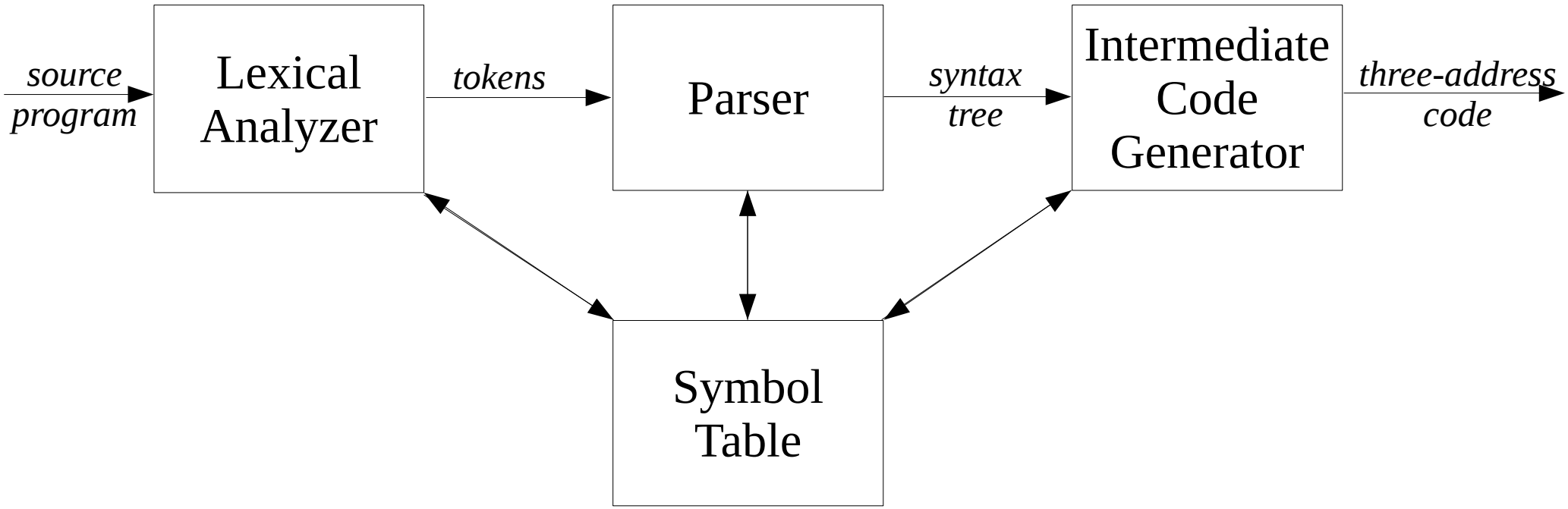
Concepts Introduced in Chapter 2

- A more detailed overview of the compilation process.
  - Parsing
  - Scanning
  - Semantic Analysis
  - Syntax-Directed Translation
  - Intermediate Code Generation

Model of A Compiler Front-End



Context-Free Grammar

- A grammar can be used to describe the possible hierarchical structure of a program.
- A context free grammar has 4 components:
  - A set of tokens, known as terminal symbols.
  - A set of nonterminals.
  - A set of productions where each production consists of a nonterminal, called the left side of the production, an arrow, and a sequence of tokens and/or nonterminals, called the right side of the production.
  - A designation of one of the nonterminals as the start symbol.
- The token strings that can be derived from the start symbol forms the language defined by the grammar.

Example Grammar

list → *list* + *digit*

list → *list* - *digit*

list → *digit*

digit → 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9

Parsing

- A grammar derives strings by beginning with the start symbol and repeatedly replacing a nonterminal by the body of *a* production for that nonterminal.
- The set of terminal strings that can be derived from the start symbol form the language defined by the grammar.
- *Parsing* is the process of taking a string of terminals and figuring out how to derive it from the start symbol of the language.

