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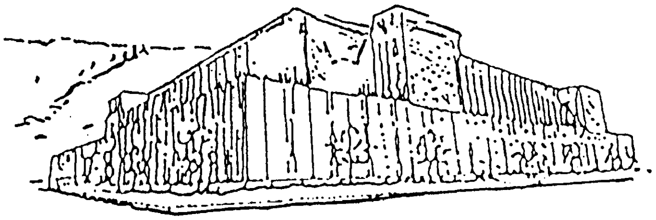

An Ordered Attribute Grammar for the Ecosystem Information System

by

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Attribute grammar methodology is used to formally specify the syntactic and static semantic aspects of a language. In his original description of attribute grammars, D.E. Knuth states that semantic rules are well-defined if they are formulated in such a way that all attributes can always be defined at all nodes in any conceivable derivation tree [D.E. Knuth, Semantics of context-free languages, Math. Syst. Theory 2, 1968, 127-145]. Uwe Kastens introduces "ordered attribute grammars" as a subclass of well-defined attribute grammars, such that grammars of this class satisfy the following condition: for each symbol of the grammar a partial order over the associated attributes can be defined, such that in any context of the symbol in any derivation the attributes are evaluable in that order [U.Kastens, Ordered Attribute Grammars, *Acta Informatica*, Berlin; New York : Spinger-Verlag, Vol 13, 1980, 229-256]. Kastens developed an algorithm to determine if an attribute grammar is "ordered". An implementation of this algorithm exists, but it contains errors and significant performance constraints. The work described here begins with debugging and reimplementing the algorithm in the programming language Java. As a major example, an attribute grammar for the Ecosystem Information System (EIS) is developed and analyzed for the "orderness" property. EIS is a network-accessible repository containing various types of information of interest to natural resource modelers and managers. Included in this repository are meta-data descriptions for various data sources, datasets, and modeling components. As such, the EIS description language involves a number of complex constraints on the use of identifiers, which represents a significant test of the use of attribute grammars in the specification of such constraints, and on the use of the new implementation of Kastens' algorithm in the analysis of such grammars.

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Chapter 1

Introduction

1.1 Overview

The Ecosystem Information System (EIS) is a network-accessible repository containing various types of information of interest to natural resource modelers and managers. Included in this repository are meta-data descriptions for various data sources, datasets, and modeling components. The EIS data repository is organized hierarchically using an object-oriented framework to order the myriad collection of components used in ecosystem modeling. In collaboration with other ecosystem modeling laboratories, the repository is being populated with information from important ecosystem modeling and management applications.

EIS needs a specification language to allow users to define EIS meta-data descriptions, datasets, and modeling components. The EIS language could be specified with a context free grammar. The context-free grammar would provide a parser/analyzer a formal description of the language's syntax, but give no corresponding formal definition of the language's "static semantics". A more complete specification of the EIS language can be formalized using an attribute grammar. An attribute grammar gives both a syntactic and static semantic language description, which can also be used as the basis for the implementation of both the parsing and the static semantic checking. This thesis uses the concepts of attribute grammars, attribute analysis algorithms, and attribute evaluation algorithms to provide a more rigorous approach to the EIS language specification and implementation.

1.2 Purpose

The thesis has several purposes. First, it describes a well-formed attribute grammar that defines the syntactic and semantic checking that must be done to process the EIS object description language. This attribute grammar formalizes the ad hoc checking currently embedded in the parser/analyzer. The attribute grammar is also well-formed, corresponding to an *ordered attribute grammar* as defined by Uwe Kastens [2].

Second, the thesis describes the effort required to mechanically prove the orderness property for a non-trivial attribute grammar, using an attribute analysis algorithm developed by Uwe Kastens [2], the implementation of that algorithm by Patricia Spencer [5], and the EIS attribute grammar. The analyzer must first guarantee that the attribute grammar has the critical "orderness" property and then produce what are known as "visit sequences" for the given attribute grammar. Testing with Spencer's implementation shows that her program does not work correctly on large grammars. Thus, a major portion of the project described here is to debug and revise the original analysis code. Ultimately the decision was made to rewrite the code in the portable programming language Java. The new implementation of the attribute analysis algorithm can be used successfully with any attribute grammar; however, for our illustration purposes we focus on only the EIS attribute grammar.

The third purpose of this project is to demonstrate, with simple examples of the EIS language, that the attribute grammar and the analysis program are "correct" in the sense that the grammar specifies semantic constraints intended for the EIS language, and that attribute evaluation identifies strings that violate the EIS semantic restrictions.

The final purpose of this thesis is to provide enough information for a future student to implement an efficient attribute evaluation algorithm. That is, the analysis currently ends with the ability to produce "visit sequences" from the analysis of any attribute grammar and an informal discussion of how evaluation would proceed. An attribute evaluation algorithm would use the visit sequences and a derivation in the same attribute grammar, and construct an attributed derivation tree which contains values for all appropriate attributes in the derivation.

1.3 Attribute Grammar Background

A language can be defined in terms of what legal strings it includes (the syntax of the language) and what meaning is attached to any string (the semantics of the language). When it comes to writing a standard definition of a language, a formal method must be used if there is any hope of the language's specification having one or more of the following qualities: completeness, consistency, precision, absence of ambiguity, conciseness, understandability, and usefulness [4].

Backus-Naur form (BNF) is a formal metalanguage that can be used to write a description or specification of a language. Basically, it is a notation that one can use to specify a *generative grammar* which defines the set of all possible strings of symbols that constitute programs in the subject language, together with a syntactic structure that reflects the generation process. Grammars expressible in BNF constitute the class of context-free grammars [4].

A BNF grammar has a set of production rules. Each production rule has a left side and a right side separated by some metasymbol. The left side consists of a *nonterminal* symbol. The right side of a rule consists of a sequence of terminal symbols and/or nonterminal symbols, where a terminal symbol is a token of the subject language.

For example, consider the following production rules; where ":" is the metasymbol used to separate left and right sides and "|" is used to separate multiple right sides with the same left side:

```
numeral : numeral digit | digit
digit : '0' | '1' | '2'
```

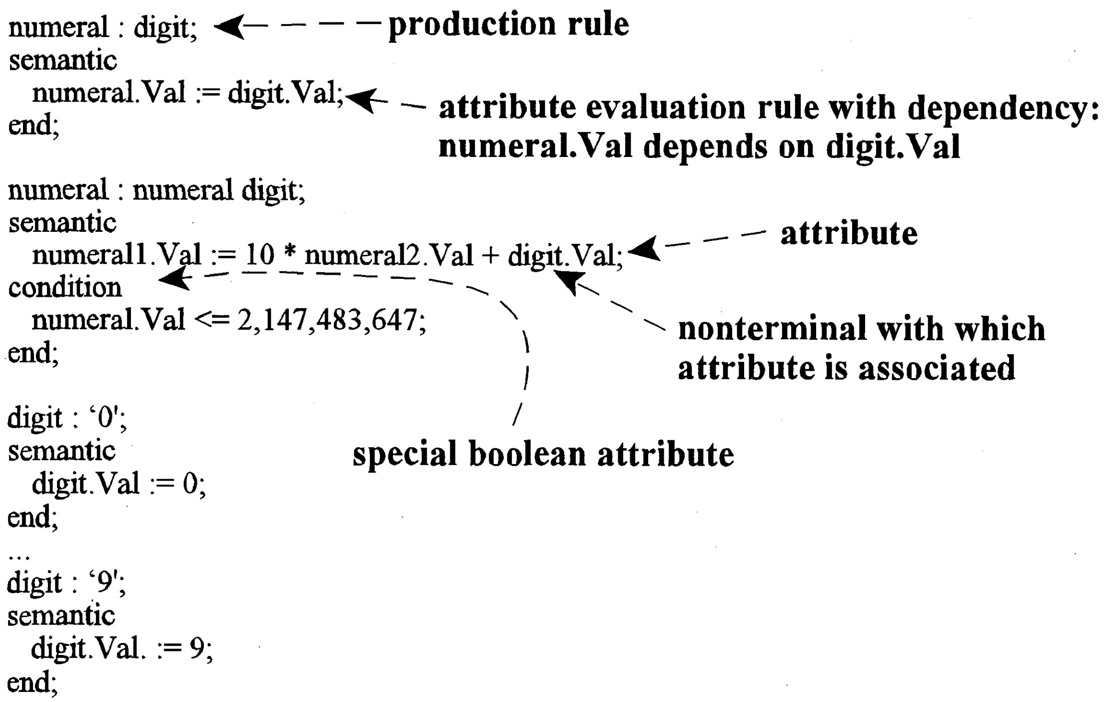
The nonterminal "numeral" consists of either the nonterminal "numeral" followed by the nonterminal "digit" or just the nonterminal "digit". The nonterminal "digit" consists of the terminal '0', '1', or '2'. The use of recursion in the first production rule allows an infinite number of terminal strings to be generated by a finite number of production rules. The rule for "numeral", together with the rules for the nonterminals it references and the rules for the nonterminals referenced in those rules, etc., determines the set of all strings of terminal symbols that constitute programs in the subject language.

An attribute grammar is a well-known language specification technique that extends a context free specification to allow one to formally specify aspects of the language's semantics. An attribute grammar is a context-free grammar augmented with finite state machine-like formal devices. These formal devices include "attributes" or variables associated with instances of non-terminal symbols, and "evaluation rules" associated with production rules. There is a finite set of attributes associated with each distinct symbol of the context-free grammar. The variables are typed, i.e., a domain of values is associated with each distinct attribute.

Each node of the syntax tree of a valid program has a set of attributes associated with the symbol represented by that node. Boolean attributes can be used to indicate whether or not “extra-grammatical” aspects of the derivation are correct, i.e., to impose conditions on the derivation that lie outside normal context-free specification. The evaluation rules associated with the grammar's production rules determine the values of all attribute occurrences. That is, when a production rule is applied to generate a step in a language string derivation, its corresponding evaluation rules are also (logically) applied to define the values of attributes at that point in the derivation.

There are two kinds of attributes, *inherited* and *synthesized*. *Inherited* attributes have values defined totally in terms of attribute values of the ancestor of the nonterminal symbol. *Synthesized* attributes have values defined in terms of attribute values of the descendants of the corresponding nonterminal symbol. Examples of an attribute grammar and a derivation tree with a synthesized attribute are given in Figures 1.1 and 1.2 respectively.

For each production rule, there must be an evaluation rule for each synthesized attribute of the symbol on the left (the symbol being defined) and for each inherited attribute of each symbol on the right. In general, a given grammatical symbol may have both synthesized and inherited attributes, and a given attribute may be synthesized with respect to one symbol and inherited with respect to another. An example of an attribute grammar with an inherited attribute is given in Figure 1.3.



```
numeral : digit;
semantic
  numeral.Val := digit.Val;
end;

numeral : numeral digit;
semantic
  numeral1.Val := 10 * numeral2.Val + digit.Val;
condition
  numeral.Val <= 2,147,483,647;
end;

digit : '0';
semantic
  digit.Val := 0;
end;
...
digit : '9';
semantic
  digit.Val. := 9;
end;
```

Figure 1.1 Example Attribute Grammar

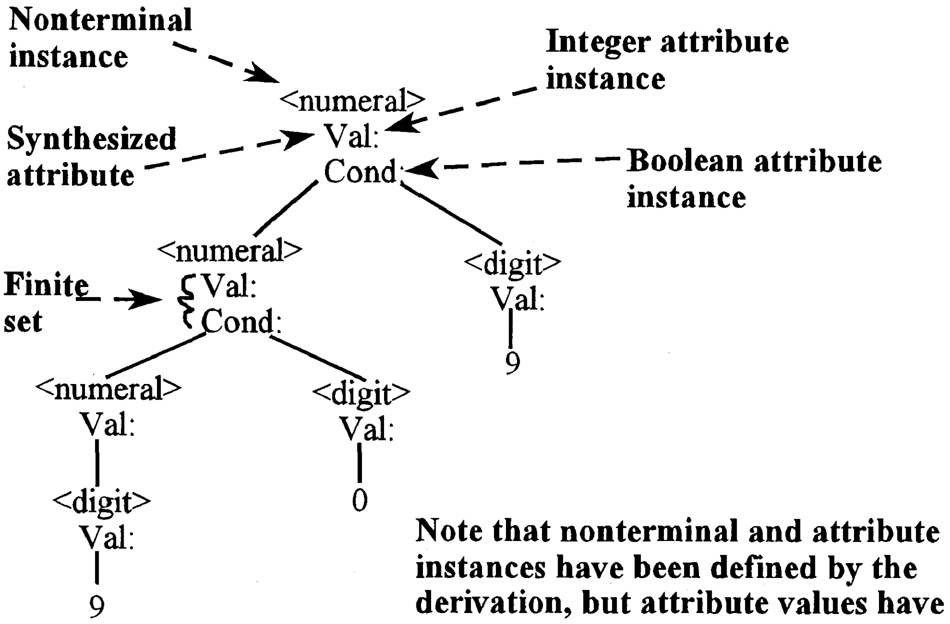


Figure 1.2 Example Derivation Tree

```
string : char;
semantic
condition
  string.Size = 1;
end;

string : string2 char;
semantic
  string2.Size := string.Size -1;
end;

char : 'A';

char : 'B';

...
```

Inherited Attribute

Figure 1.3 Example Attribute Grammar

1.4 Visit Sequences

In his original description of attribute grammars, D.E. Knuth states that semantic rules are well-defined if they are formulated in such a way that all attributes can always be defined at all nodes in any conceivable derivation tree [3]. Kastens introduces "ordered attribute grammars" as a subclass of well-defined attribute grammars, such that grammars of this class satisfy the following condition: for each symbol of the grammar a partial order over the associated attributes can be defined, such that in any context of the symbol in any derivation the attributes are evaluable in that order [2]. Furthermore, Kastens shows that for attribute grammars of this type, "visit sequences" can be derived that can drive a general purpose attribute evaluation algorithm to correctly evaluate all attributes for any valid derivation tree.

