Programming Languages
(CS 550)
Lecture 4 Summary
Scanner and Parser Generators

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Theme

- We have now seen how to describe syntax using regular expressions and grammars and how to create scanners and parsers, by hand and using automated tools. In this lecture we provide more details on parsing and scanning and indicate how these tools work.

- Reading: chapter 2 of the text by Scott.
Parser and Scanner Generators

- Tools exist (e.g. yacc/bison\(^1\) for C/C++, PLY for python, CUP for Java) to automatically construct a parser from a restricted set of context free grammars (LALR(1) grammars for yacc/bison and the derivatives CUP and PLY).
- These tools use table driven bottom up parsing techniques (commonly shift/reduce parsing).
- Similar tools (e.g. lex/flex for C/C++, Jflex for Java) exist, based on the theory of finite automata, to automatically construct scanners from regular expressions.

\(^1\)bison in the GNU version of yacc
Outline

- Scanners and DFA
- Regular Expressions and NDFA
- Equivalence of DFA and NDFA
- Regular Languages and the limitations of regular expressions
- Recursive Descent Parsing
- LL(1) Grammars and Top-down (Predictive) Parsing
- LR(1) Grammars and Bottom-up Parsing
Regular Expressions

- Alphabet = $\Sigma$
- A language over $\Sigma$ is subset of strings in $\Sigma$
- Regular expressions describe certain types of languages
  - $\emptyset$ is a regular expression
  - $\epsilon = \{\epsilon\}$ is a regular expression
  - For each $a$ in $\Sigma$, $\{a\}$ is a regular expression
  - If $r$ and $s$ are regular expressions denoting languages $R$ and $S$ respectively then $(r \mid s)$, $(rs)$, and $(r^*)$ are regular expressions
- E.G.  00, (0|1)*, (0|1)*00(0|1)*, 00*11*22*, (1|10)*
List Tokens

- LPAREN = ‘(‘
- RPAREN = ‘)’
- COMMA = ‘,’
- NUMBER = DIGIT DIGIT*
- DIGIT = 0|1|2|3|4|5|6|7|8|9
- Unix shorthand: [0-9], DIGIT+
- Whitespace: (‘ ’ | ‘\n’ | ‘\t’)∗
List Scanner

TOKEN GetToken()
{
    int val = 0;
    if (c = getchar() == eof) then return None end if;
    while c ∈ {‘ ’, ‘\n’, ‘\t’} then c = getchar() end do;
    if c ∈ {‘(’, ‘,’ , ‘)’} then return c end if;
    if c ∈ {‘0’,…, ‘9’} then
        while c ∈ {‘0’,…, ‘9’} do
            val = val*10 + (c – ‘0’);  c = getchar();
        end do;
        putchar(c);  return (NUMBER,val);
    else
        return None;
    end if;
}
Flex List Tokens

{%
#include "list.tab.h"
extern int yylval;
%

%%
[ \t\n] ;
"(" return yytext[0];
")" return yytext[0];
"," return yytext[0];
[0-9]+ { yylval = atoi(yytext); return NUMBER; }
%%
Deterministic Finite Automata

- Input comes from alphabet $A$
- Finite set of states, $S$, start state, $s_0$, Accepting States, $F$
- Transition $T$ from state to state depending on next input
  $M = (A,S,s_0,F,T)$
- The language accepted by a finite automata is the set of input strings that end up in accepting states
Example 1

- Create a finite state automata that accepts strings of a’s and b’s with an even number of a’s.

