Efficiency of Top-Down Parsing of Recursive Adjunction for Tree Adjoining Grammar

Jing Ji

Stony Brook University, jing.ji@mail.mcgill.ca

Follow this and additional works at: https://scholarworks.umass.edu/scil

Part of the Computational Linguistics Commons

Recommended Citation
Ji, Jing (2021) "Efficiency of Top-Down Parsing of Recursive Adjunction for Tree Adjoining Grammar," Proceedings of the Society for Computation in Linguistics: Vol. 4, Article 39.
DOI: https://doi.org/10.7275/2236-2333
Available at: https://scholarworks.umass.edu/scil/vol4/iss1/39

This Extended Abstract is brought to you for free and open access by ScholarWorks@UMass Amherst. It has been accepted for inclusion in Proceedings of the Society for Computation in Linguistics by an authorized editor of ScholarWorks@UMass Amherst. For more information, please contact scholarworks@library.umass.edu.
Efficiency of Top-Down Parsing of Recursive Adjunction for Tree Adjoining Grammar

Jing Ji
Stony Brook University
jing.ji@mail.mcgill.ca

Abstract

CKY-type parser and Earley-type parser are two widely-used parsing algorithms for Tree Adjoining Grammar (TAG). In contrast, a standard top-down parser is not efficient since the looping problem occurs during both the left and right recursion of standard TAG derivation. (Roark, 2001) combines the top-down parser for CFG with a beam search, showing that the probabilistic top-down parser yields a perplexity improvement over previous results. In this paper, we define the stochastic tree adjoining grammar and apply the probabilistic top-down parser for CFG to TAG. Comparing the parsing efficiency of the standard and alternative TAG derivation of the recursive adjunction, we find that the alternative derivation is more efficient since it avoids the looping problem of the right recursion, increasing the parsing efficiency of our top-down parser.

1 Introduction

Tree Adjoining Grammar (TAG), introduced by Joshi et al. (1975) (Joshi et al., 1975), falls in the class of mildly context-sensitive languages (Joshi, 1985), which contain context-free languages and can also describe cross-serial dependency as is in Dutch and Swiss German. Two well-known chart parsing algorithms for TAG are the $O(n^3)$-time CKY-type parser (Vijay-Shanker and Joshi, 1985) and Earley-type parser extended from standard algorithms for Context-Free Grammar (CFG) (Joshi and Schabes, 1997; Nederhof, 1999). Recently, neural network architectures have also been utilized to build a shift-reduce parsing model for TAG (Kasai et al., 2017).

A standard top-down parser, in contrast, is not an efficient algorithm for CFG as it suffers from looping when dealing with left recursion. For TAG, the looping problem of the top-down parser even occurs with the right recursion when adjoining to the root node of elementary trees. Thus top-down parsers are always combined with a beam search strategy. Empirical results show that probabilistic top-down parsing for CFG improves upon previous work in test corpus perplexity (Roark, 2001). Moreover, Top-down parsers are incremental in the sense that each word is attached to a fully connected derivation, a property that left-corner and bottom-up parsers do not have (Stabler, 2013).

In this paper, we apply the probabilistic top-down parser with a beam search for CFG to TAG based on the definition of stochastic tree adjoining grammar and compare parsing efficiency of the standard and alternative TAG derivation of recursive adjunction.

2 Stochastic Tree Adjoining Grammar

Tree Adjoining Grammar (TAG) is a tree-rewriting system that consists of a finite set of elementary trees. We provide the definition of TAG following (Vijay-Shanker and Weir, 1994; Kallmeyer, 2010) to set the stage.

Let $N_+$ denotes the set of positive integers. $D$ is tree domain if it is a nonempty finite subset of $N_+$ such that if $d \in D$ and $d = d_1 d_2$ then $d_1 \in D$ and if $d_i \in D$ where $i \in N$ then $d_j \in D$ for all $1 \leq j \leq i$. Note that $\epsilon$ is the address of the root node of the tree. A tree $\gamma$ is denoted by a function $\gamma : D_\gamma \rightarrow V_N \cup V_T$ where $D_\gamma$ is the domain of $\gamma$, $V_N$ and $V_T$ are the set of nonterminal and terminal node labels, respectively.