A visit sequence for an ordered attribute grammar simply formalizes the intuitive notation that if the value of attribute x depends on the value of attribute y, then attribute y must be evaluated before attribute x. The evaluation order defined by a visit sequence reflects all such dependencies. Kastens formulates his algorithm in somewhat vague, set-theoretic terms. Spencer describes an implementation of Kastens' attribute analysis algorithm that produces the visit sequences as one of its several outputs [5].

To understand what information a visit sequence must encode, consider the following. Evaluation of attributes proceeds as "control" is applied to a particular node. As part of the evaluation, control may be passed from the current node to its parent or one of its children. In this manner a node may receive control several times. When it receives control, it must resume execution where it left off, so it needs to remember its prior state. The purpose of passing around control like this is to allow the evaluation of complex sets of dependencies. If node *x* is a parent of node *y*, when control is initially passed down to node *x*, it should calculate as many of *x*'s synthesized attributes as possible. However, some attributes of *x* may depend on attributes not yet determined. So *x* passes control to node *y* and other descendants which eventually calculate the values of upon which *x*'s synthesized attributes depend. Thus *y* may return control to *x*, or pass control to one of *y*'s children, or halt if all attributes have been computed. The critical points are that when control is passed from one node to another, enough attributes have been evaluated so the node with newly granted control can proceed, and that the exchange of control eventually terminates in a state where all attributes have been assigned a value. This must be true for all possible derivations.

1.5 Spencer's Implementation of Kastens' Algorithm

In [5] Spencer describes the details of the implementation of Kastens' attribute grammar analysis algorithm, along with her design details for input/output for grammar specification and visit sequences. It is very difficult to translate Kastens' abstract algorithm design into an implementation. Kastens' algorithm describes a construction based on large abstract sets of data, different types of set operations, and multiple passes over the data. The size of the sets is determined by the number of grammar symbols, productions and symbol/attribute occurrences. As grammars increase in size, constructing and manipulating these data objects efficiently is extremely important, and is highly dependent on the data structures used to represent the sets. Spencer's implementation attempts to reduce time and space requirements by using a carefully selected sequence of set representations during different phases of the algorithm.

Spencer's original work demonstrates the correct processing of several small attribute grammars. However, excessive compute time and space requirements of her original implementation prevents the analysis of larger attribute grammars. Furthermore, recent testing of her program on larger attribute grammars reveals that it contains bugs -- for some attribute grammars it produces visit sequences that obviously are incorrect. Thus, Spencer's program has to be fixed so it executes properly.

1.6 Converting to Java

"Java is: A simple, object-oriented, distributed, interpreted, robust, secure, architecture neutral, portable, high-performance, multithreaded, and dynamic language" [10]. Spencer's original implementation of analysis algorithm is in the programming language Ada. Java is the programming language chosen for the new version of Spencer's implementation of Kastens' algorithm. How to represent data is critical in the design of the attribute analysis algorithm. Java supports the object-oriented concept of *class*, consisting of a collection of data and methods that operate on that data [10]. Java also provides several pre-defined classes, including a class "Vector" which is basically a dynamic array. This type of data structure is ideal to represent and manipulate the large abstract sets of data in Kastens' algorithm. At runtime, the standard implementation of Vector almost completely eliminates wasted space due to the dynamic growth of the Vector. More importantly, use of a standard, predefined class and its operations helps avoid subtle programming bugs.

1.7 Thesis Overview

As noted above, EIS requires a well-formed language that defines EIS meta-data descriptions, datasets, and modeling components. The goal is to formally specify the EIS language using an attribute grammar, then use the formal specification as the basis for implementation of EIS language processing tools. Currently, a parser and semantic analyzer perform all syntactic and semantic checking. The semantic analysis done for the EIS object description language is embedded in the parser/analyzer. The purpose of constructing an ordered attribute grammar for EIS, is (a) to formalize the specification of syntactic checking, (b) to formalize analysis of the static semantics specification, and (c) to formalize implementation of static semantic specification [5].

Chapter 2 discusses Kastens' algorithm, including basic notation, how the algorithm logically works, and it's inputs/outputs. This method of semantic analysis is time efficient, in the sense that the evaluation order of the attributes only needs to be determined once for a given grammar. It is space efficient because the visit sequences, which can be subsequently used to evaluate the attributes for any derivation in that attribute grammar, are also constructed only once. Chapter 3 discusses the Java implementation of Kastens algorithm, including details borrowed from Spencer's program and specific features new in the Java version. Chapter 4 discusses the EIS language specification and defines the EIS language using an attribute grammar. This attribute grammar formally defines the syntactic and semantic checking that must be done for the EIS object description language. Chapter 5 analyzes the EIS attribute grammar via Kastens' algorithm implementation in Java. It also discusses a second and third version of the analysis code that was written to meet memory requirements of large attribute grammars such as the EIS attribute grammar.

Finally, Chapter 6 discusses the correctness of the overall language design, in the sense of matching the syntactic/semantic intent for EIS. Examples are used to argue informally that the EIS attribute grammar produces computations that match the intent for object-oriented class, instance, and method specification. Chapter 6 also describes how an attribute evaluation algorithm could be constructed so that when the visit sequences produced from the analyzer with the EIS attribute grammar as input, and example derivations of meta-data descriptions, datasets, or modeling components are run through the evaluator, the results are evaluated EIS attributes.

Chapter 2

Kastens' Algorithm

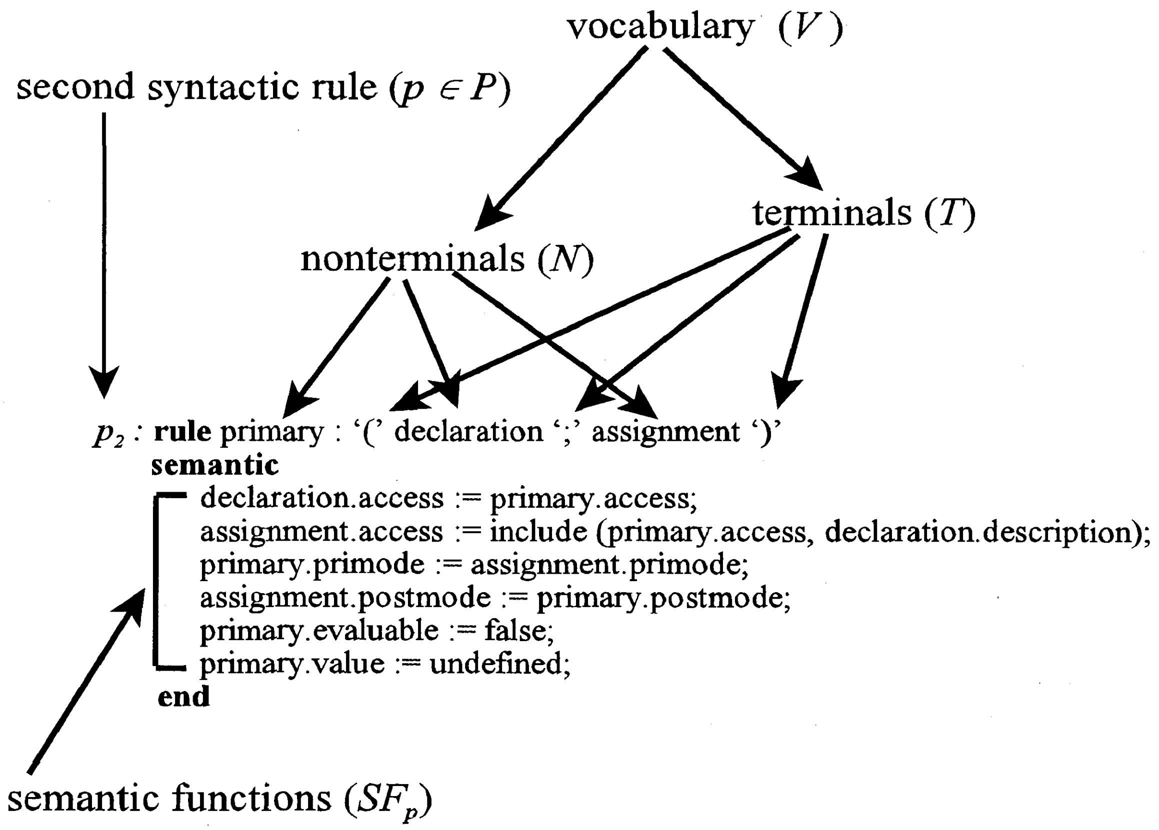
2.1 Attribute Grammar Notation

The notation for attribute grammars used by Kastens is described in the following. An attribute grammar is a context-free grammar which is augmented by attributes. Semantic functions define the value of an attribute occurrence. Boolean attributes can be used to indicate whether or not "extra-grammatical" aspects of the derivation are correct, i.e., to impose conditions on the derivation that lie outside normal context-free specification.

An attribute grammar AG is defined as $AG = (G, A, VAL, SF, SC)$. $G = (N, T, S, P)$ is a context-free grammar, where N is the set of nonterminal symbols, T is the set of terminal symbols, $V = N \; V T$ is the vocabulary of the grammar, $S \in N$ is the start symbol, and P is the set of syntactic rules. Each syntactic rule $p \in P$ has the form:

$p = X_0 : X_1, \ldots X_n,$ for $n >= 0$.

X_i denotes an occurrence of a symbol of N, for $i = 0$ and V for $i > 0$. A represents a set of attributes. A_x is the set of attributes associated to symbol X. $X \cdot a$, $X \cdot b$,... denote the elements of A_x. AI_x and AS_x are subsets of A_x that represent inherited and synthesized attributes respectively. SF_p is the set of semantic functions associated with rule $p \in P$. Each semantic function defines the value of an attribute occurrence in p. These occurrences defined by semantic functions make up the set of defining occurrences, AF_p. Figure 2.1 demonstrates the elements of an attribute grammar.



```
p2 : rule primary : '(' declaration ';' assignment ')'
     semantic
        declaration.access := primary.access;
        assignment.access := include (primary.access, declaration.description);
        primary.primode := assignment.primode;
        assignment.postmode := primary.postmode;
        primary.evaluable := false;
        primary.value := undefined;
     end
```

the set of defining occurrences for this production are: (AF_p)

declaration.access
assignment.access
primary.primode
assignment.postmode
primary.evaluable
primary.value

inherited attributes: (AI)

declaration.access
assignment.access
assignment.postmode

synthesized attributes: (AS)

primary.primode
primary.evaluable
primary.value

Figure 2.1 Elements of an Attribute Grammar

2.2 The "orderness" property

D. E. Knuth proposes the concept of well-defined attribute grammars, and states that an attribute grammar is well-defined if and only if there is no sentence of the language with circularly dependent attributes [3]. Kastens goes on to introduce "ordered attribute grammars" as a subclass of well-defined attribute grammars. Grammars of this class meet the following condition: "For each symbol of the grammar a partial order over the associated attributes can be defined, such that in any context of the symbol the attributes are evaluable in that order" [2]. Further, Kastens demonstrates that one can automatically construct algorithms to evaluate the attributes of any sentence of an ordered attribute grammar.

The problem of deciding whether a given attribute grammar is ordered is solved by projection of the attribute dependencies into dependency relations associated with production rules and symbols. The basic idea for ordered attribute grammars is: for each symbol of a given attribute grammar, construct a partial order over the attributes. This order determines the evaluation order for the attributes of a symbol, in any derivation context in which that symbol occurs. The evaluation order must reflect all direct and indirect dependencies, which may be derived from any possible context of that symbol. The evaluation order is used to construct "visit-sequences" that describe the control flow of an efficient attribute evaluation algorithm. Elements of the visit-sequence give instructions to move up to the ancestor, move down to a certain descendant, or evaluate a certain attribute.

The syntactic structure of a given terminal string generated by a grammar is depicted in Figure 2.2. During a visit to node K_y some attributes of AF_p are evaluated according to semantic functions of SF_p. Several visits to each node are generally needed until all

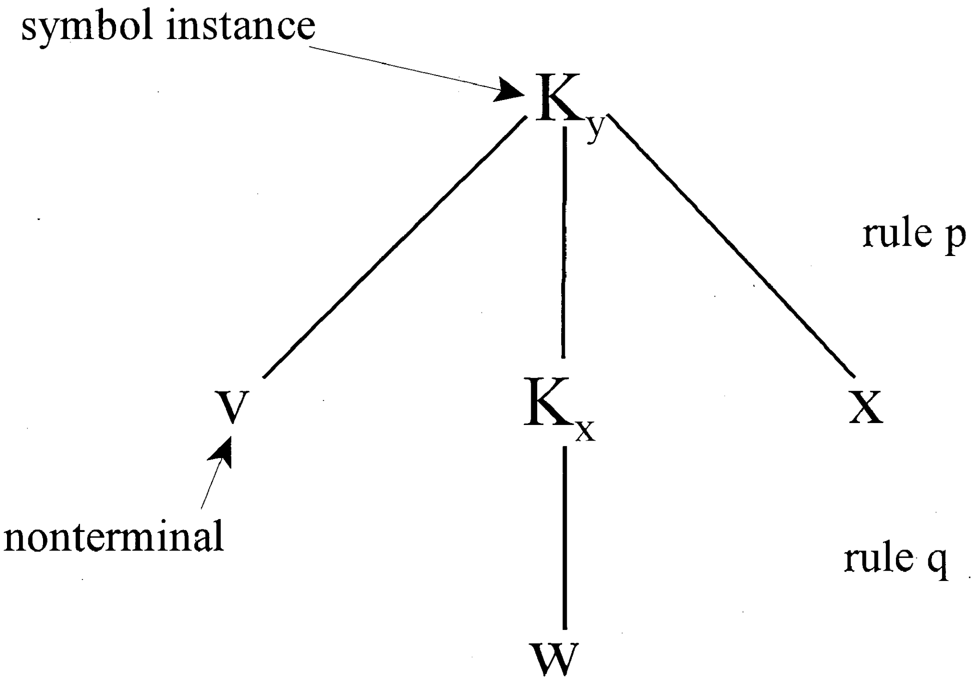


Figure 2.2 Derivation Tree

attributes are evaluated. The partial order constructed for each symbol is used to assure that the visit-sequences for a tree node and for its descendants fit together. A move down from K_y to K_x is made in order to evaluate a certain subset of synthesized attributes of symbol X. Any move back up to K_y is used to evaluate a certain subset of inherited attributes of symbol X. Therefore the partial order for symbol X must define a linear order over subsets of A_x, which contain alternating inherited and synthesized attributes. The order is partial because the evaluation order within each subset is not relevant.