![Automata Diagram](image)
Program to implement DFA

bool EA()
{
  S0:  x = getchar();
      if (x == ‘b’) goto S0;
      if (x == ‘a’) goto S1;
      if (x == ENDM) return true;
  S1:  x = getchar();
      if (x == ‘b’) goto S1;
      if (x == ‘a’) goto S0;
      if (x == ENDM) return false;
}
List DFA
Calculator Tokens

- **ASSIGN = ‘:=’**
- **PLUS = ‘+’, MINUS = ‘-’, TIMES = ‘*’, DIV = ‘/’**
- **LPAREN = ‘(’, RPAREN = ‘)’**
- **NUMBER = DIGIT DIGIT* | DIGIT* (. DIGIT|DIGIT .) DIGIT**
- **ID = LETTER (LETTER | DIGIT)**
- **DIGIT = 0|1| … |9, LETTER = a|…|z|A|…|Z**
- **COMMENT = /* (non-* | * non-/)* */ | // (non-newline)* newline**
- **WHITESPACE = (‘ ’ | ‘\n’ | ‘\t’)**
Calculator DFA
# Table Driven Scanner

| State | ',' | 't' | '
' | '/' | '*' | '(' | ')' | '+' | '-' | ':' | '=' | ' ' | digit | letter | other token |
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Non-Deterministic Finite Automata

- Same as DFA $M = (A, S, s_0, F, T)$ except
  - Can have multiple transitions from the same state with the same input
  - Can have epsilon transitions
  - Except input strings if there is a path to an accepting state

- The languages accepted by NDFA are the same as DFA
Example 2a

- DFA accepting \((a|b)^*abb\)
Example 2b

- NDFA accepting \((a|b)^*abb\)
Simulating an NDFA

- Compute $S =$ set of states NDFA could be in after reading each symbol in the input.
- $S_i =$ set of possible states after reading $i$ input symbols

1. Initialize $S_0 =$ EpsilonClosure{0}
2. for $i = 1, \ldots, \text{len(str)}$
   1. $T_i = \bigcup_{s \in S_{i-1}} T[s, \text{str}[i]]$
   2. $S_i =$ EpsilonClosure($T_i$)

\[
\begin{align*}
&b &a &b &b \\
&\{0,1\} &\{0,1\} &\{0,1,2\} &\{0,1,3\} &\{0,1,4\}
\end{align*}
\]
NDFA from Regular Expressions

- **Base case** – $c$

- **Union** – $R|S$

- **Concatenation** – $RS$

- **Closure** – $R^*$
Example 3

- Construct a NDFA that accepts the language generated by the regular expression (a|bc)
Regular Expression Compiler

```c
#include "machine.h"
char input[100];
%
union {
    MachinePtr ndfa;
    char symbol;
}
%
%token <symbol> LETTER
%type <ndfa> regexp
%type <ndfa> cat
%type <ndfa> kleene
%%

statement: regexp {
    do {
        printf("Enter string\n");
        if (scanf("%s",input) != EOF)
            Simulate($1,input);
        else exit(1);
    } while (1); }
regexp:   regexp '|' cat  { $$ = MachineOr($1,$3); }
          |     cat     { $$ = $1; }  ;
cat:      cat kleene { $$ = MachineConcat($1,$2); }
          |   kleene     { $$ = $1; } ;
kleene:   '(' regexp ')' { $$ = $2; }
          |    kleene '*'     { $$ = MachineStar($1); }
          |    LETTER         { $$ = BaseMachine($1); }
%%
```
NDFA → DFA

- Find an equivalent DFA for Example 3
  - States in DFA are sets of states from NDFA [keep track of all possible transitions]
Exercise 1

1. Construct NDFA that recognizes (see pages 55-57 of text)
   1. \(d^* (.d \mid d.) d^*\)

2. Convert NDFA from (1) to DFA (see pages 56-58 of text)
Solution 1.1
Solution 1.2
Minimizing States in DFA

- The exists a unique minimal state DFA for any language described by a regular expression

- Combine equivalent states
  - \( p \equiv q \) if for each input string \( x \) \( T(p,x) \) is an accepting state iff \( T(q,x) \) is an accepting state
  - Initialize two sets of states: accepting and non-accepting
  - Partition state sets which transition into multiple sets of states
Exercise 2