Definition 1 (Auxiliary Trees). Auxiliary trees is a set of trees $\beta : D_\beta \rightarrow V_T \cup V_N$ where

- the root and internal nodes of $\beta$ are labelled by some $V \in V_N$;
- all leaf nodes of $\beta$ except one are labelled by some $v \in V_T$. The remaining leaf node is the foot nodemarked by an asterisk (*)..

Proceedings of the Society for Computation in Linguistics (SCIL) 2021, pages 374-379.
Held on-line February 14-19, 2021
Definition 2 (Initial Trees). Initial trees is a set of trees \( \alpha : D_\alpha \rightarrow VT \cup VN \) and the following hold.

- The root and internal nodes of \( \alpha \) are labelled by some \( V \in VN \).
- Leaf nodes of \( \alpha \) are labelled by some \( v \in VT \) or some \( V \in VN \) which is a substitution node marked by a down arrow (\( \downarrow \)).

Elementary trees are the union of auxiliary and initial trees. In lexicalized TAG (LTAG), every elementary tree \( \alpha \) has at least one non-empty lexical item, its lexical anchor. LTAG is weakly equivalent to TAG (defining the same language) (Kuhlmann and Satta, 2012).

Definition 3 (Tree Adjoining Grammar). A TAG is a tuple \( G = \langle V_N, V_T, I, A, S, f_OA, f_SA, \dashv \rangle \) where

- \( V_L \) is a finite set of tree labels,
- \( I \) is a finite subset of initial trees,
- \( A \) is a finite subset of auxiliary trees,
- \( S \) in \( VN \) is a start symbol,
- \( f_OA \) and \( f_SA \) are functions representing adjunction constraints:
  \[
  f_OA : \langle \gamma, d \rangle \rightarrow \{true, false\} \quad \text{where } d \in D_\gamma, \gamma \in I \cup A, \gamma(d) \in V_N,
  \]
  \[
  f_SA : \langle \gamma, d \rangle \rightarrow P(A) \quad \text{where } d \in D_\gamma, \gamma \in I \cup A, \gamma(d) \in V_N,
  \]
  \[
  \dashv : I \cup A \rightarrow V_L \text{ is the elementary tree labelling function.}
  \]

Adjunction applies to nonterminal internal nodes of elementary trees. For \( \gamma \in I \cup A, d \in D_\gamma, \gamma(d) \in V_N \), if \( f_SA(\gamma, d) = \emptyset \), adjunction is forbidden for \( \gamma(d) \); if \( f_OA(\gamma, d) = true \), adjunction is obligatory; otherwise, adjunction is optional.

Definition 4 (Adjunction and Substitution). Given a TAG \( G = \langle V_N, V_T, V_L, I, A, S, f_OA, f_SA, \dashv \rangle \), for \( \gamma \in I \cup A, \alpha \in I, \beta \in A, d \in D_\gamma, d' \in N_+^*, \gamma' = \gamma[d, \alpha] \) and \( \gamma'' = \gamma[d, \beta] \) are the result of substituting \( \alpha \) and adjoining \( \beta \) into \( \gamma \), which are defined below.

\[
\gamma'(d') = \begin{cases} 
\gamma(d') & \text{if } d = d' \\
\alpha(d'') & \text{if } d' = dd'' \text{ and } d'' \in D_\alpha
\end{cases}
\]

\[
\gamma''(d') = \begin{cases} 
\gamma(d') & \text{if } d = d' \\
\beta(d'') & \text{if } d' = dd'' \text{ and } d'' \in D_\beta \\
\gamma(dd'') & \text{if } d' = dd_f d'' \text{ and } d_f \text{ is the address of the foot node of } \beta
\end{cases}
\]

Definition 5 (Derived Trees and Derivation Trees). Let \( G = \langle V_N, V_T, V_L, I, A, S, f_OA, f_SA, \dashv \rangle \) be a TAG. A derivation tree in \( G \) can be taken as a directed graph, which is a pair \( (V, E) \) where \( V \) is a finite set of vertices and \( E \subseteq V \times V \) is a set of edges.

- Every \( \gamma \in I \cup A \) is a derived tree in \( G \). The corresponding derivation tree is \( \{(-\gamma)\}, \emptyset \).
- Let \( \gamma \) be a derived tree and \( (V, E) \) be its derivation tree. If \( \gamma' = \gamma[d, \eta] \) for \( d \in D_\gamma \) and \( \eta \in I \cup A \), then \( \gamma' \) is a derived tree and the derivation tree of \( \gamma' \) is \( (V', E') \) such that
  - \( V' = V \cup \{\{-\eta\}\} \),
  - \( E' = E \cup \{\{(-\gamma), \{-\eta\}\}\} \),
  - \( g((-\gamma), \{-\eta\}) = d \).

