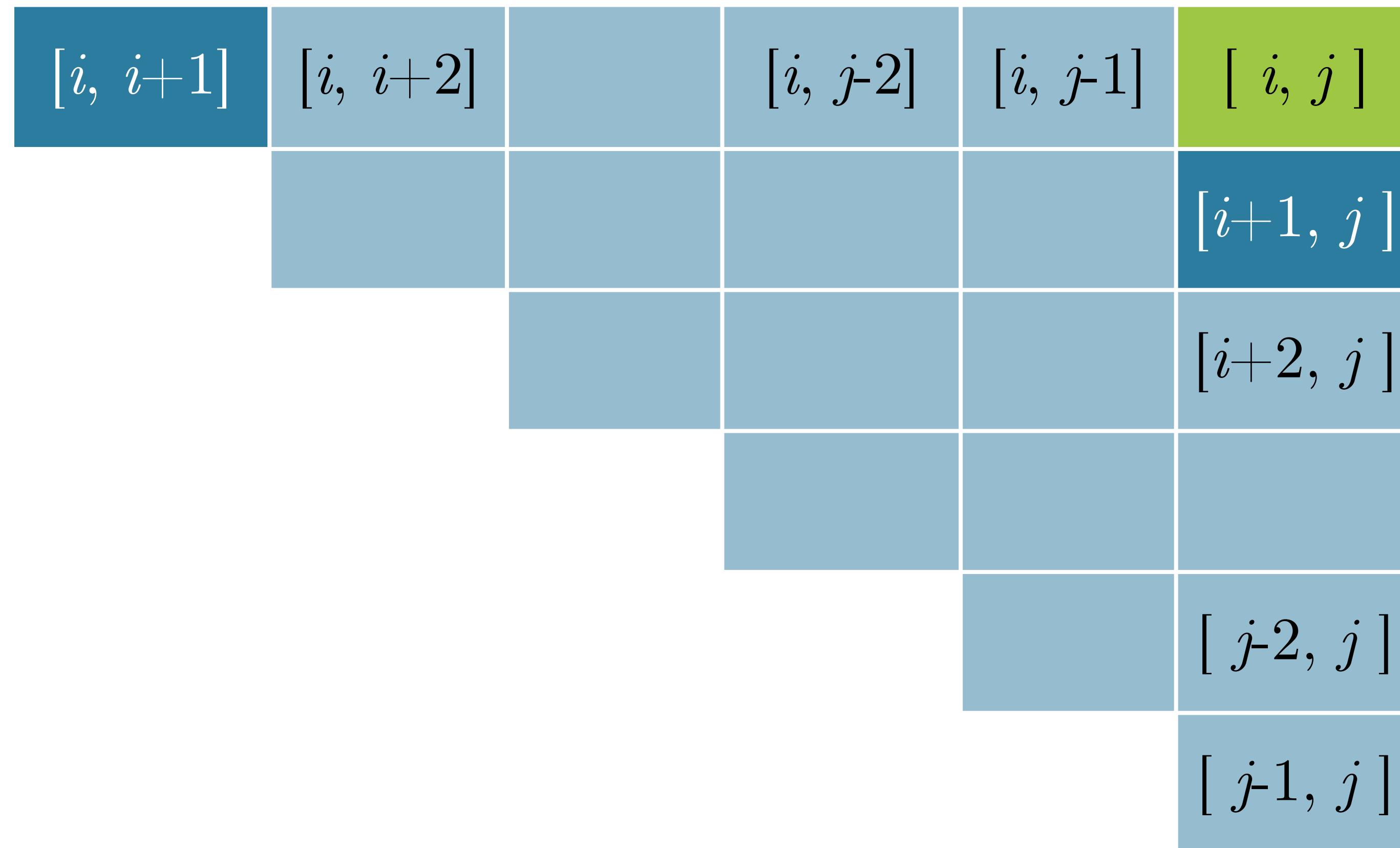
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Sliding k as the pivot for child nodes

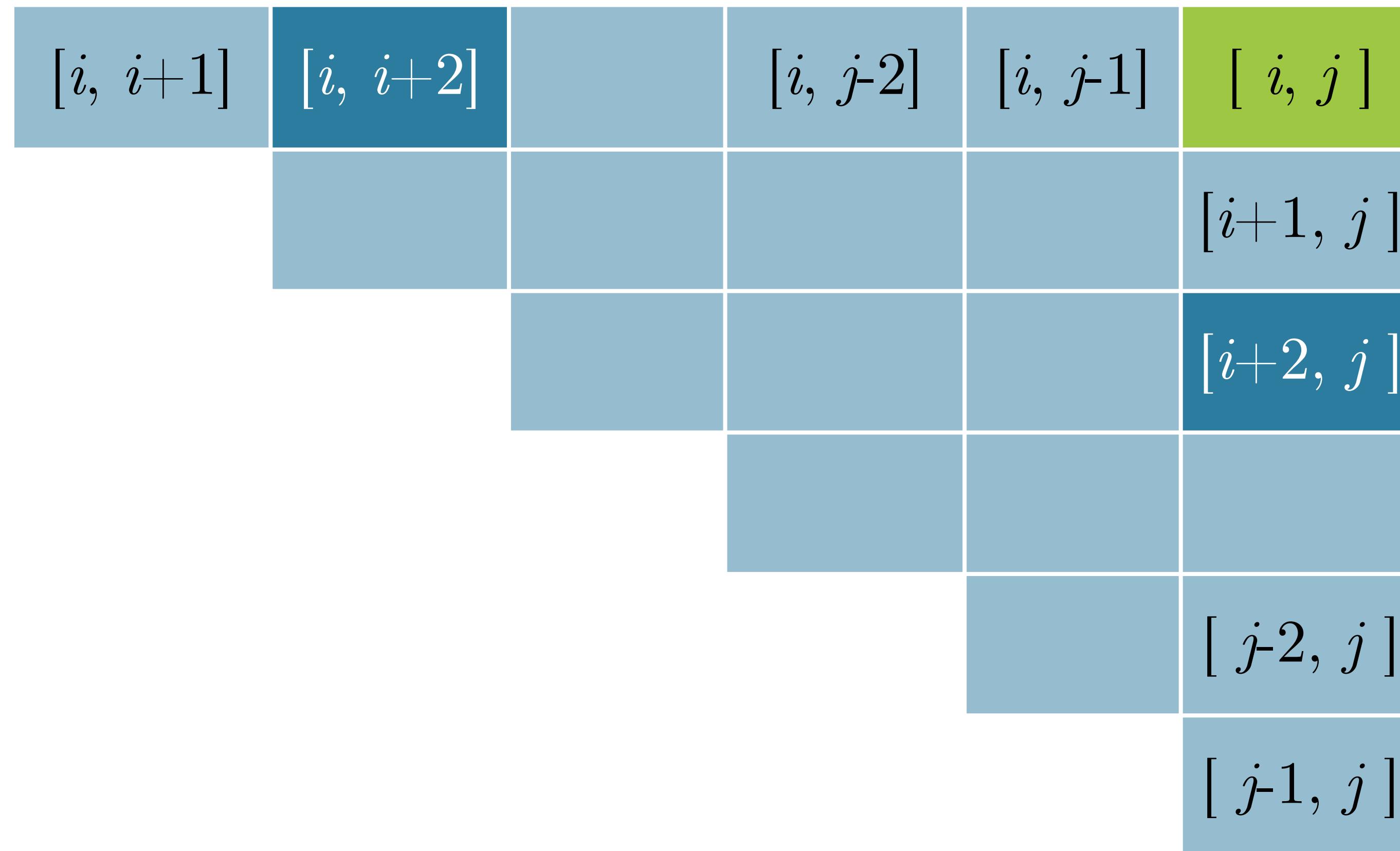
Filling the cell with set of applicable rules

