# Context-Free Parsing:
## Outside Probabilities, Earley's Algorithm, and Treebank Transformations

Introduction to Natural Language Processing
Computer Science 585—Fall 2009
University of Massachusetts Amherst

David Smith

# Announcements

- If you haven't gotten your HW #1, please let me know
- HW #2: think of part 2 as tagging when you don't know what the tags mean; please do email source code
- Jason's request: please hand in printout of non-source-code if you want comments
- I'd like to postpone the midterm till next Thursday

# Overview

- Complete inside-outside: outside computations
- Earley's algorithm: combining bottom-up and top-down parsing
- Better treebank grammars: annotating nonterminals

# Inside & Viterbi Algorithms

NB: index *between* words; M&S index words

**Let** $\beta_A(i,j) = p(constit(A,i,j))$

$= p(w_{ij} \mid \text{nonterminal A from i to j})$

$$\beta_A(i,k) = \sum_{B,C,j} \beta_B(i,j) \cdot \beta_C(j,k) \cdot p(A \rightarrow B\ C)$$

**Let** $\delta_A(i,j) = p_{best}(constit(A,i,j))$

$$\delta_A(i,k) = \max_{B,C,j} \delta_B(i,j)) \cdot \delta_C(j,k) \cdot p(A \rightarrow B\ C)$$

$\beta_S(0,n) = ?$ $\qquad$ $\delta_S(0,n) = ?$

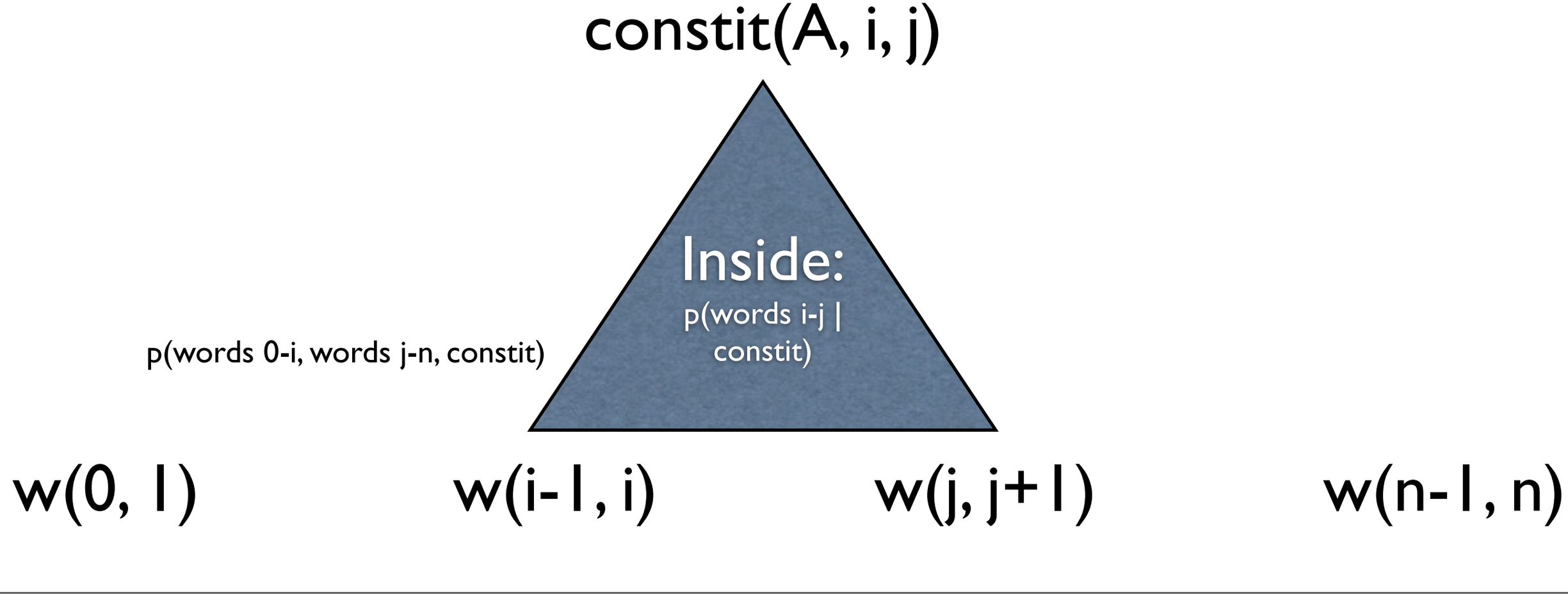
# Inside & Outside

constit(A, i, j)

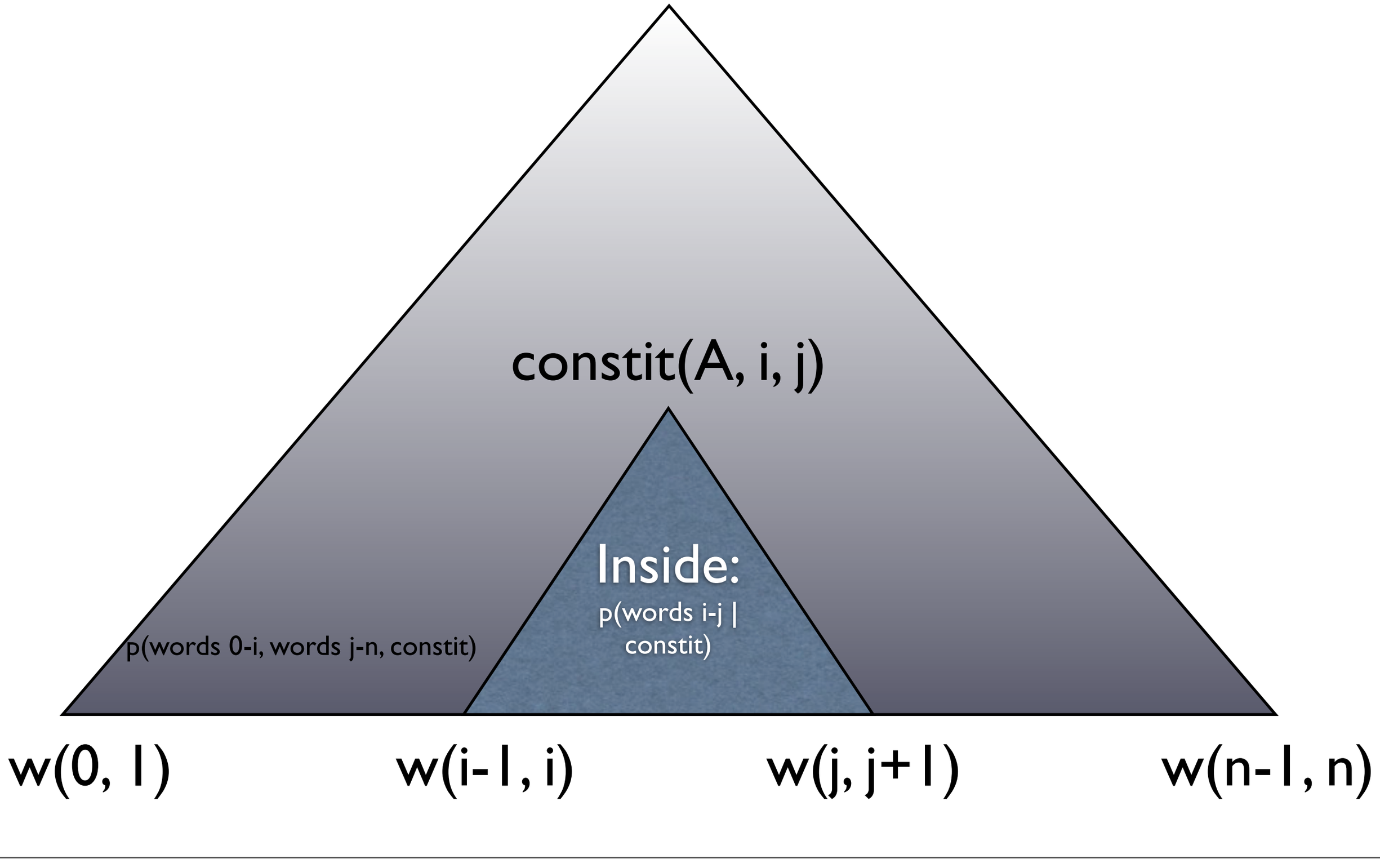
p(words 0-i, words j-n, constit)

w(0, 1) w(i-1, i) w(j, j+1) w(n-1, n)

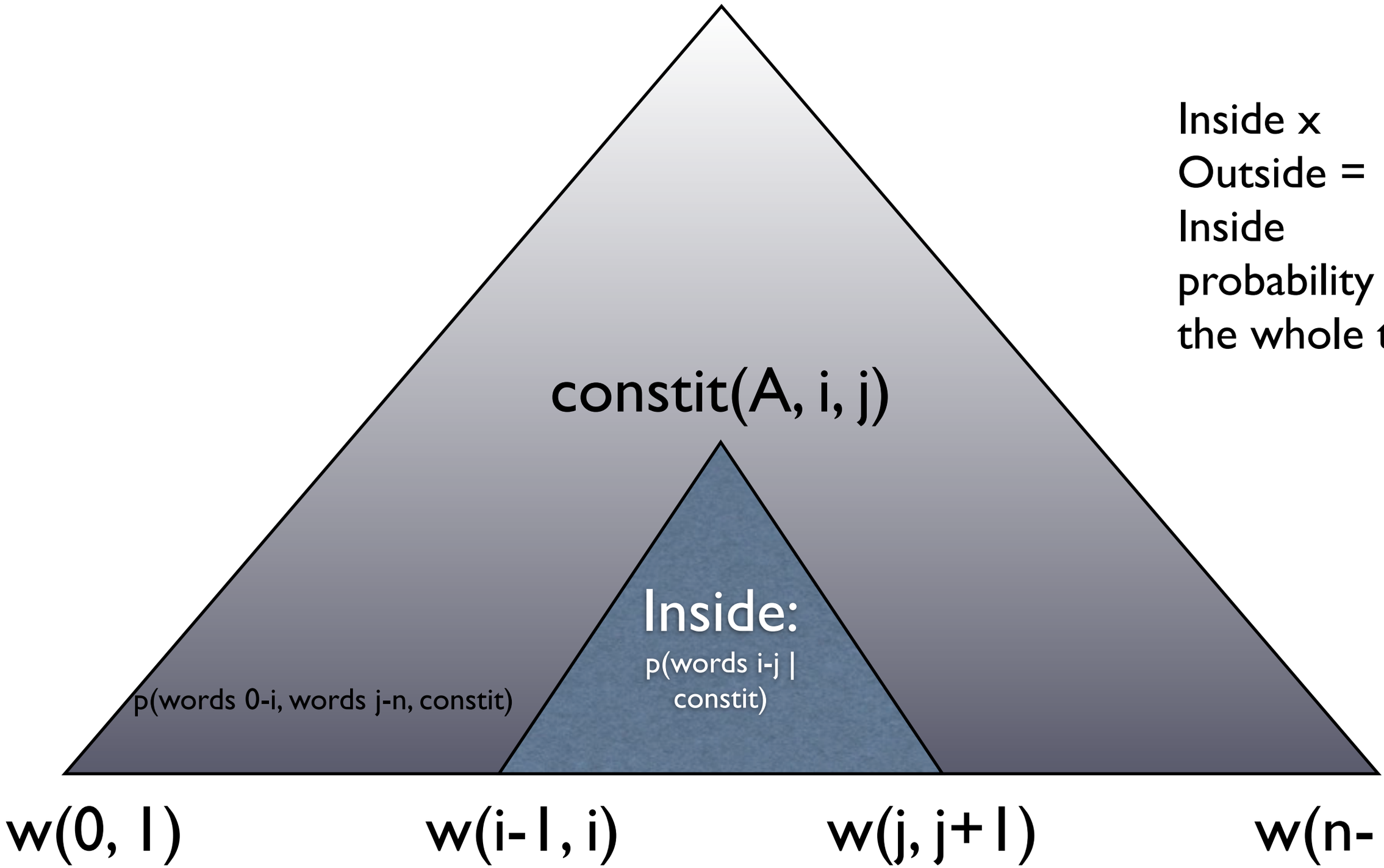
# Inside & Outside



# Inside & Outside



# Inside & Outside




Inside x Outside = Inside probability of the whole tree

# Outside Algorithm

$$\alpha_A(i,j) = p(w_{0,i}, A_{i,j}, w_{j,n})$$

Uses inside probs.