1. Find an equivalent DFA to the one in Exercise 1 that minimizes the number of states (see page 59 of text)

Ambiguity: $T(A,d) = T(B,d) \neq T(C,d) \Rightarrow$ split $ABC \rightarrow AB,C$
Solution 2

A → B
d

C → DEFG
d

B → DEFG
d
The languages accepted by finite automata are equivalent to those generated by regular expressions

- Given any regular expression $R$, there exists a finite state automata $M$ such that $L(M) = L(R)$
  - Proof is given by previous construction
- Given any finite state automata $M$, there exists a regular expression $R$ such that $L(R) = L(M)$
  - The basic idea is to combine the transitions in each node along all paths that lead to an accepting state. The combination of the characters along the paths are described using regular expressions.
Example 4

Create a regular expression for the language that consists of strings of a’s and b’s with an even number of a’s.

$b^*|(b^*ab^*)^*$
Grammars and Regular Expressions

- Given a regular expression $R$, there exists a grammar with syntactic category $<S>$ such that $L(R) = L(<S>)$.

- There are grammars such that there does NOT exist a regular expression $R$ with $L(<S>) = L(R)$.

  - $<S> \rightarrow a<S>b | \epsilon$
  - $L(<S>) = \{a^n b^n, \ n=0,1,2,\ldots\}$
Example 5

- Create a grammar that generates the language that consists of strings of a’s and b’s with an even number of a’s.

\[
\begin{align*}
<S0> & \rightarrow b<S0> \\
<S0> & \rightarrow a<S1> \\
<S0> & \rightarrow \varepsilon \\
<S1> & \rightarrow b<S1> \\
<S1> & \rightarrow a<S0>
\end{align*}
\]
Proof that $a^n b^n$ is not Recognized by a Finite State Automata

To show that there is no finite state automata that recognizes the language $L = \{a^n b^n, n = 0,1,2,\ldots\}$, we assume that there is a finite state automata $M$ that recognizes $L$ and show that this leads to a contradiction.

Since $M$ is a finite state automata it has a finite number of states. Let the number of states = $m$.

Since $M$ recognizes the language $L$ all strings of the form $a^k b^k$ must end up in accepting states. Choose such a string with $k = n$ which is greater than $m$. 
Proof that \(a^n b^n\) is not Recognized by a Finite State Automata

- Since \(n > m\) there must be a state \(s\) that is visited twice while the string \(a^n\) is read [we can only visit \(m\) distinct states and since \(n > m\) after reading \((m+1)\) a’s, we must go to a state that was already visited].

- Suppose that state \(s\) is reached after reading the strings \(a^j\) and \(a^k\) (\(j \neq k\)). Since the same state is reached for both strings, the finite state machine can not distinguish strings that begin with \(a^j\) from strings that begin with \(a^k\).

- Therefore, the finite state automata must either accept or reject both of the strings \(a^j b^j\) and \(a^k b^j\). However, \(a^j b^j\) should be accepted, while \(a^k b^j\) should not be accepted.
List Grammar

- \(< \text{list} > \rightarrow ( < \text{sequence} > ) | ( )\)

- \(< \text{sequence} > \rightarrow < \text{listelement} > , < \text{sequence} > \mid < \text{listelement} >\)

- \(< \text{listelement} > \rightarrow < \text{list} > \mid \text{NUMBER}\)
Recursive Descent Parser

list()
{
    match('(');
    if token ≠ ')
    then
        seq();
    endif;
    match(')');
}
Recursive Descent Parser

seq()
{
  elt();
  if token = ‘,’ then
    match(‘,’);
  seq();
  endif;
}

Recursive Descent Parser

elt()
{
    if token = '(' then
        list();
    else
        match(NUMBER);
    endif;
}

Yacc (bison) Example

%token NUMBER /* needed to communicate with scanner */

%%

list:

