LR(0) Drawbacks

Consider the unambiguous augmented grammar:

```
0.) S → E $
1.) E → T + E
2.) E → T
3.) T → x
```

If we build the LR(0) DFA table, we find that there is a shift-reduce conflict.

This arises because the reduce rule was too naïve for LR(0). It put the reduce action for all terminals, when realistically, we would only reduce when we see something in the Follow set of the production we are reducing by.

Simple LR (SLR)

New algorithm for adding reduce actions into an SLR table:

```
R ← {}
for each state I in T
    for each item A → α• in I
        for each token X in Follow(A)
            R ← R ∪ {(I, X, A→α)}
            //i.e., M[I, X] = rn
```

SLR is actually useful as it is powerful enough to deal with many programming language constructs we'd wish to use.

However, SLR parsers cannot do handle constructs such as pointer dereferences in C.

SLR Parse

Stack	Input	Action
$ s1	x + x + x $	Shift 5
$ s1 x s5	+ x + x $	Reduce T → x
$ s1 T s3	+ x + x $	Shift 4
$ s1 T s3 + s4	x + x $	Shift 5
$ s1 T s3 + s4 x s5	+ x $	Reduce T → x
$ s1 T s3 + s4 T s3	+ x $	Shift 4
$ s1 T s3 + s4 T s3 + s4	x $	Shift 5
$ s1 T s3 + s4 T s3 + s4 x s5	$	Reduce T → x
$ s1 T s3 + s4 T s3 + s4 T s3	$	Reduce E → T
$ s1 T s3 + s4 T s3 + s4 E s6	$	Reduce E → T + E
$ s1 T s3 + s4 E s6	$	Reduce E → T + E
$ s1 E s2	$	Accept

	x	+	$	E	T
1	s5			g2	g3
2			a		
3		s4	r2		
4	s5			g6	g3
5		r3	r3		
6			r1		

LR(1)

An LR(1) item consists of:

- A grammar production,
- A right-hand-side position (•), and
- A lookahead symbol.

An LR(1) item (A →α•β, x) indicates that the sequence α is on top of the stack, and at the head of the input is a string derivable from βx.

LR(1) Items

```
Closure(I) =
    repeat
        for any item (A → α•Xβ, z) in I
            for any production X →γ
                for any w ∈ First(βz)
                    I ← I ∪ {(X →•γ , w)}
    until I does not change
    return I

Goto(I, X) =
    J ← {}
    for any item (A →α•Xβ, z) in I
        add (A →αX•β, z) to J
    return Closure(J).
```

LR(1) Start State and Reduce

The start state is the closure of the item (S → •S $, ?), where the lookahead symbol ? will not matter, because $ will never be shifted.

Reduce actions are chosen by this algorithm:

```
R ← {}
for each state I in T
    for each item (A →α•, z) in I
        R ← R ∪ {(I, z, A →α)}
```

LR(1) Drawbacks

The number of states is now potentially huge.

Every SLR(1) grammar is LR(1) but LR(1) has more states than SLR(1) – orders of magnitude differences

LALR(1) – look ahead LR parsing method

- Used in practice because most syntactic structure can be represented by LALR (not true for SLR)
- Same number of states as SLR
- Can be constructed by merging states with the same core

Construction on LALR Parser

One solution:

- construct LR(1) items
- merge states ignoring lookahead
- if no conflicts, you have a LALR parser

Inefficient because of building LR(1) items are expensive in time and space

Efficient construction of LALR parsers

- avoid construction of LR(1) items
- construction states containing only LR(0) kernel items
- compute look ahead for the kernel items
- predict actions using kernel items

LALR vs. LR Parsing

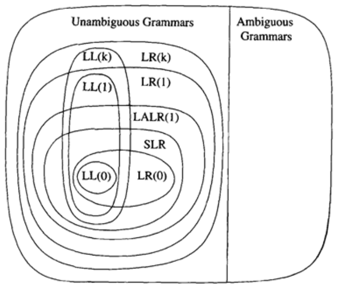
LALR languages are not natural

- They are an efficiency hack on LR languages

Any reasonable programming language has a LALR(1) grammar

LALR(1) has become a standard for programming languages and for parser generators

A Hierarchy of Grammar Classes



Summary

Regular languages were insufficient for programming language constructs. While entire programs are not context free, the grammars of most programming languages are.

Approaches to CFG parsers usually limit the grammar productions in some way to reduce the cost of parsing.

Top-down parsers try to parse from the start symbol to the sentence:

- Recursive descent parsers may backtrack and get stuck in left recursion
- LL(1) works without backtracking, but requires left-factored languages

More powerful parsers can be built bottom-up: LR(k)

- LL(0) is insufficient, but SLR can be useful.
- LR(1) is huge but LALR(1) is powerful and fast enough for most programming language constructs today.

