Chapter 5

Syntax-Directed Translation

This chapter develops the theme of Section 2.3: the translation of languages guided by context-free grammars. The translation techniques in this chapter will be applied in Chapter 6 to type checking and intermediate-code generation. The techniques are also useful for implementing little languages for specialized tasks; this chapter includes an example from typesetting.

We associate information with a language construct by attaching *attributes* to the grammar symbol(s) representing the construct, as discussed in Section 2.3.2. A syntax-directed definition specifies the values of attributes by associating semantic rules with the grammar productions. For example, an infix-to-postfix translator might have a production and rule

PRODUCTION	SEMANTIC RULE	(5.1)
$E \rightarrow E_1 + T$	$E.code = E_1.code \parallel T.code \parallel \text{'+'}$	

This production has two nonterminals, E and T; the subscript in E_1 distinguishes the occurrence of E in the production body from the occurrence of E as the head. Both E and T have a string-valued attribute *code*. The semantic rule specifies that the string $E.code$ is formed by concatenating $E_1.code$, $T.code$, and the character '+'. While the rule makes it explicit that the translation of E is built up from the translations of E_1, T, and '+', it may be inefficient to implement the translation directly by manipulating strings.

From Section 2.3.5, a syntax-directed translation scheme embeds program fragments called semantic actions within production bodies, as in

$$E \rightarrow E_1 + T \quad \{ \text{ print '+' } \} \tag{5.2}$$

By convention, semantic actions are enclosed within curly braces. (If curly braces occur as grammar symbols, we enclose them within single quotes, as in

'{' and '}'.) The position of a semantic action in a production body determines the order in which the action is executed. In production (5.2), the action occurs at the end, after all the grammar symbols; in general, semantic actions may occur at any position in a production body.

Between the two notations, syntax-directed definitions can be more readable, and hence more useful for specifications. However, translation schemes can be more efficient, and hence more useful for implementations.

The most general approach to syntax-directed translation is to construct a parse tree or a syntax tree, and then to compute the values of attributes at the nodes of the tree by visiting the nodes of the tree. In many cases, translation can be done during parsing, without building an explicit tree. We shall therefore study a class of syntax-directed translations called "L-attributed translations" (L for left-to-right), which encompass virtually all translations that can be performed during parsing. We also study a smaller class, called "S-attributed translations" (S for synthesized), which can be performed easily in connection with a bottom-up parse.

5.1 Syntax-Directed Definitions

A *syntax-directed definition* (SDD) is a context-free grammar together with attributes and rules. Attributes are associated with grammar symbols and rules are associated with productions. If X is a symbol and a is one of its attributes, then we write $X.a$ to denote the value of a at a particular parse-tree node labeled X. If we implement the nodes of the parse tree by records or objects, then the attributes of X can be implemented by data fields in the records that represent the nodes for X. Attributes may be of any kind: numbers, types, table references, or strings, for instance. The strings may even be long sequences of code, say code in the intermediate language used by a compiler.

5.1.1 Inherited and Synthesized Attributes

We shall deal with two kinds of attributes for nonterminals:

1. A *synthesized attribute* for a nonterminal A at a parse-tree node N is defined by a semantic rule associated with the production at N. Note that the production must have A as its head. A synthesized attribute at node N is defined only in terms of attribute values at the children of N and at N itself.

2. An *inherited attribute* for a nonterminal B at a parse-tree node N is defined by a semantic rule associated with the production at the parent of N. Note that the production must have B as a symbol in its body. An inherited attribute at node N is defined only in terms of attribute values at N's parent, N itself, and N's siblings.

An Alternative Definition of Inherited Attributes

No additional translations are enabled if we allow an inherited attribute $B.c$ at a node N to be defined in terms of attribute values at the children of N, as well as at N itself, at its parent, and at its siblings. Such rules can be "simulated" by creating additional attributes of B, say $B.c_1, B.c_2, \ldots$. These are synthesized attributes that copy the needed attributes of the children of the node labeled B. We then compute $B.c$ as an inherited attribute, using the attributes $B.c_1, B.c_2, \ldots$ in place of attributes at the children. Such attributes are rarely needed in practice.