    '(' sequence ')' { printf("L -> ( seq )\n"); }
|   '(' ')' { printf("L -> () \n "); }

sequence:

    listelement ',' sequence { printf("seq -> LE,seq\n"); }
|   listelement { printf("seq -> LE\n"); } ;

listelement:

    NUMBER { printf("LE -> %d\n",$1); }
|   list { printf("LE -> L\n"); } ;

/* since no code here, default main constructed that simply calls parser. */
Top-down vs. Bottom-up Parsing

```
id_list
  id_A, id_list_tail

id_list
  id_A, id_list_tail
    , id_B, id_list_tail
      , id_C, id_list_tail

id_list
  id_A, id_list_tail
    , id_B, id_list_tail
      , id_C, id_list_tail

id_list -> id id_list_tail
id_list_tail -> , id id_list_tail
id_list_tail -> ;
```

```
id(A), id(B)
id(A), id(B), id(C)
id(A), id(B), id(C) ;
```

```
id(A), id(B) id_list_tail
  , id_C, id_list_tail

id(A) id_list_tail
  , id_B, id_list_tail
    , id_C, id_list_tail

id(A) id_list_tail
  , id_B, id_list_tail
    , id_C, id_list_tail
```

Bottom-up Parsing LR Grammar

\[
\begin{align*}
    id(A) \\
    id\_list\_prefix \\
    \quad id(A) \\
    id\_list\_prefix \ , \ id(B) \\
    \quad id(A) \\
    id\_list\_prefix \\
    \quad id\_list\_prefix \ , \ id(B) \\
    \quad id(A) \\
    id\_list \rightarrow id\_list\_prefix \ ; \\
    id\_list\_prefix \rightarrow id\_list\_prefix \ , \ id \\
    \rightarrow id
\end{align*}
\]
LR Calculator Grammar

Figure 2.24

Program → stmt list $$
stmt_list → stmt_list stmt
     | stmt
stmt → id := expr
     | read id
     | write expr
expr → term
     | expr add op term
term → factor
     | term mult op factor
factor → ( expr )
     | id
     | number
add op → + | -
mult op → * | /
Here is an LL(1) grammar (Fig 2.15): 

1. program → stmt_list $$
2. stmt_list → stmt stmt_list
3. |
4. stmt → id := expr
5. | read id
6. | write expr
7. expr → term term_tail
8. term_tail → add op term term_tail
9. | ε
LL(1) grammar (continued)

10. term → factor fact_tail
11. fact_tail → mult_op fact fact_tail
12. | ε
13. factor → ( expr )
14. | id
15. | number
16. add_op → +
17. | –
18. mult_op → *
19. | /
Predictive Parser

- Predict which rules to match

- \( A \rightarrow \alpha \)
  - when next token can start \( \alpha \)
  - \( \alpha \rightarrow ^* \varepsilon \) and the next token can follow \( A \)

- \( \text{PREDICT}(A \rightarrow \alpha) = \text{FIRST}(\alpha) \cup \text{FOLLOW}(A) \) if \( \text{EPS}(\alpha) \)
  - \( \text{PREDICT}(\text{program} \rightarrow \text{stmt_list} \; $$) \)
  - \( \text{FIRST}(\text{stmt_list}) = \{\text{id, read, write}\} \)
  - \( \text{FOLLOW}(\text{stmt_list}) = \{$$\} \)

- Intersection of \( \text{PREDICT} \) sets for same lhs must be empty
Recursive Descent Parser

procedure program
  case input_token of
    id, read, write, $$:
      stmt_list; match($$)
    otherwise error
  end;

procedure stmt_list
  case input_token of
    id, read, write:
      stmt; stmt_list
    $$: skip
    otherwise error
  end;

procedure stmt
  case input_token of
    id:  match(id); match(:=); expr
    read: match(read); match(id)
    write: match(write); expr
    otherwise error
  end;

procedure expr
  case input_token of
    id, number, (: term; termtail
    otherwise error
  end;

procedure termtail
  case input_token of
    +, -: add_op; term; term_tail
    , id, read, write, $$: skip
    otherwise error
  end;

procedure term
  case input_token of
    id, number, (: factor; factor_tail
    otherwise error
  end;
Exercise 3

