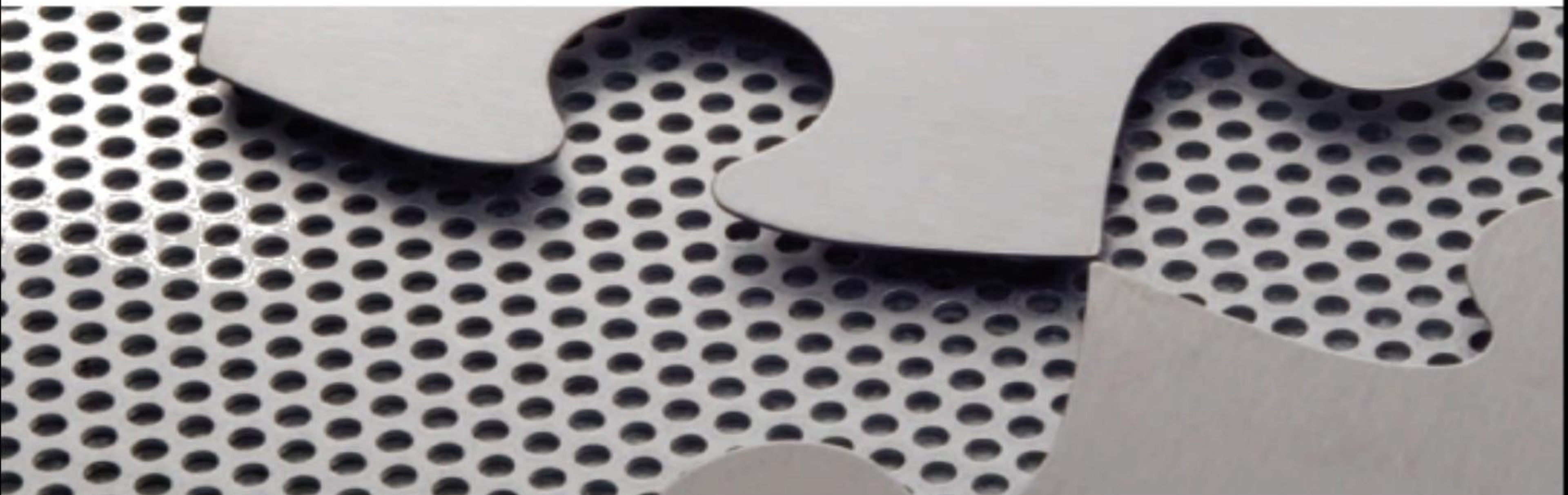
Programming Languages
Third Edition



Chapter 6
Syntax

Objectives

- Understand the lexical structure of programming languages
- Understand context-free grammars and BNFs
- Become familiar with parse trees and abstract syntax trees
- Understand ambiguity, associativity, and precedence
- Learn to use EBNFs and syntax diagrams

Objectives (cont'd.)

- Become familiar with parsing techniques and tools
- Understand lexics vs. syntax vs. semantics
- Build a syntax analyzer for TinyAda

Introduction

- Syntax is the structure of a language
- 1950: Noam Chomsky developed the idea of context-free grammars
- John Backus and Peter Naur developed a notational system for describing these grammars, now called **Backus-Naur forms**, or **BNFs**
  - First used to describe the syntax of Algol60
- Every modern computer scientist needs to know how to read, interpret, and apply BNF descriptions of language syntax

Introduction (cont'd.)

- Three variations of BNF:
  - Original BNF
  - Extended BNF (EBNF)
  - Syntax diagrams

Lexical Structure of Programming Languages

- **Lexical structure**: the structure of the **tokens**, or words, of a language
  - Related to, but different than, the syntactic structure
- **Scanning** phase: the phase in which a translator collects sequences of characters from the input program and forms them into tokens
- **Parsing** phase: the phase in which the translator processes the tokens, determining the program's syntactic structure

Lexical Structure of Programming Languages (cont'd.)

- Tokens generally fall into several categories:
  - **Reserved words** (or **keywords**)
  - **Literals** or **constants**
  - **Special symbols**, such as “;”m “<=“, or “+”
  - **Identifiers**
- **Predefined identifiers**: identifiers that have been given an initial meaning for all programs in the language but are capable of redirection
- **Principle of longest substring**: process of collecting the longest possible string of nonblank characters

Lexical Structure of Programming Languages (cont'd.)

- **Token delimiters** (or **white space**): formatting that affects the way tokens are recognized
- Indentation can be used to determine structure
- **Free-format** language: one in which format has no effect on program structure other than satisfying the principle of longest substring
- **Fixed format** language: one in which all tokens must occur in prespecified locations on the page
- Tokens can be formally described by **regular expressions**

Lexical Structure of Programming Languages (cont'd.)

- Three basic patterns of characters in regular expressions:
  - Concatenation: done by sequencing the items
  - Repetition: indicated by an asterisk after the item to be repeated
  - Choice, or selection: indicated by a vertical bar between items to be selected
- [ ] with a hyphen indicate a range of characters
- ? indicates an optional item
- Period indicates any character

Lexical Structure of Programming Languages (cont'd.)

- Examples:
  - Integer constants of one or more digits

    ```
    [0-9]+
    ```

  - Unsigned floating-point literals

    ```
    [0-9]+(\.[0-9]+)?
    ```

- Most modern text editors use regular expressions in text searches
- Utilities such as `lex` can automatically turn a regular expression description of a language's tokens into a scanner

Lexical Structure of Programming Languages (cont'd.)

- Simple scanner input:

```
* + ( ) 42 # 345
```

- Produces this output:

```
TT_TIMES
TT_PLUS
TT_LPAREN
TT_RPAREN
TT_NUMBER: 42
TT_ERROR: #
TT_NUMBER: 345
TT_EOL
```

Context-Free Grammars and BNFs

- Example: simple grammar

(1) *sentence* → *noun-phrase verb-phrase* .
(2) *noun-phrase* → *article noun*
(3) *article* → a | the
(4) *noun* → girl | dog
(5) *verb-phrase* → *verb noun-phrase*
(6) *verb* → sees | pets

Figure 6.2 A grammar for simple english sentences

- → separates left and right sides
- | indicates a choice

Context-Free Grammars and BNFs (cont'd.)

- **Metasymbols**: symbols used to describe the grammar rules
- Some notations use angle brackets and pure text metasymbols
  - Example: <sentence> ::= <noun-phrase> <verb-phrase> "."
- **Derivation**: the process of building in a language by beginning with the **start symbol** and replacing left-hand sides by choices of right-hand sides in the rules

Context-Free Grammars and BNFs (cont'd.)

sentence ⇒ *noun-phrase verb-phrase* . (rule 1)
⇒ *article noun verb-phrase* . (rule 2)
⇒ `the` *noun verb-phrase* . (rule 3)
⇒ `the girl` *verb-phrase* . (rule 4)
⇒ `the girl` *verb noun-phrase* . (rule 5)
⇒ `the girl sees` *noun-phrase* . (rule 6)
⇒ `the girl sees` *article noun* . (rule 2)
⇒ `the girl sees a` *noun* . (rule 3)
⇒ `the girl sees a dog` . (rule 4)

Figure 6.3 A derivation using the grammar of Figure 6.2

Context-Free Grammars and BNFs (cont'd.)

- Some problems with this simple grammar:
  - A legal sentence does not necessarily make sense
  - Positional properties (such as capitalization at the beginning of the sentence) are not represented
  - Grammar does not specify whether spaces are needed
  - Grammar does not specify input format or termination symbol

Context-Free Grammars and BNFs (cont'd.)

