# PCFGs: Parsing & Evaluation

LING 571 — Deep Processing Techniques for NLP
October 10, 2018
Ryan Georgi

# Announcements & Misc

- For CKY Implementation:
  - NLTK's **`CFG.productions()`** method:
    - optional `rhs=` argument *only looks at first token of RHS*

# CKY Follow-up: Backpointers

# Backpointers

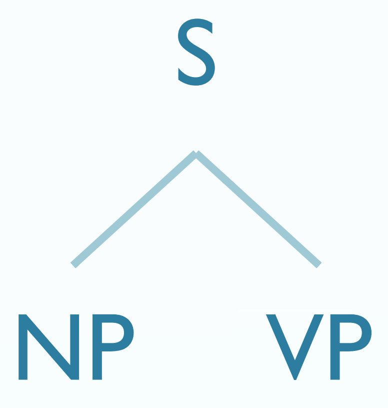
- Instead of list of possible nonterminals for that node, each cell should have:
  - Nonterminal for the node
  - Pointer to left and right children cells
    - Either direct pointer to cell, or indices

One Option:

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

```
cky_table[0,6][S] = {(NP, (0,1),
                      VP, (1,6))}
```

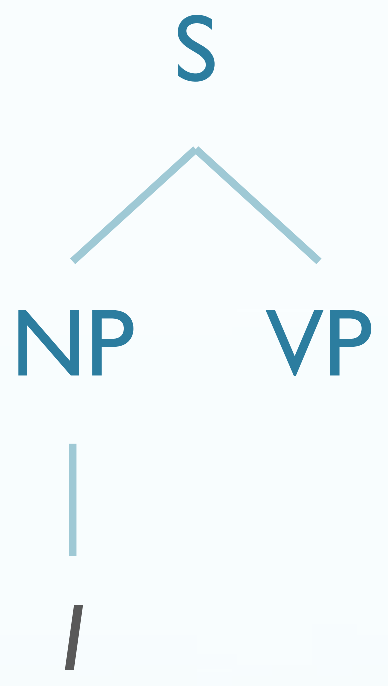
| | | | | | |
|---|---|---|---|---|---|
| **NP, Pronoun** [0,1] | **S** [0,2] | [0,3] | **S** [0,4] | [0,5] | **S** [0,6] |
| | **Verb, VP, S** [1,2] | [1,3] | **VP, X2, S** [1,4] | [1,5] | **VP, X2, S** [1,6] |
| | | **Det** [2,3] | **NP** [2,4] | [2,5] | **NP** [2,6] |
| | | | **Noun, Nom** [3,4] |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




*I* *prefer* *a* *flight* *on* *TWA*

```
cky_table[0,6][S] = {(NP, (0,1),
                      VP, (1,6))}
cky_table[0,1][NP] = {('I')}
```

| | | | | | |
|---|---|---|---|---|---|
| NP, Pronoun [0,1] | S [0,2] | [0,3] | S [0,4] | [0,5] | S [0,6] |
| | Verb, VP, S [1,2] | [1,3] | VP, X2, S [1,4] | [1,5] | VP, X2, S [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] |




*I* *prefer* *a* *flight* *on* *TWA*

```
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                      VP, (1,6))}
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cky_table[1,6][VP] = {(Verb, (1,2),
                      NP, (2,6)),
                     (X2, (1,4),
                      PP, (4,6))}
```
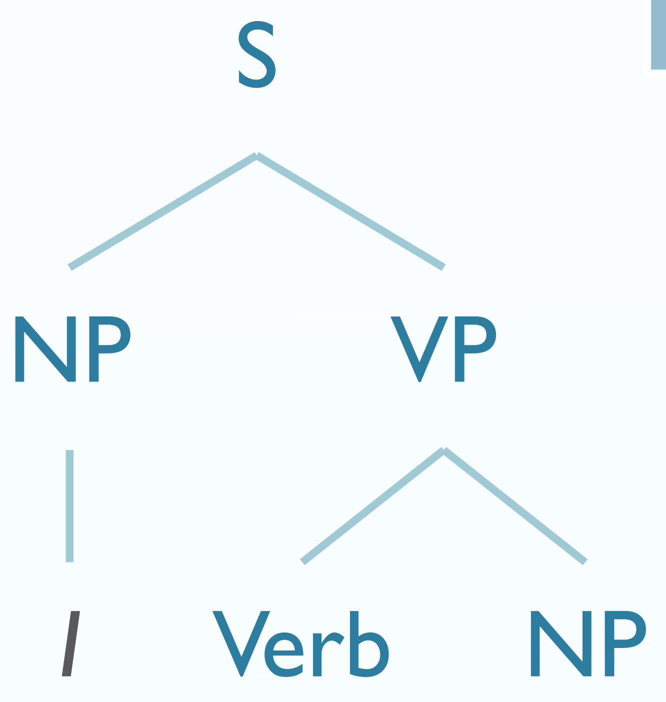

| | | | | | |
|---|---|---|---|---|---|
| NP, Pronoun [0,1] | S [0,2] | [0,3] | S [0,4] | [0,5] | S [0,6] |
| | Verb, VP, S [1,2] | [1,3] | VP, X2, S [1,4] | [1,5] | VP, X2, S [1,6] |
| | | Det [2,3] | NP [2,4] | [2,5] | NP [2,6] |
| | | | Noun, Nom [3,4] | [3,5] | Nom [3,6] |
| | | | | Prep [4,5] |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




*I* *prefer* *a* *flight* *on* *TWA*

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cky_table[0,1][NP] = {('I')}
cky_table[1,6][VP] = {(Verb, (1,2),
                       NP, (2,6)),
                      (X2, (1,4),
                       PP, (4,6))}

cky_table[1,2][Verb] = {('prefer')}
```

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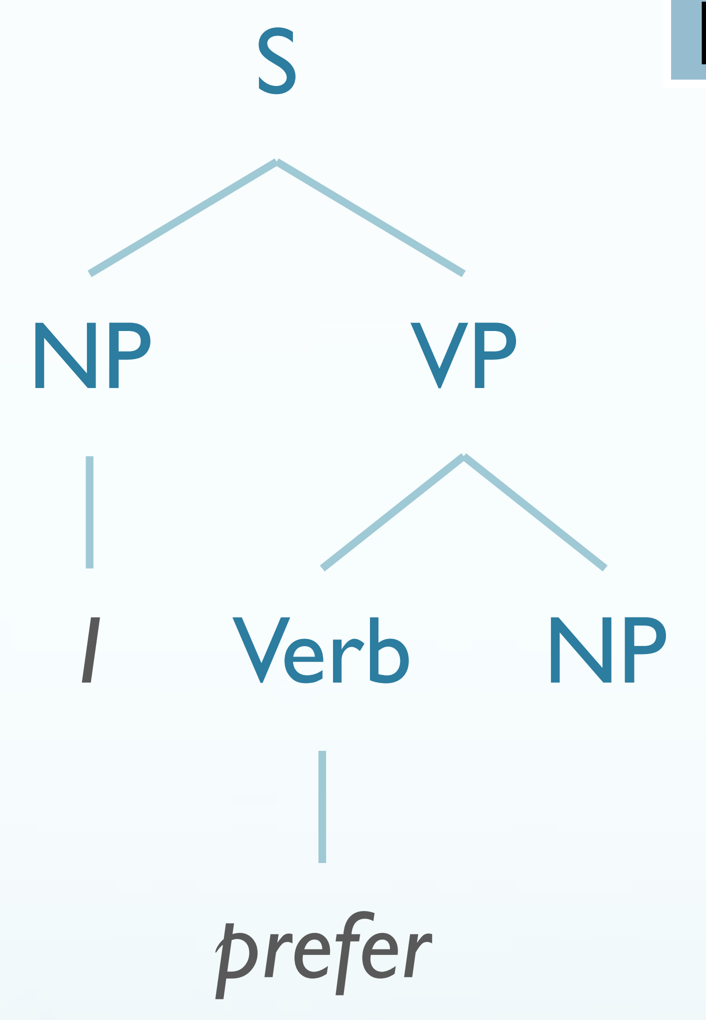


*I* *prefer* *a* *flight* *on* *TWA*

```
cky_table[0,6][S] = {(NP, (0,1),
                      VP, (1,6))}
cky_table[0,1][NP] = {('I')}
cky_table[1,6][VP] = {(Verb, (1,2),
                       NP, (2,6)),
                      (X2, (1,4),
                       PP, (4,6))}
cky_table[1,2][Verb] = {('prefer')}
cky_table[2,6][NP] = {(Det, (2,3),
                       Nom, (3,6)}
```

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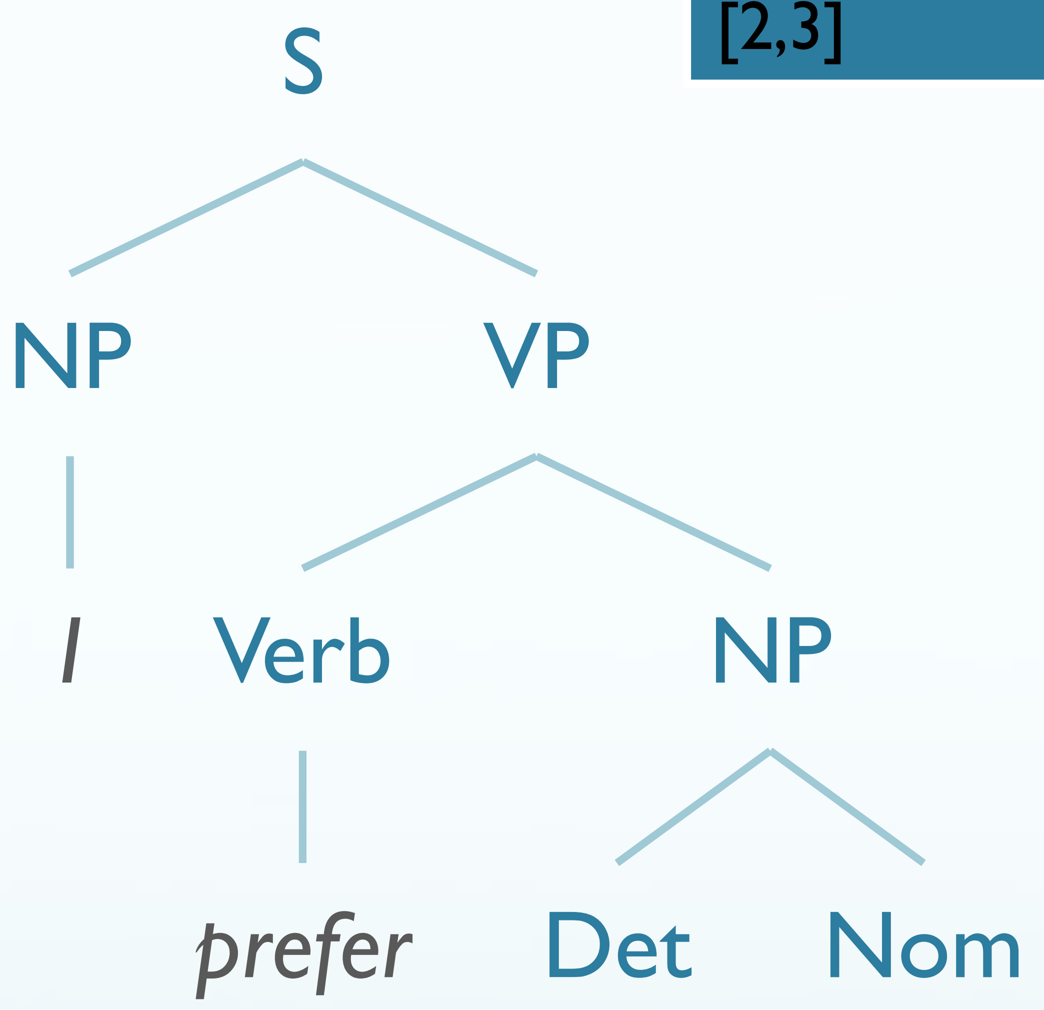


*I* *prefer* *a* *flight* *on* *TWA*

```
cky_table[0,6][S] = {(NP, (0,1),
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cky_table[0,1][NP] = {('I')}
cky_table[1,6][VP] = {(Verb, (1,2),
                       NP, (2,6)),
                      (X2, (1,4),
                       PP, (4,6))}
cky_table[1,2][Verb] = {('prefer')}
cky_table[2,6][NP] = {(Det, (2,3),
                       Nom, (3,6)}
cky_table[2,3][Det] = {('a')}
```

| | | | | | |
|---|---|---|---|---|---|
| **NP, Pronoun** [0,1] | **S** [0,2] | [0,3] | **S** [0,4] | [0,5] | **S** [0,6] |
| | **Verb, VP, S** [1,2] | [1,3] | **VP, X2, S** [1,4] | [1,5] | **VP, X2, S** [1,6] |
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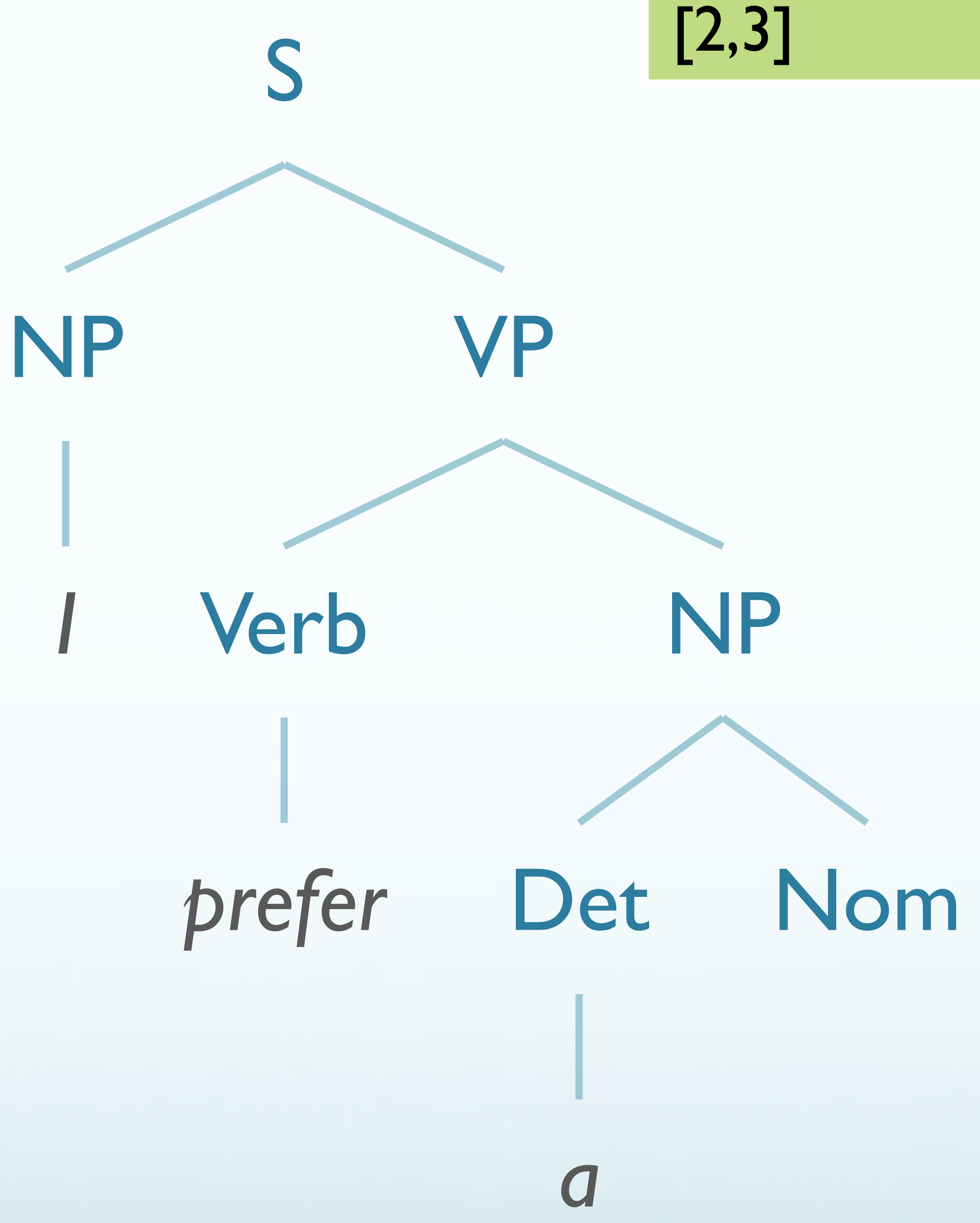


*I prefer a flight on TWA*