$$\alpha_A(i,j) = \sum_{B,C,k=j}^{n} \alpha_B(i,k) \cdot \beta_C(j,k) \cdot p(B \rightarrow A\ C)$$

$$+ \sum_{B,C,k=0}^{i} \alpha_B(k,j) \cdot \beta_C(k,i) \cdot p(B \rightarrow C\ A)$$

$$\alpha_S(0,n) = ?$$

$$\alpha_{PP}(0,n) = ?$$

Some resemblance to derivative product rule

# Top-Down/Bottom-Up

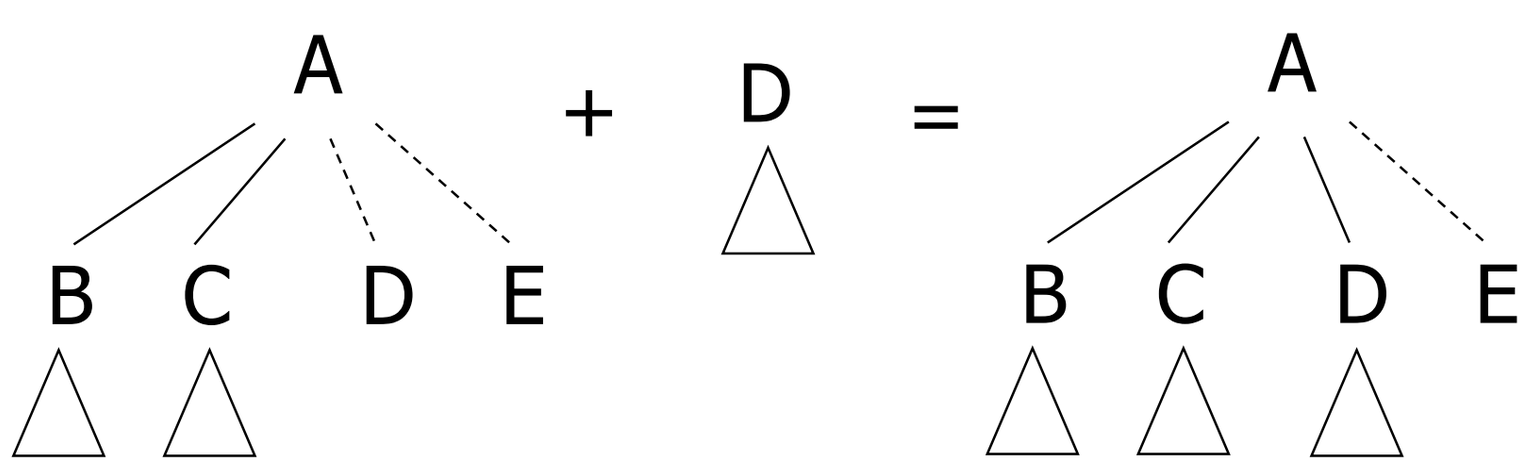
- Top-down parsers
  - Can get caught in infinite loops
  - Take exponential time backtracking
- CKY
  - Needs Chomsky normal form
  - Builds all possible constituents

# Earley Parser (1970)

- Nice combination of
  - dynamic programming
  - incremental interpretation
  - avoids infinite loops
  - no restrictions on the form of the context-free grammar.
    ***A → B C the D of*** causes no problems
  - $O(n^3)$ worst case, but faster for many grammars
  - Uses left context and optionally right context to constrain search.

# Overview of the Algorithm

- Finds constituents and partial constituents in input
  - A → B C . D E is partial: only the first half of the A



# Overview of the Algorithm

- Proceeds incrementally left-to-right
  - Before it reads word 5, it has already built all hypotheses that are consistent with first 4 words
  - Reads word 5 & attaches it to immediately preceding hypotheses. Might yield new constituents that are then attached to hypotheses immediately preceding *them …*
  - E.g., attaching D to A → B C . D E gives A → B C D . E
  - Attaching E to that gives A → B C D E .
  - Now we have a complete A that we can attach to hypotheses immediately preceding the A, etc.

# The Parse Table

- Columns 0 through n corresponding to the gaps between words
- Entries in column 5 look like (3, NP → NP . PP)

  (but we'll omit the → etc. to save space)
  - Built while processing word 5
  - Means that the input substring from 3 to 5 matches the initial NP portion of a **NP → NP PP** rule
  - Dot shows how much we've matched as of column 5
  - Perfectly fine to have entries like **(3, VP → is it . true that S)**

# The Parse Table

- Entries in column 5 look like (3, NP → NP . PP)
- What will it mean that we have this entry?
  - *Unknown right context: Doesn't* mean we'll necessarily be able to find a VP starting at column 5 to complete the S.
  - *Known left context: Does* mean that some dotted rule back in column 3 is looking for an S that starts at 3.
    - So if we actually do find a VP starting at column 5, allowing us to complete the S, then we'll be able to attach the S to something.
    - And when that something is complete, it too will have a customer to *its* left …
    - In short, a top-down (i.e., goal-directed) parser: it chooses to start building a constituent not because of the input but because that's what the left context needs. In **the spoon**, won't build **spoon** as a verb because there's no way to use a verb there.
    - So any hypothesis in column 5 *could* get used in the correct parse, if words 1-5 are continued in just the right way by words 6-n.

# Earley's Algorithm, recognizer version

- Add **ROOT → . S** to column 0.
- For each j from 0 to n:
  - For each dotted rule in column j, (including those we add as we go!) look at what's after the dot:
    - If it's a word w, SCAN:
      - If w matches the input word between j and j+1, advance the dot and add the resulting rule to column j+1
    - If it's a non-terminal X, PREDICT:
      - Add all rules for X to the bottom of column j, wth the dot at the start: e.g. **X → . Y Z**
    - If there's nothing after the dot, ATTACH:
      - We've finished some constituent, A, that started in column I<j. So for each rule in column  j that has A after the dot: Advance the dot and add the result to the bottom of column j.
- Output "yes" just if last column has **ROOT → S .**
- **NOTE: Don't add an entry to a column if it's already there!**

# Summary of the Algorithm

- Process all hypotheses one at a time in order. (Current hypothesis is shown in blue.)
- This may add new hypotheses to the end of the to-do list, or try to add old hypotheses again.

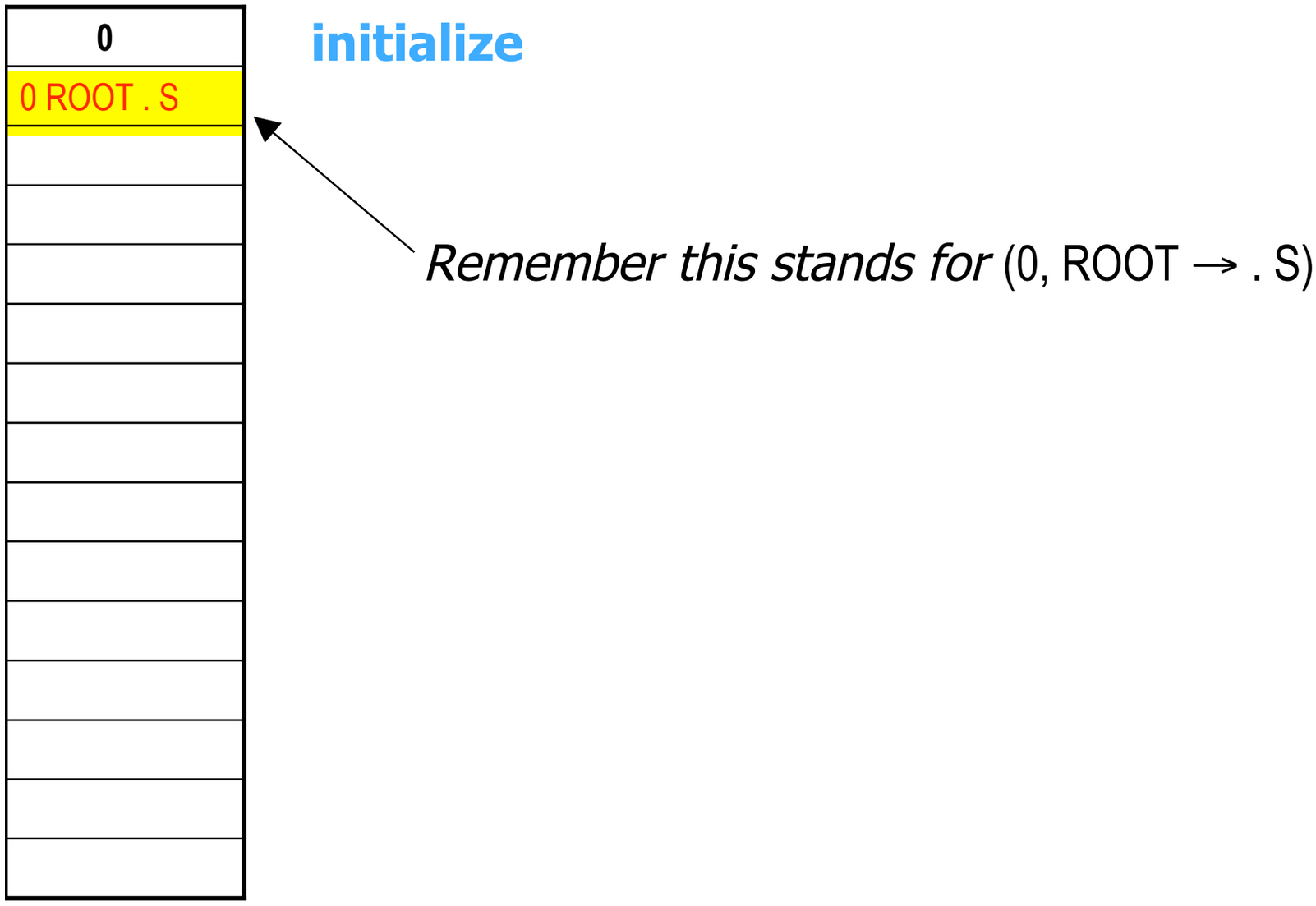
- Process a hypothesis according to what follows the dot:
  - If a word, **scan** input and see if it matches
  - If a nonterminal, **predict** ways to match it
    - (we'll predict blindly, but could reduce # of predictions by *looking ahead* k symbols in the input and only making predictions that are compatible with this limited *right context*)
  - If nothing, then we have a complete constituent, so **attach** it to all its customers

## A Grammar

| | | | |
|---|---|---|---|
| S | → NP VP | NP | → Papa |
| NP | → Det N | N | → caviar |
| NP | → NP PP | N | → spoon |
| VP | → V NP | V | → ate |
| VP | → VP PP | P | → with |
| PP | → P NP | Det | → the |
| | | Det | → a |

## An Input Sentence

*Papa ate the caviar with a spoon.*


0
0 ROOT . S
initialize
Remember this stands for (0, ROOT → . S)


**predict** the kind of S we are looking for

*Remember this stands for* (0, S → . NP VP)

| 0 |
| --- |
| 0 ROOT . S |
| 0 S . NP VP |
| 0 NP . Det N |
| 0 NP . NP PP |
| 0 NP . Papa |
| |
| |
| |
| |
| |
| |
| |
| |
| |

**predict** the kind of NP we are looking for
*(actually we'll look for 3 kinds: any of the 3 will do)*

| 0 |
| --- |
| 0 ROOT . S |
| 0 S . NP VP |
| 0 NP . Det N |
| 0 NP . NP PP |
| 0 NP . Papa |
| 0 Det . the |
| 0 Det . a |
| |
| |
| |
| |
| |
| |
| |

**predict** the kind of Det we are looking for *(2 kinds)*

| 0 |
|---|
| 0 ROOT . S |
| 0 S . NP VP |
| 0 NP . Det N |
| 0 NP . NP PP |
| 0 NP . Papa |
| 0 Det . the |
| 0 Det . a |
| |
| |
| |
| |
| |
| |
| |

**predict** the kind of NP we're looking for

*but we were already looking for these so don't add duplicate goals! Note that this happened when we were processing a left-recursive rule.*

| 0 Papa 1 | |
|---|---|
| 0 ROOT . S | 0 NP Papa . |
| 0 S . NP VP | |
| 0 NP . Det N | |
| 0 NP . NP PP | |
| 0 NP . Papa | |
| 0 Det . the | |
| 0 Det . a | |
| | |
| | |
| | |
| | |
| | |
| | |
| | |

