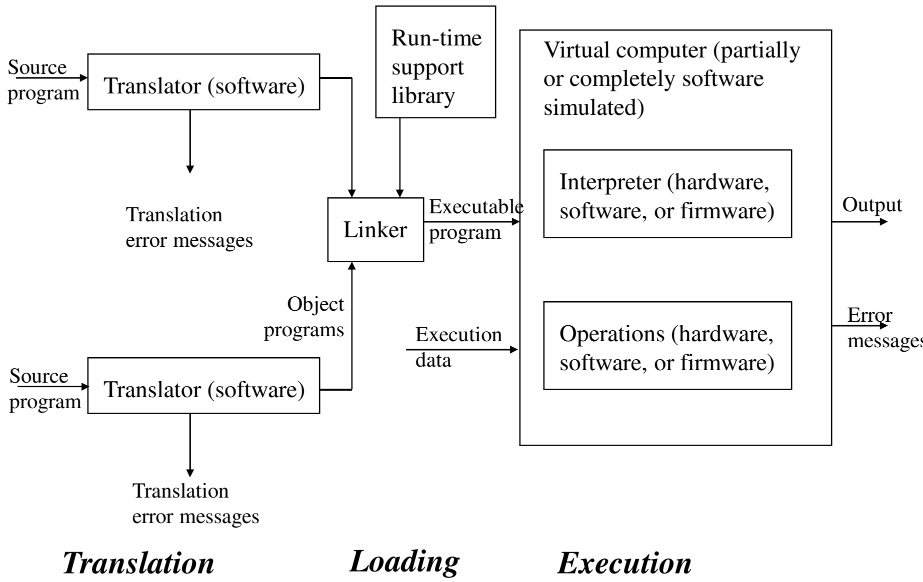
Software II: Principles of Programming Languages

Lecture 4 –Language Translation: Lexical and Syntactic Analysis

Translation

- A translator transforms source code (a program written in one language) into object code (the equivalent program in another language, presumably the computer's native language).
- Such translators include:
  - ***Assemblers*** – translators where the source language (language of the source code) is a symbolic equivalent of the machine language.
  - ***Compilers*** – translators where the source language is a higher-level language and the object language is either assembly language or machine language.
  - ***Loader*** (or ***Link Editor***) – assembles one or more object program (together with library routines) into a single program that the computer can run with all its addresses accessible.
  - ***Preprocessor*** – which perform work in preparation for compiling

Structure Of a Typical Language Implementation



Compiled vs. Interpreted Language

Most programming languages are designed with the intent of implementing it through compilation or interpretation.

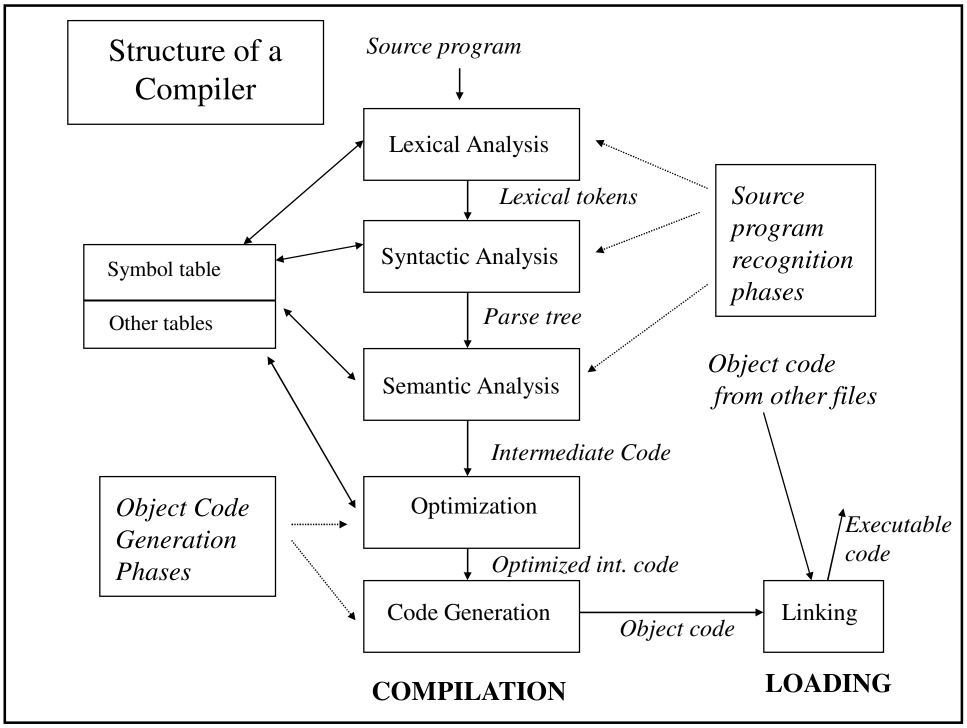
- Compiled languages include:
  - C, C++, FORTRAN, Pascal and Ada.
  - Their runtime routines are limited to supporting a few operations without a close analogue in the machine language (e.g., input/output)
- Interpreted languages include:
  - LISP, ML, Perl, Postscript, Prolog and Smalltalk.
  - The translator produces an intermediate form of the program which the executor can interpret quickly.

