Military Techincal Academy

Principles of Programming Language

Lexical and Syntax Analysis

(Not all slides are required, only selected ones will be lectured)

Introduction

- Language implementation systems must analyze source code, regardless of the specific implementation approach

- Nearly all syntax analysis is based on a formal description of the syntax of the source language (BNF)

Syntax Analysis

- The syntax analysis portion of a language processor nearly always consists of two parts:
  - A low-level part called a *lexical analyzer* (mathematically, a finite automaton based on a regular grammar)
  - A high-level part called a *syntax analyzer*, or parser (mathematically, a push-down automaton based on a context-free grammar, or BNF)

Advantages of Using BNF to Describe Syntax

- Provides a clear and concise syntax description

- The parser can be based directly on the BNF

- Parsers based on BNF are easy to maintain

Reasons to Separate Lexical and Syntax Analysis

- *Simplicity* - less complex approaches can be used for lexical analysis; separating them simplifies the parser

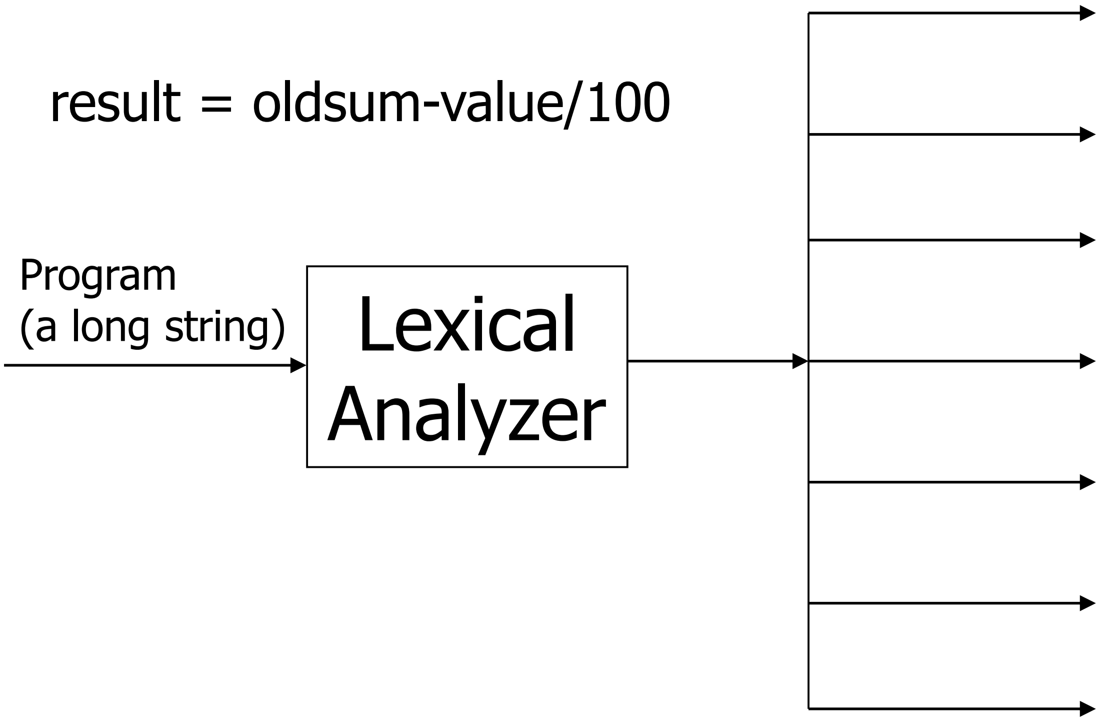
- *Efficiency* - separation allows optimization of the lexical analyzer

- *Portability* - parts of the lexical analyzer may not be portable, but the parser always is portable

Lexical Analysis

- A lexical analyzer is a pattern matcher for character strings
- A lexical analyzer is a “front-end” for the parser
- Identifies substrings of the source program that belong together – *lexemes*
  - Lexemes match a character pattern, which is associated with a lexical category called a *token*
  - sum is a lexeme; its token may be IDENT

Lexical Analysis



Logical Grouping

Token	Lexeme
IDENT	result
ASSIGN_OP	=
IDENT	oldsum
SUBTRACT_OP	-
IDENT	value
DIVISION_OP	/
INT_LIT	100
SEMICOLON	;

Lexical Analysis (continued)

- The lexical analyzer is usually a function that is called by the parser when it needs the next token

- Three approaches to building a lexical analyzer:

  - Write a formal description of the tokens and use a software tool that constructs table-driven lexical analyzers given such a description
  - Design a state diagram that describes the tokens and write a program that implements the state diagram
  - Design a state diagram that describes the tokens and hand-construct a table-driven implementation of the state diagram

State Diagram Design

- A naïve state diagram would have a transition from every state on every character in the source language - such a diagram would be very large!