```
cky_table[0,6][S] = {(NP, (0,1),
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cky_table[1,6][VP] = {(Verb, (1,2)
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| **NP, Pronoun** [0,1] | **S** [0,2] | [0,3] | **S** [0,4] | [0,5] | **S** [0,6] |
| | **Verb, VP, S** [1,2] | [1,3] | **VP, X2, S** [1,4] | [1,5] | **VP, X2, S** [1,6] |
| | | **Det** [2,3] | **NP** [2,4] | [2,5] | **NP** [2,6] |
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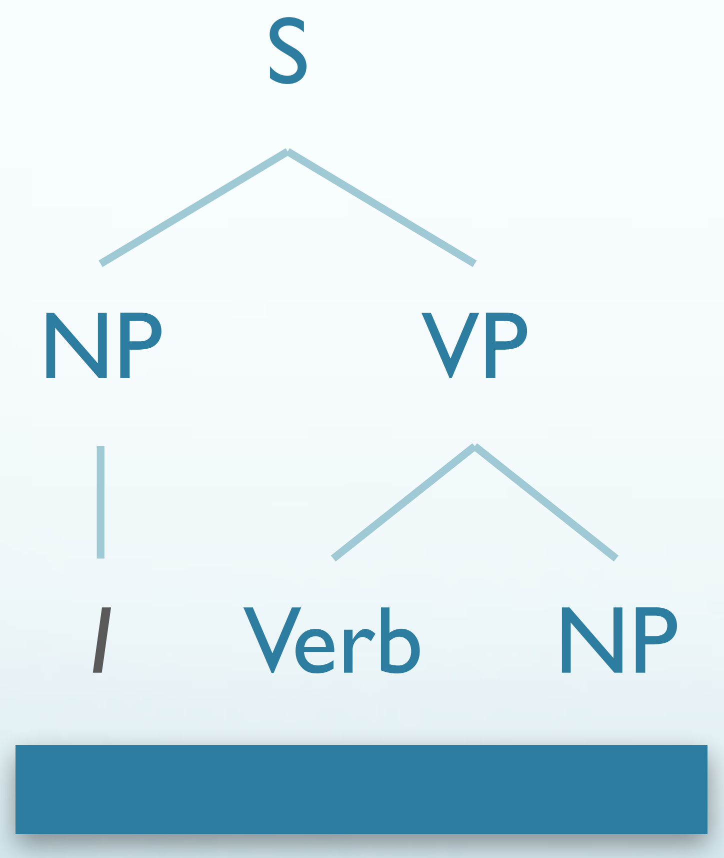
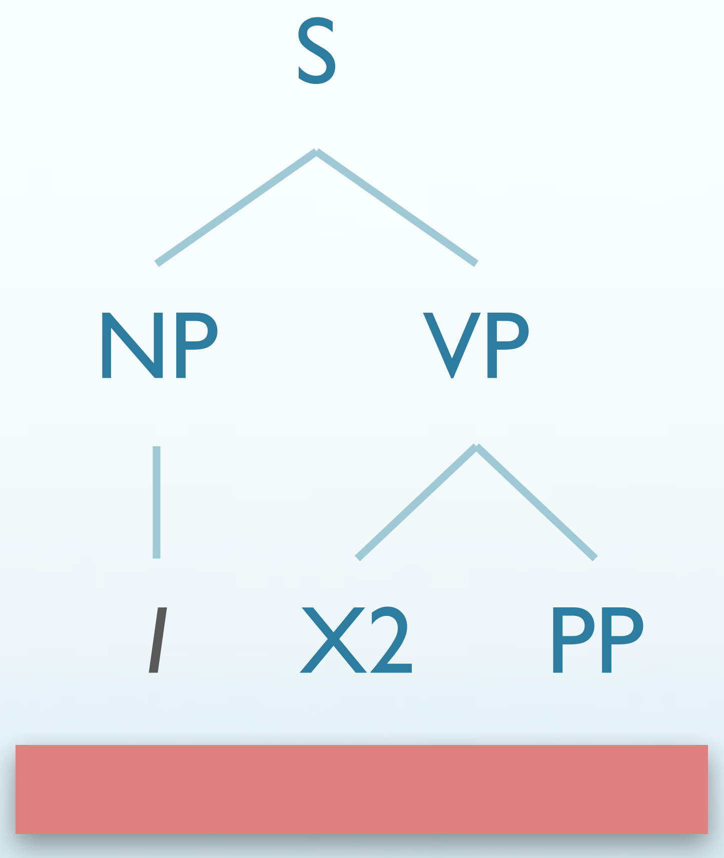



*I* *prefer* *a* *flight* *on* *TWA*

# PCFGs: Recap

# PCFGs: Formal Definition

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

# Disambiguation

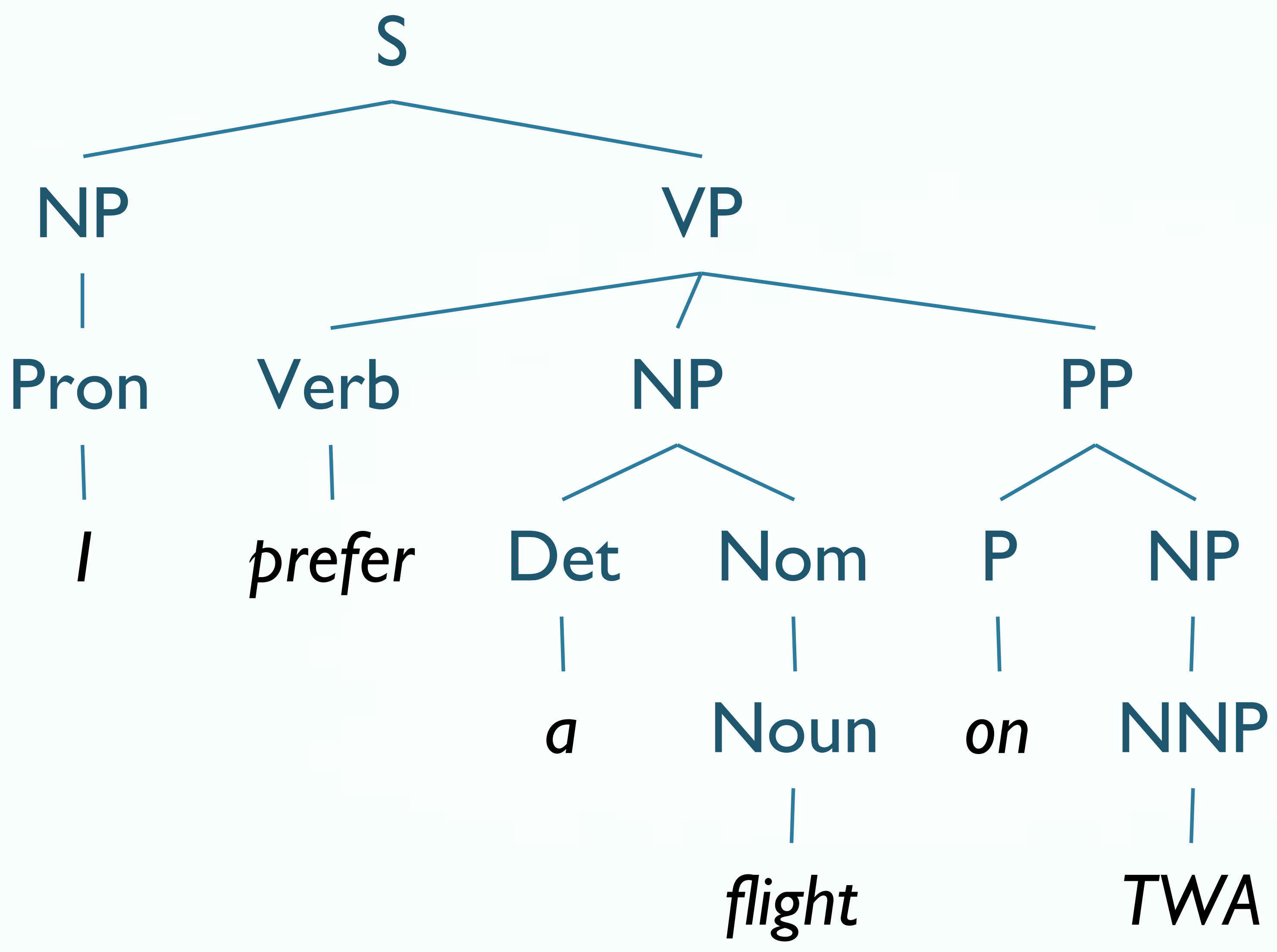
- A PCFG assigns probability to each parse tree $T$ for input $S$
- Probability of $T$: product of all rules used to derive $T$

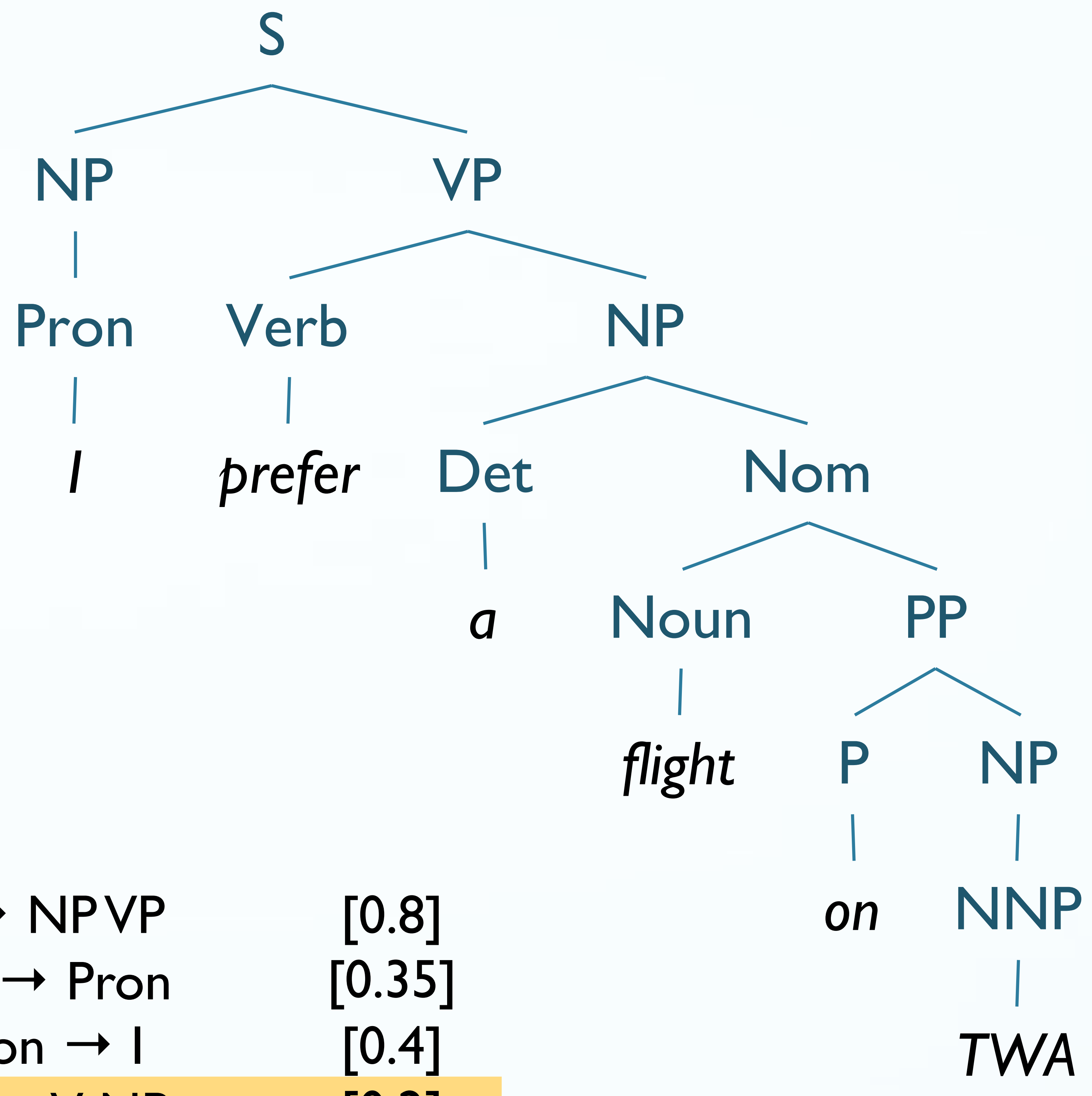
$$P(T,S) = \prod_{i=1}^{n} P(RHS_i \mid LHS_i)$$

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

# Application: Language Modeling

- *n*-grams helpful for modeling the probability of a string
- To model a whole sentence with *n-grams* either:
  - Must use 10+-grams… too sparse
  - Approximate using conditioning on limited context: $\dfrac{P(w_{i-1}, w_i)}{P(w_{i-1})}$
- PCFGs are able to give probability of entire string without as bad sparsity
- Model probability of *syntactically valid* sentences
  - Not just probability of sequence of words




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

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

| | |
|---|---|
| S → NP VP | [0.8] |
| NP → Pron | [0.35] |
| Pron → I | [0.4] |
| VP → V NP | [0.2] |
| V → prefer | [0.4] |
| NP → Det Nom | [0.2] |
| Det → a | [0.3] |
| Nom → Nom PP | [0.05] |
| Nom → N | [0.75] |
| N → flight | [0.3] |
| PP → P NP | [1.0] |
| P → on | [0.2] |
| NP → NNP | [0.3] |
| NNP → NWA | [0.4] |

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

# Parsing Problem for PCFGs

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

$$\hat{T}(S) = \underset{T s.t. S = yield(T)}{\mathbf{argmax}} P(T)$$

- String of words $S$ is ***yield*** of parse tree
- Select the tree $\hat{T}$ that maximizes the probability of the parse
- Extend existing algorithms: e.g. CKY

# PCFGs: Parsing

# Probabilistic CKY (PCKY)

- Like regular CKY
  - Assumes grammar in Chomsky Normal Form (CNF)
    - $A \rightarrow B\ C$
    - $A \rightarrow \mathrm{w}$
  - Represent input with indices b/t words:
    - $_0$ Book $_1$ that $_2$ flight $_3$ through $_4$ Houston $_5$

# Probabilistic CKY (PCKY)

- For input string length $n$ and non-terminals $V$
  - Cell $[\ i, j, A\ ]$ in $(\ n{+}1\ ) \times (\ n{+}1\ ) \times V$ matrix
  - Contains probability that $A$ spans $[i, j]$

# PCKY Algorithm

**function** PROBABILISTIC-CKY-PARSE(*words*, *grammar*) **returns** most probable parse and its probability

**for** j ← **from** 1 to LENGTH(*words*) **do**

for all { $A \mid A \rightarrow words[j] \in grammar$ }

$table[j-1, j, A] \leftarrow P(A \rightarrow words[j])$

**for** *i* ← **from** *j*–2 **downto** 0 **do**

**for** *k* ← *i* + 1 **to** *j*–1 **do**

**for all** { $A \mid A \rightarrow B\ C \in grammar$,

**and** $table[i, k, B] > 0$ **and** $table[k, j, C] > 0$ }

**if** $(table[i, j, A] < P(A \rightarrow BC) \times table[i, k, B] \times table[k,j,C])$ **then**

$table[i, j, A] \leftarrow P(A \rightarrow BC) \times table[i,k,B] \times table[k,j,C]$