The Java Virtual Machine

- While Java is closer to C++ than to LISP in form, it is translated into an intermediate representation called ***bytecodes***.
  - These bytecodes are interpreted by the Java Virtual Machine.
  - The time needed to interpret the bytecodes is relatively small compared to the transmission time for Java applets.

The Translation Process

- The translation process may be fairly simple (as in the case of Perl, Prolog or LISP), especially if one is willing to write a software interpreter and accept poor execution speed.
- Translation process is usually divided into 2 parts: analysis of the source program and synthesis of the object program



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 (Scanning)

- Lexical analysis involves the recognition of the elementary constituents of a program.
  - These are the keywords, operators, comments, delimiters, identifiers, literals, etc.
  - The individual characters of the source program must be grouped together to form these constituents.
- The scanner must identify each lexeme and associate with it the grammatical component within the program with which the lexeme is associated. We call the grammatical component the ***token***.
- The formal model for lexical analysis is a finite automaton.
- This is sometimes complicated by the difficulty in recognizing where the boundaries between tokens is:
  - e.g., DO 10 I = 1, 5 DO 10 I = 1.5

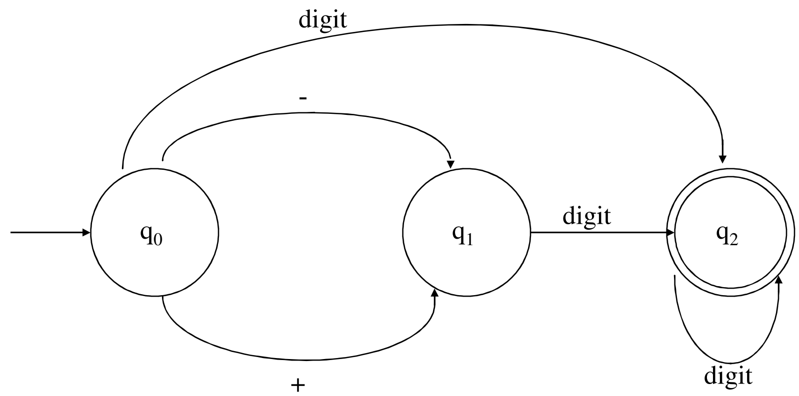
Implementing A Scanner

- We can construct a lexical analyzer (or ***scanner***)by one of three methods:
  - Write a formal description of the regular expressions that we wish to accept and use a software tool to generate a scanner automatically.
  - Write a program that simulates the finite automaton that recognizes the regular expressions that we wish to accept.
  - Construct a table that describes the finite automaton and write a program that uses the the data in the table.

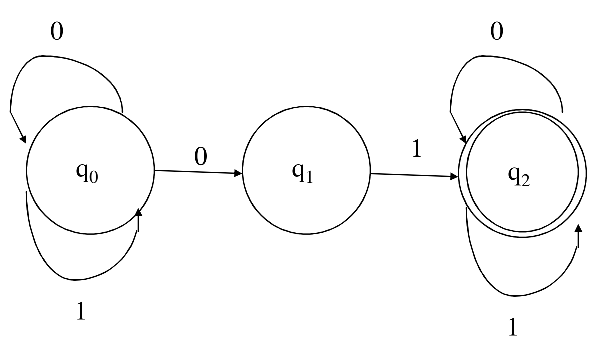
Finite-State Automata

- A Finite Automaton is a state machine that changes state as it processes each character is an expression and then:
  - ***accepts*** the expression if it is in a final state (the expression belongs to the language) or
  - ***reject*** the expression if it is not in a final state (the expression does not belong to the language)