2.3 Constructing partial orders for symbols

An attribute grammar is ordered if a partial order *DS* (dependencies between symbols) with the properties discussed above can be constructed according to the following definitions [2]. Examples from the simple expression language given by Kastens' [2], listed in Appendix A, are given in bold in the cases below.

Definition 1. Let DP_p be the relation of direct dependencies between attribute occurrences associated to production rules, where

$DP_p = \{(X_i.a, X_j.b) |$ there is a semantic function in SF_p defining $X_j.b$ in terms of $X_i.a\}$

DP_2 = {(primary.access,declaration.access), (primary.access,assignment.access), (declaration.access, assignment.access), (assignment.primode,primary.primode), (primary.postmode, assignment.postmode)}

DP_2 is the set of dependencies given directly by the semantic functions.

Definition 2. Let IDP_p be the relation of induced dependencies between attribute occurrences, where

$IDP_p = DP_p \vee \{(X_i.a,\ X_i.b) |\ X_i$ occurs in rule p, Y_j occurs in rule q, $X_i = Y_j$ and $(Y_j.a, Y_j.b) \in IDP_q^{+}\}$.

IDP_1 = **{(primary.access, primary.postmode), (primary.access, primary.primode),
(primary.access, primary.value),(primary.primode, primary.postmode),
(primary.postmode, primary.value),(primary.primode, primary.value),}**

IDP_1 contains all the direct dependencies of rule 1 and those induced by attributes of similar symbol occurrences in other productions.

Definition 3. Let IDS_X be the relation of induced dependencies between attribute of symbols, where

$IDS_X = \{(X.a,\ X.b) |$ *there is an* $X_i = X$ in a rule p and $(X_i.a, X_i.b) \in IDP_p\}$.

$IDS_{primary}$ = **{(primary.access, primary.postmode), (primary.access, primary.primode),
(primary.access, primary.value),(primary.primode, primary.postmode),
(primary.postmode, primary.value),(primary.primode, primary.value),}**

$IDS_{primary}$ contains direct and induced dependencies of attributes of symbol occurrence *primary* found in some production p. Figure 2.3 gives a graphical representation of $IDS_{primary}$. If *IDS* is cyclic, the grammar is not "ordered". In the next steps *IDS* is completed to *DS*.

DS_X defines a linear order over disjoint alternating subsets of synthesized and inherited attributes of symbol X. Each subset, denoted by $A_{X,k}$ consists of those attributes (synthesized or inherited) whose values are additionally available after a move up or down in the syntax tree. The evaluation order corresponds to the decreasing value of k. Therefore, $A_{X,k}$ contains attributes that need to be evaluated before attributes in $A_{X,k-1}$.

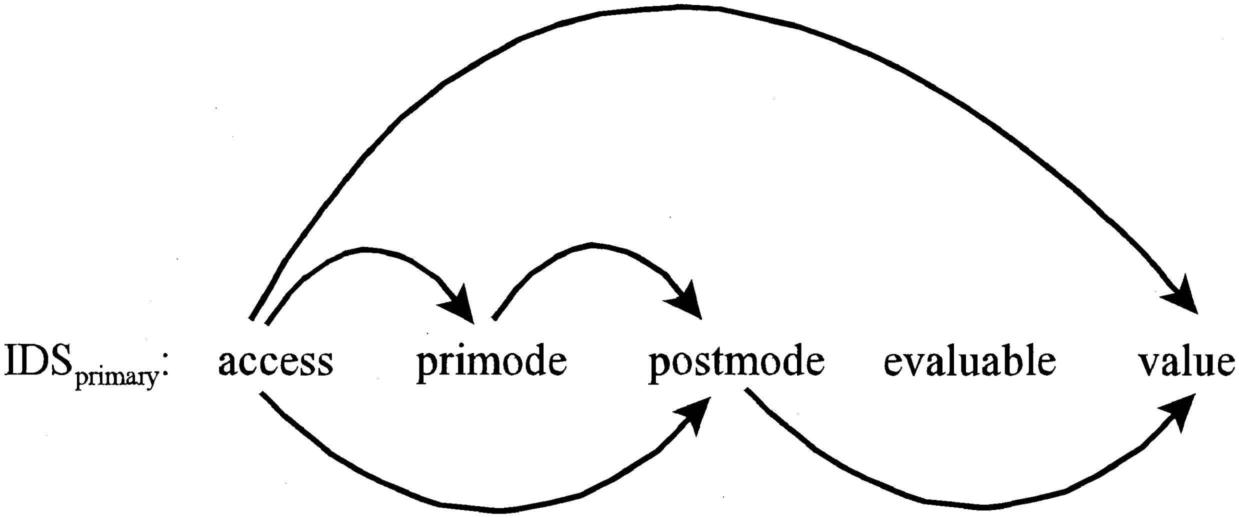


Figure 2.3 Dependency graph $IDS_{primary}$

Definition 4. Let *IDS* be acyclic. For each $X \in V$:

$$A_{X,1} = \{\, X.a \in AS \mid \text{there is no } X.b \text{ such that } (X.a, X.b) \in IDS^{+} \},$$

$$A_{X,2n} = \{\, X.a \in AI \mid \text{for all } X.b \in A_X : (X.a, X.b) \in IDS^{+} \text{ implies}$$

$$X.b \in A_{X,m},\ m < 2n\} \setminus A_{X,1} \cup \ldots \cup A_{X,2n-1},$$

$$A_{X,2n+1} = \{\, X.a \in AS \mid \text{for all } X.b \in A_X : (X.a, X.b) \in IDS^{+} \text{ implies}$$

$$X.b \in A_{X,m},\ m < 2n+1\} \setminus A_{X,1} \cup \ldots \cup A_{X,2n},$$

This is done until each attribute $X.a \in A_X$ is in a disjoint partition $A_{X,k}$. The subsets are defined such that the values of $A_{X,k}$ are needed to compute the values of $A_{X,k-1.,}$ the values of $A_{X,-1k}$ are needed to compute the values of $A_{X,k-2}$, etc. Let m_X equal the largest *k* value for symbol *X*.

$A_{primary,1}$ **= {value, evaluable}**
$A_{primary,2}$ **= {postmode}**
$A_{primary,3}$ **= {primode}**
$A_{primary,4}$ **= {access}**
$m_{primary}$ **= 4**

Definition 5. Let *IDS* be acyclic.

$$DS_X = IDS_X \vee \{(X.a, X.b) \mid X.a \in A_{X,k}, X.b \in A_{X,k-1}\ 2 \leq \mathrm{k} \leq \mathrm{m}_X\}.$$

DS_X defines a linear order over the subset $A_{x,k}$ of A_x. For each two attributes $X.a \in AI$, $X.b \in AS$, either $(X\,a, X.b) \in DS_X$ or $(X.b, X.a) \in DS_X$.

Definition 6.

$$EDP_p = DP_p \vee \{(X_r.a, X_r.b) \mid (X.a, X.b) \in DS_X, X_i = X \text{ for each } X \text{ that is contained in } p\}.$$

EDP_p extends the dependencies of a production to reflect all dependencies (direct, induced and linearly ordered) between attributes of symbols, for the symbols contained in *p*.

Definition 7. A given attribute grammar is "ordered" if the dependency relationship *DS* exists and the extended dependency relationship *EDP* is acyclic.

2.4 Visit Sequences

Just because an attribute grammar is ordered does not imply that a predefined strategy for attribute evaluation exists. An algorithm that produces such a strategy can be constructed based on the attribute dependencies as discussed above, in the form of what are known as *visit sequences.* Visit sequences are independent of the compilation of any particular sentence of the language; therefore they can be constructed once for a given attribute grammar as part of its analysis.

Chapter 3

Kastens' Implementation

3.1 Attribute Grammar

The first decision Spencer makes when implementing Kastens' algorithm is, how to represent the attribute grammar. An example of her syntax for specifying the attribute grammar is given in Appendix A. Attributes and their corresponding types are listed first, terminated with a "%". Function names follow, terminated by a "%". The grammar is then listed, in BNF form, with some minor syntactic rules. Each production begins with the word "rule". A ":" follows the lefthand symbol of a production, and a ":=" follows the left hand side of a semantic function. Each production, semantic function and semantic condition must termintate with a ";". The word "semantic" must proceed the list of semantic functions, the word "condition" must proceed the list of semantic conditions, and the word "end" must terminate each production. All nonterminals must be enclosed by single quotes. Symbol/attribute occurrences are represented by "symbol.attribute".

3.2 Data Structures

Data is constantly being manipulated throughout Kastens' algorithm. How to represent this data is critical. Spencer uses the programming language Ada and data structures including: arrays, records, and pointers. These data structures are easy to manipulate, but the size of datasets places maximum values on the number of symbols, attributes, productions and symbol/attribute occurrences allowed in the grammar. This creates a problem in attempting to analyze very large grammars. In addition, since Spencer's program uses statically allocated arrays, allocated space is wasted on smaller grammars. Due to the uncertain size of the grammar ahead of time, Spencer's implementation [5] is not as efficient as we would like it to be. In addition, Ada programming environments are becoming somewhat rare, so the decision was made to re-implement Kastens' algorithm in the more portable language Java.

Java is an object-oriented programming language. A *class* is a collection of data and methods that operate on that data. Java comes with a large number of predefined classes. One of those predefined classes is *Vector*, which implements a variable sized list of objects. In this case, an object is some instance of another class. The methods associated with the class *Vector* allow you to store and retrieve objects of any type, as well as to easily manipulate and keep track of the size of the *Vector*. Thus, our reimplementation is based on Spencer's implementation, but with data structures converted into more appropriate Java forms.

Java also has many other nice features. It is relatively easy to learn. It is an interpreted language. The Java compiler generates byte-codes for the Java Virtual Machine (JVM) (instead of the native machine code) which executes the compiled byte-codes. Java byte-codes are platform independent. Therefore Java programs can run on any platform that the JVM has been ported to. Java is designed for writing robust software. There are no pointers, which eliminates one of the most bug-prone aspects of other programming languages. There is extensive compile-time type checking. There are many more advantages to using Java; however, those listed above are the most important in why the language was chosen for this project.

A symbol table, attribute table, production table, and symbol/attribute occurrence maps are the initial data structures created to implement Kastens' algorithm. The Java version is based on the following class definitions. The class *symbol* represents a grammar symbol:

```
public class symbol {
        String sym_name;
        int sym_base;
}
```

The variable *symbol.sym_name* holds the string representation of the lexical token. A Vector *sym_table* represents a symbol table. A unique integer is associated with each symbol that is given by the index of *sym_table*. Production rules can be recursive, i.e., *numeral : numeral2 '+' digit*. For those symbols that have an integer attached at the end, *symbol.sym_base* holds the unique integer representation of the symbol without the integer attached. For those symbols without an integer attached to the end, *symbol.sym_base* holds the unique integer representation of that symbol.

The class *attribute* represents an attribute:

```
public class attribute {
        String att_name;
        String att_type;
        public boolean check_type() { ... }
}
```

The variable *attribute.att_name* holds the string representation of the lexical token that represents the attribute name. The variable *attribute.att_type* holds the string representation of the lexical token that represents the attribute type. The Vector *att_table* represents an attribute table. A unique integer is associated with each attribute that is given by the index of *att_table*. The method *attribute.check_type*() determines if a particular attribute type is legal or not.

Symbol/attribute occurrences are represented in two maps. As a semantic function is being parsed, if the symbol/attribute occurrence did not previously exist it is assigned a unique integer value (starting at 1). *map1* is a one dimensional array of *maprec*. *maprec* is the following class:

```
public class maprec {
        int sym;
        int att;
}
```

The index of *map1* represents a unique integer for a particular symbol/attribute occurrence. *maprec* contains the unique integer representation of the symbol for that occurrence in the variable *maprec.sym*, and the unique integer representation of the attribute for that occurrence in the variable *maprec.att*. *map2* is a two dimensional array whose indices (the integer representation of a symbol, and the integer representation of an attribute) yield the unique integer representation for that occurrence. These are the only two arrays used in the Java implementation of Kastens' algorithm. There is a maximum limit of 500 symbol/attribute occurrences. The ease of manipulating these arrays became more of a priority than the small amount of wasted space allocated. Figure 3.1 shows the symbol table, attribute table, occurrence map 1, and occurrence map 2 for the simple attribute grammar listed in Appendix B.