$back[i, j, A] \leftarrow \{k, B, C\}$

**return** BUILD_TREE(*back*[ 1, LENGTH(*words*), *S* ]), *table*[ 1,LENGTH(*words*), *S* ]

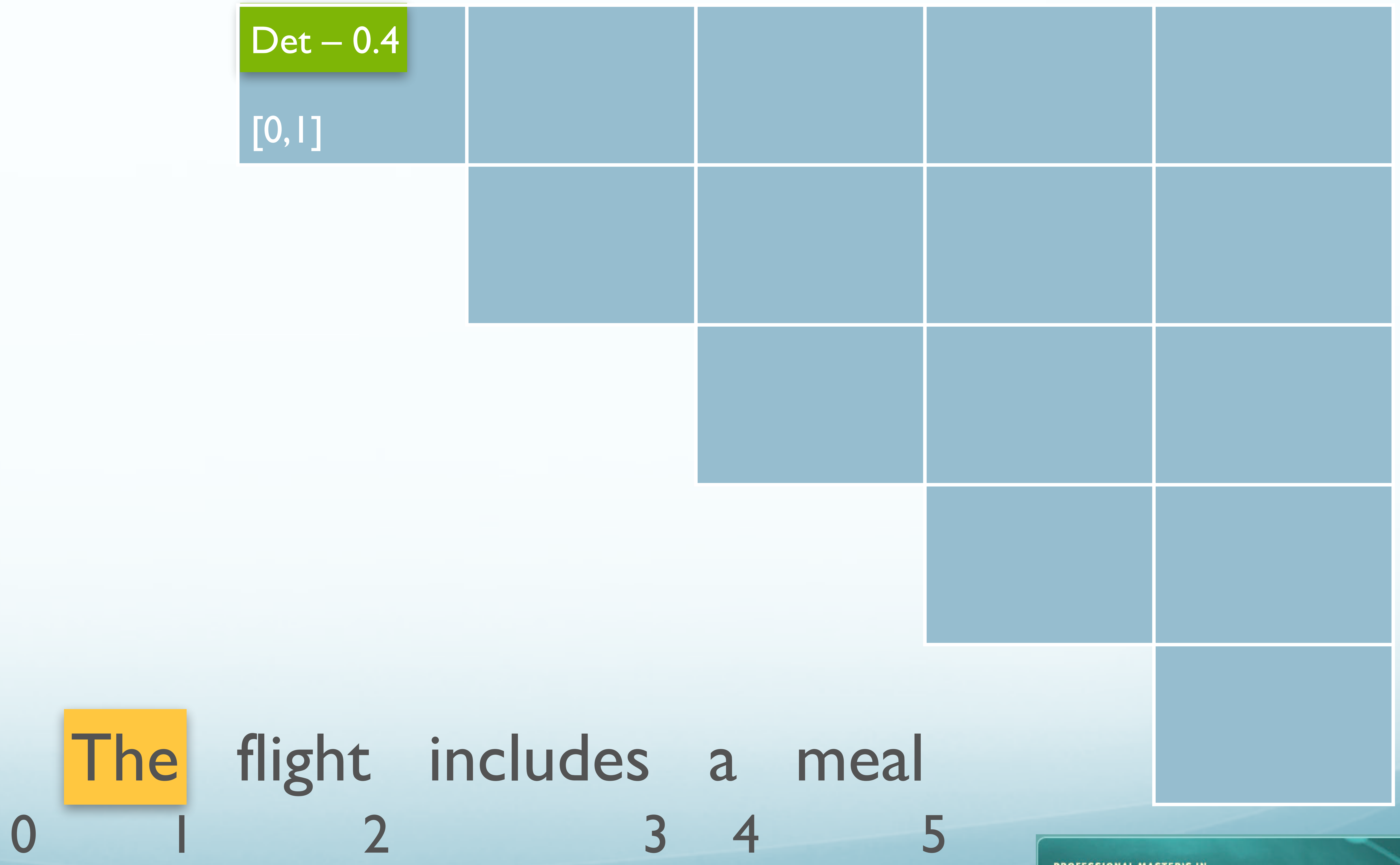
# PCKY Grammar Segment

| | | | |
|---|---|---|---|
| $S \rightarrow NP\ VP$ | [0.80] | $Det \rightarrow$ the | [0.40] |
| $NP \rightarrow Det\ N$ | [0.30] | $Det \rightarrow$ a | [0.40] |
| $VP \rightarrow V\ NP$ | [0.20] | $V \rightarrow$ includes | [0.05] |
| | | $N \rightarrow$ meal | [0.01] |
| | | $N \rightarrow$ flight | [0.02] |

# PCKY Matrix

$$S \rightarrow NP\ VP \quad [0.80]$$
$$NP \rightarrow Det\ N \quad [0.30]$$
$$VP \rightarrow V\ NP \quad [0.20]$$

$$Det \rightarrow \text{the} \quad [0.40]$$
$$Det \rightarrow \text{a} \quad [0.40]$$
$$V \rightarrow \text{includes} \quad [0.05]$$
$$N \rightarrow \text{meal} \quad [0.01]$$
$$N \rightarrow \text{flight} \quad [0.02]$$



# PCKY Matrix

$$
\begin{aligned}
S &\rightarrow NP\ VP & [0.80]\\
NP &\rightarrow Det\ N & [0.30]\\
VP &\rightarrow V\ NP & [0.20]
\end{aligned}
$$

$$
\begin{aligned}
Det &\rightarrow \text{the} & [0.40]\\
Det &\rightarrow \text{a} & [0.40]\\
V &\rightarrow \text{includes} & [0.05]\\
N &\rightarrow \text{meal} & [0.01]\\
N &\rightarrow \text{flight} & [0.02]
\end{aligned}
$$

| | | | | |
|---|---|---|---|---|
| Det – 0.4<br>[0,1] | | | | |
| | N – 0.02<br>[1,2] | | | |
| | | | | |
| | | | | |
| | | | | |

The flight includes a meal

0 1 2 3 4 5

# PCKY Matrix

$$S \rightarrow NP\ VP \quad [0.80]$$
$$NP \rightarrow Det\ N \quad [0.30]$$
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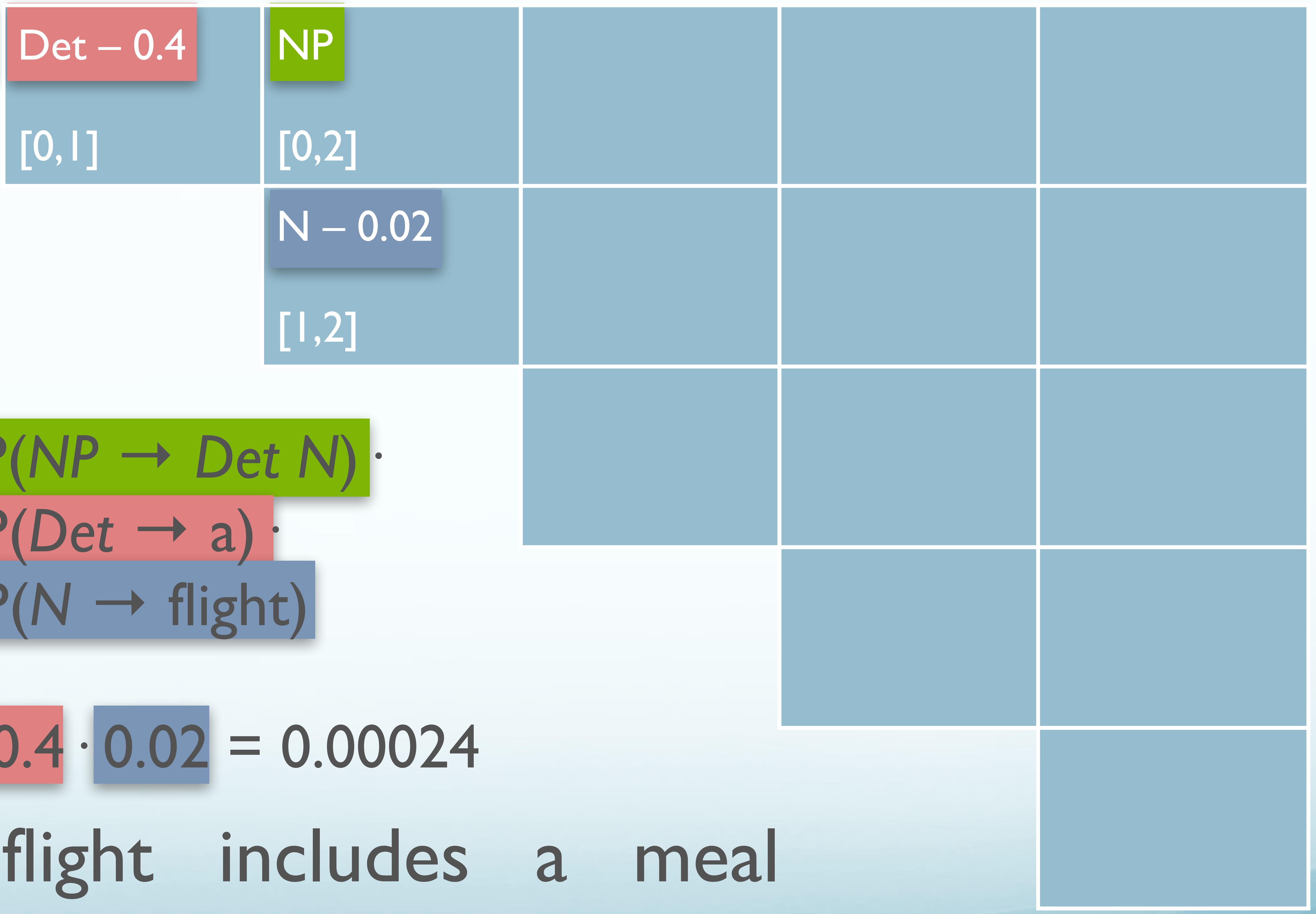


$$P = P(NP \rightarrow Det\ N) \cdot P(Det \rightarrow a) \cdot P(N \rightarrow flight)$$

$$P = 0.3 \cdot 0.4 \cdot 0.02 = 0.00024$$

The flight includes a meal

0 1 2 3 4 5

# PCKY Matrix

$$S \rightarrow NP\ VP \quad [0.80]$$
$$NP \rightarrow Det\ N \quad [0.30]$$
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$$Det \rightarrow \text{a} \quad [0.40]$$
$$V \rightarrow \text{includes} \quad [0.05]$$
$$N \rightarrow \text{meal} \quad [0.01]$$
$$N \rightarrow \text{flight} \quad [0.02]$$

| | | | | |
|---|---|---|---|---|
| Det – 0.4 [0,1] | NP – 0.0024 [0,2] | | | |
| | N – 0.02 [1,2] | | | |
| | | | | |
| | | | | |
| | | | | |

$$P = P(NP \rightarrow Det\ N) \cdot P(Det \rightarrow a) \cdot P(N \rightarrow flight)$$

$$P = 0.3 \cdot 0.4 \cdot 0.02 = 0.00024$$

The flight includes a meal

0 1 2 3 4 5

# PCKY Matrix

$$
\begin{array}{lll}
S \rightarrow NP\ VP & [0.80] \\
NP \rightarrow Det\ N & [0.30] \\
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\end{array}
$$

$$
\begin{array}{lll}
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N \rightarrow \text{meal} & [0.01] \\
N \rightarrow \text{flight} & [0.02]
\end{array}
$$

| | | | | |
|---|---|---|---|---|
| Det – 0.4 [0,1] | NP – 0.0024 [0,2] | [0,3] | [0,4] | S – $2.304\times10^{-8}$ [0,5] |
| | N – 0.02 [1,2] | [1,3] | [1,4] | [1,5] |
| | | V – 0.05 [2,3] | [2,4] | VP – $1.2\times10^{-5}$ [2,5] |
| | | | Det – 0.4 [3,4] | NP – 0.0012 [3,5] |
| | | | | N – 0.01 [4,5] |

The flight includes a meal

0 1 2 3 4 5

# Inducing a PCFG

# Learning Probabilities

- Simplest way:
  - Use treebank of parsed sentences
  - To compute probability of a rule, count:
    - Number of times a nonterminal is expanded: $\Sigma_\gamma\ Count(\alpha\rightarrow\gamma)$
    - Number of times a nonterminal is expanded by a given rule: $Count(\alpha\rightarrow\beta)$

$$P(\alpha \rightarrow \beta \mid \alpha) = \frac{Count(\alpha \rightarrow \beta)}{\sum_\gamma Count(\alpha \rightarrow \gamma)} = \frac{Count(\alpha \rightarrow \beta)}{Count(\alpha)}$$

- Alternative: Learn probabilities by re-estimating
  - (Later)

# Probabilistic Parser Development Paradigm

| | Train | Dev | Test |
|---|---|---|---|
| **Size** | Large<br><br>(eg. WSJ 2–21, 39,830 sentences) | Small<br><br>(e.g. WSJ 22) | Small/Med<br><br>(e.g. WSJ, 23, 2,416 sentences) |
| **Usage** | Estimate rule probabilities | Tuning/Verification, Check for Overfit | Held Out, Final Evaluation |

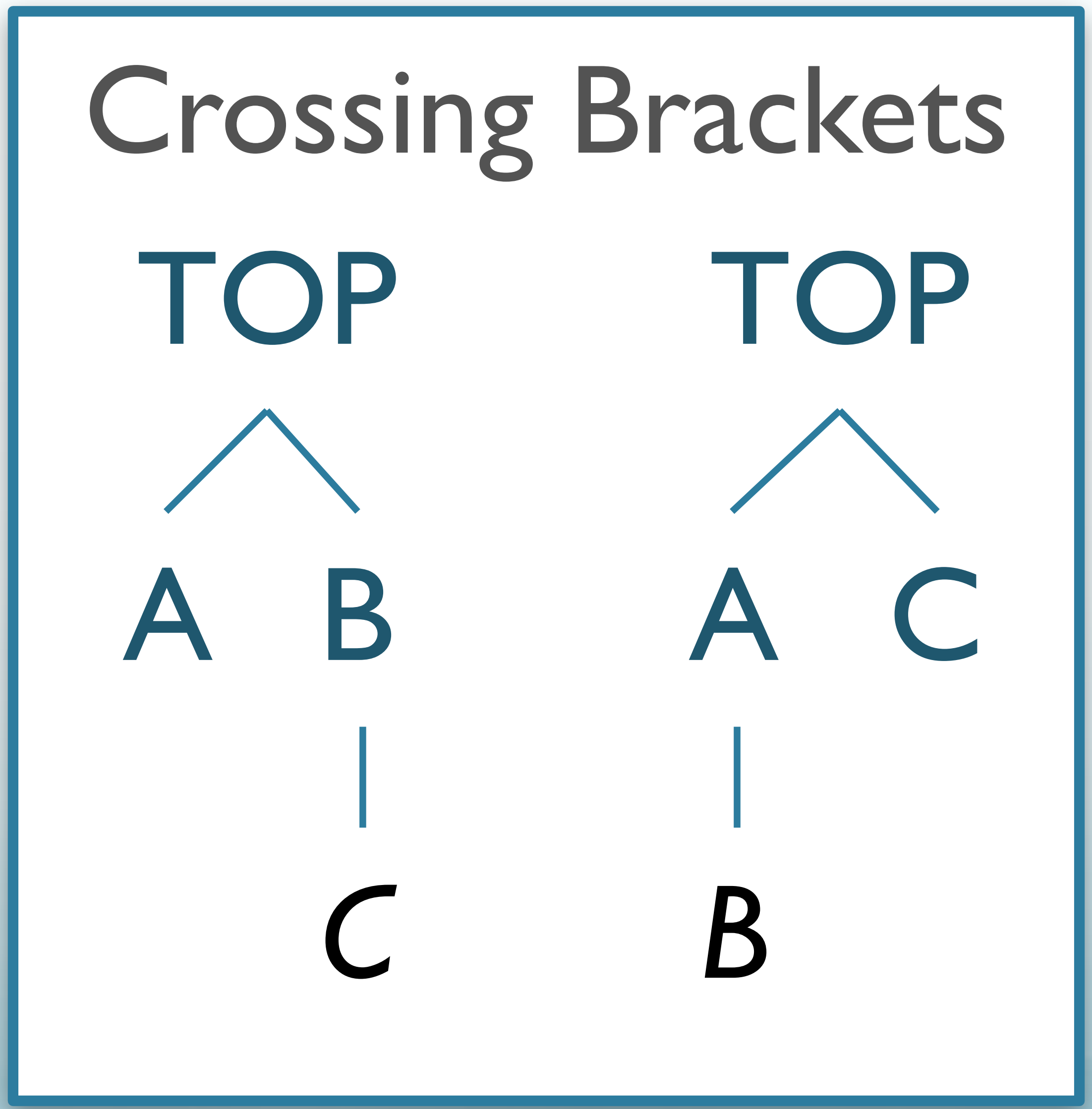
# Parser Evaluation

# Parser Evaluation

- Assume a 'gold standard' set of parses for test set
- How can we tell how good the parser is?
- How can we tell how good a parse is?
  - Maximally strict: identical to 'gold standard'
  - Partial credit:
    - Constituents in output match those in reference
      - Same start point, end point, non-terminal symbol

# Parser Evaluation

- Crossing Brackets:
  - # of constituents where produced parse has bracketings that overlap for the siblings:
  - ((A B) C) — { (0,2), (2,3) }
    and hyp. has
    (A (B C)) — { (0,1), (1, 3) }