Filling Cell $[i, j]$



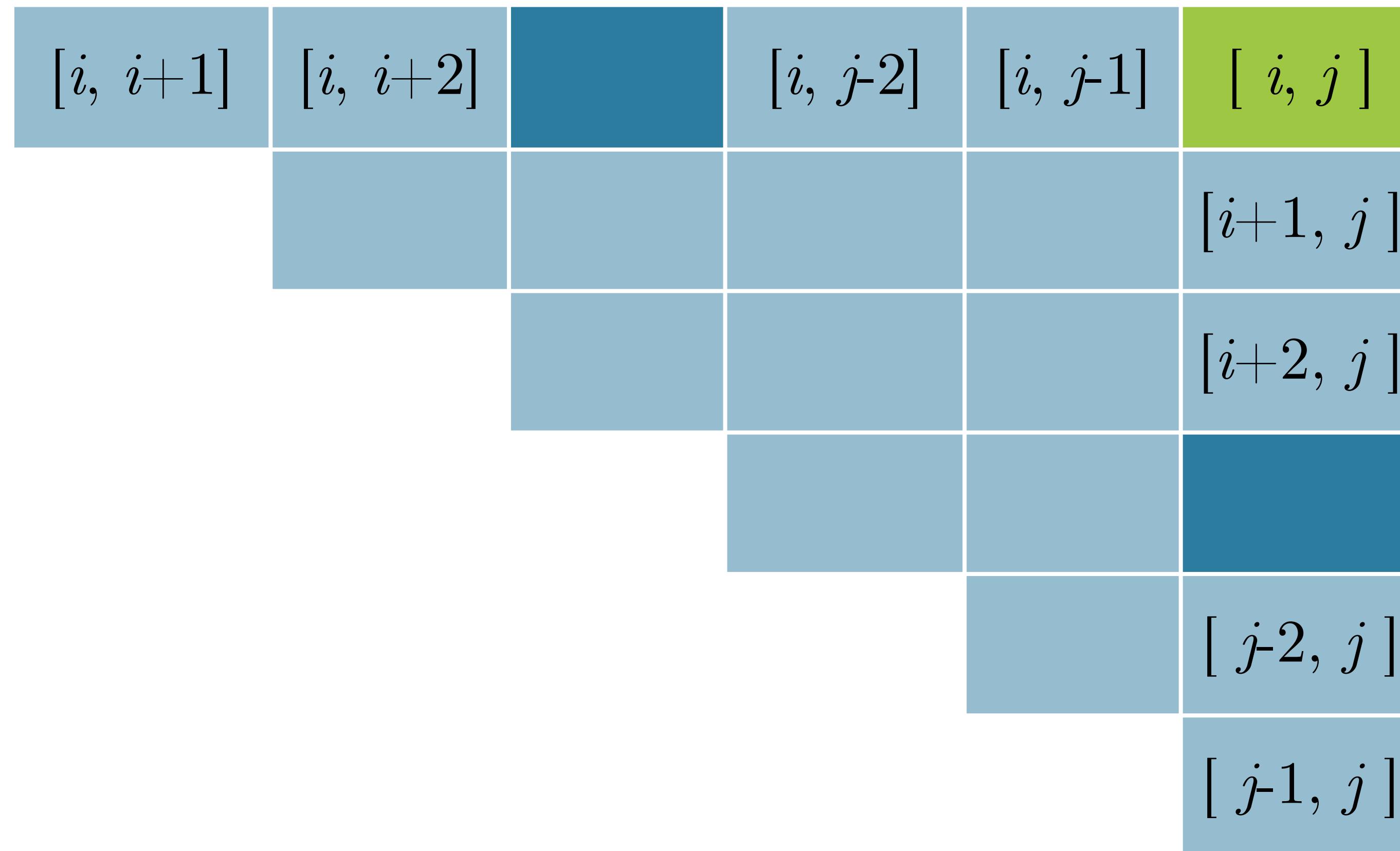
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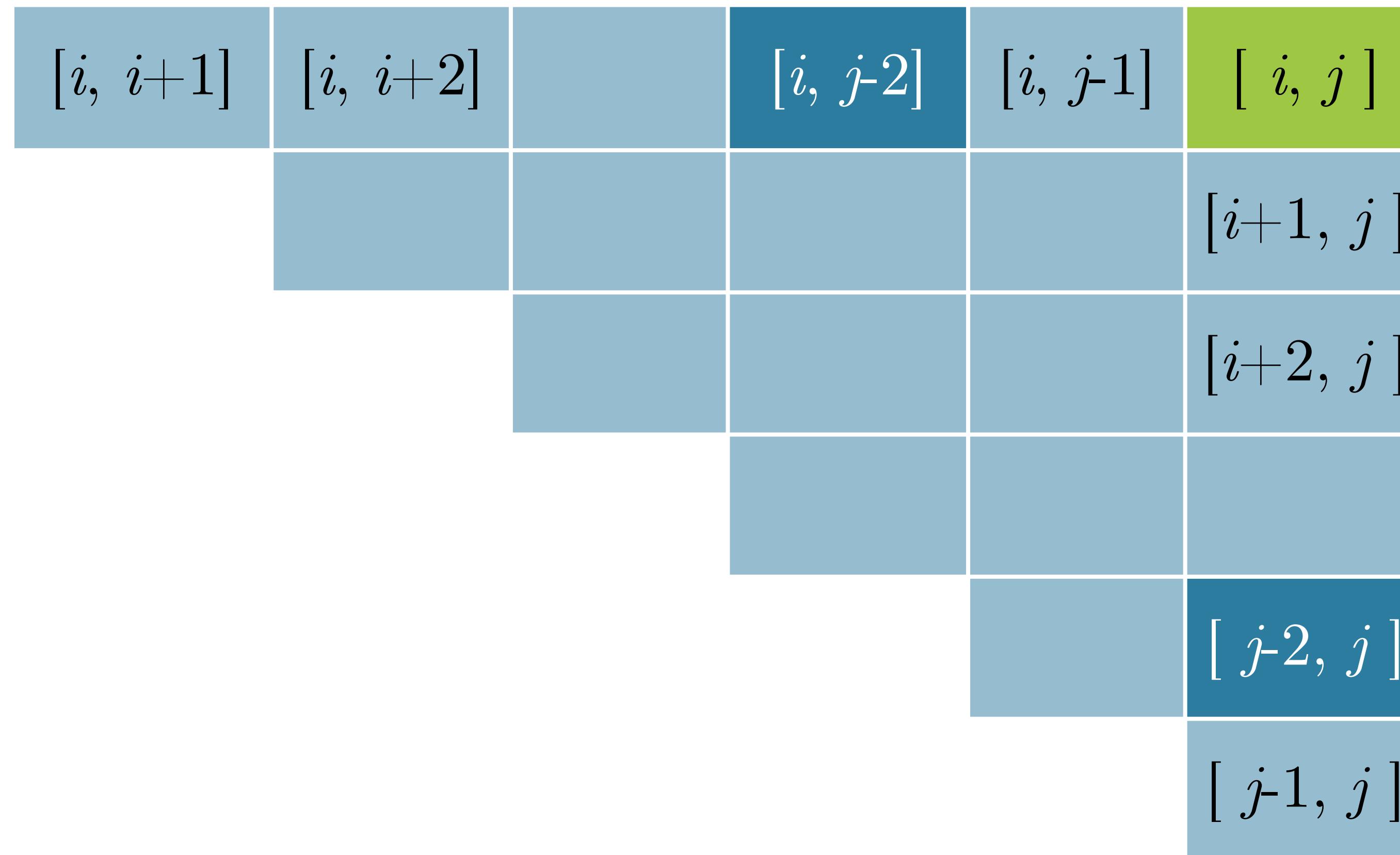
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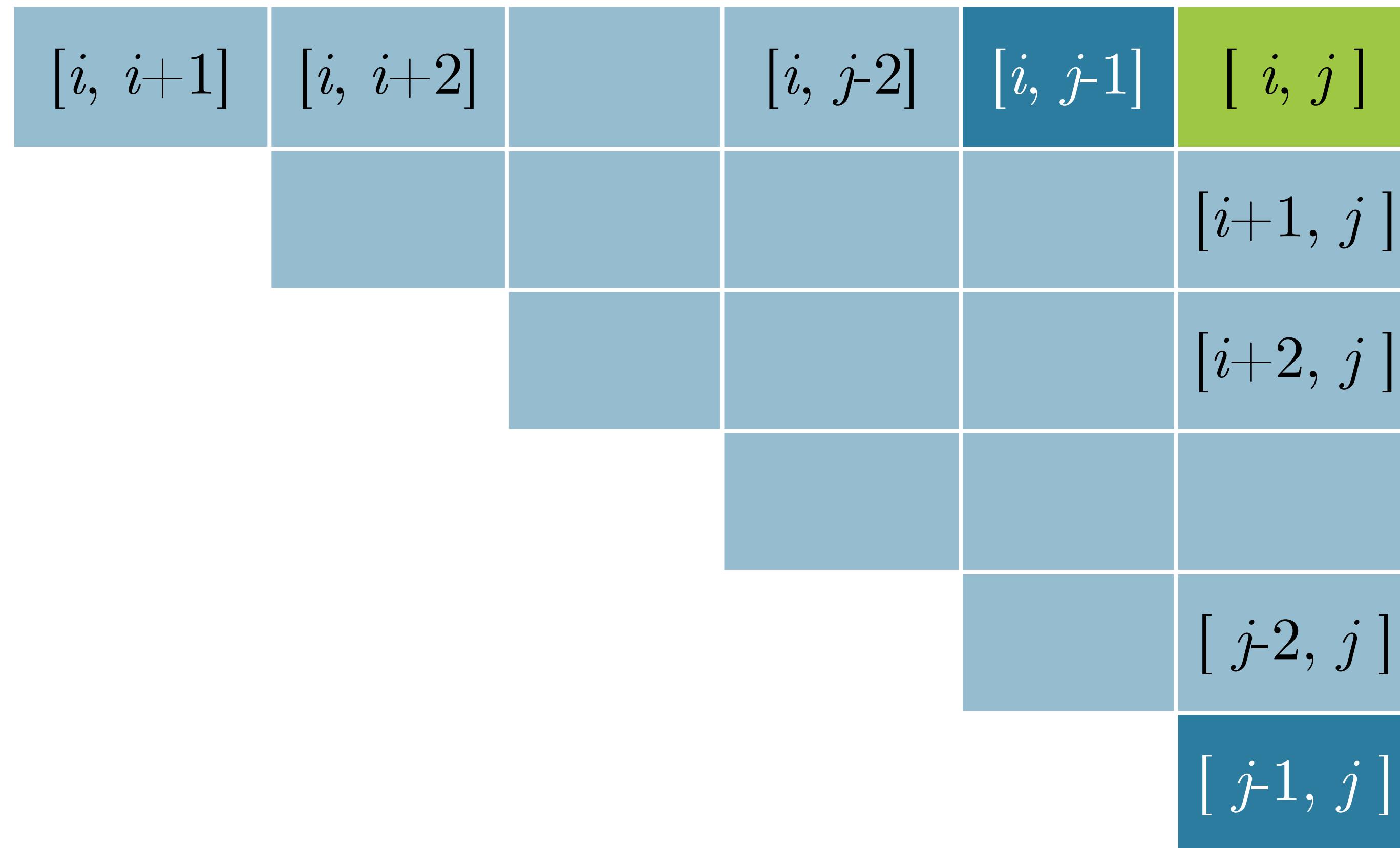
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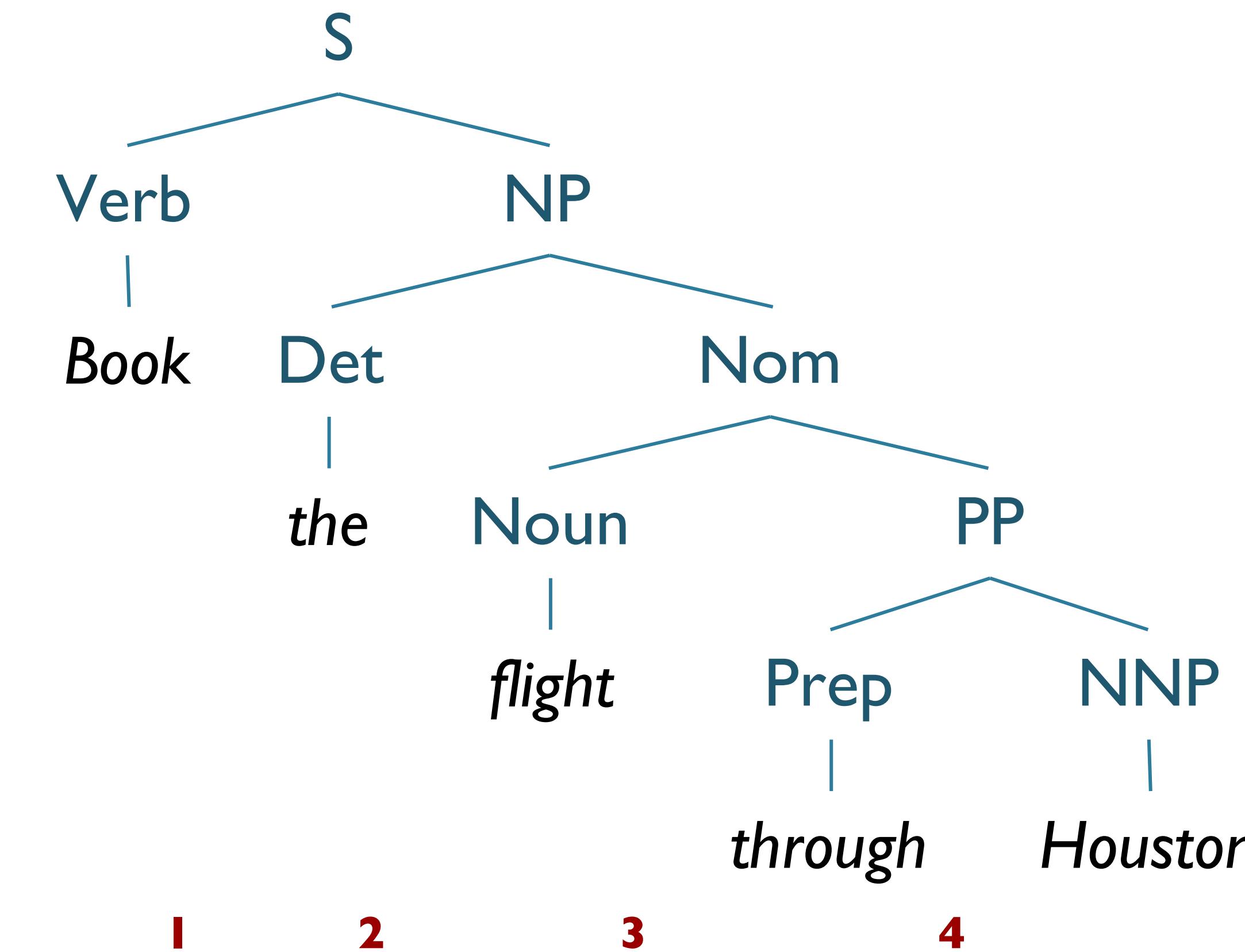
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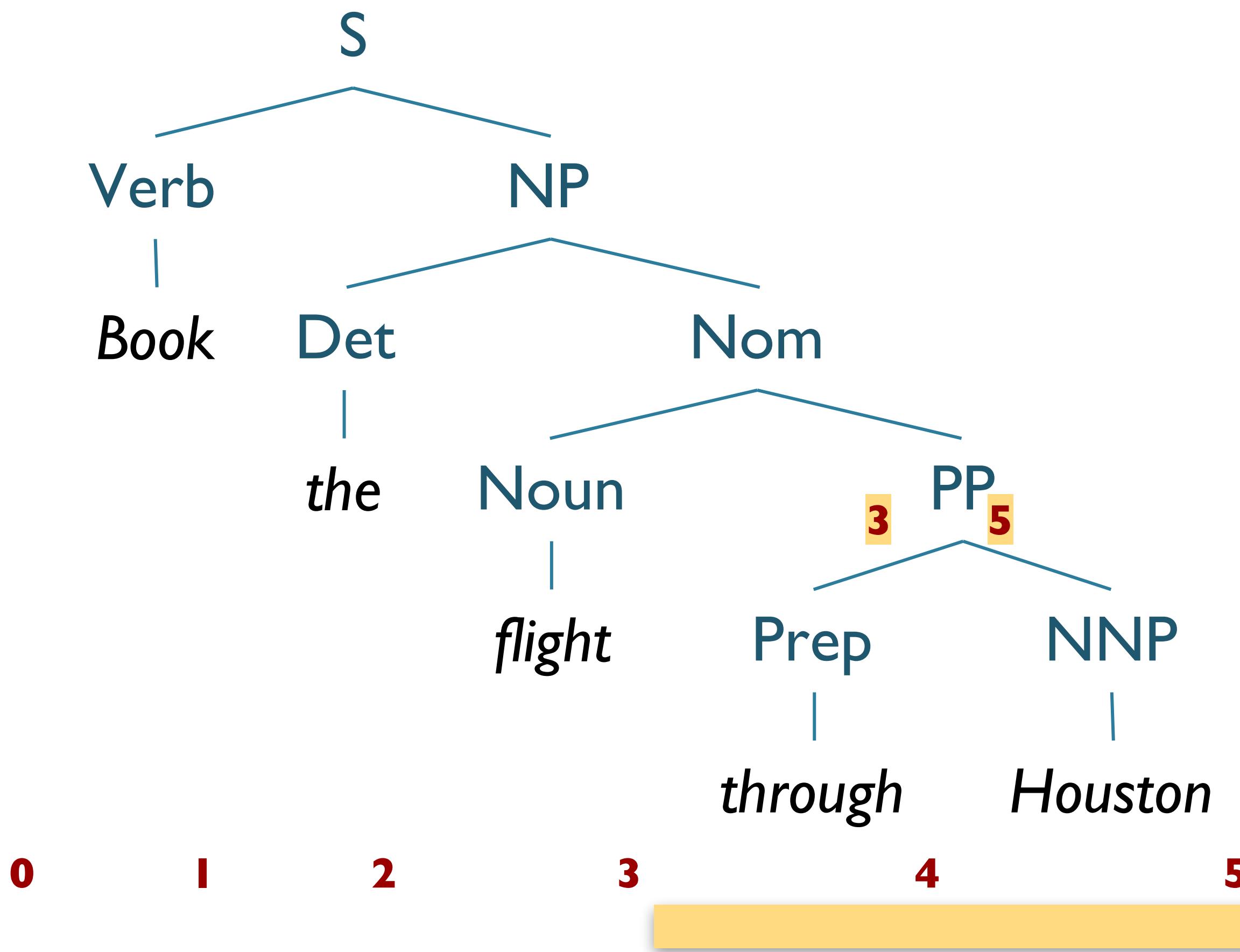
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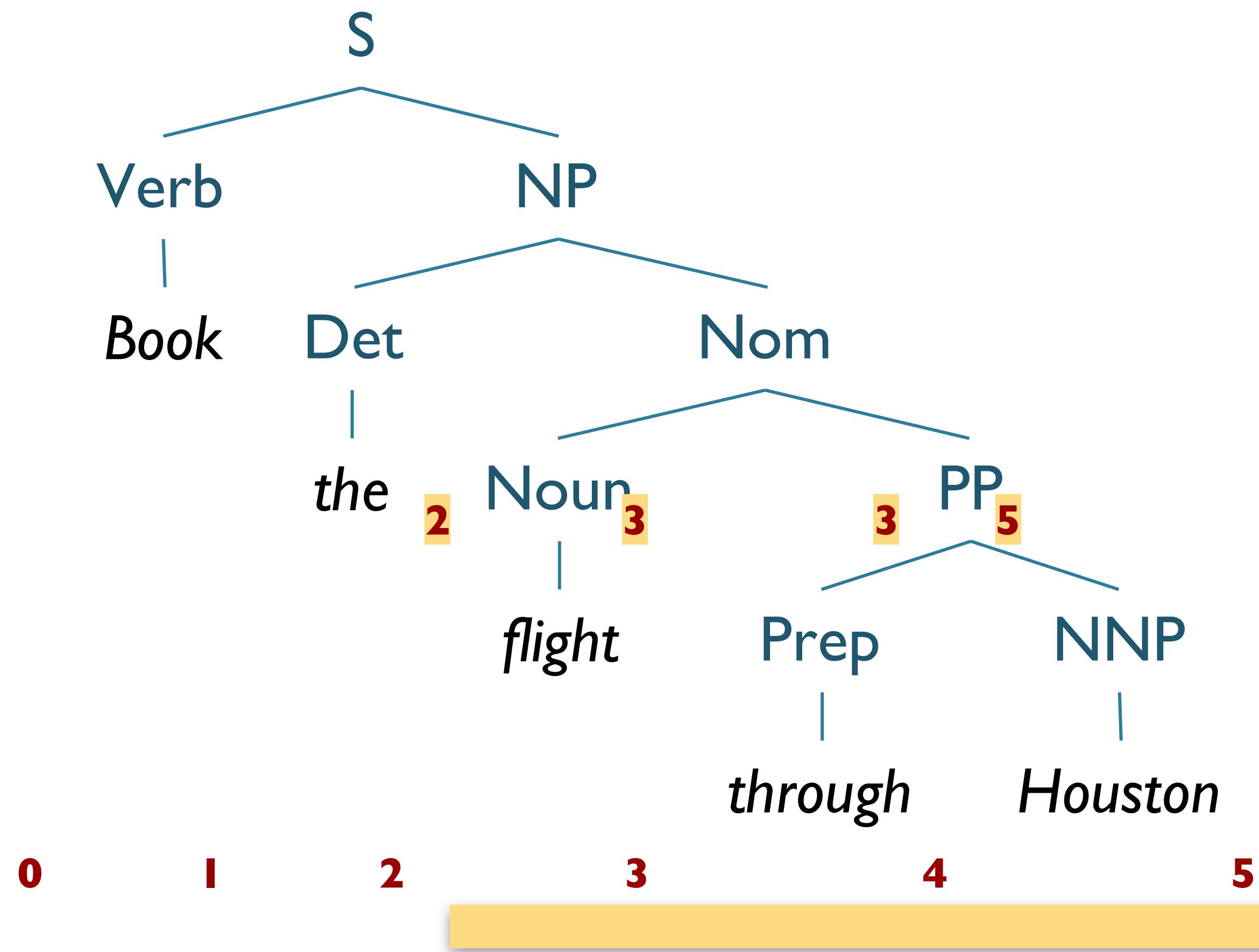
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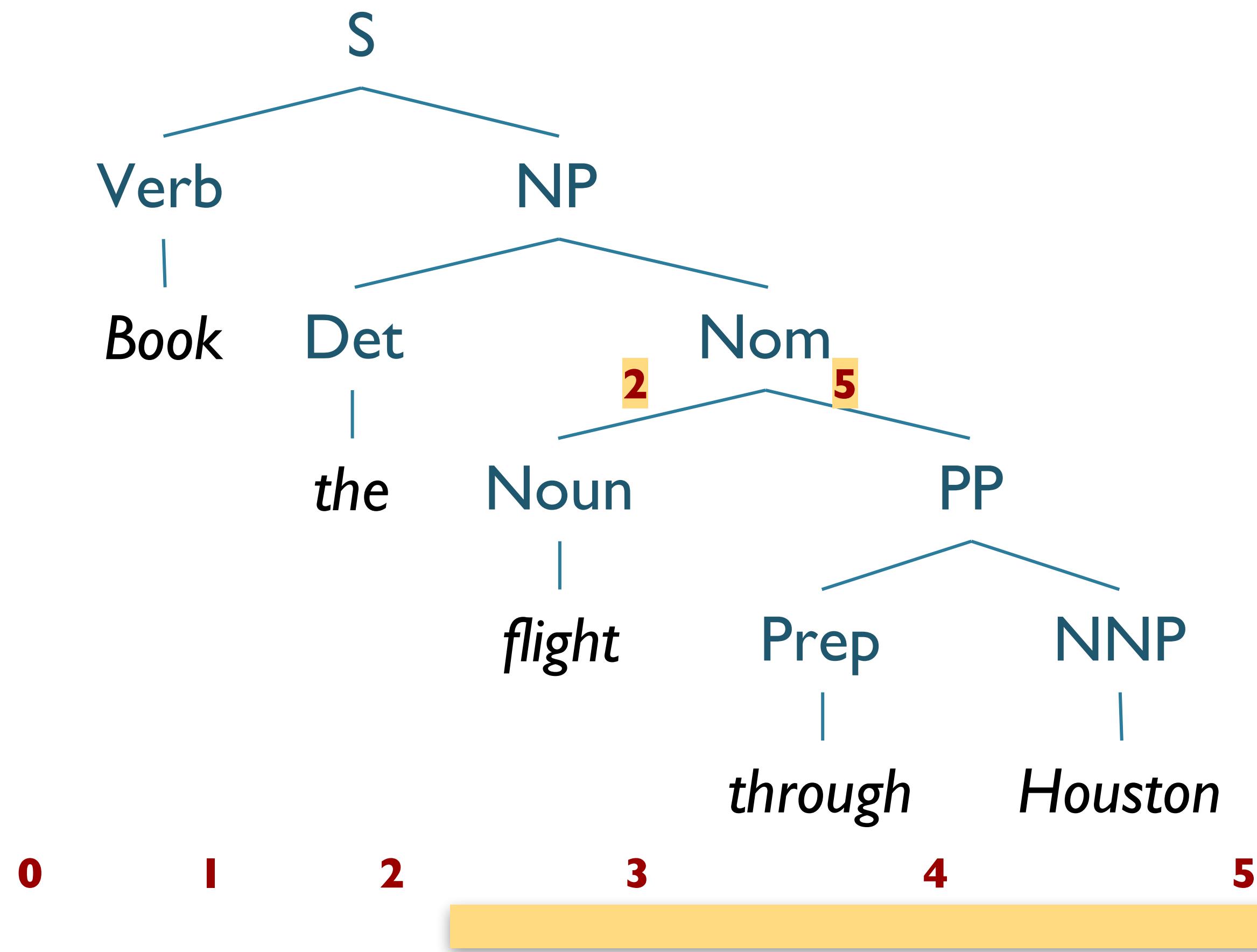
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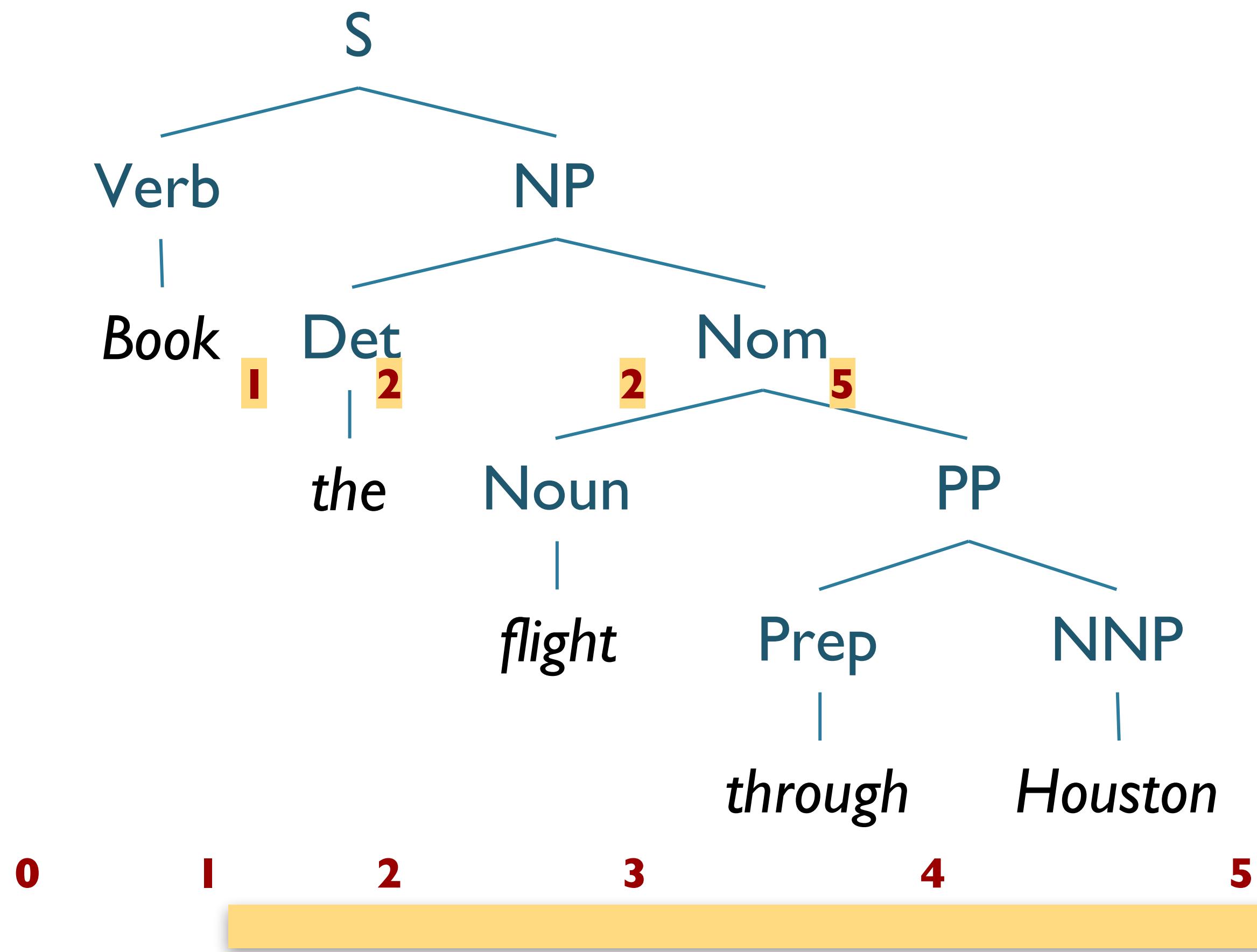
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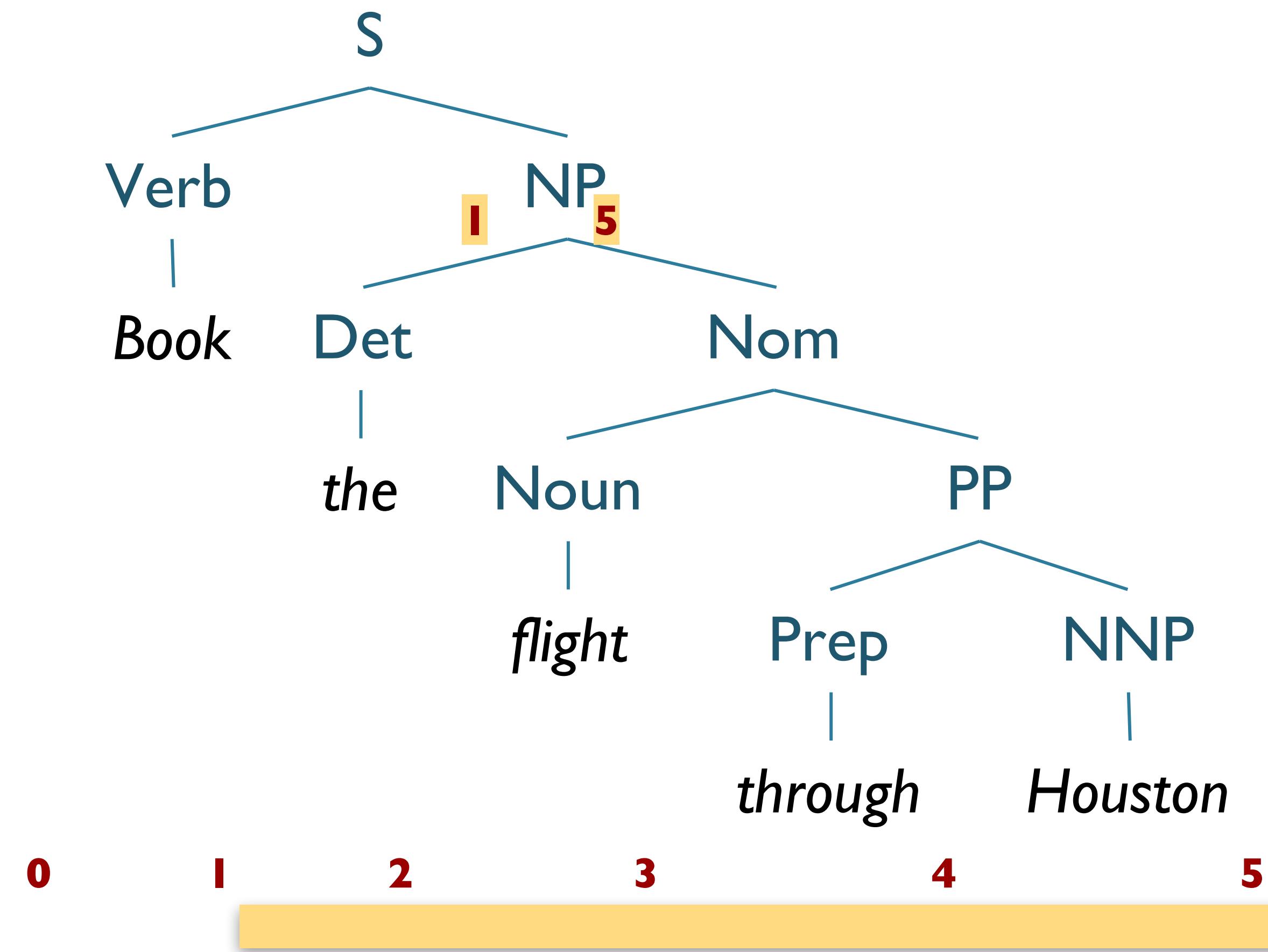
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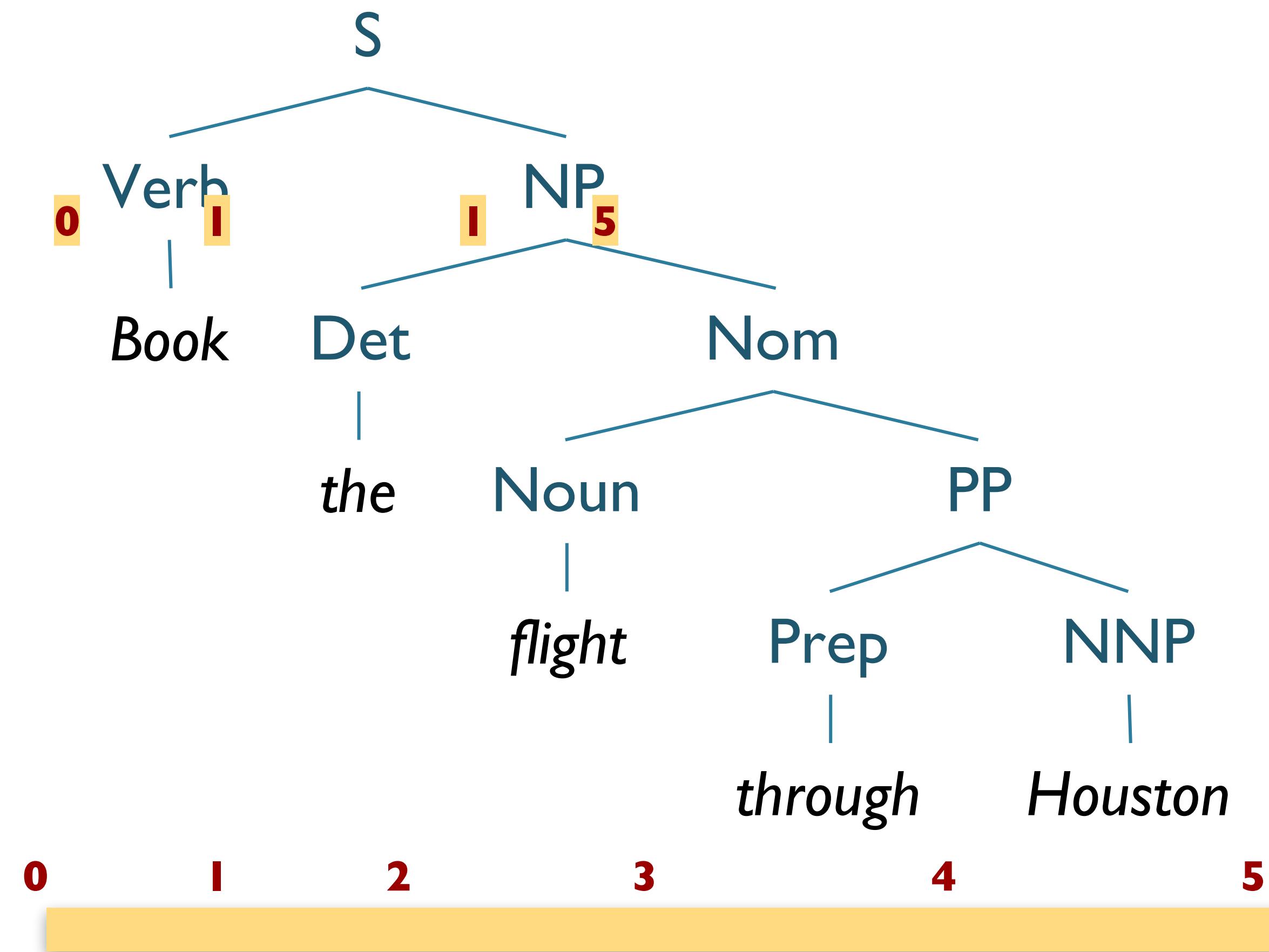
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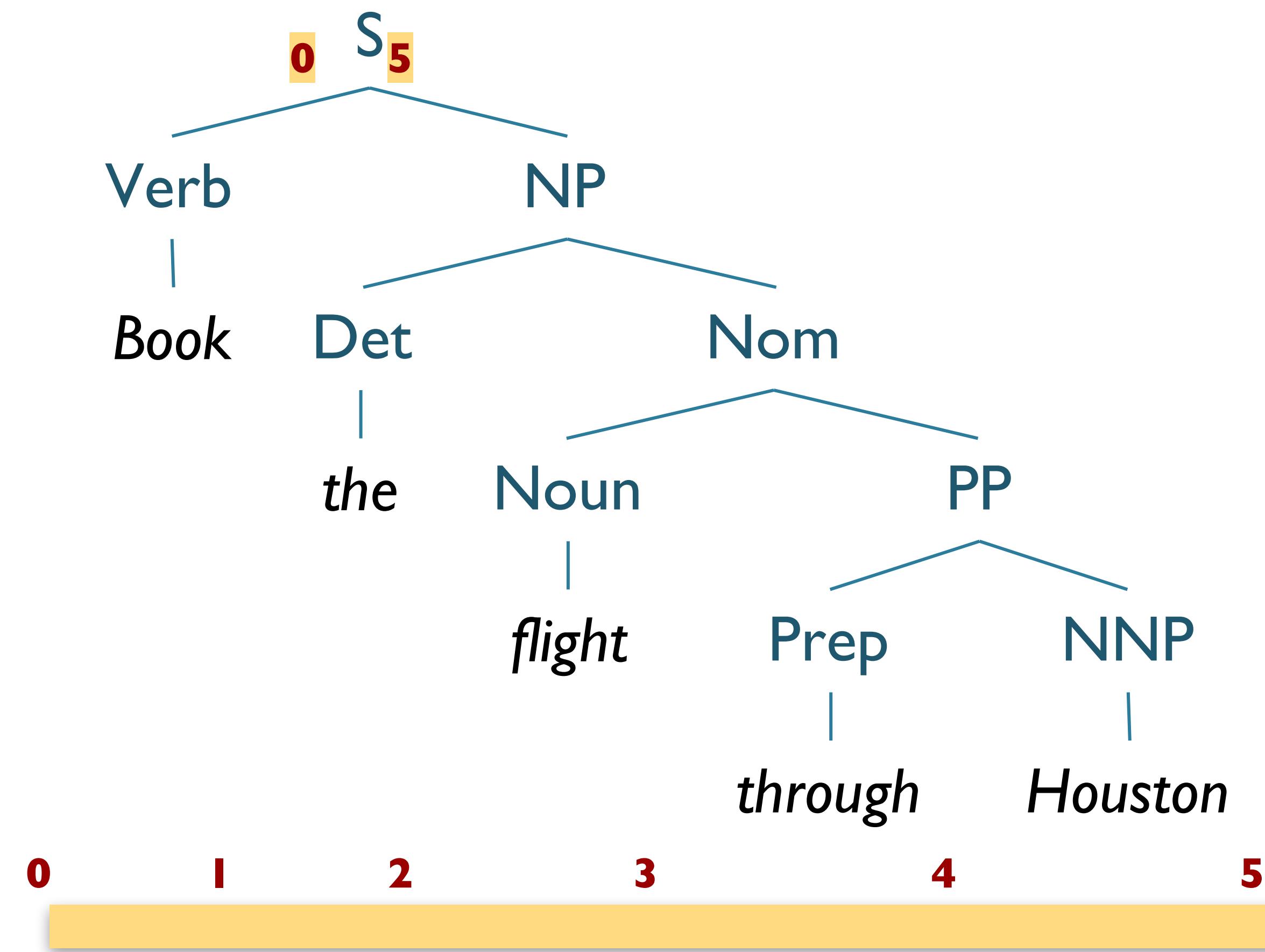
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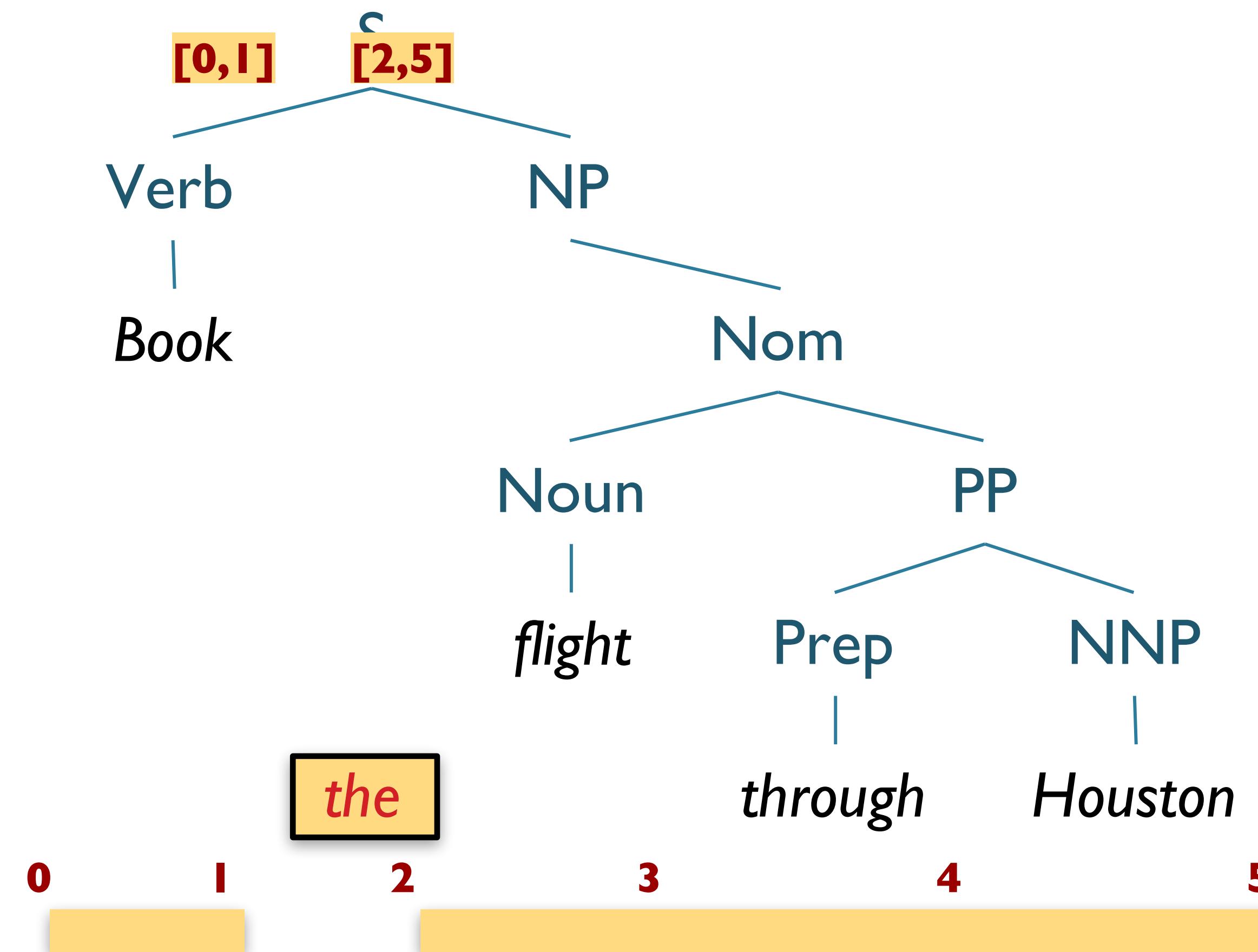
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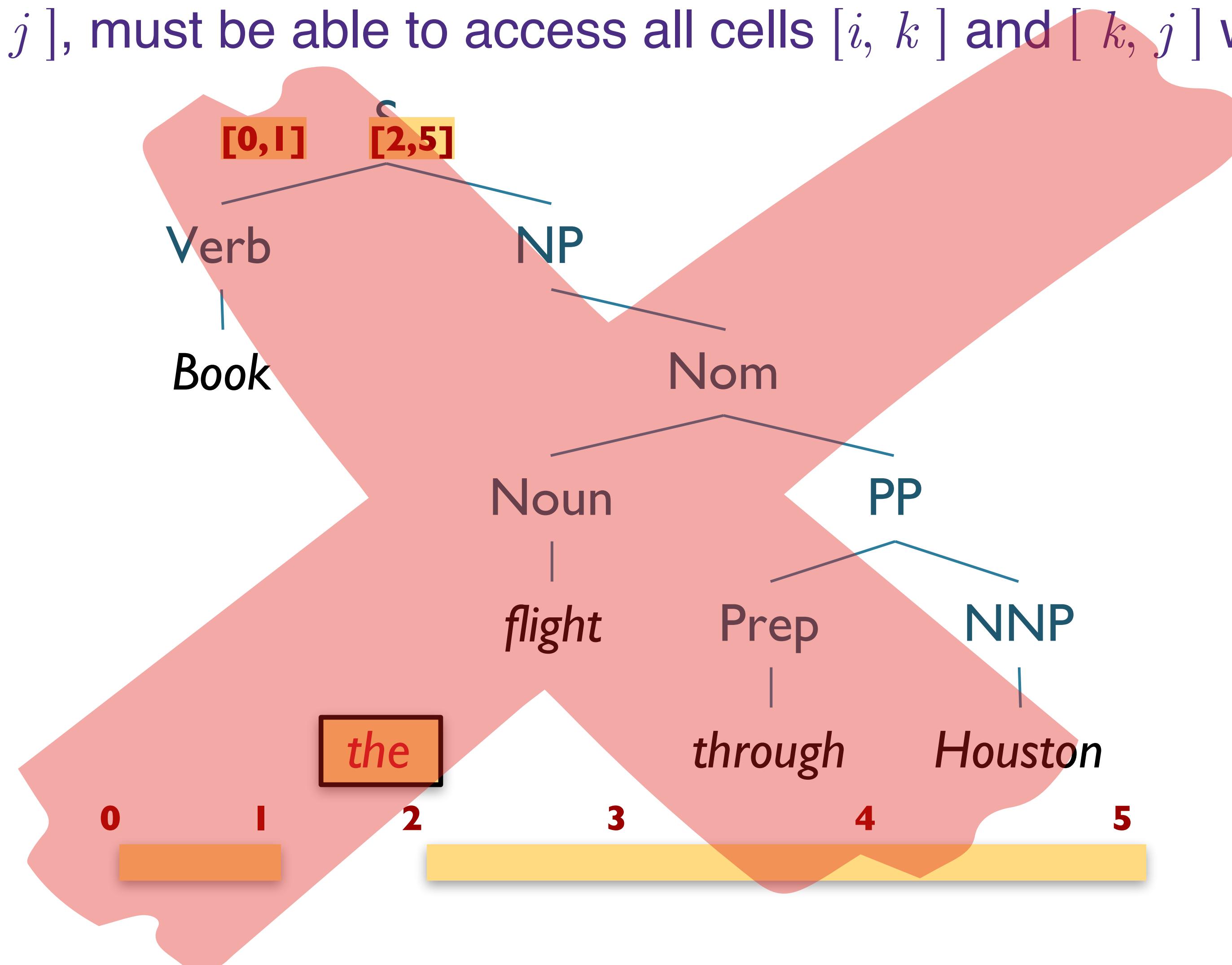
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CKY Parsing Example

