CS412/413

Introduction to Compilers
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Lecture 7: AST Construction and
Bottom-up Parsing
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LL(1) Parsing

- Last time:
  - how to build a parsing table for an LL(1) grammar (use FIRST/FOLLOW sets)
  - how to construct a recursive-descent parser from the parsing table
- Grammars may not be LL(1)
  - Use left factoring when grammar has multiple productions starting with the same symbol.
  - Other problematic cases?

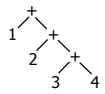
Left vs. Right Associativity

- Have been using grammar for language of "sums with parentheses" e.g., (1+(3+4))+5
- Started with simple, right-associative grammar:
  S → E + S | E
  E → num | (S)
- Transformed it to an LL(1) grammar by left-factoring:
  S → ES'
  S' → ε | + S
  E → number | (S)
- What if we start with a left-associative grammar?
  S → S + E | E
  E → num | (S)

Left vs. Right Associativity

Right recursion : right-associative

S → E + S
S → E
E → num



Left recursion : left-associative

S → S + E
S → E
E → num

Left Recursion

- Left-recursive grammars don't work with top-down parsing: we don't know where to stop the recursion

derived string	lookahead	read/unread
S	1	1 + 2 + 3 + 4
S + E	1	1 + 2 + 3 + 4
S + E + E	1	1 + 2 + 3 + 4
S + E + E + E	1	1 + 2 + 3 + 4
E + E + E + E	1	1 + 2 + 3 + 4
1 + E + E + E	2	1 + 2 + 3 + 4
1 + 2 + E + E	3	1 + 2 + 3 + 4
1 + 2 + 3 + E	4	1 + 2 + 3 + 4
1 + 2 + 3 + 4	$	1 + 2 + 3 + 4

Left-Recursive Grammars

- Usually, left-recursive grammars are not LL(1) !

  S → S α
  S → β

- FIRST(β) ⊆ FIRST(Sα)
- Both productions will appear in the predictive table, at row S in all the columns corresponding to symbols in FIRST(β)

Eliminate Left Recursion

- Method for left-recursion elimination:
  Replace
  $X \rightarrow X\ \alpha_1 \mid \ldots \mid X\ \alpha_m$
  $X \rightarrow \beta_1 \mid \ldots \mid \beta_n$
  with
  $X \rightarrow \beta_1\ X' \mid \ldots \mid \beta_n\ X'$
  $X' \rightarrow \alpha_1\ X' \mid \ldots \mid \alpha_m\ X' \mid \varepsilon$
- (See the complete algorithm in the Dragon Book)

Creating an LL(1) Grammar

- Start with a left-recursive grammar:
  $S \rightarrow S + E$
  $S \rightarrow E$
  and apply left-recursion elimination algorithm:
  $S \rightarrow E\ S'$
  $S' \rightarrow +E\ S' \mid \varepsilon$
- Start with a right-recursive grammar:
  $S \rightarrow E + S$
  $S \rightarrow E$
  and apply left-factoring to eliminate common prefixes:
  $S \rightarrow E\ S'$
  $S' \rightarrow +\ S \mid \varepsilon$

Top-Down Parsing

- Now we know:
  - how to build a parsing table for an LL(1) grammar (use FIRST/FOLLOW sets)
  - how to construct a recursive-descent parser from the parsing table
- Can we use recursive descent to build an abstract syntax tree too?

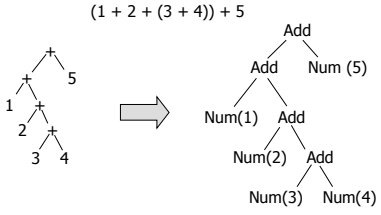
Creating the AST

```
abstract class Expr { }

class Add extends Expr {
   Expr left, right;
   Add(Expr L, Expr R) {
        left = L; right = R;
   }
}

class Num extends Expr {
   int value;
   Num (int v) { value = v; }
}
```

Class Hierarchy

AST Representation

(1 + 2 + (3 + 4)) + 5



How can we generate this structure during recursive-descent parsing?

