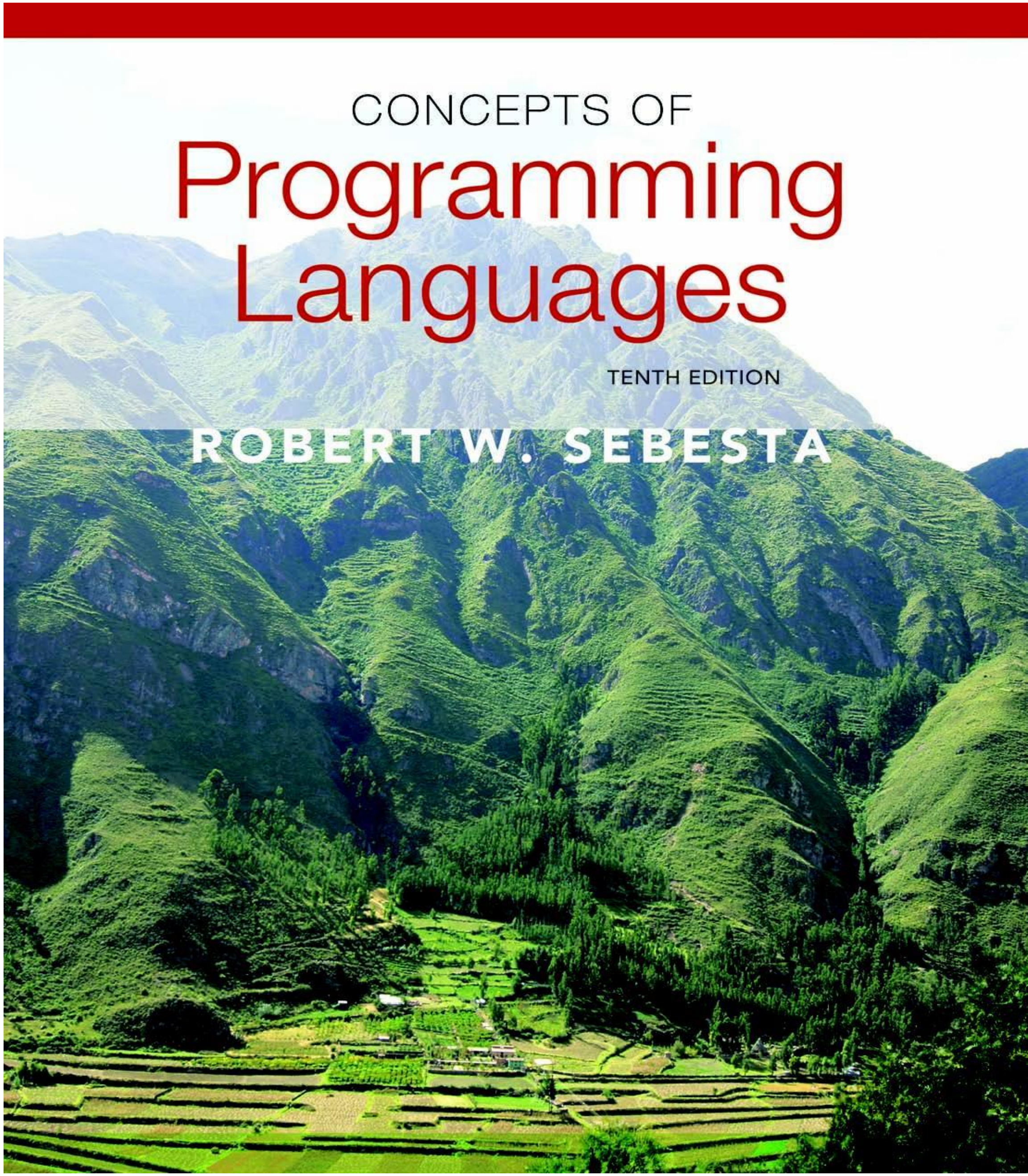
Chapter 4

Lexical and Syntax Analysis



Chapter 4 Topics

- Introduction
- Lexical Analysis
- The Parsing Problem
- Recursive-Descent Parsing
- Bottom-Up Parsing

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)

Introduction

- 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)

Introduction

- Reasons to use 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

Introduction

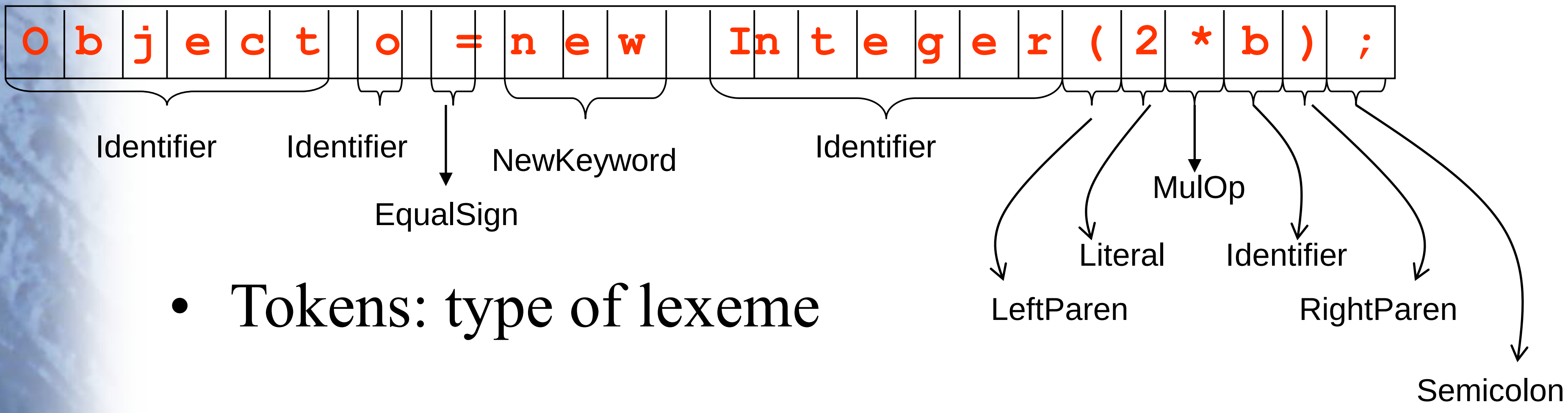
- Reasons to separate lexical and syntax analysis:
  - Simplicity - less complex approaches can be used for lexical analysis; separating them simplifies the parser
  - Efficiency - separation allows optimization of the lexical analyzer
  - Portability - parts of the lexical analyzer may not be portable, but the parser always is portable

Lexical Analysis

- A lexical analyzer (Scanner) 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`**

Lexemes and Tokens

- Lexeme: smallest unit of syntax
  - lexemes identified by lexical analyzers
  - e.g.