Generating Parsers

Using Parser Generator

Most common parser generators are LALR(1)

A parser generator constructs a LALR(1) table and reports an error when a table entry is multiply defined

- A shift and a reduce – report shift/reduce conflict
- Multiple reduces – report reduce/reduce conflict

- An ambiguous grammar will generate conflicts
- Must resolve conflicts

Shift/Reduce Conflicts

Typically due to ambiguities in the grammar
Classic example: the dangling else

```
S → if  E then S | if E then S else S | …
```

will have DFA state containing

```
[S → if E then S•, else]
[S → if E then S• else S, x]
```

If `else` follows `then` we can shift or reduce.

The default (YACC, bison, Java CUP, etc.) resolution is to shift

- The default behavior is correct in this case

More Shift/Reduce Conflicts

Consider the ambiguous grammar:

```
E → E+E | E*E | int
```

we will have the states containing:

```
[E → E*•E, +]            [E → E*E•, +]
                   E
[E → •E+E, +]      ⇒     [E → E•+E, +]
. . .                    . . .
```

We have a shift/reduce conflict on input +

- we need to reduce (* is higher than +)
- **Solution**: specify the precedence of * and +

Dangling Else

Back to our dangling else example

```
[S → if E then S•, else]
[S → if E then S• else S, x]
```

can eliminate conflict by declaring `else` with higher precedence than `then`

But this starts to look like "hacking the tables"

Best to avoid overuse of precedence declarations or you will end with unexpected parse trees.

Reduce/Reduce Conflicts

Usually due to ambiguity in the grammar

Example: a sequence of identifiers

```
S → ε | id | id S
```

There are two parse trees for the string id

```
S → id
S → id S → id
```

How does this confuse the parser?

Reduce/Reduce Conflicts

Consider the states

```
[S'→ •S, $]                 [S → id•, $]
[S → •, $]                  [S → id•S, $]
                     E
[S → •id, $]         ⇒      [S → •, $]
[S → •id S, $]              [S → •id, $]
                            [S → •id S, $]
```

Reduce/reduce conflict on input "id$"

```
S' → S → id
S' → S → id S → id
```

Better to rewrite the grammar:

```
S → ε | id S
```

Semantic Actions

Semantic actions are implemented for LR parsing

- keep attributes on the semantic stack – parallel syntax stack
- on shift a, push attribute for a on semantic stack
- on reduce $X \rightarrow \alpha$
  - pop attributes for α
  - compute attribute for X
  - push it on the semantic stack

Create AST

- Bottom up
- Creating leaf node for tokens and create internal nodes from subtrees.

Error Recovery

Error detected when parser consults parsing table

- empty entry
- Canonical LR will not make a single reduction before announcing an error
- SLR and LALR parser may make several reductions before announcing an error but not shift an erroneous symbol on the stack

Simple error recovery

- continue to scan down the stack until a state S with a goto on a particular non-terminal A is found
- zero or more input symbols are discarded until a symbol “a” is found that can follow A
- goto[s,A] put on stack and parsing continues

Choice of A – non-terminal representing major program piece

- e.g. if A is ‘stmt’ the ‘a’ may be ‘end’ or ‘;’

Java CUP

Java Based Constructor of Useful Parsers (CUP).

CUP is a system for generating LALR parsers from simple specifications.

It serves the same role as the widely used program YACC and in fact offers most of the features of YACC.

However, CUP is written in Java, uses specifications including embedded Java code, and produces parsers which are implemented in Java.

Lexer

```
import java_cup.runtime.Symbol;
%%
%class ExprLex
%cup
%implements sym
%line
%column
%{
  private void error(String message) {
    System.err.println("Error at line "+(yyline+1)+", column
"+(yycolumn+1)+" : "+message);
  }
%}
int = 0 | -?[1-9][0-9]*
new_line = \r|\n|\r\n|\z;
white_space = {new_line} | [ \t\f]
%%
```

Lexer

```
/* keywords */
"+"     { return new Symbol(PLUS, yyline+1, yycolumn+1); }
"-"     { return new Symbol(MINUS, yyline+1, yycolumn+1); }
"*"     { return new Symbol(TIMES, yyline+1, yycolumn+1); }
"/"     { return new Symbol(DIV, yyline+1, yycolumn+1); }
"("     { return new Symbol(LPAREN, yyline+1, yycolumn+1); }
")"     { return new Symbol(RPAREN, yyline+1, yycolumn+1); }

{int}   {return new Symbol(INT, yyline+1, yycolumn+1, new
Integer(Integer.parseInt(yytext())));}

{new_line} { return new Symbol(EOL, yyline+1, yycolumn+1); }

{white_space}  { /* ignore */ }

/* error fallback */
.|\n    { error("Illegal character <"+ yytext()+">"); }
```

Parser

```
import java_cup.runtime.Symbol;

/* Preliminaries to use the scanner.  */
scan with {: return lexer.next_token(); :};
parser code {: ExprLex lexer;
public ExprParser(ExprLex lex) { super(lex); lexer = lex; } :};

/* Terminals (tokens returned by lexer). */
terminal TIMES, DIV;
terminal PLUS, MINUS;
terminal LPAREN, RPAREN;
terminal EOL;
terminal Integer INT;

non terminal line_list;
non terminal Integer line;
non terminal Integer expr;
```

