

# CSE 401/M501 – Compilers

LL and Recursive-Descent Parsing

Hal Perkins

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# Administrivia

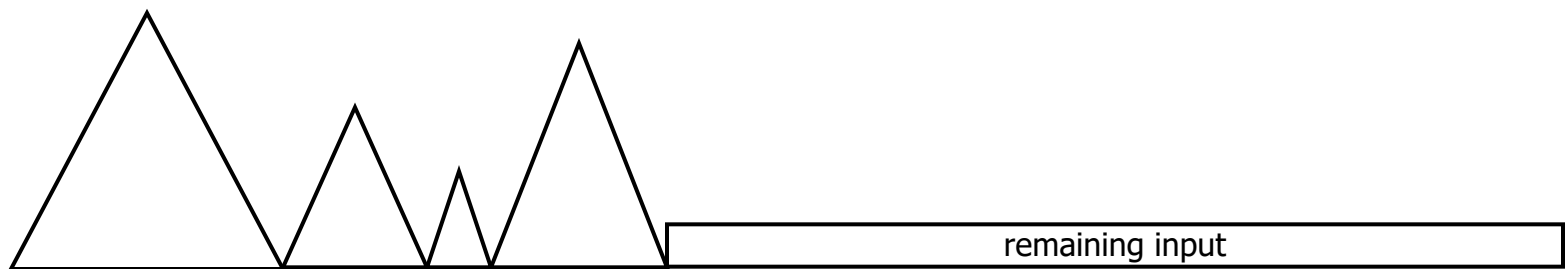
- HW2 (LR parsing) due Thursday night
- Parser/AST project part due a week later Thur. 4/27
  - Details, overview, tools, etc. in sections Thursday
- Short HW3 out shortly, due **Monday 5/1**
  - Questions on LL grammars
  - LL grammars today, more in sections this week and next
  - **Only one late day allowed** on this so we can hand out solutions in time for midterm on Fri. 5/5
- Sections this week: Parser/AST project, LL grammars, and any last-minute FIRST/FOLLOW questions
  - More on LL grammars and hw3 next week

# Agenda

- Top-Down Parsing
- Predictive Parsers
- LL(k) Grammars
- Recursive Descent
- Grammar Hacking
  - Left recursion removal
  - Left factoring

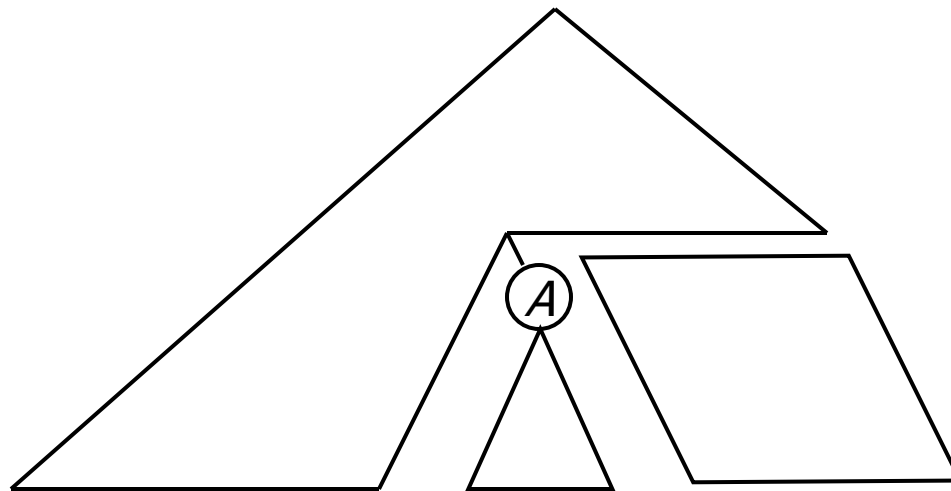
# Basic Parsing Strategies (1)

- Bottom-up
  - Build up tree from leaves
    - Shift next input or reduce a handle
    - Accept when all input read and reduced to start symbol of the grammar
  - LR(k) and subsets (SLR, LALR(k), ...)