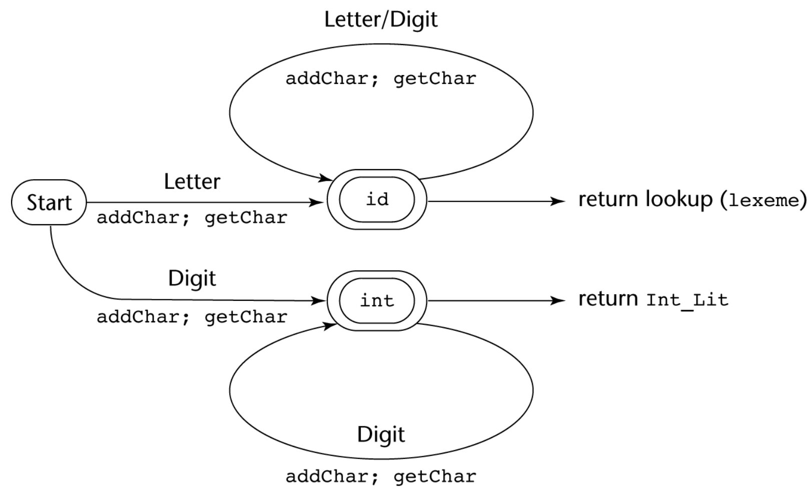
FA To Recognize Optionally Signed Integers



Converting **(0+1)*01(0+1)*** to an FA



State Diagram



Scanning Integer Expressions

```
#include    <ctype.h>
#include    <stdio.h>

/* The token as an enumerated type */
typedef enum      {PLUS, TIMES, LPAREN, RPAREN,
                  EOL, NUMBER, ERROR} TokenType;

int   numval;     /* computed numeric value of a
                        NUMBER */
int   curr_char;  /* Current character */
```

```
TokenType   getToken(void)
{
  while ((curr_char = getchar()) == ' ')
      ;     /* Skip white space */

  if (isdigit(curr_char))           {
      /*  recognize a NUMBER token */
      numval = 0;
      while (isdigit(curr_char))    {
            /* compute numeric value */
            numval = 10 * numval
                              + curr_char - '0';
            curr_char = getchar();
      }
```

```
      /* put back last character onto input */
      ungetc(curr_char, stdin);
      return(NUMBER);
  }
  else      {
      /* recognize a special symbol */
      switch(curr_char) {
      case '(': return (LPAREN);
      case ')': return (RPAREN);
      case '+': return (PLUS);
      case '*': return (TIMES);
      case '\n': return (EOL);
      default: return (ERROR);
      }
  }
}
```

```
int   main(void)
{
  TokenType token;
  do  {
      token = getToken();
      switch(token)     {
      case PLUS:  printf("PLUS\n"); break;
      case TIMES: printf("TIMES\n"); break;
      case LPAREN:printf("LPAREN\n"); break;
      case RPAREN:printf("RPAREN\n"); break;
      case EOL:   printf("EOL\n"); break;
      case NUMBER:printf("NUMBER: %d\n", numval);
                  break;
```

```
      case ERROR: printf("ERROR: %c\n", curr_char);
      }
  } while (token != EOL);
        return(0);
}
```

Syntactic Analysis (Parsing)

- The grammatical structure of the program is identified (e.g., statements, procedures, expressions, etc.)
- The parser must recognize how lexemes are grouped to form expressions, statements, declarations, etc.
- The actions of semantic analysis are are usually initiated by the parser.
- The formal model for the parser is the pushdown automaton.