Lexical Analysis (cont.)

- In many cases, transitions can be combined to simplify the state diagram
  - When recognizing an identifier, all uppercase and lowercase letters are equivalent
    - Use a character class that includes all letters
  - When recognizing an integer literal, all digits are equivalent - use a digit class

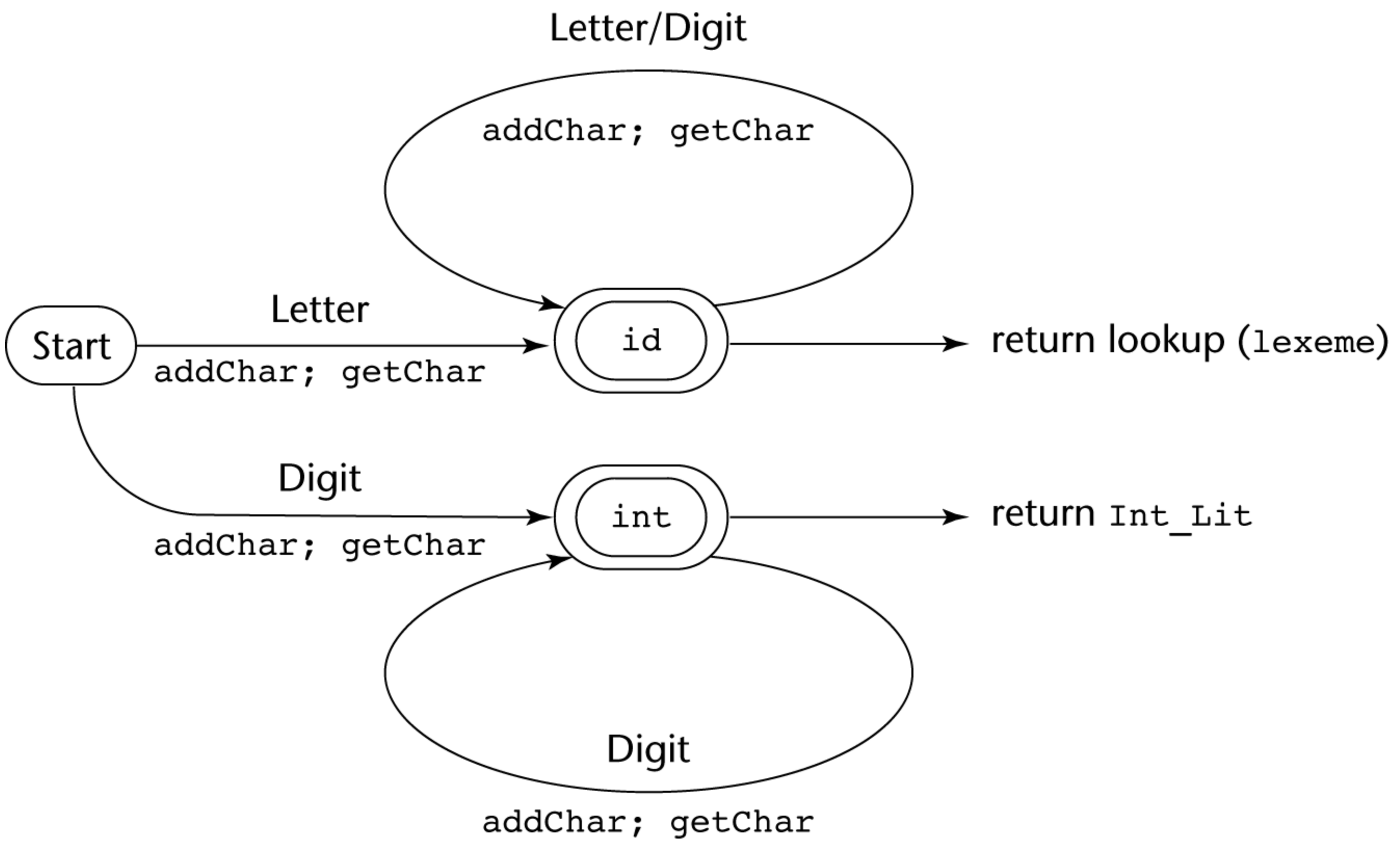
Lexical Analysis (cont.)

