

UNIVERSITY OF COPENHAGEN  
Computer Science Department  
Data-Parallel Compilation  
Lexical analysis & Syntax Tree Construction

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**Abstract**

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## 1 Introduction

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## 2 Theory

Hills paper “Parallel lexical analysis and parsing on the AMT distributed array processor” [1] describes a method to obtain the path in a deterministic finite automata given a input string. This section will describe the theory of this method and extend the it for tokenization.

### 2.1 Data-parallel Lexical Analysis

To explain the theory of parallel lexical analysis we first remind the reader of the definition of a deterministic finite automaton.

**Definition 2.1** (DFA). A deterministic finite automata [2] [6] is given by a 5-tuple  $(Q, \Sigma, \delta, q_0, F)$  where.

1.  $Q$  is the set of states where  $|Q| < \infty$ .
2.  $\Sigma$  is the set of symbols where  $|\Sigma| < \infty$ .
3.  $\delta : \Sigma \times Q \rightarrow Q$  is the transition function.
4.  $q_0 \in Q$  is the initial state.
5.  $F \subseteq Q$  is the set of accepting states.

This definition is fine as is but we will need to reformualte it to develop data-parallel lexical analysis. We would want the definition to use a curried transition function. But for this to hold then the DFA would also have to be total.

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**Definition 2.2** (Total DFA). A DFA  $(Q, \Sigma, \delta, q_0, F)$  is said to be total if and only if

$$\delta(a, q) \in Q : \forall (a, q) \in \Sigma \times Q$$

If a DFA is total we may use a curried transition function  $\delta : \Sigma \rightarrow Q \rightarrow Q$ .

This is needed since else the the function would not be fully defined in the domains  $\Sigma$  and  $Q$ .

The reason for doing so is because if we have any two functions  $g = \delta(a)$  and  $f = \delta(a')$  then it follows from composition that.

$$g(f(q)) = (g \circ f)(q)$$

This allows for an alternative way of determining if a string can be produced by an DFA. Instead of first evaluating  $f(q)$ , then  $g(f(q))$  and then checking if this state is a member of  $F$ . We could instead partially apply  $\delta$  to the symbols and then compose them to a single function which could be used to determine if a string is valid. This sets the stage for data-parallel lexing, we want to find a way to make the problem into a **map-reduce**. We want to do this because it can be computed using a data-parallel implementation unlike the normal way of traversing a DFA.

For the ability to use a data-parallel **map-reduce** we must have a monoidal structure. Here  $\Delta$  is the set of all the composed partially applied  $\delta$  functions needs to be closed under function composition.

**Proposition 2.1** (DFA Composition Closure). Given a total DFA then the set of endofunctions  $\Delta : Q^Q$  will be closed under composition. The set  $\Delta$  is the set  $\Delta_i$  in the recurrence relation with the smallest  $i$  such that  $\Delta_i = \Delta_{i+1}$ .

$$\begin{aligned}\Delta_1 &= \{\delta(a) : a \in \Sigma\} \\ \Delta_{i+1} &= \Delta_i \cup \{f \circ g : f, g \in \Delta_i\}\end{aligned}$$

*Proof.* We will first by showing that a solution  $\Delta$  exists. First note that the cardinality is monotonically increasing i.e.  $\Delta_i \subseteq \Delta_{i+1}$  since  $\Delta_{i+1}$  is a union of  $\Delta_i$  and another set. Secondly note that since  $|Q| < \infty$  then a finite amount of functions of the form  $Q \rightarrow Q$  can exist. Since the set is bounded and increasing then at some point  $\Delta_i = \Delta_{i+1}$  and the smallest  $i$  where it holds is the solution  $\Delta$ .

For  $\Delta$  to be closed under composition, then for arbitrary  $f, g \in \Delta$  it must hold that  $f \circ g \in \Delta$ . Since  $\Delta_1$  is the set of endofunctions that constructs  $\Delta$  and composition is associative then all elements of  $\Delta$  can be expressed of the form.

$$\delta(a_1) \circ \dots \circ \delta(a_n) \in \Delta$$

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If all permutations with replacement of  $\Delta_1$  of any sequence length are members of  $\Delta$  then  $\Delta$  would be closed under composition. Furthermore, it is known that  $\Delta$  is finite so the sequences at some point  $\Delta_i = \Delta_{i+1}$  would only add new sequences but no new endofunctions. Therefore it suffices to show that if all sequences of length  $k$  where  $1 \leq k \leq i$  is a subset of  $\Delta_i$  then  $\Delta$  is closed under composition. This can be shown using a proof by induction.

