# Earley algorithm

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# Today's lecture





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# Top-down parsing

In naive search, top-down parsing is inefficient because structures are created over and over again.

- Need a way to record that a particular structure has been predicted
- Need a way to record *where* the structure was predicted wrt the input



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# Pros/cons of top-down strategy

- √ Never explores trees that aren't potential solutions, ones with the wrong kind of root node.



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- X But explores trees that do not match the input sentence (predicts input before inspecting input).



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# Pros/cons of top-down strategy

- √ Never explores trees that aren't potential solutions, ones with the wrong kind of root node.
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- X Naive top-down parsers never terminate if $G$ contains recursive rules like $X \rightarrow X\ Y$ (left recursive rules).



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- X Backtracking may discard valid constituents that have to be re-discovered later (duplication of effort).



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- X But explores trees that do not match the input sentence (predicts input before inspecting input).
- X Naive top-down parsers never terminate if $G$ contains recursive rules like $X \rightarrow X\ Y$ (left recursive rules).
- X Backtracking may discard valid constituents that have to be re-discovered later (duplication of effort).

Use a top-down strategy when you know what kind of constituent you want to end up with (e.g. NP extraction, named entity extraction). Avoid this strategy if you're stuck with a highly recursive grammar.



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# Earley algorithm

The Earley Parsing Algorithm: an efficient top-down parsing algorithm that avoids some of the inefficiency associated with purely naive search with the same top-down strategy (cf. recursive descent parser).

- Intermediate solutions are created only once and stored in a chart (dynamic programming).
- Left-recursion problem is solved by examining the input.
- Earley is not picky about what type of grammar it accepts, i.e., it accepts arbitrary CFGs (cf. CKY).



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# Earley Parsing Algorithm (J&M, p. 444)

**function** EARLEY-PARSE(*words*,*grammar*) **returns** *chart*

ENQUEUE(($\gamma \rightarrow \bullet S$, [0,0]),*chart[0]*)
**for** i $\leftarrow$ **from** 0 **to** LENGTH(*words*) **do**
  **for each** *state* **in** *chart[i]* **do**
    **if** INCOMPLETE?(*state*) **and** NEXT-CAT(state) is not POS **then**
      PREDICTOR(*state*)
    **elseif** INCOMPLETE?(*state*) **and** NEXT-CAT(*state*) is POS **then**
      SCANNER(*state*)
    **else**
      COMPLETER(*state*)
  **end**
**end**
**return**(*chart*)

# Setting up the Earley algorithm: the chart

The rationale is to fill in a chart with the solutions to the subproblems encountered in the top-down parsing process.

- Based on an input string of length $n$, build a 1D array (called a **chart**) of length $n + 1$ to record the solutions to subproblems
- Chart entries are lists of **states**, or info about partial solutions.
- States represent attempts to discover constituents.



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# Empty Earley chart

| | |
|---|---|
| Chart[0]: | • astronomers saw stars with ears<br>partial solutions ... |
| Chart[1]: | astronomers • saw stars with ears<br>partial solutions ... |
| Chart[2]: | astronomers saw • stars with ears<br>partial solutions ... |
| Chart[3]: | astronomers saw stars • with ears<br>partial solutions ... |
| Chart[4]: | astronomers saw stars with • ears<br>partial solutions ... |
| Chart[5]: | astronomers saw stars with ears • |

Assumed indexing scheme:

$\bullet_0$ *astronomers* $\bullet_1$ *saw* $\bullet_2$ *stars* $\bullet_3$ *with* $\bullet_4$ *ears* $\bullet_5$



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# Setting up the Earley algorithm: the states

A *state* consists of:



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# Setting up the Earley algorithm: the states

A *state* consists of:

1. a subtree corresponding to a grammar rule $S \rightarrow NP\ VP$



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# Setting up the Earley algorithm: the states

A *state* consists of:

1. a subtree corresponding to a grammar rule
   $S \rightarrow NP\ VP$
2. info about progress made towards completing this subtree
   $S \rightarrow NP \bullet VP$



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# Setting up the Earley algorithm: the states

A *state* consists of:

1. a subtree corresponding to a grammar rule
   $S \rightarrow NP\ VP$
2. info about progress made towards completing this subtree
   $S \rightarrow NP \bullet VP$
3. the position of the subtree wrt input
   $S \rightarrow NP \bullet VP, [0, 3]$



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# Setting up the Earley algorithm: the states

A *state* consists of:

1. a subtree corresponding to a grammar rule
   $S \rightarrow NP\ VP$
2. info about progress made towards completing this subtree
   $S \rightarrow NP \bullet VP$
3. the position of the subtree wrt input
   $S \rightarrow NP \bullet VP, [0, 3]$
4. pointers to all contributing states in the case of a parser (cf. recognizer)



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# Setting up the Earley algorithm: dotted rules

**Definition**

A dotted rule is a data structure used in top-down parsing to record parital solutions towards discovering a constituent.

- $S \rightarrow \bullet VP, [0, 0]$
  Predict an $S$ will be found which consists of a $VP$; the $S$ will begin at 0.
- $NP \rightarrow Det \bullet Nominal, [1, 2]$
  Predict an $NP$ starting at 1; an $Det$ has been found; $Nominal$ is expected next.
- $VP \rightarrow V\ NP \bullet, [0, 3]$
  A $VP$ has been found starting at 0 and spanning to 3; the constituents of $VP$ are $V$ and $NP$.