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# Parseval

- How can we compute parse score from constituents?
- Multiple Measures:

$$\text{Labeled Recall (LR)} = \frac{\text{\# of } \textbf{correct} \text{ constituents in } \textbf{hypothetical} \text{ parse}}{\text{\# of } \textbf{total} \text{ constituents in } \textbf{reference} \text{ parse}}$$

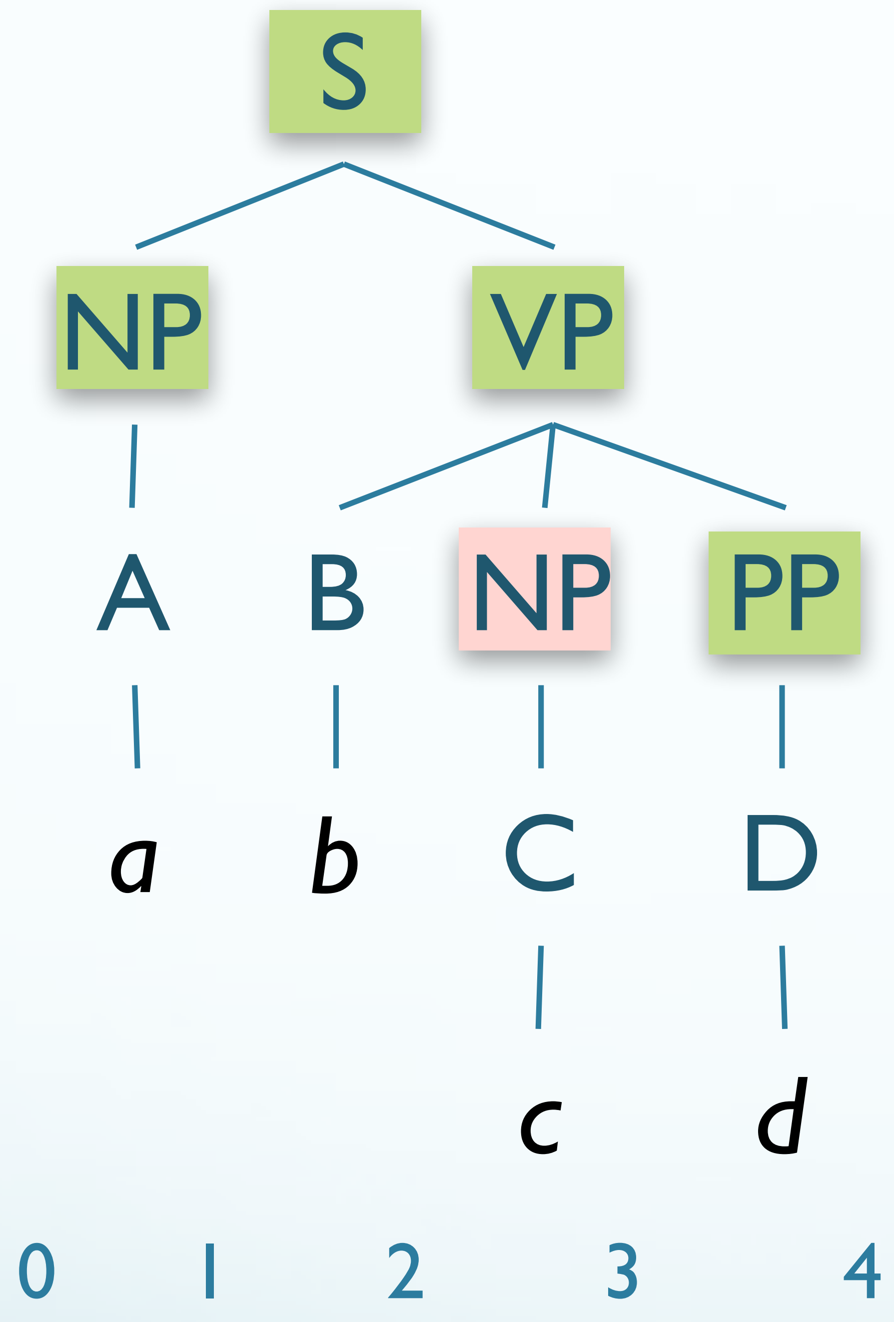
$$\text{Labeled Precision (LP)} = \frac{\text{\# of } \textbf{correct} \text{ constituents in } \textbf{hypothetical} \text{ parse}}{\text{\# of } \textbf{total} \text{ consituents in } \textbf{hypothetical} \text{ parse}}$$

# Parseval

- F-measure:
  - Combines precision and recall
  - Let $\beta \in \mathbb{R}, \ \beta > 0$ that adjusts $P$ vs. $R$ s.t. $\beta \propto \frac{R}{P}$
  - $F_\beta$ -measure is then: $F_\beta = (1 + \beta^2) \cdot \frac{P \cdot R}{\beta^2 \cdot P + R}$
  - With F1-measure as $F_1 = \frac{2PR}{P + R}$

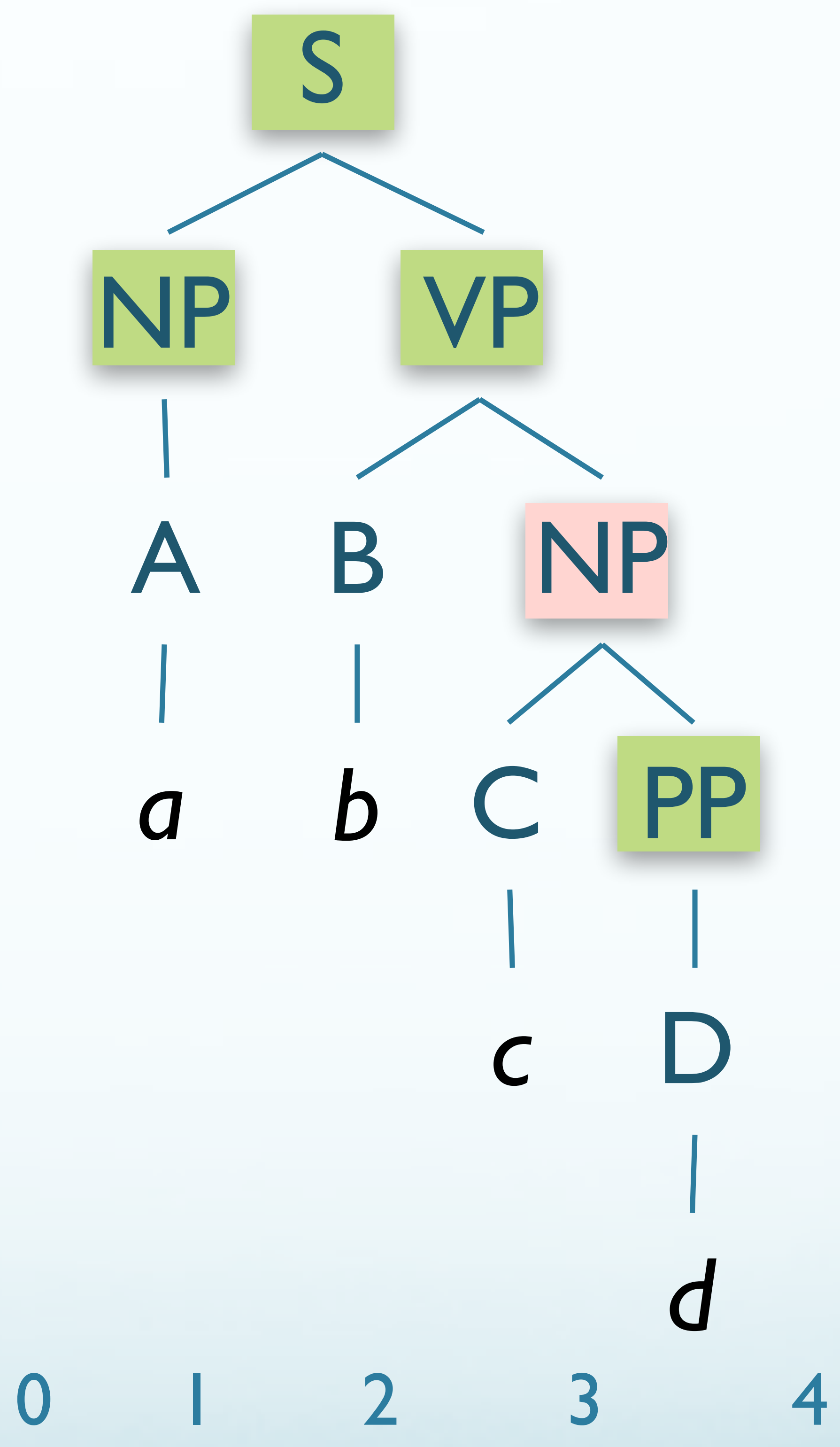
# Evaluation: Example

Reference




| |
|---|
| S(0,4) |
| NP(0,1) |
| VP(1,4) |
| NP(2,3) |
| PP(3,4) |

Hypothesis




| |
|---|
| S(0,4) |
| NP(0,1) |
| VP(1,4) |
| NP(2,4) |
| PP(3,4) |

| | |
|---|---|
| LP: | 4/5 |
| LR: | 4/5 |
| $F_1$: | 4/5 |

# State-of-the-Art Parsing

- Parsers trained/tested on Wall Street Journal PTB
  - LR: 90%+;
  - LP: 90%+;
  - Crossing brackets: 1%

- Standard implementation of Parseval:
  - `evalb`

# Evaluation Issues

- Only evaluating constituency
- There are other grammar formalisms:
  - LFG (Constraint-based)
  - Dependency Structure
- **Extrinsic** evaluation
  - How well does getting the correct parse match the semantics, etc?

# Earley Parsing

# Earley vs. CKY

- CKY doesn't capture full original structure
  - Can back-convert binarization, terminal conversion
  - Unit non-terminals require change in CKY
- Earley algorithm
  - Supports parsing efficiently with arbitrary grammars
  - Top-down search
  - Dynamic programming
    - Tabulated partial solutions
  - Some bottom-up constraints

# Earley Algorithm

- Another dynamic programming solution
  - Partial parses stored in "chart"
  - Compactly encodes ambiguity
  - $O(N^3)$
- Chart entries contain:
  - Subtree for a single grammar rule
  - Progress in completing subtree
  - Position of subtree w.r.t. input

# Earley Algorithm

- First, left-to-right pass fills out a chart with $N+1$ states
  - Chart entires — sit between words in the input string
  - Keep track of states of the parse at those positions
  - For each word position, chart contains set of states representing all partial parse trees generate so far
    - e.g. `chart[0]` contains all partial parse trees generated at the beginning of sentence

# Chart Entries

- Three types of constituents:
  - Predicted constituents
  - In-progress constituents
  - Completed constituents

# Parse Progress

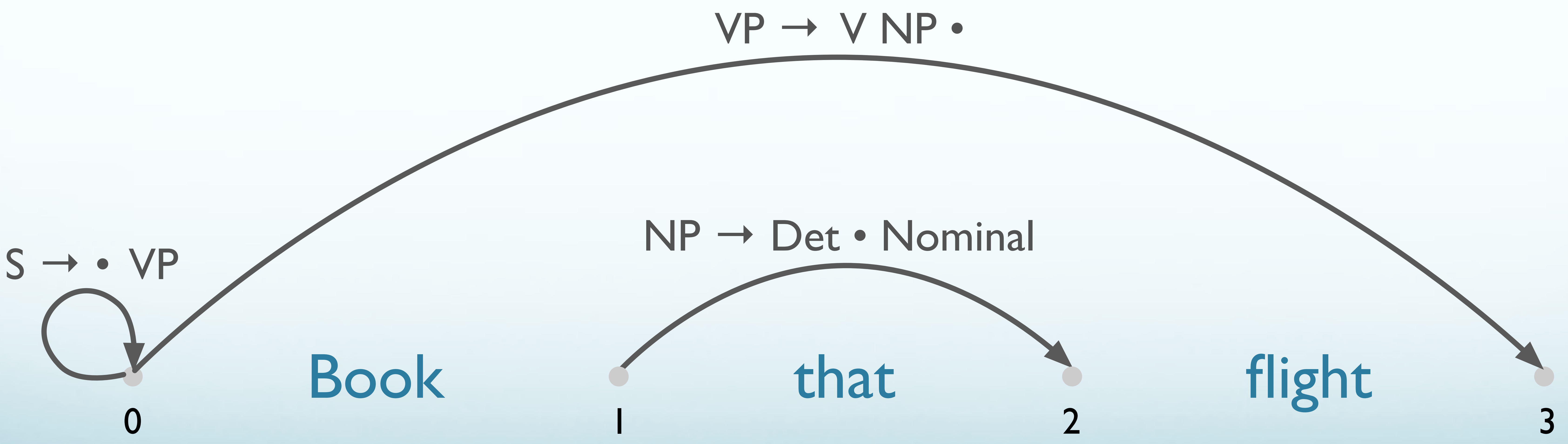
- Represented by Dotted Rules
  - Position of • indicates type of constituent
- $_0$ Book $_1$ that $_2$ flight $_3$
  - $S \rightarrow \bullet\ VP$ [0,0] (predicted)
  - $NP \rightarrow Det \bullet Nom$ [1,2] (in progress)
  - $VP \rightarrow V\ NP \bullet$ [0,3] (completed)
- [x,y] tells us what portion of the input is spanned so far by rule
- Each state $s_i$: *<dotted rule>*, [*<back pointer>*, *<current position>*]

# $_0$ Book $_1$ that $_2$ flight $_3$

- $S \rightarrow VP$, [0,0]
  - First 0 means S constituent begins at the start of input
  - Second 0 means the dot is here too
  - So, this is a top-down prediction
- $NP \rightarrow Det \bullet Nom$, [1,2]
  - the NP begins at position 1
  - the dot is at position 2
  - so, Det has been successfully parsed
  - Nom predicted next

# $_0$ Book $_1$ that $_2$ flight $_3$ (continued)

- $V \rightarrow V\ NP\ \bullet\ [0,3]$
  - Successful VP parse of entire input



# Successful Parse

- Final answer found by looking at last entry in chart
- If entry resembles $S \rightarrow \alpha \bullet [0,N]$ then input parsed successfully
- Chart will also contain record of all possible parses of input string, given the grammar

# Parsing Procedure for the Earley Algorithm

- Move through each set of states in order, applying one of three operations:
  - **predictor**: add predictions to the chart
  - **scanner**: read input and add corresponding state to chart
  - **completer**: move dot to right when new constituent found
- Results (new states) added to current or next set of states in chart
- No backtracking and no states removed: keep complete history of parse

# Earley Algorithm from J&M

```
function EARLEY-PARSE(words, grammar) returns chart
  ENQUEUE((γ ⟶ • S, [0,0]), chart[0])
  for i ⟵ from 0 to LENGTH(words) do
    for each state in chart[i] do
      if INCOMPLETE?(state) and
          NEXT-CAT(state) is not a part of speech then
        PREDICTOR(state)
      elseif INCOMPLETE?(state) and
          NEXT-CAT(state) is a part of speech then
        SCANNER(state)
      else
        COMPLETER(state)
      end
    end
  return(chart)
```

# Earley Algorithm from Book

```
procedure PREDICTOR((A→α • B β , [i,j]))
  for each (B → γ) in GRAMMAR-RULES-FOR(B,grammar) do
    ENQUEUE((B→• γ, [j,j]), chart[j])
  end

procedure SCANNER((A → α • B β,[i,j]))
  if B ⊂ PARTS-OF-SPEECH(word[j]) then
    ENQUEUE((B → word[j], [j,j+1]), chart[j+1] )

procedure COMPLETER((B → γ •, [j,k]))
  for each (A → α • B β, [i,j]) in chart[j] do
    ENQUEUE((A → α B •  β, [i,k]), chart[k])
  end
```

# 3 Main Subroutines of Earley

- Predictor
  - Adds predictions into the chart
- Completer
  - Moves the dot to the right when new constituents are found
- Scanner
  - Reads the input words and enters states representing those words into the chart

# Predictor

- Intuition:
  - Create new state for top-down prediction of new phrase
- Applied when non part-of-speech non-terminals are to the right of a dot:
  - $S \rightarrow \bullet\ VP$ [0,0]
- Adds new states to *current* chart
  - One new state for each expansion of the non-terminal in the grammar

| | | | |
|---|---|---|---|
| $VP \rightarrow \bullet$ | [0,0] | $S_j$: $A \rightarrow \alpha \bullet B\ \beta$ | [i,j] |
| $VP \rightarrow \bullet\ V\ NP$ | [0,0] | $S_i$: $B \rightarrow \bullet\ \gamma$, | [j,j] |