Base:  $\Delta_1$  trivially holds since it only contains sequences of length one and they are the initial endofunctions.

Step: Given  $\Delta_i$  contains every sequence of length  $i$  or less then we to show this implies that  $\Delta_{i+1}$  will contain every sequence of length  $i + 1$  or less.

By the induction hypothesis  $\Delta_{i+1}$  must contain every sequence of length  $i$  or less due to  $\Delta_i \subseteq \Delta_{i+1}$ . It remains to show that every sequence of length  $i + 1$  is a member of  $\Delta_{i+1}$ . It is known that a direct product of  $\Delta_i$  is used in the definition of  $\Delta_{i+1}$  so  $\{f \circ g : f, g \in \Delta_i\} \subseteq \Delta_{i+1}$ . A direct product between sequences of length 1 and  $i$  will create every sequence of length  $i + 1$  and therefore every sequence of length  $i + 1$  is a member of  $\Delta_{i+1}$ . Thereby  $\Delta$  is closed under composition.  $\square$

Now since  $\Delta$  is closed under an arbitrary binary associative operations then it follows that  $\Delta$  and function composition induces a monoidal structure.

**Corollary 2.1** (DFA Composition Monoid). DFA composition closure induces a semigroup which in turn induces the monoid  $(\Delta \cup \{id\}, \circ)$  where  $id : Q \rightarrow Q$  and  $id(q) = q$ .

Knowing this we can establish the following algorithm

**Algorithm 2.1** (Data-parallel String Match). It can be determined in  $O(n)$  work and  $O(\log n)$  span if a string can be produced by a DFA. First construct the total DFA  $(Q, \Sigma, \delta, q_0, F)$  from the DFA.

1. Partially apply  $\delta$  to every symbol in the input string such that it becomes a sequence of endofunctions.

$$\mathbf{map} \, \delta [a_1, a_2, \dots, a_{n-1}, a_n] = [\delta(a_1), \delta(a_2), \dots, \delta(a_{n-1}), \delta(a_n)]$$

2. Reduce the endofunction into a single endofunction  $\delta' : Q \rightarrow Q$ .

$$\mathbf{reduce} \, (\circ) \, id [\delta(a_1), \delta(a_2), \dots, \delta(a_{n-1}), \delta(a_n)] = \delta'$$

3. Evaluate  $\delta'(q_0)$  and determine if  $\delta'(q_0) \in F$ .

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## 2.2 Data-parallel Tokenization

For data-parallel tokenization we need to extend data-parallel algorithm 2.1 will be needed to be extended. The idea will be to use a data-parallel `map-scan` instead since it will give all the states. This is also the methods described in Hills [1] paper. The problem is we need to be able to recognize the longest stretch of symbols that results in a token. And we also need to restart the traversal of DFA if a final state is hit while no options to traverse further. To do so we first need a function to define a function to recognize tokens.

**Definition 2.3** (Token Function). Given a DFA and a set of tokens  $T$ . The token function  $\mathcal{T} : F \rightarrow T$  is a function that maps accepting states to some token.

We will also need a single state to point to which is the dead state. This will become useful when the DFA needs to be traversed multiple times. Since we will need to be able to recognize when the end of a traversal is reached and we have to restart.

**Definition 2.4** (Total DFA with a Dead State). Given a DFA it is made total with a dead state by defining a new set of states  $Q' = Q \cup \{d\}$  where  $d$  is the dead state. Additionally a new transition function  $\delta'$  is defined.

$$\delta'(a, q) = \begin{cases} d & (a, q) \notin \text{dom}(\delta) \\ \delta(a, q) & \text{otherwise} \end{cases}$$

Now that we have a definition of a DFA where the dead state is known another problem is needed to be solved. The problem is as mentioned before that the traversal of the DFA has to be restarted if a dead state is reached after an accepting state. This is done using the following binary operation.