**scan**: the desired word is in the input!

| 0 Papa 1 | |
|---|---|
| 0 ROOT . S | 0 NP Papa . |
| 0 S . NP VP | |
| 0 NP . Det N | |
| 0 NP . NP PP | |
| 0 NP . Papa | |
| 0 Det . the | |
| 0 Det . a | |
| | |
| | |
| | |
| | |
| | |
| | |
| | |

**scan:** failure

| 0 Papa 1 | |
|---|---|
| 0 ROOT . S | 0 NP Papa . |
| 0 S . NP VP | |
| 0 NP . Det N | |
| 0 NP . NP PP | |
| 0 NP . Papa | |
| 0 Det . the | |
| 0 Det . a | |
| | |
| | |
| | |
| | |
| | |
| | |
| | |

**scan:** failure

| 0 Papa 1 | |
|---|---|
| 0 ROOT . S | 0 NP Papa . |
| 0 S . NP VP | 0 S NP . VP |
| 0 NP . Det N | 0 NP NP . PP |
| 0 NP . NP PP | |
| 0 NP . Papa | |
| 0 Det . the | |
| 0 Det . a | |
| | |
| | |
| | |
| | |
| | |
| | |
| | |

**attach** the newly created NP
(which starts at 0) to its customers
(incomplete constituents that *end* at 0
and have NP after the dot)

| 0 Papa 1 | |
|---|---|
| 0 ROOT . S | 0 NP Papa . |
| 0 S . NP VP | 0 S NP . VP |
| 0 NP . Det N | 0 NP NP . PP |
| 0 NP . NP PP | 1 VP . V NP |
| 0 NP . Papa | 1 VP . VP PP |
| 0 Det . the | |
| 0 Det . a | |
| | |
| | |
| | |
| | |
| | |
| | |
| | |

**predict**

| 0 Papa 1 | |
|---|---|
| 0 ROOT . S | 0 NP Papa . |
| 0 S . NP VP | 0 S NP . VP |
| 0 NP . Det N | 0 NP NP . PP |
| 0 NP . NP PP | 1 VP . V NP |
| 0 NP . Papa | 1 VP . VP PP |
| 0 Det . the | 1 PP . P NP |
| 0 Det . a | |
| | |
| | |
| | |
| | |
| | |
| | |
| | |

**predict**

| 0 Papa 1 | |
|---|---|
| 0 ROOT . S | 0 NP Papa . |
| 0 S . NP VP | 0 S NP . VP |
| 0 NP . Det N | 0 NP NP . PP |
| 0 NP . NP PP | 1 VP . V NP |
| 0 NP . Papa | 1 VP . VP PP |
| 0 Det . the | 1 PP . P NP |
| 0 Det . a | 1 V . ate |
| | |
| | |
| | |
| | |
| | |
| | |
| | |

**predict**

| 0 Papa 1 | |
|---|---|
| 0 ROOT . S | 0 NP Papa . |
| 0 S . NP VP | 0 S NP . VP |
| 0 NP . Det N | 0 NP NP . PP |
| 0 NP . NP PP | 1 VP . V NP |
| 0 NP . Papa | 1 VP . VP PP |
| 0 Det . the | 1 PP . P NP |
| 0 Det . a | 1 V . ate |
| | |
| | |
| | |
| | |
| | |
| | |
| | |

**predict**

| 0 Papa 1 | |
|---|---|
| 0 ROOT . S | 0 NP Papa . |
| 0 S . NP VP | 0 S NP . VP |
| 0 NP . Det N | 0 NP NP . PP |
| 0 NP . NP PP | 1 VP . V NP |
| 0 NP . Papa | 1 VP . VP PP |
| 0 Det . the | 1 PP . P NP |
| 0 Det . a | 1 V . ate |
| | 1 P . with |
| | |
| | |
| | |
| | |
| | |
| | |

**predict**

| 0 Papa 1 ate 2 | | |
|---|---|---|
| 0 ROOT . S | 0 NP Papa . | 1 V ate . |
| 0 S . NP VP | 0 S NP . VP | |
| 0 NP . Det N | 0 NP NP . PP | |
| 0 NP . NP PP | 1 VP . V NP | |
| 0 NP . Papa | 1 VP . VP PP | |
| 0 Det . the | 1 PP . P NP | |
| 0 Det . a | 1 V . ate | |
| | 1 P . with | |
| | | |
| | | |
| | | |
| | | |
| | | |
| | | |

**scan**: success!

| 0 Papa 1 ate 2 | | |
|---|---|---|
| 0 ROOT . S | 0 NP Papa . | 1 V ate . |
| 0 S . NP VP | 0 S NP . VP | |
| 0 NP . Det N | 0 NP NP . PP | |
| 0 NP . NP PP | 1 VP . V NP | |
| 0 NP . Papa | 1 VP . VP PP | |
| 0 Det . the | 1 PP . P NP | |
| 0 Det . a | 1 V . ate | |
| | 1 P . with | |
| | | |
| | | |
| | | |
| | | |
| | | |
| | | |

**scan**: failure

| 0 Papa 1 ate 2 | | |
|---|---|---|
| 0 ROOT . S | 0 NP Papa . | 1 V ate . |
| 0 S . NP VP | 0 S NP . VP | 1 VP V . NP |
| 0 NP . Det N | 0 NP NP . PP | |
| 0 NP . NP PP | 1 VP . V NP | |
| 0 NP . Papa | 1 VP . VP PP | |
| 0 Det . the | 1 PP . P NP | |
| 0 Det . a | 1 V . ate | |
| | 1 P . with | |
| | | |
| | | |
| | | |
| | | |
| | | |
| | | |

**attach**

| 0 Papa 1 ate 2 | | |
|---|---|---|
| 0 ROOT . S | 0 NP Papa . | 1 V ate . |
| 0 S . NP VP | 0 S NP . VP | 1 VP V . NP |
| 0 NP . Det N | 0 NP NP . PP | 2 NP . Det N |
| 0 NP . NP PP | 1 VP . V NP | 2 NP . NP PP |
| 0 NP . Papa | 1 VP . VP PP | 2 NP . Papa |
| 0 Det . the | 1 PP . P NP | |
| 0 Det . a | 1 V . ate | |
| | 1 P . with | |
| | | |
| | | |
| | | |
| | | |
| | | |
| | | |

**predict**

| 0 Papa 1 ate 2 | | |
|---|---|---|
| 0 ROOT . S | 0 NP Papa . | 1 V ate . |
| 0 S . NP VP | 0 S NP . VP | 1 VP V . NP |
| 0 NP . Det N | 0 NP NP . PP | 2 NP . Det N |
| 0 NP . NP PP | 1 VP . V NP | 2 NP . NP PP |
| 0 NP . Papa | 1 VP . VP PP | 2 NP . Papa |
| 0 Det . the | 1 PP . P NP | 2 Det . the |
| 0 Det . a | 1 V . ate | 2 Det . a |
| | 1 P . with | |
| | | |
| | | |
| | | |
| | | |
| | | |
| | | |

**predict** *(these next few steps should look familiar)*

| 0 Papa 1 ate 2 | | |
|---|---|---|
| 0 ROOT . S | 0 NP Papa . | 1 V ate . |
| 0 S . NP VP | 0 S NP . VP | 1 VP V . NP |
| 0 NP . Det N | 0 NP NP . PP | 2 NP . Det N |
| 0 NP . NP PP | 1 VP . V NP | 2 NP . NP PP |
| 0 NP . Papa | 1 VP . VP PP | 2 NP . Papa |
| 0 Det . the | 1 PP . P NP | 2 Det . the |
| 0 Det . a | 1 V . ate | 2 Det . a |
| | 1 P . with | |
| | | |
| | | |
| | | |
| | | |
| | | |
| | | |

**predict**

| 0 Papa 1 ate 2 | | |
|---|---|---|
| 0 ROOT . S | 0 NP Papa . | 1 V ate . |
| 0 S . NP VP | 0 S NP . VP | 1 VP V . NP |
| 0 NP . Det N | 0 NP NP . PP | 2 NP . Det N |
| 0 NP . NP PP | 1 VP . V NP | 2 NP . NP PP |
| 0 NP . Papa | 1 VP . VP PP | 2 NP . Papa |
| 0 Det . the | 1 PP . P NP | 2 Det . the |
| 0 Det . a | 1 V . ate | 2 Det . a |
| | 1 P . with | |
| | | |
| | | |
| | | |
| | | |
| | | |
| | | |

**scan** *(this time we fail since Papa is not the next word)*

| 0 Papa 1 ate 2 the 3 | | | |
|---|---|---|---|
| 0 ROOT . S | 0 NP Papa . | 1 V ate . | 2 Det the . |
| 0 S . NP VP | 0 S NP . VP | 1 VP V . NP | |
| 0 NP . Det N | 0 NP NP . PP | 2 NP . Det N | |
| 0 NP . NP PP | 1 VP . V NP | 2 NP . NP PP | |
| 0 NP . Papa | 1 VP . VP PP | 2 NP . Papa | |
| 0 Det . the | 1 PP . P NP | 2 Det . the | |
| 0 Det . a | 1 V . ate | 2 Det . a | |
| | 1 P . with | | |
| | | | |
| | | | |
| | | | |
| | | | |
| | | | |
| | | | |

**scan:** success!

| 0 Papa 1 ate 2 the 3 | | | |
|---|---|---|---|
| 0 ROOT . S | 0 NP Papa . | 1 V ate . | 2 Det the . |
| 0 S . NP VP | 0 S NP . VP | 1 VP V . NP | |
| 0 NP . Det N | 0 NP NP . PP | 2 NP . Det N | |
| 0 NP . NP PP | 1 VP . V NP | 2 NP . NP PP | |
| 0 NP . Papa | 1 VP . VP PP | 2 NP . Papa | |
| 0 Det . the | 1 PP . P NP | 2 Det . the | |
| 0 Det . a | 1 V . ate | 2 Det . a | |
| | 1 P . with | | |
| | | | |
| | | | |
| | | | |
| | | | |
| | | | |
| | | | |

| 0 Papa 1 ate 2 the 3 | | | |
|---|---|---|---|
| 0 ROOT . S | 0 NP Papa . | 1 V ate . | 2 Det the . |
| 0 S . NP VP | 0 S NP . VP | 1 VP V . NP | 2 NP Det . N |
| 0 NP . Det N | 0 NP NP . PP | 2 NP . Det N | |
| 0 NP . NP PP | 1 VP . V NP | 2 NP . NP PP | |
| 0 NP . Papa | 1 VP . VP PP | 2 NP . Papa | |
| 0 Det . the | 1 PP . P NP | 2 Det . the | |
| 0 Det . a | 1 V . ate | 2 Det . a | |
| | 1 P . with | | |
| | | | |
| | | | |
| | | | |
| | | | |
| | | | |
| | | | |

| 0 Papa 1 ate 2 the 3 | | | |
|---|---|---|---|
| 0 ROOT . S | 0 NP Papa . | 1 V ate . | 2 Det the . |
| 0 S . NP VP | 0 S NP . VP | 1 VP V . NP | 2 NP Det . N |
| 0 NP . Det N | 0 NP NP . PP | 2 NP . Det N | 3 N . caviar |
| 0 NP . NP PP | 1 VP . V NP | 2 NP . NP PP | 3 N . spoon |
| 0 NP . Papa | 1 VP . VP PP | 2 NP . Papa | |
| 0 Det . the | 1 PP . P NP | 2 Det . the | |
| 0 Det . a | 1 V . ate | 2 Det . a | |
| | 1 P . with | | |
| | | | |
| | | | |
| | | | |
| | | | |
| | | | |
| | | | |

| 0 Papa 1 | ate 2 | the 3 | caviar 4 | |
|---|---|---|---|---|
| 0 ROOT . S | 0 NP Papa . | 1 V ate . | 2 Det the . | 3 N caviar . |
| 0 S . NP VP | 0 S NP . VP | 1 VP V . NP | 2 NP Det . N | |
| 0 NP . Det N | 0 NP NP . PP | 2 NP . Det N | 3 N . caviar | |
| 0 NP . NP PP | 1 VP . V NP | 2 NP . NP PP | 3 N . spoon | |
| 0 NP . Papa | 1 VP . VP PP | 2 NP . Papa | | |
| 0 Det . the | 1 PP . P NP | 2 Det . the | | |
| 0 Det . a | 1 V . ate | 2 Det . a | | |
| | 1 P . with | | | |
| | | | | |
| | | | | |
| | | | | |
| | | | | |
| | | | | |
| | | | | |