- Reserved words and identifiers can be recognized together (rather than having a part of the diagram for each reserved word)
  - Use a table lookup to determine whether a possible identifier is in fact a reserved word

Lexical Analysis (cont.)

- Convenient utility subprograms:
  - **getChar** - gets the next character of input, puts it in **nextChar**, determines its class and puts the class in **charClass**
  - **addChar** - puts the character from **nextChar** into the place the lexeme is being accumulated, **lexeme**
  - lookup - determines whether the string in **lexeme** is a reserved word (returns a code)

State Diagram



Lexical Analysis (cont.)

Implementation (assume initialization):

```
/* Global variables */
int charClass;
char lexeme [100];
char nextChar;
int lexLen;
int Letter = 0;
int DIGIT = 1;
int UNKNOWN = -1;
```

Lexical Analysis (cont.)

```
int lex() {
  lexLen = 0;
  static int first = 1;
/* If it is the first call to lex, initialize by calling getChar */
  if (first) {
    getChar();
    first = 0;
  }
  getNonBlank();
  switch (charClass) {

/* Parse identifiers and reserved words */
    case LETTER:
      addChar();
      getChar();
      while (charClass == LETTER || charClass == DIGIT){
        addChar();
        getChar();
      }
      return lookup(lexeme);
      break;
          ...
```

Lexical Analysis (cont.)

```
…
/* Parse integer literals */
    case DIGIT:
      addChar();
      getChar();
      while (charClass == DIGIT) {
        addChar();
        getChar();
      }
      return INT_LIT;
      break;
  }  /* End of switch */
}  /* End of function lex */
```

The Parsing Problem

- Goals of the parser, given an input program:
  - Find all syntax errors; for each, produce an appropriate diagnostic message and recover quickly
  - Produce the parse tree, or at least a trace of the parse tree, for the program

The Parsing Problem (cont.)

- Two categories of parsers
  - *Top down* - produce the parse tree, beginning at the root
    - Order is that of a leftmost derivation
    - Traces or builds the parse tree in preorder
  - *Bottom up* - produce the parse tree, beginning at the leaves
    - Order is that of the reverse of a rightmost derivation
- Useful parsers look only one token ahead in the input

The Parsing Problem (cont.)

- Top-down Parsers
  - Given a sentential form, $xA\alpha$, the parser must choose the correct A-rule to get the next sentential form in the leftmost derivation, using only the first token produced by A
- The most common top-down parsing algorithms:
  - Recursive descent - a coded implementation
  - LL parsers - table driven implementation

The Parsing Problem (cont.)

- Bottom-up parsers
  - Given a right sentential form, α, determine what substring of α is the right-hand side of the rule in the grammar that must be reduced to produce the previous sentential form in the right derivation
  - The most common bottom-up parsing algorithms are in the LR family

The Parsing Problem (cont.)

- The Complexity of Parsing
  - Parsers that work for any unambiguous grammar are complex and inefficient ($O(n^3)$, where n is the length of the input)
  - Compilers use parsers that only work for a subset of all unambiguous grammars, but do it in linear time ($O(n)$, where n is the length of the input)

Recursive-Descent Parsing

- There is a subprogram for each nonterminal in the grammar, which can parse sentences that can be generated by that nonterminal
- The responsibility of the subprogram associated with a particular nonterminal is:
  - When given an input string, it traces out the parse tree that can be rooted at that nonterminal and whose leaves match the input string
- In effect, a recursive-descent parsing subprogram is a parser for the language (sets of strings) that can be generated by its associated nonterminal.