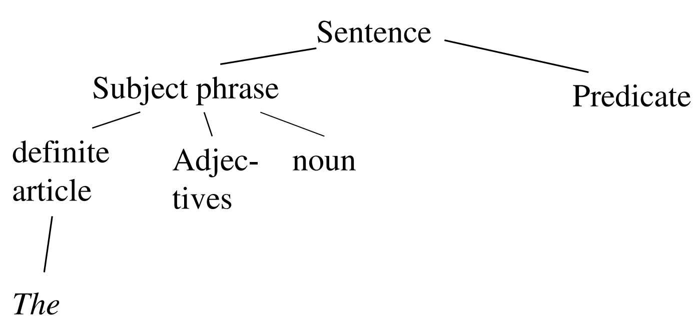
The Parsing Problem

- 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

Types of Parsers

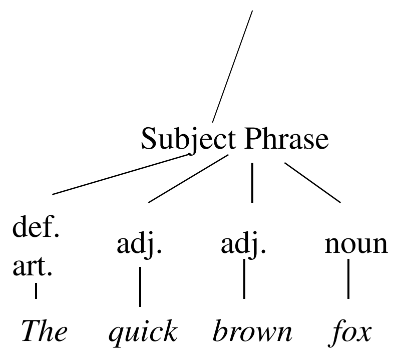
- Parsers can be either ***top-down*** or ***bottom-up***:
  - – Top-down parsers build the parse-tree starting from the root building until all the tokens are associated with a leaf on the parse tree.
  - – Bottom-up parsers build the parse-tree starting from the leaves, assembling the tree fragments until the parse tree is complete.

Top-down Parsers



Top-down parsing assumes a certain minimum structure as we start building the parse tree

Bottom-up parsers



Bottom-up parsers ***shift*** by each token, ***reducing*** them into a non-terminal as the grammar requires.

Nb: Until we finish building the predicate, we have no reason to reduce anything into the nonterminal ***Sentence***

Types of Parsers (continued)

- Parsers can be either ***table-driven*** or ***handwritten***:
  - Table-driven parsers perform the parsing using a driver procedure and a table containing pertinent information about the grammar. The table is usually generated by automated software tools called ***parser generators.***
  - Handwritten parsers are hand-coded using the grammar as a guide for the various parsing procedures.

Types of Parsers (continued)

- LL(1) and LR(1) parsers are table-driven parsers which are top-down and bottom-up respectively.
- Recursive-descent parsers are top-down hand-written parsers.
- Operator-precedence parsers are bottom-up parsers which are largely handwritten for parsing expressions.

What is top-down parsing?

- Top-down parsing is a parsing-method where a sentence is parsed starting from the root of the parse tree (with the *"Start"* symbol), working recursively down to the leaves of the tree (with the terminals).
- In practice, top-down parsing algorithms are easier to understand than bottom-up algorithms.
- Not all grammars can be parsed top-down, but most context-free grammars can be parsed bottom-up.

An example of top-down parsing

Let's consider the expression grammar:

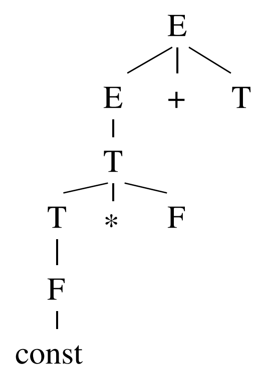
E ::= E **+** T | T

T ::= T ***** F | F

F ::= **id** | **const** | (E)

How will it begin parsing the expression:

3*x + y* z



LL(k) grammars

- Top-down grammars are referred to as LL(k) grammars:
  - The first L indicates ***L***eft-to-Right scanning.
  - The second L indicates ***L***eft-most derivation
  - The k indicates k lookahead characters.
- We will be examining LL(1) grammars, which spot errors at the earliest opportunity but provide strict requirements on our grammars.

LL(1) grammars

- LL(1) grammars determine from a single lookahead token which alternative derivation to use in parsing a sentence.
- This requires that if a nonterminal A has two different productions:

  A ::= α and A ::= β

  - that a and ß cannot begin with the same token.

    α ***or*** ß can derive an empty string but not both.
  - if ß $=>^*$ ε, α cannot derive any string that begins with a token that could immediately follow A.

Converting an expression grammar into LL(1) form

- If our expression grammar is originally:

$$E ::= E + T \mid T$$

$$T ::= T * F \mid F$$

$$F ::= \textbf{id} \mid \textbf{const} \mid (E)$$

- We must convert to the following form if it is to be LL(1)

$$E ::= T E'$$

$$E' ::= + T E' \mid \varepsilon$$

$$T ::= F T'$$

$$T' ::= * F T' \mid \varepsilon$$

$$F ::= \textbf{id} \mid \textbf{const} \mid (E)$$

Parse Table

Once the grammar is in LL(1) form, we create a table showing which production we use in parsing each nonterminal for every possible lookahead token:

	E	E'	T	T'	F
+		2		6	
*				5	
(	1		4		9
)		3		6	
id	1		4		7
const	1		4		8
$		3		6	

1 E ::= TE'
2 E' ::= +TE'
3 E' ::= ε
4 T ::= FT'
5 T' ::= *FT'
6 T' ::= ε
7 F ::= id
8 F ::= const
9 F ::= (E)

The Parsing Algorithm

Processing context-free expressions requires the use of a stack. The Parsing algorithm uses a stack:

Place the start symbol in a node and push it onto the stack.
Fetch a token
REPEAT
- Pop a node from the stack
- IF it contains a terminal, match it to the current token (no match indicates a parsing error) and fetch another token
- ELSE IF it contains a nonterminal, look it up in the production table using the nontermina and the current token. Place the variables in REVERSE order on the stack

UNTIL the stack is empty

Recursive-Descent Parsing

- Recursive-descent parsing is a top-down parsing technique which shows a series of recursive procedures to parse the program
- There is a separate procedure for each individual nonterminal.
- Each procedure is essentially a large if-then-else structure which looks for the appropriate tokens when the grammar requires a particular terminal and calls another procedure recursively when the grammar requires a nonterminal.

Recursive-Descent Parsing of Expressions

```
#include    <ctype.h>
#include    <stdlib.h>
#include    <stdio.h>

int   token;      /* holds the current input
                  character for the parse */

/* declaration to allow arbitrary recursion */
void  command(void);
int   expr(void);
int   term(void);
int   factor(void);
int   number(void);
int   digit(void);
```

```c
void  error(void)
{
  printf("parse error\n");
  exit(1);
}

void  getToken(void)
{
  /* tokens are characters */
  token = getchar();
}

void  match(char c)
{
  if (token == c) getToken();
  else  error();
}
```

```c
void  command(void)
/* command -> expr '\n' */
{
  int result = expr();
  if (token == '\n')
     /* End the parse and print the result */
     printf("The result is %d\n", result);
  else
       error();
}
```

```
int   expr(void)
/* expr -> term {'+' term } */
{
  int result = term();
  while     (token == '+')    {
      match('+');
      result += term();
  }
  return(result);
}
```

```
int   term(void)
/* term -> factor {'*' factor } */
{
  int result = factor();
  while     (token == '*')    {
      match('*');
      result *= factor();
  }
  return(result);
}
```

```
int   factor(void)
/* factor -> '(' expr ')' | number */
{
  int result;
  if (token == '(')     {
      match('(');
      result = expr();
      match(')');
  }
  else
      result = number();
  return(result);
}
```

```
int   number(void)
/* number -> digit {digit } */
{
  int       result = digit();
  while (isdigit(token))
      /* The value of a number with a new
             trailing digit is its previous value
             shifted by a decimal place plus the
             value of the new digit  */
      result = 10 * result + digit();
  return(result);
}
```

```c
int   digit(void)
/* digit -> '0' | '1' | '2' | '3' | '4'
   | '5' | '6' | '7' | '8' | '9' */
{
   int result;
   if (isdigit(token))   {
       /* The numeric value of a digit character
             is the difference between its ASCII
             value and the ASCII value of the
             character '0' */
       result = token - '0';
       match(token);
   }
   else
       error();
   return(result);
}
```

```c
void  parse(void)
{
   getToken();      /* Get the first token */
   command();       /* Call the parsing
             procedure for the start symbol */
}

int   main(void)
{
   parse();
   return(0);
}
```

Bottom-up Parsing

- Bottom-up parsers parse a programs from the leaves of a parse tree, collecting the pieces until the entire parse tree is built all the way to the root.
- Bottom-up parsers emulate pushdown automata:
  - requiring both a state machine (to keep track of what you are looking for in the grammar) and a stack (to keep track of what you have already read in the program).
  - making it fairly easy to automate the process of creating the parser
  - ensuring that all context-free grammars can be parsed by this method.

Bottom-up parsers as shift-reduce parsers

- Bottom-up parsers are frequently called shift-reduce parsers because of their two basic operations:
  - A shift involves moving pushing the current input token onto the stack and fetching the next input token.
  - A reduce involves popping all the variables that comprise the right-sentential form for a nonterminal and replacing them on the stack with the equivalent nonterminal that appears on the left-hand side of that production.
  - While shifting involve pushing and reducing involve popping, do not think of them as equivalent: a shift also involve advancing the input token stream and a reduce involves zero or more pops followed by a push.