- Tokens: type of lexeme

Lexical Analyzer (Scanner)

- **Main task: identify tokens**
  - **Basic building blocks of programs**
  - ***E.g.* keywords, identifiers, numbers, punctuation marks**
- **Desk calculator language example:**

```
read A
sum := A + 3.45e-3
write sum
write sum / 2
```

Formal definition of tokens

- **A set of tokens is a set of strings over an alphabet**
  - **{read, write, +, -, *, /, :=, 1, 2, …, 10, …, 3.45e-3, …}**
- **A set of tokens is a *regular set* that can be defined by comprehension using a *regular expression***
- **For every regular set, there is a *deterministic finite automaton* (DFA) that can recognize it**
  - **(Aka deterministic Finite State Machine (FSM))**
  - ***i.e.* determine whether a string belongs to the set or not**
  - **Scanners extract tokens from source code in the same way DFAs determine membership**

Regular Expressions

A regular expression (RE) is:

- **A single character**
- **The empty string, ε**
- **The concatenation of two regular expressions**
  - ***Notation:* RE_1 RE_2 (*i.e.* RE_1 followed by RE_2)**
- **The union of two regular expressions**
  - ***Notation:* RE_1 | RE_2**
- **The closure of a regular expression**
  - ***Notation:* RE***
  - *** is known as the *Kleene star***
  - *** represents the concatenation of 0 or more strings**
- **Caution: notations for regular expressions vary**
  - **Learn the basic concepts and the rest is just syntactic sugar**

Lexical Analysis

- 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
- We only discuss approach 2

Lexical Analysis

- 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

- 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

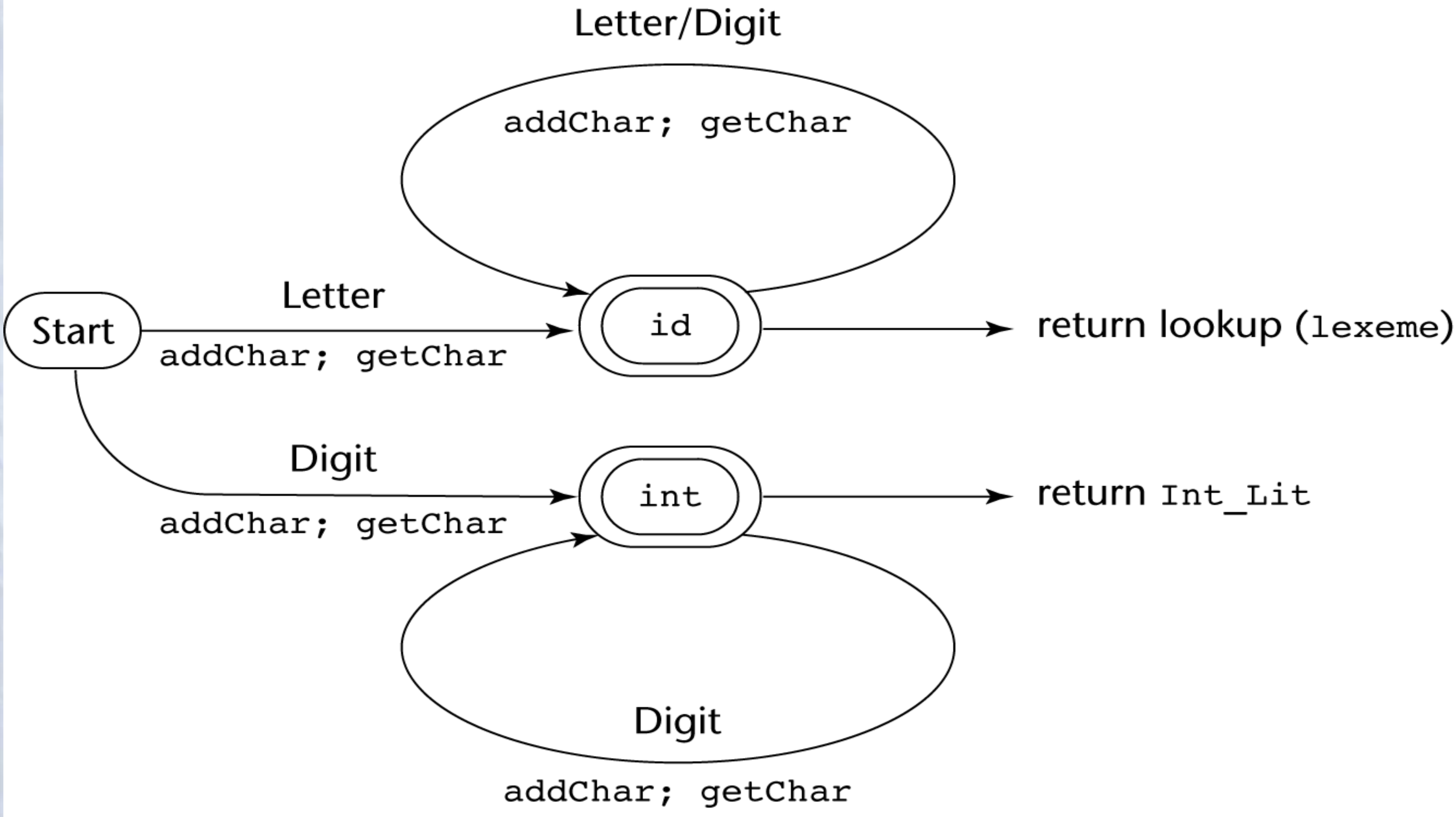
Lexical Analysis

- 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

- 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

- Implementation (assume initialization):

```
int lex() {
  getChar();
  switch (charClass) {
    case LETTER:
      addChar();
      getChar();
      while (charClass == LETTER || charClass == DIGIT)
      {
        addChar();
        getChar();
      }
      return lookup(lexeme);
      break;

       …
```

Lexical Analysis

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

Lexical Analyzer

Implementation:

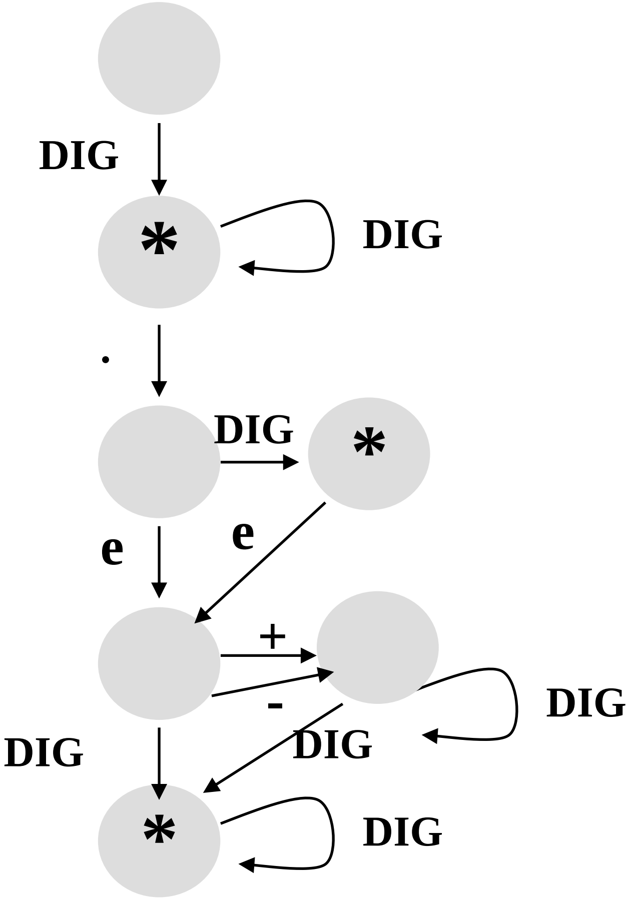
→ SHOW `front.c` (pp. 172-177)

- Following is the output of the lexical analyzer of `front.c` when used on `(sum + 47) / total`

```
Next token is: 25 Next lexeme is (
Next token is: 11 Next lexeme is sum
Next token is: 21 Next lexeme is +
Next token is: 10 Next lexeme is 47
Next token is: 26 Next lexeme is )
Next token is: 24 Next lexeme is /
Next token is: 11 Next lexeme is total
Next token is: -1 Next lexeme is EOF
```

Token Definition Example

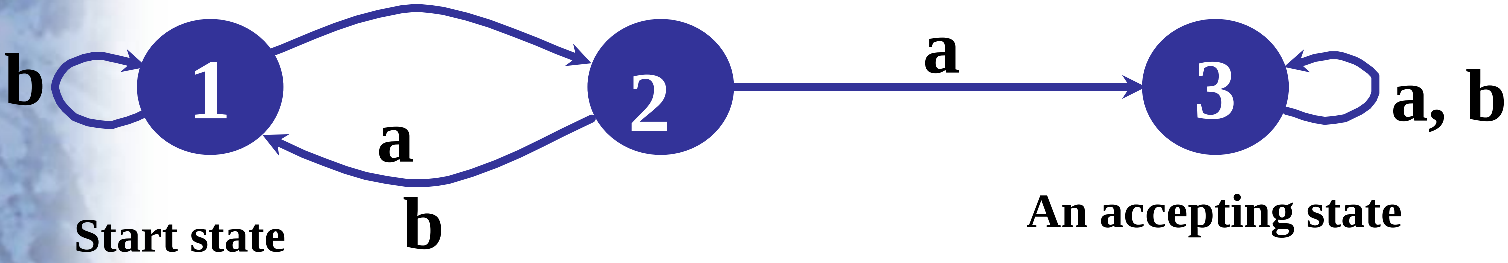
- **Numeric literals in Pascal, e.g.**
  1, 123, 3.1415, 10e-3, 3.14e4
- **Definition of token *unsignedNum***
  DIG **→ 0|1|2|3|4|5|6|7|8|9**
  unsignedInt* → *DIG DIG*
  ***unsignedNum* →**
  unsignedInt
  ((. *unsignedInt*) | ε)
  ((e (+ | – | ε) *unsignedInt*) | ε)
- **Notes:**
  - **Recursion is not allowed!**
  - **Parentheses used to avoid ambiguity**
  - **It's always possible to rewrite removing epsilons**



- **FAs with epsilons are nondeterministic.**
- **NFAs are much harder to implement (use backtracking)**
- **Every NFA can be rewriten as a DFA (gets larger, though)**

Simple Problem

- **Write a C program which reads in a character string, consisting of a’s and b’s, one character at a time. If the string contains a double aa, then print string accepted else print string rejected.**
- **An abstract solution to this can be expressed as a DFA**



The state transitions of a DFA can be encoded as a table which specifies the new state for a given current state and input

	input	
current state	a	b
1	2	1
2	3	1
3	3	3

an approach in C

```
#include <stdio.h>
main()
{   enum State {S1, S2, S3};
    enum State currentState = S1;
    int c = getchar();
    while (c != EOF) {
         switch(currentState) {
            case S1:  if (c == ‘a’) currentState = S2;
                      if (c == ‘b’) currentState = S1;
                      break;
            case S2:  if (c == ‘a’) currentState = S3;
                      if (c == ‘b’) currentState = S1;
                      break;
            case S3:  break;
           }
           c = getchar();
     }
     if (currentState == S3) printf(“string accepted\n”);
     else printf(“string rejected\n”);
}
```