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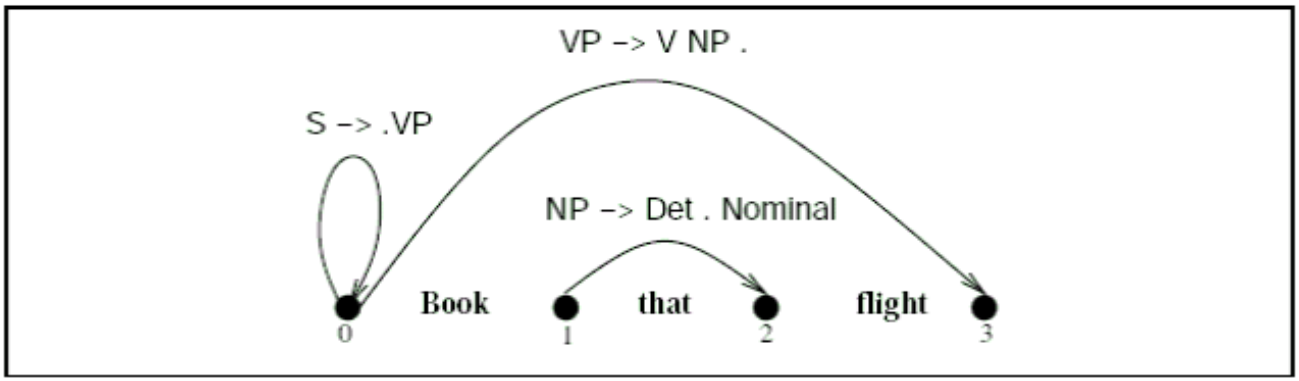
# Dotted rules and corresponding graph



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# Earley: fundamental operations

- **Predict** sub-structure (based on grammar)
- **Scan** partial solutions for a match
- **Complete** a sub-structure (i.e., build constituents)



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# Sample grammar from J&M

| | |
|---|---|
| $S \rightarrow NP\ VP$ | $NP \rightarrow NP\ PP$ |
| $PP \rightarrow P\ NP$ | $NP \rightarrow N$ |
| $VP \rightarrow V\ NP$ | $N \rightarrow$ *astronomers* |
| $VP \rightarrow VP\ PP$ | $N \rightarrow$ *ears* |
| $P \rightarrow$ *with* | $N \rightarrow$ *stars* |
| $V \rightarrow$ *saw* | $N \rightarrow$ *telescopes* |

**ambiguous, PP attachment**

*astronomers saw stars with ears*



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# An extra rule

How to represent progress towards finding an $S$ node?

Add a dummy rule to grammar:

$\gamma \rightarrow \quad S$

This seeds the chart as the base case for recursion.



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# An extra rule

**How to represent progress towards finding an $S$ node?**

Add a dummy rule to grammar:

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This seeds the chart as the base case for recursion.



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# Chart[0]: "• astronomers saw stars with ears"

| state ID | dotted rule | position | back pointer | operation |
|---|---|---|---|---|



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Enqueue dummy start state



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# Chart[0]: "• astronomers saw stars with ears"

| state ID | dotted rule | position | back pointer | operation |
|---|---|---|---|---|
| S0 | $TOP \rightarrow \bullet S$ | [0,0] | [] | Seed |



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For each state in chart[i]... processing S0



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if state incomplete and NEXTCAT is not POS, then PREDICTOR

**procedure** PREDICTOR($(A \rightarrow \alpha \bullet B\ \beta$, *[i,j]*))
  **for each** $(B \rightarrow \gamma)$ **in** GRAMMAR-RULES-FOR(*B*,*grammar*) **do**
    ENQUEUE($(B \rightarrow \bullet\gamma$, *[j,j]*),*chart[j]*)
  **end**



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  **end**

| | |
|---|---|
| $S \rightarrow NP\ VP$ | $NP \rightarrow NP\ PP$ |
| $PP \rightarrow P\ NP$ | $NP \rightarrow N$ |
| $VP \rightarrow V\ NP$ | $N \rightarrow astronomers$ |
| $VP \rightarrow VP\ PP$ | $N \rightarrow ears$ |
| $P \rightarrow with$ | $N \rightarrow stars$ |
| $V \rightarrow saw$ | $N \rightarrow telescopes$ |



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| state ID | dotted rule | position | back pointer | operation |
|---|---|---|---|---|
| S0 | $TOP \rightarrow \bullet S$ | [0,0] | [] | Seed |
| S1 | $S \rightarrow \bullet NP\ VP$ | [0,0] | [] | Predictor |



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processing S1





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  **end**

| | |
|---|---|
| $S \rightarrow NP\ VP$ | $NP \rightarrow NP\ PP$ |
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| $VP \rightarrow V\ NP$ | $N \rightarrow astronomers$ |
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# Chart[0]: "• astronomers saw stars with ears"

| state ID | dotted rule | position | back pointer | operation |
|---|---|---|---|---|
| S0 | $TOP \rightarrow \bullet S$ | [0,0] | [] | Seed |
| S1 | $S \rightarrow \bullet NP\ VP$ | [0,0] | [] | Predictor |
| S2 | $NP \rightarrow \bullet NP\ PP$ | [0,0] | [] | Predictor |



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| S3 | $NP \rightarrow \bullet N$ | [0,0] | [] | Predictor |



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| S1 | $S \rightarrow \bullet NP\ VP$ | [0,0] | [] | Predictor |
| S2 | $NP \rightarrow \bullet NP\ PP$ | [0,0] | [] | Predictor |
| S3 | $NP \rightarrow \bullet N$ | [0,0] | [] | Predictor |

processing S2... but NP at position [0,0] has already been considered





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| S1 | $S \rightarrow \bullet NP\ VP$ | [0,0] | [] | Predictor |
| S2 | $NP \rightarrow \bullet NP\ PP$ | [0,0] | [] | Predictor |
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# Chart[0]: "• astronomers saw stars with ears"

| state ID | dotted rule | position | back pointer | operation |
|---|---|---|---|---|
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| S1 | $S \rightarrow \bullet NP\ VP$ | [0,0] | [] | Predictor |
| S2 | $NP \rightarrow \bullet NP\ PP$ | [0,0] | [] | Predictor |
| S3 | $NP \rightarrow \bullet N$ | [0,0] | [] | Predictor |

processing S3 ...