Creating the AST

- Just add code to each parsing routine to create the appropriate nodes!
- Works because parse tree and call tree have same shape
- parse_S, parse_S', parse_E all return an Expr:

```
void parse_E()          Expr parse_E()
void parse_S()    ⇒     Expr parse_S()
void parse_S'()         Expr parse_S'()
```

AST Creation: parse_E

```
Expr parse_E() {
     switch(token) {
       case num: // E → number
             Expr result = Num (token.value);
             token = input.read(); return result;
       case '(': // E → ( S )
             token = input.read();
             Expr result = parse_S();
             if (token != ')') throw new ParseError();
             token = input.read(); return result;
       default: throw new ParseError();
     }
}
```


AST Creation: parse_S

S → E S'
S' → ε | + S
E → **num** | (S)

```
Expr parse_S() {
   switch (token) {
       case num:
       case '(':
         Expr left = parse_E();
         Expr right = parse_S'();
         if (right == null) return left;
         else return new Add(left, right);
       default: throw new ParseError();
   }
}
```


Or…an Interpreter!

S → E S '
S ' → ε | + S
E → **num** | (S)

```
int parse_E() {
     switch(token) {
          case number:
               int result = token.value;
               token = input.read(); return result;
          case '(':
               token = input.read();
               int result = parse_S();
               if (token != ')') throw new ParseError();
               token = input.read(); return result;
               default: throw new ParseError(); }}

int parse_S() {
     switch (token) {
          case number:
          case '(':
            int left = parse_E();
            int right = parse_S'();
            if (right == 0) return left;
             else return left + right;
          default: throw new ParseError(); } }
```


EBNF: Extended BNF Notation

- Extended Backus-Naur Form = a form of specifying grammars which allows some regular expression syntax on RHS

  *, +, ( ), ? operators (also [X] means X?)

S → E S'
S' → ε | + S

S → E (+ E)*

- EBNF version: no position on + associativity

Top-down Parsing EBNF

- Recursive-descent code can directly implement the EBNF grammar:

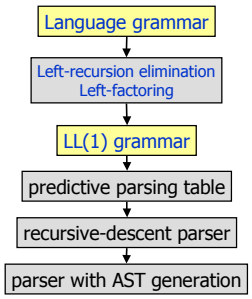
S → E (+ E)*

```
void parse_S () { // parses sequence of E + E + E ...
    parse_E ();
    while (true) {
       switch (token) {
          case '+': token = input.read(); parse_E();
                    break;
          case ')': case EOF: return;
          default: throw new ParseError();
    }
}
```


Reassociating the AST

```
Expr parse_S() {
   Expr result = parse_E();
   while (true) {
     switch (token) {
       case '+': token = input.read();
                 result = new Add(result, parse_E());
                 break;
       case ')': case EOF: return result;
       default: throw new ParseError();
     }
}
```

Top-Down Parsing Summary



Next: Bottom-up Parsing

- A more powerful parsing technology
- LR grammars -- more expressive than LL
  - construct right-most derivation of program
  - left-recursive grammars, virtually all programming languages
  - Easier to express programming language syntax
- Shift-reduce parsers
  - Parsers for LR grammars
  - automatic parser generators (*e.g.* yacc,CUP)

Bottom-up Parsing

- Right-most derivation -- backward
  - Start with the tokens
  - End with the start symbol

S → S + E | E
E → num | (S)

(1+2+(3+4))+5 ← (E+2+(3+4))+5
← (S+2+(3+4))+5 ←(S+E+(3+4))+5
← (S+(3+4))+5 ← (S+(E+4))+5 ←(S+(S+4))+5
← (S+(S+E))+5 ← (S+(S))+5 ←(S+E)+5 ← (S)+5
← E+5 ← S+E ← S

Progress of Bottom-up Parsing

right-most derivation ↑

(1+2+(3+4))+5 ←	(1+2+(3+4))+5
(E+2+(3+4))+5 ←	(1 +2+(3+4))+5
(S+2+(3+4))+5 ←	(1 +2+(3+4))+5
(S+E+(3+4))+5 ←	(1+2 +(3+4))+5
(S+(3+4))+5 ←	(1+2+(3 +4))+5
(S+(E+4))+5 ←	(1+2+(3 +4))+5
(S+(S+4))+5 ←	(1+2+(3 +4))+5
(S+(S+E))+5 ←	(1+2+(3+4))+5
(S+(S))+5 ←	(1+2+(3+4))+5
(S+E)+5 ←	(1+2+(3+4))+5
(S)+5 ←	(1+2+(3+4))+5
E+5 ←	(1+2+(3+4)) +5
S+E ←	(1+2+(3+4))+5
S	(1+2+(3+4))+5