Recursive-Descent Parsing

- EBNF is ideally suited for being the basis for a recursive-descent parser, because EBNF minimizes the number of nonterminals

Recursive-Descent Parsing (cont.)

- A grammar for simple expressions:

```
<expr> → <term> {(+ | -) <term>}
<term> → <factor> {(* | /) <factor>}
<factor> → id | ( <expr> )
```

Recursive-Descent Parsing (cont.)

- Assume we have a lexical analyzer named lex, which puts the next token code in nextToken

- The coding process when there is only one RHS:
  - For each terminal symbol in the RHS, compare it with the next input token; if they match, continue, else there is an error

  - For each nonterminal symbol in the RHS, call its associated parsing subprogram

Recursive-Descent Parsing (cont.)

```
/* Function expr
   Parses strings in the language
   generated by the rule:
   <expr> → <term> {(+ | -) <term>}
 */

void expr() {

/* Parse the first term */

 term();
  ...
```

Recursive-Descent Parsing (cont.)

```
/* As long as the next token is + or -, call
   lex to get the next token, and parse the
   next term */

  while (nextToken == PLUS_CODE ||
         nextToken == MINUS_CODE){
    lex();
    term();
  }
}
```

- This particular routine does not detect errors
- Convention: Every parsing routine leaves the next token in `nextToken`

Recursive-Descent Parsing (cont.)

- A nonterminal that has more than one RHS requires an initial process to determine which RHS it is to parse
  - The correct RHS is chosen on the basis of the next token of input (the lookahead)
  - The next token is compared with the first token that can be generated by each RHS until a match is found
  - If no match is found, it is a syntax error

Recursive-Descent Parsing (cont.)

```
/* Function factor
   Parses strings in the language
   generated by the rule:
   <factor> -> id  |  (<expr>)  */

 void factor() {

 /* Determine which RHS */

  if (nextToken) == ID_CODE)

 /* For the RHS id, just call lex */

    lex();
```

Recursive-Descent Parsing (cont.)

```
/* If the RHS is (<expr>) – call lex to pass
     over the left parenthesis, call expr, and
     check for the right parenthesis */

  else if (nextToken == LEFT_PAREN_CODE) {
   lex();
     expr();
    if (nextToken == RIGHT_PAREN_CODE)
       lex();
     else
       error();
   }  /* End of else if (nextToken == ...  */

   else error(); /* Neither RHS matches */
 }
```

Recursive-Descent Parsing (cont.)

- The LL Grammar Class
  - The Left Recursion Problem
    - If a grammar has left recursion, either direct or indirect, it cannot be the basis for a top-down parser
      - A grammar can be modified to remove left recursion

For each nonterminal, A,

Group the A-rules as $A \rightarrow A\alpha 1 \mid \ldots \mid A\alpha m \mid \beta 1 \mid \beta 2 \mid \ldots \mid \beta n$

where none of the β's begins with A

2. Replace the original A-rules with

$A \rightarrow \beta 1A' \mid \beta 2A' \mid \ldots \mid \beta nA'$

$A' \rightarrow \alpha 1A' \mid \alpha 2A' \mid \ldots \mid \alpha mA' \mid \varepsilon$

Recursive-Descent Parsing (cont.)

- The other characteristic of grammars that disallows top-down parsing is the lack of pairwise disjointness
  - The inability to determine the correct RHS on the basis of one token of lookahead
  - Def: FIRST(α) = {a | α =>* aβ }

    (If α =>* ε, ε is in FIRST(α))

Recursive-Descent Parsing (cont.)

- Pairwise Disjointness Test:
  - For each nonterminal, A, in the grammar that has more than one RHS, for each pair of rules, $A \rightarrow \alpha i$ and $A \rightarrow \alpha j$, it must be true that

$$\text{FIRST}(\alpha i) \cap \text{FIRST}(\alpha j) = \phi$$

Examples:

$$A \rightarrow a \mid bB \mid cAb$$

$$A \rightarrow a \mid aB$$

Recursive-Descent Parsing (cont.)