| 0 Papa 1 ate 2 the 3 caviar 4 | | | | |
|---|---|---|---|---|
| 0 ROOT . S | 0 NP Papa . | 1 V ate . | 2 Det the . | 3 N caviar . |
| 0 S . NP VP | 0 S NP . VP | 1 VP V . NP | 2 NP Det . N | |
| 0 NP . Det N | 0 NP NP . PP | 2 NP . Det N | 3 N . caviar | |
| 0 NP . NP PP | 1 VP . V NP | 2 NP . NP PP | 3 N . spoon | |
| 0 NP . Papa | 1 VP . VP PP | 2 NP . Papa | | |
| 0 Det . the | 1 PP . P NP | 2 Det . the | | |
| 0 Det . a | 1 V . ate | 2 Det . a | | |
| | 1 P . with | | | |
| | | | | |
| | | | | |
| | | | | |
| | | | | |
| | | | | |
| | | | | |

| 0 Papa 1 ate 2 the 3 caviar 4 | | | | |
|---|---|---|---|---|
| 0 ROOT . S | 0 NP Papa . | 1 V ate . | 2 Det the . | 3 N caviar . |
| 0 S . NP VP | 0 S NP . VP | 1 VP V . NP | 2 NP Det . N | 2 NP Det N . |
| 0 NP . Det N | 0 NP NP . PP | 2 NP . Det N | 3 N . caviar | |
| 0 NP . NP PP | 1 VP . V NP | 2 NP . NP PP | 3 N . spoon | |
| 0 NP . Papa | 1 VP . VP PP | 2 NP . Papa | | |
| 0 Det . the | 1 PP . P NP | 2 Det . the | | |
| 0 Det . a | 1 V . ate | 2 Det . a | | |
| | 1 P . with | | | |
| | | | | |
| | | | | |
| | | | | |
| | | | | |
| | | | | |
| | | | | |

attach

| 0 Papa 1 ate 2 the 3 caviar 4 | | | | |
|---|---|---|---|---|
| 0 ROOT . S | 0 NP Papa . | 1 V ate . | 2 Det the . | 3 N caviar . |
| 0 S . NP VP | 0 S NP . VP | 1 VP V . NP | 2 NP Det . N | 2 NP Det N . |
| 0 NP . Det N | 0 NP NP . PP | 2 NP . Det N | 3 N . caviar | 1 VP V NP . |
| 0 NP . NP PP | 1 VP . V NP | 2 NP . NP PP | 3 N . spoon | 2 NP NP . PP |
| 0 NP . Papa | 1 VP . VP PP | 2 NP . Papa | | |
| 0 Det . the | 1 PP . P NP | 2 Det . the | | |
| 0 Det . a | 1 V . ate | 2 Det . a | | |
| | 1 P . with | | | |
| | | | | |
| | | | | |
| | | | | |
| | | | | |
| | | | | |
| | | | | |

**attach**
*(again!)*

| 0 Papa 1 ate 2 the 3 caviar 4 | | | | |
|---|---|---|---|---|
| 0 ROOT . S | 0 NP Papa . | 1 V ate . | 2 Det the . | 3 N caviar . |
| 0 S . NP VP | 0 S NP . VP | 1 VP V . NP | 2 NP Det . N | 2 NP Det N . |
| 0 NP . Det N | 0 NP NP . PP | 2 NP . Det N | 3 N . caviar | 1 VP V NP . |
| 0 NP . NP PP | 1 VP . V NP | 2 NP . NP PP | 3 N . spoon | 2 NP NP . PP |
| 0 NP . Papa | 1 VP . VP PP | 2 NP . Papa | | 0 S NP VP . |
| 0 Det . the | 1 PP . P NP | 2 Det . the | | 1 VP VP . PP |
| 0 Det . a | 1 V . ate | 2 Det . a | | |
| | 1 P . with | | | |
| | | | | |
| | | | | |
| | | | | |
| | | | | |
| | | | | |
| | | | | |

**attach**
*(again!)*

| 0 Papa 1 ate 2 the 3 caviar 4 | | | | |
|---|---|---|---|---|
| 0 ROOT . S | 0 NP Papa . | 1 V ate . | 2 Det the . | 3 N caviar . |
| 0 S . NP VP | 0 S NP . VP | 1 VP V . NP | 2 NP Det . N | 2 NP Det N . |
| 0 NP . Det N | 0 NP NP . PP | 2 NP . Det N | 3 N . caviar | 1 VP V NP . |
| 0 NP . NP PP | 1 VP . V NP | 2 NP . NP PP | 3 N . spoon | 2 NP NP . PP |
| 0 NP . Papa | 1 VP . VP PP | 2 NP . Papa | | 0 S NP VP . |
| 0 Det . the | 1 PP . P NP | 2 Det . the | | 1 VP VP . PP |
| 0 Det . a | 1 V . ate | 2 Det . a | | 4 PP . P NP |
| | 1 P . with | | | |
| | | | | |
| | | | | |
| | | | | |
| | | | | |
| | | | | |
| | | | | |

| 0 Papa 1 ate 2 the 3 caviar 4 | | | | |
|---|---|---|---|---|
| 0 ROOT . S | 0 NP Papa . | 1 V ate . | 2 Det the . | 3 N caviar . |
| 0 S . NP VP | 0 S NP . VP | 1 VP V . NP | 2 NP Det . N | 2 NP Det N . |
| 0 NP . Det N | 0 NP NP . PP | 2 NP . Det N | 3 N . caviar | 1 VP V NP . |
| 0 NP . NP PP | 1 VP . V NP | 2 NP . NP PP | 3 N . spoon | 2 NP NP . PP |
| 0 NP . Papa | 1 VP . VP PP | 2 NP . Papa | | 0 S NP VP . |
| 0 Det . the | 1 PP . P NP | 2 Det . the | | 1 VP VP . PP |
| 0 Det . a | 1 V . ate | 2 Det . a | | 4 PP . P NP |
| | 1 P . with | | | 0 ROOT S . |
| | | | | |
| | | | | |
| | | | | |
| | | | | |
| | | | | |
| | | | | |

**attach**
*(again!)*

| 0 Papa | 1 ate | 2 the | 3 caviar | 4 |
|---|---|---|---|---|
| 0 ROOT . S | 0 NP Papa . | 1 V ate . | 2 Det the . | 3 N caviar . |
| 0 S . NP VP | 0 S NP . VP | 1 VP V . NP | 2 NP Det . N | 2 NP Det N . |
| 0 NP . Det N | 0 NP NP . PP | 2 NP . Det N | 3 N . caviar | 1 VP V NP . |
| 0 NP . NP PP | 1 VP . V NP | 2 NP . NP PP | 3 N . spoon | 2 NP NP . PP |
| 0 NP . Papa | 1 VP . VP PP | 2 NP . Papa | | 0 S NP VP . |
| 0 Det . the | 1 PP . P NP | 2 Det . the | | 1 VP VP . PP |
| 0 Det . a | 1 V . ate | 2 Det . a | | 4 PP . P NP |
| | 1 P . with | | | 0 ROOT S . |
| | | | | |
| | | | | |
| | | | | |
| | | | | |
| | | | | |
| | | | | |

| 0 Papa 1 | ate 2 | the 3 | caviar 4 | |
|---|---|---|---|---|
| 0 ROOT . S | 0 NP Papa . | 1 V ate . | 2 Det the . | 3 N caviar . |
| 0 S . NP VP | 0 S NP . VP | 1 VP V . NP | 2 NP Det . N | 2 NP Det N . |
| 0 NP . Det N | 0 NP NP . PP | 2 NP . Det N | 3 N . caviar | 1 VP V NP . |
| 0 NP . NP PP | 1 VP . V NP | 2 NP . NP PP | 3 N . spoon | 2 NP NP . PP |
| 0 NP . Papa | 1 VP . VP PP | 2 NP . Papa | | 0 S NP VP . |
| 0 Det . the | 1 PP . P NP | 2 Det . the | | 1 VP VP . PP |
| 0 Det . a | 1 V . ate | 2 Det . a | | 4 PP . P NP |
| | 1 P . with | | | 0 ROOT S . |
| | | | | 4 P . with |
| | | | | |
| | | | | |
| | | | | |
| | | | | |
| | | | | |

| 0 Papa 1 | ate 2 | the 3 | caviar 4 | |
|---|---|---|---|---|
| 0 ROOT . S | 0 NP Papa . | 1 V ate . | 2 Det the . | 3 N caviar . |
| 0 S . NP VP | 0 S NP . VP | 1 VP V . NP | 2 NP Det . N | 2 NP Det N . |
| 0 NP . Det N | 0 NP NP . PP | 2 NP . Det N | 3 N . caviar | 1 VP V NP . |
| 0 NP . NP PP | 1 VP . V NP | 2 NP . NP PP | 3 N . spoon | 2 NP NP . PP |
| 0 NP . Papa | 1 VP . VP PP | 2 NP . Papa | | 0 S NP VP . |
| 0 Det . the | 1 PP . P NP | 2 Det . the | | 1 VP VP . PP |
| 0 Det . a | 1 V . ate | 2 Det . a | | 4 PP . P NP |
| | 1 P . with | | | 0 ROOT S . |
| | | | | 4 P . with |
| | | | | |
| | | | | |
| | | | | |
| | | | | |
| | | | | |

| 0 Papa | 1 ate | 2 the | 3 caviar | 4 with | 5 |
|---|---|---|---|---|---|
| 0 ROOT . S | 0 NP Papa . | 1 V ate . | 2 Det the . | 3 N caviar . | 4 P with . |
| 0 S . NP VP | 0 S NP . VP | 1 VP V . NP | 2 NP Det . N | 2 NP Det N . | |
| 0 NP . Det N | 0 NP NP . PP | 2 NP . Det N | 3 N . caviar | 1 VP V NP . | |
| 0 NP . NP PP | 1 VP . V NP | 2 NP . NP PP | 3 N . spoon | 2 NP NP . PP | |
| 0 NP . Papa | 1 VP . VP PP | 2 NP . Papa | | 0 S NP VP . | |
| 0 Det . the | 1 PP . P NP | 2 Det . the | | 1 VP VP . PP | |
| 0 Det . a | 1 V . ate | 2 Det . a | | 4 PP . P NP | |
| | 1 P . with | | | 0 ROOT S . | |
| | | | | 4 P . with | |
| | | | | | |
| | | | | | |
| | | | | | |
| | | | | | |
| | | | | | |

| 0 Papa 1 ate 2 the 3 caviar 4 with 5 | | | | | |
|---|---|---|---|---|---|
| 0 ROOT . S | 0 NP Papa . | 1 V ate . | 2 Det the . | 3 N caviar . | 4 P with . |
| 0 S . NP VP | 0 S NP . VP | 1 VP V . NP | 2 NP Det . N | 2 NP Det N . | 4 PP P . NP |
| 0 NP . Det N | 0 NP NP . PP | 2 NP . Det N | 3 N . caviar | 1 VP V NP . | |
| 0 NP . NP PP | 1 VP . V NP | 2 NP . NP PP | 3 N . spoon | 2 NP NP . PP | |
| 0 NP . Papa | 1 VP . VP PP | 2 NP . Papa | | 0 S NP VP . | |
| 0 Det . the | 1 PP . P NP | 2 Det . the | | 1 VP VP . PP | |
| 0 Det . a | 1 V . ate | 2 Det . a | | 4 PP . P NP | |
| | 1 P . with | | | 0 ROOT S . | |
| | | | | 4 P . with | |
| | | | | | |
| | | | | | |
| | | | | | |
| | | | | | |
| | | | | | |

| 0 Papa 1 ate 2 the 3 caviar 4 with 5 | | | | | |
|---|---|---|---|---|---|
| 0 ROOT . S | 0 NP Papa . | 1 V ate . | 2 Det the . | 3 N caviar . | 4 P with . |
| 0 S . NP VP | 0 S NP . VP | 1 VP V . NP | 2 NP Det . N | 2 NP Det N . | 4 PP P . NP |
| 0 NP . Det N | 0 NP NP . PP | 2 NP . Det N | 3 N . caviar | 1 VP V NP . | 5 NP . Det N |
| 0 NP . NP PP | 1 VP . V NP | 2 NP . NP PP | 3 N . spoon | 2 NP NP . PP | 5 NP . NP PP |
| 0 NP . Papa | 1 VP . VP PP | 2 NP . Papa | | 0 S NP VP . | 5 NP . Papa |
| 0 Det . the | 1 PP . P NP | 2 Det . the | | 1 VP VP . PP | |
| 0 Det . a | 1 V . ate | 2 Det . a | | 4 PP . P NP | |
| | 1 P . with | | | 0 ROOT S . | |
| | | | | 4 P . with | |
| | | | | | |
| | | | | | |
| | | | | | |
| | | | | | |
| | | | | | |

