# CSE 401/M501 – Compilers

LL and Recursive-Descent Parsing

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# Administrivia

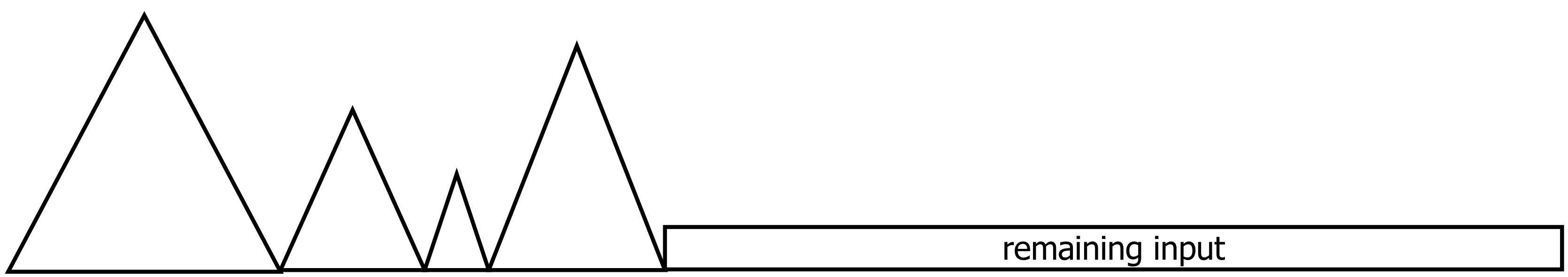
- Parser/AST project assignment out – due on Oct. 25, a week from this Thursday
- HW3 schedule constraints: need to make solutions available before midterm
  - Working backwards:
    - Midterm, Fri. Nov. 2
    - Review in sections, Thur. Nov. 1
    - HW3 due Monday night, Oct. 29.
    - Allow 1 late day (solutions out in class Oct. 30), or usual 2 late days (solutions not out until sections Thur. Nov. 1)?
    - You decide!!

# Agenda

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

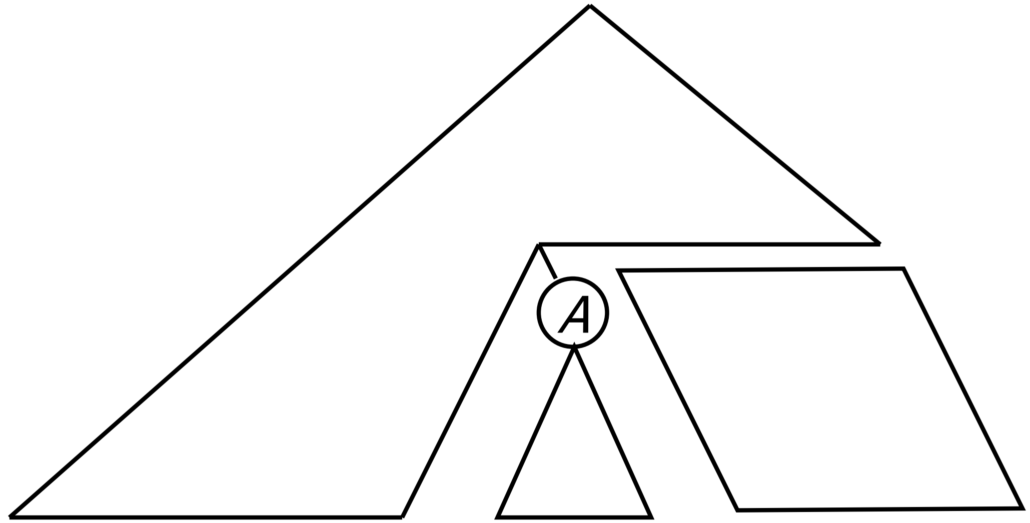
# Basic Parsing Strategies (1)

- 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(k), 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