While we do not allow an inherited attribute at node N to be defined in terms of attribute values at the children of node N, we do allow a synthesized attribute at node N to be defined in terms of inherited attribute values at node N itself.

Terminals can have synthesized attributes, but not inherited attributes. Attributes for terminals have lexical values that are supplied by the lexical analyzer; there are no semantic rules in the SDD itself for computing the value of an attribute for a terminal.

Example 5.1: The SDD in Fig. 5.1 is based on our familiar grammar for arithmetic expressions with operators + and $*$. It evaluates expressions terminated by an endmarker **n**. In the SDD, each of the nonterminals has a single synthesized attribute, called *val*. We also suppose that the terminal **digit** has a synthesized attribute *lexval*, which is an integer value returned by the lexical analyzer.

	PRODUCTION	SEMANTIC RULES
1)	$L \to E\ \mathbf{n}$	$L.val = E.val$
2)	$E \to E_1 + T$	$E.val = E_1.val + T.val$
3)	$E \to T$	$E.val = T.val$
4)	$T \to T_1 * F$	$T.val = T_1.val \times F.val$
5)	$T \to F$	$T.val = F.val$
6)	$F \to (E)$	$F.val = E.val$
7)	$F \to \mathbf{digit}$	$F.val = \mathbf{digit}$.lexval

Figure 5.1: Syntax-directed definition of a simple desk calculator

The rule for production 1, $L \to E\ \mathbf{n}$, sets $L.val$ to $E.val$, which we shall see is the numerical value of the entire expression.

Production 2, $E \to E_1 + T$, also has one rule, which computes the *val* attribute for the head E as the sum of the values at E_1 and T. At any parse-

tree node N labeled E, the value of *val* for E is the sum of the values of *val* at the children of node N labeled E and T.

Production 3, $E \rightarrow T$, has a single rule that defines the value of *val* for E to be the same as the value of *val* at the child for T. Production 4 is similar to the second production; its rule multiplies the values at the children instead of adding them. The rules for productions 5 and 6 copy values at a child, like that for the third production. Production 7 gives $F.val$ the value of a digit, that is, the numerical value of the token **digit** that the lexical analyzer returned. □

An SDD that involves only synthesized attributes is called *S-attributed*; the SDD in Fig. 5.1 has this property. In an S-attributed SDD, each rule computes an attribute for the nonterminal at the head of a production from attributes taken from the body of the production.

For simplicity, the examples in this section have semantic rules without side effects. In practice, it is convenient to allow SDD's to have limited side effects, such as printing the result computed by a desk calculator or interacting with a symbol table. Once the order of evaluation of attributes is discussed in Section 5.2, we shall allow semantic rules to compute arbitrary functions, possibly involving side effects.

An S-attributed SDD can be implemented naturally in conjunction with an LR parser. In fact, the SDD in Fig. 5.1 mirrors the Yacc program of Fig. 4.58, which illustrates translation during LR parsing. The difference is that, in the rule for production 1, the Yacc program prints the value $E.val$ as a side effect, instead of defining the attribute $L.val$.

An SDD without side effects is sometimes called an *attribute grammar*. The rules in an attribute grammar define the value of an attribute purely in terms of the values of other attributes and constants.

5.1.2 Evaluating an SDD at the Nodes of a Parse Tree

To visualize the translation specified by an SDD, it helps to work with parse trees, even though a translator need not actually build a parse tree. Imagine therefore that the rules of an SDD are applied by first constructing a parse tree and then using the rules to evaluate all of the attributes at each of the nodes of the parse tree. A parse tree, showing the value(s) of its attribute(s) is called an *annotated parse tree*.