- **Context-free grammar**: consists of a series of grammar rules
- Each rule has a single phrase structure name on the left, then a → metasymbol, followed by a sequence of symbols or other phrase structure names on the right
- **Nonterminals**: names for phrase structures, since they are broken down into further phrase structures
- **Terminals**: words or token symbols that cannot be broken down further

Context-Free Grammars and BNFs (cont'd.)

- **Productions**: another name for grammar rules
  - Typically there are as many productions in a context-free grammar as there are nonterminals
- **Backus-Naur form**: uses only the metasymbols "$\rightarrow$" and "|"
- **Start symbol**: a nonterminal representing the entire top-level phrase being defined
- **Language of the grammar**: defined by a context-free grammar

Context-Free Grammars and BNFs (cont'd.)

- A grammar is **context-free** when nonterminals appear singly on the left sides of productions
  - There is no **context** under which only certain replacements can occur
- Anything not expressible using context-free grammars is a semantic, not a syntactic, issue
- BNF form of language syntax makes it easier to write translators
- Parsing stage can be automated

Context-Free Grammars and BNFs (cont'd.)

- Rules can express recursion

$$
\begin{aligned}
expr &\rightarrow expr \; \texttt{+} \; expr \mid expr \; \texttt{*} \; expr \mid \texttt{(} \; expr \; \texttt{)} \mid number \\
number &\rightarrow number \; digit \mid digit \\
digit &\rightarrow \texttt{0} \mid \texttt{1} \mid \texttt{2} \mid \texttt{3} \mid \texttt{4} \mid \texttt{5} \mid \texttt{6} \mid \texttt{7} \mid \texttt{8} \mid \texttt{9}
\end{aligned}
$$

Figure 6.4 A simple integer arithmetic expression grammar

$$
\begin{aligned}
number &\Rightarrow number \; digit \\
&\Rightarrow number \; digit \; digit \\
&\Rightarrow digit \; digit \; digit \\
&\Rightarrow \texttt{2} \; digit \; digit \\
&\Rightarrow \texttt{23} \; digit \\
&\Rightarrow \texttt{234}
\end{aligned}
$$

Figure 6.5 A derivation for the *number* 234 using the grammar of Figure 6.4

Context-Free Grammars and BNFs (cont'd.)

translation-unit → *external-declaration*
| *translation-unit external-declaration*

external-declaration → *function-definition* | *declaration*

function-definition → *declaration-specifiers declarator declaration-list compound-statement*
| *declaration-specifiers declarator compound-statement*
| *declarator declaration-list compound-statement*
| *declarator compound-statement*

declaration → *declaration-specifiers* '*;*'
| *declaration-specifiers init-declarator-list* '*;*'

init-declarator-list → *init-declarator*

Figure 6.6 Partial BNFs for C (adapted from Kernighan and Ritchie [1988]) (*continues*)

Context-Free Grammars and BNFs (cont'd.)

```
                | init-declarator-list ',' init-declarator

init-declarator → declarator | declarator '=' initializer
declarator → pointer direct-declarator | direct-declarator

pointer → '*' type-qualifier-list pointer | '*' type-qualifier-list
        | '*' pointer | '*'

direct-declarator → ID
        | '(' declarator ')' | direct_declarator '[' ']'
        | direct_declarator '[' constant_expression ']'
        | direct_declarator '(' parameter_type_list ')'
        | direct_declarator '(' identifier_list ')'
        | direct_declarator '(' ')'
...
...
```

Figure 6.6 Partial BNFs for C (adapted from Kernighan and Ritchie [1988])

Parse Trees and Abstract Syntax Trees

- Syntax establishes structure, not meaning
  – But meaning is related to syntax
- **Syntax-directed semantics**: process of associating the semantics of a construct to its syntactic structure
  – Must construct the syntax so that it reflects the semantics to be attached later
- **Parse tree**: graphical depiction of the replacement process in a derivation

Parse Trees and Abstract Syntax Trees (cont'd.)

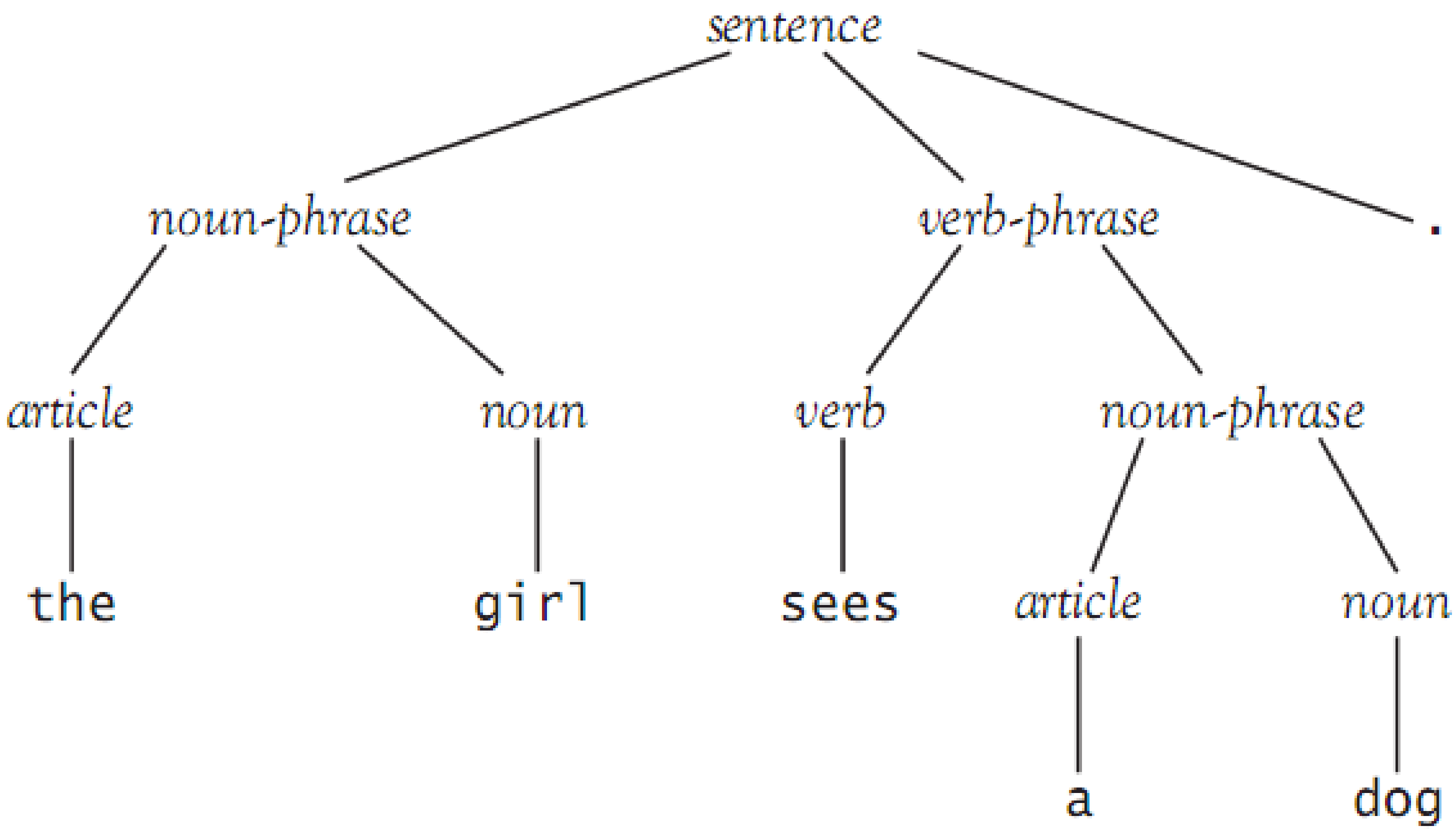


Figure 6.7: Parse tree for the sentence "the girl sees a dog."

Parse Trees and Abstract Syntax Trees (cont'd.)