| 0 Papa 1 ate 2 the 3 caviar 4 with 5 | | | | | |
|---|---|---|---|---|---|
| 0 ROOT . S | 0 NP Papa . | 1 V ate . | 2 Det the . | 3 N caviar . | 4 P with . |
| 0 S . NP VP | 0 S NP . VP | 1 VP V . NP | 2 NP Det . N | 2 NP Det N . | 4 PP P . NP |
| 0 NP . Det N | 0 NP NP . PP | 2 NP . Det N | 3 N . caviar | 1 VP V NP . | 5 NP . Det N |
| 0 NP . NP PP | 1 VP . V NP | 2 NP . NP PP | 3 N . spoon | 2 NP NP . PP | 5 NP . NP PP |
| 0 NP . Papa | 1 VP . VP PP | 2 NP . Papa | | 0 S NP VP . | 5 NP . Papa |
| 0 Det . the | 1 PP . P NP | 2 Det . the | | 1 VP VP . PP | 5 Det . the |
| 0 Det . a | 1 V . ate | 2 Det . a | | 4 PP . P NP | 5 Det . a |
| | 1 P . with | | | 0 ROOT S . | |
| | | | | 4 P . with | |
| | | | | | |
| | | | | | |
| | | | | | |
| | | | | | |
| | | | | | |

| 0 Papa 1 ate 2 the 3 caviar 4 with 5 | | | | | |
|---|---|---|---|---|---|
| 0 ROOT . S | 0 NP Papa . | 1 V ate . | 2 Det the . | 3 N caviar . | 4 P with . |
| 0 S . NP VP | 0 S NP . VP | 1 VP V . NP | 2 NP Det . N | 2 NP Det N . | 4 PP P . NP |
| 0 NP . Det N | 0 NP NP . PP | 2 NP . Det N | 3 N . caviar | 1 VP V NP . | 5 NP . Det N |
| 0 NP . NP PP | 1 VP . V NP | 2 NP . NP PP | 3 N . spoon | 2 NP NP . PP | 5 NP . NP PP |
| 0 NP . Papa | 1 VP . VP PP | 2 NP . Papa | | 0 S NP VP . | 5 NP . Papa |
| 0 Det . the | 1 PP . P NP | 2 Det . the | | 1 VP VP . PP | 5 Det . the |
| 0 Det . a | 1 V . ate | 2 Det . a | | 4 PP . P NP | 5 Det . a |
| | 1 P . with | | | 0 ROOT S . | |
| | | | | 4 P . with | |
| | | | | | |
| | | | | | |
| | | | | | |
| | | | | | |
| | | | | | |

| 0 Papa 1 ate 2 the 3 caviar 4 with 5 | | | | | |
|---|---|---|---|---|---|
| 0 ROOT . S | 0 NP Papa . | 1 V ate . | 2 Det the . | 3 N caviar . | 4 P with . |
| 0 S . NP VP | 0 S NP . VP | 1 VP V . NP | 2 NP Det . N | 2 NP Det N . | 4 PP P . NP |
| 0 NP . Det N | 0 NP NP . PP | 2 NP . Det N | 3 N . caviar | 1 VP V NP . | 5 NP . Det N |
| 0 NP . NP PP | 1 VP . V NP | 2 NP . NP PP | 3 N . spoon | 2 NP NP . PP | 5 NP . NP PP |
| 0 NP . Papa | 1 VP . VP PP | 2 NP . Papa | | 0 S NP VP . | 5 NP . Papa |
| 0 Det . the | 1 PP . P NP | 2 Det . the | | 1 VP VP . PP | 5 Det . the |
| 0 Det . a | 1 V . ate | 2 Det . a | | 4 PP . P NP | 5 Det . a |
| | 1 P . with | | | 0 ROOT S . | |
| | | | | 4 P . with | |
| | | | | | |
| | | | | | |
| | | | | | |
| | | | | | |
| | | | | | |

| 0 Papa 1 ate 2 the 3 caviar 4 with 5 | | | | | |
|---|---|---|---|---|---|
| 0 ROOT . S | 0 NP Papa . | 1 V ate . | 2 Det the . | 3 N caviar . | 4 P with . |
| 0 S . NP VP | 0 S NP . VP | 1 VP V . NP | 2 NP Det . N | 2 NP Det N . | 4 PP P . NP |
| 0 NP . Det N | 0 NP NP . PP | 2 NP . Det N | 3 N . caviar | 1 VP V NP . | 5 NP . Det N |
| 0 NP . NP PP | 1 VP . V NP | 2 NP . NP PP | 3 N . spoon | 2 NP NP . PP | 5 NP . NP PP |
| 0 NP . Papa | 1 VP . VP PP | 2 NP . Papa | | 0 S NP VP . | 5 NP . Papa |
| 0 Det . the | 1 PP . P NP | 2 Det . the | | 1 VP VP . PP | 5 Det . the |
| 0 Det . a | 1 V . ate | 2 Det . a | | 4 PP . P NP | 5 Det . a |
| | 1 P . with | | | 0 ROOT S . | |
| | | | | 4 P . with | |
| | | | | | |
| | | | | | |
| | | | | | |
| | | | | | |
| | | | | | |

| e | 2 the | 3 caviar | 4 with | 5 a | 6 |
|---|---|---|---|---|---|
| | 1 V ate . | 2 Det the . | 3 N caviar . | 4 P with . | 5 Det a . |
| | 1 VP V . NP | 2 NP Det . N | 2 NP Det N . | 4 PP P . NP | |
| P | 2 NP . Det N | 3 N . caviar | 1 VP V NP . | 5 NP . Det N | |
| | 2 NP . NP PP | 3 N . spoon | 2 NP NP . PP | 5 NP . NP PP | |
| P | 2 NP . Papa | | 0 S NP VP . | 5 NP . Papa | |
| | 2 Det . the | | 1 VP VP . PP | 5 Det . the | |
| | 2 Det . a | | 4 PP . P NP | 5 Det . a | |
| | | | 0 ROOT S . | | |
| | | | 4 P . with | | |
| | | | | | |
| | | | | | |
| | | | | | |
| | | | | | |
| | | | | | |

| e | 2 | the | 3 | caviar | 4 | with | 5 | a | 6 | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 1 V ate . | | 2 Det the . | | 3 N caviar . | | 4 P with . | | 5 Det a . | |
| | 1 VP V . NP | | 2 NP Det . N | | 2 NP Det N . | | 4 PP P . NP | | 5 NP Det . N | |
| P | 2 NP . Det N | | 3 N . caviar | | 1 VP V NP . | | 5 NP . Det N | | | |
| | 2 NP . NP PP | | 3 N . spoon | | 2 NP NP . PP | | 5 NP . NP PP | | | |
| P | 2 NP . Papa | | | | 0 S NP VP . | | 5 NP . Papa | | | |
| | 2 Det . the | | | | 1 VP VP . PP | | 5 Det . the | | | |
| | 2 Det . a | | | | 4 PP . P NP | | 5 Det . a | | | |
| | | | | | 0 ROOT S . | | | | | |
| | | | | | 4 P . with | | | | | |
| | | | | | | | | | | |
| | | | | | | | | | | |
| | | | | | | | | | | |
| | | | | | | | | | | |
| | | | | | | | | | | |

| e | 2 | the | 3 | caviar | 4 | with | 5 | a | 6 | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 1 V ate . | | 2 Det the . | | 3 N caviar . | | 4 P with . | | 5 Det a . | |
| | 1 VP V . NP | | 2 NP Det . N | | 2 NP Det N . | | 4 PP P . NP | | 5 NP Det . N | |
| P | 2 NP . Det N | | 3 N . caviar | | 1 VP V NP . | | 5 NP . Det N | | 6 N . caviar | |
| | 2 NP . NP PP | | 3 N . spoon | | 2 NP NP . PP | | 5 NP . NP PP | | 6 N . spoon | |
| P | 2 NP . Papa | | | | 0 S NP VP . | | 5 NP . Papa | | | |
| | 2 Det . the | | | | 1 VP VP . PP | | 5 Det . the | | | |
| | 2 Det . a | | | | 4 PP . P NP | | 5 Det . a | | | |
| | | | | | 0 ROOT S . | | | | | |
| | | | | | 4 P . with | | | | | |
| | | | | | | | | | | |
| | | | | | | | | | | |
| | | | | | | | | | | |
| | | | | | | | | | | |
| | | | | | | | | | | |

| e | 2 the | 3 caviar | 4 with | 5 a | 6 |
|---|---|---|---|---|---|
| | 1 V ate . | 2 Det the . | 3 N caviar . | 4 P with . | 5 Det a . |
| | 1 VP V . NP | 2 NP Det . N | 2 NP Det N . | 4 PP P . NP | 5 NP Det . N |
| P | 2 NP . Det N | 3 N . caviar | 1 VP V NP . | 5 NP . Det N | 6 N . caviar |
| | 2 NP . NP PP | 3 N . spoon | 2 NP NP . PP | 5 NP . NP PP | 6 N . spoon |
| P | 2 NP . Papa | | 0 S NP VP . | 5 NP . Papa | |
| | 2 Det . the | | 1 VP VP . PP | 5 Det . the | |
| | 2 Det . a | | 4 PP . P NP | 5 Det . a | |
| | | | 0 ROOT S . | | |
| | | | 4 P . with | | |
| | | | | | |
| | | | | | |
| | | | | | |
| | | | | | |
| | | | | | |

| e | 2 the | 3 caviar | 4 with | 5 a | 6 spoon | 7 |
|---|---|---|---|---|---|---|
| | 1 V ate . | 2 Det the . | 3 N caviar . | 4 P with . | 5 Det a . | 6 N spoon . |
| | 1 VP V . NP | 2 NP Det . N | 2 NP Det N . | 4 PP P . NP | 5 NP Det . N | |
| P | 2 NP . Det N | 3 N . caviar | 1 VP V NP . | 5 NP . Det N | 6 N . caviar | |
| | 2 NP . NP PP | 3 N . spoon | 2 NP NP . PP | 5 NP . NP PP | 6 N . spoon | |
| P | 2 NP . Papa | | 0 S NP VP . | 5 NP . Papa | | |
| | 2 Det . the | | 1 VP VP . PP | 5 Det . the | | |
| | 2 Det . a | | 4 PP . P NP | 5 Det . a | | |
| | | | 0 ROOT S . | | | |
| | | | 4 P . with | | | |
| | | | | | | |
| | | | | | | |
| | | | | | | |
| | | | | | | |
| | | | | | | |

| e | 2 the | 3 caviar | 4 with | 5 a | 6 spoon | 7 |
|---|---|---|---|---|---|---|
| | 1 V ate . | 2 Det the . | 3 N caviar . | 4 P with . | 5 Det a . | 6 N spoon . |
| | 1 VP V . NP | 2 NP Det . N | 2 NP Det N . | 4 PP P . NP | 5 NP Det . N | 5 NP Det N . |
| P | 2 NP . Det N | 3 N . caviar | 1 VP V NP . | 5 NP . Det N | 6 N . caviar | |
| | 2 NP . NP PP | 3 N . spoon | 2 NP NP . PP | 5 NP . NP PP | 6 N . spoon | |
| P | 2 NP . Papa | | 0 S NP VP . | 5 NP . Papa | | |
| | 2 Det . the | | 1 VP VP . PP | 5 Det . the | | |
| | 2 Det . a | | 4 PP . P NP | 5 Det . a | | |
| | | | 0 ROOT S . | | | |
| | | | 4 P . with | | | |
| | | | | | | |
| | | | | | | |
| | | | | | | |
| | | | | | | |
| | | | | | | |