The class prod represents a production:

```
public class prod {
        int lhs;
        Vector sym_list = new Vector();
        Vector occur_list = new Vector();
        Vector cond_list = new Vector();
        Vector vis_seq = new Vector();
}
```

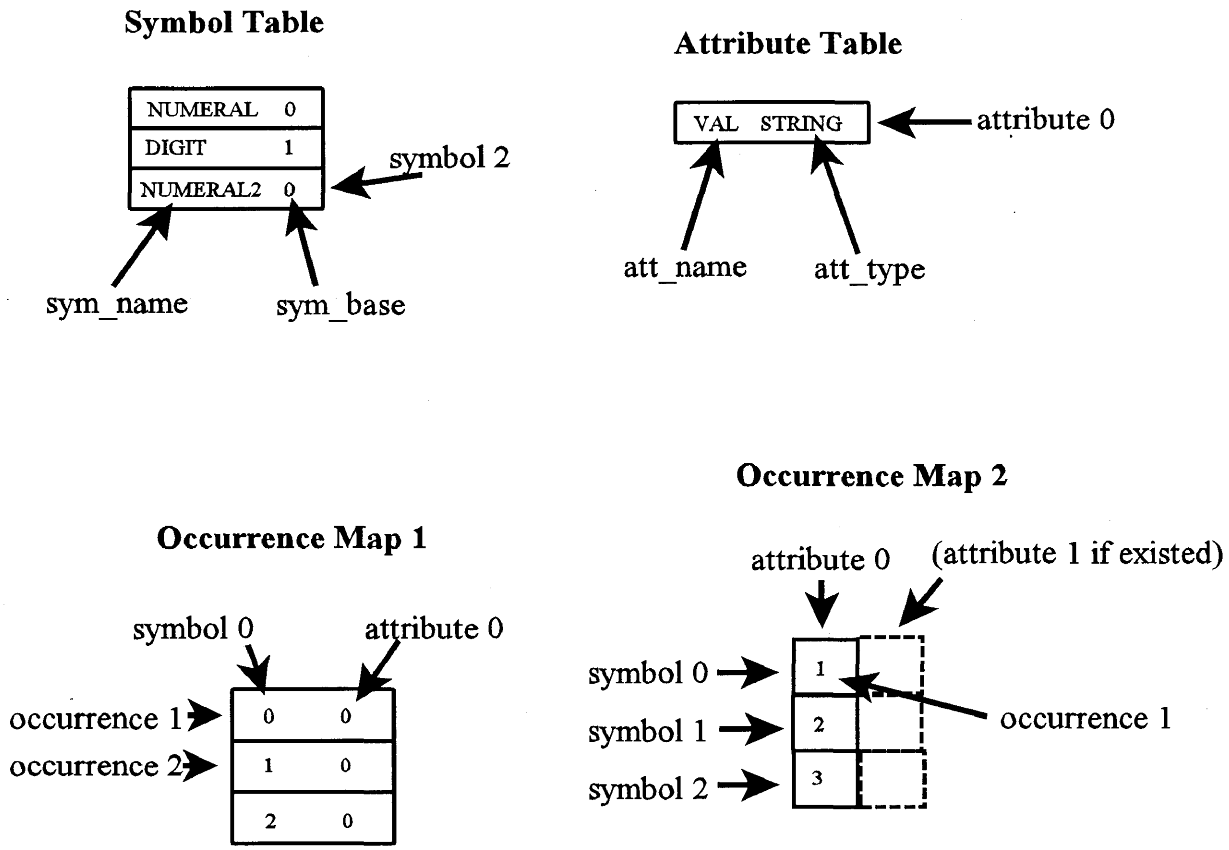


Figure 3.1 Example Symbol Table, Attribute Table, Occurrence Map1 and Occurrence Map2

The variable *prod.lhs* holds the integer for the nonterminal symbol representing the left hand side of the production. *prod.sym_list* is a Vector containing the integer representation of all the symbols in the production. *prod.occur_list* is a Vector containing *"occur"(s)* (holds the occurrence arguments for the function definition of an occurrence). *prod.cond_list* is a Vector containing *"cond"(s)* (holds the occurrence arguments for a condition). And finally, *prod.vis_seq* is a Vector containing *"seq"(s)* (holds an action for the visit sequence). The Vector *prod_table* is created to represent a production table. Figure 3.2 shows the production table for the attribute grammar listed in Appendix B immediately after the grammar has been parsed.

The main data structure in Kastens' algorithm represents dependency relations. Dependencies are easily represented in adjacency matrices. Logically, matrix(i,j) = 1 indicates that j depends on i, where as matrix(i,j) = 0, indicates that there is no dependency. In the Java version, Vectors are used to simulate and replace Spencer's adjacency matrices. A Vector of Vectors takes the place of a two-dimensional matrix.

3.3 Implementation

Before we actually begin implementing Kastens' algorithm we must take an attribute grammar with the correct syntax as input and create a symbol table, attribute table, production table and occurrence maps as discussed above. Additionally, a function table, lists of all attributes *(A)*, inherited attributes *(AI)*, and synthesized attributes *(AS)* for each symbol must be defined as well as defining occurrences *(AF)* for each production. These data structures are referred to throughout the entire program.

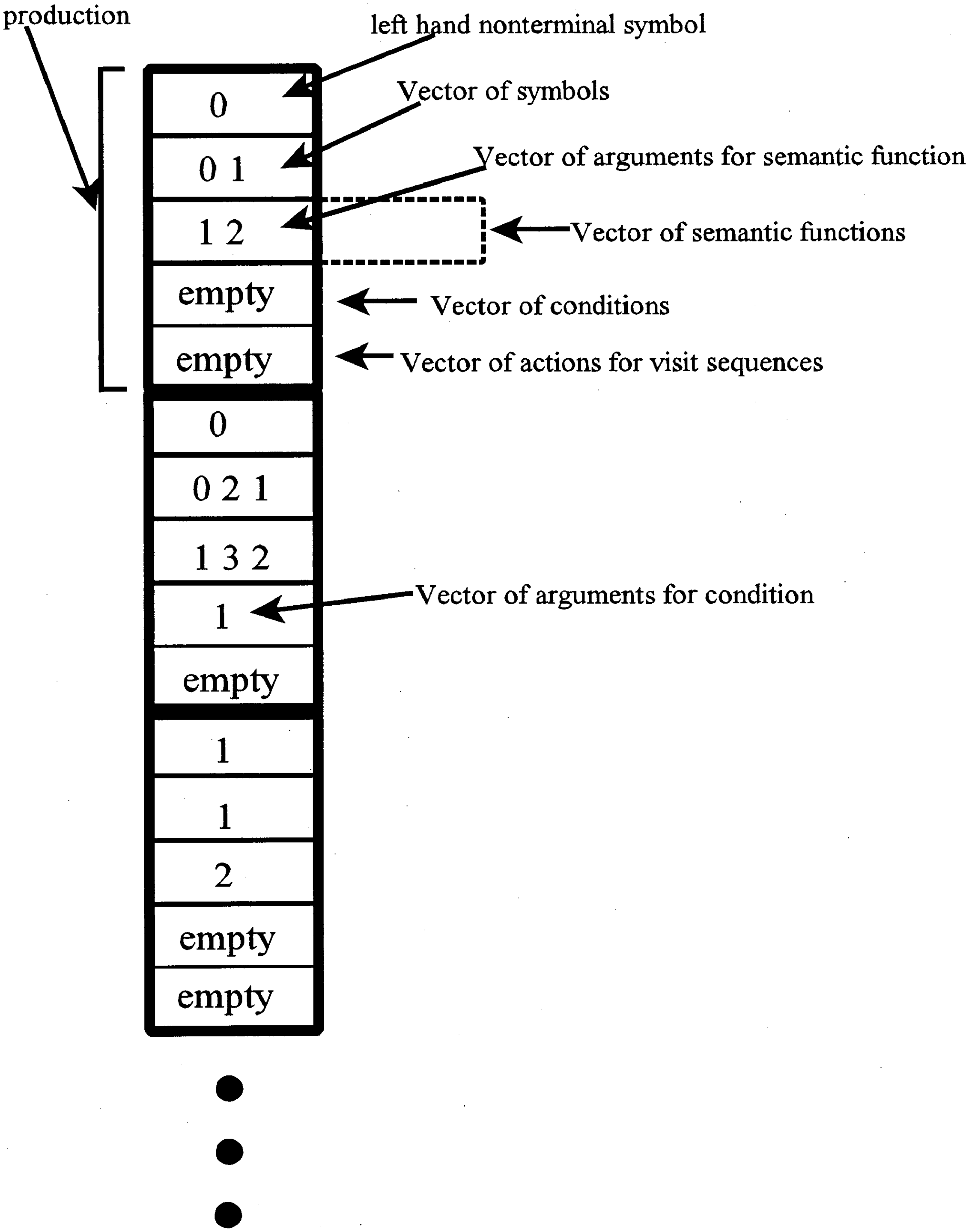


Figure 3.2 Example Production Table

The class *grammar* was created to hold all of the data structures associated with an attribute grammar. .

```
public class grammar {
  Vector att_table = new Vector(); // attribute table
  Vector sym_table = new Vector(); // symbol table
  Vector prod_table = new Vector();  // production table
  Vector fun_table = new Vector(); // function table
  occmaps omaps = new occmaps();  // contains maps for occurrences
  attsets aset = new attsets();  // contains A, AI and AS as well as AF
  Vector tdp = new Vector();   // contains dependencies for each production
  Vector tds = new Vector();  // contains dependencies for each symbol
  Vector mark = new Vector();  // temporary variable
  Vector partition = new Vector(): // contains disjoint partitions of occurrences
  Vector f = new Vector(); // contains the smallest even number >=k (partion for each symbol)
  Vector vseq = new Vector(); //contains the visit sequences for each production
}
```

Values in the variables tdp, tds, mark, partition, f, and vseq are constructed in the rest of the algorithm to hold dependency relations, partitions and visit sequences.

Dependency relations between attribute occurrences in productions as well as between attributes of symbols are the basis for computing the visit sequences for a given attribute grammar. If at any point a dependency relationship is found to be cyclic, that particular attribute grammar is not ordered. Each rule in the attribute grammar is represented by a dependency relation TDP_p over attribute occurrences in that production. Each symbol is represented by a dependency relation TDS_X over attributes A_X. Several functions are used in the next steps for updating dependency relations.

add_arc_trans(Vector am, int size, int v1, int v2)

adds the dependency "*v2* depends on *v1*" to the adjacency matrix am, and then adds any additional dependancies needed to implement the closure on *am*.

add_arc_induce(Vector mark, Vector tdp, Vector am, Vector tds, int v1, int v2, occmaps occ, Vector sym_table)

adds the dependency *"v2* depends on *v1,"* and then adds any additional dependencies needed to implement the closure on *am*. This function is applied to the relation TDP_p. Additionally, each new dependency added is also added to TDS_X, along with additional dependancies needed to reach the transitive closure on TDS_X, if the symbols of symbol/attribute occurrence *v1* and *v2* are the same.

The following steps convert the recursive definitions of DP_p, IDP_p and EDP_p listed in Chapter 3 into iterative algorithms that compute their transitive closures. The first step computes DP^+. Below is an outline of the method *create_tdp_and_tds*.

```
create_tdp_and_tds(grammar g) {
   for each production $p$
    loop
         for each semantic function $f \in SF_p$ defining $X_j.b$
         loop
              for each arguement $X_i.a$ of $f$
              loop
                    if $(X_i.a, X_j.b) \notin TDP_p$
                    then    $add\_arc\_induce(TDP_p, X_i.a, X_j.b)$
                    fi
              repeat
         repeat
    repeat
}
```

After the completion of this method $TDP = DP^+$ and TDS currently contains the transitive closure of direct dependencies between attributes of symbols.

The second step computes the relations IDP^+ and DS^+.

```
create_idp(grammar g) {
  while there is a dependency $(X.a, X.b)$ in $TDS$ not marked
  loop
      $mark(X.a, X.b)$
      for each occurrence $X_i$ of $X$ in any rule $p$
      loop
          if $(X_i.a, X_i.b) \notin TDP_p$
          then $add\_arc\_induce(TDP_p, X_i.a, X_i.b)$
          fi
      repeat
  repeat
}
```

Each dependency in *TDS* which is not marked is induced at each occurrence of the symbol in *TDP*. If new dependencies are found that need to be induced, they are added to *TDS* by *add_arc_induce*. When the algorithm is completed $TDP = IDP^+$ where *IDP* is the set of all induced dependencies (including direct dependencies) between attribute occurrences. IDP^+ ensures that all attribute dependencies for a symbol X are obtained for any context of X. Marking the dependency in *TDS* ensures that no dependency is unnecessarily induced more than once. $TDS = IDS^+$ where *IDS* is the set of all induced dependencies (including direct dependencies) between attributes of symbols. The variables *tdp* and *tds* in the Java implementation hold the dependency relations for a given attribute grammar. Figure 3.3 shows the dependencies graphs *TDP* and *TDS* at this point for the example attribute grammar.