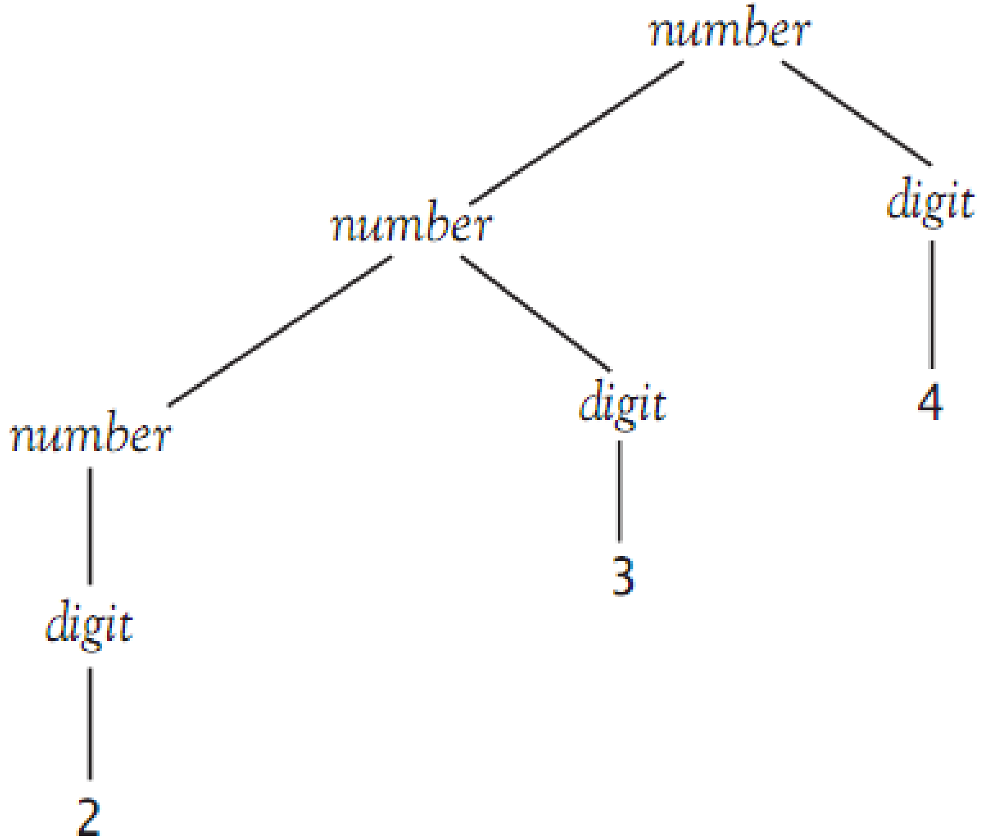


Figure 6.8: Parse tree for the number 234

Parse Trees and Abstract Syntax Trees (cont'd.)

- Nodes that have at least one child are labeled with nonterminals
- Leaves (nodes with no children) are labeled with terminals
- The structure of a parse tree is completely specified by the grammar rules of the language and a derivation of the sequence of terminals
- All terminals and nonterminals in a derivation are included in the parse tree

Parse Trees and Abstract Syntax Trees (cont'd.)

- Not all terminals and nonterminals are needed to determine completely the syntactic structure of an expression or sentence

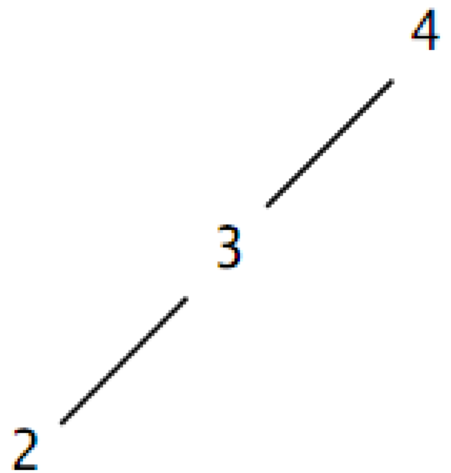


Figure 6.9: Parse tree for determining structure of the number 234

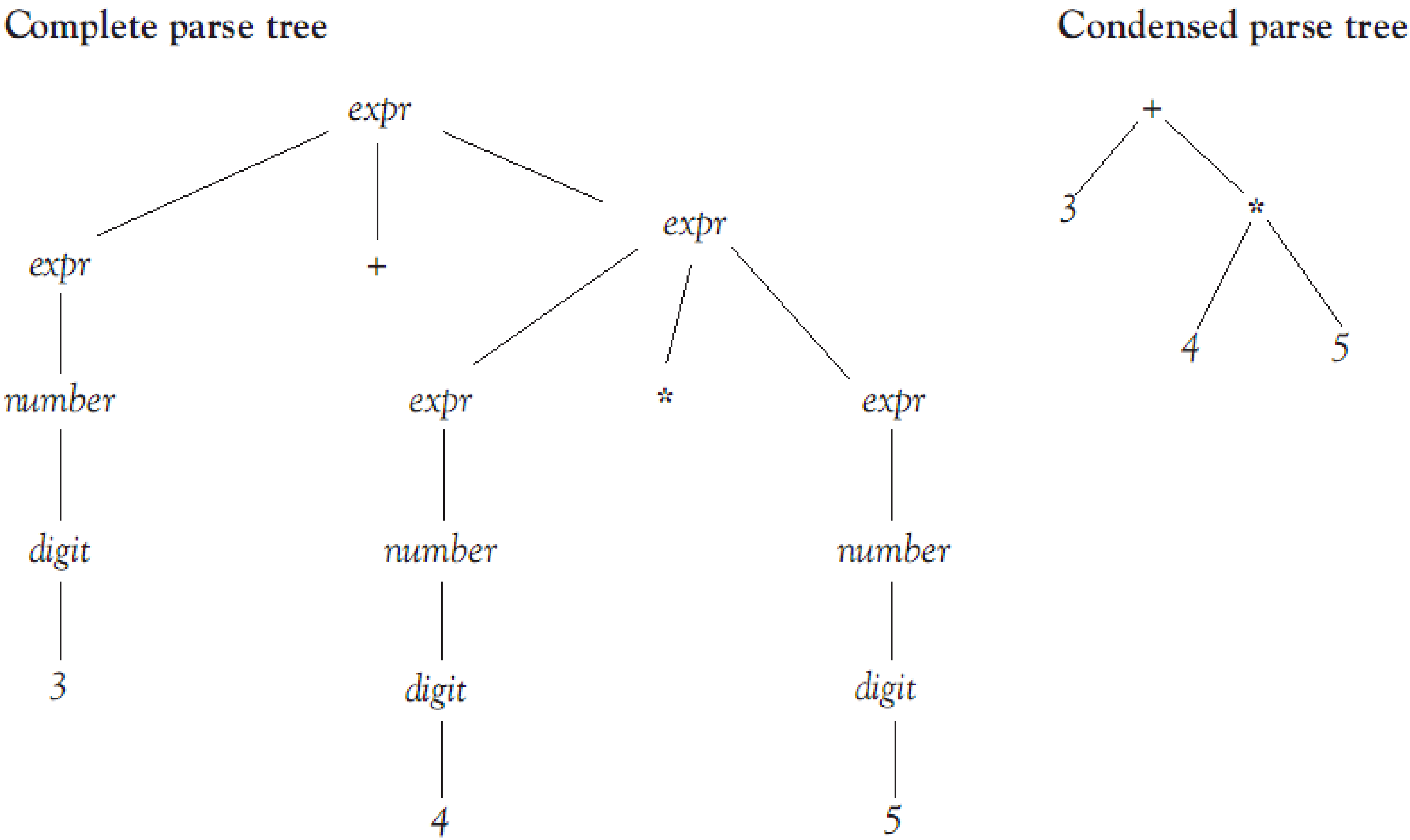


Figure 6.10: Condensing parse tree for `3 + 4 * 5`

Parse Trees and Abstract Syntax Trees (cont'd.)