Trace through the recursive descent parser and build parse tree for the following program

1. read A
2. read B
3. sum := A + B
4. write sum
5. write sum / 2
Solution 3
# Table-Driven LL Parser

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<th>id</th>
<th>number</th>
<th>read</th>
<th>Current input token</th>
<th>write</th>
<th>:=</th>
<th>( )</th>
<th>+</th>
<th>–</th>
<th>*</th>
<th>/</th>
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</tr>
<tr>
<td>term_tail</td>
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<td>add_op</td>
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<td>–</td>
</tr>
</tbody>
</table>
Table-Driven LL Parser

**Parse Stack**

program
stmt_list $$
read id stmt_list $$
stmt_list $$
stmt stmt_list $$
...
stmt_list $$
$$

**Input Stream**

read A read B …
read A read B …
read A read B …
A read B …
read B …

**Comment**

Initial stack contents
program → stmt_list $$
stmt_list → stmt stmt_list
stmt → read id
match(read)
match(id)
stmt_list → stmt stmt_list
...
term_tail → ε
stmt_list → ε
Algorithm First/Follow/Predict:

- FIRST(\(\alpha\)) = \{c : \alpha \rightarrow^* c \beta\}
- FOLLOW(A) = \{c : S \rightarrow^+ \alpha A c \beta\}
- EPS(\(\alpha\)) = \text{if } \alpha \rightarrow^* \varepsilon \text{ then true else false}
- Predict (A \rightarrow \alpha) = FIRST(\(\alpha\)) \cup (\text{if EPS}(\alpha) \text{ then FOLLOW(A) else } \emptyset)
Predict Set for LL Parser

FIRST

program {id, read, write, $$}
stmt_list {id, read, write, $$}
stmt {id, read, write}
expr {(), id, number}
term_tail {+, -, $$}
term {(), id, number}
factor_tail {*, /, $$}
factor {(), id, number}
add_op {+, -}
mult_op {*, /}

Also note that FIRST(a) = \{a\} \forall tokens a.

FOLLOW

id {+, -, *, /, :=, id, read, write, $$}
number {+, -, *, /, :=, id, read, write, $$}
read {id}
write {(), id, number}
( {(), id, number}
) {+, -, *, /, :=, id, read, write, $$}
:= {(), id, number}
+ {(), id, number}
- {(), id, number}
* {(), id, number}
/ {(), id, number}
$$ {\epsilon}
expr {(), id, read, write, $$}
term_tail {+, -, $$}
term {+, -, $$}
factor_tail {+, -, $$}
factor {+, -, $$}
add_op {(), id, number}
mult_op {(), id, number}

PREDICT

1. program \rightarrow stmt_list $$ {id, read, write, $$}
2. stmt_list \rightarrow stmt stmt_list {id, read, write}
3. stmt_list \rightarrow $$
4. stmt \rightarrow id := expr {id}
5. stmt \rightarrow read id {read}
6. stmt \rightarrow write expr {write}
7. expr \rightarrow term term_tail {+, -}
8. term_tail \rightarrow add_op term term_tail {+, -}
9. term_tail \rightarrow $$
10. term \rightarrow factor factor_tail {*, /}
11. factor_tail \rightarrow mult_op factor factor_tail {*, /}
12. factor_tail \rightarrow $$
13. factor \rightarrow ( expr ) {()}
14. factor \rightarrow id {id}
15. factor \rightarrow number {number}
16. add_op \rightarrow + {+}
17. add_op \rightarrow - {-}
18. mult_op \rightarrow * {\ast}
19. mult_op \rightarrow / {/}

Figure 2.22: FIRST, FOLLOW, and PREDICT sets for the calculator language.
LR Parsing

