CS412/413

Introduction to Compilers
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Lecture 7: AST Construction and
Bottom-up Parsing
4 Feb 02

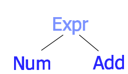
Top-Down Parsing

- 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

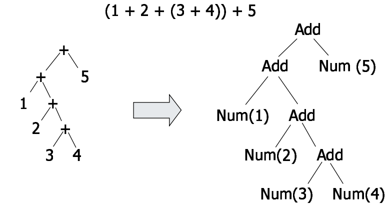
```
abstract class Expr { }

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

```
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();
   }
}
```

$S \to E\ S'$
$S' \to \varepsilon\ |\ +\ S$
$E \to$ **num** $|\ (\ S\ )$

Or…an Interpreter!

$S \to E\ S'$
$S' \to \varepsilon\ |\ +\ S$
$E \to$ **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(); } }
```

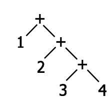

Grammars

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

Left vs. Right Associativity

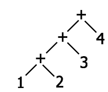
Right recursion : right-associative

$S \to E + S$
$S \to E$
$E \to num$



Left recursion : left-associative

$S \to S + E$
$S \to E$
$E \to num$



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

- Left-recursive grammars are not LL(1) !

  $S \to S\ \alpha$
  $S \to \beta$

- $FIRST(\beta) \subseteq FIRST(S\alpha)$
- Both productions will appear in the predictive table, at row S in all the columns corresponding to symbols in $FIRST(\beta)$

Eliminate Left Recursion

- Method for left-recursion elimination:
  Replace
  $X \rightarrow X\,\alpha_1 \mid \dots \mid X\,\alpha_m$
  $X \rightarrow \beta_1 \mid \dots \mid \beta_n$
  with
  $X \rightarrow \beta_1\,X' \mid \dots \mid \beta_n\,X'$
  $X' \rightarrow \alpha_1\,X' \mid \dots \mid \alpha_m\,X' \mid \varepsilon$
- (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:
  $S \rightarrow E\,S'$
  $S' \rightarrow +\,S \mid \varepsilon$

EBNF

- Extended Backus-Naur Form = a form of specifying grammars which allows some regular expression syntax on RHS
  - *, +, ( ), ? operators (also [X] means X?)

  $S \rightarrow E\,S'$
  $S' \rightarrow \varepsilon \mid +\,S$
  ⇒
  $S \rightarrow E\,(+\,E)^*$
- EBNF version: no position on + associativity

Top-down Parsing EBNF

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

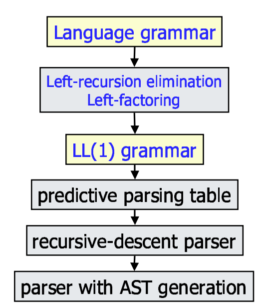
$$S \rightarrow E\,(+\,E)^*$$

```
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 (read upward)

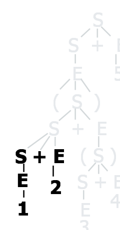
(1+2+(3+4))+5 ←		(1+2+(3+4))+5
(E+2+(3+4))+5 ←	(1	+2+(3+4))+5
(S+2+(3+4))+5 ←	(1	+2+(3+4))+5
(S+E+(3+4))+5 ←	(1+2	+(3+4))+5
(S+(3+4))+5 ←	(1+2+(3	+4))+5
(S+(E+4))+5 ←	(1+2+(3	+4))+5
(S+(S+4))+5 ←	(1+2+(3	+4))+5
(S+(S+E))+5 ←	(1+2+(3+4	))+5
(S+(S))+5 ←	(1+2+(3+4	))+5
(S+E)+5 ←	(1+2+(3+4)	)+5
(S)+5 ←	(1+2+(3+4)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



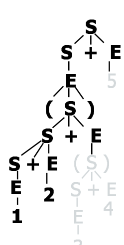
Top-down Parsing

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

S → S + E | E
E → num | (S)

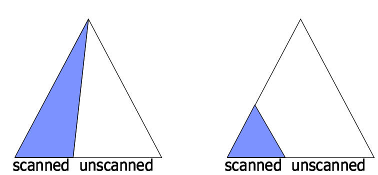
S → S+E → E+E → (S)+E → (S+E)+E
→ (S+E+E)+E →(E+E+E)+E
→ (1+E+E)+E → (1+2+E)+E ...

- 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 $X \to \gamma$ (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 $X \to \gamma$ assuming that stack has the form $\alpha\,\gamma$ (making it αX)

- If stack has form $\alpha\,\gamma$, should apply reduction $X \to \gamma$ (or shift) depending on stack prefix α
  - α is different for different possible reductions, since γ's have different length.