A derived tree \( \gamma \) with no substitution nodes and no internal node \( \gamma(d) \) such that \( f_OA(\gamma, d) = true \) is a saturated derived tree. A derivation tree is complete if its corresponding derived tree is saturated. Let \( \omega^n_j \) denote the string \( \omega_{i+1} \cdots \omega_j \). Let \( T_{\omega^n_j} \) be the set of all complete derivation trees with \( \omega^n_j \) as leaves of their corresponding derived trees. A Stochastic TAG (STAG) is a TAG with a probability assigned to each rule. A STAG defines a probability distribution over strings of words in the following way.

\[
P(\omega^n_j) = \sum_{t \in T_{\omega^n_j}} P(t)
\]

3 A Probabilistic Top-Down Parser with Beam Search for TAG

The definition of probabilistic top-down parser stems from the top-down parser (left-to-right, depth-first) described in (Roark, 2001) for PCFG. We apply it to STAG parsing without left-factorization. The parser takes an input string \( \omega^n_j \), a STAG, and a priority queue of candidate analyses. A candidate analysis \( C = (E, S, P_E, F, \omega^n_j) \) consists of a set of edges \( E \) of a derivation tree, a stack \( S \), a derivation probability \( P_E \), a figure of merit \( F \), and a string \( \omega^n_j \) to be parsed. The first word in the string remaining to be parsed, \( \omega_{i+1} \), is the look-ahead word. The stack \( S \) contains a sequence of node labels superscripted with the tree-labels and an end-of-stack marker \( \dagger \) at the bottom. The probability \( P_E \) is the product of the probabilities of all the edges in \( E \). \( F \) is the product of \( P_E \) and a look-ahead probability \( LAP(S, \omega_{i+1}) \).

A derives relation between two candidate analyses, denoted as \( \rightarrow \), is defined based on the following conditions.

Condition 1: the first symbol on the stack is not a foot node, and no substitution or adjunction performs. \( (E, S, P_E, F, \omega^n_i) \rightarrow (E', S', P_E', F', \omega'^n_i) \) where
• \( E' = E \)
• \( S = V^{\gamma \pi} \chi \) if \( \gamma \in V_L, \pi \in V_L^* \)
• if \( V^{\gamma} \rightarrow X_1^{\gamma} \ldots X_k^{\gamma} \), then \( S' = X_1^{\gamma \pi} \ldots X_k^{\gamma \pi} \chi \), and \( i = j \); if \( V^{\gamma} \rightarrow \omega_{i+1} \) or \( V^{\gamma} = \omega_{i+1} \), then \( j = i + 1 \), and \( S' = \chi \chi \);
• if \( V^{\gamma} \rightarrow X_1^{\gamma} \ldots X_k^{\gamma} \), then \( P_{E'} = P_{E} \) \( P(V^{\gamma} \rightarrow X_1^{\gamma} \ldots X_k^{\gamma}) \), otherwise \( P_{E'} = P_{E} \).
• \( F' = P_{E'}LAP(S', \omega_{j+1}) \)

Condition 2: \( V^{\gamma} \) is the foot node of \( \gamma \) adjoining to the tree labeled \( \eta \). \((E, S, P_E, F, \omega_n^i) \mapsto (E', S', P_{E'}, F', \omega_j^i) \) where

- \( E' = E \)
- \( S = V^{\gamma \pi} \chi \)
- if \( V^{\gamma} \rightarrow X_1^{\gamma} \ldots X_k^{\gamma} \), then \( S' = X_1^{\gamma \pi} \ldots X_k^{\gamma \pi} \chi \), and \( \pi = \chi \chi \); if \( V^{\gamma} \rightarrow \omega_{i+1} \) or \( V^{\gamma} = \omega_{i+1} \), then \( j = i + 1 \), and \( S' = \chi \chi \);
- \( P_{E'} = P_E \)
- \( F' = P_{E'}LAP(S', \omega_{j+1}) \)