# Chart[0]

| | | | |
|---|---|---|---|
| S0 | $\gamma \rightarrow \bullet\ S$ | [0,0] | Dummy start state |
| S1 | $S \rightarrow \bullet\ NP\ VP$ | [0.0] | Predictor |
| S2 | $S \rightarrow \bullet\ Aux\ NP\ VP$ | [0,0] | Predictor |
| S3 | $S \rightarrow \bullet\ VP$ | [0,0] | Predictor |
| S4 | $NP \rightarrow \bullet\ Pronoun$ | [0,0] | Predictor |
| S5 | $NP \rightarrow \bullet\ Proper\text{-}Noun$ | [0,0] | Predictor |
| S6 | $NP \rightarrow \bullet\ Det\ Nominal$ | [0,0] | Predictor |
| S7 | $VP \rightarrow \bullet\ Verb$ | [0,0] | Predictor |
| S8 | $VP \rightarrow \bullet\ Verb\ NP$ | [0,0] | Predictor |
| S9 | $VP \rightarrow \bullet\ Verb\ NP\ PP$ | [0,0] | Predictor |
| S10 | $VP \rightarrow \bullet\ Verb\ PP$ | [0,0] | Predictor |
| S11 | $VP \rightarrow \bullet\ VP\ PP$ | [0,0] | Predictor |

# Chart[1]

| | | | |
|---|---|---|---|
| S12 | $Verb \rightarrow book \bullet$ | [0,1] | Scanner |
| S13 | $VP \rightarrow Verb \bullet$ | [0,1] | Completer |
| S14 | $VP \rightarrow Verb \bullet NP$ | [0,1] | Completer |
| S15 | $VP \rightarrow Verb \bullet NP\ PP$ | [0,1] | Completer |
| S16 | $VP \rightarrow Verb \bullet PP$ | [0,1] | Completer |
| S17 | $S \rightarrow VP \bullet$ | [0,1] | Completer |
| S18 | $VP \rightarrow VP \bullet PP$ | [0,1] | Completer |
| S19 | $NP \rightarrow \bullet Pronoun$ | [1,1] | Predictor |
| S20 | $NP \rightarrow \bullet Proper\text{-}Noun$ | [1,1] | Predictor |
| S21 | $NP \rightarrow \bullet Det\ Nominal$ | [1,1] | Predictor |
| S22 | $PP \rightarrow \bullet Prep\ NP$ | [1,1] | Predictor |

# *Book that flight*

S0: $\gamma \rightarrow \bullet\, S$ [0,0]

$$\gamma$$
$$|$$
$$\bullet\, S$$

# *Book that flight*

S0: $\gamma \rightarrow \bullet\ S\ [0,0]$

S3: $S \rightarrow \bullet\ VP\ [0,0]$

$\gamma$

|

S

|

• VP

# *Book that flight*

S0: $\gamma \rightarrow \bullet\ S$ [0,0]

S3: $S \rightarrow \bullet\ VP$ [0,0]

S8: $VP \rightarrow \bullet\ Verb\ NP$ [0,0]

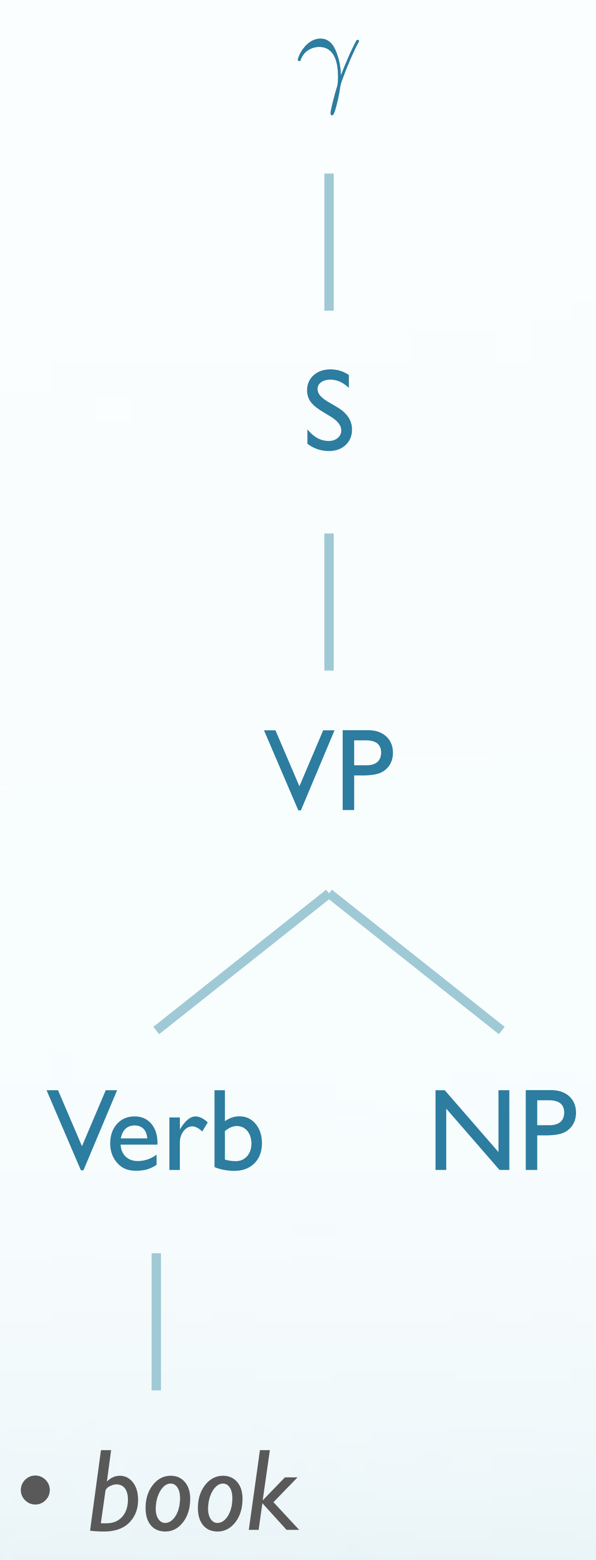
# *Book that flight*

S0: $\gamma \rightarrow \bullet\ S$ [0,0]

S3: $S \rightarrow \bullet\ VP$ [0,0]

S8: $VP \rightarrow \bullet\ Verb\ NP$ [0,0]

S12: $Verb \rightarrow \bullet\ book$ [0,0]



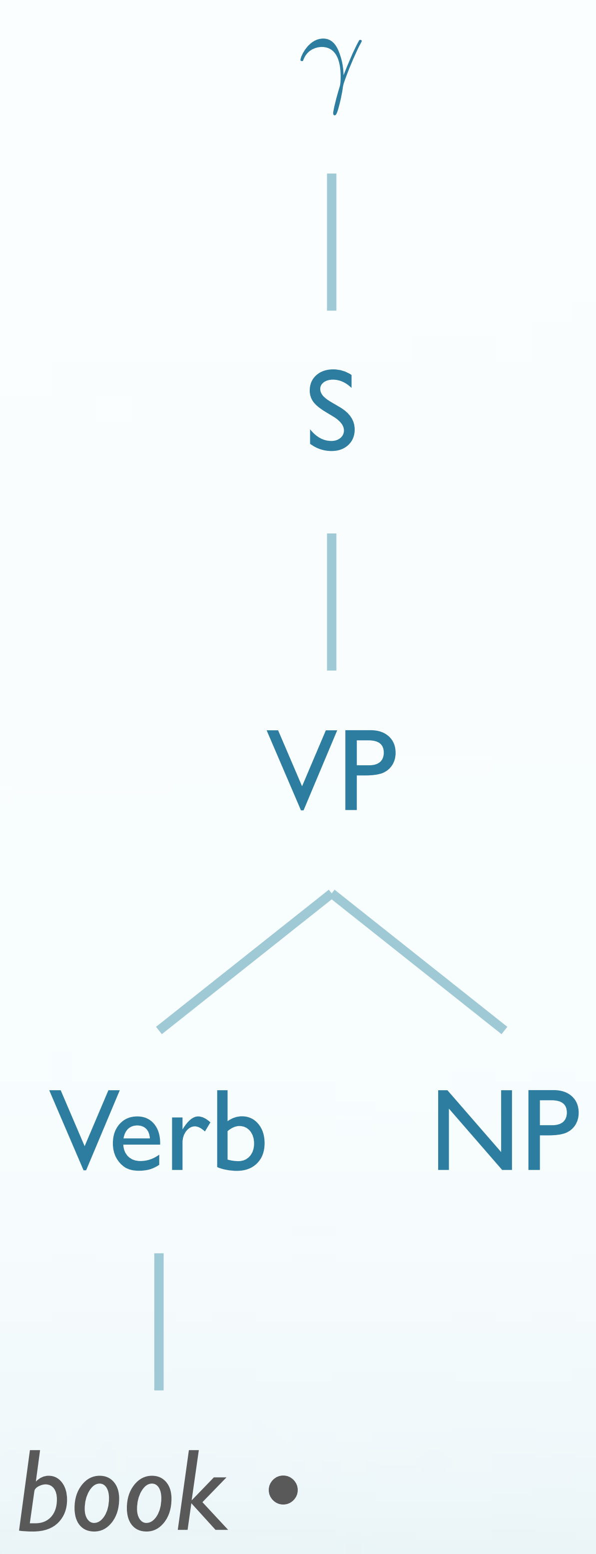
# *Book that flight*

S0: $\gamma \rightarrow \bullet\ S$ [0,0]

S3: $S \rightarrow \bullet\ VP$ [0,0]

S8: $VP \rightarrow \bullet\ Verb\ NP$ [0,0]

S12: $Verb \rightarrow book\ \bullet$ [0,1]

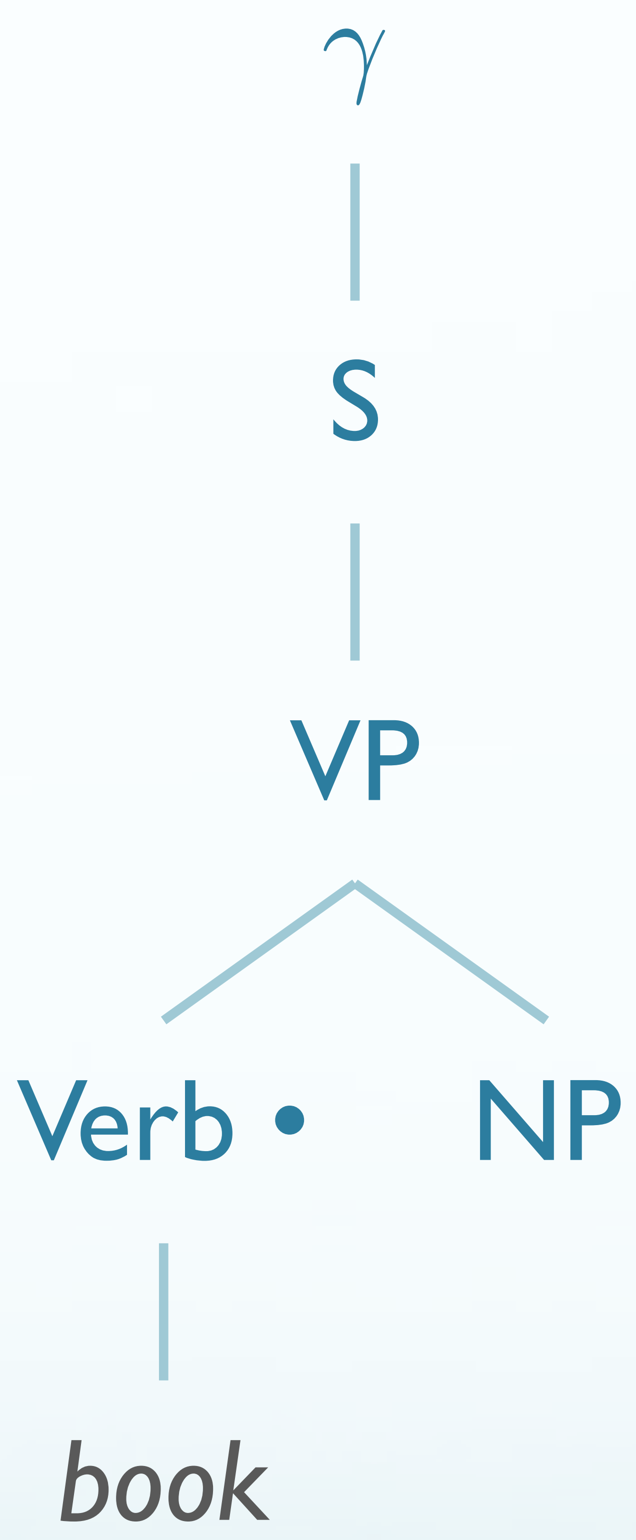


# *Book that flight*

S0: $\gamma \rightarrow \bullet\ S\ [0,0]$

S3: $S \rightarrow \bullet\ VP\ [0,0]$

S8: $VP \rightarrow Verb \bullet NP\ [0,1]$



# *Book that flight*

S0: $\gamma \rightarrow \bullet\, S$ [0,0]

S3: $S \rightarrow VP\, \bullet$ [0,1]

S8: $VP \rightarrow Verb \bullet NP$ [0,1]

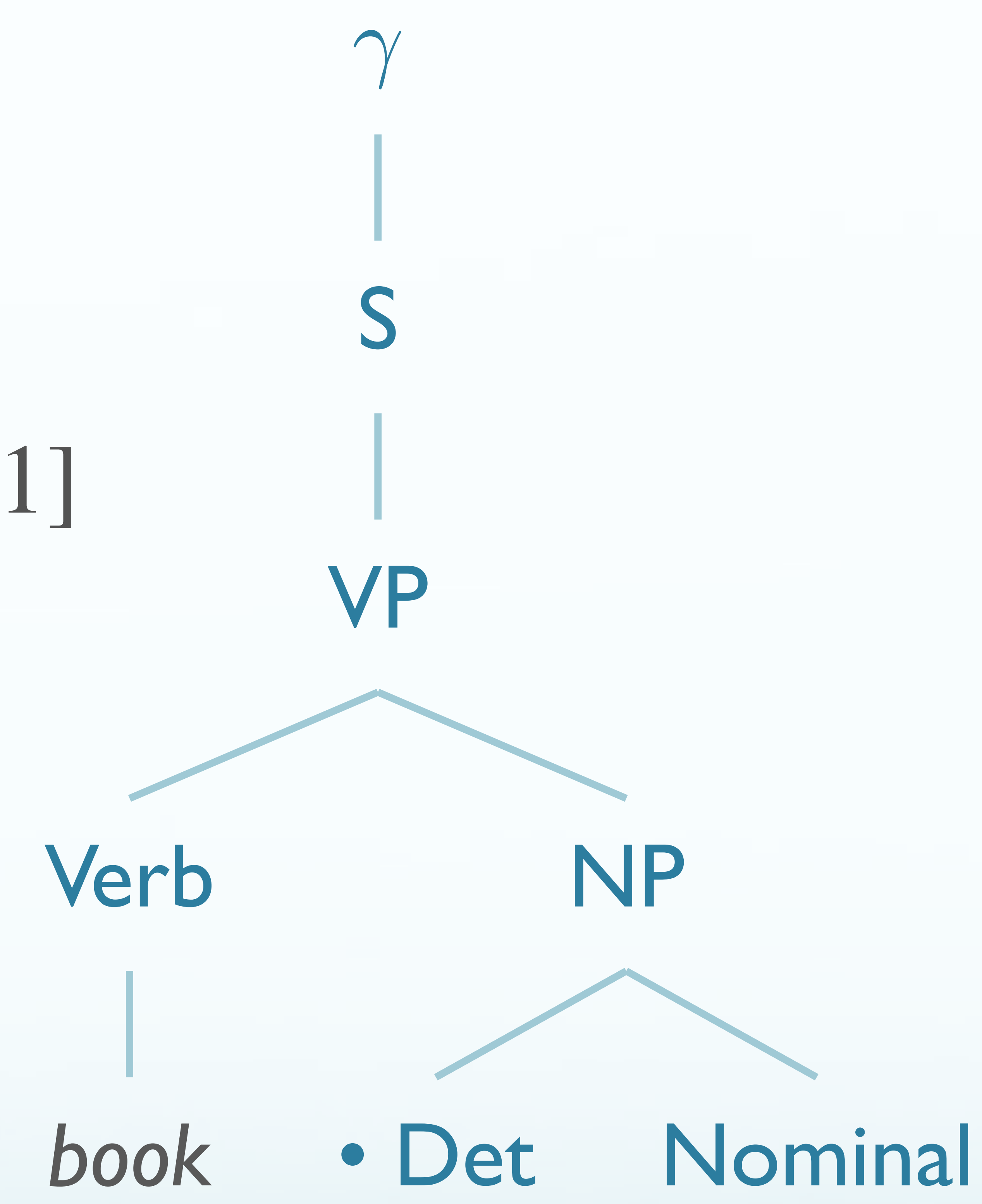
# *Book that flight*

S0: $\gamma \rightarrow \bullet\ S$ [0,0]