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| S1 | $S \rightarrow \bullet NP\ VP$ | [0,0] | [] | Predictor |
| S2 | $NP \rightarrow \bullet NP\ PP$ | [0,0] | [] | Predictor |
| S3 | $NP \rightarrow \bullet N$ | [0,0] | [] | Predictor |

if state incomplete and NextCat is a POS, then Scanner

**procedure** SCANNER($(A \rightarrow \alpha \bullet B\ \beta$, *[i,j]*))
if B $\subset$ POS(*word[j]*) **then**
ENQUEUE($(B \rightarrow$ *word[j], [j,j+1])*,*chart[j+1]*)



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|---|---|---|---|---|
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| S1 | $S \rightarrow \bullet NP\ VP$ | [0,0] | [] | Predictor |
| S2 | $NP \rightarrow \bullet NP\ PP$ | [0,0] | [] | Predictor |
| S3 | $NP \rightarrow \bullet N$ | [0,0] | [] | Predictor |

Scanner: Add $N \rightarrow astronomers\bullet$ [0,1] at Chart[0+1]



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# Chart[1]: "astronomers • saw stars with ears"

| state ID | dotted rule | position | back pointer | operation |
|---|---|---|---|---|
| S4 | $N \rightarrow$ *astronomers*• | [0,1] | [] | Scanner |



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processing S4...**else** COMPLETER



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| S4 | $N \rightarrow$ *astronomers*• | [0,1] | [] | Scanner |

**procedure** COMPLETER((*B* $\rightarrow \gamma\bullet$, [j,k]))
  **for each** (*A* $\rightarrow \alpha \bullet$ *B* $\beta$, *[i,j]*) **in** *chart[j]* **do**
    ENQUEUE((*A* $\rightarrow \alpha$ *B* $\bullet \beta$, *[i,k]*), *chart[k]*)
  **end**

Which states from Chart[0] require the current constit. to be complete?



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# Chart[1]: "astronomers • saw stars with ears"

| state ID | dotted rule | position | back pointer | operation |
|---|---|---|---|---|
| S4 | $N \rightarrow$ *astronomers*• | [0,1] | [] | Scanner |
| S5 | $NP \rightarrow N$• | [0,1] | [S4] | Completer |



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|---|---|---|---|---|
| S4 | $N \rightarrow$ *astronomers*• | [0,1] | [] | Scanner |
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processing S5...**else** COMPLETER



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|---|---|---|---|---|
| S4 | $N \rightarrow$ *astronomers*• | [0,1] | [] | Scanner |
| S5 | $NP \rightarrow N$• | [0,1] | [S4] | Completer |

**procedure** COMPLETER((*B* $\rightarrow \gamma$•, [j,k]))
  **for each** (*A* $\rightarrow \alpha$ • *B* $\beta$, *[i,j]*) **in** *chart[j]* **do**
    ENQUEUE((*A* $\rightarrow \alpha$ *B* • $\beta$, *[i,k]*), *chart[k]*)
  **end**

Which states from Chart[0] require the current constit. to be complete?



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| state ID | dotted rule | position | back pointer | operation |
|---|---|---|---|---|
| S4 | $N \rightarrow astronomers\bullet$ | [0,1] | [] | Scanner |
| S5 | $NP \rightarrow N\bullet$ | [0,1] | [S4] | Completer |
| S6 | $S \rightarrow NP \bullet VP$ | [0,1] | [S5] | Completer |



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# Chart[1]: "astronomers • saw stars with ears"

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|---|---|---|---|---|
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| S5 | $NP \rightarrow N\bullet$ | [0,1] | [S4] | Completer |
| S6 | $S \rightarrow NP \bullet VP$ | [0,1] | [S5] | Completer |
| S7 | $NP \rightarrow NP \bullet PP$ | [0,1] | [S5] | Completer |



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| state ID | dotted rule | position | back pointer | operation |
|---|---|---|---|---|
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| S5 | $NP \rightarrow N$• | [0,1] | [S4] | Completer |
| S6 | $S \rightarrow NP \bullet VP$ | [0,1] | [S5] | Completer |
| S7 | $NP \rightarrow NP \bullet PP$ | [0,1] | [S5] | Completer |

processing S6...PREDICTOR



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|---|---|---|---|---|
| S4 | $N \rightarrow astronomers\bullet$ | [0,1] | [] | Scanner |
| S5 | $NP \rightarrow N\bullet$ | [0,1] | [S4] | Completer |
| S6 | $S \rightarrow NP \bullet VP$ | [0,1] | [S5] | Completer |
| S7 | $NP \rightarrow NP \bullet PP$ | [0,1] | [S5] | Completer |
| S8 | $VP \rightarrow \bullet V\ NP$ | [1,1] | [] | Predictor |