- Left factoring can resolve the problem

  Replace

<variable> → identifier | identifier [<expression>]

with

<variable> → identifier <new>

<new> → ε | [<expression>]

or

<variable> → identifier [[<expression>]]

(the outer brackets are metasymbols of EBNF)

Bottom-up Parsing

- The parsing problem is finding the correct RHS in a right-sentential form to reduce to get the previous right-sentential form in the derivation

Bottom-up Parsing (Continued)

- Intuition about handles:
  - Def: β is the *handle* of the right sentential form $\gamma = \alpha\beta w$ if and only if $S \Rightarrow^*_{rm} \alpha A w \Rightarrow_{rm} \alpha\beta w$
  - Def: β is a *phrase* of the right sentential form γ if and only if $S \Rightarrow^* \gamma = \alpha_1 A \alpha_2 \Rightarrow^+ \alpha_1\beta\alpha_2$
  - Def: β is a *simple phrase* of the right sentential form γ if and only if $S \Rightarrow^* \gamma = \alpha_1 A \alpha_2 \Rightarrow \alpha_1\beta\alpha_2$

Bottom-up Parsing (Continued)

- Intuition about handles (continued):
  - The handle of a right sentential form is its leftmost simple phrase
  - Given a parse tree, it is now easy to find the handle
  - Parsing can be thought of as handle pruning

Bottom-up Parsing (Continued)

- Shift-Reduce Algorithms
  - Reduce is the action of replacing the handle on the top of the parse stack with its corresponding LHS
  - Shift is the action of moving the next token to the top of the parse stack

Bottom-up Parsing (Continued)

- Advantages of LR parsers:
  - They will work for nearly all grammars that describe programming languages.
  - They work on a larger class of grammars than other bottom-up algorithms, but are as efficient as any other bottom-up parser.
  - They can detect syntax errors as soon as it is possible.
  - The LR class of grammars is a superset of the class parsable by LL parsers.

Bottom-up Parsing (Continued)

- LR parsers must be constructed with a tool
- Knuth's insight: A bottom-up parser could use the entire history of the parse, up to the current point, to make parsing decisions
  - There were only a finite and relatively small number of different parse situations that could have occurred, so the history could be stored in a parser state, on the parse stack

Bottom-up Parsing (Continued)

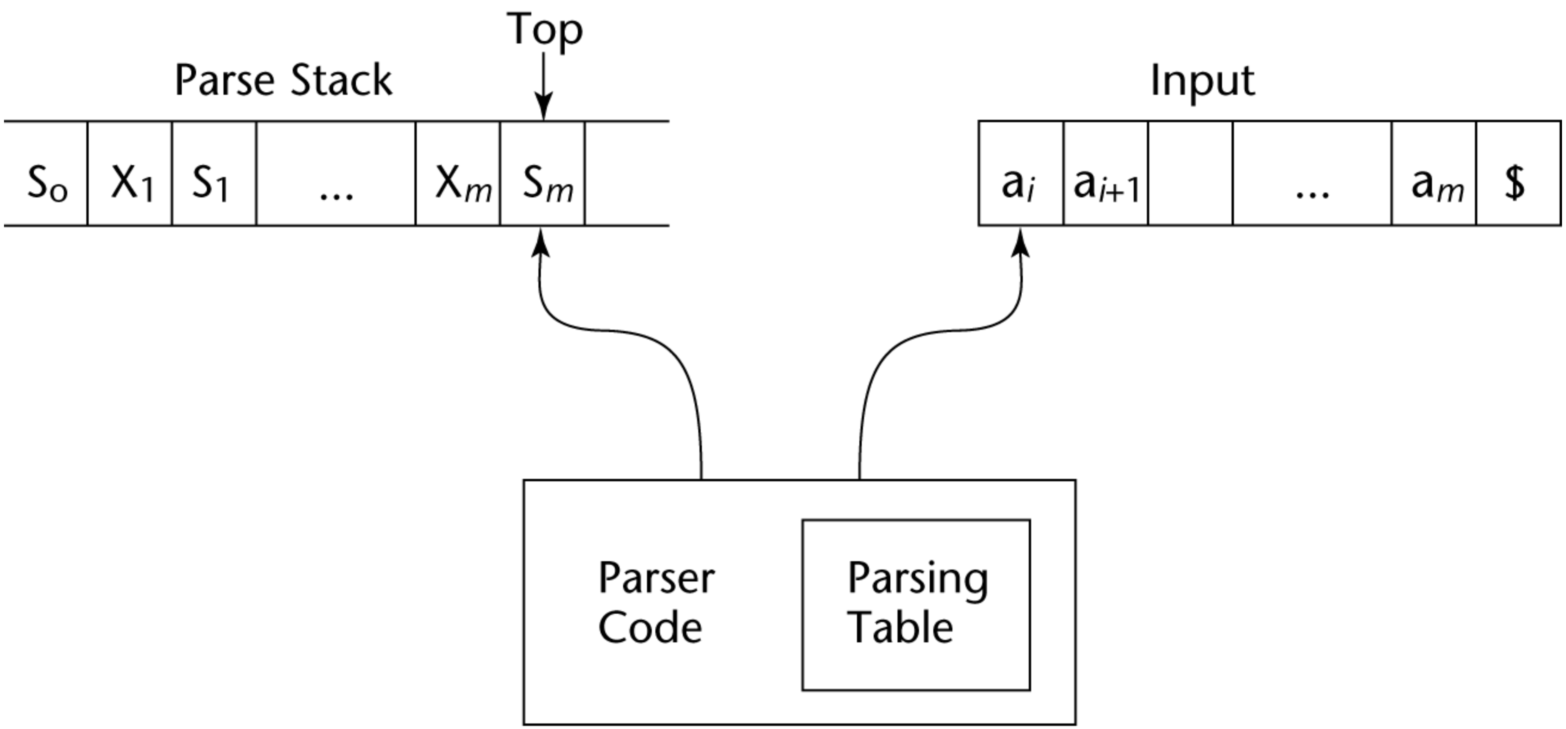
- An LR configuration stores the state of an LR parser