S3: $S \rightarrow VP \bullet$ [0,1]

S8: $VP \rightarrow Verb \bullet NP$ [0,1]

S21: $NP \rightarrow \bullet\ Det\ Nominal$ [1,1]



# *Book that flight*

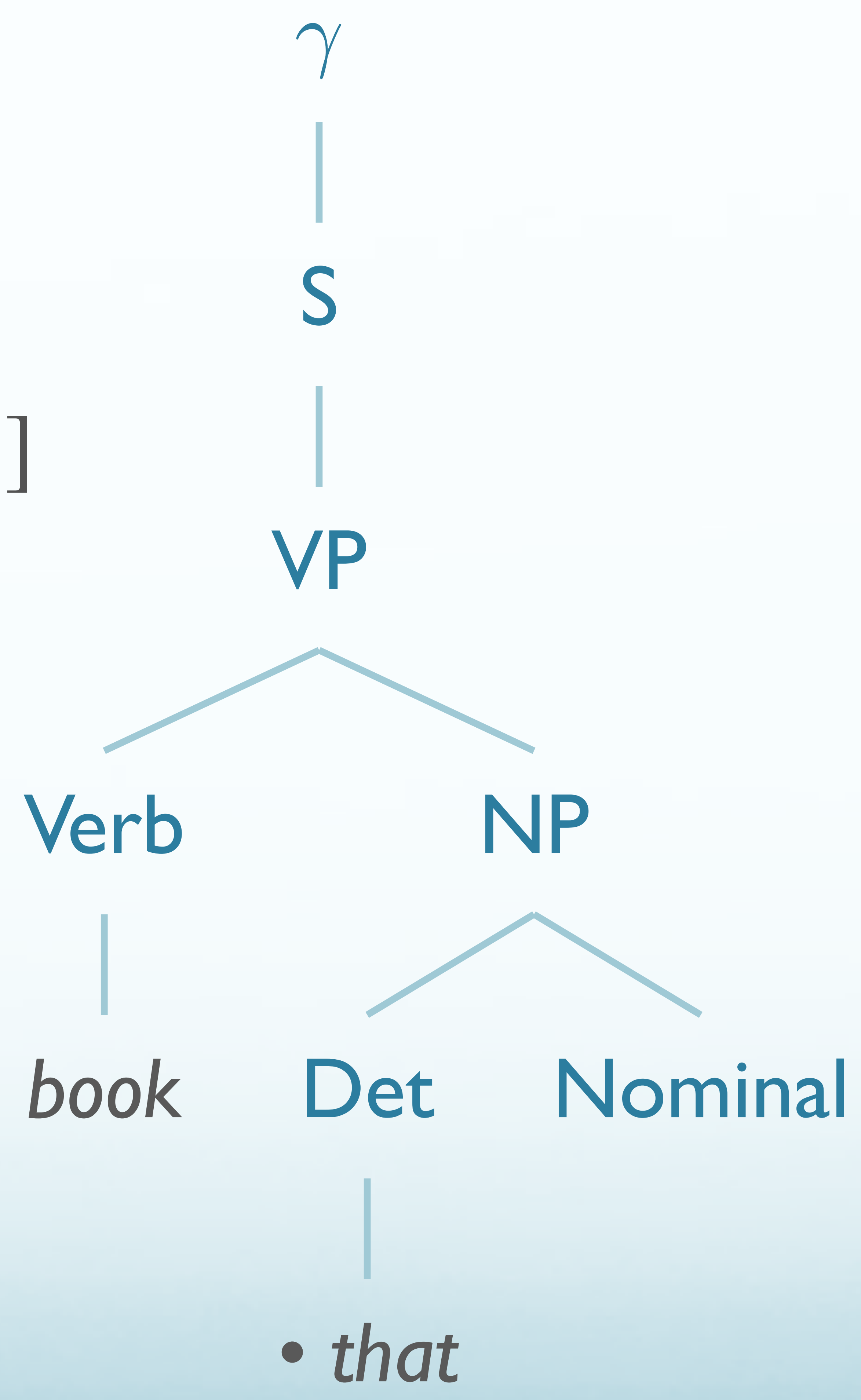
S0: $\gamma \rightarrow \bullet\ S$ [0,0]

S3: $S \rightarrow VP \bullet$ [0,1]

S8: $VP \rightarrow Verb \bullet NP$ [0,1]

S21: $NP \rightarrow \bullet\ Det\ Nominal$ [1,1]

S23: $Det \rightarrow \bullet$ *"that"* [1,1]



# Book that flight

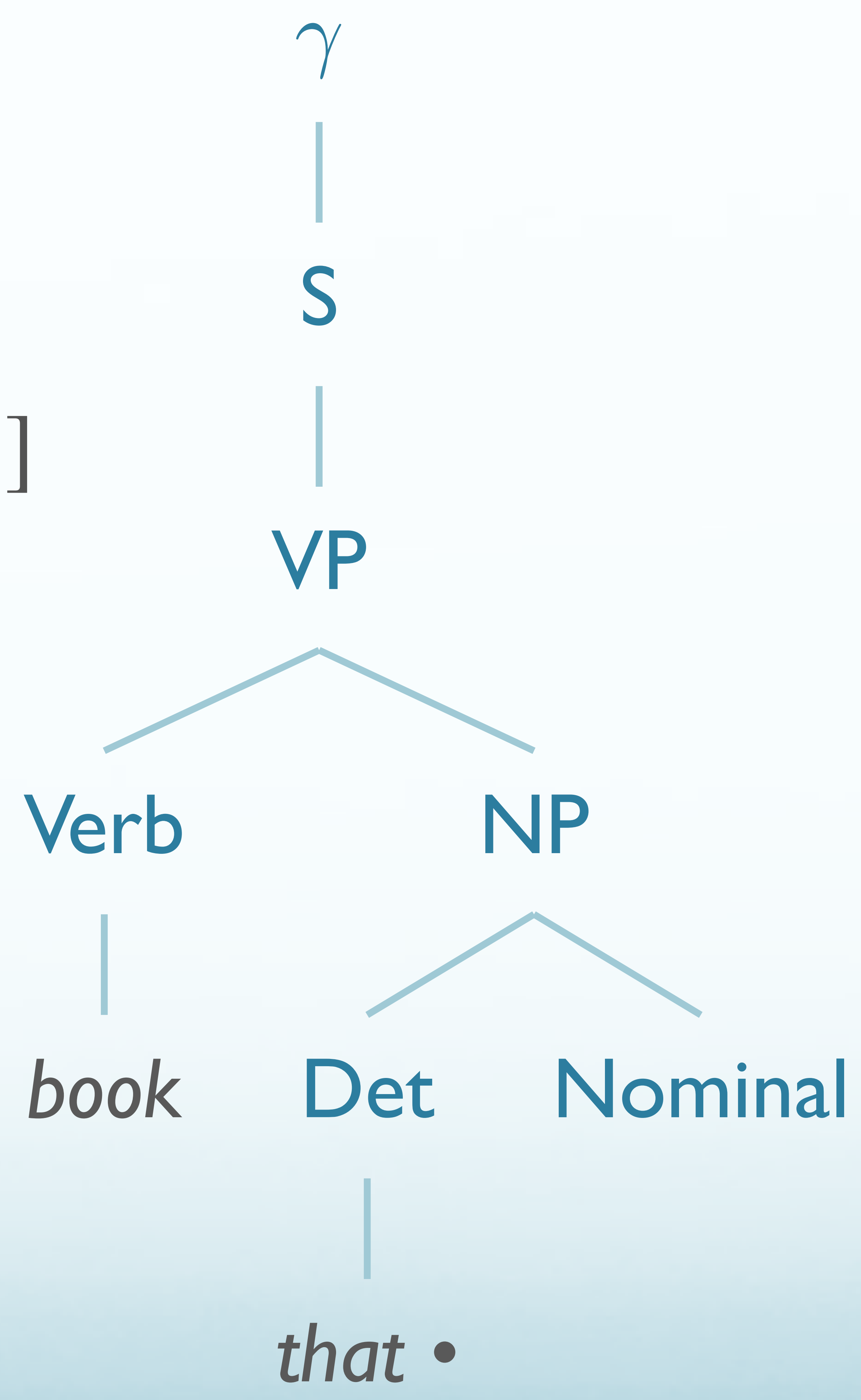
S0: $\gamma \rightarrow \bullet\ S$ [0,0]

S3: $S \rightarrow VP \bullet$ [0,1]

S8: $VP \rightarrow Verb \bullet NP$ [0,1]

S21: $NP \rightarrow \bullet\ Det\ Nominal$ [1,1]

S23: $Det \rightarrow$ *"that"* $\bullet$ [1,2]



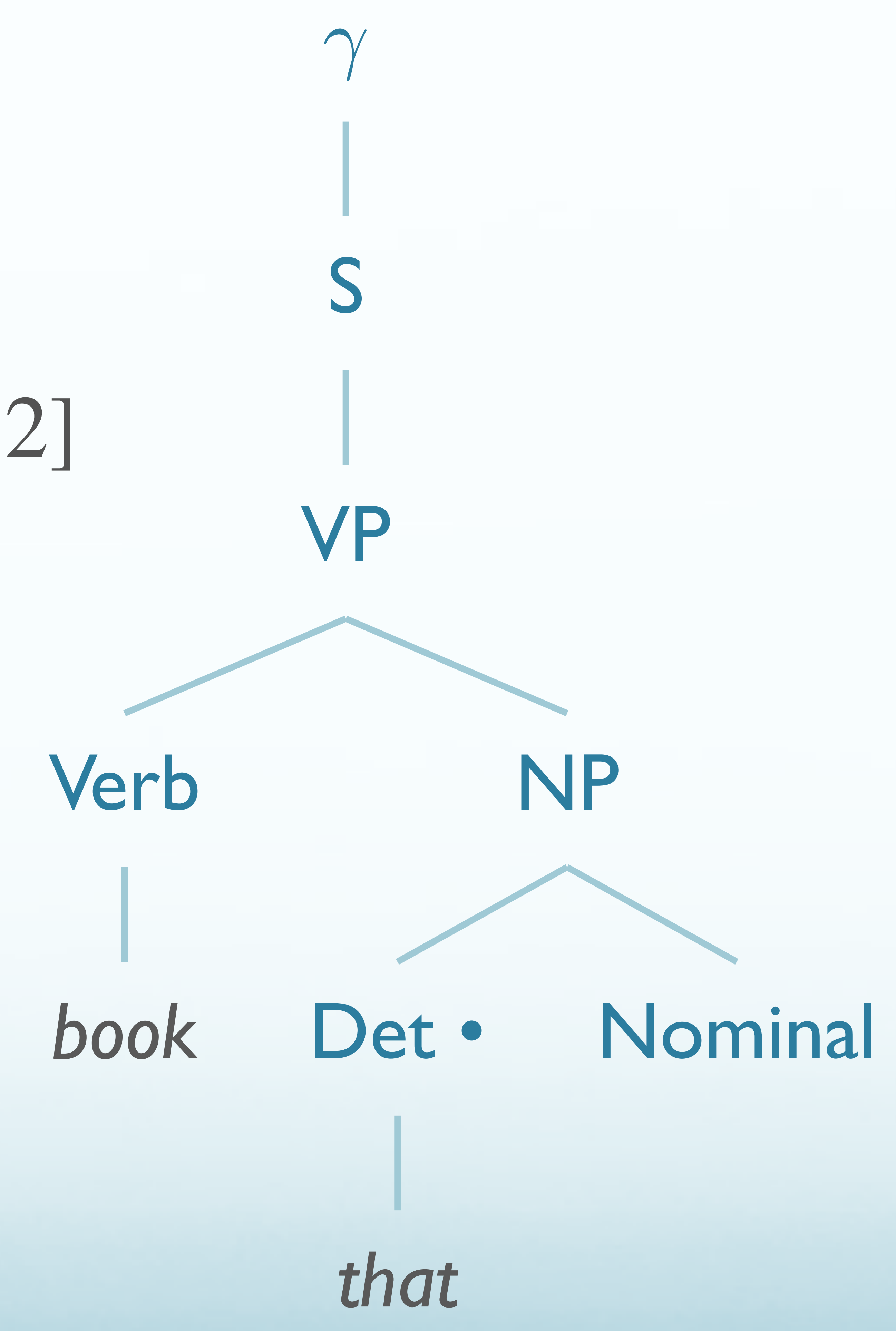
# Book that flight

S0: $\gamma \rightarrow \bullet\ S$ [0,0]

S3: $S \rightarrow VP\ \bullet$ [0,1]

S8: $VP \rightarrow Verb\ \bullet\ NP$ [0,1]

S21: $NP \rightarrow Det\ \bullet\ Nominal$ [1,2]



# *Book that flight*

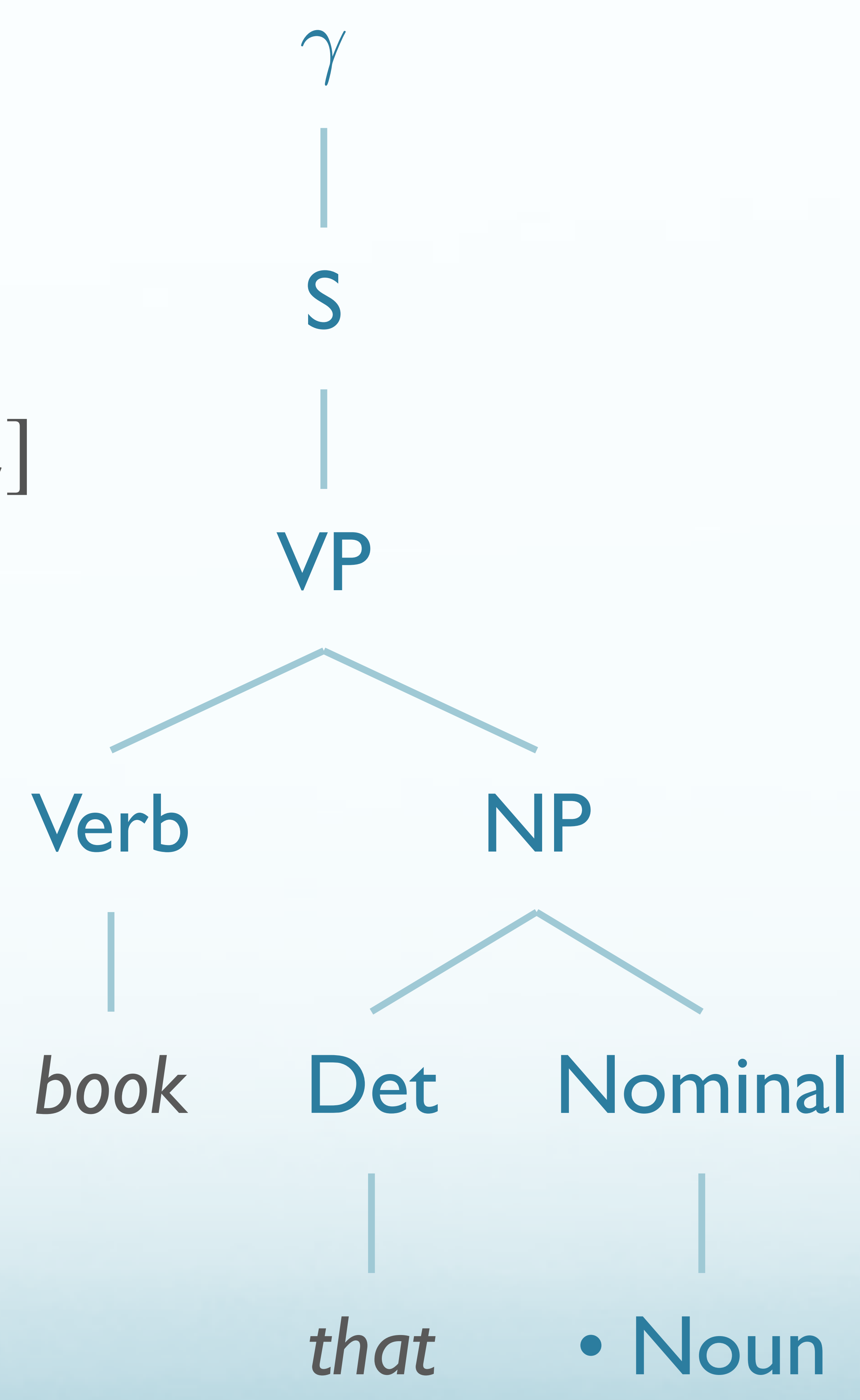
S0: $\gamma \rightarrow \bullet\ S$ [0,0]