| e | 2 | the | 3 | caviar | 4 | with | 5 | a | 6 | spoon | 7 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 V ate . | | 2 Det the . | | 3 N caviar . | | 4 P with . | | 5 Det a . | | 6 N spoon . | |
| | 1 VP V . NP | | 2 NP Det . N | | 2 NP Det N . | | 4 PP P . NP | | 5 NP Det . N | | 5 NP Det N . | |
| P | 2 NP . Det N | | 3 N . caviar | | 1 VP V NP . | | 5 NP . Det N | | 6 N . caviar | | 4 PP P NP . | |
| | 2 NP . NP PP | | 3 N . spoon | | 2 NP NP . PP | | 5 NP . NP PP | | 6 N . spoon | | 5 NP NP . PP | |
| P | 2 NP . Papa | | | | 0 S NP VP . | | 5 NP . Papa | | | | | |
| | 2 Det . the | | | | 1 VP VP . PP | | 5 Det . the | | | | | |
| | 2 Det . a | | | | 4 PP . P NP | | 5 Det . a | | | | | |
| | | | | | 0 ROOT S . | | | | | | | |
| | | | | | 4 P . with | | | | | | | |
| | | | | | | | | | | | | |
| | | | | | | | | | | | | |
| | | | | | | | | | | | | |
| | | | | | | | | | | | | |
| | | | | | | | | | | | | |

| 0 Papa 1 ate 2 the 3 caviar 4 with a spoon 7 | | | | | | |
|---|---|---|---|---|---|---|
| 0 ROOT . S | 0 NP Papa . | 1 V ate . | 2 Det the . | 3 N caviar . | ... | 6 N spoon . |
| 0 S . NP VP | 0 S NP . VP | 1 VP V . NP | 2 NP Det . N | 2 NP Det N . | | 5 NP Det N . |
| 0 NP . Det N | 0 NP NP . PP | 2 NP . Det N | 3 N . caviar | 1 VP V NP . | | 4 PP P NP . |
| 0 NP . NP PP | 1 VP . V NP | 2 NP . NP PP | 3 N . spoon | 2 NP NP . PP | | 5 NP NP . PP |
| 0 NP . Papa | 1 VP . VP PP | 2 NP . Papa | | 0 S NP VP . | | 2 NP NP PP . |
| 0 Det . the | 1 PP . P NP | 2 Det . the | | 1 VP VP . PP | | 1 VP VP PP . |
| 0 Det . a | 1 V . ate | 2 Det . a | | 4 PP . P NP | | |
| | 1 P . with | | | 0 ROOT S . | | |
| | | | | 4 P . with | | |
| | | | | | | |
| | | | | | | |
| | | | | | | |
| | | | | | | |
| | | | | | | |

| 0 Papa 1 ate 2 the 3 caviar 4 with a spoon 7 | | | | | | |
|---|---|---|---|---|---|---|
| 0 ROOT . S | 0 NP Papa . | 1 V ate . | 2 Det the . | 3 N caviar . | ... | 6 N spoon . |
| 0 S . NP VP | 0 S NP . VP | 1 VP V . NP | 2 NP Det . N | 2 NP Det N . | | 5 NP Det N . |
| 0 NP . Det N | 0 NP NP . PP | 2 NP . Det N | 3 N . caviar | 1 VP V NP . | | 4 PP P NP . |
| 0 NP . NP PP | 1 VP . V NP | 2 NP . NP PP | 3 N . spoon | 2 NP NP . PP | | 5 NP NP . PP |
| 0 NP . Papa | 1 VP . VP PP | 2 NP . Papa | | 0 S NP VP . | | 2 NP NP PP . |
| 0 Det . the | 1 PP . P NP | 2 Det . the | | 1 VP VP . PP | | 1 VP VP PP . |
| 0 Det . a | 1 V . ate | 2 Det . a | | 4 PP . P NP | | 7 PP . P NP |
| | 1 P . with | | | 0 ROOT S . | | |
| | | | | 4 P . with | | |
| | | | | | | |
| | | | | | | |
| | | | | | | |
| | | | | | | |
| | | | | | | |

| 0 Papa 1 ate | | 2 the | 3 caviar | 4 with a spoon 7 | | |
|---|---|---|---|---|---|---|
| 0 ROOT . S | 0 NP Papa . | 1 V ate . | 2 Det the . | 3 N caviar . | ... | 6 N spoon . |
| 0 S . NP VP | 0 S NP . VP | 1 VP V . NP | 2 NP Det . N | 2 NP Det N . | | 5 NP Det N . |
| 0 NP . Det N | 0 NP NP . PP | 2 NP . Det N | 3 N . caviar | 1 VP V NP . | | 4 PP P NP . |
| 0 NP . NP PP | 1 VP . V NP | 2 NP . NP PP | 3 N . spoon | 2 NP NP . PP | | 5 NP NP . PP |
| 0 NP . Papa | 1 VP . VP PP | 2 NP . Papa | | 0 S NP VP . | | 2 NP NP PP . |
| 0 Det . the | 1 PP . P NP | 2 Det . the | | 1 VP VP . PP | | 1 VP VP PP . |
| 0 Det . a | 1 V . ate | 2 Det . a | | 4 PP . P NP | | 7 PP . P NP |
| | 1 P . with | | | 0 ROOT S . | | 1 VP V NP . |
| | | | | 4 P . with | | 2 NP NP . PP |
| | | | | | | |
| | | | | | | |
| | | | | | | |
| | | | | | | |
| | | | | | | |

| 0 Papa 1 ate 2 the 3 caviar 4 with a spoon 7 | | | | | | |
|---|---|---|---|---|---|---|
| 0 ROOT . S | 0 NP Papa . | 1 V ate . | 2 Det the . | 3 N caviar . | ... | 6 N spoon . |
| 0 S . NP VP | 0 S NP . VP | 1 VP V . NP | 2 NP Det . N | 2 NP Det N . | | 5 NP Det N . |
| 0 NP . Det N | 0 NP NP . PP | 2 NP . Det N | 3 N . caviar | 1 VP V NP . | | 4 PP P NP . |
| 0 NP . NP PP | 1 VP . V NP | 2 NP . NP PP | 3 N . spoon | 2 NP NP . PP | | 5 NP NP . PP |
| 0 NP . Papa | 1 VP . VP PP | 2 NP . Papa | | 0 S NP VP . | | 2 NP NP PP . |
| 0 Det . the | 1 PP . P NP | 2 Det . the | | 1 VP VP . PP | | 1 VP VP PP . |
| 0 Det . a | 1 V . ate | 2 Det . a | | 4 PP . P NP | | 7 PP . P NP |
| | 1 P . with | | | 0 ROOT S . | | 1 VP V NP . |
| | | | | 4 P . with | | 2 NP NP . PP |
| | | | | | | 0 S NP VP . |
| | | | | | | 1 VP VP . PP |
| | | | | | | |
| | | | | | | |
| | | | | | | |

| 0 Papa 1 ate 2 the 3 caviar 4 with a spoon 7 | | | | | | |
|---|---|---|---|---|---|---|
| 0 ROOT . S | 0 NP Papa . | 1 V ate . | 2 Det the . | 3 N caviar . | ... | 6 N spoon . |
| 0 S . NP VP | 0 S NP . VP | 1 VP V . NP | 2 NP Det . N | 2 NP Det N . | | 5 NP Det N . |
| 0 NP . Det N | 0 NP NP . PP | 2 NP . Det N | 3 N . caviar | 1 VP V NP . | | 4 PP P NP . |
| 0 NP . NP PP | 1 VP . V NP | 2 NP . NP PP | 3 N . spoon | 2 NP NP . PP | | 5 NP NP . PP |
| 0 NP . Papa | 1 VP . VP PP | 2 NP . Papa | | 0 S NP VP . | | 2 NP NP PP . |
| 0 Det . the | 1 PP . P NP | 2 Det . the | | 1 VP VP . PP | | 1 VP VP PP . |
| 0 Det . a | 1 V . ate | 2 Det . a | | 4 PP . P NP | | 7 PP . P NP |
| | 1 P . with | | | 0 ROOT S . | | 1 VP V NP . |
| | | | | 4 P . with | | 2 NP NP . PP |
| | | | | | | 0 S NP VP . |
| | | | | | | 1 VP VP . PP |
| | | | | | | 7 P . with |
| | | | | | | |
| | | | | | | |

| 0 Papa | 1 ate | 2 the | 3 caviar | 4 with a spoon 7 | | |
|---|---|---|---|---|---|---|
| 0 ROOT . S | 0 NP Papa . | 1 V ate . | 2 Det the . | 3 N caviar . | ... | 6 N spoon . |
| 0 S . NP VP | 0 S NP . VP | 1 VP V . NP | 2 NP Det . N | 2 NP Det N . | | 5 NP Det N . |
| 0 NP . Det N | 0 NP NP . PP | 2 NP . Det N | 3 N . caviar | 1 VP V NP . | | 4 PP P NP . |
| 0 NP . NP PP | 1 VP . V NP | 2 NP . NP PP | 3 N . spoon | 2 NP NP . PP | | 5 NP NP . PP |
| 0 NP . Papa | 1 VP . VP PP | 2 NP . Papa | | 0 S NP VP . | | 2 NP NP PP . |
| 0 Det . the | 1 PP . P NP | 2 Det . the | | 1 VP VP . PP | | 1 VP VP PP . |
| 0 Det . a | 1 V . ate | 2 Det . a | | 4 PP . P NP | | 7 PP . P NP |
| | 1 P . with | | | 0 ROOT S . | | 1 VP V NP . |
| | | | | 4 P . with | | 2 NP NP . PP |
| | | | | | | 0 S NP VP . |
| | | | | | | 1 VP VP . PP |
| | | | | | | 7 P . with |
| | | | | | | |
| | | | | | | |

| 0 Papa 1 ate | 2 the | 3 caviar | 4 with a spoon 7 | | | |
|---|---|---|---|---|---|---|
| 0 ROOT . S | 0 NP Papa . | 1 V ate . | 2 Det the . | 3 N caviar . | ... | 6 N spoon . |
| 0 S . NP VP | 0 S NP . VP | 1 VP V . NP | 2 NP Det . N | 2 NP Det N . | | 5 NP Det N . |
| 0 NP . Det N | 0 NP NP . PP | 2 NP . Det N | 3 N . caviar | 1 VP V NP . | | 4 PP P NP . |
| 0 NP . NP PP | 1 VP . V NP | 2 NP . NP PP | 3 N . spoon | 2 NP NP . PP | | 5 NP NP . PP |
| 0 NP . Papa | 1 VP . VP PP | 2 NP . Papa | | 0 S NP VP . | | 2 NP NP PP . |
| 0 Det . the | 1 PP . P NP | 2 Det . the | | 1 VP VP . PP | | 1 VP VP PP . |
| 0 Det . a | 1 V . ate | 2 Det . a | | 4 PP . P NP | | 7 PP . P NP |
| | 1 P . with | | | 0 ROOT S . | | 1 VP V NP . |
| | | | | 4 P . with | | 2 NP NP . PP |
| | | | | | | 0 S NP VP . |
| | | | | | | 1 VP VP . PP |
| | | | | | | 7 P . with |
| | | | | | | |
| | | | | | | |

| 0 Papa 1 | ate 2 | the 3 | caviar 4 | with a spoon 7 | | |
|---|---|---|---|---|---|---|
| 0 ROOT . S | 0 NP Papa . | 1 V ate . | 2 Det the . | 3 N caviar . | ... | 6 N spoon . |
| 0 S . NP VP | 0 S NP . VP | 1 VP V . NP | 2 NP Det . N | 2 NP Det N . | | 5 NP Det N . |
| 0 NP . Det N | 0 NP NP . PP | 2 NP . Det N | 3 N . caviar | 1 VP V NP . | | 4 PP P NP . |
| 0 NP . NP PP | 1 VP . V NP | 2 NP . NP PP | 3 N . spoon | 2 NP NP . PP | | 5 NP NP . PP |
| 0 NP . Papa | 1 VP . VP PP | 2 NP . Papa | | 0 S NP VP . | | 2 NP NP PP . |
| 0 Det . the | 1 PP . P NP | 2 Det . the | | 1 VP VP . PP | | 1 VP VP PP . |
| 0 Det . a | 1 V . ate | 2 Det . a | | 4 PP . P NP | | 7 PP . P NP |
| | 1 P . with | | | 0 ROOT S . | | 1 VP V NP . |
| | | | | 4 P . with | | 2 NP NP . PP |
| | | | | | | 0 S NP VP . |
| | | | | | | 1 VP VP . PP |
| | | | | | | 7 P . with |
| | | | | | | 0 ROOT S . |
| | | | | | | |