- Bottom up (rightmost derivation)
  - Maintain forest of partially completed subtrees of the parse tree
  - Join trees together when recognizing symbols in rhs of production
  - Keep roots of partially completed trees on stack
    - Shift when new token
    - Reduce when top symbols match rhs
- Table driven
Top-down vs. Bottom-up Parsing

```
id_list
  id_list
  id(A)  id_list_tail

  id_list
  id(A)  id_list_tail
    ,  id(B)  id_list_tail

  id_list
  id(A)  id_list_tail
    ,  id(B)  id_list_tail
      ,  id(C)  id_list_tail

id_list → id  id_list_tail
id_list_tail → ,  id  id_list_tail
id_list_tail → ;
```

```
id(A)
  id(A)  ,  id(B)
  id(A)  ,  id(B)  ,  id(C)
  id(A)  ,  id(B)  ,  id(C)

id(A)  ,  id(B)  ,  id(C)  id_list_tail
  ,  id(C)  id_list_tail

id(A)  ,  id(B)  ,  id(C)  id_list_tail
  ,  id(C)  id_list_tail

id(A)  id_list_tail
  ,  id(B)  id_list_tail
    ,  id(C)  id_list_tail

id(A)  id_list_tail
  ,  id(B)  id_list_tail
    ,  id(C)  id_list_tail

id_list
  id(A)  id_list_tail
    ,  id(B)  id_list_tail
      ,  id(C)  id_list_tail
  id(A)  id_list_tail
    ,  id(B)  id_list_tail
      ,  id(C)  id_list_tail
```
LR Parsing Example

Stack
ε
id(A)
id(A), id(B)
id(A), id(B), id(C)
id(A), id(B), id(C) id_list_tail
id(A), id(B) id_list_tail
id(A) id_list_tail
id_list

Remaining Input
A, B, C;
, B, C;
B, C;
, C;
C;
;
LR Calculator Grammar

(Figure 2.24, Page 73):

1. program → stmt list $$
2. stmt_list → stmt_list stmt
3. \| stmt
4. stmt → id := expr
5. \| read id
6. \| write expr
7. expr → term
8. \| expr add op term
LR Calculator Grammar

LR grammar (continued):

9. term → factor
10. | term mult_op factor
11. factor → ( expr )
12. | id
13. | number
14. add op → +
15. | −
16. mult op → ∗
17. | /
LR Parser State

- Keep track of set of productions we might be in along with where in those productions we might be

- Initial state for calculator grammar

program → . stmt_list $$ // basis
stmt_list → . stmt_list stmt // yield
stmt_list → . stmt
stmt → . id := expr
stmt → . write expr
LR Parser States

<table>
<thead>
<tr>
<th>State</th>
<th>Transitions</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. <code>stmt</code></td>
<td>read : id</td>
</tr>
<tr>
<td>2. <code>stmt</code></td>
<td>read : expr</td>
</tr>
<tr>
<td>3. <code>stmt</code></td>
<td>write : expr</td>
</tr>
<tr>
<td>4. <code>stmt</code></td>
<td>read : car</td>
</tr>
<tr>
<td>5. <code>stmt</code></td>
<td>write : term</td>
</tr>
<tr>
<td>6. <code>stmt</code></td>
<td>write : addExp term</td>
</tr>
</tbody>
</table>

Figure 2.25: CFSM for the calculator grammar (Figure 2.24). Basis and closure items in each state are separated by a horizontal rule. Trivial reduce-only states have been eliminated by use of "shift and reduce" transitions (continued).
Figure 2.26: Pictorial representation of the CFSM of Figure 2.25. Symbol names have been abbreviated for clarity. Reduce actions are not shown.
### LR Parser Table