# Basic Parsing Strategies (2)

- Top-Down
  - Begin at root with start symbol of grammar
  - Repeatedly pick a non-terminal and expand
  - Success when expanded tree matches input
  - LL(k)



# Top-Down Parsing

- Situation: have completed part of a left-most derivation

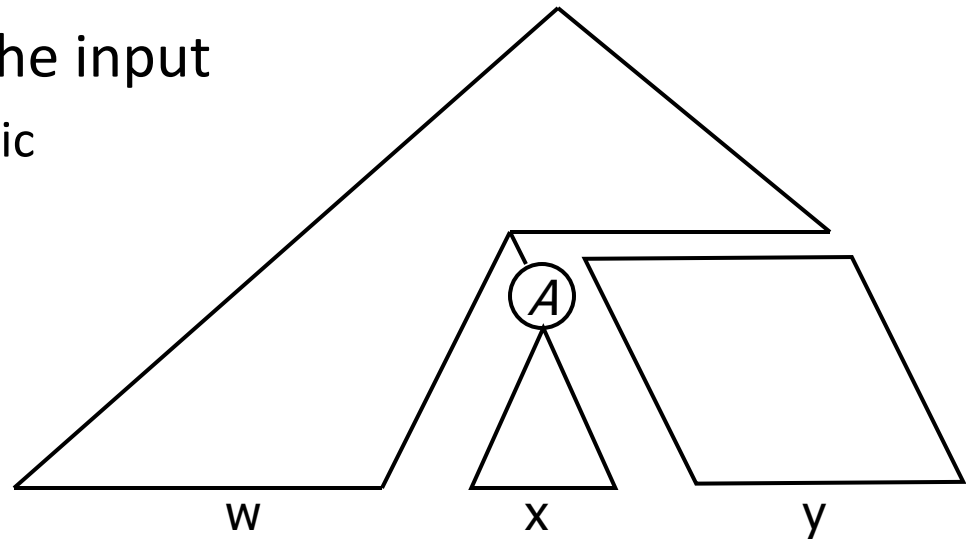
$$S \Rightarrow^* wA\alpha \Rightarrow^* wxy$$

- Basic Step: Pick some production

$$A ::= \beta_1 \beta_2 \dots \beta_n$$

that will properly expand the leftmost non-terminal  $A$  to match the input

- Want this to be deterministic (i.e., no backtracking)



# Predictive Parsing

- If we are located at some non-terminal  $A$ , and there are two or more possible productions for  $A$

$A ::= \alpha$

$A ::= \beta$

we want to make the correct choice by looking at just the next input symbol

- If we can do this, we can build a *predictive parser* that can perform a top-down parse without backtracking

# Example

- Programming language grammars are often suitable for predictive parsing
- Typical example

$$\begin{aligned} stmt ::= id = exp ; & \mid \text{return } exp ; \\ & \mid \text{if } ( exp ) stmt \mid \text{while } ( exp ) stmt \end{aligned}$$

If the next part of the input begins with the tokens

IF LPAREN ID(x) ...

we should expand *stmt* to an if-statement



# LL(1) Property

- A grammar has the LL(1) property if, for all non-terminals  $A$ , if productions  $A ::= \alpha$  and  $A ::= \beta$  both appear in the grammar, then it is true that

$$\text{FIRST}(\alpha) \cap \text{FIRST}(\beta) = \emptyset$$

(Provided that neither  $\alpha$  or  $\beta$  is  $\epsilon$  (i.e., empty). If either one is  $\epsilon$  then we need to look at FOLLOW sets. ...)

- If a grammar has the LL(1) property, we can build a predictive parser for it that uses 1 symbol lookahead

# LL(k) Parsers

- An LL(k) parser
  - Scans the input **L**eft to right
  - Constructs a **L**eftmost derivation
  - Looking ahead at most **k** symbols
- 1-symbol lookahead is enough for many practical programming language grammars
  - LL(k) for  $k > 1$  is rare in practice
    - and even if the grammar isn't quite LL(1), it may be close enough that we can pretend it is LL(1) and cheat a little when it isn't

# Table-Driven LL(k) Parsers

- As with LR(k), a table-driven parser can be constructed from the grammar
- Super-simple example
  1.  $S ::= ( S ) S$
  2.  $S ::= [ S ] S$
  3.  $S ::= \epsilon$
- Table (one row per non-terminal showing which production to apply given the next input symbol)