\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

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

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

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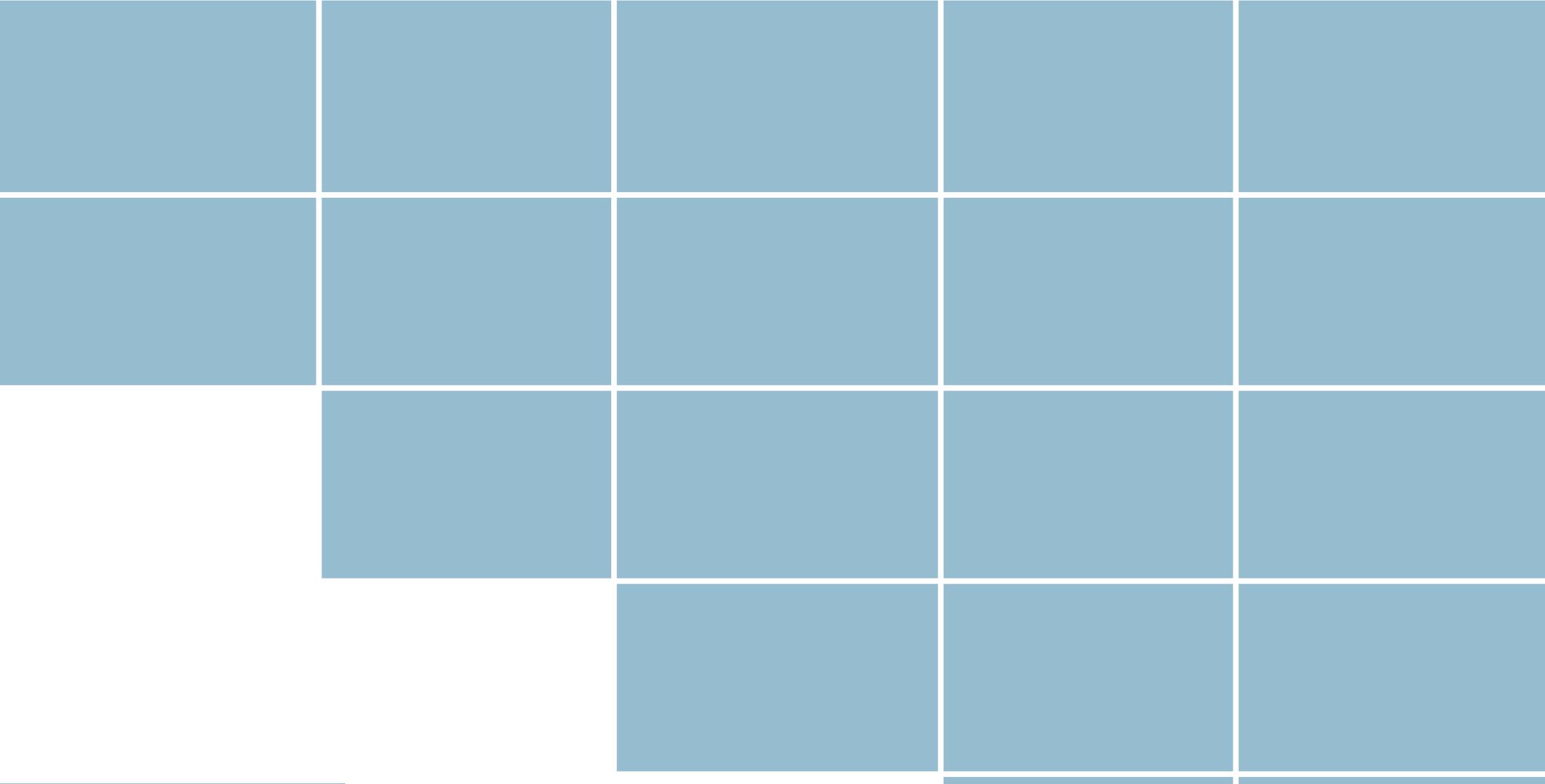
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NP