- **Abstract syntax trees** (or **syntax trees**): trees that abstract the essential structure of the parse tree
  - Do away with terminals that are redundant
- Example:

if-statement → `if` (*expression*) *statement* `else` *statement*

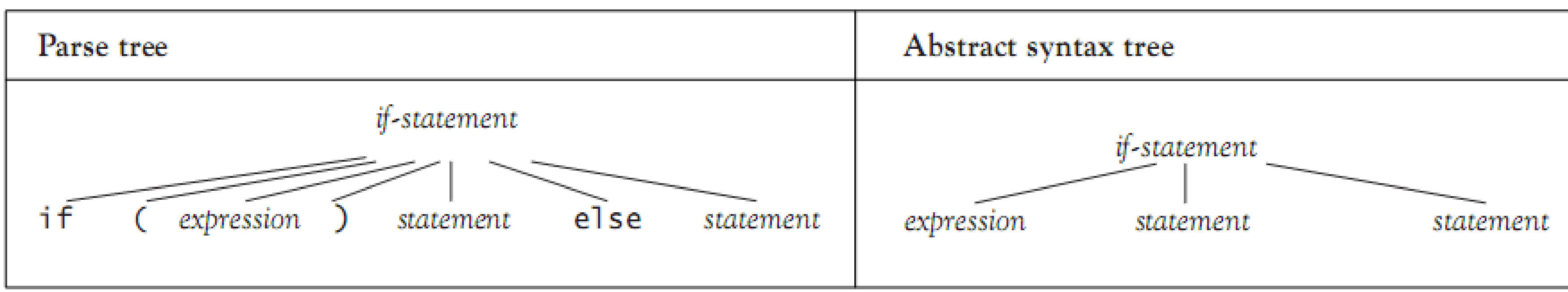


Figure 6.11: Parse tree and abstract syntax tree for grammar rule *if-statement* → `if` (*expression*) *statement* `else` *statement*

Parse Trees and Abstract Syntax Trees (cont'd.)

- Can write out rules for abstract syntax similar to BNF rules, but they are of less interest to a programmer
- Abstract syntax is important to a language designer and translator writer
- **Concrete syntax**: ordinary syntax

Ambiguity, Associativity, and Precedence

- Two different derivations can lead to the same parse tree or to different parse trees
- **Ambiguous** grammar: one for which two distinct parse or syntax trees are possible
- Example: derivation for 234 given earlier

$$
\begin{aligned}
\textit{number} &\Rightarrow \textit{number digit} \\
&\Rightarrow \textit{number}\ 4 \\
&\Rightarrow \textit{number digit}\ 4 \\
&\Rightarrow \textit{number}\ 3\,4 \\
&\ldots
\end{aligned}
$$

Ambiguity, Associativity, and Precedence (cont'd.)

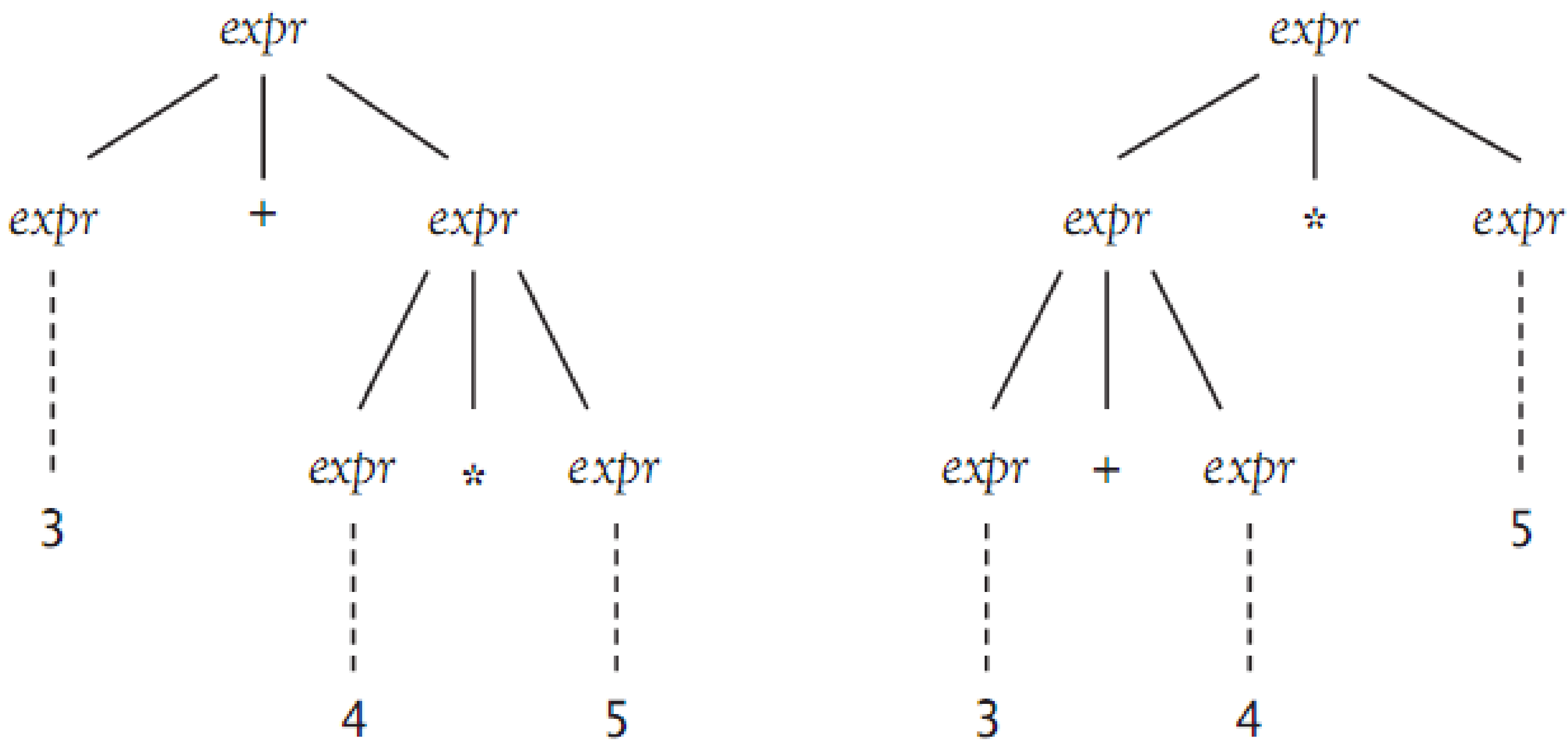


Figure 6.12: Two parse trees for 3 + 4 * 5

Ambiguity, Associativity, and Precedence (cont'd.)