The third step computes the disjoint partitions of A_X. Starting with *symbol 0* and $k=1$, the algorithm loops until all attributes A are assigned to some $A_{X,k}$. Partitions with odd k contain only synthesized attributes. Partitions with even k contain only inherited attributes.

```
create_partition(grammar g) {
  for each symbol $X$
  loop
      $k = 1;$
      $not\_assigned = A_X$
      while ($not\_assigned \neq$ empty)
```

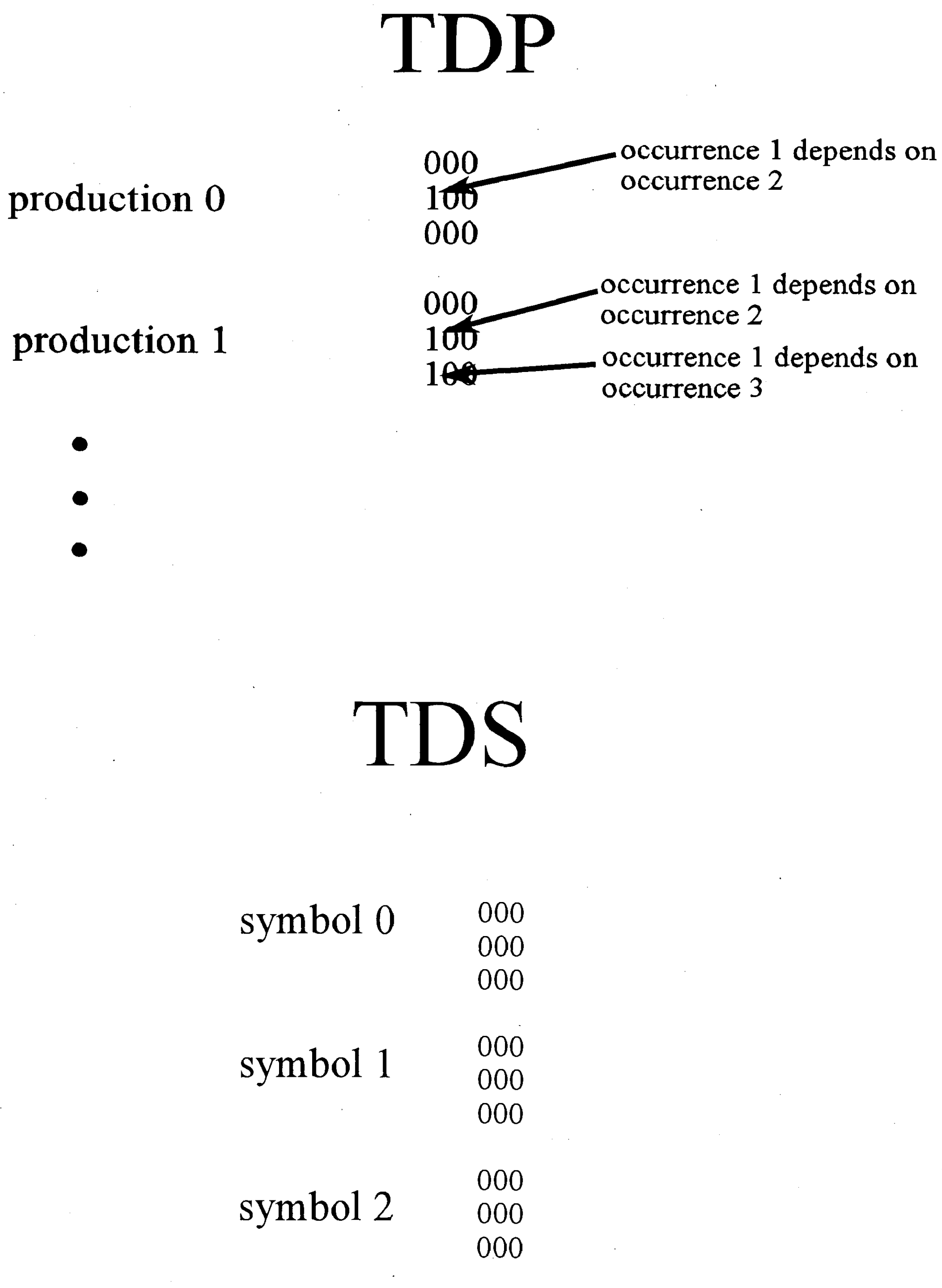
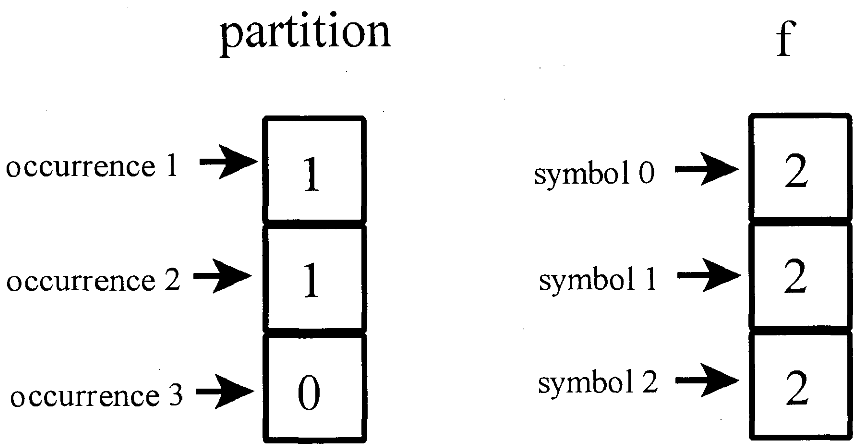


Figure 3.3 Dependency graphs TDP and TDS

```
            loop
               found_one = false;
               for each attribute $X.a \in$ (not_assigned && if odd k then $AS_X$ else $AI_X$ fi)
               loop
                   condition_holds = true;
                    for each $X.b \in$ not_assigned
                    loop
                         if $(X.a, X.b) \in TDS_X$
                       then condition_holds = false;
                            break;
                       fi
                    repeat
                    if condition_holds
                    then partition(X.a) = k;
                       not_assigned = not_assigned \ {X.a};
                       found_one = true;
                       break;
                    fi
               repeat
               if (!found_one && not_assigned ≠0)
               then k = k + 1;
               fi
            repeat
            $m_X = k$;
            $f_X$ = if (odd k) then k+1 else k fi
        repeat
    }
```

The algorithm loops for each symbol of the attribute grammar. *k* is initially 1. The variable *not_assigned* contains all the attributes associated with symbol *X*. If *k* is odd and an attribute *X.a* is synthesized and an element of *not_assigned*, then the algorithm determines if any other element in *not_assigned* depends on *X.a*. In the actual Java implementation a Vector *partition,* whose index is the integer representation of that occurrence is assigned the value of *k*. A Vector *f*, whose index is the integer representation of a symbol is assigned the smallest even number >= *k*. Figure 3.4 shows the variables *partition* and *f* for the attribute grammar in Appendix B.

The next step computes the relation EDP^+. The algorithm adds dependencies to *TDP* according to the relation given by the disjoint partitions of the attribute occurrences for each



NOTE: All occurrences with symbols whose base value differs from the integer representation are given the value of 0

Figure 3.4 Disjoint Partitions and F values symbol, $A_{X,k}$.

```
create_edp(grammar g) {
    for each production $p$
    loop
        for each symbol $X$ in $p$
        loop
            $X = X_i$
            for each $X.a$
            loop
                for each $X.b$
                loop
                    if $partition(X.a) > partition(X.b)$
                    then $add\_arc\_trans(TDP_p, X_i.a, X_i.b)$
                    fi
                repeat
            repeat
        repeat
    repeat
}
```

When the algorithm is completed $TDP = EDP^+$. If each TDP_p is acyclic, then the attribute grammar is ordered.

The final step of Kastens' algorithm constructs the visit-sequences. Consider evaluating the attributes of symbol X where $f_X = 4$ and the largest value of $k = 4$. $A_{X,4}$ are those inherited attributes evaluated first. A move to a descendant must be made and then the synthesized attributes $A_{X,3}$ are evaluated and so forth.

$$\begin{array}{cccccccc} A_{X,4} & & & & A_{X,2} & & & \\ & \downarrow 1 & & \uparrow 1 & & \downarrow 2 & & \uparrow 2 \\ & & A_{X,3} & & & & A_{X,1} & \end{array}$$

The number of ancestor and descendant visits are both f_X div 2.

An occurrence is created to represent a visit. This makes it easy to keep track of dependencies between occurrences and visits. If a production contains the symbol in the example above, two occurrences would be created to represent the two visits needed. The integer representation of the symbol (of the occurrence), represents the symbol to be visited. The integer representation of the attribute represents the value of k (in the form of k + number of attributes). Due to the fact the value of the attribute of the occurrence is greater than the total number of attributes, we know the occurrence is a visit.

Conditions are also represented as an additional occurrence. The integer representation of the symbol (of the occurrence) represents the number of the condition (in the form of cond + number of symbols). Due to the fact the value of the symbol of the occurrence is greater that the total number of symbols, we know the occurrence is a condition. The integer representation of the attribute has no relevant value. Figure 3.5 show the occurrences maps of the attribute grammar in Appendix B after the visit values and conditions have been added.

3.3.1 Creating Visit Sequences

The following algorithm presented by Kastens and implemented by Spencer is intended to construct the visit sequences:

```
create_visseq(grammar g) {
   for each production $p$
    loop
        for each $(X_i.a, X_j.b) \in TDP_p$
        loop
            $mi = partition(X_i.a)$;
            $mj = partition(X_j.b)$;
            $ki = (f_{xi} - mi + 1) div 2$;
            $kj = (f_{xi} - mi + 1) div 2$;
            if $(ki > 0$ && $kj > 0)$
           then $add\_arc\_trans(VS_p$,(if $X_i.a \in AF_p$ then $X_i.a$ else $v_{ki,i}$ fi),(if $X_i.b \in AF_p$ then $X_i.b$ else $v_{ki,i}$ fi))
           fi
       repeat
        $add\_cond\_vertices\_to\_vs()$;
        for each $g \in {}_{Avp}$
```

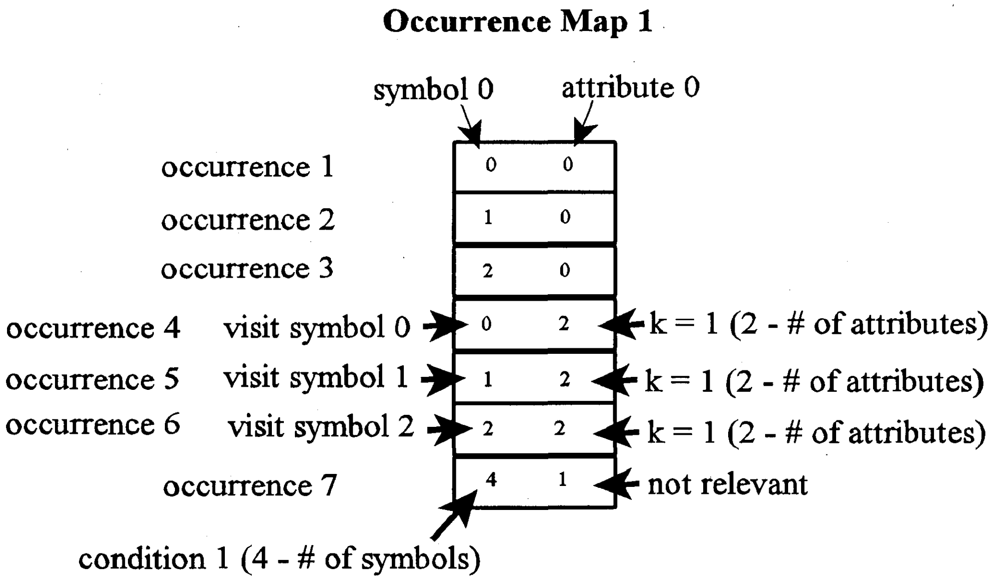


Figure 3.5 Example Occurrence Map 1 after visit values and condition are added

```
    loop
      for each $h \in AV_p$
      loop
        if $(g,h)$, (h,g) $\notin VS_p$
        then  if $(g = v_k, 0$ && $k = nv_X, X=X_0)$
              then add_arc_trans($VS_p$,h,g)
              else add_arc_trans($VS_p$,g,h)
              fi
        fi
      repeat
    repeat
  repeat
}
```

The algorithm takes the relation *TDP*, and for each dependency determines whether the occurrences for that dependency are inherited and can be evaluated immediately, i.e; **if** *(ki > 0 && kj > 0)*. If the occurrences can be, this dependencies is not added to the new dependency relation *VS*. If they can't, the dependency is added to the new dependency relation *VS*. If an occurrence is not in the defining occurrence set AF_p, then the occurrence value of visiting the given symbol with the given k value is determined. Therefore, *VS* contains dependencies between occurrences of the defining occurrence set, and dependencies between occurrences of the defining occurrence set and visit values (which are represented by occurrence values).

A couple of changes were made to the above algorithm in the Java implementation. The statement **if** *(ki > 0 && kj > 0)* implies if two occurrence's k values are not greater than zero they can be evaluated immediately and there is no need to add the dependency to the relation *VS*. This isn't correct. The second occurrence depends on the first occurrence regardless of the k value. Therefore, the first occurrence must be evaluated before the second occurrence and this dependency must show up in the list of visit sequences unless the first occurrence has a k value less than or equal to zero. The Java implementation changed the statement to **if** (*ki* > *0*), meaning if the occurrence that is depended on has a value less than or equal to zero, its occurrence value is available immediately so the occurrence that depended on it can be evaluated immediately also and the dependency does not need to be added to *VS*.

The second change was the positioning of the procedure *add_cond_vertices_to_vs*. *add_cond_vertices_to_vs* adds the dependencies found in conditions to *VS*. As mentioned before, conditions are represented as occurrences. The occurrence value of the condition depends on the occurrence values of the arguments of the condition. Therefore *add_cond_vertices_to_vs* was moved to the beginning of *create_visseq* and conditions are treated just like any other occurrences. If a condition depends on an occurrence with a k value equal to zero, the dependency does not need to be added to *VS* because the occurrence value is available immediately and the condition can be evaluated immediately.

The final part of the algorithm arbitrarily adds dependencies to *VS* until it is linearly ordered, ensuring that the last move to the ancestor is the last element of the visit sequence by making it depend on all other occurrences (regular or visit). The final change made to Kastens' algorithm has to do with evaluating occurrences after a move up or down a derivation tree. All dependencies are reflected in the dependency relation *VS*. However when a move is made up or down the tree there is nothing to indicate that available attributes should be evaluated at that moment before any other move takes place. The available attributes and the move may not depend on one another but attributes in the node visited may depend on evaluated previous attributes. The Java implementation corrects this problem by comparing occurrences in the defining, visit, and condition occurrence set of a production. If two occurrences have no dependency and one of them is a visit, a dependency is added to *VS* where the visit depends on the other occurrence. This ensures all available attributes and conditions will be evaluated before a move up to an ancestor or down to a descendant. The rest of the occurrences that have no dependencies between them are evaluated arbitrarily.

3.4 Problems with Spencer's Implementation

Spencer did an excellent job of creating data structures and manipulating them throughout her implementation of Kastens' algorithm. However, the excessive compute time and space required by the data structures in the analysis algorithm prevent her implementation from use with larger attribute grammars. In fact, Spencer's implementation has one major mistake that is easily overlooked with smaller attribute grammars.