Parse Trees

- A parse tree pictorially shows how the start symbol of a grammar derives a specific string in the language.
- Given a context free grammar, a parse tree is a tree with the following properties:
  - The root is labeled by the start symbol.
  - Each leaf is labeled by a token or by ε.
  - Each interior node is labeled by a nonterminal.
  - If A is the nonterminal labeling some interior node and X1, X2, ..., Xn are the labels of the children of that node from left to right, then A → X1X2...Xn is a production.

followed by Fig. 2.5

Ambiguous Grammars

- The leaves (tokens) of a parse tree read from left to right form a legal string in the language defined by the associated grammar.
- If a grammar can have more than one parse tree generating the same string of tokens, then the grammar is said to be ambiguous.
- For a grammar representing a programming language, we need to ensure that the grammar is unambiguous or there are additional rules to resolve the ambiguities.

string → string + string | string - string

string → 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9

followed by Fig. 2.6

Precedence and Associativity

- Precedence determines which operator is applied first when different operators appear in an expression and parentheses do not explicitly indicate the order.
- Associativity is used to define the order of operations when there are multiple operators with the same precedence in an expression.
  - Left associativity means that (x op1 y) is applied first in the expression (x op1 y op2 z) when op1 and op2 have the same precedence.
  - Right associativity means that (y op2 z) is applied first in the expression (x op1 y op2 z) when op1 and op2 have the same precedence.

followed by Fig. 2.7

Syntax-Directed Translation

- Syntax-directed translation is the process of converting a string in the language specified by the grammar into a string in some other language.
- Syntax-directed translation is achieved by attaching *rules* or *program fragments* to productions in the grammar.
- Execution of these attached rules or program fragments, during parsing, results in the translation of the input string.

Converting Infix to Postfix

- If E is a variable or constant, then the postfix notation for E is E itself.
- If E is an expression of the form E1 op E2, where op is any binary operator, then the postfix notation for E is E1' E2' op, where E1' and E2' are the postfix notations for E1 and E2, respectively.
- If E is an expression of the form (E1), then the postfix notation for E1 is also the postfix notation for E.

(9−5)+2 ⇨ 95−2+ 9−(5+2) ⇨ 952+−

Syntax-Directed Definition

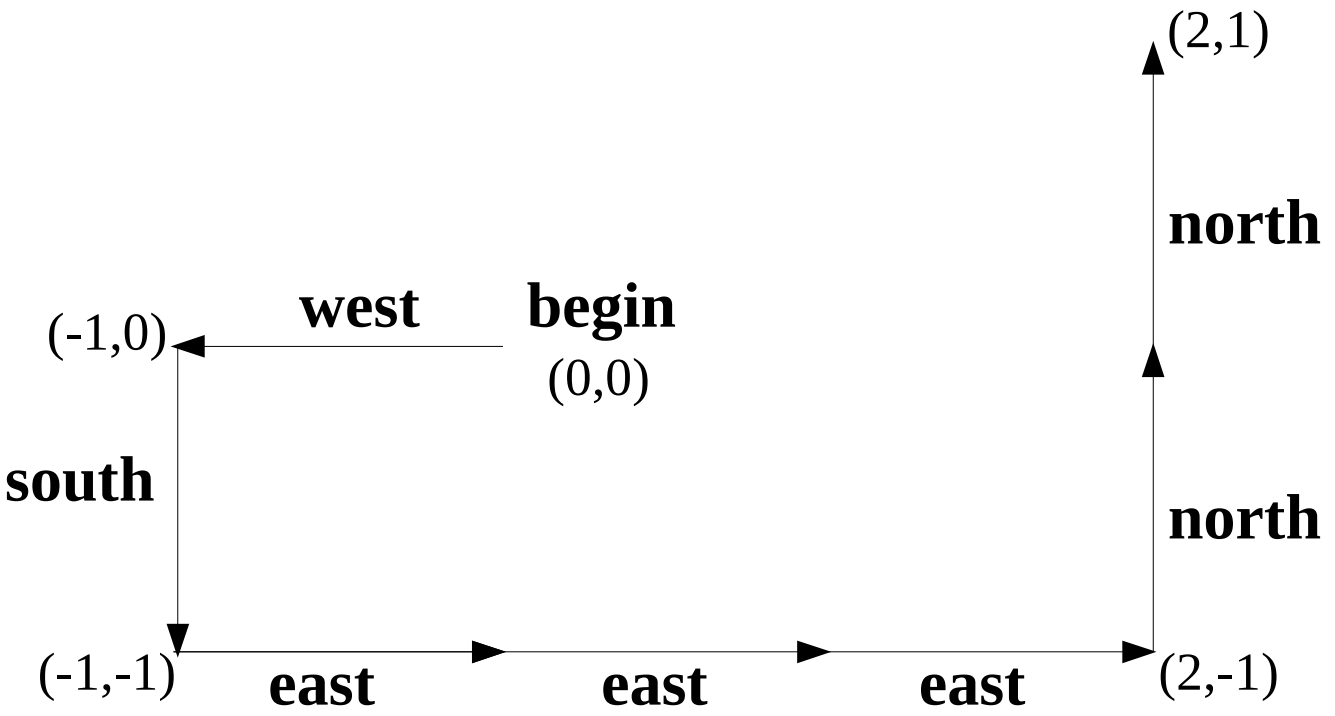
- Uses a grammar to define the syntactic structure.
- Associates attributes with each grammar symbol.
- Associates semantic rules for computing the values of the attributes.