	(	)	[	]	\$
$S$	1	3	2	3	3

# LL vs LR (1)

- Tools can automatically generate parsers for both LL(1) and LR(1) grammars
- LL(1) has to make a decision based on a single non-terminal and the next input symbol
- LR(1) can base the decision on the entire left context (i.e., contents of the stack) as well as the next input symbol

## LL vs LR (2)

- ∴ LR(1) is more powerful than LL(1)
  - Includes a larger set of languages
- ∴ (editorial opinion) If you're going to use a tool-generated parser, might as well use LR
  - But there are some very good LL parser tools out there (ANTLR, JavaCC, ...) that might win for other reasons (documentation, IDE support, integrated AST generation, local culture/politics/economics, etc.)

# Recursive-Descent Parsers

- One big advantage of top-down parsing is that it is easy to implement by hand
  - And even if you use automatic tools, generated source code may be easier to follow and debug
- Key idea: write one procedure (function, method) corresponding to each major non-terminal in the grammar
  - Each of these methods is responsible for matching its non-terminal with the next part of the input

# Example: Statements

## Grammar production

```
stmt ::= id = exp ;  
      | return exp ;  
      | if ( exp ) stmt  
      | while ( exp ) stmt
```

## Method for this production

```
// parse stmt ::= id=exp; | ...  
void stmt( ) {  
    switch(nextToken) {  
        RETURN: returnStmt(); break;  
        IF: ifStmt(); break;  
        WHILE: whileStmt(); break;  
        ID: assignStmt(); break;  
    }  
}
```

# Example (more statements)

```
// parse while (exp) stmt
void whileStmt() {
    // skip "while" "("
    getNextToken();
    getNextToken();

    // parse condition
    exp();

    // skip ")"
    getNextToken();

    // parse stmt
    stmt();
}
```

```
// parse return exp ;
void returnStmt() {
    // skip "return"
    getNextToken();

    // parse expression
    exp();

    // skip ";"
    getNextToken();
}
```



# Recursive-Descent Recognizer

- Easy!
- Pattern of method calls traces leftmost derivation in parse tree
- Examples here only handle valid programs and choke on errors. Real parsers need:
  - Better error recovery (don't get stuck on a bad token)
    - Often: skip input until something in the FOLLOW set of the nonterminal being expanded is reached
  - Semantic checks (declarations, type checking, ...)
  - Some sort of processing after recognizing (build AST, generate code, immediate evaluation [interpreter], ...)

# Invariant for Parser Functions

- The parser functions need to agree on where they are in the input
- Useful invariant: When a parser function is called, the current token (next unprocessed piece of the input) is the token that begins the expanded non-terminal being parsed
  - Corollary: when a parser function is done, it must have completely consumed the input correspond to that non-terminal

# Possible Problems

- Two common problems for recursive-descent (and LL(1)) parsers
  - Left recursion (e.g.,  $E ::= E + T \mid \dots$ )
  - Common prefixes on the right side of productions

# Left Recursion Problem

## Grammar rule

$expr ::= expr + term$   
 $\quad | term$

## Code

```
// parse expr ::= ...  
void expr() {  
    expr();  
    if (current token is PLUS) {  
        getNextToken();  
        term();  
    }  
}
```

And the bug is????

# Left Recursion Problem

- If we code up a left-recursive rule as-is, we get an infinite recursion
- Non-solution: replace with a right-recursive rule

*expr ::= term + expr | term*

– Why isn't this the right thing to do?

# Formal Left Recursion Solution

- Rewrite using right recursion and a new non-terminal
- Original:  $expr ::= expr + term \mid term$
- New:
  - $expr ::= term exprtail$
  - $exprtail ::= + term exprtail \mid \epsilon$
- Properties
  - No infinite recursion if coded up directly
  - Maintains required left associativity (*if you handle things correctly in the semantic actions*)

# Another Way to Look at This

- Observe that

$$expr ::= expr + term \mid term$$

generates the sequence

$$(\dots((term + term) + term) + \dots) + term$$

- We can sugar the original rule to reflect this

$$expr ::= term \{ + term \}^*$$

- This leads directly to recursive-descent parser code
  - Just be sure to do the correct thing to handle associativity as the terms are parsed