Using a table simplifies the program

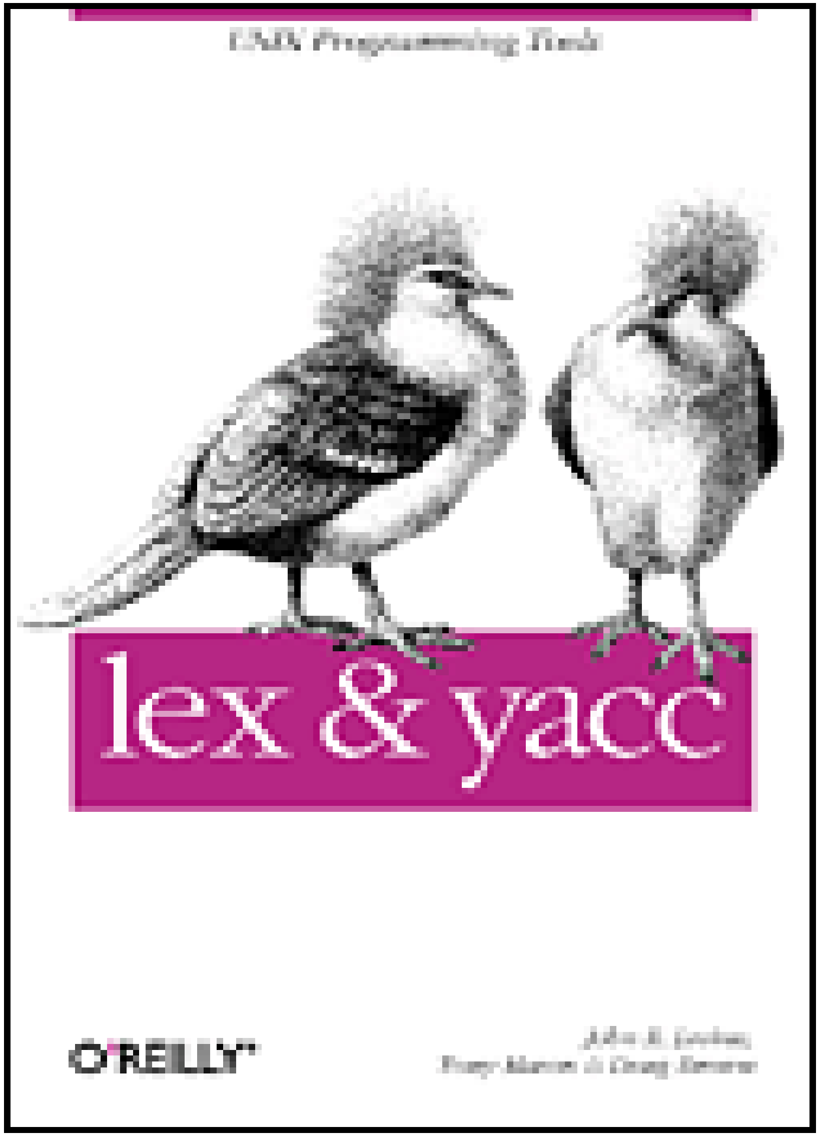
```
#include <stdio.h>
main()
{  enum State {S1, S2, S3};
    enum Label {A, B};
    enum State currentState = S1;
    enum State table[3][2] = {{S2, S1}, {S3, S1}, {S3, S3}};
    int label;
    int c = getchar();
    while (c != EOF) {
         if (c == ‘a’) label = A;
         if (c == ‘b’) label = B;
         currentState = table[currentState][label];
         c = getchar();
     }
    if (currentState == S3) printf(“string accepted\n”);
    else printf(“string rejected\n”);
}
```

Lex

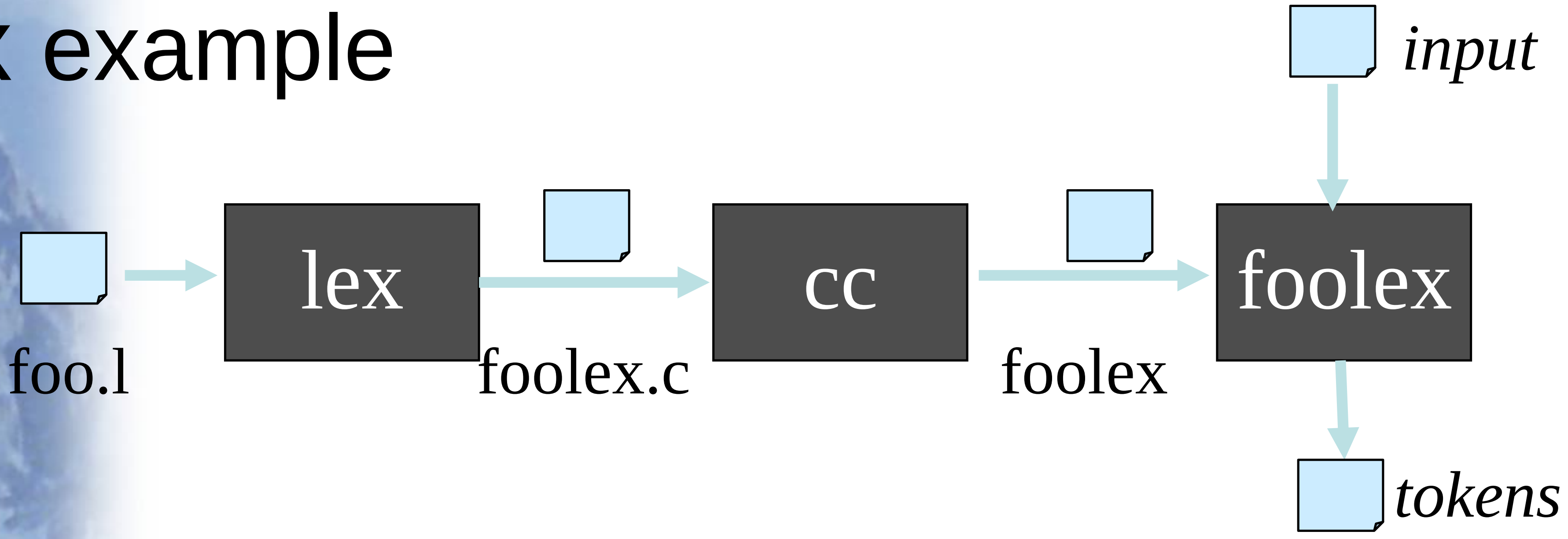
- **Lexical analyzer generator**
  - **It writes a lexical analyzer**
- **Assumption**
  - **each token matches a regular expression**
- **Needs**
  - **set of regular expressions**
  - **for each expression an action**
- **Produces**
  - **A C program**
- **Automatically handles many tricky problems**
- **flex is the gnu version of the venerable unix tool lex.**
  - **Produces highly optimized code**

Scanner Generators

- E.g. lex, flex
- These programs take a table as their input and return a program (*i.e.* a <u>scanner</u>) that can extract tokens from a stream of characters
- A very useful programming utility, especially when coupled with a parser generator (e.g., yacc)
- standard in Unix