| 0 Papa | 1 ate | 2 the | 3 caviar | 4 with a spoon 7 | | |
|---|---|---|---|---|---|---|
| 0 ROOT . S | 0 NP Papa . | 1 V ate . | 2 Det the . | 3 N caviar . | ... | 6 N spoon . |
| 0 S . NP VP | 0 S NP . VP | 1 VP V . NP | 2 NP Det . N | 2 NP Det N . | | 5 NP Det N . |
| 0 NP . Det N | 0 NP NP . PP | 2 NP . Det N | 3 N . caviar | 1 VP V NP . | | 4 PP P NP . |
| 0 NP . NP PP | 1 VP . V NP | 2 NP . NP PP | 3 N . spoon | 2 NP NP . PP | | 5 NP NP . PP |
| 0 NP . Papa | 1 VP . VP PP | 2 NP . Papa | | 0 S NP VP . | | 2 NP NP PP . |
| 0 Det . the | 1 PP . P NP | 2 Det . the | | 1 VP VP . PP | | 1 VP VP PP . |
| 0 Det . a | 1 V . ate | 2 Det . a | | 4 PP . P NP | | 7 PP . P NP |
| | 1 P . with | | | 0 ROOT S . | | 1 VP V NP . |
| | | | | 4 P . with | | 2 NP NP . PP |
| | | | | | | 0 S NP VP . |
| | | | | | | 1 VP VP . PP |
| | | | | | | 7 P . with |
| | | | | | | 0 ROOT S . |
| | | | | | | |

| 0 Papa 1 ate 2 the 3 caviar 4 with a spoon 7 | | | | | | |
|---|---|---|---|---|---|---|
| 0 ROOT . S | 0 NP Papa . | 1 V ate . | 2 Det the . | 3 N caviar . | ... | 6 N spoon . |
| 0 S . NP VP | 0 S NP . VP | 1 VP V . NP | 2 NP Det . N | 2 NP Det N . | | 5 NP Det N . |
| 0 NP . Det N | 0 NP NP . PP | 2 NP . Det N | 3 N . caviar | 1 VP V NP . | | 4 PP P NP . |
| 0 NP . NP PP | 1 VP . V NP | 2 NP . NP PP | 3 N . spoon | 2 NP NP . PP | | 5 NP NP . PP |
| 0 NP . Papa | 1 VP . VP PP | 2 NP . Papa | | 0 S NP VP . | | 2 NP NP PP . |
| 0 Det . the | 1 PP . P NP | 2 Det . the | | 1 VP VP . PP | | 1 VP VP PP . |
| 0 Det . a | 1 V . ate | 2 Det . a | | 4 PP . P NP | | 7 PP . P NP |
| | 1 P . with | | | 0 ROOT S . | | 1 VP V NP . |
| | | | | 4 P . with | | 2 NP NP . PP |
| | | | | | | 0 S NP VP . |
| | | | | | | 1 VP VP . PP |
| | | | | | | 7 P . with |
| | | | | | | 0 ROOT S . |
| | | | | | | |

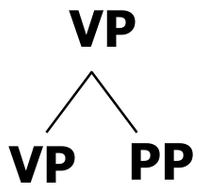
| 0 Papa 1 | ate 2 | the 3 | caviar 4 | with a spoon 7 | | |
|---|---|---|---|---|---|---|
| 0 ROOT . S | 0 NP Papa . | 1 V ate . | 2 Det the . | 3 N caviar . | ... | 6 N spoon . |
| 0 S . NP VP | 0 S NP . VP | 1 VP V . NP | 2 NP Det . N | 2 NP Det N . | | 5 NP Det N . |
| 0 NP . Det N | 0 NP NP . PP | 2 NP . Det N | 3 N . caviar | 1 VP V NP . | | 4 PP P NP . |
| 0 NP . NP PP | 1 VP . V NP | 2 NP . NP PP | 3 N . spoon | 2 NP NP . PP | | 5 NP NP . PP |
| 0 NP . Papa | 1 VP . VP PP | 2 NP . Papa | | 0 S NP VP . | | 2 NP NP PP . |
| 0 Det . the | 1 PP . P NP | 2 Det . the | | 1 VP VP . PP | | 1 VP VP PP . |
| 0 Det . a | 1 V . ate | 2 Det . a | | 4 PP . P NP | | 7 PP . P NP |
| | 1 P . with | | | 0 ROOT S . | | 1 VP V NP . |
| | | | | 4 P . with | | 2 NP NP . PP |
| | | | | | | 0 S NP VP . |
| | | | | | | 1 VP VP . PP |
| | | | | | | 7 P . with |
| | | | | | | 0 ROOT S . |
| | | | | | | |

| 0 Papa 1 | ate 2 | the 3 | caviar 4 | with a spoon 7 | | |
|---|---|---|---|---|---|---|
| 0 ROOT . S | 0 NP Papa . | 1 V ate . | 2 Det the . | 3 N caviar . | ... | 6 N spoon . |
| 0 S . NP VP | 0 S NP . VP | 1 VP V . NP | 2 NP Det . N | 2 NP Det N . | | 5 NP Det N . |
| 0 NP . Det N | 0 NP NP . PP | 2 NP . Det N | 3 N . caviar | 1 VP V NP . | | 4 PP P NP . |
| 0 NP . NP PP | 1 VP . V NP | 2 NP . NP PP | 3 N . spoon | 2 NP NP . PP | | 5 NP NP . PP |
| 0 NP . Papa | 1 VP . VP PP | 2 NP . Papa | | 0 S NP VP . | | 2 NP NP PP . |
| 0 Det . the | 1 PP . P NP | 2 Det . the | | 1 VP VP . PP | | 1 VP VP PP . |
| 0 Det . a | 1 V . ate | 2 Det . a | | 4 PP . P NP | | 7 PP . P NP |
| | 1 P . with | | | 0 ROOT S . | | 1 VP V NP . |
| | | | | 4 P . with | | 2 NP NP . PP |
| | | | | | | 0 S NP VP . |
| | | | | | | 1 VP VP . PP |
| | | | | | | 7 P . with |
| | | | | | | 0 ROOT S . |
| | | | | | | |

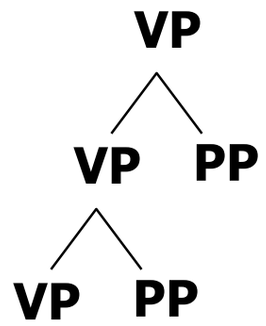
# Left Recursion Kills Pure Top-Down Parsing …

**VP**

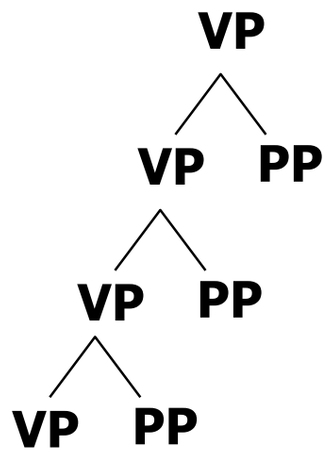
# Left Recursion Kills Pure Top-Down Parsing …



# Left Recursion Kills Pure Top-Down Parsing …



# Left Recursion Kills Pure Top-Down Parsing …




makes new hypotheses ad infinitum before we've seen the PPs at all

hypotheses try to predict in advance how many PP's will arrive in input

# … but Earley's Alg is Okay!

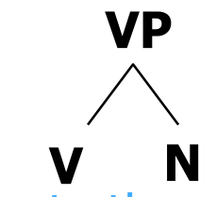

1 VP → . VP PP

*(in column 1)*

# … but Earley's Alg is Okay!


1 VP → . VP PP

*(in column 1)*

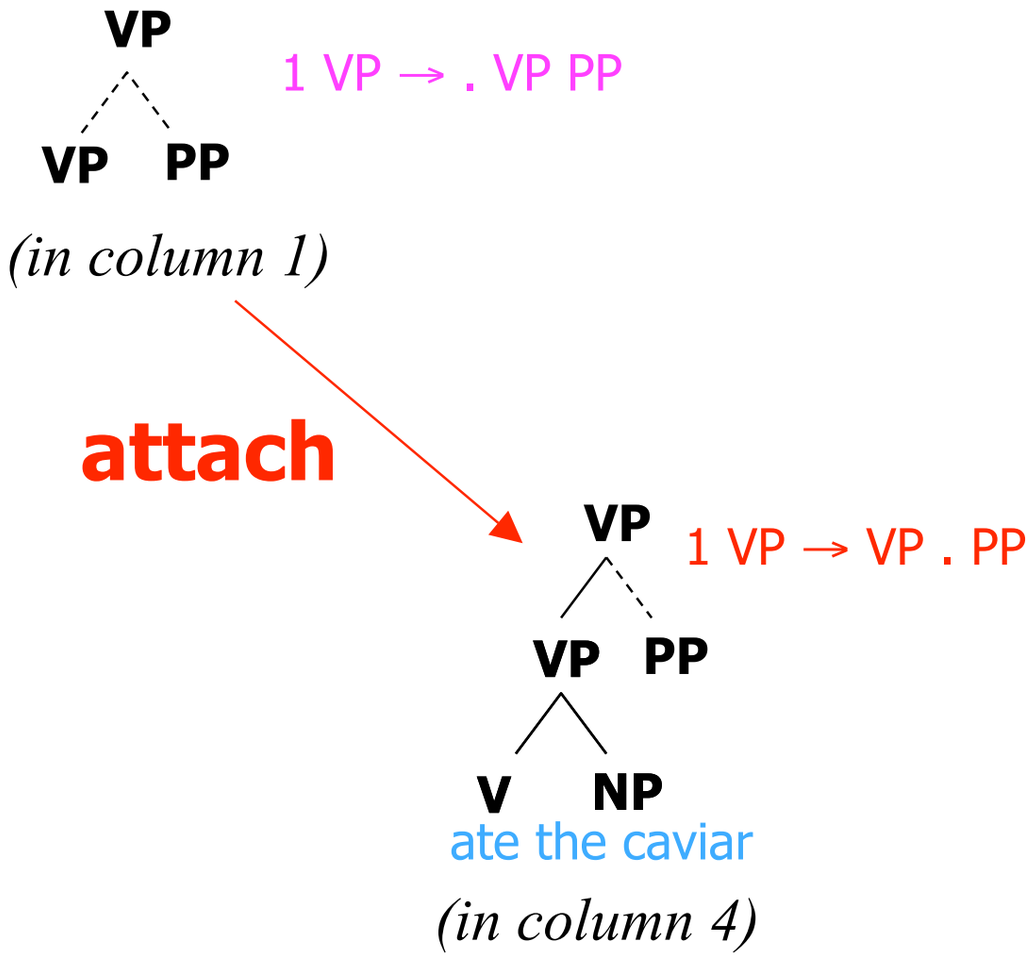



1 VP → V NP .

ate the caviar

*(in column 4)*

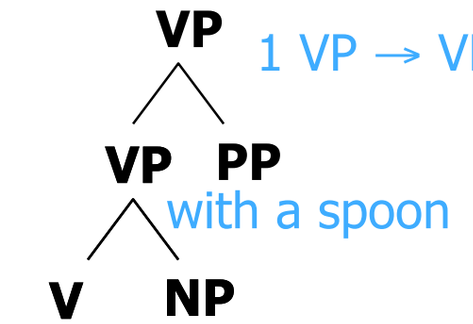
# … but Earley's Alg is Okay!



