CSE 401/M501 – Compilers

LL and Recursive-Descent Parsing

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Administrivia

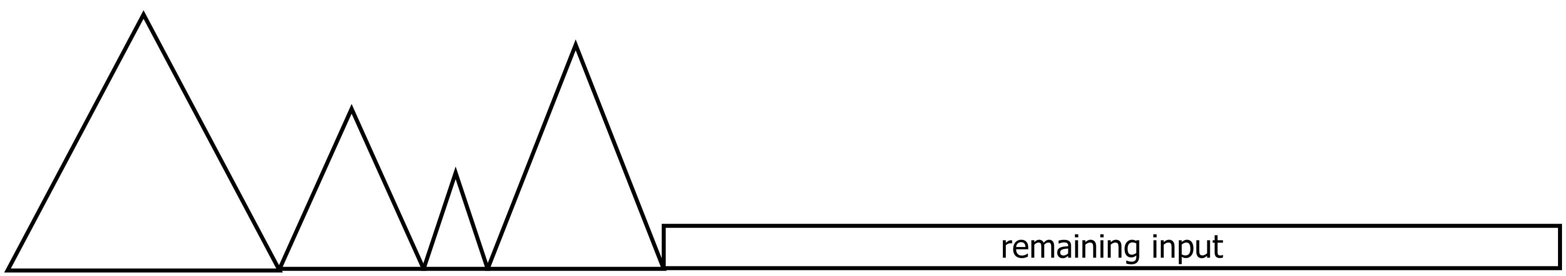
- HW2 (LR parsing) due Thursday (tomorrow) night
- Parser/AST project part due a week later Thur. 4/25
  - Details, overview, tools, etc. in sections tomorrow
- Mini-HW3 out tomorrow night, due **Monday** 4/29
  - Questions on LL grammars
  - **Only one late day allowed** on this so we an hand out solutions in time for midterm on Fri. 5/3
- Sections this week: Parser/AST project demo, 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

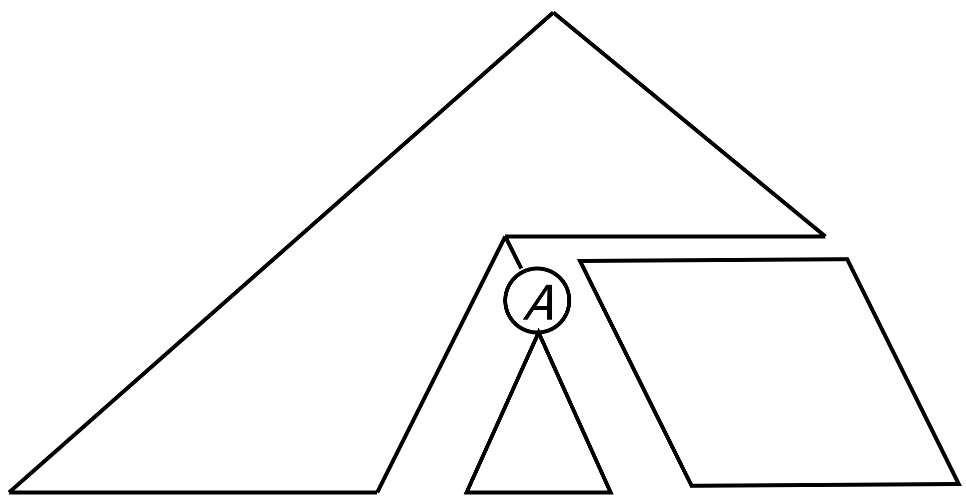
Basic Parsing Strategies (1)

- 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

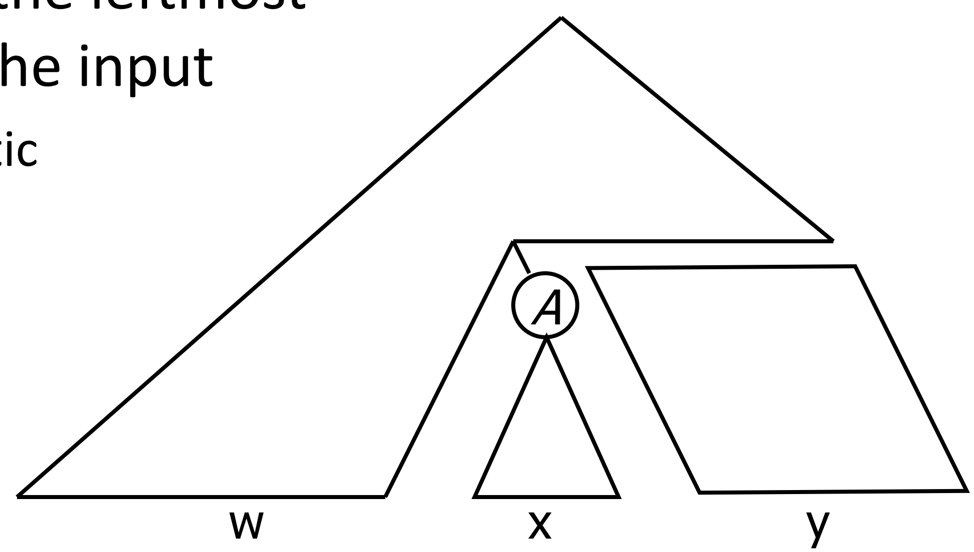
  $S \Rightarrow^* wA\alpha \Rightarrow^* wxy$

- Basic Step: Pick some production

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

  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

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* ::= α and *A* ::= β both appear in the grammar, then it is true that

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

(Provided that neither α or β 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 where it's not

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* ::= ε
- 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., $E ::= E + T \mid \ldots$)
  - 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 (1)

- Basic idea: Rewrite all productions *A* ::= *B*… where *A* and *B* are different non-terminals by using all *B* ::= … productions to create new productions replacing the original *B* that begins the rhs
- Example:
  - Suppose we have *A* ::= *B*δ, *B* ::= α, and *B* ::= β
  - Replace *A* ::= *B*δ with *A* ::= αδ and *A* ::= βδ
  - Continue to process all other non-terminals

Eliminating Indirect Left Recursion (2)

- Need to do this carefully to avoid re-introducing indirect left recursion
- Idea: pick an order to process the non-terminals. Not complicated, just be systematic and careful.
  - Details in compiler or formal-language textbooks
    - *Engineering a Compiler* (textbook) sec. 3.3.1
      - Also covers left factoring (next slides)

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

  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 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*) | *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., 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…