followed by Fig. 2.9, 2.10

Example Syntax-Directed Definition

- seq → seq instr | **begin**
- instr → **east | north | west | south**

Keeping Track of a Robot's Position



Input String:

begin west south east east east north north

followed by Fig. A, B, 2.11

Translation Scheme

- A translation scheme is a grammar with program fragments called semantic actions that are embedded within the right hand side of the productions.
- Unlike a syntax-directed definition, the order of evaluation of the semantic rules is explicitly shown.

followed by Fig. 2.15, 2.14

Syntax-Directed Definition (SDD) Vs. Translation Scheme (TS)

- SDD – Semantic rules NOT embedded within the right sides of grammar productions

  TS – Semantic rules embedded within right sides of productions

- SDD – We need to define an evaluation order to compute the attribute values at each node in the parse tree. A dependency graph may be used. (It is possible that no such order exists.)

  TS – Evaluation order of semantic rules is explicitly shown by their position in the right side of grammar productions. Actions executed in the order in which they are encountered in a depth-first traversal of the parse tree

- SDD – Semantic rules are NOT part of the parse tree

  TS – Actions are included in the constructed parse tree

Parsing

- Parsing is the process of determining how/if a string of tokens can be generated by a grammar.
- Parsing Methods
  - Top-Down
    - Construction starts at the root and proceeds to the leaves.
    - Can be easily constructed by hand.
  - Bottom-Up
    - Construction starts at the leaves and proceeds to the root.
    - Can accept a larger class of grammars.

followed by Fig. 2.17, 2.18

Recursive Descent Parsing

- Top-down method for syntax analysis.
- A procedure is associated with each nonterminal of a grammar.
- Can be implemented by hand.
  - Decides which production to use by examining the lookahead symbol.
  - The appropriate procedure is invoked for each nonterminal in the rhs of the production.
- Predictive parsing means that a single lookahead symbol can be used to determine the procedure to be called for the next nonterminal.

followed by Fig. 2.15

Example Grammar for Recursive Descent Parsing

- Must not be left recursive.
- Must be left factored.