Lex example



```
> flex -ofoolex.c foo.l
> cc -ofoolex foolex.c -lfl
```

```
>more input
begin
 if size>10
   then size * -3.1415
end
```

```
> foolex < input
Keyword: begin
Keyword: if
Identifier: size
Operator: >
Integer: 10 (10)
Keyword: then
Identifier: size
Operator: *
Operator: -
Float: 3.1415 (3.1415)
Keyword: end
```

A Lex Program

… **definitions** …

%%

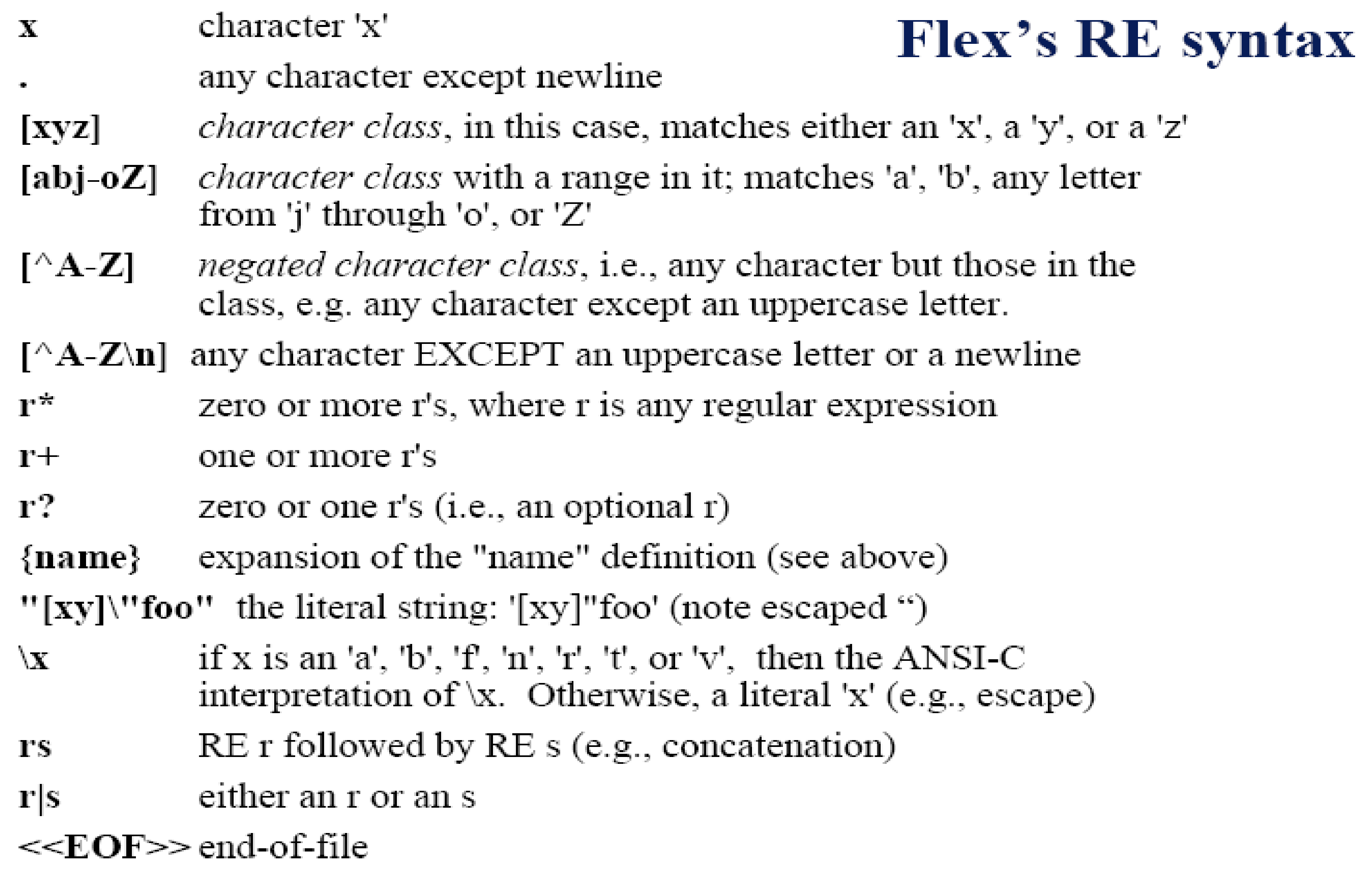
… **rules** …

%%

… **subroutines** …

```
DIG [0-9]
ID [a-z][a-z0-9]*
%%
{DIG}+                printf("Integer\n”);
{DIG}+"."{DIG}* printf("Float\n”);
{ID}                     printf("Identifier\n”);
[ \t\n]+                 /* skip whitespace */
.                         printf(“Huh?\n");
%%
main(){yylex();}
```

RE Syntax



Flex’s RE syntax

x	character 'x'
.	any character except newline
[xyz]	*character class*, in this case, matches either an 'x', a 'y', or a 'z'
[abj-oZ]	*character class* with a range in it; matches 'a', 'b', any letter from 'j' through 'o', or 'Z'
[^A-Z]	*negated character class*, i.e., any character but those in the class, e.g. any character except an uppercase letter.
[^A-Z\n]	any character EXCEPT an uppercase letter or a newline
r*	zero or more r's, where r is any regular expression
r+	one or more r's
r?	zero or one r's (i.e., an optional r)
{name}	expansion of the "name" definition (see above)
"[xy]\"foo"	the literal string: '[xy]"foo' (note escaped “)
\x	if x is an 'a', 'b', 'f', 'n', 'r', 't', or 'v', then the ANSI-C interpretation of \x. Otherwise, a literal 'x' (e.g., escape)
rs	RE r followed by RE s (e.g., concatenation)
r|s	either an r or an s
<<EOF>>	end-of-file