**Definition 2.5** (Safe Composition). Given a DFA with two endofunctions  $f = \delta(a)$  and  $g = \delta(b)$ . The operation  $\oplus$  makes  $f$  safe to compose such that it will continue traversing the DFA.

$$(f \oplus g)(x) = \begin{cases} q_0 & f(g(x)) = d \wedge g(x) \in F \\ g(x) & \text{otherwise} \end{cases}$$

This definition will make every possible final state become the initial state. This forgets the final state but it allows for the traversal to continue. The forgetfulness is not a problem this can be solved by looking at the previous endofunction. This puts a limit on the lexer which is it only allows for going back to the previous state if a dead state is hit. Using this and previous definitions can be put together to the following algorithm.

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**Algorithm 2.2** (Data-parallel Tokenization). Given a total DFA with a dead state where  $q_0 \notin F$  and a token function  $\mathcal{T} : F \rightarrow T$ . A string can be tokenized in  $O(n)$  work and  $O(\log n)$  span.

1. Let  $s = [a_1, a_2, \dots, a_{n-1}, a_n]$  be a string that will be tokenized then partially apply  $\delta$  to every symbol.

$$\mathbf{map}(\delta) s = x$$

2. Make every endofunction safe for composition beside for the last endofunction.

$$\mathbf{map}(\oplus) (\mathbf{init} x) (\mathbf{tail} x) ++ [\delta_n] = [\delta_1 \oplus \delta_2, \dots, \delta_{n-1} \oplus \delta_n, \delta_n] = y$$

3. Do a scan to get every composition.

$$\mathbf{scan}(\circ) id y = z$$

4. Compute the actual state and determine weather it is an end state<sup>1</sup>.

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let  $f = \lambda i \rightarrow$ 
  let  $s = \mathbf{if} i = 0 \mathbf{then} x[i](q_0) \mathbf{else} (z[i - 1] \circ x[i])(q_0)$ 
  in  $(i = n - 1 \vee (z[i](q_0) = q_0 \wedge s \in F), s)$ 
in map  $f$  (iota  $n$ )

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5. Remove every state that is not an ending state.

$$\mathbf{filter} (\lambda(b, s) \rightarrow b)$$

6. Assert that the ending state is an accepting state.

$$(\lambda(b, s) \rightarrow s \in F) \circ \mathbf{last}$$

7. Produce the token sequence.

$$\mathbf{map} (\lambda(b, s) \rightarrow \mathcal{T}(s))$$

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<sup>1</sup>If you were to also keep track of the index then the span of each token could also be found.

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*Proof.* We wish to show that the algorithm produces an array of paths where each path starts in  $q_0$  and is not included in the path. Knowing where these paths ends it can then be trivially used to construct the token sequence using the token function  $\mathcal{T}$ . We will also show that it can be correctly determine whether the DFA paths taken are correct.

We know in step 1-2. every endofunction is created and we know at this point either it maps to some original states or some maps to  $q_0$  because of safe composition. At step 3. a prefix sum using function composition is computed of these endofunctions. Which by Algorithm 2.1 can give us all states traversed in the DFA. But due to safe composition  $\oplus$  is used then an accepting state followed by an dead states will become the initial state  $q_0$ . This almost gives all the paths, since now when a final state in a path is reach it becomes the initial state and the traversal i restarted.

Then at step 4. the paths taken in the DFA from state  $q_0$  is found. We know for a given state  $s$  in a path it will can be one of these cases.

- If  $i = 0$  then  $x[i](q_0)$  will be the first state visited after  $q_0$  by definition of the transition function.
- If  $i \neq 0$  then  $s$  will be  $(z[i - 1] \circ x[i])(q_0)$ .  $z[i - 1](q_0)$  could wrongly map to  $q_0$  by definition of safe composition.
  - If  $z[i - 1](q_0)$  maps wrongly to  $q_0$  then the traversal of the DFA will be reset and  $(z[i - 1] \circ x[i])(q_0)$  will map to the correct state of a new path.
  - If  $z[i - 1](q_0)$  maps to the correct state then  $(z[i - 1] \circ x[i])(q_0)$  will also map to the correct state.

It can be determined where each path ends by the following predicate.

$$i = n - 1 \vee (z[i](q_0) = q_0 \wedge s \in F)$$

We know if  $i = n - 1$  then it must be the last state of the last path. The second case is if  $z[i](q_0) = q_0$  and  $s \in F$  holds. We know if  $z[i](q_0) = q_0$  holds then it is possible a final state was mapped to  $q_0$  by safe composition. And if  $s \in F$  then since  $q_0 \notin F$  we know  $z[i](q_0) \neq s$  meaning the reason  $z[i](q_0) = q_0$  must be because of a reset by safe composition meaning then it must be a final state in a path that is not the last path.