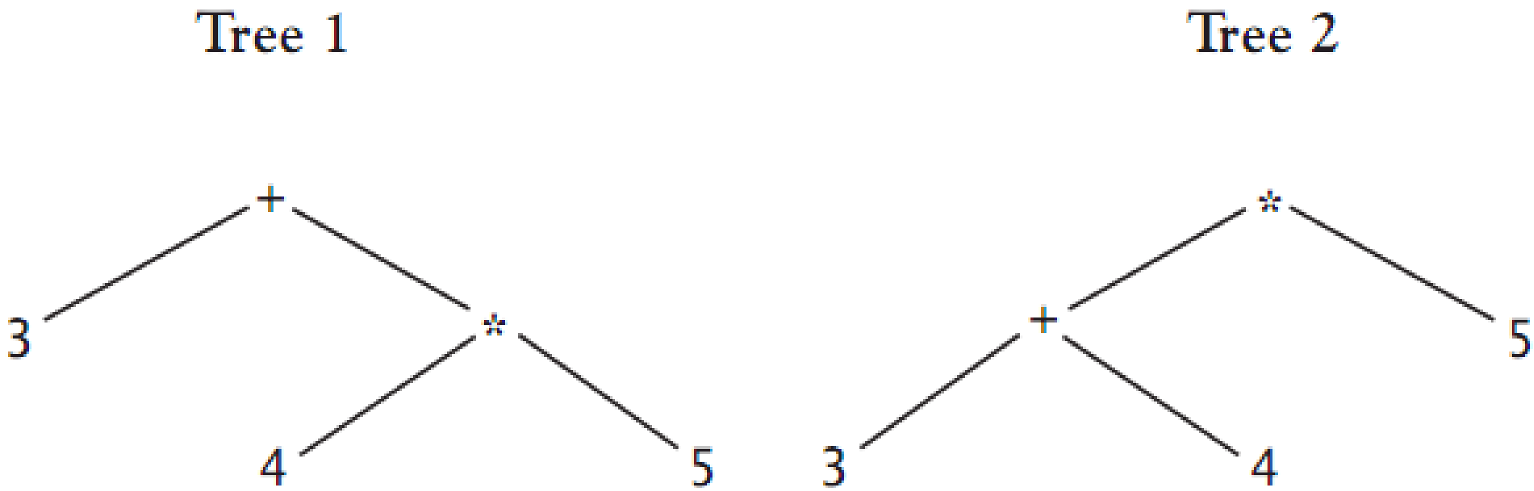


Figure 6.13 Two abstract syntax trees for `3 + 4 * 5`, indicating the ambiguity of the grammar of Figure 6.4

Ambiguity, Associativity, and Precedence (cont'd.)

- Certain special derivations that are constructed in a special order can only correspond to unique parse trees
- **Leftmost derivation**: the leftmost remaining nonterminal is singled out for replacement at each step
  - Each parse tree has a unique leftmost derivation
- Ambiguity of a grammar can be tested by searching for two different leftmost derivations

Ambiguity, Associativity, and Precedence (cont'd.)

Leftmost Derivation 1 (Corresponding to Tree 1 of Figure 6.13)	Leftmost Derivation 2 (Corresponding to Tree 2 of Figure 6.13)
expr ⇒ *expr* + *expr*	expr ⇒ expr * *expr*
⇒ *number* + *expr*	⇒ *expr* + *expr* * *expr*
⇒ *digit* + *expr*	⇒ *number* + *expr* * *expr*
⇒ 3 + *expr*	⇒ . . . (etc.)
⇒ 3 + *expr* * *expr*	
⇒ 3 + *number* * *expr*	
⇒ . . . (etc.)	

Figure 6.14 Two leftmost derivations for `3 + 4 * 5`, indicating the ambiguity of the grammar of Figure 6.4

Ambiguity, Associativity, and Precedence (cont'd.)

- Ambiguous grammars present difficulties
  - Must either revise them to remove ambiguity or state a **disambiguating rule**
- Usual way to revise the grammar is to write a new grammar rule called a term that establishes a precedence cascade
- Can replace $expr \rightarrow expr + expr$
  - With either $expr \rightarrow expr + term$ or $expr \rightarrow term + expr$
- First rule is **left-recursive**; second rule is **right-recursive**

Ambiguity, Associativity, and Precedence (cont'd.)

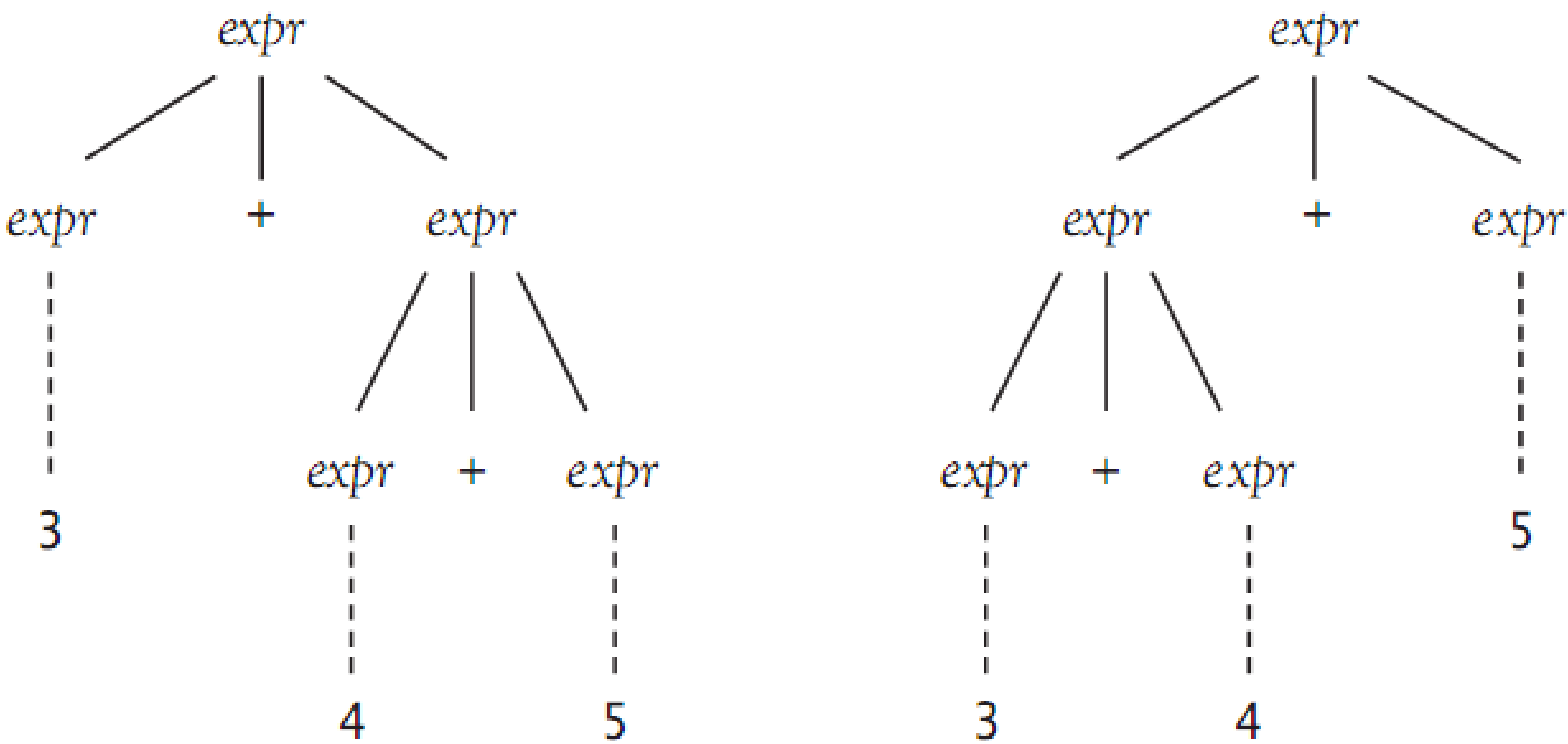


Figure 6.15: Addition as either right- or left-associative

Ambiguity, Associativity, and Precedence (cont'd.)