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

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

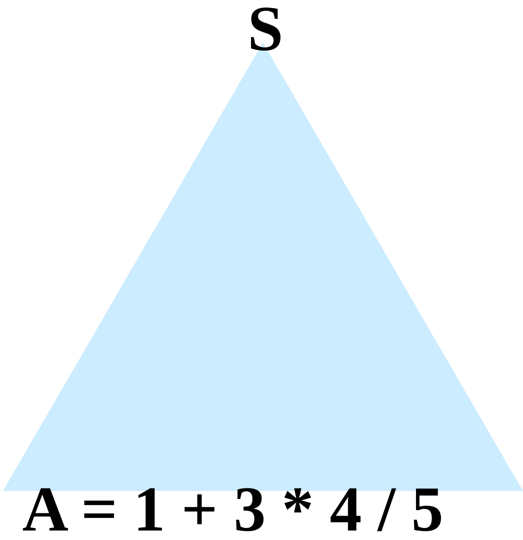
The Parsing Problem

- 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

- 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

Top down vs. bottom up parsing



S

A = 1 + 3 * 4 / 5

- The parsing problem is to connect the root node S with the tree leaves, the input
- **Top-down parsers:** starts constructing the parse tree at the top (root) of the parse tree and move down towards the leaves. Easy to implement by hand, but work with restricted grammars. examples:
  - Predictive parsers (e.g., LL(k))
- **Bottom-up parsers:** build the nodes on the bottom of the parse tree first. Suitable for automatic parser generation, handle a larger class of grammars. examples:
  - shift-reduce parser (or LR(*k*) parsers)
- Both are general techniques that can be made to work for all languages (but not all grammars!).

Parsing complexity

- How hard is the parsing task?
- Parsing an arbitrary Context Free Grammar is O(n^3), e.g., it can take time proportional the cube of the number of symbols in the input. This is bad!
- If we constrain the grammar somewhat, we can always parse in linear time. This is good!
- 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)
- Linear-time parsing
  - LL parsers
    - Recognize LL grammar
    - Use a top-down strategy
  - LR parsers
    - Recognize LR grammar
    - Use a bottom-up strategy

- **LL(n) : Left to right, Leftmost derivation, look ahead at most n symbols.**
- **LR(n) : Left to right, Right derivation, look ahead at most n symbols.**

Recursive-Descent Parsing

- Recursive Descent Process
  - There is a subprogram for each nonterminal in the grammar, which can parse sentences that can be generated by that nonterminal
  - EBNF is ideally suited for being the basis for a recursive-descent parser, because EBNF minimizes the number of nonterminals

Recursive-Descent Parsing

- A grammar for simple expressions:

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

Recursive-Descent Parsing

- 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

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

void expr() {

/* Parse the first term */

  term();
```

Recursive-Descent Parsing

```
/* 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

- 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

```
/* 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

```
/* 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 (continued)

- Trace of the lexical and syntax analyzers on `(sum + 47) / total`

```
Next token is: 25 Next lexeme is (
Enter <expr>
Enter <term>
Enter <factor>
Next token is: 11 Next lexeme is sum
Enter <expr>
Enter <term>
Enter <factor>
Next token is: 21 Next lexeme is +
Exit <factor>
Exit <term>
Next token is: 10 Next lexeme is 47
Enter <term>
Enter <factor>
Next token is: 26 Next lexeme is )
Exit <factor>
Exit <term>
Exit <expr>
Next token is: 24 Next lexeme is /
Exit <factor>
```

```
Next token is: 11 Next lexeme is total
Enter <factor>
Next token is: -1 Next lexeme is EOF
Exit <factor>
Exit <term>
Exit <expr>
```

Recursive-Descent Parsing

- 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
      - Direct
        - » A → A + B
      - Indirect
        - » A → B a A
        - » B → A b

Recursive-Descent Parsing

- 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) = $\{a \mid \alpha =>^* a\beta\}$

(If $\alpha =>^* \varepsilon$, ε is in FIRST(α))

Recursive-Descent Parsing

- 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:

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

$$A \rightarrow a \mid aB$$

-The FIRST sets for RHSs of these rules are a, b, and c for the first example which are disjoint.

-For the second example FIRST sets are a, a which are not disjoint.

Recursive-Descent Parsing

- Left factoring can resolve the problem

  Replace

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

with

<variable> → identifier <new>

<new> → ε | [<expression>]

or

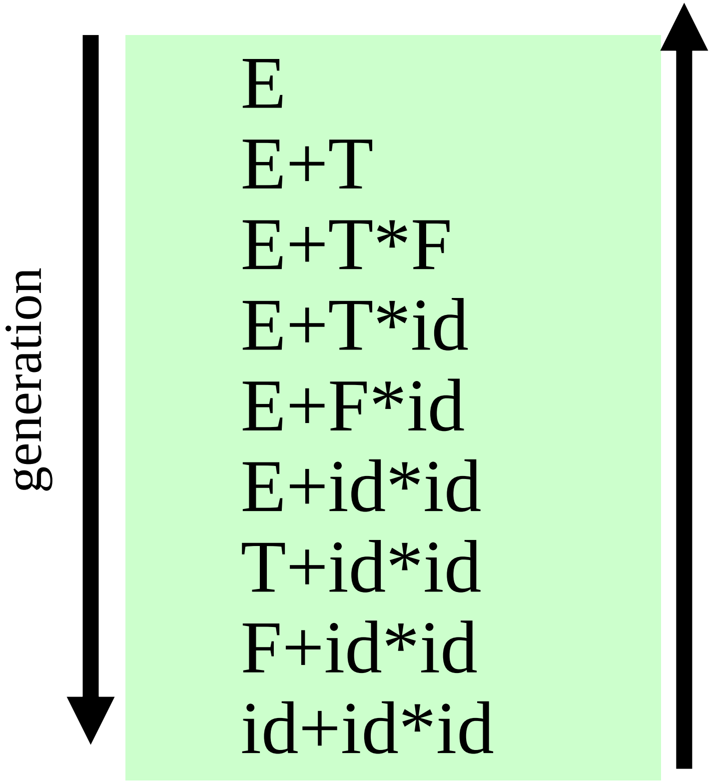
<variable> → identifier [[<expression>]]

(the outer brackets are metasymbols of EBNF)

Bottom-up Parsing

- Recall the definition of a derivation and a rightmost derivation.
- Each of the lines is a (right) sentential form
- 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

```
E -> E+T
E -> T
T -> T*F
E -> F
F -> (E)
F -> id
```



E
E+T
E+T*F
E+T*id
E+F*id
E+id*id
T+id*id
F+id*id
id+id*id

Handles

- Intuition: A handle of a string s is a substring a such that :
  - a matches the RHS of a production A -> a; and
  - replacing a by the LHS A represents a step in the reverse of a rightmost derivation of s.
- Example : Consider the grammar

  S -> aABe

  A -> Abc | b

  B -> d
- The rightmost derivation for the input abbcde is

  S => aABe => aAde => aAbcde => abbcde
- The string aAbcde can be reduced in two ways:

  (1) aAbcde => aAde; and

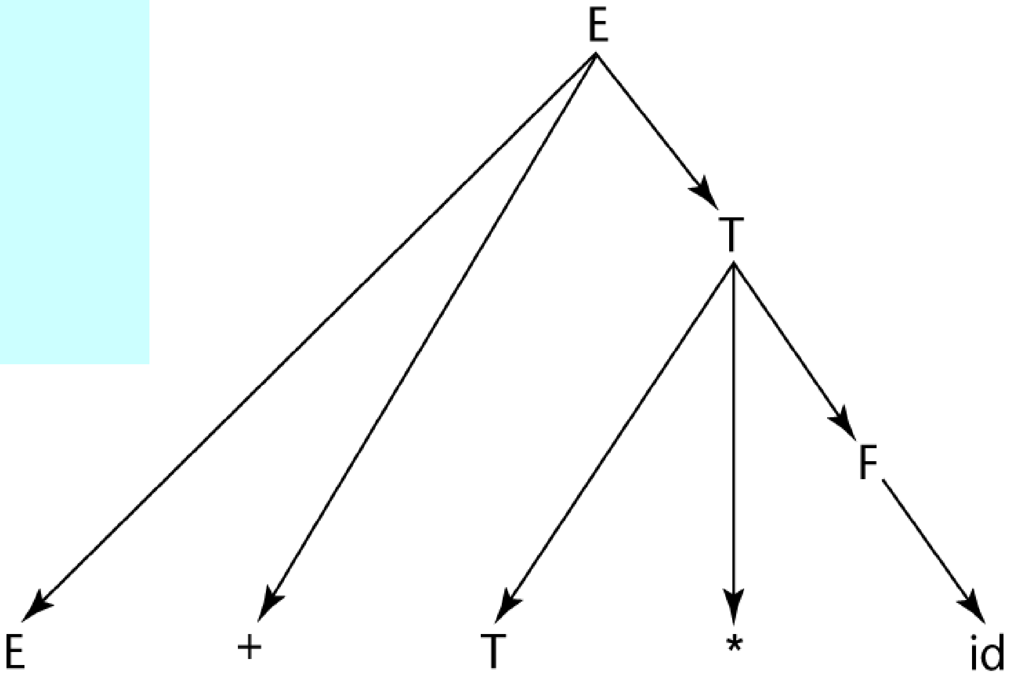
  (2) aAbcde => aAbcBe
- But (2) isn't a rightmost derivation, so Abc is the only handle.
- Note: the string to the right of a handle will only contain non-terminals

Phrases, simple phrases and handles

- Def: β is the *handle* of the right sentential form $\gamma = \alpha\beta w$ if and only if $S \Rightarrow^*_{rm} \alpha A w \Rightarrow \alpha\beta w$
- 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 $S \Rightarrow^* \gamma = \alpha_1 A \alpha_2 \Rightarrow \alpha_1 \beta \alpha_2$
- 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

Phrases, simple phrases and handles

```
E -> E+T
E -> T
T -> T*F
T -> F
F -> (E)
F -> id
```



E
E+T
E+T*F
E+T*id
E+F*id
E+id*id
T+id*id
F+id*id
id+id*id

Bottom-up Parsing

- 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

- 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

- 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

- An LR configuration stores the state of an LR parser

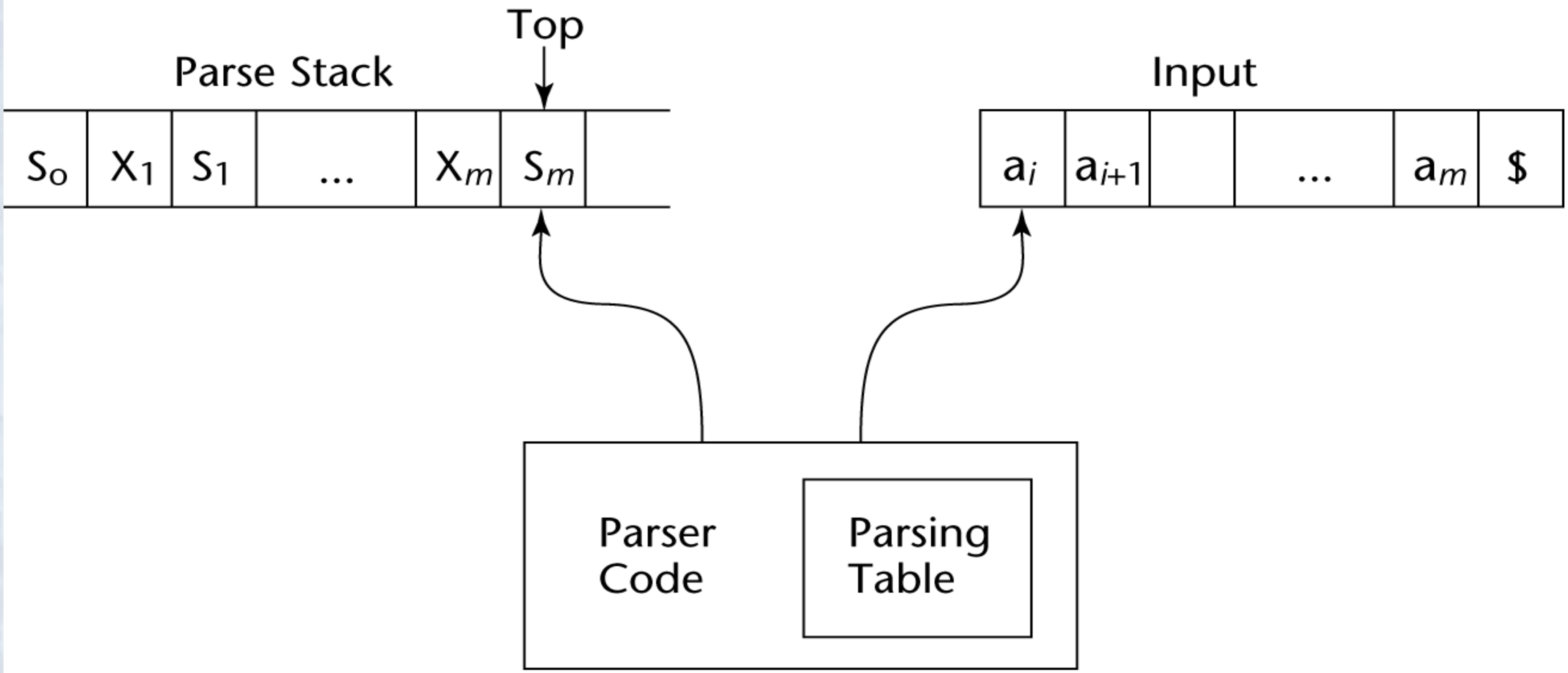
$$(S_0X_1S_1X_2S_2\ldots X_mS_m,\ a_ia_i+1\ldots a_n\$)$$