The problem occurs in the creation of the dependency relation *TDS*. As mentioned before, the procedure ***add_arc_induce*** adds the dependency *"v2* depends on *v1*," and then updates TDP_p and TDS_X appropriately. Spencer's implementation of *add_arc_induce* calls a procedure *ADD_TO_TDS*.

```
procedure ADD_TO_TDS
(TDS          : in out ADJ_MATRIX_PTR_TYPE;
V1,V2         : in OCCURRENCE.OCCUR_VALUES)  is

ATT1,ATT2       : INTEGER;
SYM1,SYM2       : INTEGER;
TEMP_PTR        : ADJ_MATRIX_PTR_TYPE;
TEMP_V1,TEMP_V2 : INTEGER;

begin

SYM1 := OCCURRENCE.LOOKUP_SYM(OCCURRENCE.MAP1,V1);
SYM2 := OCCURRENCE.LOOKUP_SYM(OCCURRENCE.MAP1,V2);
```

```
14      SYM1 := SYMBOLS.SYM_TABLE(SYM1).BASE;
15      SYM2 := SYMBOLS.SYM_TABLE(SYM2).BASE;
16      if SYM1 = SYM2 then
17         ATT1 := OCCURRENCE.LOOKUP_ATT(OCCURRENCE.MAP1,V1);
18                 ATT2 := OCCURRENCE.LOOKUP_ATT(OCCURRENCE.MAP1,V2);
19         if ATT1 /= ATT2 then
20            TEMP_V1 := OCCURRENCE.LOOKUP2(ATT1,SYM1,OCCURRENCE.MAP2);
21             TEMP_V2 := OCCURRENCE.LOOKUP2(ATT2,SYM1,OCCURRENCE.MAP2);
22              if TEMP_V1 = 0 then
23                OCCURRENCE.MAP_OCCUR(ATT1,SYM1,OCCURRENCE.MAP1,
                                                 OCCURRENCE.MAP2,SIZE);
24                        TEMP_V1 := SIZE;
25             end if;
26             if TEMP_V2 = 0 then
27               OCCURRENCE.MAP_OCCUR(ATT2,SYM1,OCCURRENCE.MAP1,
                                                 OCCURRENCE.MAP2,SIZE);
28               TEMP_V2 := SIZE;
29              end if;
30              TEMP_PTR := TDS;
31              for I in 1..SYM1-1 loop
32                  TEMP_PTR := TEMP_PTR.NEXT;
33              end loop;
34              ADD_ARC_TRANS(TEMP_PTR.AM,SIZE,TEMP_V1,TEMP_V2);
35         end if;
36      end if;
37    end ADD_TO_TDS;
```

In Spencer's procedure *ADD_TO_TDS* occurrence values *V1* and *V2* are to be added to the adjacency matrix *TDS* if the occurrences share the same symbol. However, a problem occurs in lines **12 - 16**. In lines **12** and **13** the symbol for occurrence *V1* and occurrence *V2* are found. Lines **13** and **14** determine the base values of the symbols found in lines **12** and **13.** If the base values are the same and the attributes are not the same the dependency is added to *TDS* .

This procedure will produce circular dependencies when two occurrences have different symbols yet share the same base symbol, e.g., *expression2.postmode :=* *expression.primode*. *TDS* is supposed to contain dependencies between attributes of symbols. *expression2* and *expression* share the same base symbol, *expression,* but do not share the same instance of the symbol *expression*, so no such dependency should get added to the relation $TDS_{expression}$. This mistake is easily overlooked, because many grammars do not have constructs like one discussed above, especially small grammars. This problem is easy to correct once it is discovered and traced back, by making sure two occurrences share the same symbol, not the same base symbol, when creating the dependency relation *TDS*.

Chapter 4

The EIS Attribute Grammar

4.1 Overview of EIS

The Ecosystem Information System has two major components. First, EIS is a software system that supports a particular set of operations that are used to create, access, and share a distributed data repository. The database is partitioned among a number of host machines. The potential database user does not need to be concerned with which machine the data is physically located. He or she only needs to be aware that there exists a database "out there" somewhere in the global information space accessible via the network, and that the EIS software system is the tool that permits access to this database. The second component of EIS is that it is a data repository organized hierarchically using an object-oriented framework. The object-oriented approach is relatively simple, inherently hierarchical, and easily extensible.

The EIS data repository is represented by a hierarchical structure known as a class hierarchy. At each primary point in the hierarchy is a class definition, which represents a meta-description of a particular type of dataset. The meta-description includes both the description of data attributes and the description of operational components that are used to access, give values to, and manipulate the data attributes. Also included in the hierarchy, attached to particular class nodes, are class instances that represent datasets of that type. Finally, also attached to class nodes are class methods that represent program components that implement an operation defined for that class. Figure 4.1 shows an example of a class hierarchy through the EIS interface.

This object-oriented approach to data modeling places primary emphasis upon the data objects in terms of the attributes of those objects that are most relevant in the application domain [8]. Identifying critical relationships between classes allows the development of the class hierarchy. Figure 4.2 represents an EIS hierarchy. Class A is the root of the hierarchy. Class A is extended by the subclasses B, and C. B and C have all the properties of their parent class, A, plus one or more new properties. Class B and class C are specializations of class A, while class A is a generalization of classes B and C.

Class B and class C inherit the operations "read" and "display" from their parent class A. Inherited properties need not be defined in a class specification; only newly defined properties need to be specified in the class interface. Instance X is an instance of "B" and any ancestor of "B", including "A". Therefore, the principle of attribute inheritance provides an effective means to organize data on the basis of shared properties. Dataset instances that are similar to one another will be found closer together in the hierarchy, while instances that are dissimilar will be located further apart.

Data transformations or operations, have two components: an operation specification (i.e., its name, argument types and return type), and an operation method (i.e., program). Only the operation specification is part of the class interface. The operation specification in the interface of class "A" indicates that "read" takes no arguments, returns no value, and that is defined for all the classes shown. Two operation methods provide implementation for this operation specification -- one implementation for each subclass. Therefore, clients need not

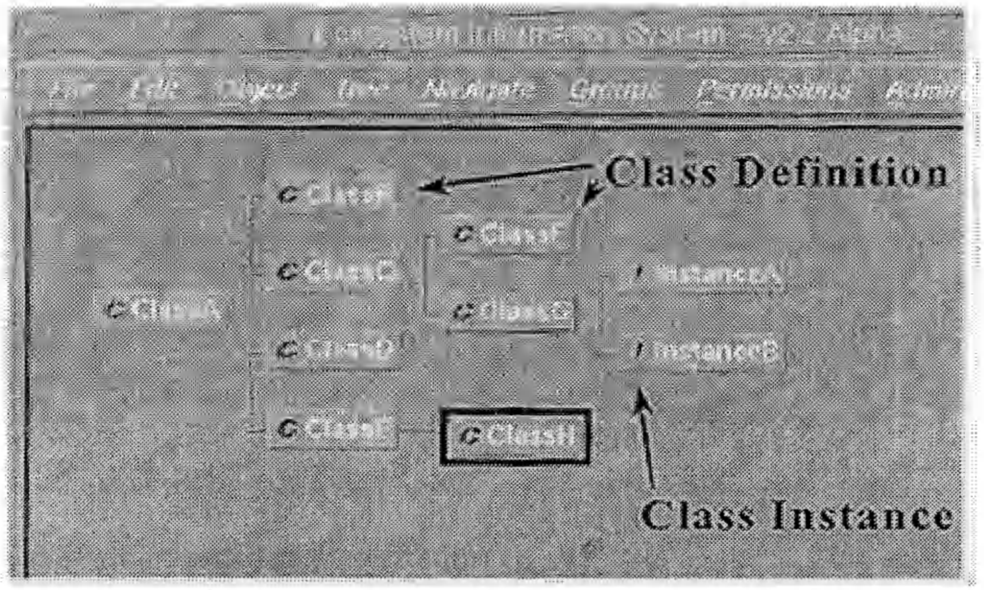


Figure 4.1 Example of EIS Interface

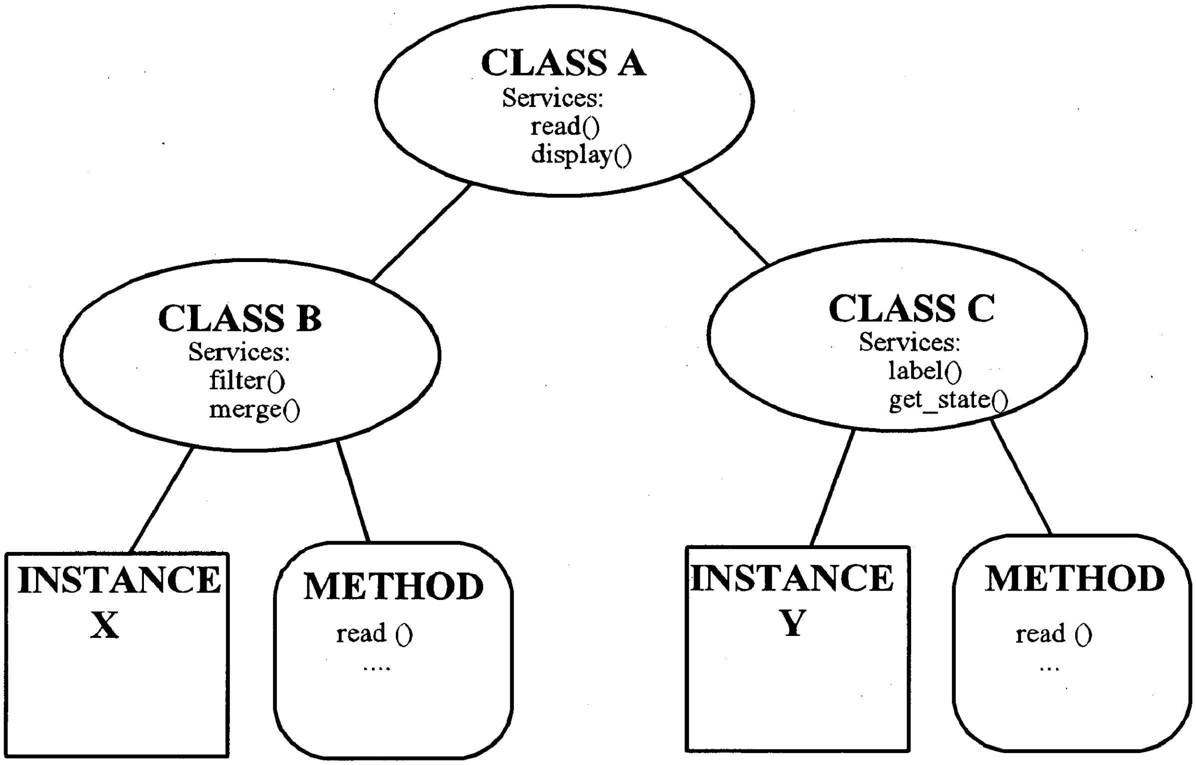


Figure 4.2 An EIS Hierarchy

be aware of low-level details of operation execution. The implementation of "read" can be changed without affecting clients that use instances of "A" [8].

4.2 The EIS Language

Each node in an EIS hierarchy has its own description in a syntax specified by the EIS language. The syntax is different for a class, method or instance. The EIS language also describes the syntax of the whole hierarchy, which mainly consists of the concatenation of the syntax of the nodes in the hierarchy in an ordered form.

4.2.1 EIS Classes

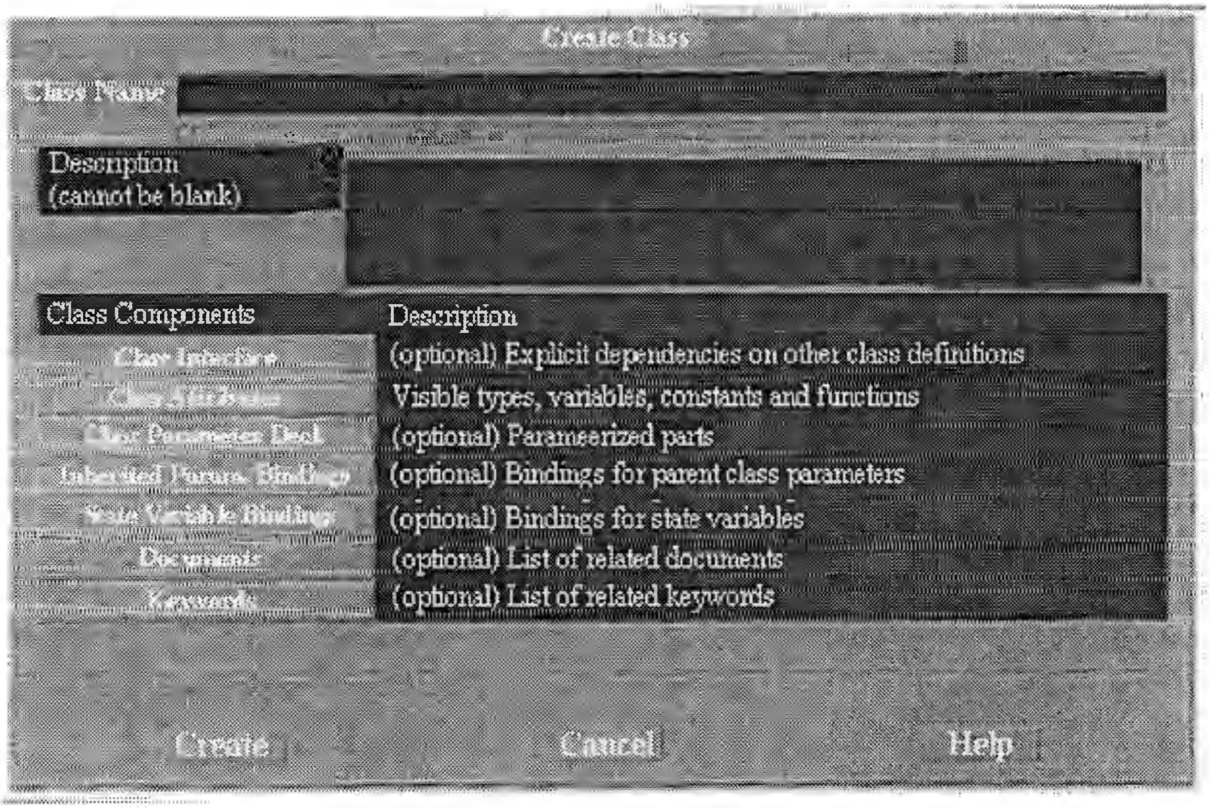
The production rule for a class definition is shown in Figure 4.3. "class", "of" and "end_class" are terminals or tokens of the EIS language. "class_defn", "id1", "id2", "interface_uses_section", ... etc. are all nonterminals. As implied by the production rule, the class specification allows for much more information than just a class name. Figure 4.4 shows the EIS interface for constructing a class.