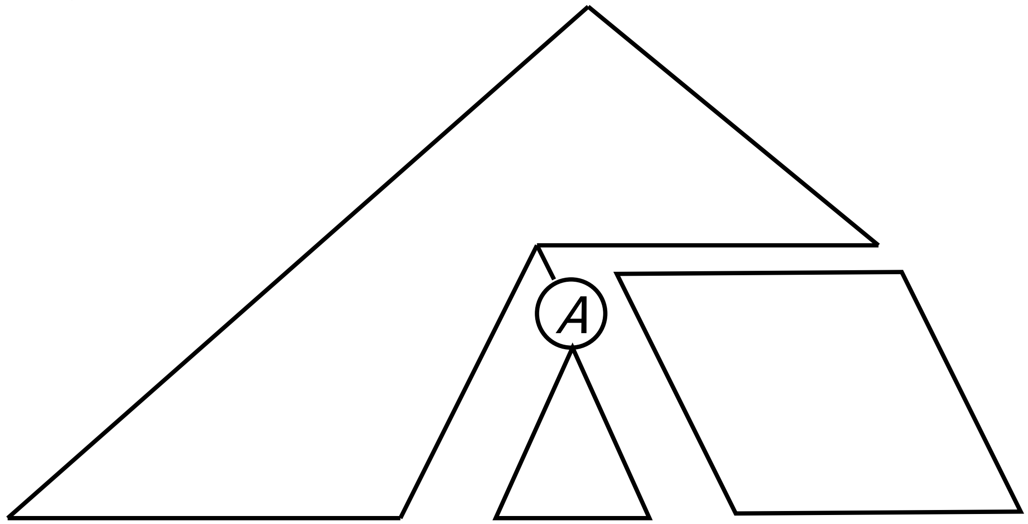
  $S$ =>* w$A\alpha$ =>* wxy

- Basic Step: Pick some production

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

  that will properly expand $A$ to match the input

  – Want this to be deterministic



# Predictive Parsing

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

  $A ::= \alpha$

  $A ::= \beta$

  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

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

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 ε (i.e., empty). If either one is ε 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 Left to right
  - Constructs a Leftmost 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
- Example
    1. $S$ ::= ( $S$ ) $S$
    2. $S$ ::= [ $S$ ] $S$
    3. $S$ ::= ε
- Table (entries are rule # to use to expand current non-terminal if next input is a particular terminal)

| | ( | ) | [ | ] | $ |
|---|---|---|---|---|---|
| $S$ | 1 | 3 | 2 | 3 | 3 |

# LL vs LR (1)

- Table-driven parsers for both LL and LR can be automatically generated by tools
- 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 advantage of top-down parsing is that it is easy to implement by hand
  - And even if you use automatic tools, the code may be easier to follow and debug
- Key idea: write a function (method, procedure) corresponding to each non-terminal in the grammar
  - Each of these functions is responsible for matching its non-terminal with the next part of the input

# Example: Statements

Grammar

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

Method for this grammar rule

```
// 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 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 something being expanded is reached
  - Semantic checks (declarations, type checking, …)
  - Some sort of processing after recognizing (build AST, 1-pass code generation, …)

# 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 input correspond to that non-terminal

# Possible Problems

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

# Left Recursion Problem

Grammar rule

*expr* ::= *expr* + *term*
  | *term*

And the bug is????

Code

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

# 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* | *term*
- New:

  *expr* ::= *term exprtail*

  *exprtail* ::= + *term exprtail* | ε
- Properties
  - No infinite recursion if coded up directly
  - Maintains required left associatively (*if* you handle things correctly in the semantic actions)

# Another Way to Look at This

- Observe that

  *expr* ::= *expr* + *term* | *term*

  generates the sequence

  (…((*term* + *term*) + *term*) + …) + *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 ::= aα – i.e., starts with a terminal symbol, or

  A ::= Aα – 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… where A and B are different non-terminals by using all B ::= … productions to replace the initial rhs B
- Example: Suppose we have A ::= Bδ, B ::= α, and B ::= β. Replace A ::= Bδ with A ::= αδ and A ::= βδ.
- 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
- Solution: Factor the common prefix into a separate production

# Left Factoring Example

- Original grammar

  *ifStmt* ::= if ( *expr* ) *stmt*

  | if ( *expr* ) *stmt* else *stmt*

- Factored grammar

  *ifStmt* ::= if ( *expr* ) *stmt* *ifTail*

  *ifTail* ::= else *stmt* | ε

# 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 with the two productions handled by a single routine)

```
// parse
//    if (expr) stmt [ else stmt ]
void ifStmt() {
      getNextToken();
      getNextToken();
      expr();
      getNextToken();
      stmt();
      if (next symbol is ELSE) {
        getNextToken();
        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* ) | *id* ( *arguments* ) | …
- 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., types)

# Top-Down Parsing Concluded

- Works with a smaller set of grammars 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
  - Intermediate representations (ASTs etc.)
  - Semantic analysis (including type checking)
  - Symbol tables
  - & more…