S3: $S \rightarrow VP\ \bullet$ [0,1]

S8: $VP \rightarrow Verb \bullet NP$ [0,1]

S21: $NP \rightarrow Det \bullet Nominal$ [1,2]

S25: $Nominal \rightarrow \bullet\ Noun$ [2,2]



# *Book that flight*

S0: $\gamma \rightarrow \bullet\ S\ [0,0]$

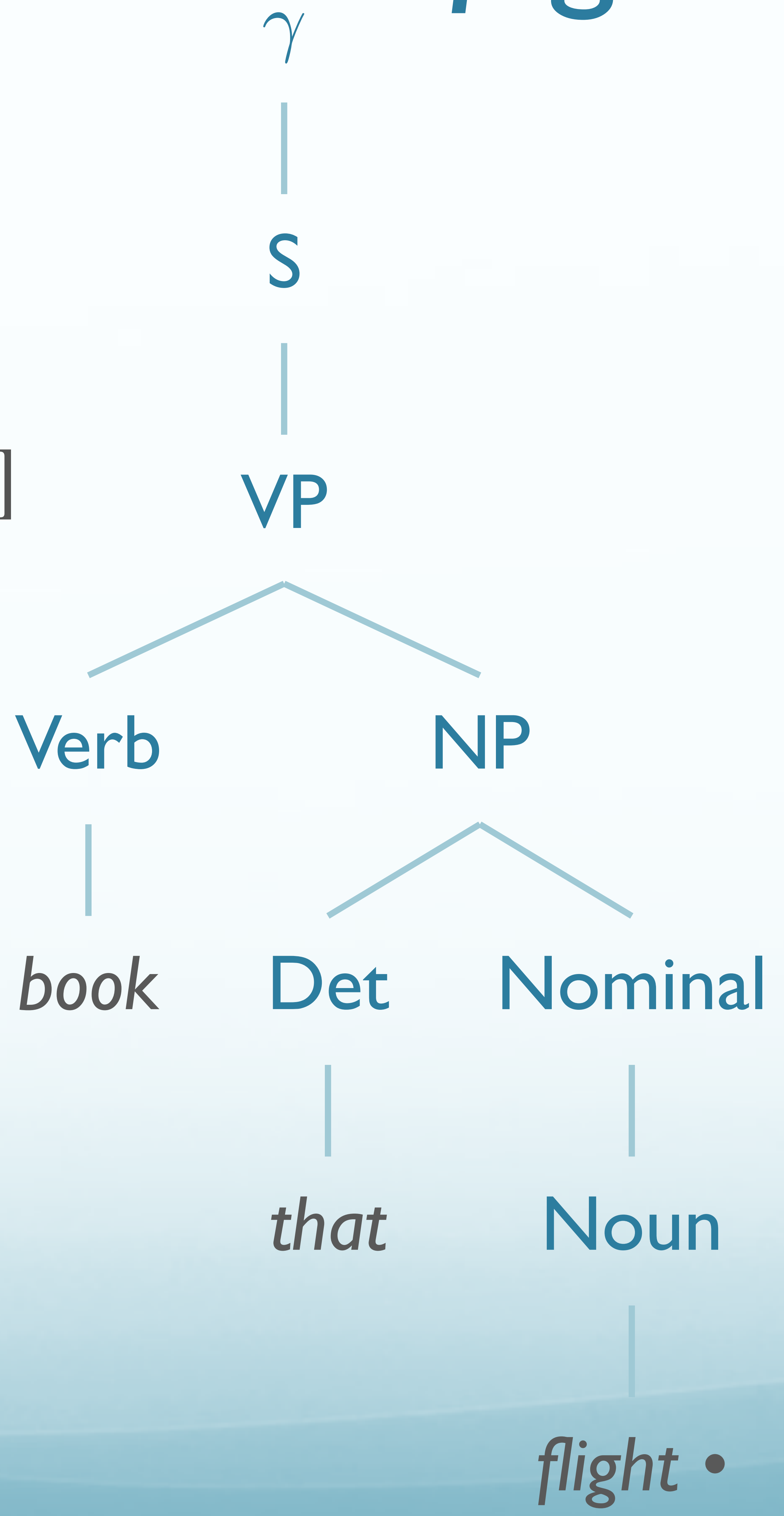
S3: $S \rightarrow VP\ \bullet\ [0,1]$

S8: $VP \rightarrow Verb\ \bullet\ NP\ [0,1]$

S21: $NP \rightarrow Det\ \bullet\ Nominal\ [1,2]$

S25: $Nominal \rightarrow \bullet\ Noun\ [2,2]$

S28: $Noun \rightarrow$ "*flight*" $\bullet\ [2,3]$



# *Book that flight*

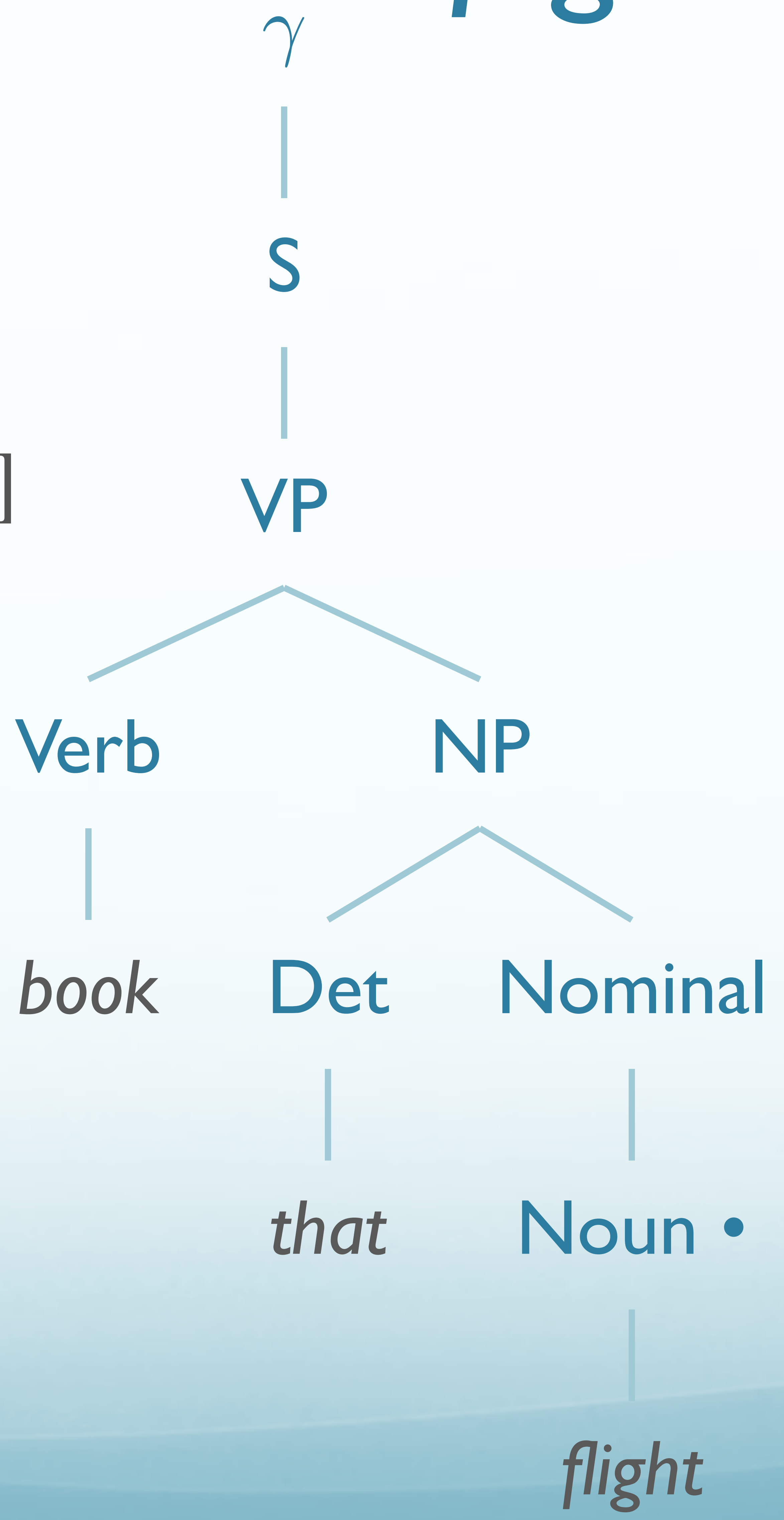
S0: $\gamma \rightarrow \bullet\ S$ [0,0]

S3: $S \rightarrow VP \bullet$ [0,1]

S8: $VP \rightarrow Verb \bullet NP$ [0,1]

S21: $NP \rightarrow Det \bullet Nominal$ [1,2]

S25: $Nominal \rightarrow Noun \bullet$ [2,3]



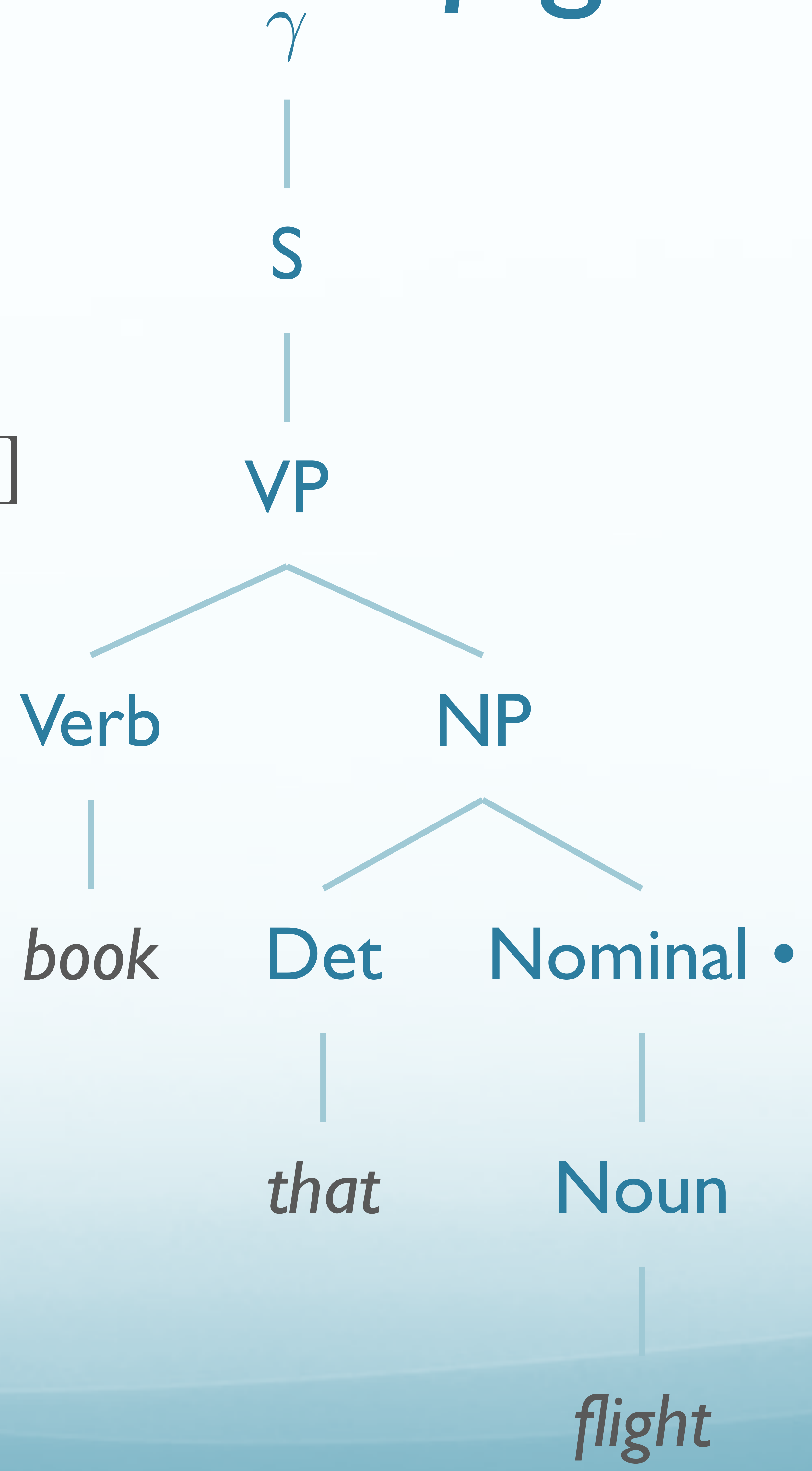
# Book that flight

S0: $\gamma \rightarrow \bullet\, S$ [0,0]

S3: $S \rightarrow VP\, \bullet$ [0,1]

S8: $VP \rightarrow Verb\, \bullet\, NP$ [0,1]

S21: $NP \rightarrow Det\ Nominal\, \bullet$ [1,3]

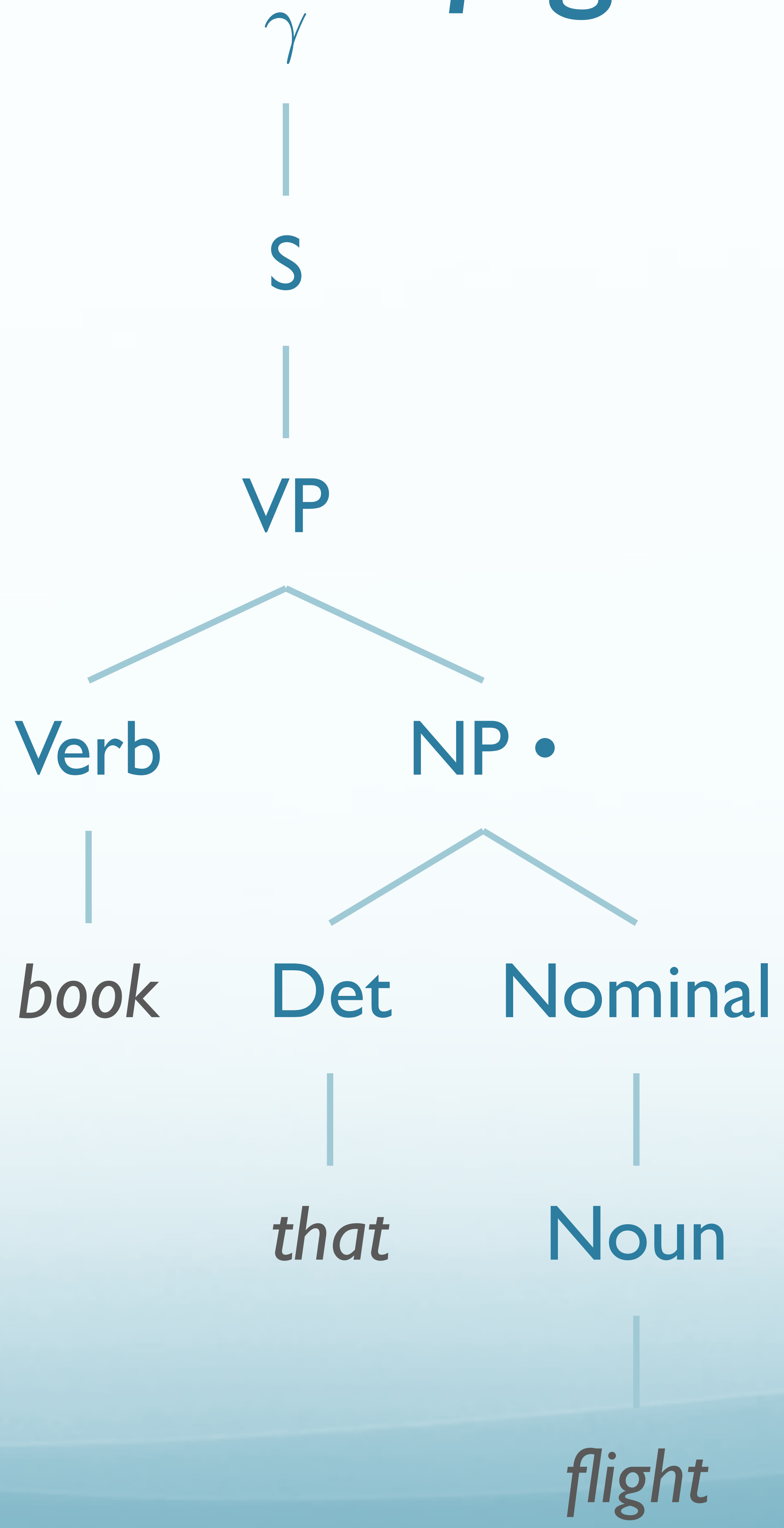


# *Book that flight*

S0: $\gamma \rightarrow \bullet\ S$ [0,0]