[0, 1]



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 $Nominal \rightarrow Nominal\ PP$

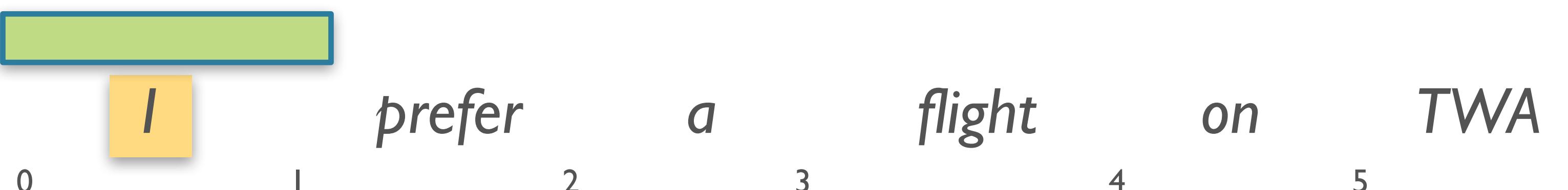
$VP \rightarrow book\ / include\ / prefer$
 $VP \rightarrow Verb\ NP$
 $VP \rightarrow X2\ PP$
 $X2 \rightarrow Verb\ NP$
 $VP \rightarrow Verb\ PP$
 $VP \rightarrow VP\ PP$

$PP \rightarrow Preposition\ NP$

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

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]**

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

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

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

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

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

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

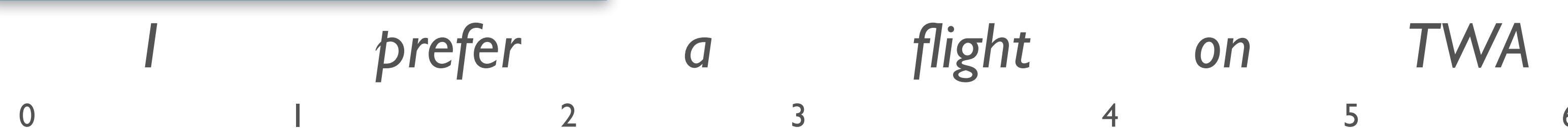
$PP \rightarrow Preposition NP$

NP, NP, Pronoun
[0,1]

Verb, VP, S
[1,2]

Lexicon

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



\mathcal{L}_1 Grammar

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

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

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

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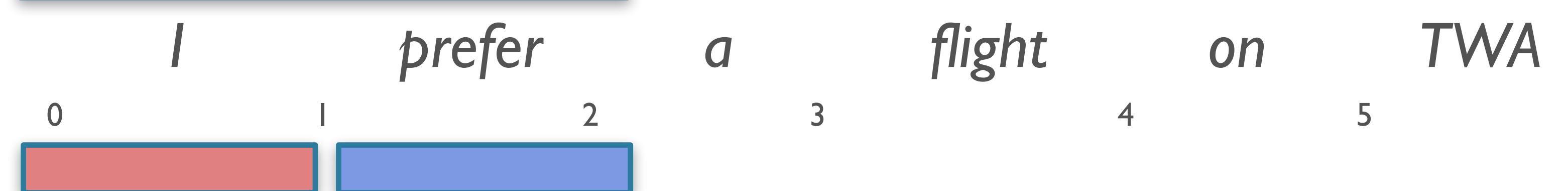
$PP \rightarrow Preposition NP$

NP, NP, Pronoun
[0,1]

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

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

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

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

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

$Nominal \rightarrow Nominal\ Noun$
 $Nominal \rightarrow Nominal\ PP$

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

$PP \rightarrow Preposition\ NP$

**NP, NP,
Pronoun**

[0,1]

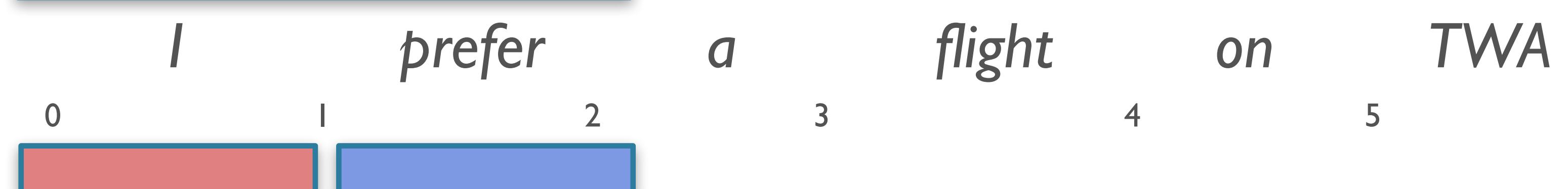
[0,2]

Verb, VP, S

[1,2]

Lexicon

$Det \rightarrow that\ | this\ | a$
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 $Pronoun \rightarrow I\ | she\ | me$
 $Proper-Noun \rightarrow Houston\ | TWA$
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 $Preposition \rightarrow from\ | to\ | on\ | near\ | through$
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\mathcal{L}_1 Grammar

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

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

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

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

$Nominal \rightarrow Nominal Noun$
 $Nominal \rightarrow Nominal PP$

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

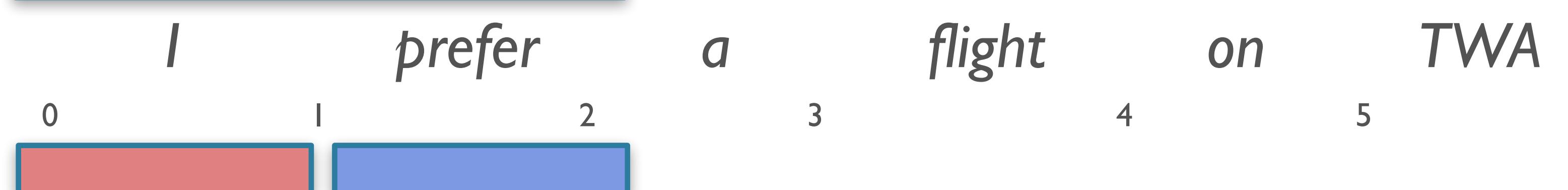
$PP \rightarrow Preposition NP$

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

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

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

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

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

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

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

$PP \rightarrow Preposition NP$

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

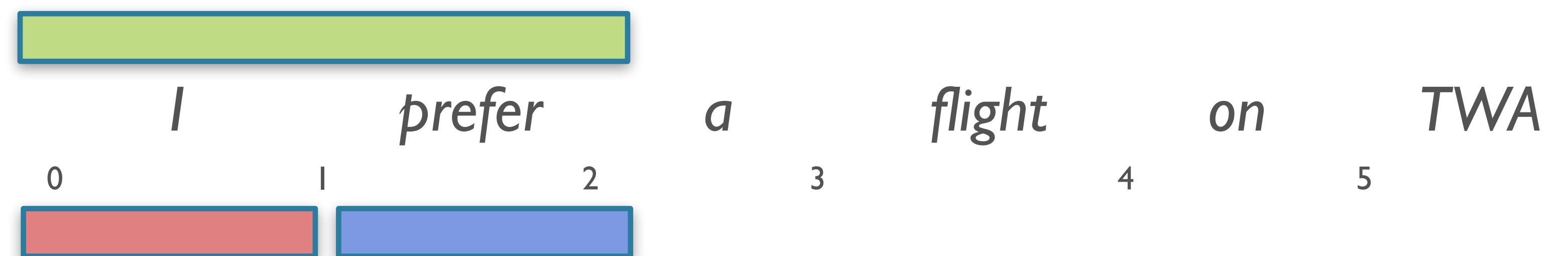
S S

$[0,2]$

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

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

$S \rightarrow Verb NP$
 $S \rightarrow X2 PP$
 $S \rightarrow Verb PP$
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$NP \rightarrow I / she / me$
 $NP \rightarrow TWA / Houston$
 $NP \rightarrow Det Nominal$

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

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

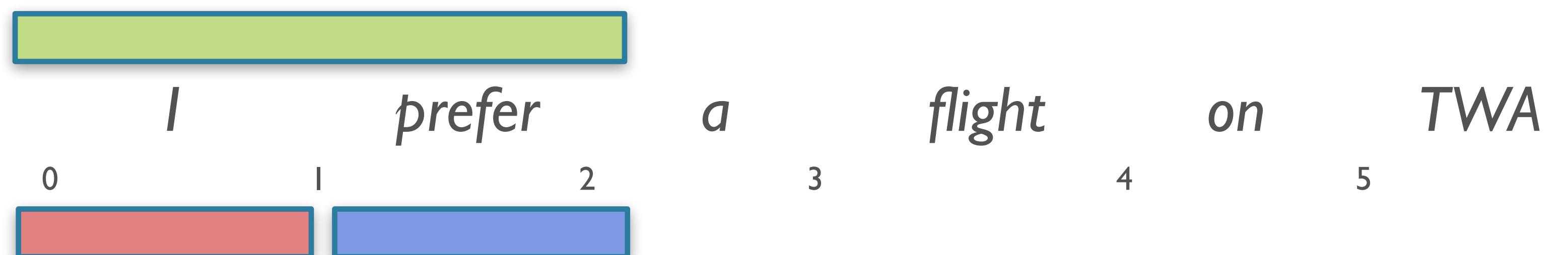
S

[0,2]

Verb, VP, S
[1,2]

Lexicon

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



\mathcal{L}_1 Grammar

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

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

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

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

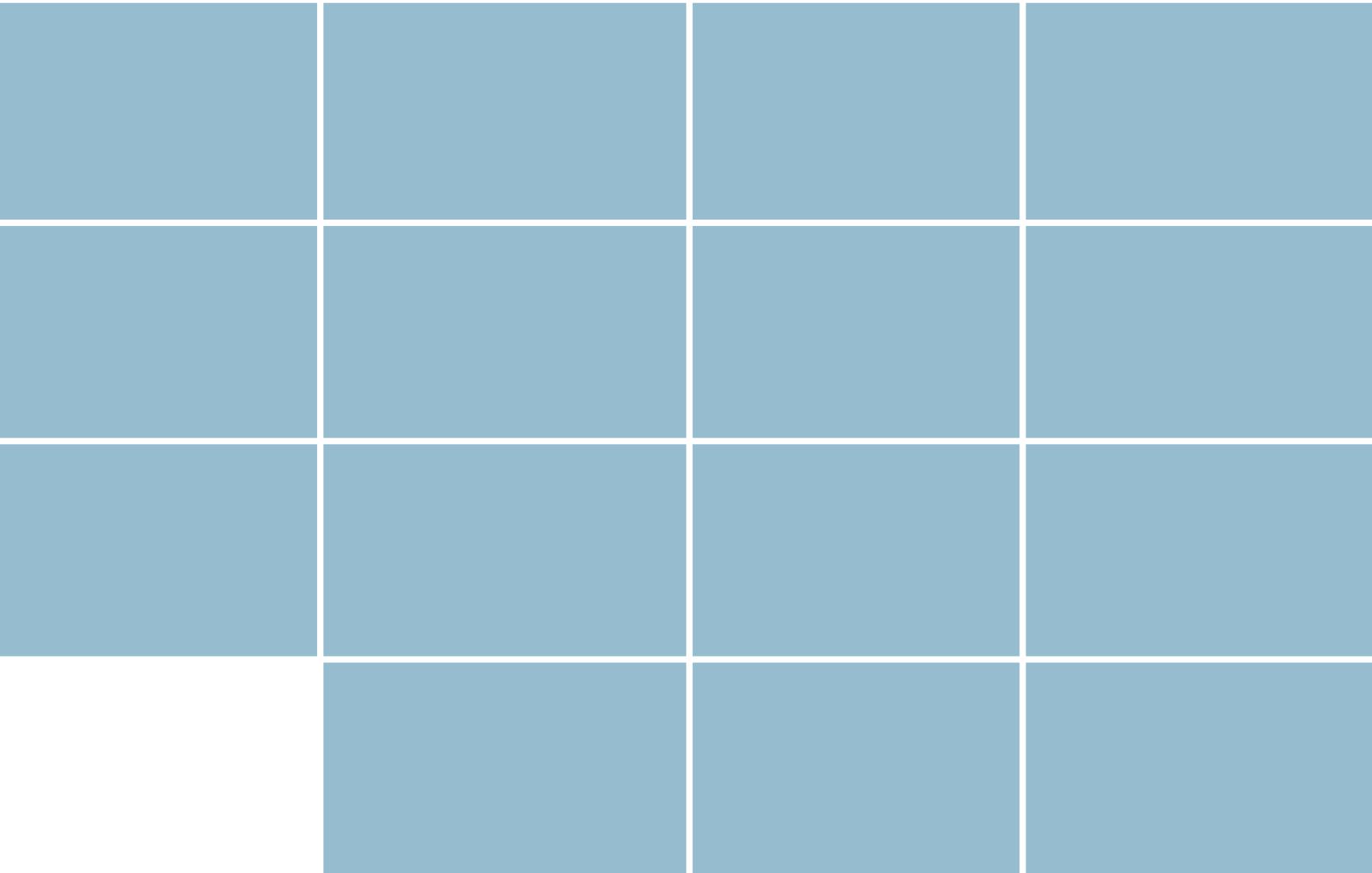
$Nominal \rightarrow Nominal Noun$
 $Nominal \rightarrow Nominal PP$

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

$PP \rightarrow Preposition NP$

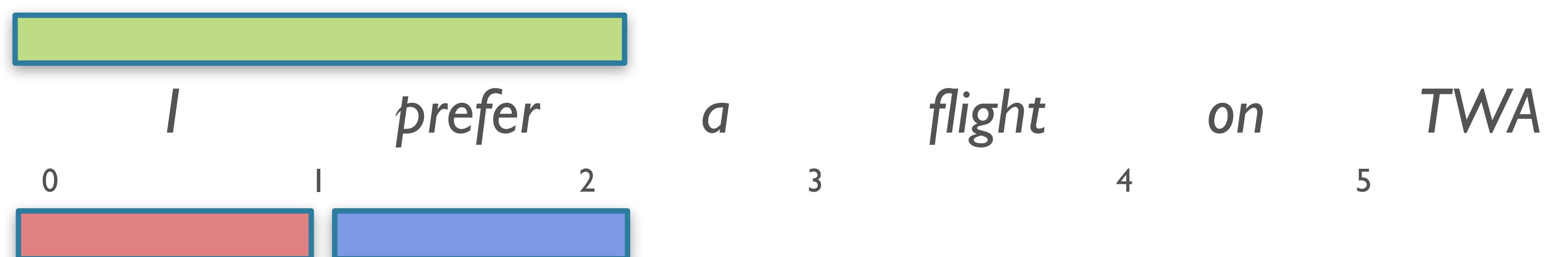
**NP, NP,
ProNoun**
 $[0,1]$

S 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

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

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

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

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

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 $Nominal \rightarrow Nominal\ PP$

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

$PP \rightarrow Preposition\ NP$

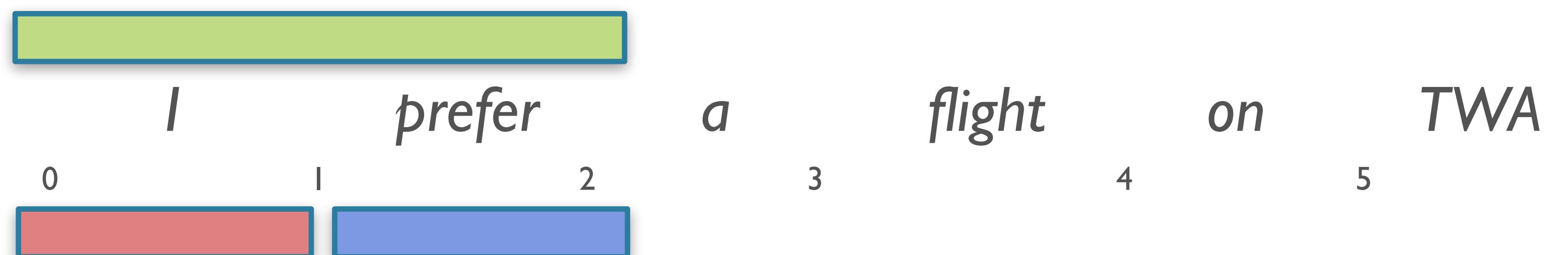
**NP, NP,
Pronoun**
[0,1]

S S
[0,2]

Verb, VP, S
[1,2]

Lexicon

$Det \rightarrow that\ | this\ | a$
 $Noun \rightarrow book\ | flight\ | meal\ | money$
 $Pronoun \rightarrow I\ | she\ | me$
 $Proper-Noun \rightarrow Houston\ | TWA$
 $Aux \rightarrow does$
 $Preposition \rightarrow from\ | to\ | on\ | near\ | through$
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\mathcal{L}_1 Grammar

$S \rightarrow NP VP$
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 $S \rightarrow X2 PP$
 $S \rightarrow Verb PP$
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$NP \rightarrow I / she / me$
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$NP \rightarrow Det Nominal$

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$Nominal \rightarrow Nominal Noun$

$Nominal \rightarrow Nominal PP$

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$VP \rightarrow Verb NP$

$VP \rightarrow X2 PP$

$X2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

$VP \rightarrow VP PP$

$PP \rightarrow Preposition NP$

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

S
[0,2]

Verb, VP, S
[1,2]

Det
[2,3]

Lexicon

Det → that | this | a

Noun → book | flight | meal | money

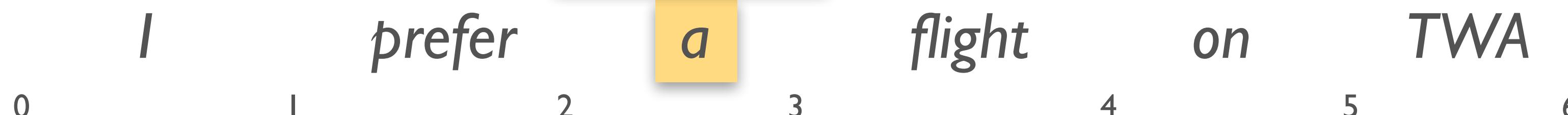
Pronoun → I | she | me

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]

Verb, VP, S
[1,2]

Det
[1,3]
[2,3]

Lexicon

$Det \rightarrow that\ | this\ | a$
 $Noun \rightarrow book\ | flight\ | meal\ | money$
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 $Preposition \rightarrow from\ | to\ | on\ | near\ | through$
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\mathcal{L}_1 Grammar

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

$PP \rightarrow Preposition NP$

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

S
 $[0,2]$

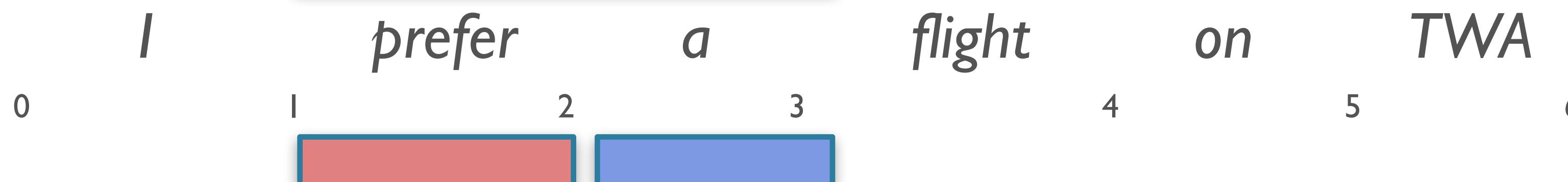
Verb, VP, S
 $[1,2]$

Det
 $[1,3]$

Det
 $[2,3]$

Lexicon

$Det \rightarrow that | this | a$
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 $Pronoun \rightarrow I | she | me$
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\mathcal{L}_1 Grammar