Step 5-7. will first keep every last state by this predicate. Afterwards it is asserted that the last state  $s \in F$ . Only the last state of the last path is needed since all previous path would had been valid else it would had not been reset by safe composition. Finally just map every state to the token it has.  $\square$

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**Example 2.1** (Problem with this method). If we had the following three patterns.

$$\tau_1 = a(a \quad \tau_2 = a+ \quad \tau_3 = a)a$$

Then the algorithm would not be able to determine the tokens for the following input.

$$a(aaa)a$$

The token sequence of this input could be determined to be  $\tau_1, \tau_2, \tau_3$  with spans  $(0, 3), (3, 4), (4, 7)$  if you reset at the last accepting state. But since the algorithm resets at the last state from an accepting state then it fails. Meaning it would be able to recognize  $\tau_1$ . The problem is at the token  $\tau_2$  would get the span  $(3, 5)$  and then the algorithm would not recognize any token with the pattern  $)a$ .

## 3 Implementation

### 3.1 Tokenization

The implementation of tokenization is done by a variation of 2.1. We do not have to do fixed point iteration on all of the endofunctions but only endofunctions that are neighbouring each other. Then when you compose two transitions then you would need to add them as new transitions. So if you had the following pattern you wanted to match  $abc$  then  $a$  is a neighbor to  $b$  and  $b$  is a neighbor to  $c$ . So initially we have a set of endofunctions.

$$\{\delta(a), \delta(b), \delta(c)\}$$

Then we compose both  $\delta(a)$  with  $\delta(b)$  and  $\delta(b)$  with  $\delta(c)$  since both pairs are neighbouring transitions. Then the set of the new composition together with the old compositions results in the set.

$$\{\delta(a), \delta(b), \delta(c)\} \cup \{\delta(a) \circ \delta(b), \delta(b) \circ \delta(c)\}$$

Now  $\delta(a) \circ \delta(b)$  is composed with  $\delta(c)$  and  $\delta(a)$  is composed with  $\delta(b) \circ \delta(c)$ . The set of these compositions are then unioned with the old set.

$$\{\delta(a), \delta(b), \delta(c), \delta(a) \circ \delta(b), \delta(b) \circ \delta(c)\} \cup \{\delta(a) \circ \delta(b) \circ \delta(c)\}$$

This ends up being the final set.

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## 3.2 Tree Construction

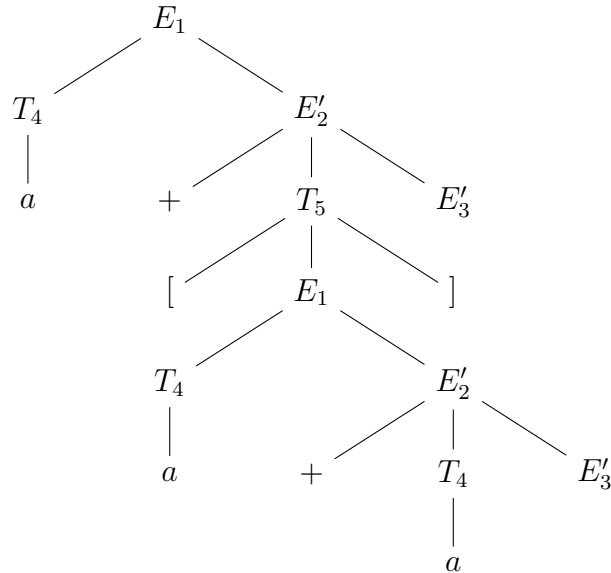
The alpacc parser generator is a parser generator which creates parser for the LLP grammar class. The LLP parsers described in the LLP parsing paper [4] only touches upon the verification and production sequence construction of parsing not the creation of the syntax tree. This would also had to be done in a data-parallel manner else we would run into a bottle-neck. A method for this is described in Voetters master thesis [5, pp. 32–33] about compilation on the GPU. Here it is described how to create a syntax tree using the representation from Hsu PhD dissertation [3, pp. 77–81] where you have a parent that can be used for multiple transformations of a syntax tree. The representation of the tree will be an array of nodes where each node has the index to its parent node. The nodes will also be given in a preorder traversal of the tree. This kind of representation is much more fit for data parallelism than som recursive datatype, since recursion does not play well with data-parallelism.