Condition 3: the node \( V^{\gamma} \) is substituted or adjoining by a tree labeled \( \gamma \), denoted as \( \gamma \Rightarrow \eta \). \((E, S, P_E, F, \omega_n^i) \mapsto (E', S', P_{E'}, F', \omega_j^i) \) where

- \( E' = E \cup \{ (\gamma, \eta) \} \)
- \( S = V^{\gamma \pi} \chi \)
- \( S' = V^{\gamma \pi \chi} \chi \)
- \( P_{E'} = P_E \) \( P(\gamma \Rightarrow \eta) \)
- \( F' = P_{E'}LAP(S', \omega_{j+1}) \)

The parse begins with a single candidate analysis on the priority queue: \((\emptyset, S^{\gamma \pi \chi}, 1, \omega_n^1) \) where \( \alpha \in I \) and \( \alpha(e) = S \). If \( S = \emptyset \) and \( \omega_{i+1} = \langle s \rangle \), the end symbol of the string, the analysis is complete. The symbols on the stack are the contracted representation of the items.

**Example 1.** Suppose \( G_{\text{raising}} = \langle \{ S, NP, VP, V \}, \{ \text{John, seems, to_sleep} \}, \{ \alpha, \alpha_n \}, \{ \beta \}, S, f_OA, f_SA, - \rangle \) is a TAG. The sentence to be generated is \( \text{John seems to_sleep} \). The elementary trees and derivation tree are shown in Figure 1 and 2. The parsing trace is presented in Table 1.

The LAP is the probability of a particular terminal being derived as the first non-empty leaf from a set of nonterminal nodes. For a stochastic LTAG (SLTAG), a stack \( S = V_1^{\gamma_1 \pi_1} \ldots V_k^{\gamma_k \pi_k} \chi \) and a look-ahead terminal item \( \omega_{i+1} \), the look-ahead probability defined in Equation 2 computes the probability of the concatenation of yield of the subtrees rooted at \( V_1^{\gamma_1 \pi_1} \ldots V_k^{\gamma_k \pi_k} \) of the derived tree starting with \( \omega_{i+1} \). Let \( P(V^{\gamma \pi} \Rightarrow \lambda) \) denote the probability of the yield of the subtree of the derived tree rooted at \( V^{\gamma \pi} \) being empty.

\[
\begin{align*}
\text{LAP}(S, \omega_{i+1}) &= P(V_1^{\gamma_1 \pi_1} \ldots V_k^{\gamma_k \pi_k} \Rightarrow \omega_{i+1}) \quad (2) \\
P(V_j^{\gamma_j \pi_j} \ldots V_k^{\gamma_k \pi_k} \Rightarrow \omega_i) &= P(V_j^{\gamma_j \pi_j} \Rightarrow \omega_i) + P(V_j^{\gamma_j \pi_j} \Rightarrow \omega_i)P(V_j^{\gamma_j \pi_j} \Rightarrow \omega_i) \quad (3)
\end{align*}
\]

where \( P(V^{\gamma \pi} \Rightarrow \omega_i) \) and \( P(V^{\gamma \pi} \Rightarrow \lambda) \) are defined recursively.

\[
\begin{align*}
P(V^{\gamma \pi} \Rightarrow \omega_i) &= P(V \Rightarrow X_1^{\gamma_1} \ldots X_n^{\gamma_n})P(X_1^{\gamma_1} \ldots X_n^{\gamma_n} \Rightarrow \omega_i) + \sum_{\eta \in V_L} P(\gamma \Rightarrow \eta)P(V^{\gamma} \Rightarrow \omega_i) \quad (4) \\
P(V^{\gamma \pi} \Rightarrow \lambda) &= P(V \Rightarrow X_1^{\gamma_1} \ldots X_n^{\gamma_n})P(X_1^{\gamma_1} \ldots X_n^{\gamma_n} \Rightarrow \omega_i) \quad (5)
\end{align*}
\]

The beam search works in the same way as (Roark, 2001). For each word position \( i \), we have a separate priority queue \( H_i \) of analyses with look-ahead \( \omega_{i+1} \). When there are enough analyses on priority queue \( H_{i+1} \), all candidate analyses remaining on \( H_i \) are discarded. The parse on \( H_{i+1} \) with the highest probability is returned for evaluation. The beam threshold at word \( \omega_i \) is the same as that of the CFG. If \( \tilde{p} \) is the probability of the highest-ranked analysis on \( H_{i+1} \), then another analysis is discarded if its probability falls below \( \tilde{p}f(t, |H_{i+1}|) \), where \( t \) is an initial parameter.
4 Parsing Efficiency with Standard and Alternative Derivations