<table>
<thead>
<tr>
<th>Top-of-stack state</th>
<th>sl</th>
<th>s</th>
<th>e</th>
<th>t</th>
<th>f</th>
<th>ao</th>
<th>mo</th>
<th>Current input symbol</th>
<th>id</th>
<th>lit</th>
<th>r</th>
<th>w</th>
<th>:=</th>
<th>( )</th>
<th>+</th>
<th>−</th>
<th>*</th>
<th>/</th>
<th>$$</th>
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<tbody>
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</tr>
</tbody>
</table>

Figure 2.27: **SLR(1) parse table for the calculator language.** Table entries indicate whether to shift (s), reduce (r), or shift and then reduce (b). The accompanying number is the new state when shifting, or the production that has been recognized when (shifting and) reducing. Production numbers are given in Figure 2.24. Symbol names have been abbreviated for the sake of formatting. A dash indicates an error. An auxiliary table, not shown here, gives the left-hand side symbol and right-hand side length for each production.
<table>
<thead>
<tr>
<th>Parse stack</th>
<th>Input stream</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>read A read B ...</td>
<td>shift read</td>
</tr>
<tr>
<td>0</td>
<td>A read B ...</td>
<td>shift id(a) &amp; reduce by stmt — read id</td>
</tr>
<tr>
<td>0</td>
<td>stmt read B ...</td>
<td>shift stmt &amp; reduce by stmtList — stmt</td>
</tr>
<tr>
<td>0 stmtList 2</td>
<td>read i</td>
<td>shift stmtList</td>
</tr>
<tr>
<td>0 stmtList 2</td>
<td>B sum := ...</td>
<td>shift read</td>
</tr>
<tr>
<td>0 stmtList 2</td>
<td>stmt sum := ...</td>
<td>shift id(B) &amp; reduce by stmt — read id</td>
</tr>
<tr>
<td>0 stmtList 2</td>
<td>stmt sum := ...</td>
<td>shift stmt &amp; reduce by stmtList — stmtList stmt</td>
</tr>
<tr>
<td>0 stmtList 2</td>
<td>sum := B := ...</td>
<td>shift stmt &amp; reduce by termList — term</td>
</tr>
<tr>
<td>0 stmtList 2</td>
<td>A + B := ...</td>
<td>shift id(a) &amp; reduce by factor — id</td>
</tr>
<tr>
<td>0 stmtList 2</td>
<td>factor := ...</td>
<td>shift factor &amp; reduce by term — factor</td>
</tr>
<tr>
<td>0 stmtList 2</td>
<td>term := ...</td>
<td>shift factor &amp; reduce by term — factor</td>
</tr>
<tr>
<td>0 stmtList 2</td>
<td>+ B write ...</td>
<td>shift expr</td>
</tr>
<tr>
<td>0 stmtList 2</td>
<td>B write ...</td>
<td>shift + &amp; reduce by addOp — +</td>
</tr>
<tr>
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<td>addOp write ...</td>
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</tr>
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<td>write stmtList 10</td>
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</tr>
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<td>write expr 9</td>
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<td>expr write 9</td>
<td>shift factor &amp; reduce by term — factor</td>
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<td>reduce by expr — expr</td>
</tr>
<tr>
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<td>reduce by expr — expr</td>
</tr>
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<td>0 stmtList 2</td>
<td>write 7</td>
<td>shift addOp &amp; reduce by addOp — addOp</td>
</tr>
<tr>
<td>0 stmtList 2</td>
<td>write 7</td>
<td>shift addOp &amp; reduce by addOp — addOp</td>
</tr>
<tr>
<td>0 stmtList 2</td>
<td>addOp write 7</td>
<td>shift addOp &amp; reduce by addOp — addOp</td>
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<tr>
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<td>shift addOp &amp; reduce by addOp — addOp</td>
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<td>addOp write 7</td>
<td>shift addOp &amp; reduce by addOp — addOp</td>
</tr>
<tr>
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<td>write 7</td>
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<td>addOp write 7</td>
<td>shift addOp &amp; reduce by addOp — addOp</td>
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<td>addOp write 7</td>
<td>shift addOp &amp; reduce by addOp — addOp</td>
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