Parser

```
precedence left PLUS, MINUS;
precedence left TIMES, DIV;

start with line_list;

line_list ::= line_list:list line
        |
        ;

line ::= expr:result EOL
        {: System.out.println("Result: " + result); :}
        |
        expr:result
        {: System.out.println("Result: " + result); :}
        ;
```

Parser

```
expr ::= expr:l PLUS expr:r
    {: RESULT = new Integer(l.intValue() + r.intValue()); :}
    |
    expr:l MINUS expr:r
    {: RESULT = new Integer(l.intValue() - r.intValue()); :}
    |
    expr:l DIV expr:r
    {: RESULT = new Integer(l.intValue() / r.intValue()); :}
    |
    expr:l TIMES expr:r
    {: RESULT = new Integer(l.intValue() * r.intValue()); :}
    |
    LPAREN expr:e RPAREN
    {: RESULT = e; :}
    |
    INT:i
    {: RESULT = i; :}
;
```

Driver Program

```
import java_cup.runtime.Symbol;

public class Calc {
    public static void main(String[] args) {
        if(args.length != 1) {
            System.err.println("Usage: java Calc file.asm");
            System.exit(1);
        }
        Symbol parse_tree = null;
        try {
            ExprParser parser = new ExprParser(new ExprLex(
                new java.io.FileInputStream(args[0])));
            parse_tree = parser.parse();
        } catch (java.io.IOException e) {
            System.err.println("Unable to open file: " + args[0]);
        } catch (Exception e) {
            e.printStackTrace(System.err);
}}}
```

Build

```
jflex ExprLex.flex
java -jar java-cup-11a.jar -interface -parser ExprParser ExprParser.cup
javac Calc.java
```

Output

```
------- CUP v0.11a beta 20060608 Parser Generation Summary -------
  0 errors and 0 warnings
  10 terminals, 3 non-terminals, and 11 productions declared,
  producing 19 unique parse states.
  0 terminals declared but not used.
  0 non-terminals declared but not used.
  0 productions never reduced.
  0 conflicts detected (0 expected).
  Code written to "ExprParser.java", and "sym.java".
---------------------------------------------------- (v0.11a beta 20060608)
```

Run

Test.txt:

```
3+4
3 * 4 - 2
(3+2)    * -2
```

java Calc test.txt

```
Result: 7
Result: 10
Result: -10
```

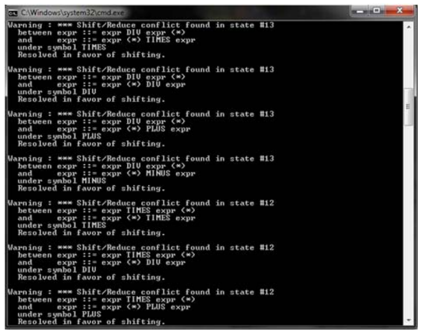
Ambiguity

```
expr:l PLUS expr:r |
expr:l MINUS expr:r |
expr:l DIV expr:r |
expr:l TIMES expr:r |
…
```

If we remove:

```
precedence left PLUS, MINUS;
precedence left TIMES, DIV;
```

Shift/Reduce Conflicts



```
Warning : *** Shift/Reduce conflict found in state #13
  between expr ::= expr DIV expr (*)
  and     expr ::= expr (*) TIMES expr
  under symbol TIMES
  Resolved in favor of shifting.

Warning : *** Shift/Reduce conflict found in state #13
  between expr ::= expr DIV expr (*)
  and     expr ::= expr (*) DIV expr
  under symbol DIV
  Resolved in favor of shifting.

Warning : *** Shift/Reduce conflict found in state #13
  between expr ::= expr DIV expr (*)
  and     expr ::= expr (*) PLUS expr
  under symbol PLUS
  Resolved in favor of shifting.

Warning : *** Shift/Reduce conflict found in state #13
  between expr ::= expr DIV expr (*)
  and     expr ::= expr (*) MINUS expr
  under symbol MINUS
  Resolved in favor of shifting.

Warning : *** Shift/Reduce conflict found in state #12
  between expr ::= expr TIMES expr (*)
  and     expr ::= expr (*) TIMES expr
  under symbol TIMES
  Resolved in favor of shifting.

Warning : *** Shift/Reduce conflict found in state #12
  between expr ::= expr TIMES expr (*)
  and     expr ::= expr (*) DIV expr
  under symbol DIV
  Resolved in favor of shifting.

Warning : *** Shift/Reduce conflict found in state #12
  between expr ::= expr TIMES expr (*)
  and     expr ::= expr (*) PLUS expr
  under symbol PLUS
  Resolved in favor of shifting.
```

Error

```
Error : *** More conflicts encountered than expected -- parser generation
aborted
------- CUP v0.11a beta 20060608 Parser Generation Summary -------
  1 error and 16 warnings
  10 terminals, 3 non-terminals, and 11 productions declared,
  producing 19 unique parse states.
  0 terminals declared but not used.
  0 non-terminals declared but not used.
  0 productions never reduced.
  16 conflicts detected (0 expected).
  No code produced.
---------------------------------------------------- (v0.11a beta 20060608)
```