4.2.1.1 Class Attributes

The EIS class specification syntax allows the definition of one or more properties within a class definition. These properties denote characteristics of the class, and can be categorized as *state variables*, *constants*, *types* or *functions*. These properties are specified by the EIS user by clicking on the "Class Attributes" button. (See Figure 4.4) *State variables* represent the data associated with any instance of the class. Every state variable has a

```
rule classdefn : ‘class’ id1 ‘of’ id2
                 interface_uses_section
                 forward_decl_section
                 bind_param_section
                 decl_param_section
                 description
                 mixed_decl_list
                 bind_stvar_section
                 keywords_section
                 document_section
                 ‘endclass’
```

Figure 4.3 Production rule for a class definition



Class Components	Description
Class Interface	(optional) Explicit dependencies on other class definitions
Class Attributes	Visible types, variables, constants and functions
Class Parameter Decl.	(optional) Parameerized parts
Inherited Param. Bindings	(optional) Bindings for parent class parameters
State Variable Bindings	(optional) Bindings for state variables
Documents	(optional) List of related documents
Keywords	(optional) List of related keywords

Figure 4.4 Interface for creating a Class

particular type, for example:

```
VAR var1 OF integer
VAR var2 OF char
```

Constants can be defined by the EIS user to provide alternative names for values. For example:

```
CONST con1 : string := "Trish"
CONST con2 : boolean := false
```

The EIS language supports several *data types* and *type constructors*. The predefined simple types are "integer", "real", "char", "string", and "boolean". The type constructors are "array", "record", "set" and "enumeration". The EIS user can construct a structured type from the simple types or structured types themselves. For example:

```
TYPE type1 := integer
TYPE type2 := (id1, id2, id3)
TYPE type3 := array [1..10] OF real
```

As mentioned before, data transformation functions, have two components: a function specification (i.e., its name, argument types and return type), and a function method (i.e., executable program). Only the function specification is part of the class interface. For example:

```
FUNCTION func1 (char, real) : integer
```

4.2.1.2 Class Interface

The EIS user can specify classes in the interface-uses section by clicking on the "Class Interface" button. (See Figure 4.4) This section lists all the classes upon which the definition of the current class relies. Ancestor class properties are automatically inherited, *so interface-*

uses is generally used to list only non-ancestor class dependencies.

4.2.1.3 Class Parameter Declarations

Class parameterization allows the EIS user to formulate meaningful class hierarchies, in a manner analogous to formal argument declarations in function specification. The formal parameters for a class can be of type *class, type, constant or function*. The EIS user can declare parameters by clicking on the **"Class Parameter Declarations"** button. (See Figure 4.4) The following is an example of some parameter declarations:

param1 : **class**
param2 : **type**

4.2.1.4 Inherited Parameter Bindings

Once a parameter has been declared, it must eventually be bound to an actual class, type, function or constant. We can specify an actual parameter value for a formal parameter in an instance or subclass of a parameterized class. The EIS user can assign parameters by clicking on the "Inherited Parameter Bindings" button. (See Figure 4.4) The following is an example of some parameter assignments:

param1 := Erdas_Lan_Class
param2 := char

4.2.1.5 State Variable Bindings

State variables defined in a parent can also be bound in an instance or subclass. This binding is interpreted as providing an initial value for the state variable in question. The EIS user can bind state variables by clicking on the "**State Variable Bindings**" button. (See Figure 4.4) The following is an example of binding state variables:

flag := true
a := 15.02

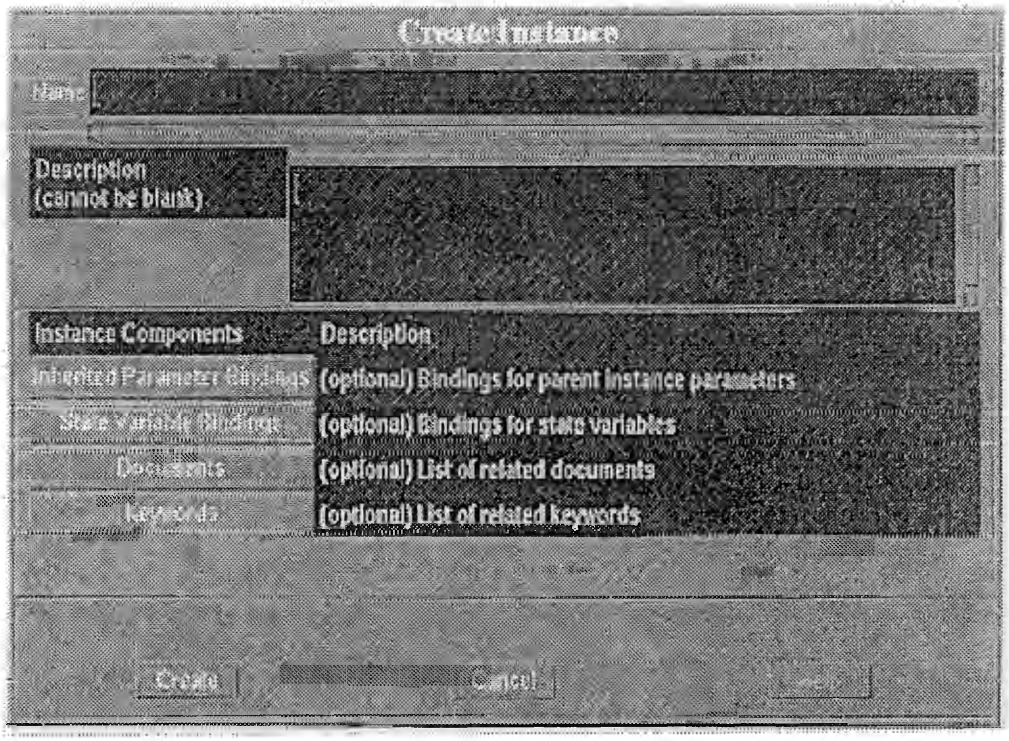
4.2.1.6 Documents and Keywords

The EIS user can specify the location of documents related to the current EIS object, or put short documentation information within the object specification itself by clicking on the "**Documents**" button. (See Figure 4.4) The "**Keywords**" button is used to specify keywords for EIS entities to support more ambitious network search functionality.

Figures 4.5 and 4.6 show the EIS interface for creating an instance and method repectively. The components of the instance and method differ from the components of the class, so the syntax of the description of EIS instances and EIS methods differs from that of EIS classes. However, most of the components listed in the instance or method description can be found as components in the class description. Therefore, the syntax of these individual components is the same as those found in the class description but the syntax for the instance, method, and class objects as a whole are not the same.

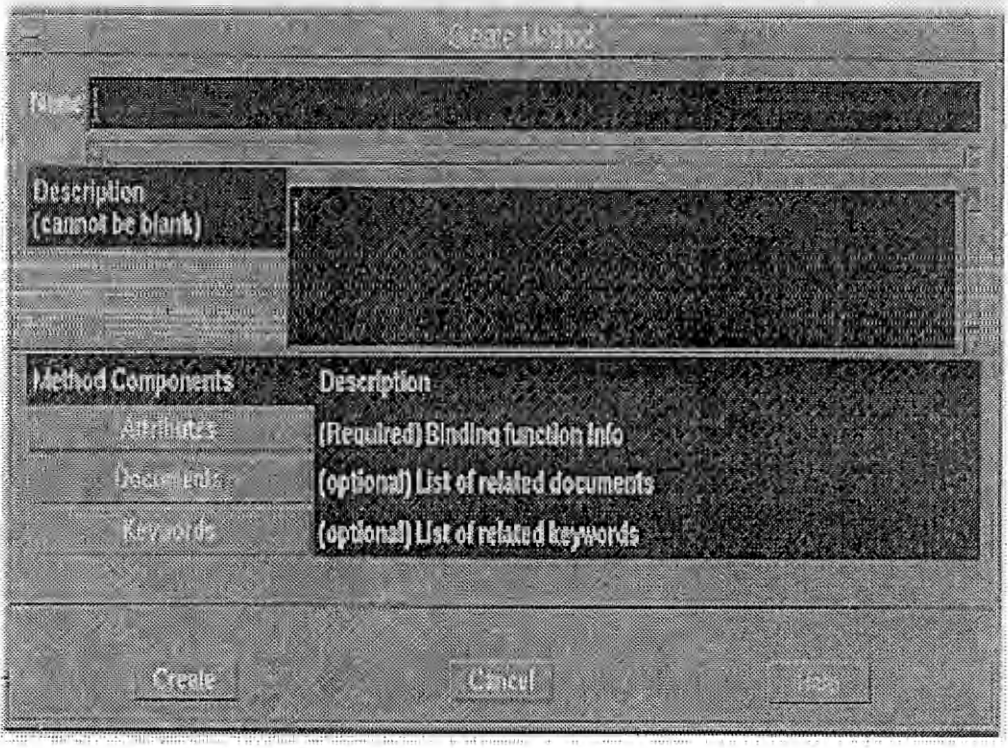
4.3 Semantic Checking in EIS

We have just seen what the EIS language looks like, the *syntax* of the language. Now lets take a look at what it means, the *semantics* of the language. As mentioned above, the EIS language supports the *definition of properties, interface-use, class parameterization,*



Instance Components	Description
Inherited Parameter Bindings	(optional) Bindings for parent instance parameters
State Variable Bindings	(optional) Bindings for state variables
Documents	(optional) List of related documents
Keywords	(optional) List of related keywords

Figure 4.5 Interface for creating an Instance



Method Components	Description
Attributes	(Required) Binding function Info
Documents	(optional) List of related documents
Keywords	(optional) List of related keywords

Figure 4.6 Interface for creating a Method

parameter and state variable binding, property inheritance, etc. In order to use the EIS language appropriately, constraints must be satisfied. Below is a list of the semantic checking that must be done to construct a well-formed class hierarchy in EIS [6].

1. All class instance and method names should be unique within a class hierarchy.
2. Each property defined locally within a class C_x must be locally unique, i.e., defined only once in C_x.
3. A formal class parameter P_i declared in class C_x must be of type *class, type, function* or *const*.
4. In function definition F_i within a class C_x, the arguments and the return value must be a class, a basic type or constructed type.
5. A class parameter P_i must be bound to an identifier of the same type (i.e., *class, type, function,* or *const*).
6. Each class name C_i used in the definition of class C_x should be listed in the "forward declarations", listed in the "interface uses", locally defined within C_x, or be defined on the path from C_x to the hierarchy root (i.e., an ancestor class name).
7. Each class C_i named in the "interface uses" of class C_x should exist as a class in the same hierarchy as C_x, be named in the "forward declarations" of C_x, or if C_i exists in another hierarchy H_j, then it should be defined as $H_j.C_i$ in the "interface uses".
8. Including the class name C_i in the "interface uses" or "forward declarations" of class C_x makes C_i visible in C_x, but does not make any properties of C_i visible in C_x. Thus, a reference to property "g" of C_i in C_x must be written in a qualified form as "C_i.g". In contrast, properties of ancestor classes of C_x are visible in C_x, and can be written without qualification.
9. A formal class parameter P_i declared in class C_x, must be unique along the path from C_x to the class hierarchy root.
10. A formal class parameter name P_i assigned in class C_x must be declared in an ancestor class C_y of C_x, where $C_y \neq C_x$, and cannot be assigned in any class on the path from C_x to C_y.
11. A formal class parameter name P_i assigned in instance I_x must be declared in an ancestor class C_y of I_x and cannot be assigned in any class on the path from I_x to C_y.

12. For an instance definition I_x, all formal class parameters defined on the path from the hierarchy root to I_x must be assigned on that path or in I_x.

In the current version of EIS, a parser and semantic analyzer performs all the syntactic checking in an ad hoc manner. Initially, there was no formal definition of the conditions listed above. An attribute grammar was created to formalize the condition checking, and replace the ad hoc implementation embedded in the parser/analyzer.

4.4 The EIS Attribute Grammar

The first attribute grammar for EIS was built several years ago as part of this thesis. Vijayant Palaiya did an implementation based on that language specification [6]. He also implemented a few grammatical changes, due to request by EIS users for modified syntactic and semantic aspects. The EIS language has thus evolved into a language with a more complete syntactic structure and a more extensive specification of static semantics. Description of the newest EIS language specification, based on the newest EIS attribute grammar completes the thesis project presented here.