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|---|---|---|---|---|
| S4 | $N \rightarrow astronomers\bullet$ | [0,1] | [] | Scanner |
| S5 | $NP \rightarrow N\bullet$ | [0,1] | [S4] | Completer |
| S6 | $S \rightarrow NP \bullet VP$ | [0,1] | [S5] | Completer |
| S7 | $NP \rightarrow NP \bullet PP$ | [0,1] | [S5] | Completer |
| S8 | $VP \rightarrow \bullet V\ NP$ | [1,1] | [] | Predictor |
| S9 | $VP \rightarrow \bullet VP\ PP$ | [1,1] | [] | Predictor |



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|---|---|---|---|---|
| S4 | $N \rightarrow astronomers\bullet$ | [0,1] | [] | Scanner |
| S5 | $NP \rightarrow N\bullet$ | [0,1] | [S4] | Completer |
| S6 | $S \rightarrow NP \bullet VP$ | [0,1] | [S5] | Completer |
| S7 | $NP \rightarrow NP \bullet PP$ | [0,1] | [S5] | Completer |
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| S5 | $NP \rightarrow N$• | [0,1] | [S4] | Completer |
| S6 | $S \rightarrow NP \bullet VP$ | [0,1] | [S5] | Completer |
| S7 | $NP \rightarrow NP \bullet PP$ | [0,1] | [S5] | Completer |
| S8 | $VP \rightarrow \bullet V\ NP$ | [1,1] | [] | Predictor |
| S9 | $VP \rightarrow \bullet VP\ PP$ | [1,1] | [] | Predictor |

processing S7...PREDICTOR



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| S6 | $S \rightarrow NP \bullet VP$ | [0,1] | [S5] | Completer |
| S7 | $NP \rightarrow NP \bullet PP$ | [0,1] | [S5] | Completer |
| S8 | $VP \rightarrow \bullet V\ NP$ | [1,1] | [] | Predictor |
| S9 | $VP \rightarrow \bullet VP\ PP$ | [1,1] | [] | Predictor |
| S10 | $PP \rightarrow \bullet P\ NP$ | [1,1] | [] | Predictor |



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# Chart[1]: "astronomers • saw stars with ears"

| state ID | dotted rule | position | back pointer | operation |
|---|---|---|---|---|
| S4 | $N \rightarrow$ *astronomers*• | [0,1] | [] | Scanner |
| S5 | $NP \rightarrow N$• | [0,1] | [S4] | Completer |
| S6 | $S \rightarrow NP \bullet VP$ | [0,1] | [S5] | Completer |
| S7 | $NP \rightarrow NP \bullet PP$ | [0,1] | [S5] | Completer |
| S8 | $VP \rightarrow \bullet V\ NP$ | [1,1] | [] | Predictor |
| S9 | $VP \rightarrow \bullet VP\ PP$ | [1,1] | [] | Predictor |
| S10 | $PP \rightarrow \bullet P\ NP$ | [1,1] | [] | Predictor |

Processing S8...SCANNER: Add $V \rightarrow$ *saw*• [1,2] at Chart[1+1]



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| state ID | dotted rule | position | back pointer | operation |
|---|---|---|---|---|
| S4 | $N \rightarrow astronomers\bullet$ | [0,1] | [] | Scanner |
| S5 | $NP \rightarrow N\bullet$ | [0,1] | [S4] | Completer |
| S6 | $S \rightarrow NP \bullet VP$ | [0,1] | [S5] | Completer |
| S7 | $NP \rightarrow NP \bullet PP$ | [0,1] | [S5] | Completer |
| S8 | $VP \rightarrow \bullet V\ NP$ | [1,1] | [] | Predictor |
| S9 | $VP \rightarrow \bullet VP\ PP$ | [1,1] | [] | Predictor |
| S10 | $PP \rightarrow \bullet P\ NP$ | [1,1] | [] | Predictor |

Processing S9...PREDICTOR, but *VP* already expanded in Chart[1]



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|---|---|---|---|---|
| S4 | $N \rightarrow astronomers\bullet$ | [0,1] | [] | Scanner |
| S5 | $NP \rightarrow N\bullet$ | [0,1] | [S4] | Completer |
| S6 | $S \rightarrow NP \bullet VP$ | [0,1] | [S5] | Completer |
| S7 | $NP \rightarrow NP \bullet PP$ | [0,1] | [S5] | Completer |
| S8 | $VP \rightarrow \bullet V\ NP$ | [1,1] | [] | Predictor |
| S9 | $VP \rightarrow \bullet VP\ PP$ | [1,1] | [] | Predictor |
| S10 | $PP \rightarrow \bullet P\ NP$ | [1,1] | [] | Predictor |

Processing S10...SCANNER, but no $P$ in input at words[1]





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# Chart[2]: “astronomers saw • stars with ears”

| state ID | dotted rule | position | back pointer | operation |
|---|---|---|---|---|



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# Chart[2]: "astronomers saw • stars with ears"

| state ID | dotted rule | position | back pointer | operation |
|---|---|---|---|---|
| S11 | $V \rightarrow saw\bullet$ | [1,2] | [] | Scanner |



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# Chart[2]: "astronomers saw • stars with ears"

| state ID | dotted rule | position | back pointer | operation |
|---|---|---|---|---|
| S11 | $V \rightarrow saw\bullet$ | [1,2] | [] | Scanner |
| S12 | $VP \rightarrow V \bullet NP$ | [1,2] | [S11] | Completer |



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# Chart[2]: "astronomers saw • stars with ears"

| state ID | dotted rule | position | back pointer | operation |
|---|---|---|---|---|
| S11 | $V \rightarrow saw\bullet$ | [1,2] | [] | Scanner |
| S12 | $VP \rightarrow V \bullet NP$ | [1,2] | [S11] | Completer |
| S13 | $NP \rightarrow \bullet NP\ PP$ | [2,2] | [] | Predictor |