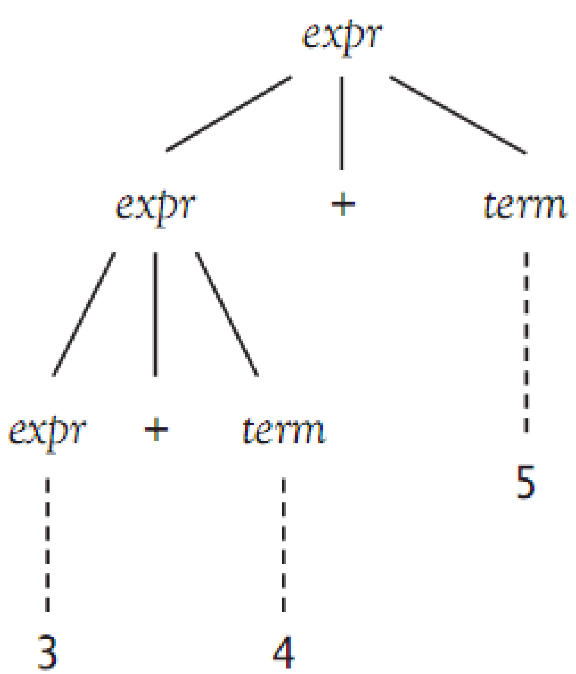
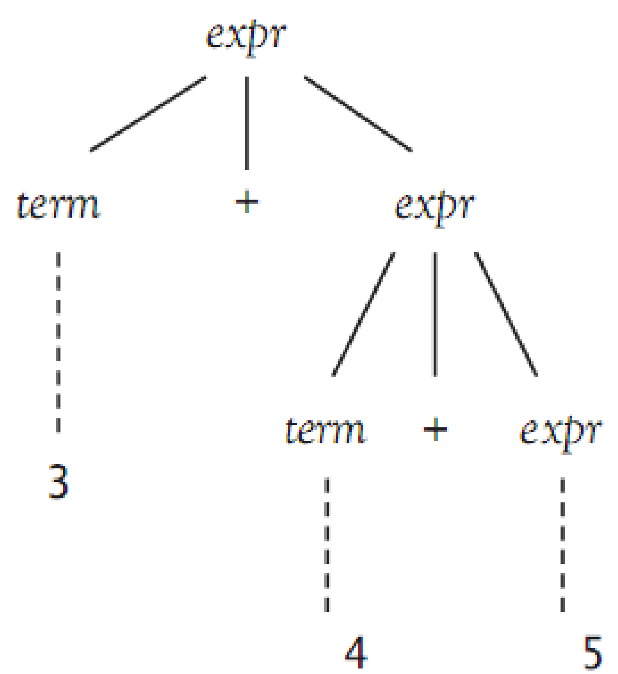
A left-recursive rule for an operation causes it to left-associate.	A right-recursive rule for an operation causes it to right-associate.
	

Figure 6.16: Parse trees showing results of left- and right-recursive rules

Ambiguity, Associativity, and Precedence (cont'd.)

$$
\begin{aligned}
expr &\rightarrow expr \ + \ term \ \mid \ term \\
term &\rightarrow term \ * \ factor \ \mid \ factor \\
factor &\rightarrow (\ expr \ ) \ \mid \ number \\
number &\rightarrow number\ digit \mid digit \\
digit &\rightarrow 0 \mid 1 \mid 2 \mid 3 \mid 4 \mid 5 \mid 6 \mid 7 \mid 8 \mid 9
\end{aligned}
$$

Figure 6.17 Revised grammar for simple integer arithmetic expressions

EBNFs and Syntax Diagrams

- **Extended Backus-Naur form** (or **EBNF**): introduces new notation to handle common issues
- Use curly braces to indicate 0 or more repetitions
  - Assumes that any operator involved in a curly bracket repetition is left-associative
  - Example: $number \rightarrow digit\ \{digit\}$
- Use square brackets to indicate optional parts
  - Example:

$$if\text{-}statement \rightarrow \texttt{if}\ (\ expression\ )\ statement\ [\ \texttt{else}\ statement\ ]$$

EBNFs and Syntax Diagrams (cont'd.)

$$expr \rightarrow term \ \{ \ + \ term \ \}$$

$$term \rightarrow factor \ \{ \ * \ factor \ \}$$

$$factor \rightarrow (\ expr \ ) \ | \ number$$

$$number \rightarrow digit \ \{ \ digit \ \}$$

$$digit \rightarrow 0 \ | \ 1 \ | \ 2 \ | \ 3 \ | \ 4 \ | \ 5 \ | \ 6 \ | \ 7 \ | \ 8 \ | \ 9$$

Figure 6.18 EBNF rules for simple integer arithmetic expressions

EBNFs and Syntax Diagrams (cont'd.)

- **Syntax diagram**: indicates the sequence of terminals and nonterminals encountered in the right-hand side of the rule

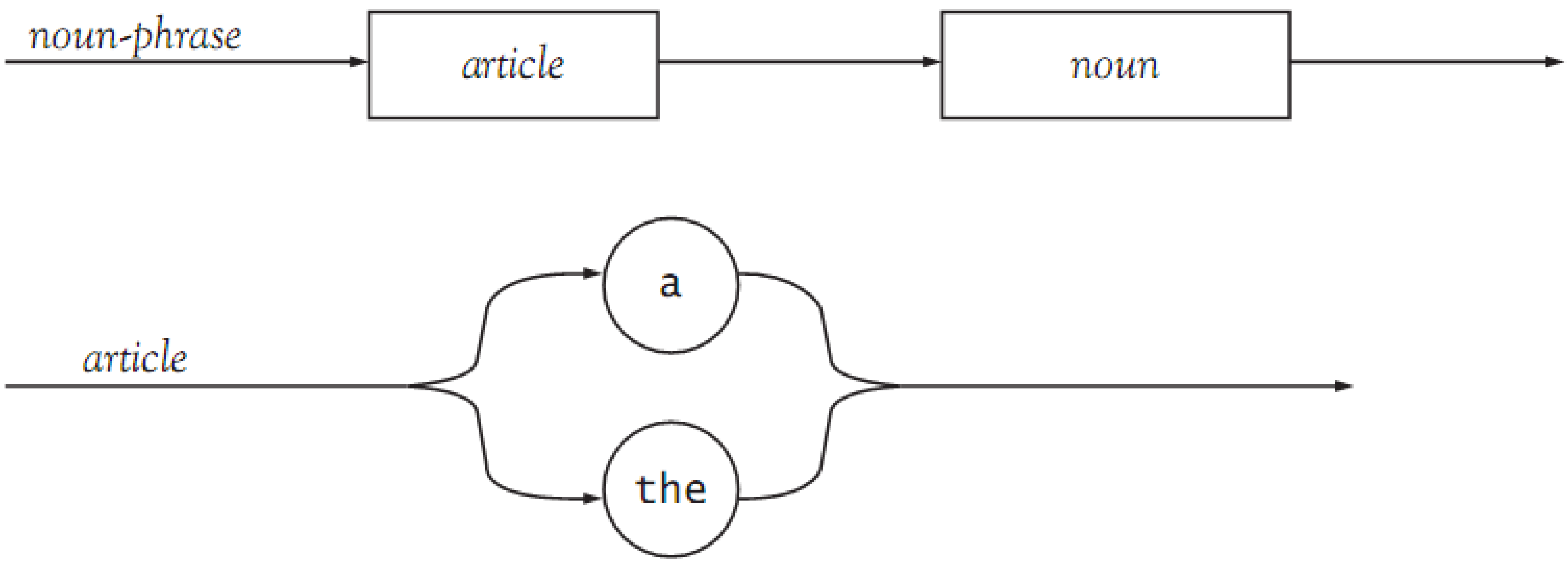


Figure 6.19: Syntax diagrams for *noun-phrase* and *article* of the simple English grammar presented in Section 6.2

EBNFs and Syntax Diagrams (cont'd.)