LR(k) grammars

- Bottom-up grammars are referred to as LR(k) grammars:
  - The first L indicates ***L***eft-to-Right scanning.
  - The R that is second indicates ***R***ight-most derivation
  - The k indicates k lookahead characters.
- There should be no need for anything more than a single lookahead, i.e, an LR(1) grammar.

An example - a LR(0) grammar

An LR(0) grammar does not use a lookahead character to determine the action that it will take - the current token will be used to determine the state into which it will go.

Consider the following grammar:

E ::= *E* **+** *T* | *T*

T ::= **+** *F* | **-** *F* | *F*

F ::= **id** | **const**

An example - a LR(0) grammar (continued)

Let's write out our grammar and add to it a special first production with a special start symbol *S:*

1 S ::= E $ (indicates that the expression is followed by EOF)

2 E ::= E + T

3 E ::= T

4 T ::= +F

5 T ::= -F

6 T ::= F

7 F ::= id

8 F ::= const

The LR(0) parse table

GOTO									
state	ACTION	+	-	id	const	$	E	T	F
0	s	4	5	6	7		1	2	3
1	s	8				12			
2	r3								
3	r6								
4	s			6	7				9
5	s			6	7				11
6	r7								
7	r8								
8	s	4	5	6	7			10	3
9	r4								
10	r2								
11	r5								
12	acc								

Tracing LR(0) parsing

There are 3 parsing operations:

Shift - moving a token and state onto the stack (we find the state using the GOTO table).

Reduce n - we pop enough items from the stack to form the right side of production n and then we push the nonterminal on its left side of production n on to thestack, together with the state indicated by the GOTO table

Accept - we accept the program as completely and correctly parsed and terminate execution.

Tracing LR(0) parsing - an example

Example - the expression ***-27 + x***

5	-
0	$

We place the state 0 and the EOF marker **$** on the stack. The action for state 0 is ***shift***. We place the **-** and GOTO(0, -) = 5 on the stack

7	const
5	-
0	$

The action for state 5 is ***shift***. We place the constant on the stack together with GOTO(5, const) = 7.

11	F
5	-
0	$

The action for state 7 is reduce by production 8. Pop the const (and state 7). Push F and GOTO(5,F) = 11

Tracing LR(0) parsing - an example (continued)

2	T
0	$

The action for state 11 is reduce by production 5. Pop the - and F (along with states 5 and 11) and push the T together with GOTO(0,T) = 2

1	E
0	$

The action for state 2 is reduce by production 3. Pop the T (and state 2). Push the E and GOTO(0,E) = 1.

8	+
1	E
0	$

The action for state 1 is shift. We move the + onto the stack together with GOTO(1, +) = 8.

Tracing LR(0) parsing - an example (continued)

6	id
8	+
1	E
0	$

The action for state 8 is shift. We move the id and GOTO(8, id) = 6 onto the stack.

3	F
8	+
1	E
0	$

The action for state 6 is reduce by production 7. We pop the id and state 6. We push F and GOTO(8, F) = 3

10	T
8	+
1	E
0	$

The action for state 3 is reduce by production 6. We pop the F and state 3. We push T and GOTO(8, T) = 10.

Tracing LR(0) parsing - an example (continued)

1	E
0	$

The action for state 10 is reduce by production 2. We pop the T (and state10), the + (and state8) and the E (and state1). We push the E and GOTO(0,E) = 1.

12	$
1	E
0	$

The action for state 1 is shift. We push the $ and GOTO (1,E) = 12 onto the stack.

The action for state 12 is accept. The only item on the stack (excluding the $s) is E, which is the start symbol in our expression grammar

YACC and Bison

- YACC (***Y***et ***A***nother ***C***ompiler ***C***ompiler) is a program that automatically generates a parser based on specifications written in a syntax similar to BNF.
- Bison is its GNU equivalent.