### 3.2.1 Overview of Tree Construction

So as an example we wish to construct syntax tree for the grammar.

- 1)  $E \rightarrow TE'$  2)  $E' \rightarrow +TE'$  3)  $E' \rightarrow \varepsilon$  4)  $T \rightarrow a$  5)  $T \rightarrow [E]$

Then for the input  $a + [a + a]$  we would want to construct the following tree.





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The first problem to tackle is terminals are not included in the left parse returned by the parser, currently it only returns the productions.

$$[E_1, T_4, E'_2, T_5, E_1, T_4, E'_2, T_4, E'_3, E'_3]$$

This problem can be solved by extending a given grammar  $(N, T, P, s)$  where  $N$  is the set of nonterminals,  $T$  is the set of terminals,  $P$  is the set of productions, and  $S$  is the initial nonterminal. The way we will extend the grammar is by adding productions that can be uniquely be related to the terminals. To do this extension we start by creating a secondary set of nonterminals.

$$N_T = \{A_t : t \in T\}, \text{ where } A_t \notin N \text{ for any } t \in T$$

And we also create an secondary set of productions.

$$P_T = \{A_t \rightarrow t : t \in T\}, \text{ where } A_t \rightarrow t \notin P \text{ for any } t \in T$$

Now we create a new set of productions by replacing every terminal in the right-hand side of a production by its corresponding nonterminal.

$$P_r = \{A \rightarrow \delta[A_t/t] : A \rightarrow \delta \in P\}$$

The final grammar that will be used for parsing is now.

$$G' = (N', T', P', S') = (N \cup N_T, T, P_r \cup P_T, S)$$

This does not affect which grammars can be parsed. To show this is correct for LLP parsing we first will need to show it is correct for LL parsing. The definition of a  $LL(k)$ <sup>2</sup> parsing table is as followed.

**Definition 3.1** ( $LL(k)$  table). Let  $G = (N, T, P, S)$  be a  $LL(k)$  context-free grammar and  $\tau : N \times T^* \rightarrow \mathbb{P}(\mathbb{N})$  denote the  $LL(k)$  table. For a given production  $A \rightarrow \delta = p_i \in P$  where  $i \in \{0, \dots, |P| - 1\}$  is a unique index.

$$i \in \tau(A, s) \text{ where } s \in \text{FIRST}_k(\delta) \bullet \text{FOLLOW}_k(A)$$

If for a given grammar it holds that  $|\tau(A, s)| \leq 1$  for all  $(A, s) \in N \times T^*$  then the grammar is  $LL(k)$ .

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<sup>2</sup>This exact definition was found in my Bachelor thesis.

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The reason for this not changing which grammars can be parse is if we have a grammar that is  $LL(k)$ . Then for a production  $A \rightarrow \delta \in P$  and a production  $A' \rightarrow \delta' \in P_r$  we have.

$$FIRST_k(\delta) \bullet^k FOLLOW_k(A) = FIRST_k(\delta') \bullet^k FOLLOW_k(A')$$

Since the first and follow-sets are unchanged for productions in  $P_r$  because all added nonterminals directly becomes their corresponding terminals in a derivation. Therefore none of these productions leads to a table conflict. Then for a production  $A_T \rightarrow t \in P_T$  we have.

$$i \in \tau(A_t, s) \text{ where } s \in FIRST_k(t) \bullet^k FOLLOW_k(A_T)$$

Since  $A_t$  only has a single production rule then it will always hold that  $|\tau(A_t, s)| \leq 1$ . Meaning the extended grammar  $G'$  will also be a  $LL(k)$  grammar.