expr → term rest

rest → + term { print('+') } rest | - term { print('-') } rest | ε

term → 0 { print('0') }

term → 1 { print('1') }

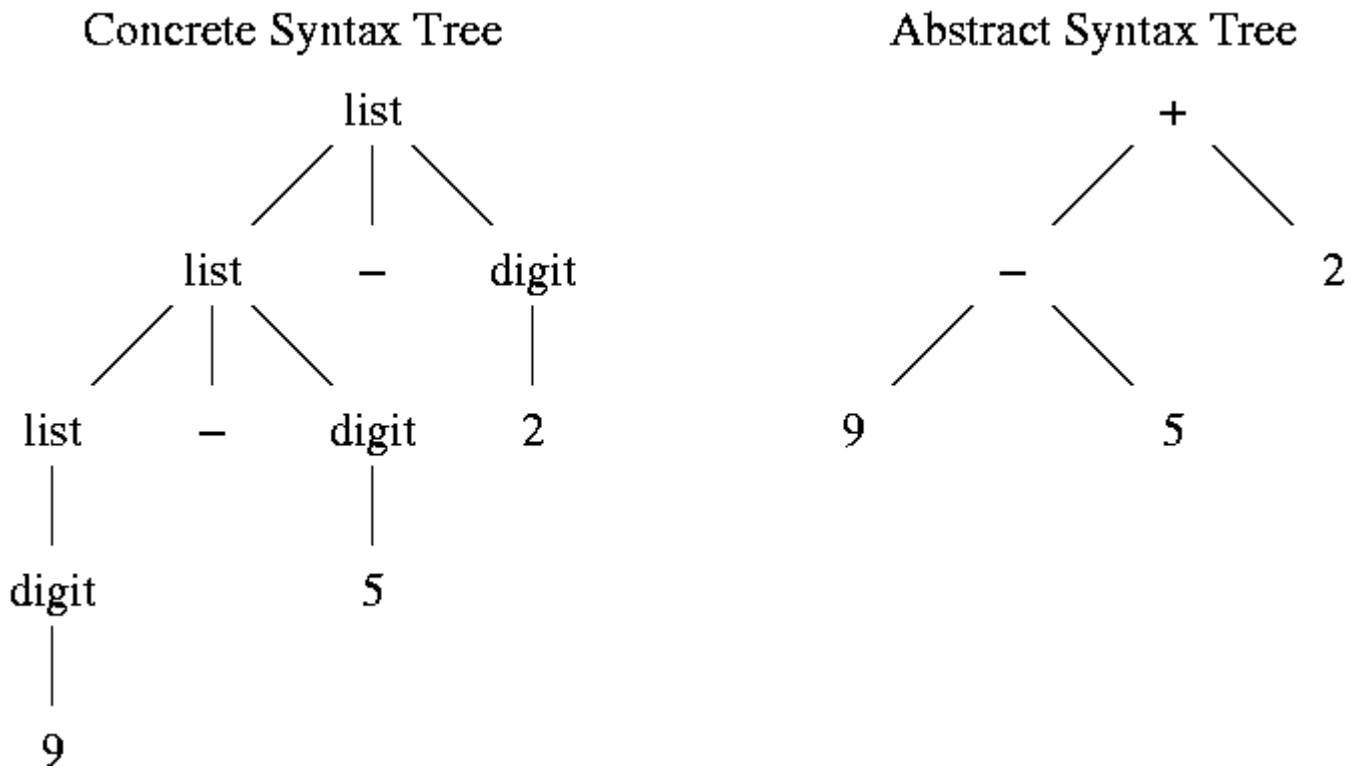
...

term → 9 { print('9') }

followed by Fig. C, D, E, F

Syntax Trees

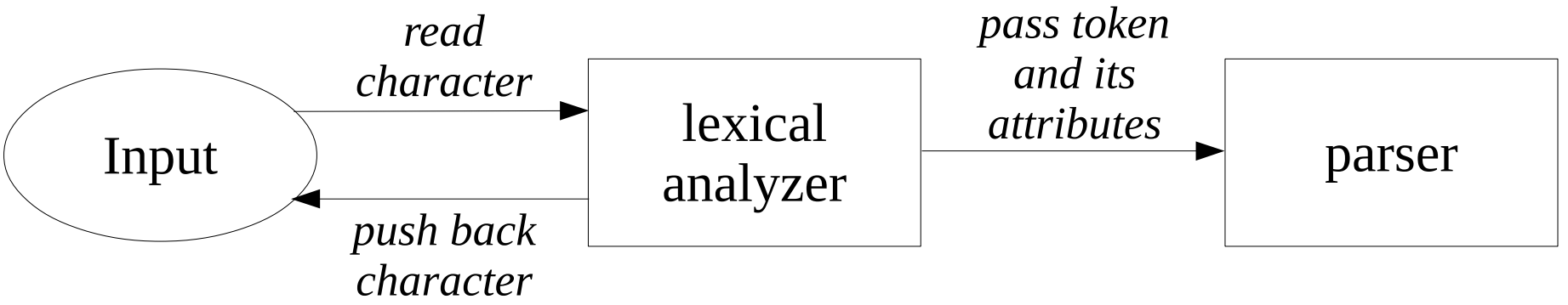
- Concrete Syntax Tree - a parse tree
- Abstract Syntax Tree
  - Each interior node is an operator rather than a nonterminal.
  - Convenient for translation.



Lexical Analysis Terms

- A token is a group of characters having a collective meaning.
  - id
- A lexeme is an actual character sequence forming a specific instance of a token.
  - `num`
- Characters between tokens are called whitespace.
  - blanks, tabs, newlines, comments

Inserting a Lexical Analyzer



Recognizing Keywords and Identifiers

- *Keywords* are character strings such as **if**, **for**, **do**, used in languages to identify constructs.
- Character strings for variables, arrays, functions, etc. are returned as *identifiers*.

```
count = count + increment
=>
<id,count> = <id,count> + < id,increment>
```

- Distinguish keywords from identifiers
  - keywords are reserved in many languages
  - initialize symbol table with keywords

followed by Fig. G

Symbol Table

- Used to save lexemes (identifiers) and their attributes.
- It is common to initialize a symbol table to include reserved words so the form of an identifier can be handled in a uniform manner.
- Attributes are stored in the symbol table for later use in semantic checks and translation.