For a top-down CFG parser, left recursion can force it to enter an infinite loop of top-down predictions. It is the same for top-down parsing of TAG. However, when the root node is the adjunction node, both the left and right-branching structure can result in an infinite loop of top-down prediction. A top-down parser with a beam threshold can avoid the infinite loop, but it cannot make a distinction between left and right recursion concerning memory load. From the psychological point of view, only left recursion leads to process difficulty. This section tries to tackle this issue with the alternative conception of adjunction instead of the standard one and compare the parsing efficiency with the probabilistic top-down parser.

The standard definition of derivation, attributable to (Vijayashanker and Joshi, 1988), requires that auxiliary trees be adjointed at distinct nodes in elementary trees. However, considering the difference between modification and predication, (Schabes and Shieber, 1994) proposed a redefinition of TAG derivation, whereby multiple auxiliary tree modification can be adjointed at a single node. For example, given an input string $S_1 = Mary has a nice big red table (\langle/s \rangle)$ with elementary trees shown in A(a)-(h), its standard and alternative derivation of the sentence are depicted in Figure A(i)-(j).

The definition of top-down parser in section 3 is based on the standard conception of derivation. In order to allow multiple adjunction at the same node, the analysis of Condition 2 can be modified as follows. $(E, S, P_E, F, \omega^n) \rightarrow (E', S', P'_E, F', \omega^{n'})$ where

- $P'_E = P_E$
- $F' = P_E L \alpha P(S', \omega_{i+1})$

For the top-down parser with a beam search, the following analysis shows that the alternative adjunction is more efficient than the standard adjunction.

Assume that there is no empty leaf in the trees. Both ways of parsing result in the same analyses from the start to $C_0 = (\langle \{ (\alpha_x, \alpha_n), (\alpha_x, \alpha_{n2}) \}, N \alpha P \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \alpha \a
References

Aravind K Joshi. 1985. How much context sensitivity is necessary for characterizing structural descriptions: Tree adjoining grammars. Natural language parsing: Psychological, computational and theoretical perspectives, pages 206–250.

Aravind K Joshi, Leon S Levy, and Masako Takahashi. 1975. Tree adjunct grammars. Journal of computer and system sciences, 10(1):136–163.

Aravind K Joshi and Yves Schabes. 1997. Tree-adjoining grammars. In Handbook of formal languages, pages 69–123. Springer.

Laura Kallmeyer. 2010. Parsing beyond context-free grammars. Springer Science & Business Media.

Jungo Kasai, Robert Frank, R Thomas McCoy, Owen Rambow, and Alexis Nasr. 2017. Tag parsing with neural networks and vector representations of supertags.

Marco Kuhlmann and Giorgio Satta. 2012. Tree-adjoining grammars are not closed under strong lexicalization. Computational Linguistics, 38(3):617–629.

Mark-Jan Nederhof. 1999. The computational complexity of the correct-prefix property for tags. Computational Linguistics, 25(3):345–360.

Brian Roark. 2001. Probabilistic top-down parsing and language modeling. Computational linguistics, 27(2):249–276.

Yves Schabes and Stuart M Shieber. 1994. An alternative conception of tree-adjoining derivation. Computational Linguistics, 20(1):91–124.

Gary-John Scott. 2002. Stacked adjectival modification and the structure of nominal phrases. Functional structure in DP and IP: The cartography of syntactic structures, 1:91–120.

Edward P Stabler. 2013. Two models of minimalist, incremental syntactic analysis. Topics in cognitive science, 5(3):611–633.

K Vijay-Shankar and Aravind K Joshi. 1985. Some computational properties of tree adjoining grammars. In Proceedings of the 23rd annual meeting on Association for Computational Linguistics, pages 82–93. Association for Computational Linguistics.

Krishnamurti Vijay-Shanker and David J Weir. 1994. The equivalence of four extensions of context-free grammars. Mathematical systems theory, 27(6):511–546.

K Vijayashanker and Aravind K Joshi. 1988. A study of tree adjoining grammars. University of Pennsylvania Philadelphia.