- Use circles or ovals for terminals, and squares or rectangles for nonterminals
  - Connect them with lines and arrows indicating appropriate sequencing
- Can condense several rules into one diagram
- Use loops to indicate repetition

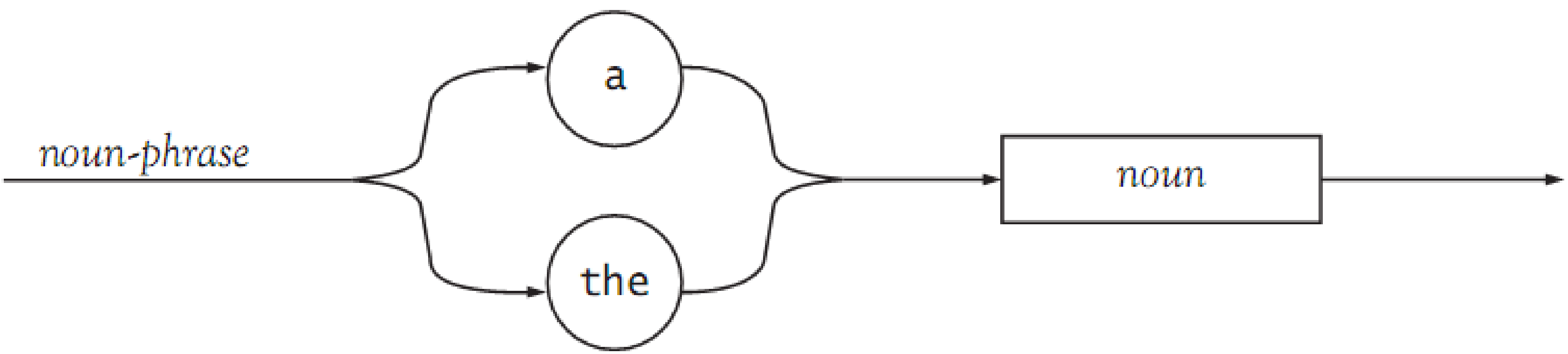


Figure 6.20: Condensed version of diagrams shown in Figure 6.19

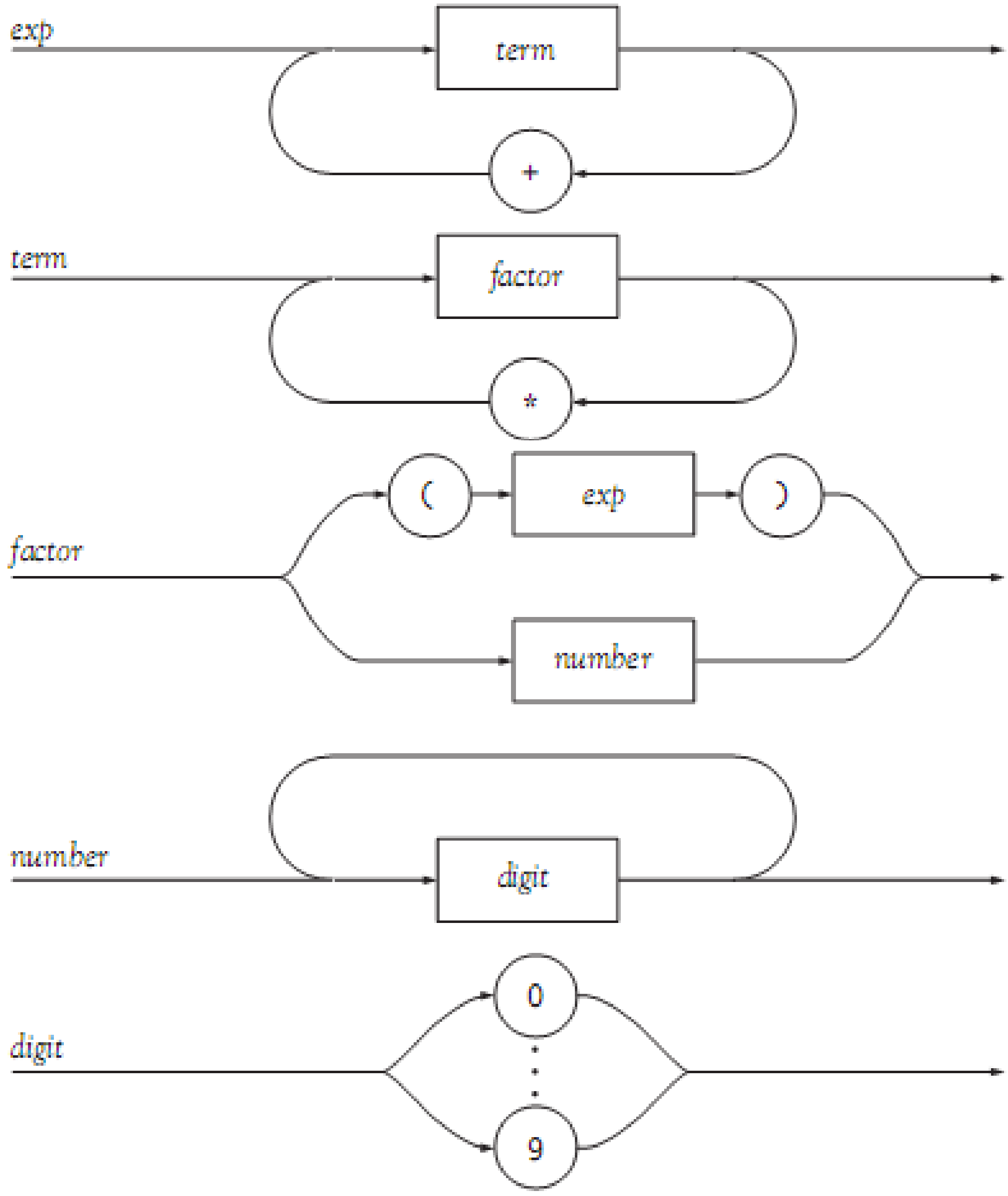


Figure 6.21: Syntax diagrams for a simple integer expression grammar

EBNFs and Syntax Diagrams (cont'd.)

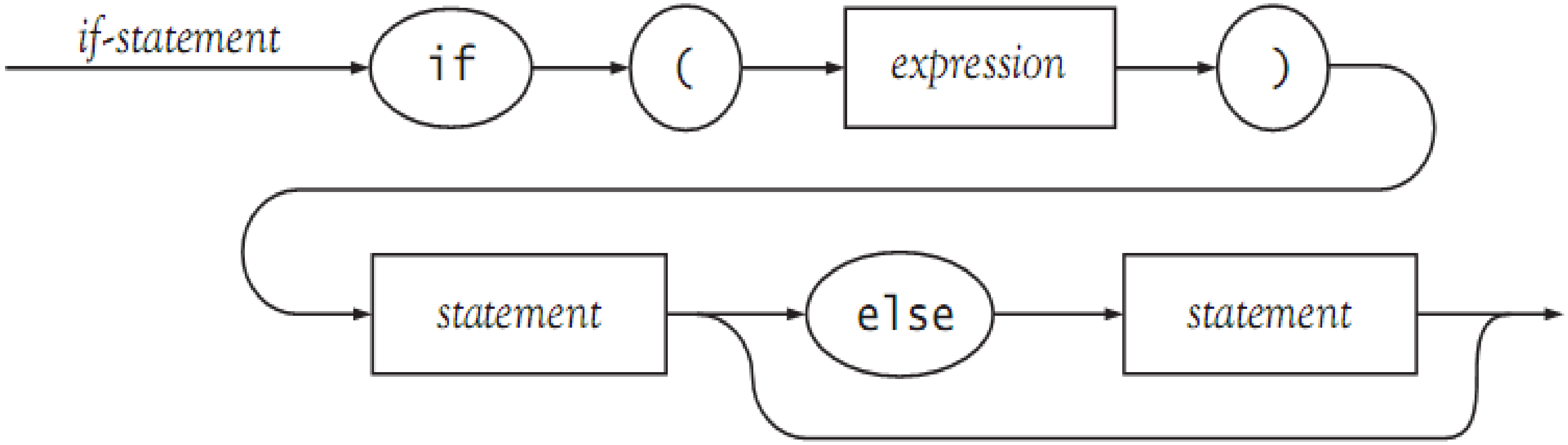


Figure 6.22 Syntax diagram for the *if-statement* in C

Parsing Techniques and Tools

- A grammar written in BNF, EBNF, or syntax diagrams describes the strings of tokens that are syntactically legal
  - It also describes how a parser must act to parse correctly
- **Recognizer**: accepts or rejects strings based on whether they are legal strings in the language
- **Bottom-up parser**: constructs derivations and parse trees from the leaves to the roots
  - Matches an input with right side of a rule and **reduces** it to the nonterminal on the left

Parsing Techniques and Tools (cont'd.)