STACK INPUT

Bottom-up Parsing

- 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

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

    $(S_0X_1S_1X_2S_2 \ldots X_mS_m a_i S, a_{i+1} \ldots a_n\$)$
  - 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

- 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

S:Shift

```
E -> E+T
E -> T
T -> T*F
T -> F
F -> (E)
F -> id
```

R: Reduce

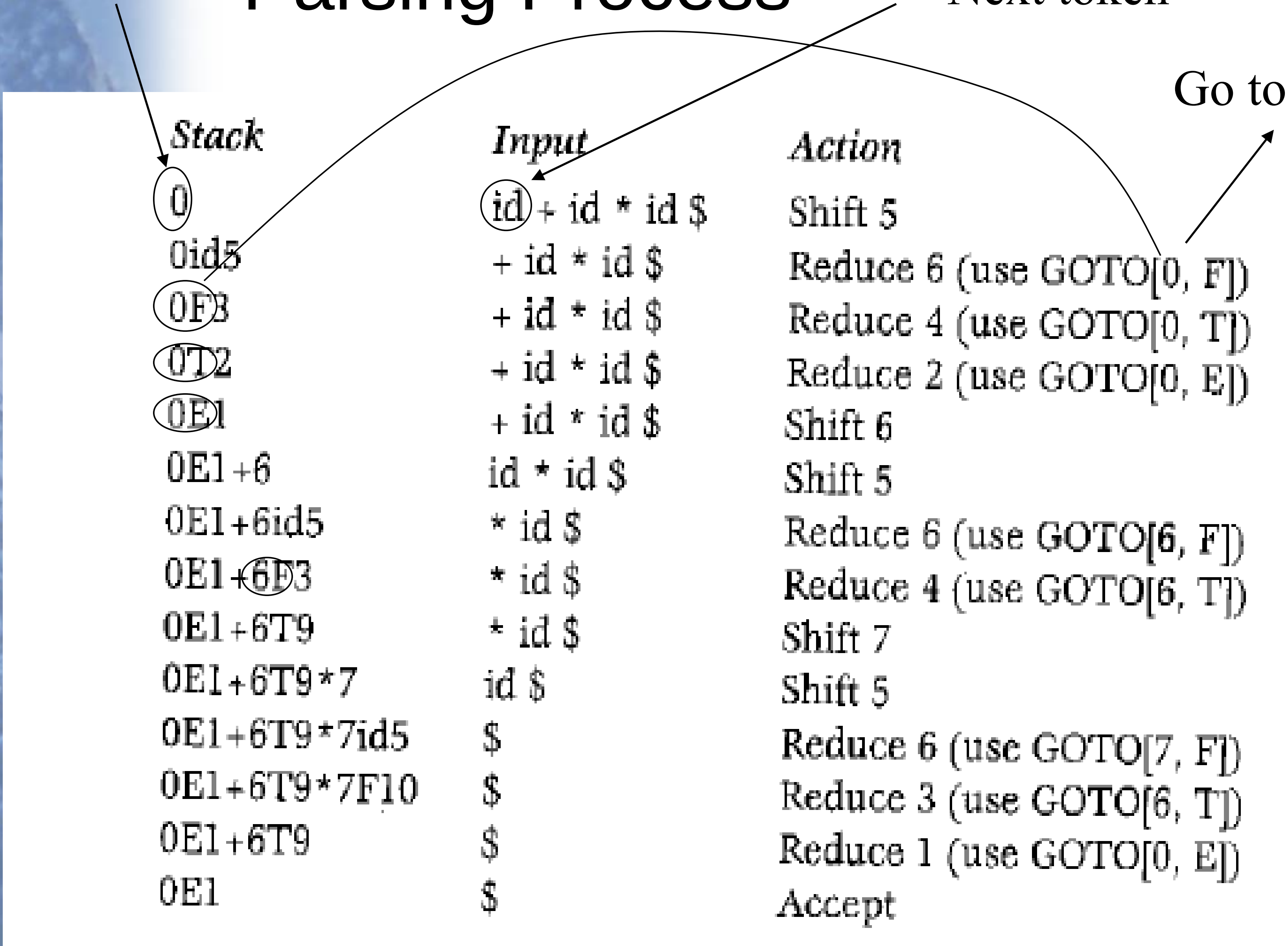
	Action						Goto		
State	id	+	*	(	)	$	E	T	F
0	S5		S4				1	2	3
1		S6				accept			
2		R2	S7		R2	R2			
3		R4	R4		R4	R4			
4	S5			S4			8	2	3
5		R6	R6		R6	R6			
6	S5			S4				9	3
7	S5			S4					10
8		S6			S11				
9		R1	S7		R1	R1			
10		R3	R3		R3	R3			
11		R5	R5		R5	R5			

Parsing Process

state

Next token

Go to state 3



Stack	*Input*	*Action*
0	id + id * id $	Shift 5
0id5	+ id * id $	Reduce 6 (use GOTO[0, F])
0F3	+ id * id $	Reduce 4 (use GOTO[0, T])
0T2	+ id * id $	Reduce 2 (use GOTO[0, E])
0E1	+ id * id $	Shift 6
0E1+6	id * id $	Shift 5
0E1+6id5	* id $	Reduce 6 (use GOTO[6, F])
0E1+6F3	* id $	Reduce 4 (use GOTO[6, T])
0E1+6T9	* id $	Shift 7
0E1+6T9*7	id $	Shift 5
0E1+6T9*7id5	$	Reduce 6 (use GOTO[7, F])
0E1+6T9*7F10	$	Reduce 3 (use GOTO[6, T])
0E1+6T9	$	Reduce 1 (use GOTO[0, E])
0E1	$	Accept

Bottom-up Parsing

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

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