A Appendices

A Appendices
| Step | Standard | $\omega_{i+1}$ | Alternative | $\omega_{i+1}$ |
|------|----------|----------------|-------------|----------------|
| 1    | $NP_{\beta a4\alpha n2\alpha s}$ | a              | $NP_{\beta a4\alpha n2\alpha s}$ | a              |
| 2    | $NP_{\beta a3\alpha a4\alpha n2\alpha s}$ | a              | $NP_{\beta a3\alpha a4\alpha n2\alpha s}$ | a              |
| 3    | $NP_{\beta a3\alpha a4\alpha n2\alpha s}$ | a              | $NP_{\beta a3\alpha a4\alpha n2\alpha s}$ | nice           |
| 4    | $NP_{\beta a3\alpha a4\alpha n2\alpha s}$ | a              | $NP_{\beta a3\alpha a4\alpha n2\alpha s}$ | nice           |
| 5    | $NP_{\beta a3\alpha a4\alpha n2\alpha s}$ | a              | $NP_{\beta a3\alpha a4\alpha n2\alpha s}$ | nice           |
| 6    | $NP_{\beta a3\alpha a4\alpha n2\alpha s}$ | a              | $NP_{\beta a3\alpha a4\alpha n2\alpha s}$ | nice           |
| 7    | $NP_{\beta a3\alpha a4\alpha n2\alpha s}$ | nice           | $NP_{\beta a3\alpha a4\alpha n2\alpha s}$ | big            |
| 8    | $NP_{\beta a3\alpha a4\alpha n2\alpha s}$ | nice           | $NP_{\beta a3\alpha a4\alpha n2\alpha s}$ | big            |
| 9    | $NP_{\beta a3\alpha a4\alpha n2\alpha s}$ | big            | $NP_{\beta a3\alpha a4\alpha n2\alpha s}$ | big            |
| 10   | $NP_{\beta a3\alpha a4\alpha n2\alpha s}$ | new            | $NP_{\beta a3\alpha a4\alpha n2\alpha s}$ | new            |
| 11   | $NP_{\beta a3\alpha a4\alpha n2\alpha s}$ | new            | $NP_{\beta a3\alpha a4\alpha n2\alpha s}$ | new            |
| 12   | $NP_{\beta a3\alpha a4\alpha n2\alpha s}$ | red            | $NP_{\beta a3\alpha a4\alpha n2\alpha s}$ | new            |
| 13   | $NP_{\beta a3\alpha a4\alpha n2\alpha s}$ | red            | $NP_{\beta a3\alpha a4\alpha n2\alpha s}$ | new            |
| 14   | $NP_{\beta a3\alpha a4\alpha n2\alpha s}$ | red            | $NP_{\beta a3\alpha a4\alpha n2\alpha s}$ | new            |
| 15   | $NP_{\beta a3\alpha a4\alpha n2\alpha s}$ | table          | $NP_{\beta a3\alpha a4\alpha n2\alpha s}$ | red            |
| 16   | $NP_{\beta a3\alpha a4\alpha n2\alpha s}$ | table          | $NP_{\beta a3\alpha a4\alpha n2\alpha s}$ | red            |
| 17   | $NP_{\beta a3\alpha a4\alpha n2\alpha s}$ | table          | $NP_{\beta a3\alpha a4\alpha n2\alpha s}$ | red            |
| 18   | $NP_{\beta a3\alpha a4\alpha n2\alpha s}$ | table          | $NP_{\beta a3\alpha a4\alpha n2\alpha s}$ | red            |
| 19   | $NP_{\beta a3\alpha a4\alpha n2\alpha s}$ | table          | $NP_{\beta a3\alpha a4\alpha n2\alpha s}$ | red            |
| 20   | $NP_{\beta a3\alpha a4\alpha n2\alpha s}$ | table          | $NP_{\beta a3\alpha a4\alpha n2\alpha s}$ | red            |
| 21   | $NP_{\beta a3\alpha a4\alpha n2\alpha s}$ | table          | $NP_{\beta a3\alpha a4\alpha n2\alpha s}$ | red            |
| 22   | $NP_{\beta a3\alpha a4\alpha n2\alpha s}$ | table          | $NP_{\beta a3\alpha a4\alpha n2\alpha s}$ | red            |

Table 2: Stack trace for standard and alternative top-down parsing of $S_1$ ($\omega_{i+1}$: look-ahead word).