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$PP \rightarrow Preposition NP$

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

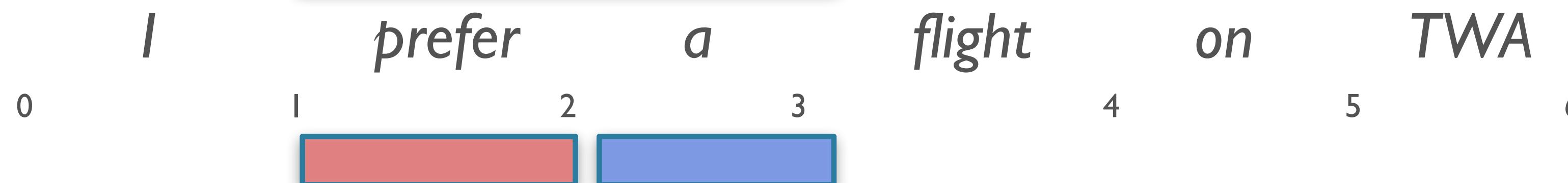
S
 $[0,2]$

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

Det
 $[1,3]$
Det
 $[2,3]$

Lexicon

$Det \rightarrow that | this | a$
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\mathcal{L}_1 Grammar

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**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

$S \rightarrow NP VP$
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**NP,
Pronoun**
 $[0,1]$

S
 $[0,2]$

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

[1,3]
Det
 $[2,3]$

Lexicon

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\mathcal{L}_1 Grammar

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$X2 \rightarrow Verb NP$

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$VP \rightarrow VP PP$

$PP \rightarrow Preposition NP$

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

S
[0,2]

[0,3]

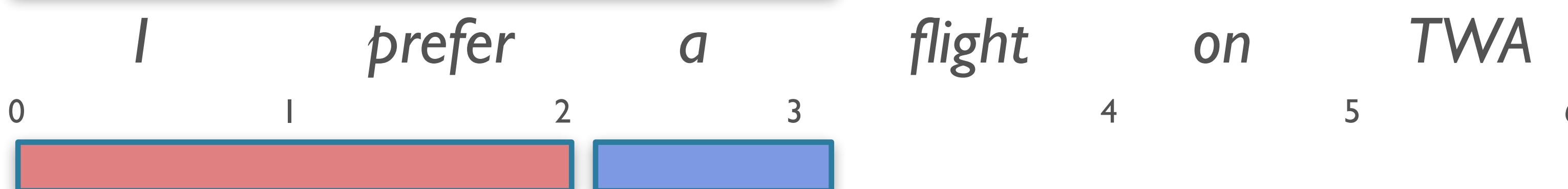
Verb, VP, S
[1,2]

[1,3]

Det
[2,3]

Lexicon

$Det \rightarrow that | this | a$
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\mathcal{L}_1 Grammar

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

$PP \rightarrow Preposition NP$

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

S
 $[0,2]$

S
 $[0,3]$

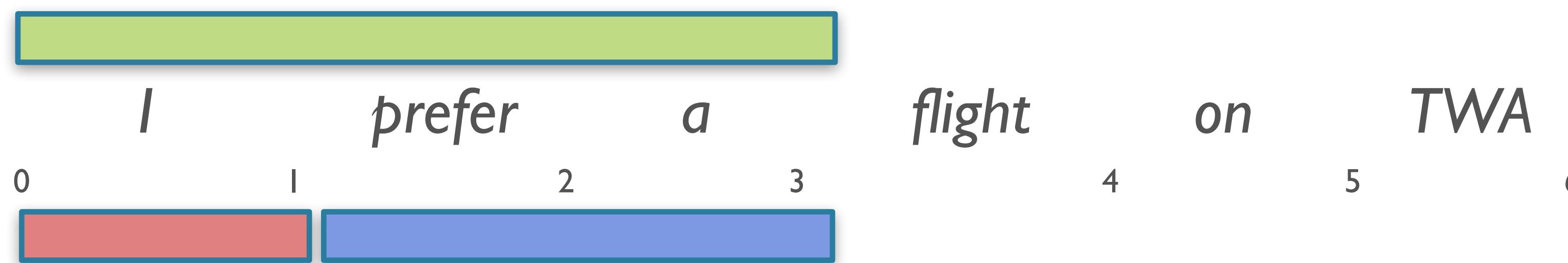
Verb, VP, S
 $[1,2]$

[1,3]

Det
 $[2,3]$

Lexicon

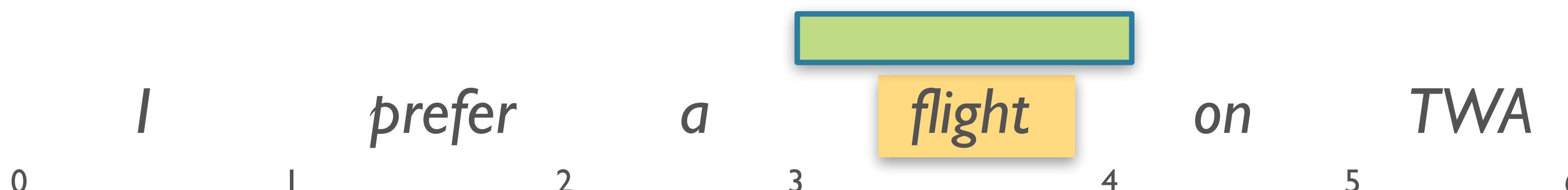
$Det \rightarrow that | this | a$
 $Noun \rightarrow book | flight | meal | money$
 $Pronoun \rightarrow I | she | me$
 $Proper-Noun \rightarrow Houston | TWA$
 $Aux \rightarrow does$
 $Preposition \rightarrow from | to | on | near | through$
 $Verb \rightarrow book | include | prefer$



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

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

Noun, Nom	[3,4]		



\mathcal{L}_1 Grammar

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

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

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

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

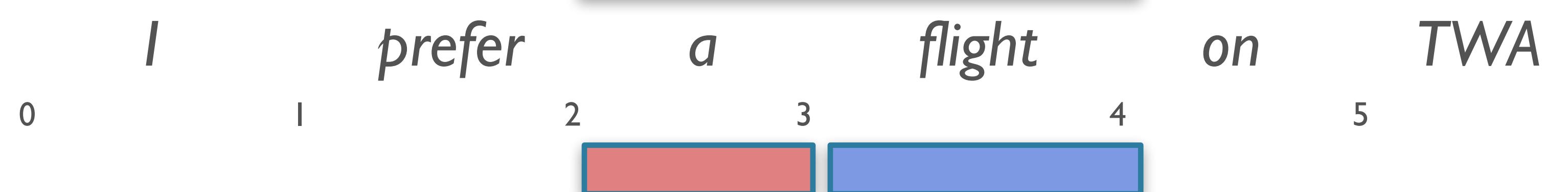
$VP \rightarrow book / include / prefer$
 $VP \rightarrow Verb NP$
 $VP \rightarrow X2 PP$
 $X2 \rightarrow Verb NP$
 $VP \rightarrow Verb PP$
 $VP \rightarrow VP PP$

$PP \rightarrow Preposition NP$

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

Lexicon

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



\mathcal{L}_1 Grammar

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

$S \rightarrow Verb NP$

$S \rightarrow X2 PP$

$S \rightarrow Verb PP$

$S \rightarrow VP PP$

$NP \rightarrow I / she / me$

$NP \rightarrow TWA / Houston$

$NP \rightarrow Det Nominal$

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

$Nominal \rightarrow Nominal Noun$

$Nominal \rightarrow Nominal PP$

$VP \rightarrow book / include / prefer$

$VP \rightarrow Verb NP$

$VP \rightarrow X2 PP$

$X2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

$VP \rightarrow VP PP$

$PP \rightarrow Preposition NP$

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

Lexicon

$Det \rightarrow that | this | a$

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

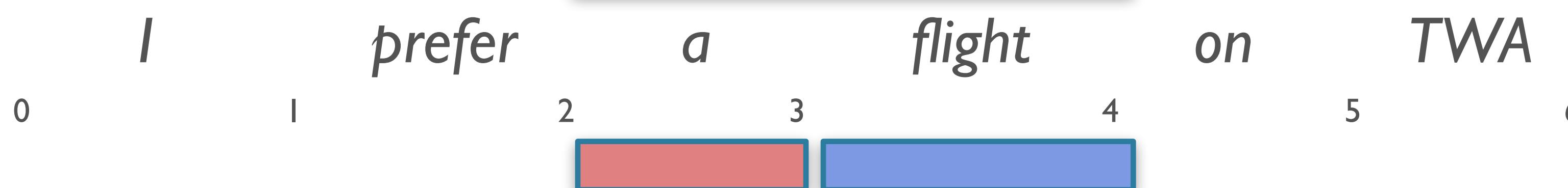
$Pronoun \rightarrow I | she | me$

$Proper-Noun \rightarrow Houston | TWA$

$Aux \rightarrow does$

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

$Verb \rightarrow book | include | prefer$



\mathcal{L}_1 Grammar

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

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

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

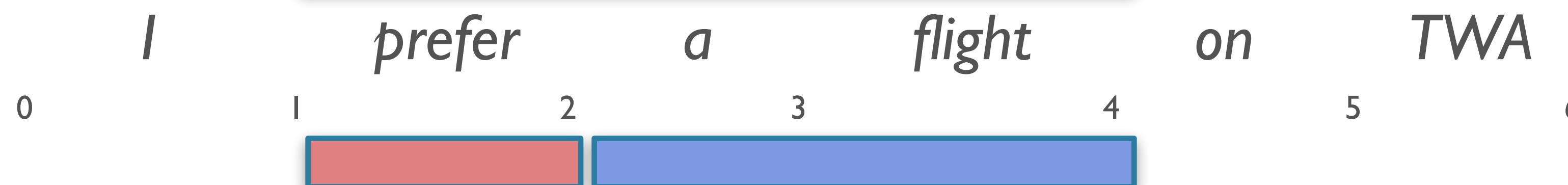
$VP \rightarrow book / include / prefer$
 $VP \rightarrow Verb NP$
 $VP \rightarrow X2 PP$
 $X2 \rightarrow Verb NP$
 $VP \rightarrow Verb PP$
 $VP \rightarrow VP PP$

$PP \rightarrow Preposition NP$

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

Lexicon

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



\mathcal{L}_1 Grammar

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

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

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

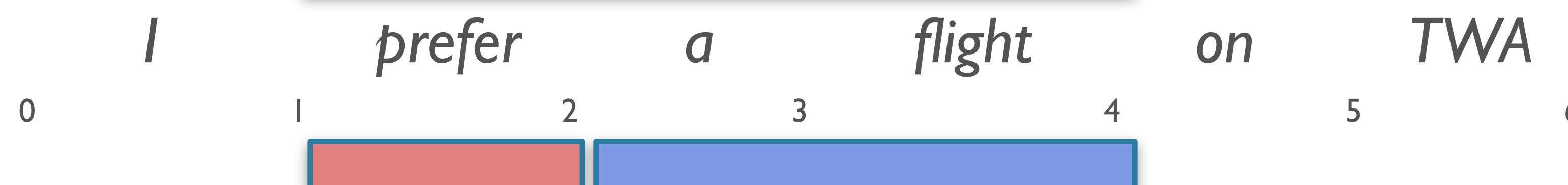
$Nominal \rightarrow book / flight / meal / money$
 $Nominal \rightarrow Nominal Noun$
 $Nominal \rightarrow Nominal PP$

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

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

Lexicon

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



\mathcal{L}_1 Grammar

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

$S \rightarrow Verb NP$

$S \rightarrow X2 PP$

$S \rightarrow Verb PP$

$S \rightarrow VP PP$

$NP \rightarrow I / she / me$

$NP \rightarrow TWA / Houston$

$NP \rightarrow Det Nominal$

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

$Nominal \rightarrow Nominal Noun$

$Nominal \rightarrow Nominal PP$

$VP \rightarrow book / include / prefer$

$VP \rightarrow Verb NP$

$VP \rightarrow X2 PP$

$X2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

$VP \rightarrow VP PP$

$PP \rightarrow Preposition NP$

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

Lexicon

$Det \rightarrow that | this | a$

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

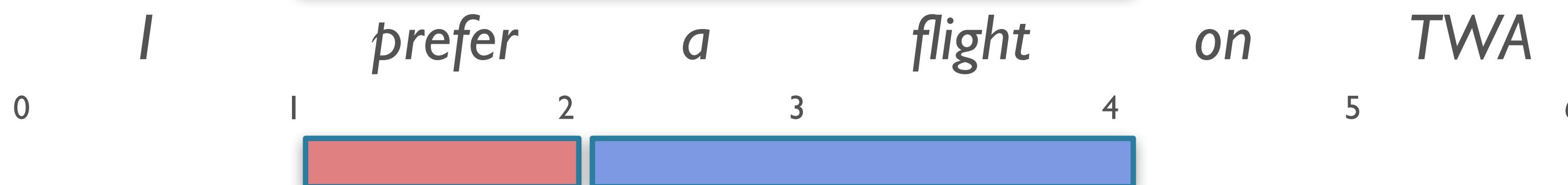
$Pronoun \rightarrow I | she | me$

$Proper-Noun \rightarrow Houston | TWA$

$Aux \rightarrow does$

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

$Verb \rightarrow book | include | prefer$



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

NP, Pronoun [0,1]	S [0,2]	[0,3]		
	Verb, VP, S [1,2]		VP, X2, S [1,4]	
		[1,3]		
	Det [2,3]		NP [2,4]	

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]	S [0,2]	[0,3]			
		Verb, VP, S [1,2]		VP, X2, S [1,4]	
			Det [1,3]	NP [2,4]	
				Noun, Nom [3,4]	

Lexicon

$Det \rightarrow that | this | a$

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

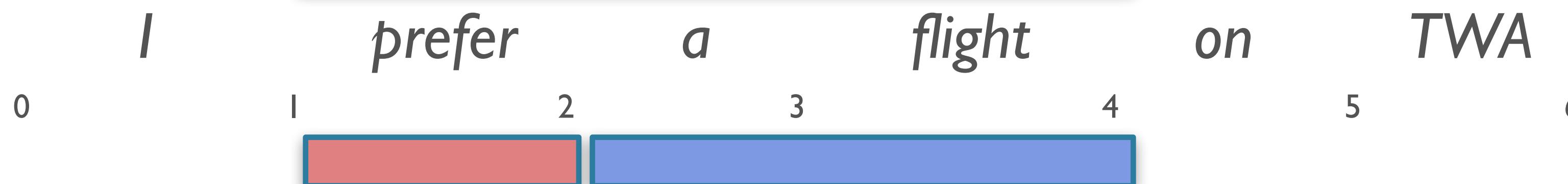
$Pronoun \rightarrow I | she | me$

$Proper-Noun \rightarrow Houston | TWA$

$Aux \rightarrow does$

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

$Verb \rightarrow book | include | prefer$



\mathcal{L}_1 Grammar

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

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

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

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

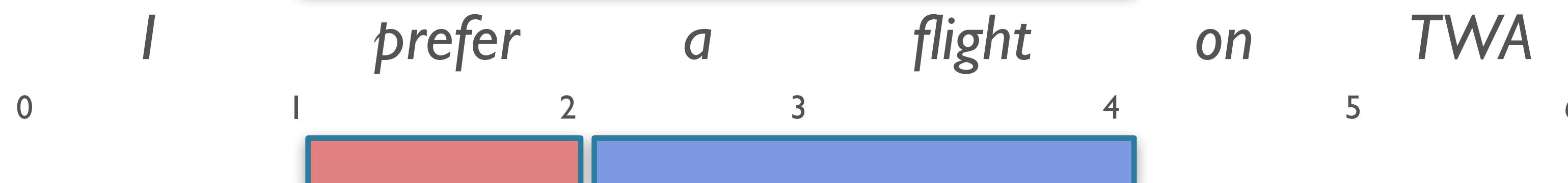
$VP \rightarrow book / include / prefer$
 $VP \rightarrow Verb NP$
 $VP \rightarrow X2 PP$
 $X2 \rightarrow Verb NP$
 $VP \rightarrow Verb PP$
 $VP \rightarrow VP PP$

$PP \rightarrow Preposition NP$

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

Lexicon

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



\mathcal{L}_1 Grammar

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

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

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

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

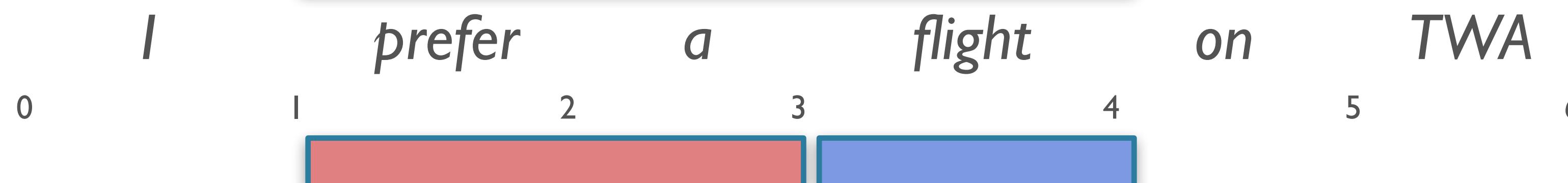
$VP \rightarrow book / include / prefer$
 $VP \rightarrow Verb NP$
 $VP \rightarrow X2 PP$
 $X2 \rightarrow Verb NP$
 $VP \rightarrow Verb PP$
 $VP \rightarrow VP PP$

$PP \rightarrow Preposition NP$

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

Lexicon

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



\mathcal{L}_1 Grammar

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

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

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

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

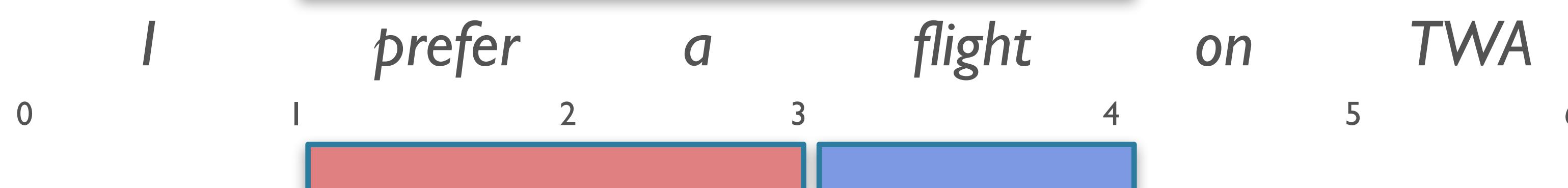
$VP \rightarrow book / include / prefer$
 $VP \rightarrow Verb NP$
 $VP \rightarrow X2 PP$
 $X2 \rightarrow Verb NP$
 $VP \rightarrow Verb PP$
 $VP \rightarrow VP PP$

$PP \rightarrow Preposition NP$

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

Lexicon

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



\mathcal{L}_1 Grammar

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

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

$NP \rightarrow I / she / me$

$NP \rightarrow TWA / Houston$

$NP \rightarrow Det Nominal$

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

$Nominal \rightarrow Nominal Noun$

$Nominal \rightarrow Nominal PP$

$VP \rightarrow book / include / prefer$

$VP \rightarrow Verb NP$

$VP \rightarrow X2 PP$

$X2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

$VP \rightarrow VP PP$

$PP \rightarrow Preposition NP$

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

S [0,2]	[0,3]	[0,4]		
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Verb, VP, S
[1,2]

Verb, VP, S [1,2]	[1,3]	[1,4]		
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Det
[2,3]

Det [2,3]	NP [2,4]			
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Noun, Nom
[3,4]