Symbol Table Per Scope

- Scope of a declaration is the portion of a program to which the declaration applies.
- The *most-closely nested* rule for blocks is that an identifier *x* is in the scope of the most-closely nested declaration of *x*.
- Implementing the most-closely nested rule:
  - create a distinct symbol table for each block.
  - chain the symbol tables in a hierarchical tree structure.

followed by Fig. 2.36, I

l-values and r-values

- l-value
  - Used on the left side of an assignment statement.
  - Used to refer to a location.
- r-value
  - Used on the right side of an assignment statement.
  - Used to refer to a value.

Intermediate Code Generation

- The front-end of the compiler produces intermediate code, from which the back-end generates the target program.
- Two important intermediate representation:
  - syntax trees
    - syntax tree nodes represent significant programming constructs
    - provides a pictorial, hierarchical structure
  - three-address code
    - list of elementary programming steps
    - a useful format for code optimization

followed by Fig. 2.39

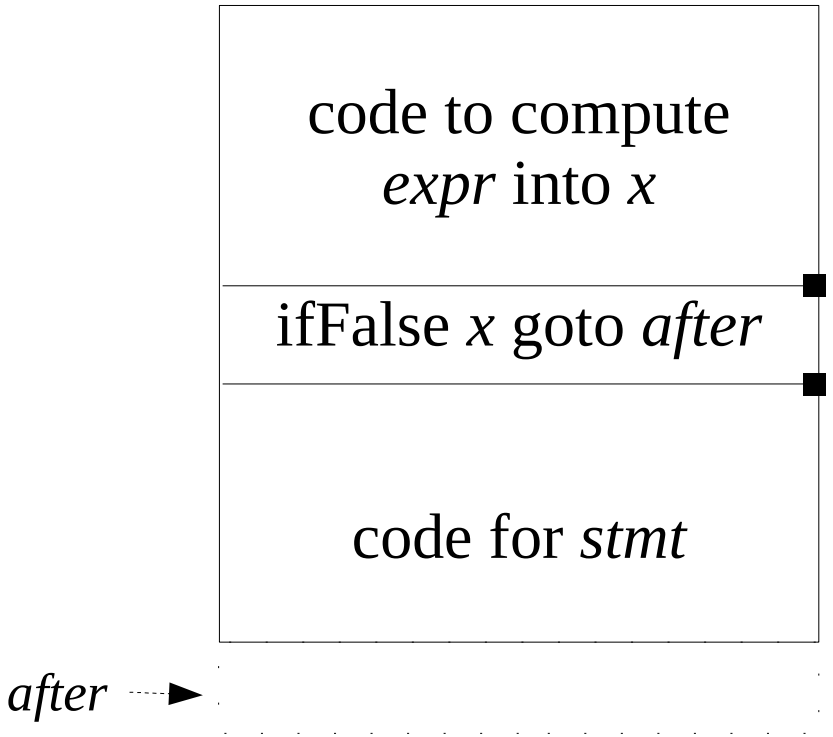
Three-Address Code

- Format of three-address code instructions:
  - General Format: $x = y$ **op** z
  - Arrays: $x\,[\,y\,] = z$, $x = y\,[\,z\,]$
  - Copy: $x = y$
  - Control flow: ifFalse x goto L,
  - ifTrue x goto L,
  - goto L

Translation to Three-Address Code

Translation of Statements:

if *expr* **then** *stmt*



Translation of Expression:

a[i] = 2*a[j-k]

```
t3 = j – k
t2 = a [ t3 ]
t1 = 2 * t2
a [ i ] = t1
```

Static Checking

- Static checks are consistency checks done during compilation.
- Static checking includes:
  - Syntactic checking
    - syntax checks that are not enforced by the grammar.
  - Type checking
    - Type checking assures that the type of a construct matches that expected by its context.
    - Coercions: automatic conversion of the type of an operand to that expected by the operator.