- Bottom-up parsers are also called shift-reduce parsers
  - They shift tokens onto a stack prior to reducing strings to nonterminals
- **Top-down parser**: expands nonterminals to match incoming tokens and directly construct a derivation
- **Parser generator**: a program that automates top-down or bottom-up parsing
- Bottom-up parsing is the preferred method for parser generators (also called **compiler compilers**)

Parsing Techniques and Tools (cont'd.)

- **Recursive-descent parsing**: turns nonterminals into a group of mutually recursive procedures based on the right-hand sides of the BNFs
  - Tokens are matched directly with input tokens as constructed by a scanner
  - Nonterminals are interpreted as calls to the procedures corresponding to the nonterminals

Parsing Techniques and Tools (cont'd.)

```
void sentence(){
    nounPhrase();
    verbPhrase();
}

void nounPhrase(){
    article();
    noun();
}

void article(){
    if (token == "a") match("a", "a expected");
    else if (token == "the") match("the", "the expected");
    else error("article expected");
}
```

Parsing Techniques and Tools (cont'd.)

- Left-recursive rules may present problems
  - Example: $expr \rightarrow expr + term \mid term$
  - May cause an infinite recursive loop
  - No way to decide which of the two choices to take until a + is seen
- The EBNF description expresses the recursion as a loop: $expr \rightarrow term \; \{ + term \}$
- Thus, curly brackets in EBNF represent **left recursion removal** by the use of a loop

Parsing Techniques and Tools (cont'd.)

- Code for a right-recursive rule such as:

$$expr \rightarrow term\ @\ expr \mid term$$

- This corresponds to the use of square brackets in EBNF:

$$expr \rightarrow term\ [\ @\ expr\ ]$$

  - This process is called **left-factoring**
- In both left-recursive and left-factoring situations, EBNF rules or syntax diagrams correspond naturally to the code of a recursive-descent parser

Parsing Techniques and Tools (cont'd.)

- **Single-symbol lookahead**: using a single token to direct a parse
- **Predictive parser**: a parser that commits itself to a particular action based only on the lookahead
- Grammar must satisfy certain conditions to make this decision-making process work
  - Parser must be able to distinguish between choices in a rule
  - For an optional part, no token beginning the optional part can also come after the optional part

Parsing Techniques and Tools (cont'd.)

- YACC: a widely used parser generator
  - Freeware version is called Bison
  - Generates a C program that uses a bottom-up algorithm to parse the grammar
- YACC generates a procedure `yyparse` from the grammar, which must be called from a main procedure
- YACC assumes that tokens are recognized by a scanner procedure called `yylex`, which must be provided

Lexics vs. Syntax vs. Semantics

- Specific details of formatting, such as white-space conventions, are left to the scanner
  - Need to be stated as lexical conventions separate from the grammar
- Also desirable to allow a scanner to recognize structures such as literals, constants, and identifiers
  - Faster and simpler and reduces the size of the parser
- Must rewrite the grammar to express the use of a token rather than a nonterminal representation

Lexics vs. Syntax vs. Semantics (cont'd.)

- Example: a number should be a token

$$expr \rightarrow term\ \{\ +\ term \}$$
$$term \rightarrow factor\ \{\ *\ factor\ \}$$
$$factor \rightarrow (\ expr\ )\ |\ \text{NUMBER}$$

Figure 6.26 Numbers as tokens in simple integer arithmetic

  - Uppercase indicates it is a token whose structure is determined by the scanner

- **Lexics**: the lexical structure of a programming language

Lexics vs. Syntax vs. Semantics (cont'd.)

- Some rules are context-sensitive and cannot be written as context-free rules
- Examples:
  - Declaration before use for variables
  - No redeclaration of identifiers within a procedure
- These are semantic properties of a language
- Another conflict occurs between **predefined identifiers** and **reserved words**
  - Reserved words cannot be used as identifiers
  - Predefined identifiers can be redefined in a program

Lexics vs. Syntax vs. Semantics (cont'd.)

- Syntax and semantics can become interdependent when semantic information is required to distinguish ambiguous parsing situations

Case Study: Building a Syntax Analyzer for TinyAda

- **TinyAda**: a small language that illustrates the syntactic features of many high-level languages
- TinyAda includes several kinds of declarations, statements, and expressions
- Rules for declarations, statements, and expressions are indirectly recursive, allowed for nested declarations, statements, and expressions
- **Parsing shell**: applies the grammar rules to check whether tokens are of the correct types
  - Later, we will add mechanisms for semantic analysis

Case Study: Building a Syntax Analyzer for TinyAda (cont'd.)

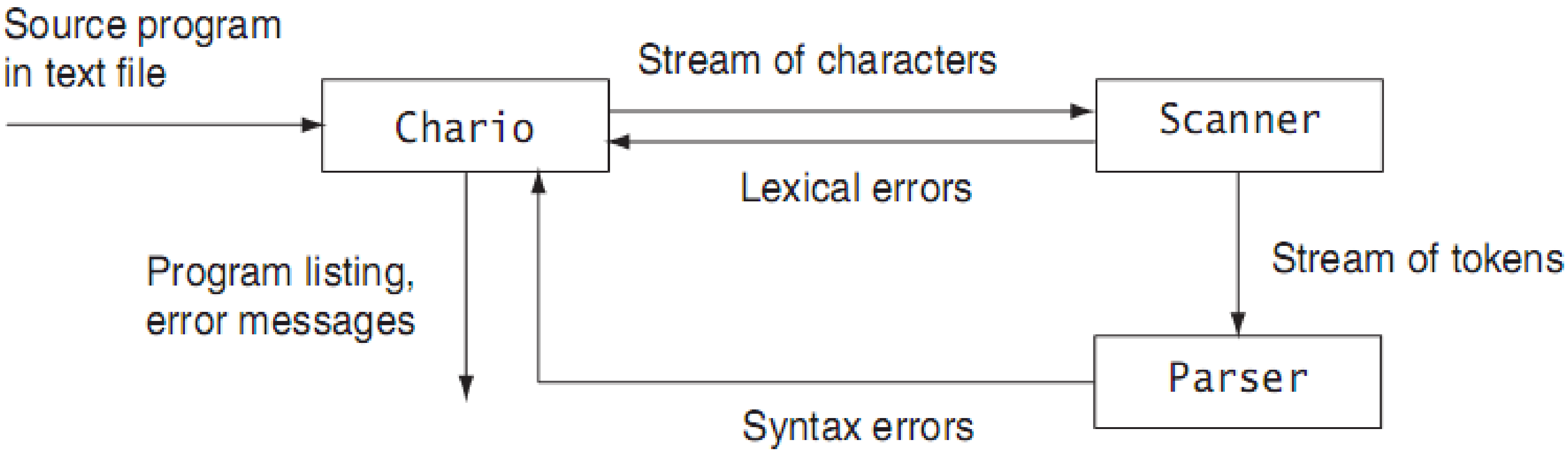


Figure 6.29 Data flow in the TinyAda syntax analyzer