S3: $S \rightarrow VP\ \bullet$ [0,1]

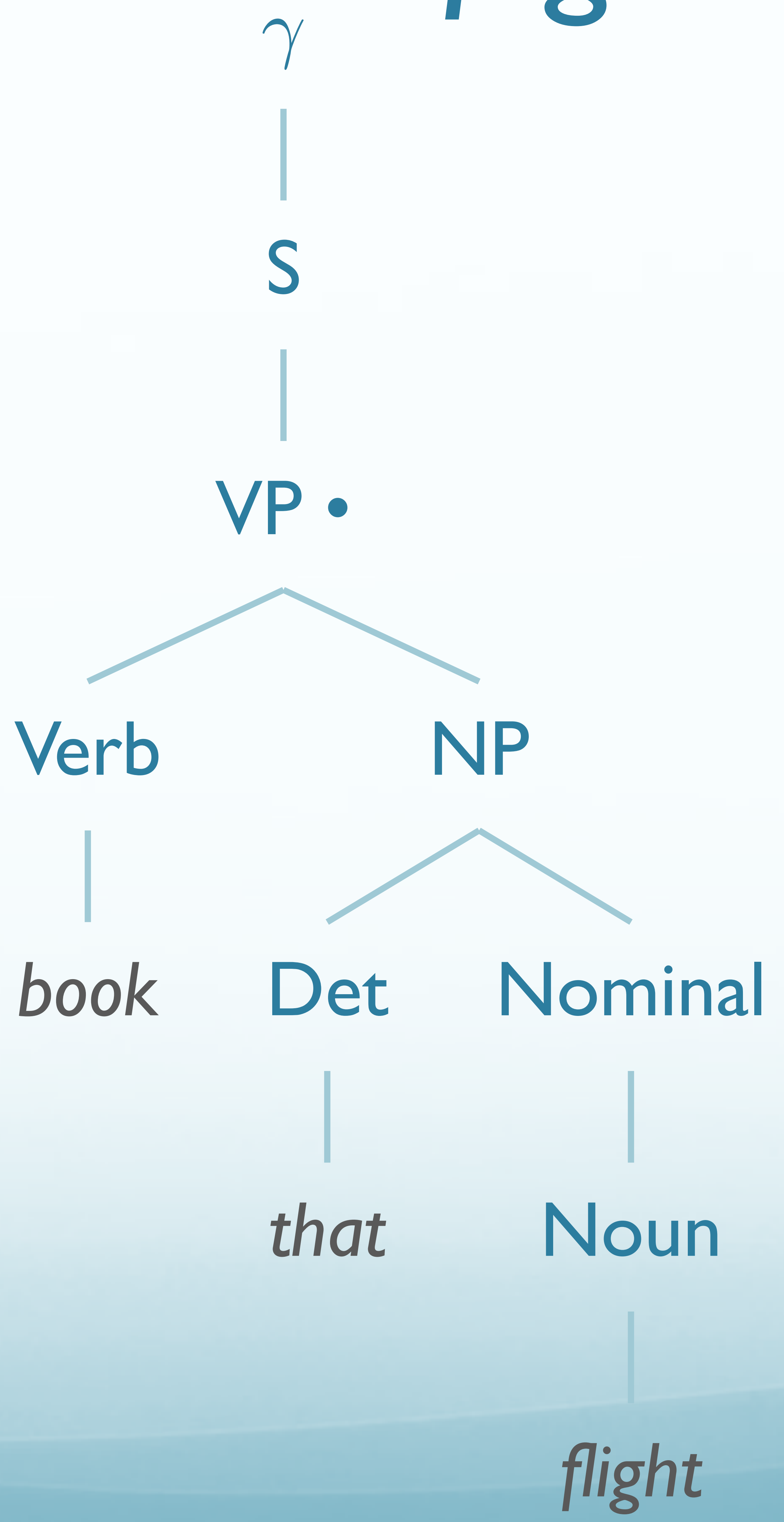
S8: $VP \rightarrow Verb\ NP\ \bullet$ [0,3]



# *Book that flight*

S0: $\gamma \rightarrow \bullet\ S\ [0,0]$

S3: $\boxed{S \rightarrow VP \bullet\ [0,3]}$



# What About Dead Ends?

# Book that flight

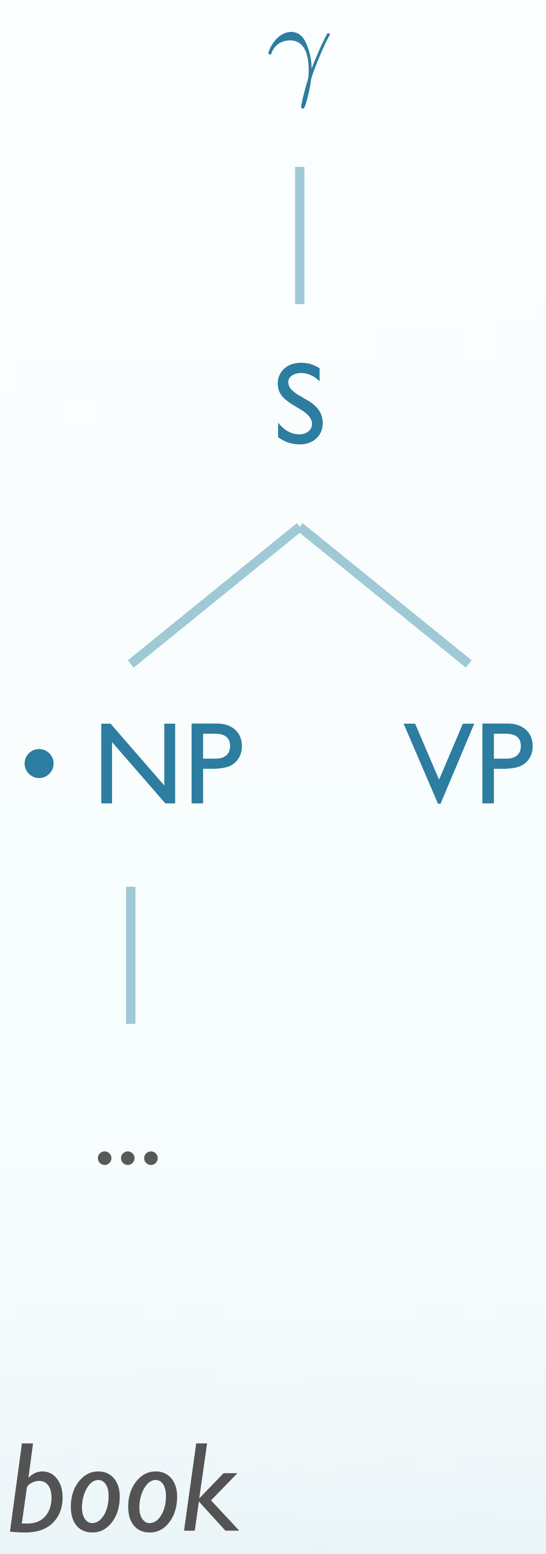
S0: $\gamma \rightarrow \bullet\ S$ [0,0]

S1: $S \rightarrow \bullet\ NP\ VP$ [0,0]

~~$NP \rightarrow \bullet\ Pronoun$~~

~~$NP \rightarrow \bullet\ Proper\text{-}Noun$~~

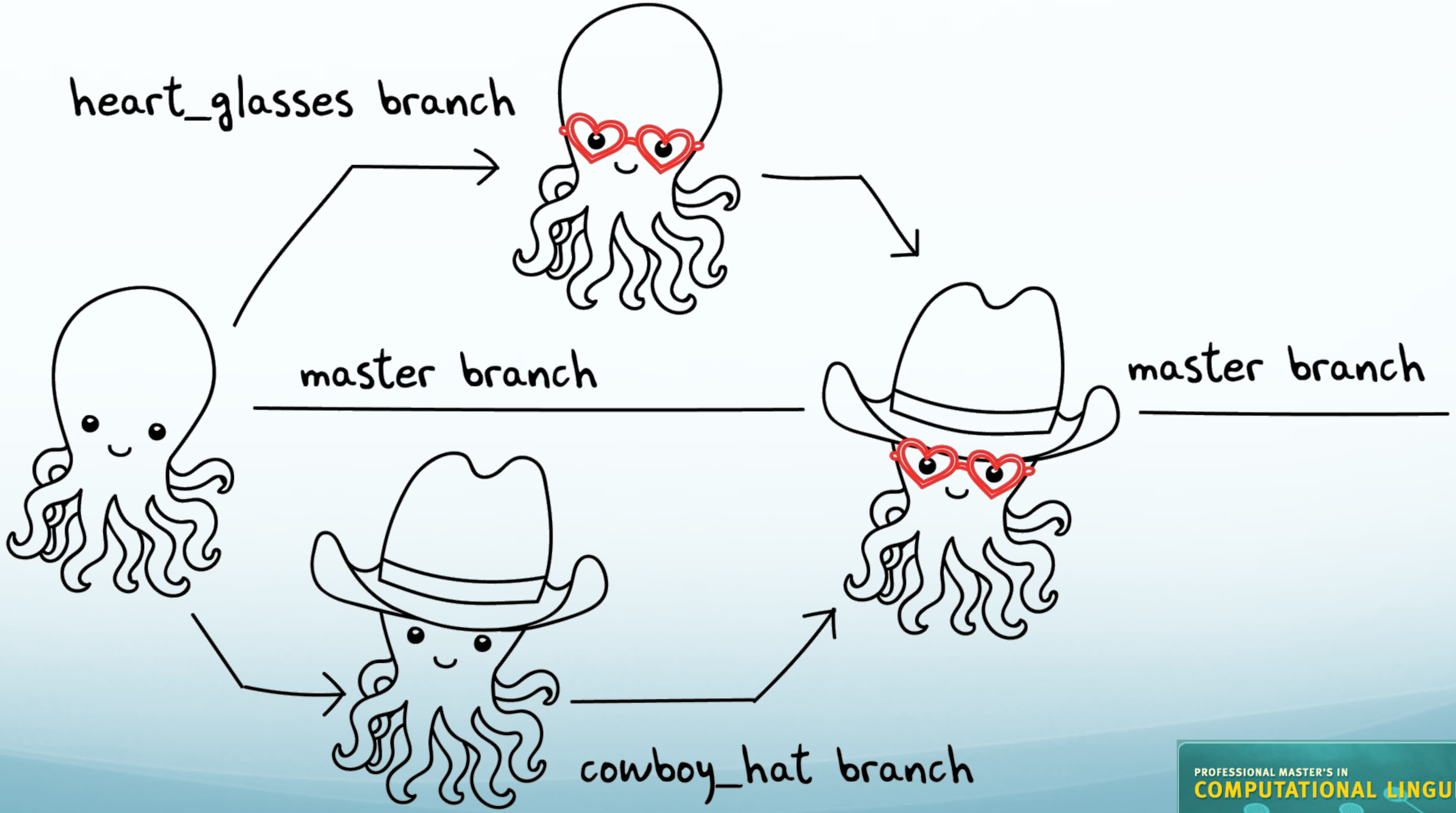
~~$NP \rightarrow \bullet\ Det\ Nominal$~~



# Some Collaboration Basics

# Git Branches

- Good for semi-isolating your development code from the shared, reviewed code



# Reccomended Git Flow

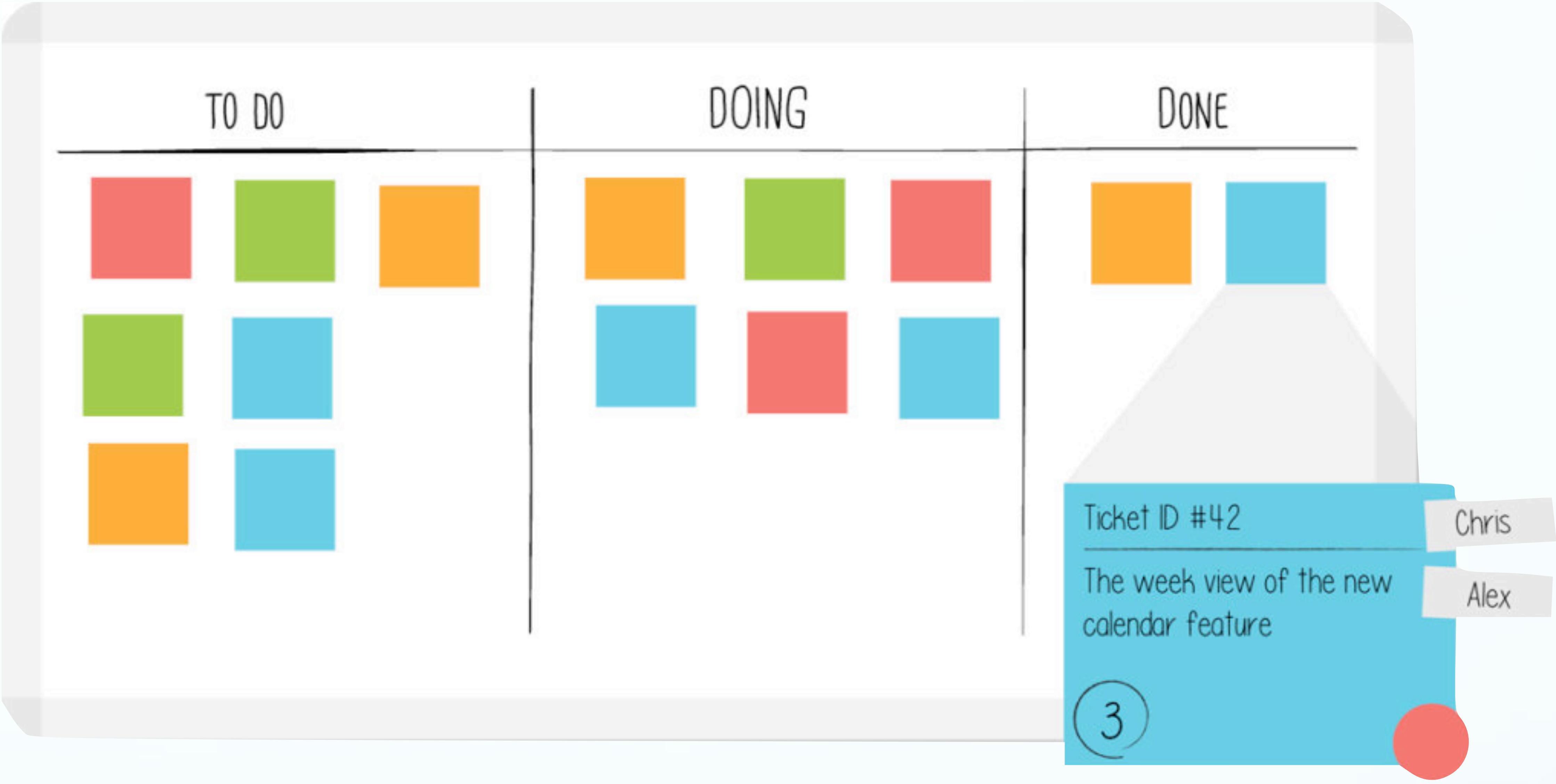
- Initialize a git repository, with a `master` branch
  - (Create initial checkin, if necessary)
- Create a new branch, maybe "`adding_rule_objects`"
- Make regular checkins on your branch (like saving)
- Switch to `master` branch, and "pull"
- Merge your branch to master
- …rinse & repeat

# Communication: Check-ins

- For check-ins, three main points:
  - What have you been working on?
  - What do you plan to work on next?
  - Is there anything "blocking" you?
- In industry, these brief check-ins among small teams are often done daily

# Project Planning: Kanban Boards

- Before you start working:
  - Write out tasks on sticky notes.
  - Place in three columns:
    - To-Do
    - Doing
    - Done
  - As you work, you can move them from column to column
  - Add tasks as new issues come up




- [trello.com](trello.com) – has free online implementation of Kanban Boards