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

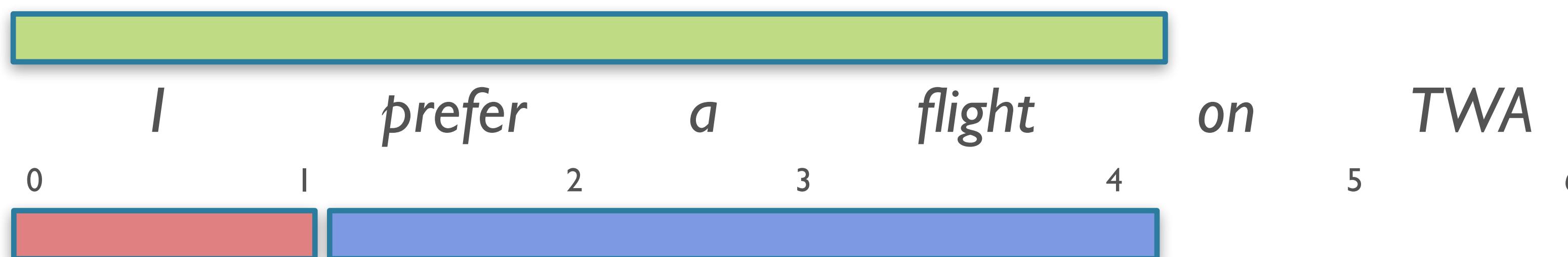


\mathcal{L}_1 Grammar

$S \rightarrow NP VP$	NP, Pronoun $[0,1]$	S	S	S		
$S \rightarrow X1 VP$		[0,2]	[0,3]	[0,4]		
$X1 \rightarrow Aux NP$						
$S \rightarrow book / include / prefer$						
$S \rightarrow Verb NP$						
$S \rightarrow X2 PP$						
$S \rightarrow Verb PP$						
$S \rightarrow VP PP$						
$NP \rightarrow I / she / me$						
$NP \rightarrow TWA / Houston$						
$NP \rightarrow Det Nominal$						
$Nominal \rightarrow book / flight / meal / money$						
$Nominal \rightarrow Nominal Noun$						
$Nominal \rightarrow Nominal PP$						
$VP \rightarrow book / include / prefer$						
$VP \rightarrow Verb NP$						
$VP \rightarrow X2 PP$						
$X2 \rightarrow Verb NP$						
$VP \rightarrow Verb PP$						
$VP \rightarrow VP PP$						
$PP \rightarrow Preposition NP$						

Lexicon

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



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

\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]

[1,3]

[1,4]

[2,4]

[3,4]

S

[0,4]

[1,4]

Det

NP

Noun, Nom

Verb, VP, S

VP, X2, S

NP

Noun, Nom

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]

[0,2]

[0,3]

[0,4]

S

Verb, VP, S

[1,2]

[1,3]

[1,4]

Det

[2,3]

[2,4]

NP

[2,4]

Noun, Nom

[3,4]

Lexicon

$Det \rightarrow that | this | a$

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

$Pronoun \rightarrow I | she | me$

$Proper-Noun \rightarrow Houston | TWA$

$Aux \rightarrow does$

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

$Verb \rightarrow book | include | prefer$



\mathcal{L}_1 Grammar

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

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

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$NP \rightarrow Det Nominal$

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

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$Nominal \rightarrow Nominal PP$

$VP \rightarrow book / include / prefer$

$VP \rightarrow Verb NP$

$VP \rightarrow X2 PP$

$X2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

$VP \rightarrow VP PP$

$PP \rightarrow Preposition NP$

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

[0,2]

[0,3]

[0,4]

S
[0,2]

[0,3]

[0,4]

[0,5]

[0,6]

[0,7]

[0,8]

[0,9]

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[0,31]

[0,32]

[0,33]

S
[0,2]

[0,3]

[0,4]

[0,5]

[0,6]

[0,7]

[0,8]

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[0,30]

[0,31]

[0,32]

[0,33]

VP, X2, S
[0,1]

[0,2]

[0,3]

[0,4]

[0,5]

[0,6]

[0,7]

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[0,31]

[0,32]

[0,33]

Lexicon

$Det \rightarrow that | this | a$

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

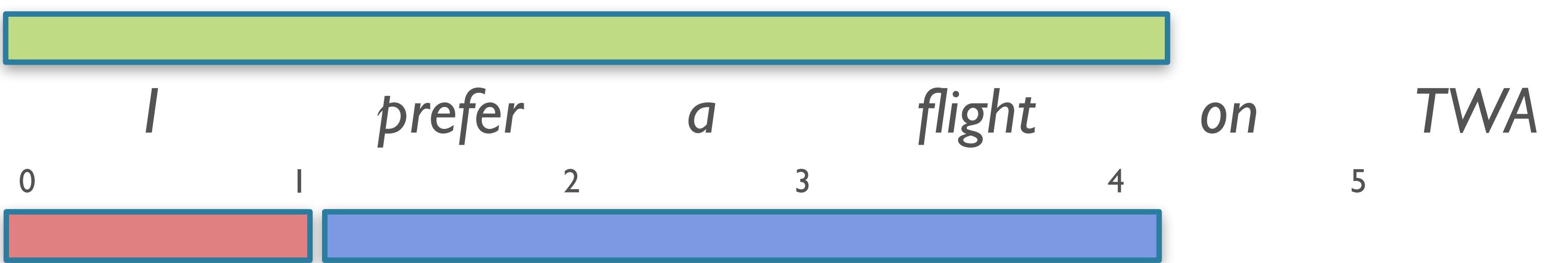
$Pronoun \rightarrow I | she | me$

$Proper-Noun \rightarrow Houston | TWA$

$Aux \rightarrow does$

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

$Verb \rightarrow book | include | prefer$



\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]

[0,2]

[0,3]

[0,4]

S
[0,2]

[0,3]

[0,4]

[0,5]

[0,6]

[0,7]

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[0,24]

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[0,26]

[0,27]

[0,28]

[0,29]

[0,30]

[0,31]

[0,32]

[0,33]

S
[0,2]

[0,3]

[0,4]

[0,5]

[0,6]

[0,7]

[0,8]

[0,9]

[0,10]

[0,11]

[0,12]

[0,13]

[0,14]

[0,15]

[0,16]

[0,17]

[0,18]

[0,19]

[0,20]

[0,21]

[0,22]

[0,23]

[0,24]

[0,25]

[0,26]

[0,27]

[0,28]

[0,29]

[0,30]

[0,31]

[0,32]

[0,33]

Verb, VP, S
[1,2]

[1,3]

[1,4]

[1,5]

[1,6]

[1,7]

[1,8]

[1,9]

[1,10]

[1,11]

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[1,26]

[1,27]

[1,28]

[1,29]

[1,30]

[1,31]

[1,32]

[1,33]

Lexicon

$Det \rightarrow that | this | a$

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

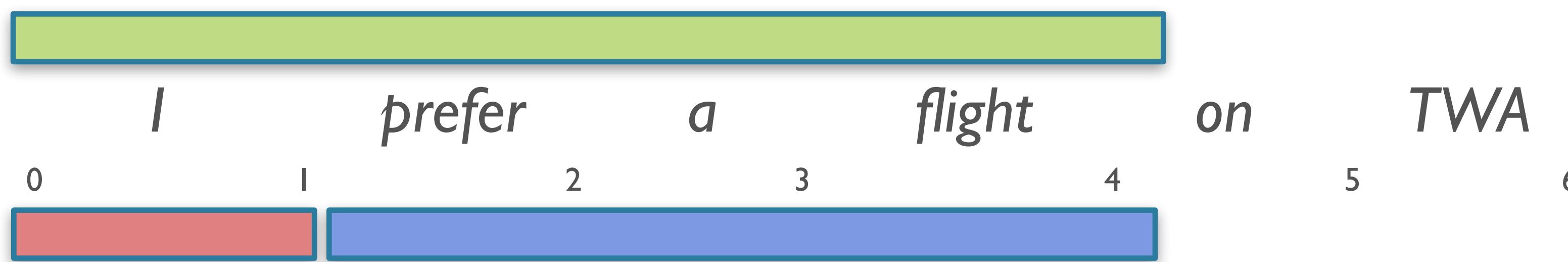
$Pronoun \rightarrow I | she | me$

$Proper-Noun \rightarrow Houston | TWA$

$Aux \rightarrow does$

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

$Verb \rightarrow book | include | prefer$



\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]

[0,2]

[0,3]

[0,4]

S
[0,2]

[0,3]

[0,4]

[0,5]

[0,6]

[0,7]

[0,8]

[0,9]

[0,10]

[0,11]

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[0,28]

[0,29]

[0,30]

[0,31]

[0,32]

[0,33]

S
[0,2]

[0,3]

[0,4]

[0,5]

[0,6]

[0,7]

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[0,30]

[0,31]

[0,32]

[0,33]

VP, X2, S
[0,2]

[0,3]

[0,4]

[0,5]

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Lexicon

$Det \rightarrow that | this | a$

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

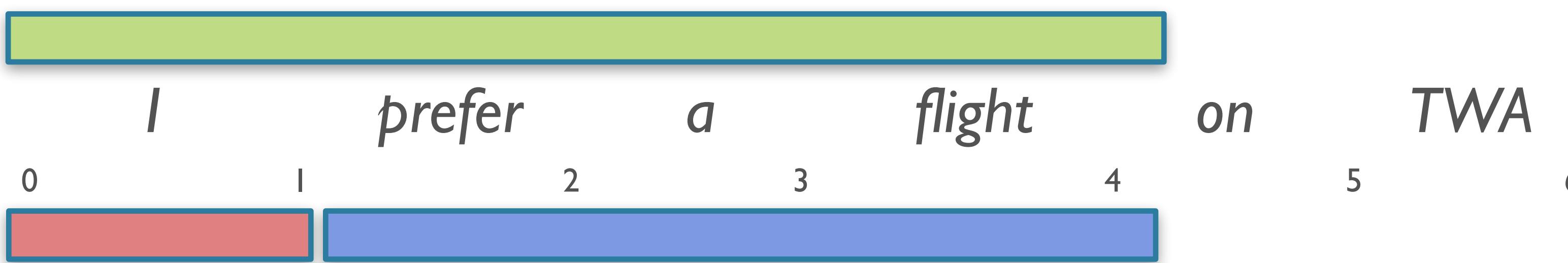
$Pronoun \rightarrow I | she | me$

$Proper-Noun \rightarrow Houston | TWA$

$Aux \rightarrow does$

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

$Verb \rightarrow book | include | prefer$



\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]

S

[0,4]

Verb, VP, S
[1,2]

[1,3]

VP, X2, S
[1,4]

Det

[2,3]

NP

[2,4]

Noun, Nom

[3,4]

Lexicon

$Det \rightarrow that | this | a$

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

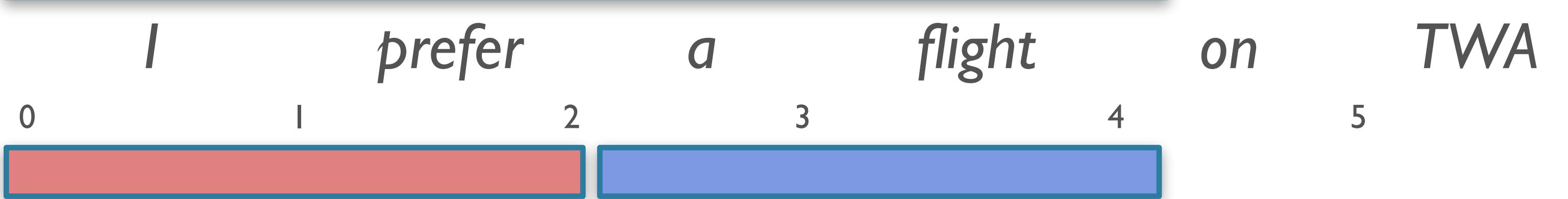
$Pronoun \rightarrow I | she | me$

$Proper-Noun \rightarrow Houston | TWA$

$Aux \rightarrow does$

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

$Verb \rightarrow book | include | prefer$



\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 [1,3]	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]

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[0,3]

[0,4]

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

Lexicon

$Det \rightarrow that | this | a$

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

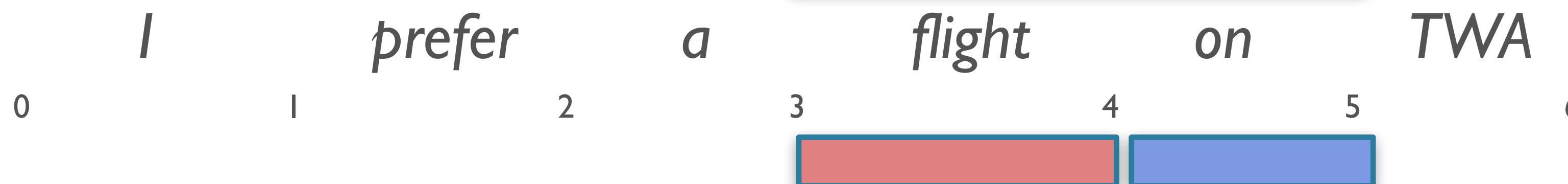
$Pronoun \rightarrow I | she | me$

$Proper-Noun \rightarrow Houston | TWA$

$Aux \rightarrow does$

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

$Verb \rightarrow book | include | prefer$



\mathcal{L}_1 Grammar

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

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

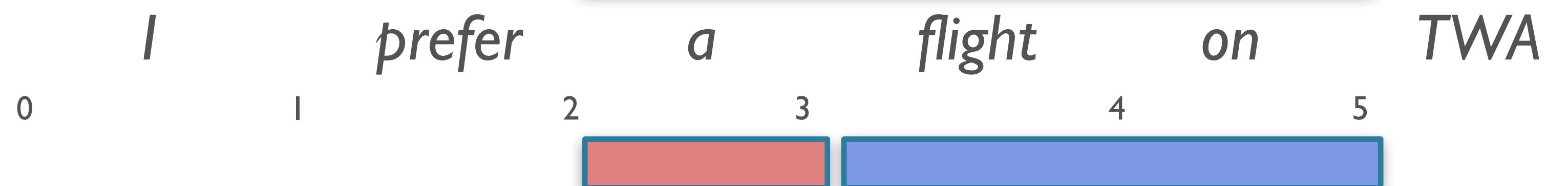
$Nominal \rightarrow book / flight / meal / money$
 $Nominal \rightarrow Nominal Noun$
 $Nominal \rightarrow Nominal PP$

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

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

Lexicon

$Det \rightarrow that | this | a$

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

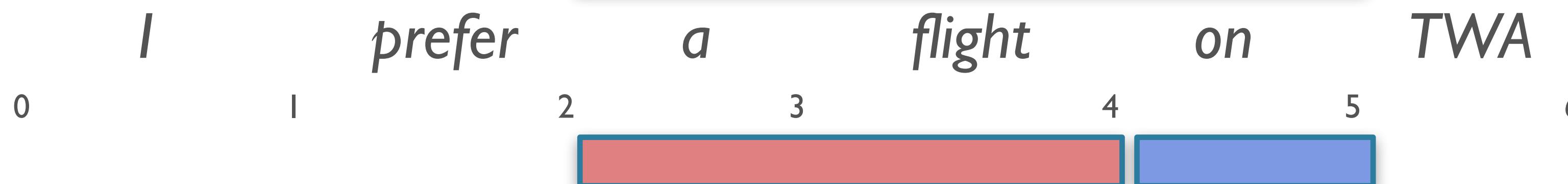
$Pronoun \rightarrow I | she | me$

$Proper-Noun \rightarrow Houston | TWA$

$Aux \rightarrow does$

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

$Verb \rightarrow book | include | prefer$



\mathcal{L}_1 Grammar

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

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

$NP \rightarrow I / she / me$

$NP \rightarrow TWA / Houston$

$NP \rightarrow Det Nominal$

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

$Nominal \rightarrow Nominal Noun$

$Nominal \rightarrow Nominal PP$

$VP \rightarrow book / include / prefer$

$VP \rightarrow Verb NP$

$VP \rightarrow X2 PP$

$X2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

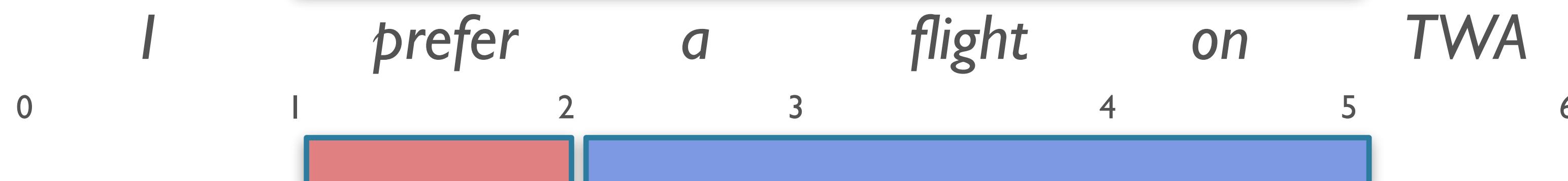
$VP \rightarrow VP PP$

$PP \rightarrow Preposition NP$

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

Lexicon

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



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

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

Lexicon

Det → *that* | *this* | *a*

Pronoun → I | she | me

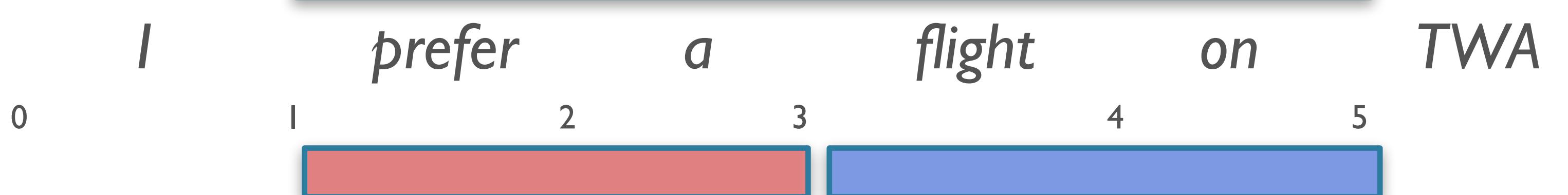
Proper-Noun → Houston

Aux → *does*

Preposition →

Verb → book | include | prefer

verb book | include | prefer



\mathcal{L}_1 Grammar

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

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

$NP \rightarrow I / she / me$

$NP \rightarrow TWA / Houston$

$NP \rightarrow Det Nominal$

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

$Nominal \rightarrow Nominal Noun$

$Nominal \rightarrow Nominal PP$

$VP \rightarrow book / include / prefer$

$VP \rightarrow Verb NP$

$VP \rightarrow X2 PP$

$X2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

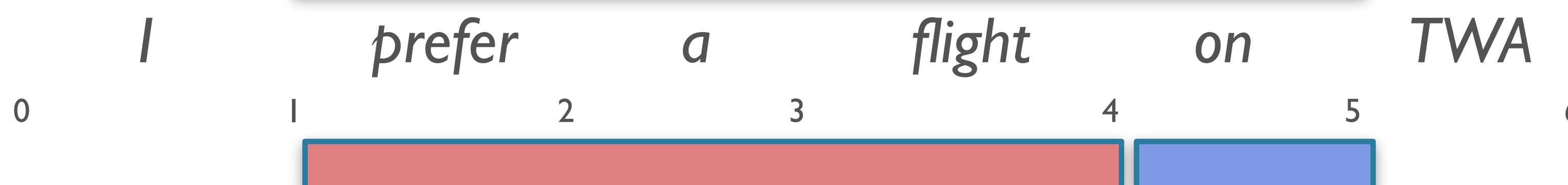
$VP \rightarrow VP PP$

$PP \rightarrow Preposition NP$

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

[0,5]

Verb, VP, S
[1,2]

Verb, VP, S
[1,3]

VP, X2, S
[1,4]

[1,5]

Det
[2,3]

NP
[2,4]

Noun, Nom
[2,5]

[3,4]

[3,5]

Prep
[4,5]