# … but Earley's Alg is Okay!


1 VP → . VP PP

*(in column 1)*



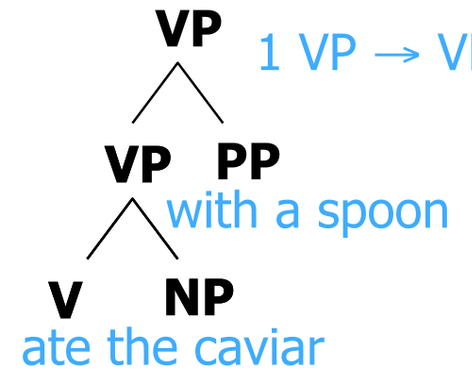

*(in column 7)*

# … but Earley's Alg is Okay!


1 VP → . VP PP

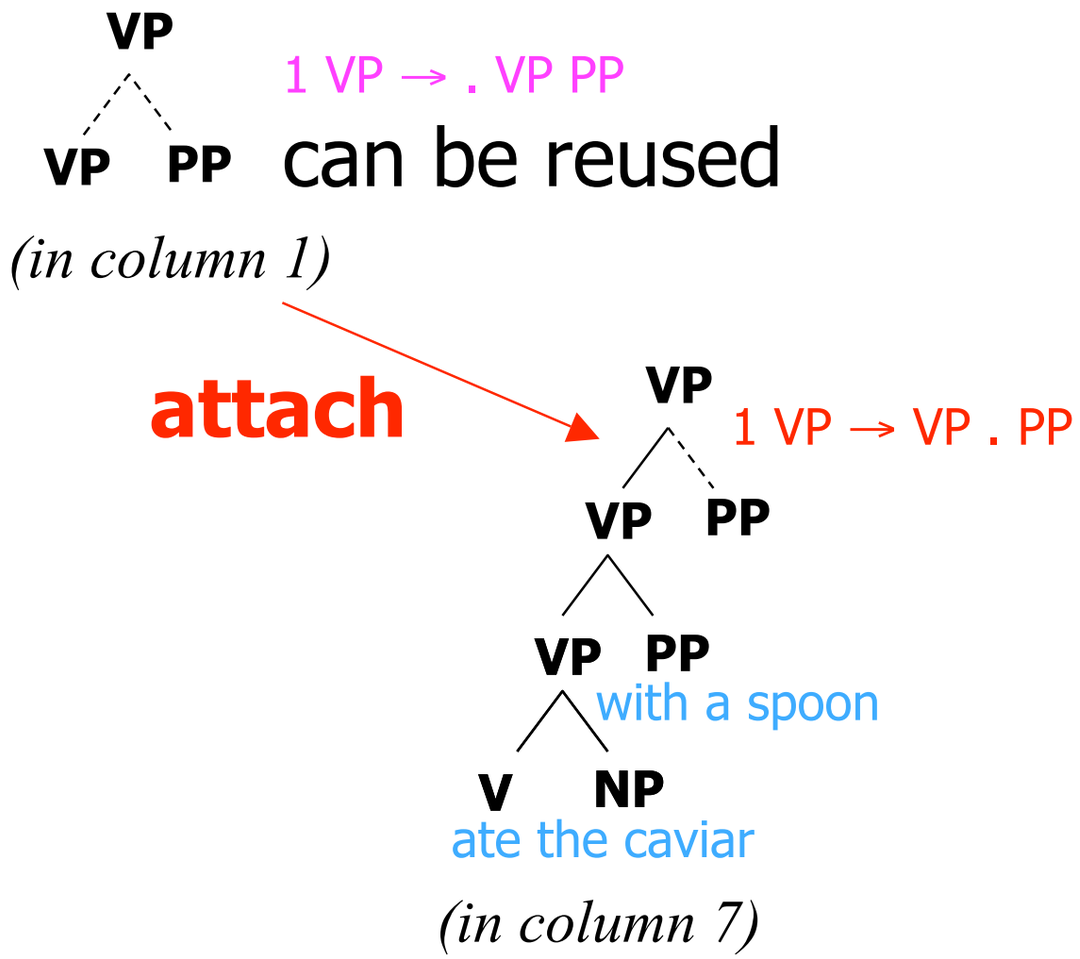
can be reused

*(in column 1)*




*(in column 7)*

# … but Earley's Alg is Okay!

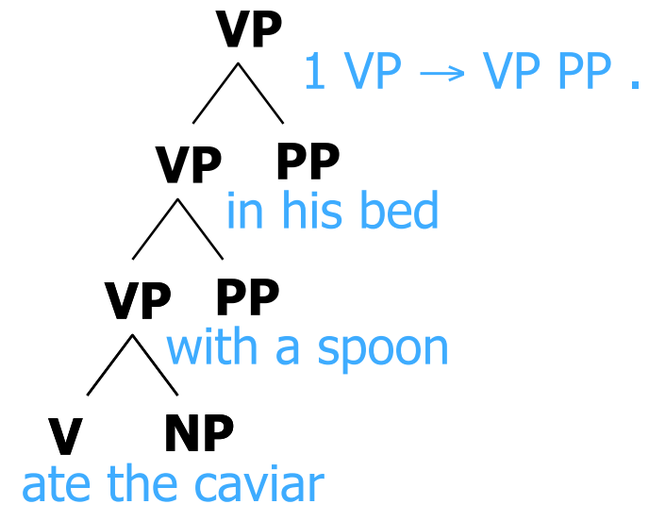


# … but Earley's Alg is Okay!


1 VP → . VP PP

can be reused

*(in column 1)*



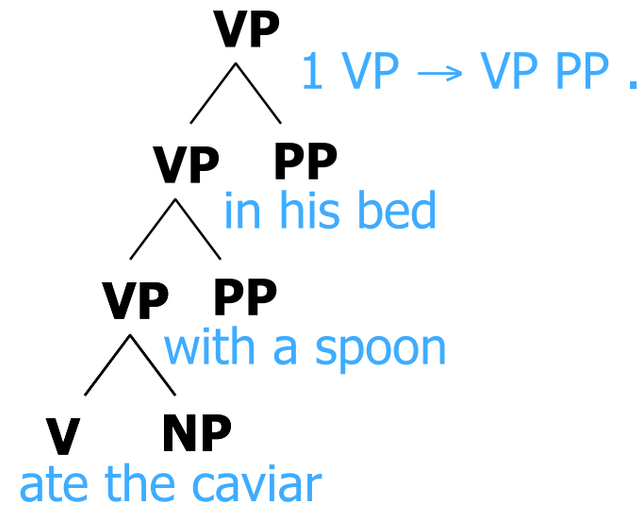

*(in column 10)*

# … but Earley's Alg is Okay!


1 VP → . VP PP

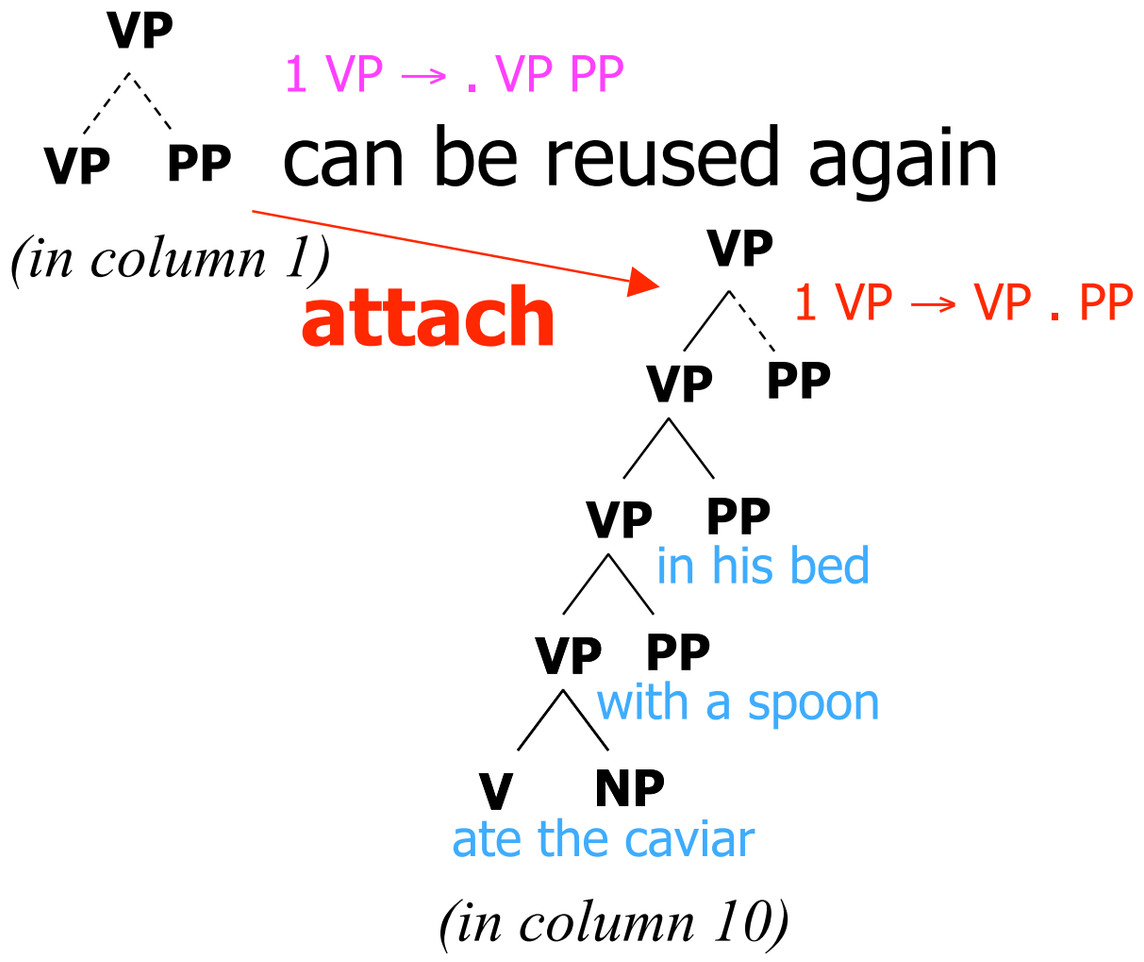
can be reused again

*(in column 1)*




*(in column 10)*

# … but Earley's Alg is Okay!



| 0 Papa | 1 ate | 2 the | 3 caviar | 4 with a spoon | 7 |
|---|---|---|---|---|---|
| 0 ROOT . S | 0 NP Papa . | 1 V ate . | 2 Det the . | 3 N caviar . | ... 6 N spoon . |
| 0 S . NP VP | 0 S NP . VP | 1 VP V . NP | 2 NP Det . N | 2 NP Det N . | 5 NP Det N . |
| 0 NP . Det N | 0 NP NP . PP | 2 NP . Det N | 3 N . caviar | 1 VP V NP . | 4 PP P NP . |
| 0 NP . NP PP | 1 VP . V NP | 2 NP . NP PP | 3 N . spoon | 2 NP NP . PP | 5 NP NP . PP |
| 0 NP . Papa | **1 VP . VP PP** | 2 NP . Papa | | 0 S NP VP . | 2 NP NP PP . |
| 0 Det . the | 1 PP . P NP | 2 Det . the | | **1 VP VP . PP** | 1 VP VP PP . |
| 0 Det . a | 1 V . ate | 2 Det . a | | 4 PP . P NP | 7 PP . P NP |
| | 1 P . with | | | 0 ROOT S . | 1 VP V NP . |
| | | | | 4 P . with | 2 NP NP . PP |
| | | | | | 0 S NP VP . |
| | | | | | 1 VP VP . PP |
| | | | | | 7 P . with |
| | | | | | 0 ROOT S . |
| | | | | | |

completed a VP in col 4
col 1 lets us use it in a VP PP structure

| 0 Papa 1 | ate 2 | the 3 | caviar 4 | with a spoon 7 | | |
|---|---|---|---|---|---|---|
| 0 ROOT . S | 0 NP Papa . | 1 V ate . | 2 Det the . | 3 N caviar . | ... | 6 N spoon . |
| 0 S . NP VP | 0 S NP . VP | 1 VP V . NP | 2 NP Det . N | 2 NP Det N . | | 5 NP Det N . |
| 0 NP . Det N | 0 NP NP . PP | 2 NP . Det N | 3 N . caviar | 1 VP V NP . | | 4 PP P NP . |
| 0 NP . NP PP | 1 VP . V NP | 2 NP . NP PP | 3 N . spoon | 2 NP NP . PP | | 5 NP NP . PP |
| 0 NP . Papa | **1 VP . VP PP** | 2 NP . Papa | | 0 S NP VP . | | 2 NP NP PP . |
| 0 Det . the | 1 PP . P NP | 2 Det . the | | 1 VP VP . PP | | 1 VP VP PP . |
| 0 Det . a | 1 V . ate | 2 Det . a | | 4 PP . P NP | | 7 PP . P NP |
| | 1 P . with | | | 0 ROOT S . | | 1 VP V NP . |
| | | | | 4 P . with | | 2 NP NP . PP |
| | | | | | | 0 S NP VP . |
| | | | | | | **1 VP VP . PP** |
| | | | | | | 7 P . with |
| | | | | | | 0 ROOT S . |
| | | | | | | |

completed that VP = VP PP in col 7
col 1 would let us use *it* in a VP PP structure
can reuse col 1 as often as we need

# Beyond Recognition

- So far, we've described an Earley *recognizer*
- Note what we did when we tried to create entries that already existed
- What should we do when combining items?
- How to derive outside algorithm?

# Better Treebank Grammars

- Last time: CNF conversion, Markovization
- Clustering and splitting nonterminals
- Grandparent annotation
- Lexicalization