$$(S_0X_1S_1X_2S_2\ldots X_mS_m,\ a_ia_i{+}1\ldots a_n\$)$$

Bottom-up Parsing (Continued)

- LR parsers are table driven, where the table has two components, an ACTION table and a GOTO table
  - The ACTION table specifies the action of the parser, given the parser state and the next token
    - Rows are state names; columns are terminals
  - The GOTO table specifies which state to put on top of the parse stack after a reduction action is done
    - Rows are state names; columns are nonterminals

Structure of An LR Parser



Bottom-up Parsing (cont.)

- Initial configuration: $(S_0, a_1 \ldots a_n\$)$
- Parser actions:
  - If ACTION$[S_m, a_i]$ = Shift S, the next configuration is:

    $(S_0X_1S_1X_2S_2 \ldots X_mS_ma_iS, a_{i+1} \ldots a_n\$)$
  - If ACTION$[S_m, a_i]$ = Reduce $A \rightarrow \beta$ and S = GOTO$[S_{m-r}, A]$, where r = the length of β, the next configuration is

    $(S_0X_1S_1X_2S_2 \ldots X_{m-r}S_{m-r}AS, a_ia_{i+1} \ldots a_n\$)$

Bottom-up Parsing (cont.)

- Parser actions (continued):
  - If ACTION[S_m, a_i] = Accept, the parse is complete and no errors were found.
  - If ACTION[S_m, a_i] = Error, the parser calls an error-handling routine.

LR Parsing Table

	Action						Goto		
State	id	+	*	(	)	$	E	T	F
0	S5		S4				1	2	3
1		S6				accept			
2		R2	S7		R2	R2			
3		R4	R4		R4	R4			
4	S5			S4			8	2	3
5		R6	R6		R6	R6			
6	S5			S4				9	3
7	S5			S4					10
8		S6			S11				
9		R1	S7		R1	R1			
10		R3	R3		R3	R3			
11		R5	R5		R5	R5			

Bottom-up Parsing (cont.)

- A parser table can be generated from a given grammar with a tool, e.g., **yacc**

Summary

- Syntax analysis is a common part of language implementation
- A lexical analyzer is a pattern matcher that isolates small-scale parts of a program
  - Detects syntax errors
  - Produces a parse tree
- A recursive-descent parser is an LL parser
  - EBNF
- Parsing problem for bottom-up parsers: find the substring of current sentential form
- The LR family of shift-reduce parsers is the most common bottom-up parsing approach