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# Chart[2]: "astronomers saw • stars with ears"

| state ID | dotted rule | position | back pointer | operation |
|---|---|---|---|---|
| S11 | $V \rightarrow saw\bullet$ | [1,2] | [] | Scanner |
| S12 | $VP \rightarrow V \bullet NP$ | [1,2] | [S11] | Completer |
| S13 | $NP \rightarrow \bullet NP\ PP$ | [2,2] | [] | Predictor |
| S14 | $NP \rightarrow \bullet N$ | [2,2] | [] | Predictor |



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# Chart[3]: "astronomers saw stars • with ears"

| state ID | dotted rule | position | back pointer | operation |
|---|---|---|---|---|
| S15 | $N \rightarrow \textit{stars}\bullet$ | [2,3] | [] | Scanner |



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# Chart[3]: "astronomers saw stars • with ears"

| state ID | dotted rule | position | back pointer | operation |
|---|---|---|---|---|
| S15 | $N \rightarrow \textit{stars}\bullet$ | [2,3] | [] | Scanner |
| S16 | $NP \rightarrow N\bullet$ | [2,3] | [S15] | Completer |



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# Chart[3]: "astronomers saw stars • with ears"

| state ID | dotted rule | position | back pointer | operation |
|---|---|---|---|---|
| S15 | $N \rightarrow stars\bullet$ | [2,3] | [] | Scanner |
| S16 | $NP \rightarrow N\bullet$ | [2,3] | [S15] | Completer |
| S17 | $VP \rightarrow V\ NP\bullet$ | [1,3] | [S11,S16] | Completer |



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# Chart[3]: "astronomers saw stars • with ears"

| state ID | dotted rule | position | back pointer | operation |
|---|---|---|---|---|
| S15 | $N \rightarrow stars\bullet$ | [2,3] | [] | Scanner |
| S16 | $NP \rightarrow N\bullet$ | [2,3] | [S15] | Completer |
| S17 | $VP \rightarrow V\ NP\bullet$ | [1,3] | [S11,S16] | Completer |
| S18 | $NP \rightarrow NP \bullet PP$ | [2,3] | [S16] | Completer |



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# Chart[3]: "astronomers saw stars • with ears"

| state ID | dotted rule | position | back pointer | operation |
|---|---|---|---|---|
| S15 | $N \rightarrow stars\bullet$ | [2,3] | [] | Scanner |
| S16 | $NP \rightarrow N\bullet$ | [2,3] | [S15] | Completer |
| S17 | $VP \rightarrow V\ NP\bullet$ | [1,3] | [S11,S16] | Completer |
| S18 | $NP \rightarrow NP \bullet PP$ | [2,3] | [S16] | Completer |
| S19 | $S \rightarrow NP\ VP\bullet$ | [0,3] | [S5,S17] | Completer |



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| state ID | dotted rule | position | back pointer | operation |
|---|---|---|---|---|
| S15 | $N \rightarrow stars\bullet$ | [2,3] | [] | Scanner |
| S16 | $NP \rightarrow N\bullet$ | [2,3] | [S15] | Completer |
| S17 | $VP \rightarrow V\ NP\bullet$ | [1,3] | [S11,S16] | Completer |
| S18 | $NP \rightarrow NP \bullet PP$ | [2,3] | [S16] | Completer |
| S19 | $S \rightarrow NP\ VP\bullet$ | [0,3] | [S5,S17] | Completer |
| S20 | $VP \rightarrow VP \bullet PP$ | [1,3] | [S17] | Completer |



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# Chart[3]: "astronomers saw stars • with ears"

| state ID | dotted rule | position | back pointer | operation |
|---|---|---|---|---|
| S15 | $N \rightarrow stars\bullet$ | [2,3] | [] | Scanner |
| S16 | $NP \rightarrow N\bullet$ | [2,3] | [S15] | Completer |
| S17 | $VP \rightarrow V\ NP\bullet$ | [1,3] | [S11,S16] | Completer |
| S18 | $NP \rightarrow NP \bullet PP$ | [2,3] | [S16] | Completer |
| S19 | $S \rightarrow NP\ VP\bullet$ | [0,3] | [S5,S17] | Completer |
| S20 | $VP \rightarrow VP \bullet PP$ | [1,3] | [S17] | Completer |
| S21 | $PP \rightarrow \bullet P\ NP$ | [3,3] | [] | Predictor |



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# Chart[4]: "astronomers saw stars with • ears"

| state ID | dotted rule | position | back pointer | operation |
|---|---|---|---|---|
| S22 | $P \rightarrow \textit{with}\bullet$ | [3,4] | [] | Scanner |



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# Chart[4]: "astronomers saw stars with • ears"

| state ID | dotted rule | position | back pointer | operation |
|---|---|---|---|---|
| S22 | $P \rightarrow with\bullet$ | [3,4] | [] | Scanner |
| S23 | $PP \rightarrow P \bullet NP$ | [3,4] | [S19] | Completer |



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# Chart[4]: "astronomers saw stars with • ears"

| state ID | dotted rule | position | back pointer | operation |
|---|---|---|---|---|
| S22 | $P \rightarrow with\bullet$ | [3,4] | [] | Scanner |
| S23 | $PP \rightarrow P \bullet NP$ | [3,4] | [S19] | Completer |
| S24 | $NP \rightarrow \bullet NP\ PP$ | [4,4] | [] | Predictor |