How do we construct an annotated parse tree? In what order do we evaluate attributes? Before we can evaluate an attribute at a node of a parse tree, we must evaluate all the attributes upon which its value depends. For example, if all attributes are synthesized, as in Example 5.1, then we must evaluate the *val* attributes at all of the children of a node before we can evaluate the *val* attribute at the node itself.

With synthesized attributes, we can evaluate attributes in any bottom-up order, such as that of a postorder traversal of the parse tree; the evaluation of S-attributed definitions is discussed in Section 5.2.3.

For SDD's with both inherited and synthesized attributes, there is no guarantee that there is even one order in which to evaluate attributes at nodes. For instance, consider nonterminals A and B, with synthesized and inherited attributes $A.s$ and $B.i$, respectively, along with the production and rules

PRODUCTION	SEMANTIC RULES
$A \rightarrow B$	$A.s = B.i;$
	$B.i = A.s + 1$

These rules are circular; it is impossible to evaluate either $A.s$ at a node N or $B.i$ at the child of N without first evaluating the other. The circular dependency of $A.s$ and $B.i$ at some pair of nodes in a parse tree is suggested by Fig. 5.2.

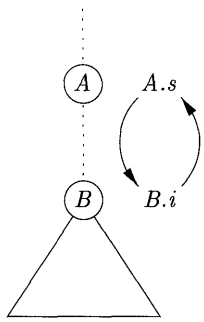

Figure 5.2: The circular dependency of $A.s$ and $B.i$ on one another

It is computationally difficult to determine whether or not there exist any circularities in any of the parse trees that a given SDD could have to translate.[1] Fortunately, there are useful subclasses of SDD's that are sufficient to guarantee that an order of evaluation exists, as we shall see in Section 5.2.

Example 5.2: Figure 5.3 shows an annotated parse tree for the input string $3 * 5 + 4$ **n**, constructed using the grammar and rules of Fig. 5.1. The values of *lexval* are presumed supplied by the lexical analyzer. Each of the nodes for the nonterminals has attribute *val* computed in a bottom-up order, and we see the resulting values associated with each node. For instance, at the node with a child labeled $*$, after computing $T.val = 3$ and $F.val = 5$ at its first and third children, we apply the rule that says $T.val$ is the product of these two values, or 15. □

Inherited attributes are useful when the structure of a parse tree does not "match" the abstract syntax of the source code. The next example shows how inherited attributes can be used to overcome such a mismatch due to a grammar designed for parsing rather than translation.

[1] Without going into details, while the problem is decidable, it cannot be solved by a polynomial-time algorithm, even if $\mathcal{P} = \mathcal{NP}$, since it has exponential time complexity.

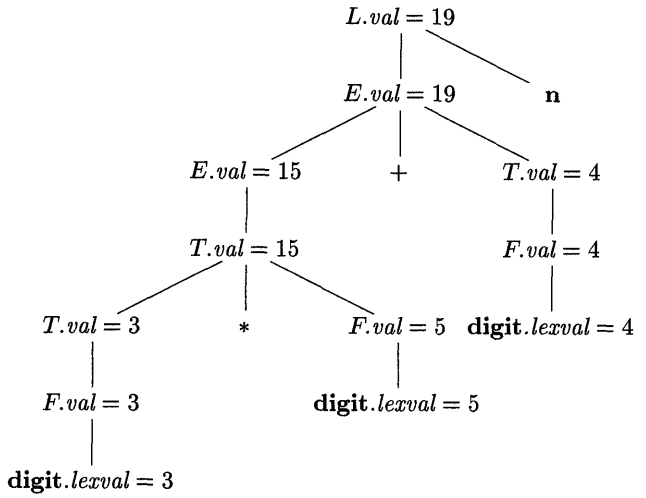

Figure 5.3: Annotated parse tree for $3 * 5 + 4$ **n**