Lexicon

$Det \rightarrow that | this | a$

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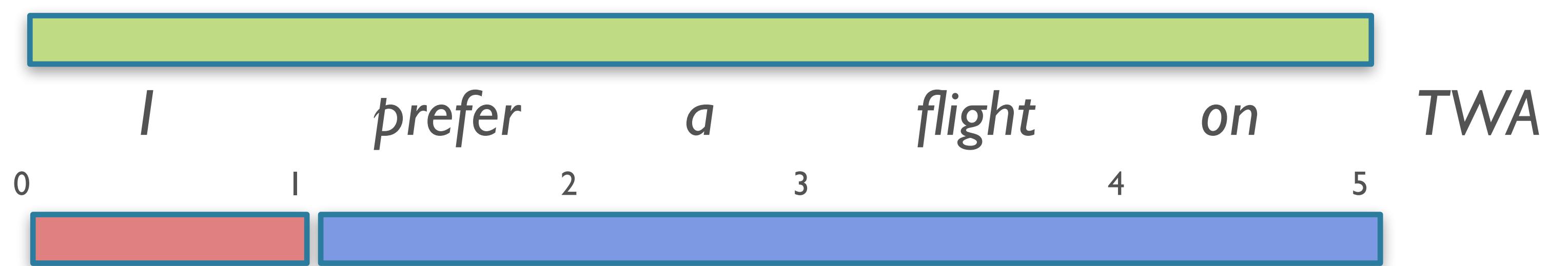
$Pronoun \rightarrow I | she | me$

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

S
[0,2]

Verb, VP, S
[1,2]

Det
[2,3]

NP
[2,4]

Noun, Nom
[3,4]

Prep
[4,5]

Lexicon

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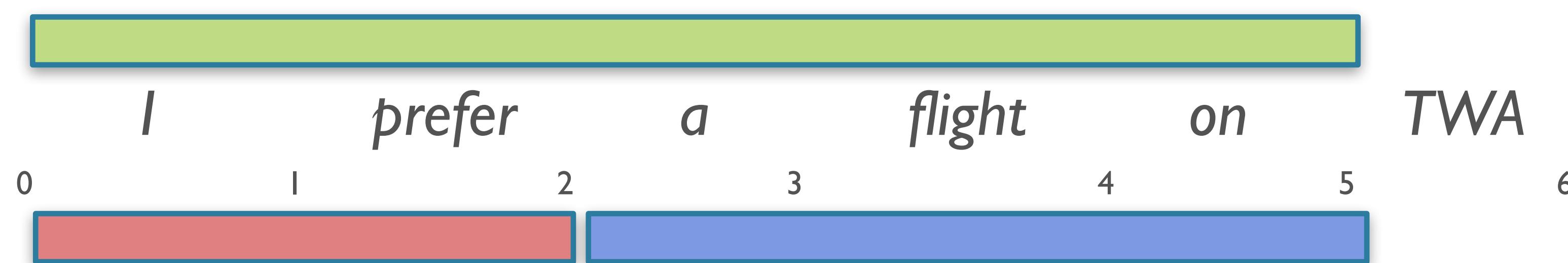
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NP, Pronoun [0,1]	S [0,2]		S [0,4]		
	Verb, VP, S [1,2]		VP, X2, S [1,4]		
		Det [2,3]	NP [2,4]		
			Noun, Nom [3,4]	[3,5]	
				Prep [4,5]	

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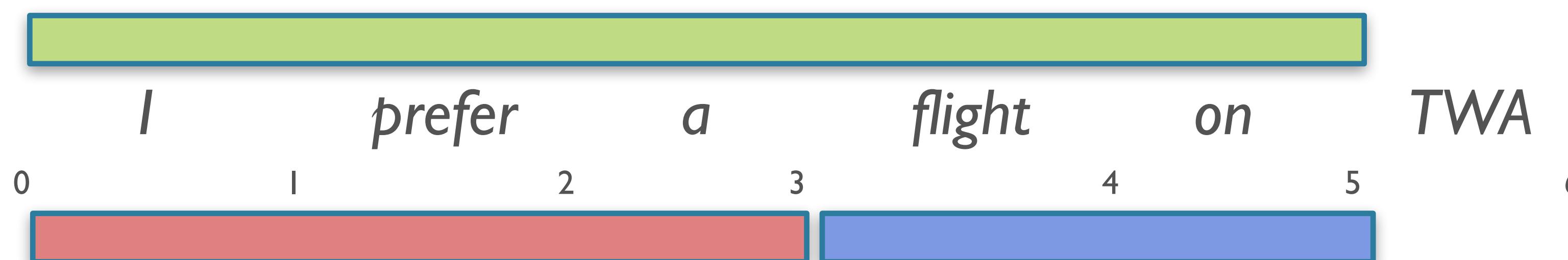
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$VP \rightarrow X2 PP$

$X2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

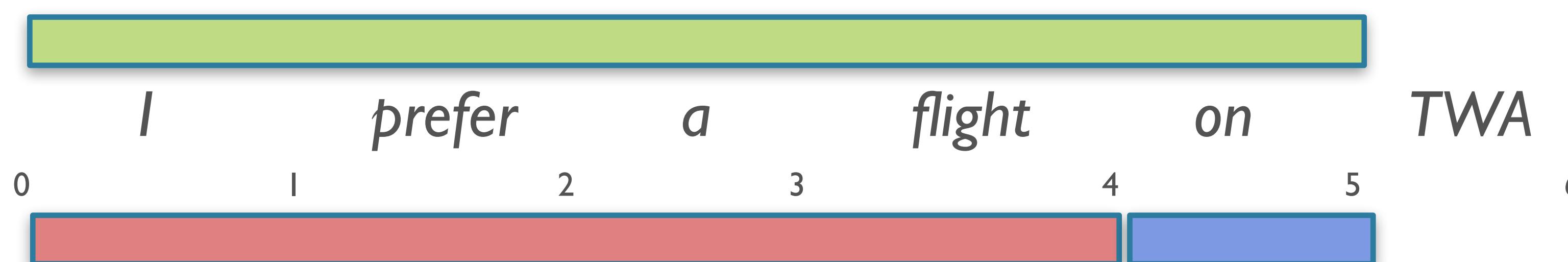
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$PP \rightarrow Preposition NP$

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

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

Lexicon

$Det \rightarrow that | this | a$

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$Aux \rightarrow does$

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$VP \rightarrow Verb PP$

$VP \rightarrow VP PP$

$PP \rightarrow Preposition NP$



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

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$VP \rightarrow book / include / prefer$

$VP \rightarrow Verb NP$

$VP \rightarrow X2 PP$

$X2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

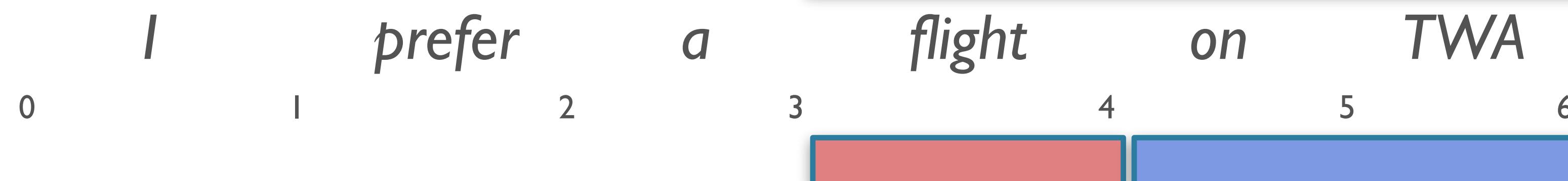
$VP \rightarrow VP PP$

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

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$X2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

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

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$Det \rightarrow that | this | a$

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$Nominal \rightarrow Nominal Noun$

$Nominal \rightarrow Nominal PP$

$VP \rightarrow book / include / prefer$

$VP \rightarrow Verb NP$

$VP \rightarrow X2 PP$

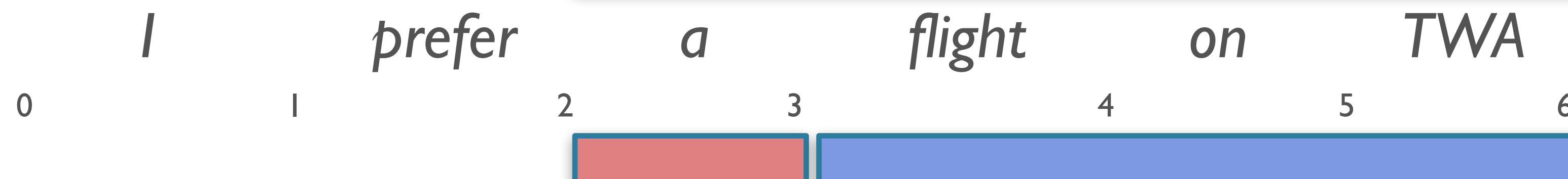
$X2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

$VP \rightarrow VP PP$

$PP \rightarrow Preposition NP$

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



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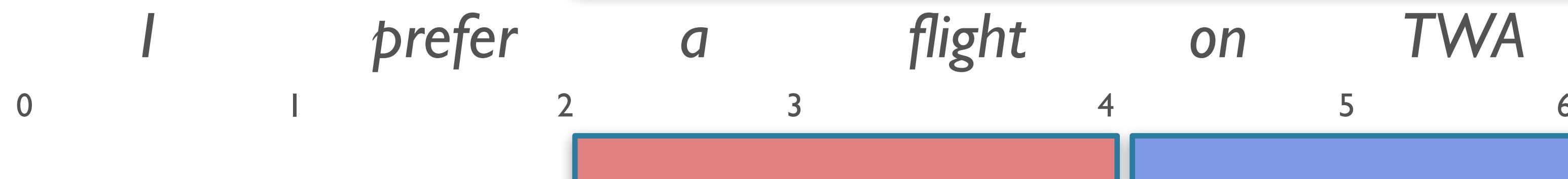
$X2 \rightarrow Verb NP$

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$VP \rightarrow VP PP$

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



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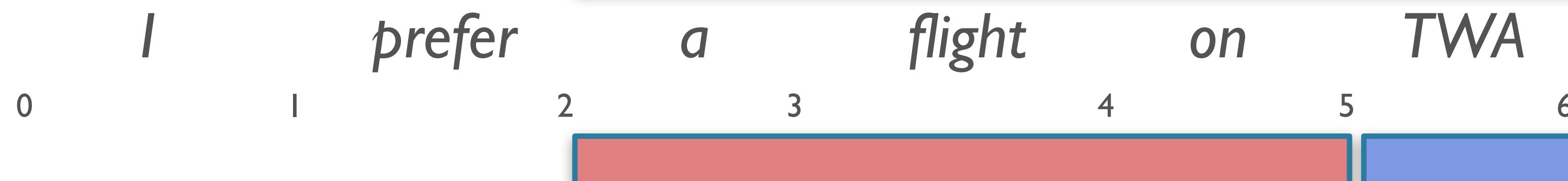
$X2 \rightarrow Verb NP$

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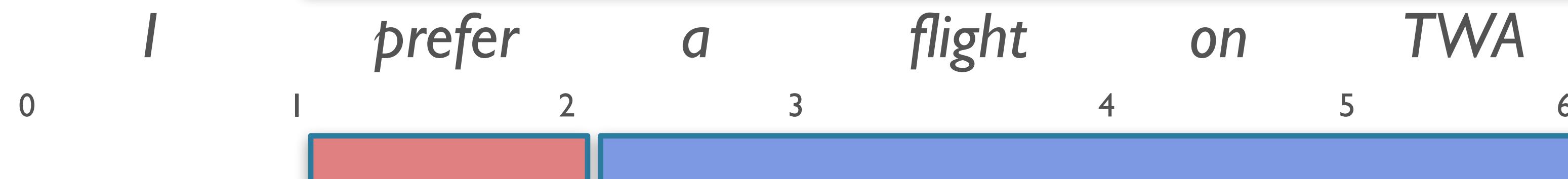
$VP \rightarrow VP PP$

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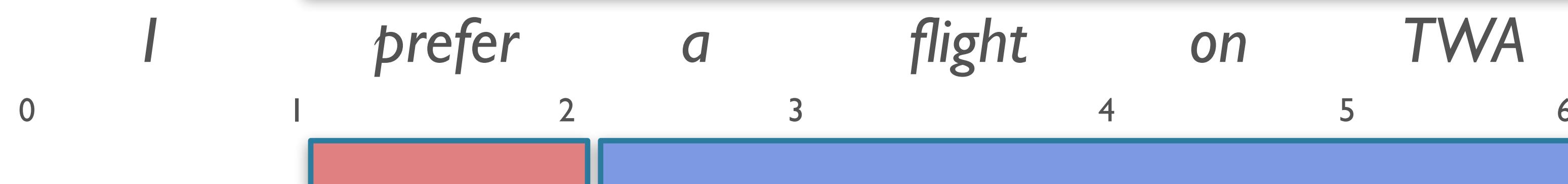
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NP, Pronoun [0,1]	S [0,2]	[0,3]	S [0,4]	[0,5]	VP [1,6]
Verb, VP, S [1,2]	Verb, VP, S [1,3]	VP, X2, S [1,4]	VP, X2, S [1,5]	VP [1,6]	NP [2,6]
Det [2,3]	Det [2,3]	NP [2,4]	NP [2,5]	NP [2,6]	Nom [3,6]
Noun, Nom [3,4]	Noun, Nom [3,4]	Noun, Nom [3,4]	Noun,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

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$VP \rightarrow VP PP$

$PP \rightarrow Preposition NP$

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



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

Lexicon

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

$Nominal \rightarrow Nominal PP$

$VP \rightarrow book / include / prefer$

$VP \rightarrow Verb NP$

$VP \rightarrow X2 PP$

$X2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

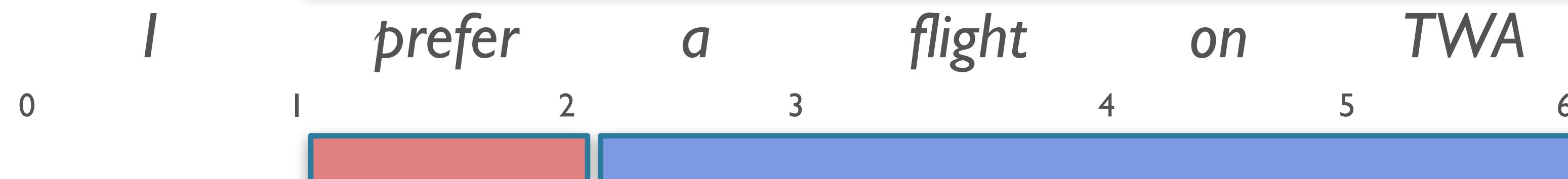
$VP \rightarrow VP PP$

$PP \rightarrow Preposition NP$

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]

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$Det \rightarrow that | this | a$
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$VP \rightarrow X2 PP$

$X2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

$VP \rightarrow VP PP$

$PP \rightarrow Preposition NP$

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

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$Det \rightarrow that | this | a$
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$VP \rightarrow Verb PP$

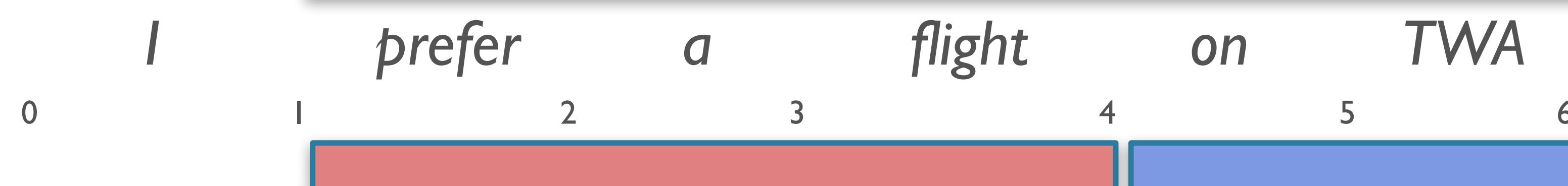
$VP \rightarrow VP PP$

$PP \rightarrow Preposition NP$

NP, Pronoun [0,1]	S [0,2]		S [0,4]		
		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]

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$VP \rightarrow Verb NP$

$VP \rightarrow X2 PP$

$X2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

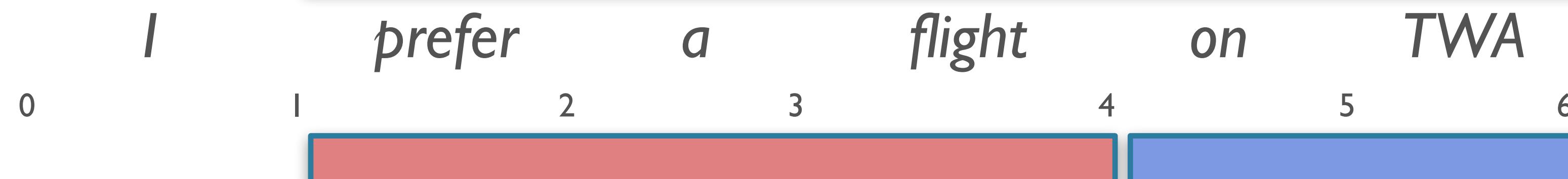
$VP \rightarrow VP PP$

$PP \rightarrow Preposition NP$

NP, Pronoun [0,1]	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]

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$X2 \rightarrow Verb NP$

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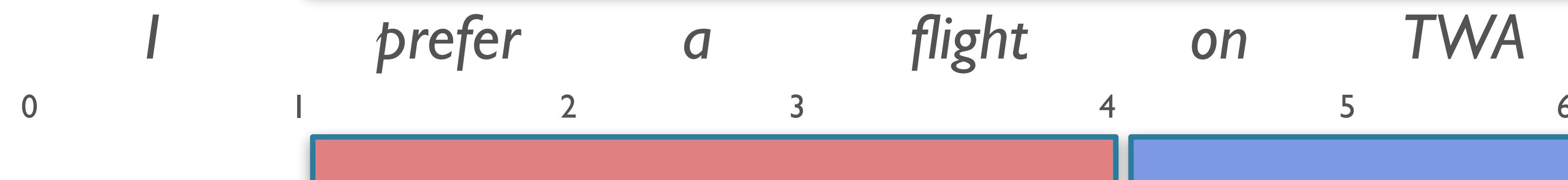
$VP \rightarrow VP PP$

$PP \rightarrow Preposition NP$

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

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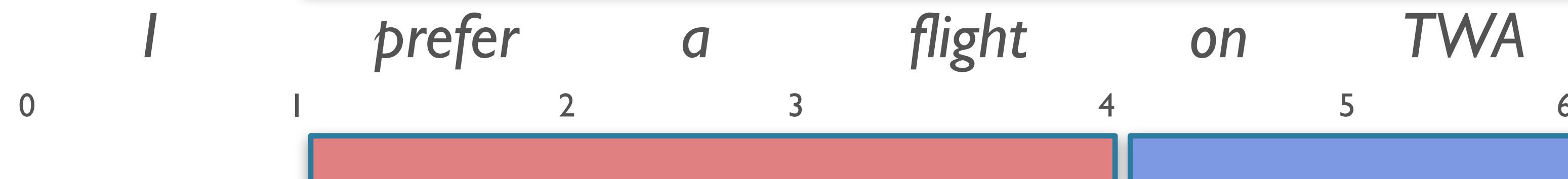
$VP \rightarrow VP PP$

$PP \rightarrow Preposition NP$

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]

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

Lexicon

$Det \rightarrow that | this | a$

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

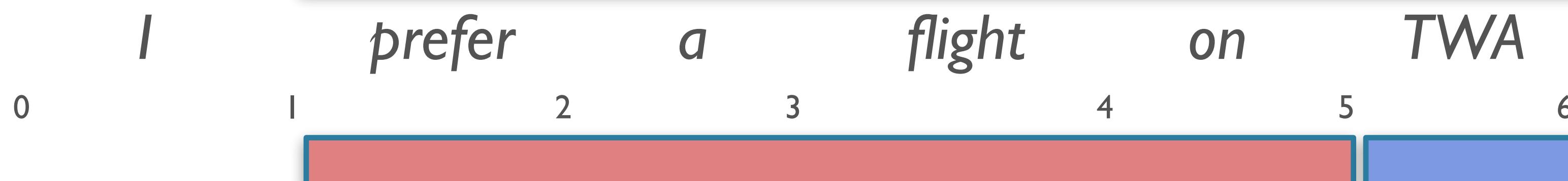
$Pronoun \rightarrow I | she | me$

$Proper-Noun \rightarrow Houston | TWA$

$Aux \rightarrow does$

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$NP \rightarrow Det Nominal$