Bottom-up Parsing

- (1+2+(3+4))+5
  ←(E+2+(3+4))+5
  ←(S+2+(3+4))+5
  ←(S+E+(3+4))+5 …

S → S + E | E
E → num | (S)

- Advantage of bottom-up parsing: can postpone the selection of productions until more of the input is scanned

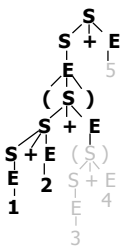
Top-down Parsing

(1+2+(3+4))+5

S → num | (S)

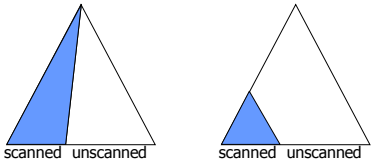
S → S+E → E+E → (S)+E → (S+E)+E
→ (S+E+E)+E →(E+E+E)+E
→ (1+E+E)+E → (1+2+E)+E …

- In left-most derivation, entire tree above a token (2) has been expanded when encountered



Top-down vs. Bottom-up

Bottom-up: Don't need to figure out as much of the parse tree for a given amount of input



Top-down Bottom-up

Shift-reduce Parsing

- Parsing actions: is a sequence of shift and reduce operations
- Parser state: a stack of terminals and non-terminals (grows to the right)
- Current derivation step = always stack+input

Derivation step	stack	unconsumed input
(1+2+(3+4))+5 ←		(1+2+(3+4))+5
(E+2+(3+4))+5 ←	(E	+2+(3+4))+5
(S+2+(3+4))+5 ←	(S	+2+(3+4))+5
(S+E+(3+4))+5 ←	(S+E	+(3+4))+5

Shift-reduce Parsing

- Parsing is a sequence of shifts and reduces
- Shift : move look-ahead token to stack

stack	input	action
(	1+2+(3+4))+5	shift 1
(1	+2+(3+4))+5	

- Reduce : Replace symbols γ from top of stack with non-terminal symbol X, corresponding to production $X \rightarrow \gamma$ (pop γ, push X)

stack	input	action
(S+E	+(3+4))+5	reduce S→ S+E
(S	+(3+4))+5	

Shift-reduce Parsing

S → S + E | E
E → num | (S)

derivation	stack	input stream	action
(1+2+(3+4))+5 ←		(1+2+(3+4))+5	shift
(1+2+(3+4))+5 ←	(	1+2+(3+4))+5	shift
(1+2+(3+4))+5 ←	(1	+2+(3+4))+5	reduce E→num
(E+2+(3+4))+5 ←	(E	+2+(3+4))+5	reduce S → E
(S+2+(3+4))+5 ←	(S	+2+(3+4))+5	shift
(S+2+(3+4))+5 ←	(S+	2+(3+4))+5	shift
(S+2+(3+4))+5 ←	(S+2	+(3+4))+5	reduce E→num
(S+E+(3+4))+5 ←	(S+E	+(3+4))+5	reduce S→ S+E
(S+(3+4))+5 ←	(S	+(3+4))+5	shift
(S+(3+4))+5 ←	(S+	(3+4))+5	shift
(S+(3+4))+5 ←	(S+(	3+4))+5	shift
(S+(3+4))+5 ←	(S+(3	+4))+5	reduce E→num

Problem

- How do we know which action to take: whether to shift or reduce, and which production?
- Issues:
  - Sometimes can reduce but shouldn't
  - Sometimes can reduce in different ways

Action Selection Problem

- Given stack σ and look-ahead symbol b, should parser:
  - shift b onto the stack (making it σb)
  - reduce $X \rightarrow \gamma$ assuming that stack has the form $\alpha\gamma$ (making it αX)
- If stack has form $\alpha\gamma$, should apply reduction $X \rightarrow \gamma$ (or shift) depending on stack prefix α
  - α is different for different possible reductions, since γ's have different length.