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# Chart[4]: "astronomers saw stars with • ears"

| state ID | dotted rule | position | back pointer | operation |
|---|---|---|---|---|
| S22 | $P \rightarrow with\bullet$ | [3,4] | [] | Scanner |
| S23 | $PP \rightarrow P \bullet NP$ | [3,4] | [S19] | Completer |
| S24 | $NP \rightarrow \bullet NP\ PP$ | [4,4] | [] | Predictor |
| S25 | $NP \rightarrow \bullet N$ | [4,4] | [] | Predictor |



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# Chart[5]: "astronomers saw stars with ears •"

| state ID | dotted rule | position | back pointer | operation |
|---|---|---|---|---|



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# Chart[5]: "astronomers saw stars with ears •"

| state ID | dotted rule | position | back pointer | operation |
|---|---|---|---|---|
| S26 | $N \rightarrow ears\bullet$ | [4,5] | [] | Scanner |



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# Chart[5]: "astronomers saw stars with ears •"

| state ID | dotted rule | position | back pointer | operation |
|---|---|---|---|---|
| S26 | $N \rightarrow ears\bullet$ | [4,5] | [] | Scanner |
| S27 | $NP \rightarrow N\bullet$ | [4,5] | [S26] | Completer |



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# Chart[5]: "astronomers saw stars with ears •"

| state ID | dotted rule | position | back pointer | operation |
|---|---|---|---|---|
| S26 | $N \rightarrow ears\bullet$ | [4,5] | [] | Scanner |
| S27 | $NP \rightarrow N\bullet$ | [4,5] | [S26] | Completer |
| S28 | $PP \rightarrow P\ NP\bullet$ | [3,5] | [S19,S27] | Completer |



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# Chart[5]: "astronomers saw stars with ears •"

| state ID | dotted rule | position | back pointer | operation |
|---|---|---|---|---|
| S26 | $N \rightarrow ears\bullet$ | [4,5] | [] | Scanner |
| S27 | $NP \rightarrow N\bullet$ | [4,5] | [S26] | Completer |
| S28 | $PP \rightarrow P\ NP\bullet$ | [3,5] | [S19,S27] | Completer |
| S29 | $NP \rightarrow NP\ PP\bullet$ | [2,5] | [S16,S28] | Completer |



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| state ID | dotted rule | position | back pointer | operation |
|---|---|---|---|---|
| S26 | $N \rightarrow ears\bullet$ | [4,5] | [] | Scanner |
| S27 | $NP \rightarrow N\bullet$ | [4,5] | [S26] | Completer |
| S28 | $PP \rightarrow P\ NP\bullet$ | [3,5] | [S19,S27] | Completer |
| S29 | $NP \rightarrow NP\ PP\bullet$ | [2,5] | [S16,S28] | Completer |
| S30 | $VP \rightarrow VP\ PP\bullet$ | [1,5] | [S17,S28] | Completer |



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| state ID | dotted rule | position | back pointer | operation |
|---|---|---|---|---|
| S26 | $N \rightarrow ears\bullet$ | [4,5] | [] | Scanner |
| S27 | $NP \rightarrow N\bullet$ | [4,5] | [S26] | Completer |
| S28 | $PP \rightarrow P\ NP\bullet$ | [3,5] | [S19,S27] | Completer |
| S29 | $NP \rightarrow NP\ PP\bullet$ | [2,5] | [S16,S28] | Completer |
| S30 | $VP \rightarrow VP\ PP\bullet$ | [1,5] | [S17,S28] | Completer |
| S31 | $VP \rightarrow V\ NP\bullet$ | [1,5] | [S11,S29] | Completer |



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| state ID | dotted rule | position | back pointer | operation |
|---|---|---|---|---|
| S26 | $N \rightarrow ears\bullet$ | [4,5] | [] | Scanner |
| S27 | $NP \rightarrow N\bullet$ | [4,5] | [S26] | Completer |
| S28 | $PP \rightarrow P\ NP\bullet$ | [3,5] | [S19,S27] | Completer |
| S29 | $NP \rightarrow NP\ PP\bullet$ | [2,5] | [S16,S28] | Completer |
| S30 | $VP \rightarrow VP\ PP\bullet$ | [1,5] | [S17,S28] | Completer |
| S31 | $VP \rightarrow V\ NP\bullet$ | [1,5] | [S11,S29] | Completer |
| S32 | $NP \rightarrow NP \bullet PP$ | [2,5] | [S29] | Completer |



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| S27 | $NP \rightarrow N\bullet$ | [4,5] | [S26] | Completer |
| S28 | $PP \rightarrow P\ NP\bullet$ | [3,5] | [S19,S27] | Completer |
| S29 | $NP \rightarrow NP\ PP\bullet$ | [2,5] | [S16,S28] | Completer |
| S30 | $VP \rightarrow VP\ PP\bullet$ | [1,5] | [S17,S28] | Completer |
| S31 | $VP \rightarrow V\ NP\bullet$ | [1,5] | [S11,S29] | Completer |
| S32 | $NP \rightarrow NP \bullet PP$ | [2,5] | [S29] | Completer |
| S33 | $VP \rightarrow V\ NP\bullet$ | [2,5] | [S11,S29] | Completer |