YACC Format

```
%{/* code to insert at beginning of the parser
}%
/* Other YACC definitions, if necessary */
%%
/* grammar and associated actions */
%%
/* auxiliary procedures */
```

YACC Specification of the Calculator

```
%{
#include    <stdio.h>
}%
%%
command:expr `\n' {printf("The result is:%d\n",
  $1);}
  ;
expr  : expr `+' term {$$ = $1 + $3; }
      | term {$$ = $1; }
  ;
term  : term `*' factor {$$ = $1 * $3; }        |
  factor {$$ = $1; }
  ;
```

```
factor: number {$$ = $1; }
      | `(` expr `)' { $$ = $2;}
  ;
number : number digit { $$ = 10 * $1 + $2; }
  ;
digit : `0' { $$ = 0; }
      | `1' { $$ = 1; }
      | `2' { $$ = 2; }
      | `3' { $$ = 3; }
      | `4' { $$ = 4; }
      | `5' { $$ = 5; }
      | `6' { $$ = 6; }
      | `7' { $$ = 7; }
      | `8' { $$ = 8; }
      | `9' { $$ = 9; }
      ;
```

```
%%
main()
{
  yyparse();
  return(0);
}
int   yylex(void)
{
  static    int   done = 0;
  int       c;
  if (done) return(0);  /* stop parsing */
  c = getchar();
  if (c == `\n')
      /* next call will end parsing */
  done = 1;
  return(c);
}
```

```
int   yyerror(char *s)
{
  /* allows for print error message */
  printf("%s\n", s);
}
```

Semantic Analysis

- Semantic analysis is the phase where the meaning of the syntactic constructs is recognized and synthesis of the object program is begun.
- While it is possible for the semantic analyzer to produce an object program, the end result of this phase is usually a language-independent, machine-independent intermediate representation of the program.

Functions of the Semantic Analyzer

The most common functions of semantic analysis include:

- Symbol-Table Management
- Insertion of Implicit Information
- Error Detection
- Macro processing and Compile-Time Operations

Symbol-Table Management

- The symbol table is one of a translator's central data structures.
- The symbol table hold data regarding every lexeme in a program, including keywords, operators, identifiers and literals.
- The data within the symbol table is assembled during the analysis phases of translation and used during the generation phases.

Insertion of Implicit Information

- Some information in the source program is implicit and must be made explicit, e.g., the type of variables declared by default in FORTRAN.

Error Detection

- All three analysis phases must be prepared to handle incorrect programs.
- Syntactic errors involve the incorrect use of grammatical constructs.
- Semantic errors involve cases where the semantics are in error, e.g., incompatible data types.

Macro processing and Compile-Time Operations

- A macro, its simplest form, is a piece of text that is inserted into a program where the appropriate macro call appears. In more complex form, it may involve the replacement of formal parameters with their actual values.
- An example of compile –time operations is conditional compilation, where a segment of source code will include compiled depending on the validity of a test condition.

Synthesis of the Object Program

The final stages of the translation process involve the generation of the object program. This includes:

- Optimization
- Code Generation
- Linking and Loading

Optimization

- Optimization is improving the efficiency of an object program (execution time and/or storage requirements), usually by removing inefficiencies created by the automated translation process.
- Optimization may be local (confined to a small section of code which will always be executed as a unit) or global (tracing through the logical sequence of instructions)

An Example of Optimization

- The statement
  `A = B + C + D`
- creates the intermediate code
  - **`Temp1 = B + C`**
  - **`Temp2  = Temp1 + d`**
  - **`A = Temp2`**

  which generates the object code
  - **Load B** *(Step a)*
  - **Add C**
  - **Store Temp1**
  - **Load Temp1** *(Step b)*
  - **Add D**
  - **Store Temp2**
  - **Load Temp2** *(Step c)*
  - **Store A**

Code Generation

- After the intermediate representation is optimized, object code is created based on this representation, usually in machine language.
- This object code may need optimization itself.
- The object code may be executable or may need linking.

Linking and Loading

- The various object modules must be combined into one executable program.
- References to external variables and procedures must be resolved and external procedures must be includes in the executable module.. This information is found in the ***loader table***.

Bootstrapping

- It is common to write a compiler in the source language.
- Once the compiler is completed, it is used to translate itself into an executable program. This is known as ***bootstrapping***.
- Frequently the first compilation of a compiler is done by hand due to the lack of a working compiler.

Diagnostic Compilers

- Production compilers usually concentrate on creating object code that can be executed efficiently. Consequently, these compilers do not always offer error messages that are useful, especially to novice programmers.
- It was particularly popular in the 1960s to create compilers that could quickly translate programs and create compiler-time and runtime error messages that were particularly helpful to nove programmers.
- These diagnostic compilers include WATFOR and PL/C.