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$Nominal \rightarrow Nominal Noun$

$Nominal \rightarrow Nominal PP$

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$VP \rightarrow X2 PP$

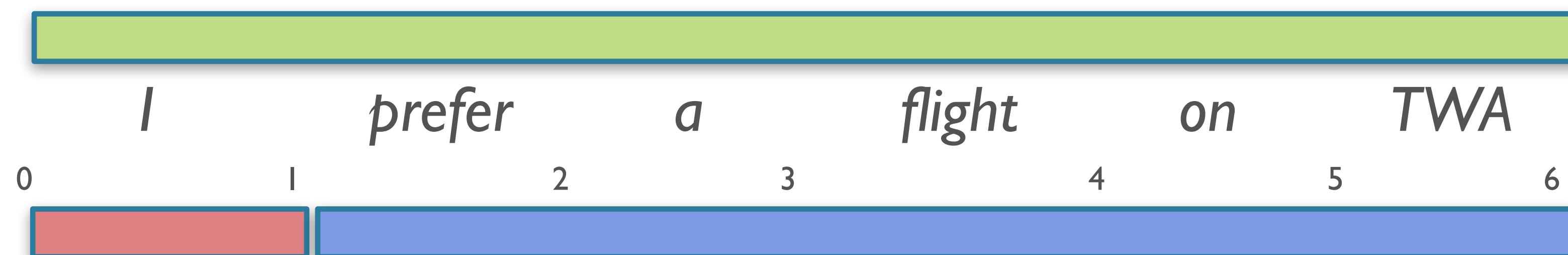
$X2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

$VP \rightarrow VP PP$

$PP \rightarrow Preposition NP$

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

[0,2]

[0,3]

[0,4]

[0,5]

[0,6]

Verb, VP, S

[1,2]

[1,3]

[1,4]

[1,5]

[1,6]

Det

[2,3]

[2,4]

[2,5]

[2,6]

NP

[3,4]

[3,5]

[3,6]

Noun, Nom

[3,4]

[3,5]

PP

[4,5]

[4,6]

Prep

[4,5]

[4,6]

NNP, NP

[5,6]

Lexicon

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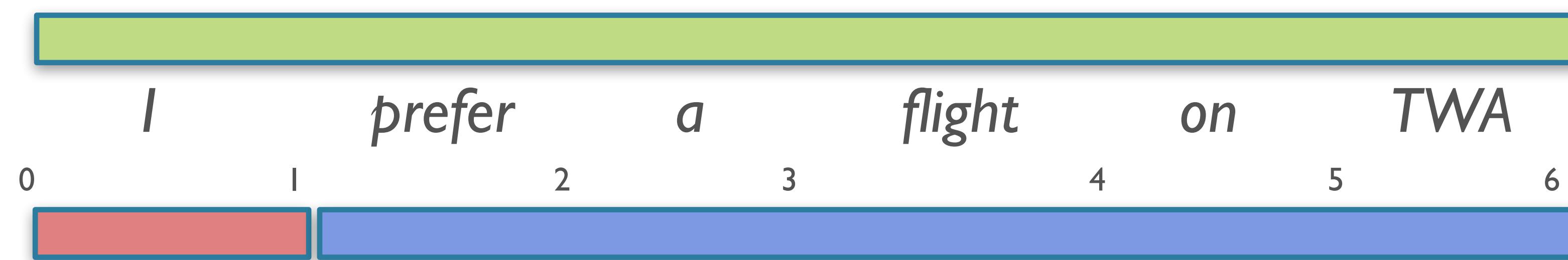
$Pronoun \rightarrow I | she | me$

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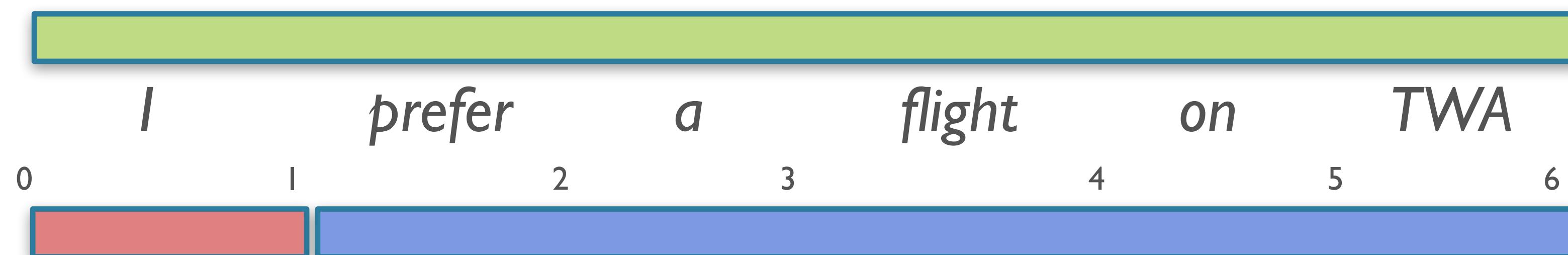
$X2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

$VP \rightarrow VP PP$

$PP \rightarrow Preposition NP$

NP, Pronoun [0,1]	S [0,2]	[0,3]	S [0,4]	[0,5]	S [0,6]
Verb, VP, S [1,2]	Verb, VP, S [1,3]	VP, X2, S [1,4]	VP, X2, S [1,5]	VP, X2, S [1,6]	VP, X2, S [1,6]
Det [2,3]	Det [2,4]	NP [2,5]	NP [2,6]	NP [2,6]	NP [2,6]
Noun, Nom [3,4]	Noun, Nom [3,4]	Nom [3,5]	Nom [3,6]	Nom [3,6]	Nom [3,6]
Lexicon	Lexicon	Lexicon	Lexicon	Lexicon	Lexicon
$Det \rightarrow that this a$					
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$VP \rightarrow book / include / prefer$

$VP \rightarrow Verb NP$

$VP \rightarrow X2 PP$

$X2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

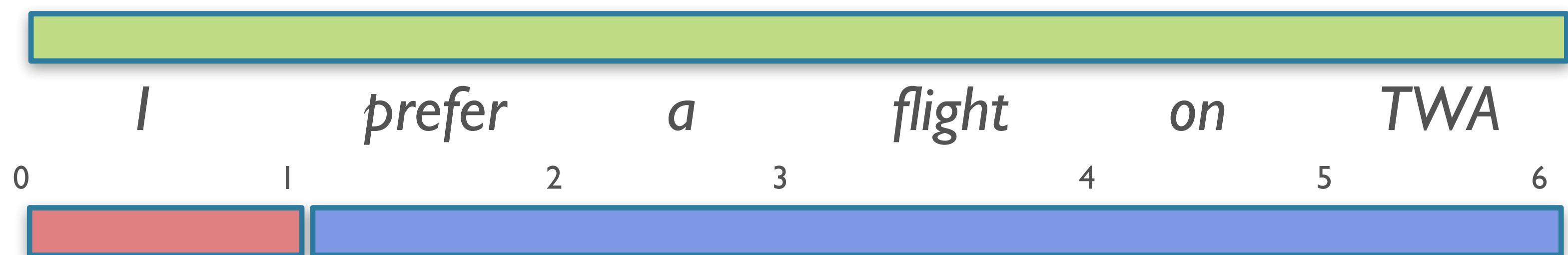
$VP \rightarrow VP PP$

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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]
						Noun, Nom [3,4]		Nom [3,5]
							Prep [4,5]	PP [4,6]
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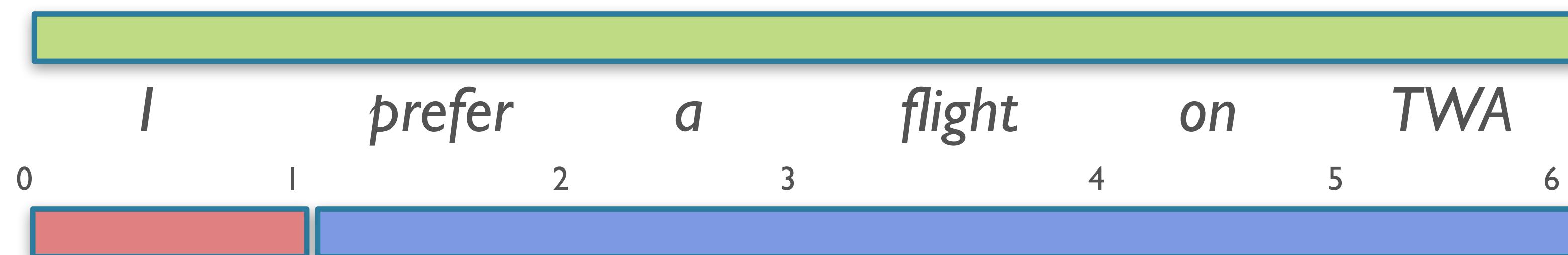
$X2 \rightarrow Verb NP$

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

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

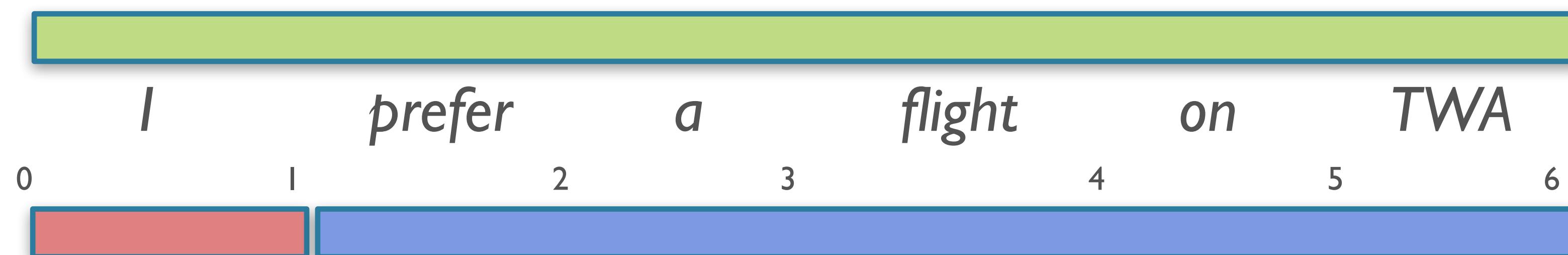
$Pronoun \rightarrow I | she | me$

$Proper-Noun \rightarrow Houston | TWA$

$Aux \rightarrow does$

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

$Verb \rightarrow book | include | prefer$



Current CKY Algorithm

Limitations:

Only stores non-terminals in cell

- Not rules or cells corresponding to RHS

- Stores SETS of non-terminals

- Multiple rules with same LHS collide

Currently only *acceptance/recognition*

CKY Parser

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

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

$VP \rightarrow VP \text{ } PP$

$bp_1 = \text{BackPointer}()$
 $bp_1.l_child = [VP, (1, 4)]$
 $bp_1.r_child = [PP, (4, 6)]$

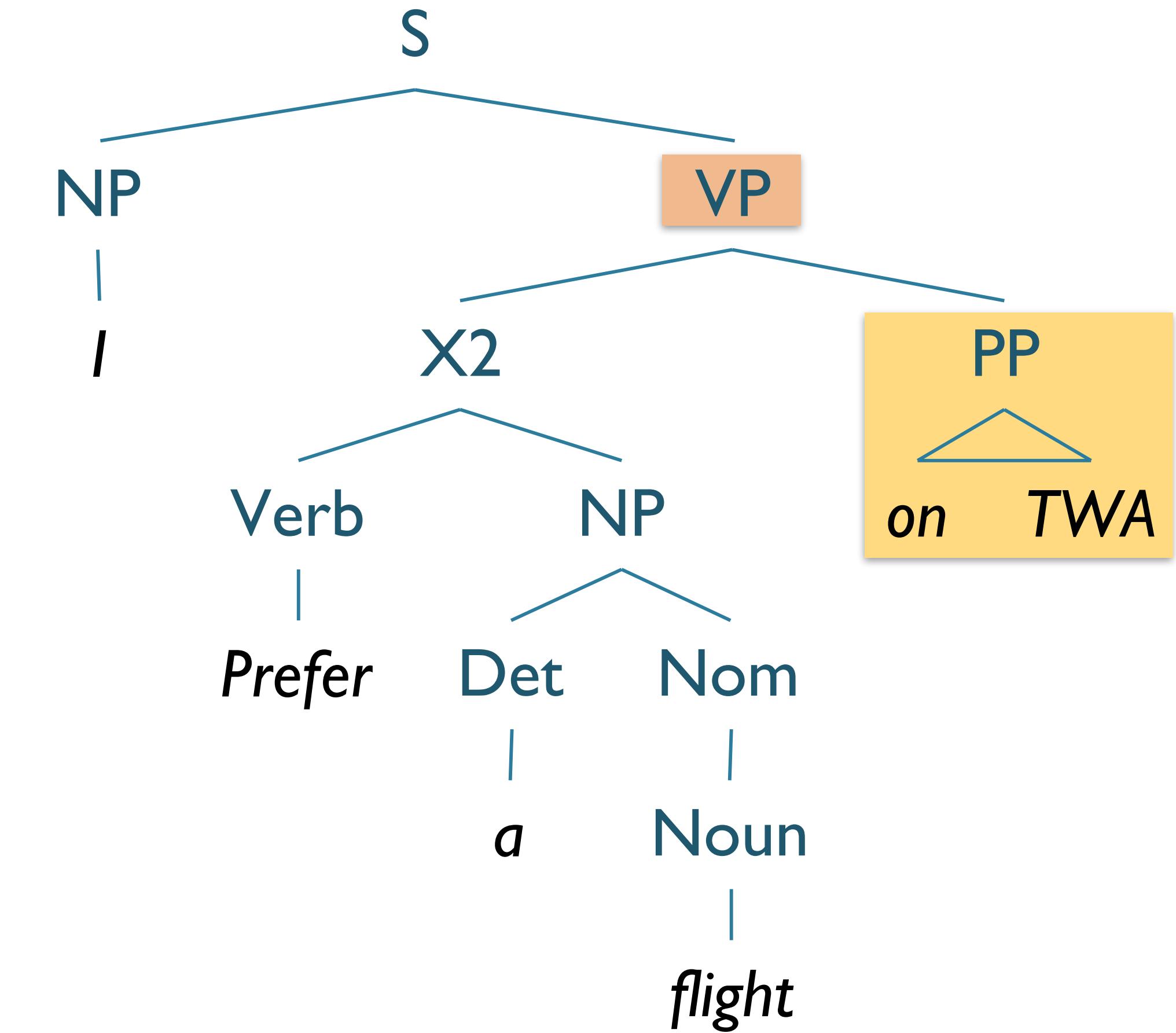
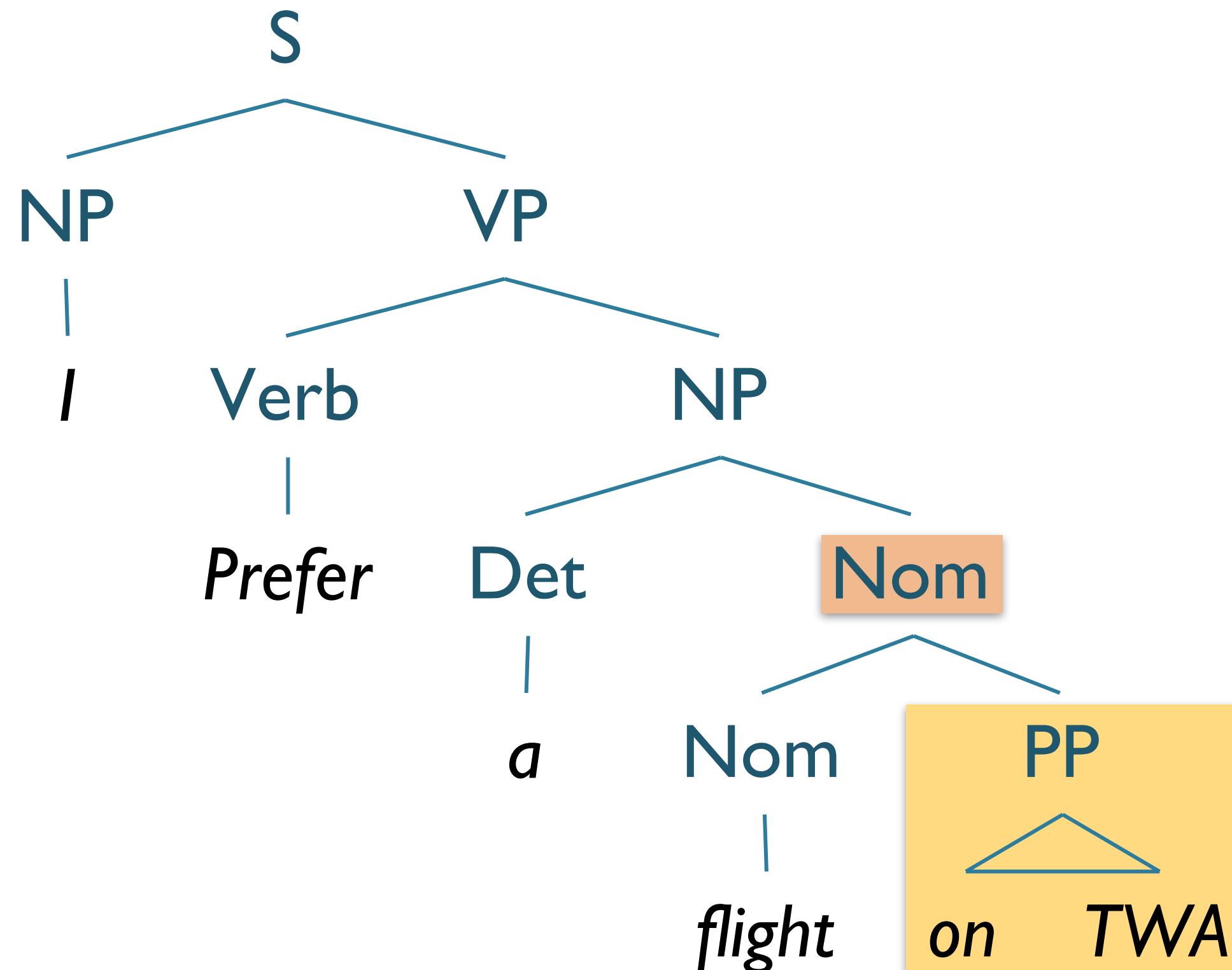
NP, Pronoun [0,1]	S [0,2]	[0,3]	S [0,4]	[0,5]	VP
	Verb, VP, S [1,2]	[1,3]	VP, X2, S [1,4]	[1,5]	VP [1,6]
		Det [2,3]	NP [2,4]	[2,5]	NP [2,6]
			Noun, Nom [3,4]	[3,5]	Nom [3,6]
				Prep [4,5]	PP [4,6]
					NNP, NP [5,6]

$VP \rightarrow X2 \text{ } PP$

$bp_2 = \text{BackPointer}()$
 $bp_2.l_child = [X2, (1, 4)]$
 $bp_2.r_child = [PP, (4, 6)]$

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

Resulting Parses



CKY Discussion

Running time:

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

Inner loop grows as square of # of non-terminals

Expressiveness:

As implemented, requires CNF

Weak equivalence to original grammar

Doesn't capture full original structure

Back-conversion?

Can do binarization, terminal conversion

Unit productions requires change in CKY

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

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

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

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

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

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

```
A -> B C
```

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

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

Unit Testing

- Good practice:
 - Save input that crashes your program for a unit test
- Other popular unit testing frameworks for python:
 - pytest: <https://docs.pytest.org/en/6.2.x/>