# Code for Expressions (1)

```
// parse
//  expr ::= term { + term }*
void expr() {
    term();
    while (next symbol is PLUS) {
        getNextToken();
        term();
    }
}
```

```
// parse
//  term ::= factor { * factor }*
void term() {
    factor();
    while (next symbol is TIMES) {
        getNextToken();
        factor();
    }
}
```



# Code for Expressions (2)

```
// parse
// factor ::= int | id | ( expr )
void factor() {

    switch(nextToken) {

        case INT:
            process int constant;
            getNextToken();
            break;
        ...

        case ID:
            process identifier;
            getNextToken();
            break;
        case LPAREN:
            getNextToken();
            expr();
            getNextToken();
        }
    }
}
```

# What About Indirect Left Recursion?

- A grammar might have a derivation that leads to a left recursion

$$A \Rightarrow \beta_1 \Rightarrow^* \beta_n \Rightarrow A \gamma$$

- Solution: transform the grammar to one where all productions are either

$A ::= a\alpha$       – i.e., starts with a terminal symbol, or

$A ::= A\alpha$       – i.e., direct left recursion

then use formal left-recursion removal to eliminate all direct left recursions

# Eliminating Indirect Left Recursion

- Basic idea: Rewrite all productions  $A ::= B\dots$  where  $A$  and  $B$  are different non-terminals by using all  $B ::= \dots$  productions to replace the original rhs  $B$
- Example: Suppose we have  $A ::= B\delta$ ,  $B ::= \alpha$ , and  $B ::= \beta$ . Replace  $A ::= B\delta$  with  $A ::= \alpha\delta$  and  $A ::= \beta\delta$ .
- Need to pick an order to process the non-terminals to avoid re-introducing indirect left recursions. Not complicated, just be systematic.
  - Details in compiler or formal-language textbooks

# Second Problem: Left Factoring

- If two rules for a non-terminal have right hand sides that begin with the same symbol, we can't predict which one to use
- Formal solution: Factor the common prefix into a separate production

# Left Factoring Example

- Original grammar

$$\begin{aligned} \textit{ifStmt} ::= & \textit{if} ( \textit{expr} ) \textit{stmt} \\ & | \textit{if} ( \textit{expr} ) \textit{stmt} \textit{else} \textit{stmt} \end{aligned}$$

- Factored grammar

$$\begin{aligned} \textit{ifStmt} ::= & \textit{if} ( \textit{expr} ) \textit{stmt} \textit{ifTail} \\ \textit{ifTail} ::= & \textit{else} \textit{stmt} \mid \varepsilon \end{aligned}$$

# Parsing if Statements

- But it's easiest to just code up the "else matches closest if" rule directly
- (If you squint properly this is really just left factoring where the two productions are parsed by a single routine)

```
// parse
//  if (expr) stmt [ else stmt ]
void ifStmt() {
    getNextToken();      // if
    getNextToken();      // (
    expr();
    getNextToken();      // )
    stmt();
    if (next symbol is ELSE) {
        getNextToken();  // else
        stmt();
    }
}
```

# Another Lookahead Problem

- In languages like FORTRAN, parentheses are used for both array subscripts and function calls
- A FORTRAN grammar includes something like
$$factor ::= id ( subscripts ) \mid id ( arguments ) \mid \dots$$
- When the parser sees “*id* (”, how can it decide whether this begins an array element reference or a function call?

## Two Ways to Handle *id* ( ... )

- Use the type of *id* to decide
  - Requires declare-before-use restriction if we want to parse in 1 pass; also means parser needs semantic information, not just grammar

- Use a *covering grammar*

*factor ::= id ( commaSeparatedList ) | ...*

and fix/check later when more information is available (e.g., type of *id* in particular)



# Top-Down Parsing Concluded

- Works for a smaller set of grammars / languages than bottom-up, but can be done for most sensible programming language constructs
  - Possibly with some grammar refactoring
    - And maybe a little cheating (occasional extra lookahead, ...)
- If you need to write a quick-n-dirty parser, recursive descent is often the method of choice
  - And some sophisticated hand-written parsers for real languages (e.g., C++) are “based on” LL parsing, but with lots of customizations

# Parsing Concluded

- That's it!
- On to the rest of the compiler
- Coming attractions
  - Semantic analysis (including type checking)
  - Symbol tables
  - & more...