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| state ID | dotted rule | position | back pointer | operation |
|---|---|---|---|---|
| S26 | $N \rightarrow ears\bullet$ | [4,5] | [] | Scanner |
| S27 | $NP \rightarrow N\bullet$ | [4,5] | [S26] | Completer |
| S28 | $PP \rightarrow P\ NP\bullet$ | [3,5] | [S19,S27] | Completer |
| S29 | $NP \rightarrow NP\ PP\bullet$ | [2,5] | [S16,S28] | Completer |
| S30 | $VP \rightarrow VP\ PP\bullet$ | [1,5] | [S17,S28] | Completer |
| S31 | $VP \rightarrow V\ NP\bullet$ | [1,5] | [S11,S29] | Completer |
| S32 | $NP \rightarrow NP \bullet PP$ | [2,5] | [S29] | Completer |
| S33 | $VP \rightarrow V\ NP\bullet$ | [2,5] | [S11,S29] | Completer |
| S34 | $NP \rightarrow NP \bullet PP$ | [2,5] | [S29] | Completer |



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| state ID | dotted rule | position | back pointer | operation |
|---|---|---|---|---|
| S26 | $N \rightarrow ears\bullet$ | [4,5] | [] | Scanner |
| S27 | $NP \rightarrow N\bullet$ | [4,5] | [S26] | Completer |
| S28 | $PP \rightarrow P\ NP\bullet$ | [3,5] | [S19,S27] | Completer |
| S29 | $NP \rightarrow NP\ PP\bullet$ | [2,5] | [S16,S28] | Completer |
| S30 | $VP \rightarrow VP\ PP\bullet$ | [1,5] | [S17,S28] | Completer |
| S31 | $VP \rightarrow V\ NP\bullet$ | [1,5] | [S11,S29] | Completer |
| S32 | $NP \rightarrow NP \bullet PP$ | [2,5] | [S29] | Completer |
| S33 | $VP \rightarrow V\ NP\bullet$ | [2,5] | [S11,S29] | Completer |
| S34 | $NP \rightarrow NP \bullet PP$ | [2,5] | [S29] | Completer |
| S35 | $S \rightarrow NP\ VP\bullet$ | [0,5] | [S5,S30] | Completer |



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|---|---|---|---|---|
| S26 | $N \rightarrow ears\bullet$ | [4,5] | [] | Scanner |
| S27 | $NP \rightarrow N\bullet$ | [4,5] | [S26] | Completer |
| S28 | $PP \rightarrow P\ NP\bullet$ | [3,5] | [S19,S27] | Completer |
| S29 | $NP \rightarrow NP\ PP\bullet$ | [2,5] | [S16,S28] | Completer |
| S30 | $VP \rightarrow VP\ PP\bullet$ | [1,5] | [S17,S28] | Completer |
| S31 | $VP \rightarrow V\ NP\bullet$ | [1,5] | [S11,S29] | Completer |
| S32 | $NP \rightarrow NP \bullet PP$ | [2,5] | [S29] | Completer |
| S33 | $VP \rightarrow V\ NP\bullet$ | [2,5] | [S11,S29] | Completer |
| S34 | $NP \rightarrow NP \bullet PP$ | [2,5] | [S29] | Completer |
| S35 | $S \rightarrow NP\ VP\bullet$ | [0,5] | [S5,S30] | Completer |
| S36 | $S \rightarrow NP\ VP\bullet$ | [0,5] | [S5,S31] | Completer |



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|---|---|---|---|---|
| S26 | $N \rightarrow ears\bullet$ | [4,5] | [] | Scanner |
| S27 | $NP \rightarrow N\bullet$ | [4,5] | [S26] | Completer |
| S28 | $PP \rightarrow P\ NP\bullet$ | [3,5] | [S19,S27] | Completer |
| S29 | $NP \rightarrow NP\ PP\bullet$ | [2,5] | [S16,S28] | Completer |
| S30 | $VP \rightarrow VP\ PP\bullet$ | [1,5] | [S17,S28] | Completer |
| S31 | $VP \rightarrow V\ NP\bullet$ | [1,5] | [S11,S29] | Completer |
| S32 | $NP \rightarrow NP \bullet PP$ | [2,5] | [S29] | Completer |
| S33 | $VP \rightarrow V\ NP\bullet$ | [2,5] | [S11,S29] | Completer |
| S34 | $NP \rightarrow NP \bullet PP$ | [2,5] | [S29] | Completer |
| S35 | $S \rightarrow NP\ VP\bullet$ | [0,5] | [S5,S30] | Completer |
| S36 | $S \rightarrow NP\ VP\bullet$ | [0,5] | [S5,S31] | Completer |
| S37 | $PP \rightarrow \bullet P\ NP$ | [5,5] | [] | Predictor |