Now the reason the grammar extension does not change which grammars can be parsed when it comes to LLP we need to look at the PSLS definition.

$$\begin{aligned} PSLS(x, y) = \{ & \alpha : \exists S \Rightarrow_{lm}^* wuA\beta \Rightarrow wxB\gamma \Rightarrow^* wxy\delta, \\ & w, u, y' \in T^*, a \in T, A, B \in N, \alpha, \beta, \gamma, \delta \in (N \cup T)^*, u \neq x, \\ & y = ay', \alpha \text{ is the shortest prefix of } B\gamma \\ & \text{such that } (y, \alpha, ()) \vdash^* (y', \omega, \pi) \} \\ \cup \{ & a : \exists S \Rightarrow^* wuA\beta \Rightarrow wxa\gamma \Rightarrow^* wxy\delta, \\ & a = FIRST_1(y), w, u \in T^*, \beta, \gamma, \delta \in (N \cup T)^*, u \neq x \} \end{aligned}$$

If we are given an admissible pair  $(x, y)$  where  $|PSLS(x, y)| = 1$  for some grammar  $G$  and some derivation.

$$S \Rightarrow_{lm}^* wuA\beta \Rightarrow wxB\gamma \Rightarrow^* wxy\delta$$

Where there only exists a single shortest prefix  $\alpha$  of  $B\gamma$  such that  $(y, \alpha, ()) \vdash^* (y', \omega, \pi)$  where  $\alpha$  may equal some  $a$ .

Then for the extended grammar  $G'$  then a derivation of the following form must also exists.

$$S' \Rightarrow_{lm}^* wu'A_tB'\gamma' \Rightarrow wxB'\gamma' \Rightarrow^* wxy\delta'$$

Both of the leftmost derivations will have the common subderivation  $wx$  since they still produce the same language and they both must produce  $x$ .

We know  $B\gamma$  and  $B'\gamma'$  are both produced by leftmost derivations. If we have two leftmost derivations from each grammar with a common terminal

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string i.e.  $S \Rightarrow_{lm}^* v\mu$  and  $S' \Rightarrow_{lm}^* v\mu'$ . Then we would know they only differ by the need to derive on  $A_t$ . Therefore substituting  $A_t$  with its terminal  $t$  one could map a derivation in  $G'$  to  $G$ . So therefore  $(B'\gamma')[t_1/A_{t_1}, \dots, t_n/A_{t_n}] = B\gamma$  and we can also go the other way  $B'\gamma' = (B\gamma)[A_{t_1}/t_1, \dots, A_{t_n}/t_n]$ . Since there is a one-to-one relation between derivations of  $wxB'\gamma'$  and  $wxB\gamma$  then there must also exist a single shortest prefix  $\alpha'$  of  $B'\gamma'$  such that  $(y, \alpha', ()) \vdash^* (y', \omega', \pi')$ . Since if  $B'\gamma'$  had multiple valid  $\alpha'$  then so would  $B\gamma$ .

If we are given an admissible pair  $(x, y)$  where  $|\text{PSLS}(x, y)| = 1$  for some grammar  $G$  and some derivation.

$$S \Rightarrow^* wuA\beta \Rightarrow wxa\gamma \Rightarrow^* wxy\delta$$

Where there only exists a single  $a = \text{FIRST}_1(y)$  where  $\alpha$  may equal some  $\alpha$ .

Then for the extended grammar  $G'$  then a derivation of the following form must also exist.

$$S' \Rightarrow_{lm}^* wu'A_tB'_a\gamma' \Rightarrow wxB'_a\gamma' \Rightarrow^* wxy\delta'$$

Once again we can reuse the same argument as before that there is a one-to-one relation between the derivations in  $G$  and  $G'$  i.e.  $(B'_a\gamma')[t_1/A_{t_1}, \dots, t_n/A_{t_n}] = a\gamma$  and  $B'_a\gamma' = (a\gamma)[A_{t_1}/t_1, \dots, A_{t_n}/t_n]$ .

$$[E_1, T_4, A_a, E'_2, A_+, T_5, A_[, E_1, T_4, A_a, E'_2, A_+, T_4, A_a, E'_3, A_], E'_3]$$

$$[E_1, T_4, a, E'_2, +, T_5, [, E_1, T_4, a, E'_2, +, T_4, a, E'_3, ], E'_3]$$

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Parent Index	Node
0	$E_1$
0	$T_4$
1	$a$
0	$E'_2$
3	$+$
3	$T_5$
5	$[$
5	$E_1$
7	$T_4$
8	$a$
7	$E'_2$
10	$+$
10	$T_4$
12	$a$
10	$E'_3$
5	$]$
3	$E'_3$

## 4 Conclusion

Conclusion.

## References

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