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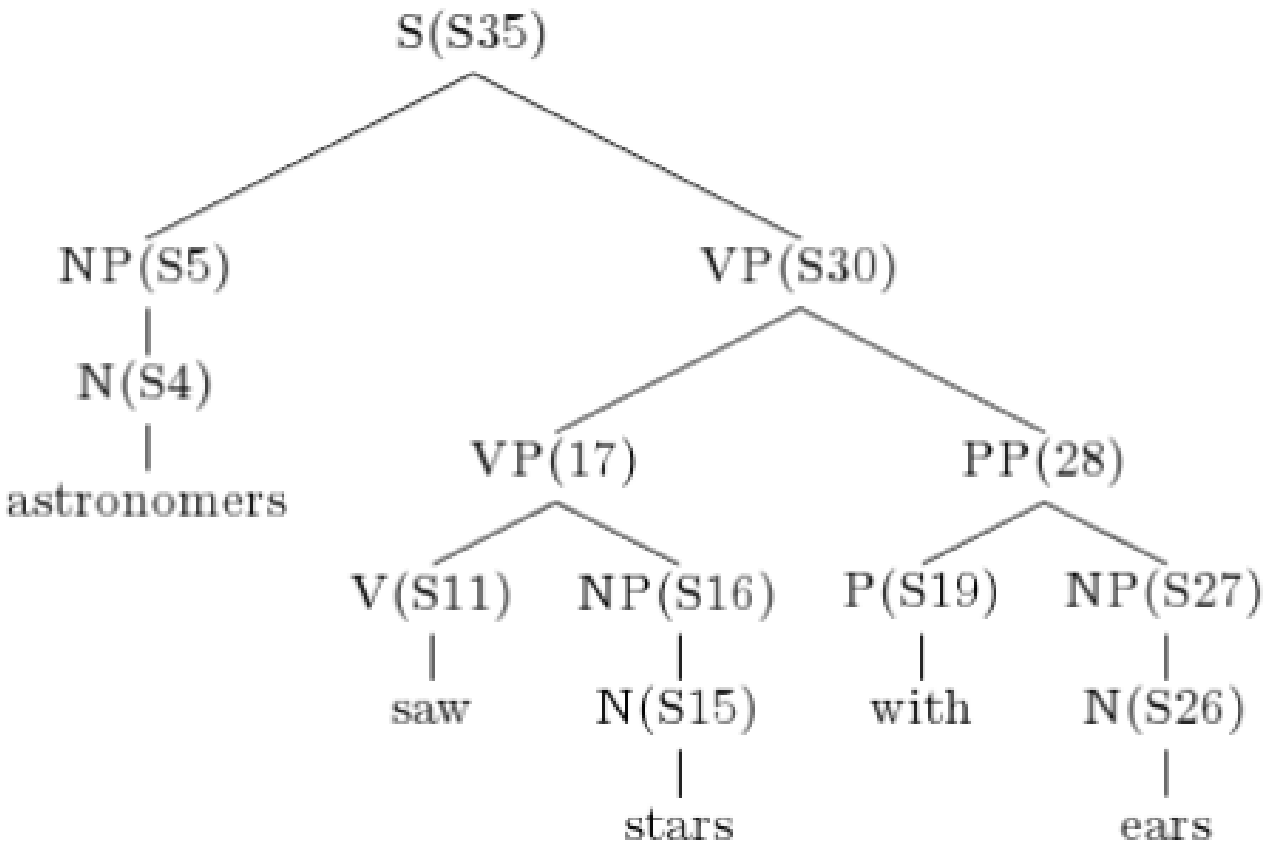
# Parse 1



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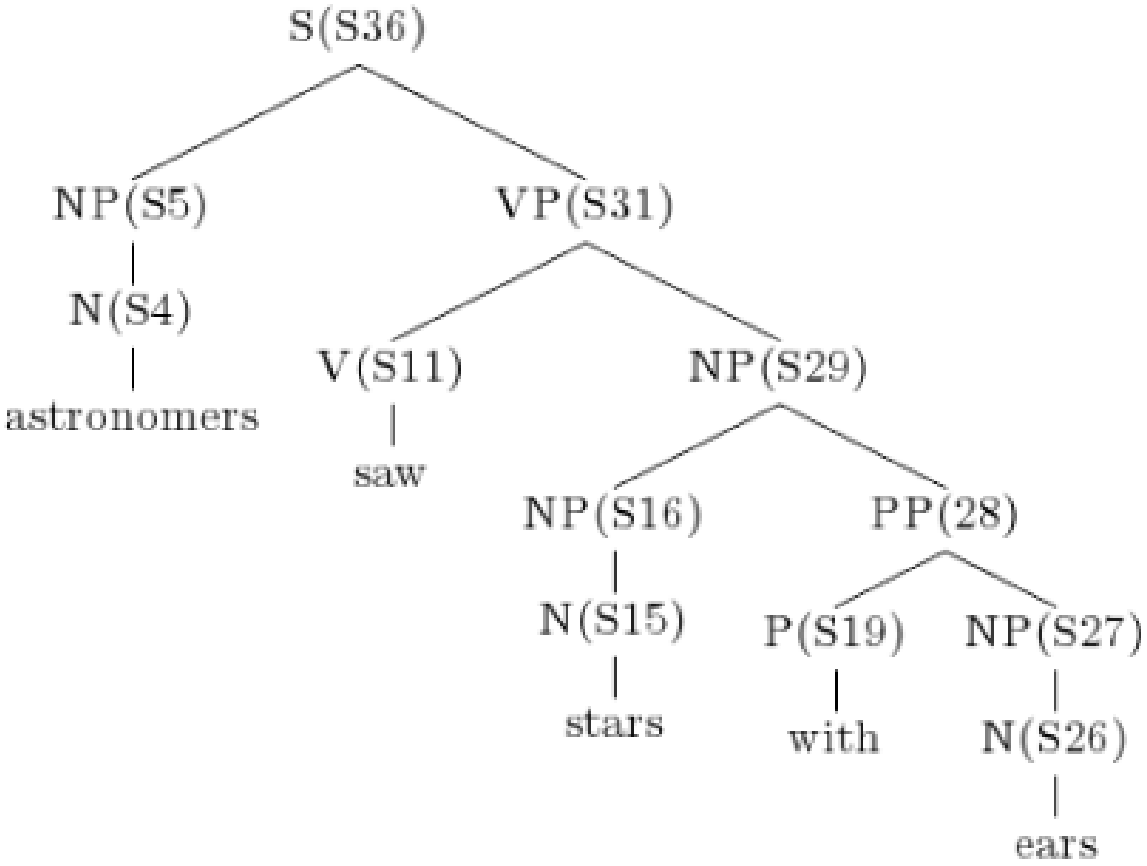
# Parse 2



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