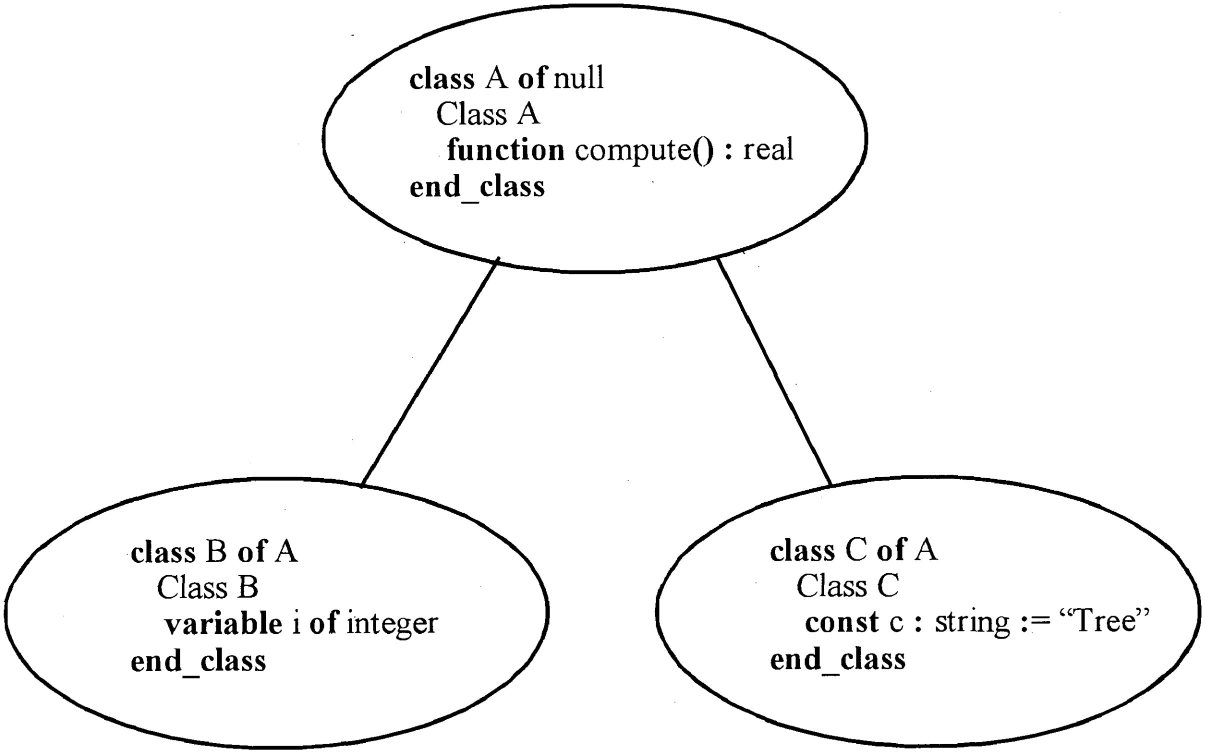
As background each semantic constraint in the EIS language can be formally specified by a boolean attribute and evaluation rules defined by the attribute grammar. Whether or not a semantic condition is met is determined by the evaluation of a boolean attribute during a derivation: *true* indicates the constraint is met, and *false* indicates that the constraint is not met.

The EIS Attribute Grammar is divided into an upper part and a lower part. The upper part of the attribute grammar defines attributes appropriate to the structure of a whole class hierarchy, and uses global attributes to perform the semantic checking based on parent-child, ancestor-descendant, and interface-uses relationships. The lower part of the attribute grammar defines attributes appropriate to the structure of individual hierarchy nodes, and uses local attributes to perform semantic checking on local uses of identifiers. Key local values are also passed to the upper part of the attribute grammar. Figure 4.7 is an EIS hierarchy that is used as an example throughout the rest of this chapter.

The lower part of the attribute grammar constructs a symbol table (the attribute *SymTab*) for each node, storing the name of all identifiers defined within the node, their type, and other relevant information. Identifiers include the names of classes, instances, methods, state variables, constants, types, functions and parameters. Figure 4.8 shows the attributed derivation tree for the node that represents class "A" in our example. The tree illustrates the computation of attribute values, as well as those values that are used to check the semantic constraints specified by the grammar. Every attribute in the derivation is synthesized.

The nonterminal "classdefn" has a key attribute called *SymTab*. *SymTab* represents the symbol table for the class node "A" in the EIS hierarchy. *SymTab* contains the identifier definitions for that node. The values of *SymTab* are computed by semantic rules in the descendants of "classdefn".

The nonterminal "functiondefn" has an attribute called *SymRec*. *SymRec* represents a symbol table record, and consists of a 4-tuple (*Name, Type, TypeDenoter, InList*). *Name* is the name of the identifier in the symbol table. In our example *Name* has the value "compute", which is the name of the function. *Type* is the type of property the identifier represents. The identifier represents a function so *Type* has the value of FUNC. *TypeDen*



```
class A of null
  Class A
   function compute() : real
end_class
```

```
class B of A
  Class B
   variable i of integer
end_class
```

```
class C of A
  Class C
   const c : string := “Tree”
end_class
```

Figure 4.7 EIS Hierarchy

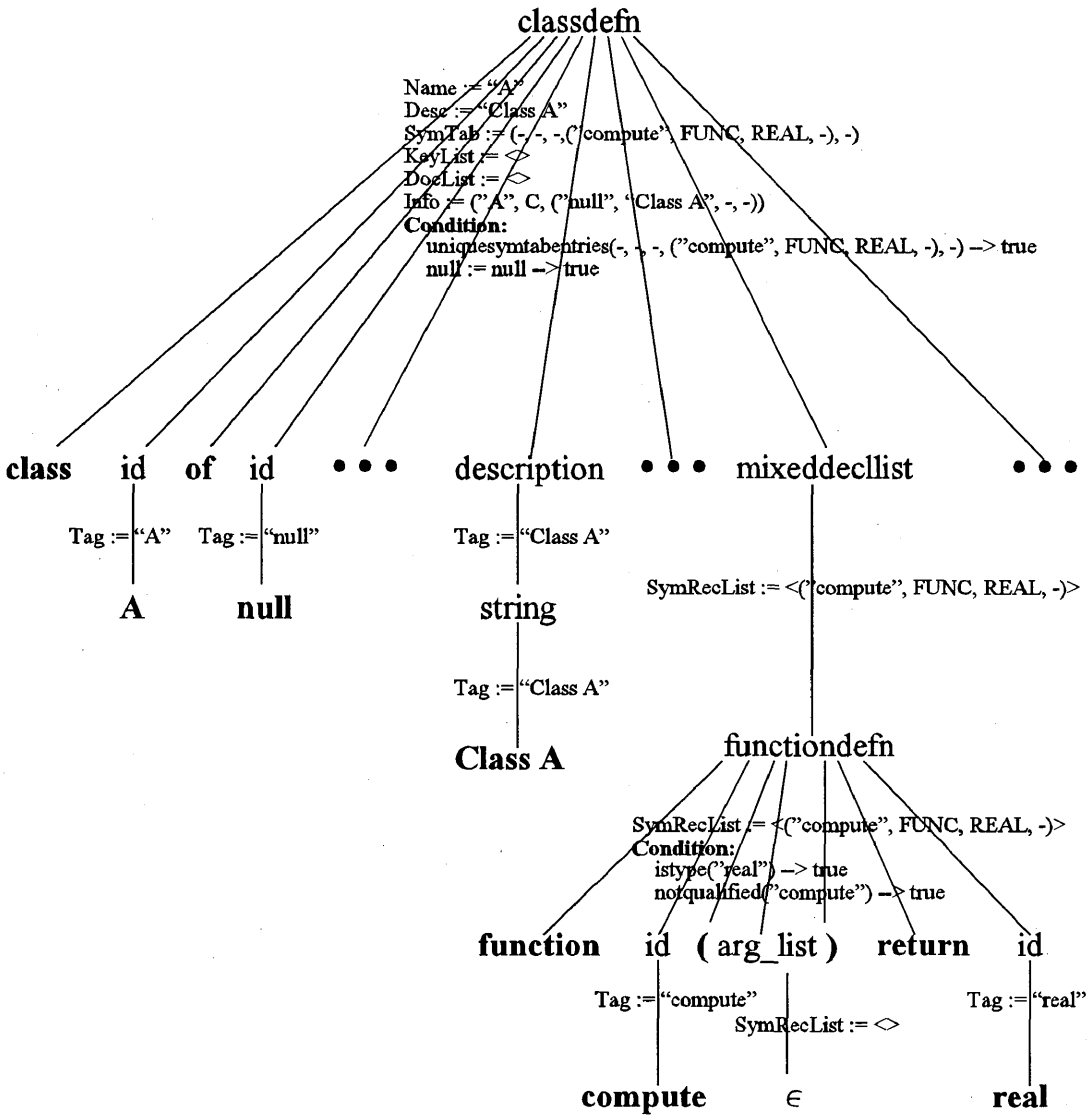


Figure 4.8 Attributed Tree for class “A”

represents the return type of the function, which can either be a primitive type or a constructed type. In the case of a constructed type, this attribute refers to a symbol table record, which contains information of the constructed type. *InList* refers to the list of argument types, which can also be a primitive type or a constructed type. If the return type is not a primitive or constructed type, the condition *istype(id2.Tag)*, evaluates to *false* which indicates the function definition is not legal. If the name of the function is qualified, the condition *notqualified(id1.Tag)*, evaluates to *false* which also indicates the function definition is not legal.

Eventually symbol table records from different property definitions of class "A" are combined to form the *SymTab* attribute as shown in Figure 4.9. Each property defined locally within class "A" must be locally unique. The condition *uniquesymtabentries(SymTab)*, checks for uniqueness of names of the identifiers. The attributed trees for classes "B" and "C" are shown in Figures 4.10 and Figure 4.11 respectively.

The upper part of the attribute grammar has an important synthesized attribute *SynST*. *SynST* is associated with every node in the hierarchy, containing the symbol table of the node itself and the symbol tables of all descendant nodes. Each symbol table in *SynST* is represented by *(Name, Type, SymTab),* where *Name* is the name of the node, *Type* is the type of the node ("class", "instance", or "method"), and *SymTab* is the symbol table of that node in the hierarchy. The lower part of the attribute grammar computes the values for individual *SymTab* entities. Only the root node of the hierarchy contains the attribute *GbST*. *GbST* contains the symbol tables of all the objects in the hierarchy. The condition *validate()* uses the global symbol table to check the semantic correctness of the whole hierarchy definition.

```
rule classdefn : 'class' id1 'of' id2
                 interfaceusessection
                 forwarddeclsection
                 bindparamsection
                 declparamsection
                 description
                 mixeddecllist
                 bindstvarsection
                 keywordssection
                 documentsection
                 'endclass';
semantic
        classdefn.Name := id1.Tag;
        classdefn.Desc := description.Tag;
        classdefn.SymTab := append((bindparamsection.SymRecList,declparamsection,
                 SymRecList),forwarddeclsection.SymRecList,interfaceusessection.SymRec
                 List,
                 mixeddecllist.SymRecList,bindstvarsection.SymRecList);
        classdefn.KeyList := keywordssection.KeyList;
        classdefn.DocList := documentsection.DocList;
        classdefn.Info :=
(classdefn.Name,C,(classdefn.Parent,classdefn.Desc,classdefn.KeyList,
        classdefn.DocList));
condition
        uniquesymtabentries(classdefn.SymTab);
        classdefn.Parent = id2.Tag;
end;
```

Figure 4.9 Attribute Grammar Specification for a “classdefn”

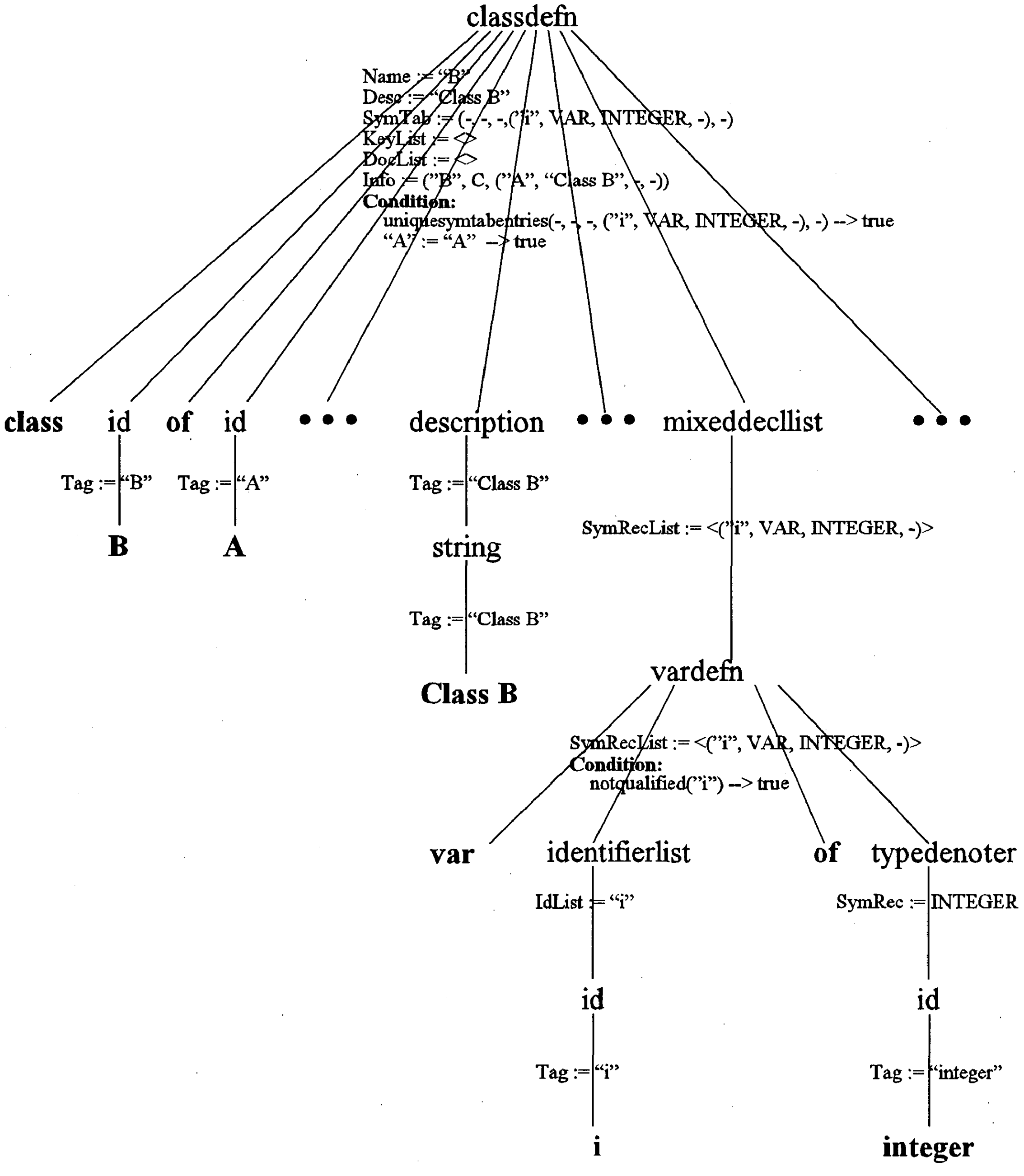


Figure 4.10 Attributed Tree for class "B"

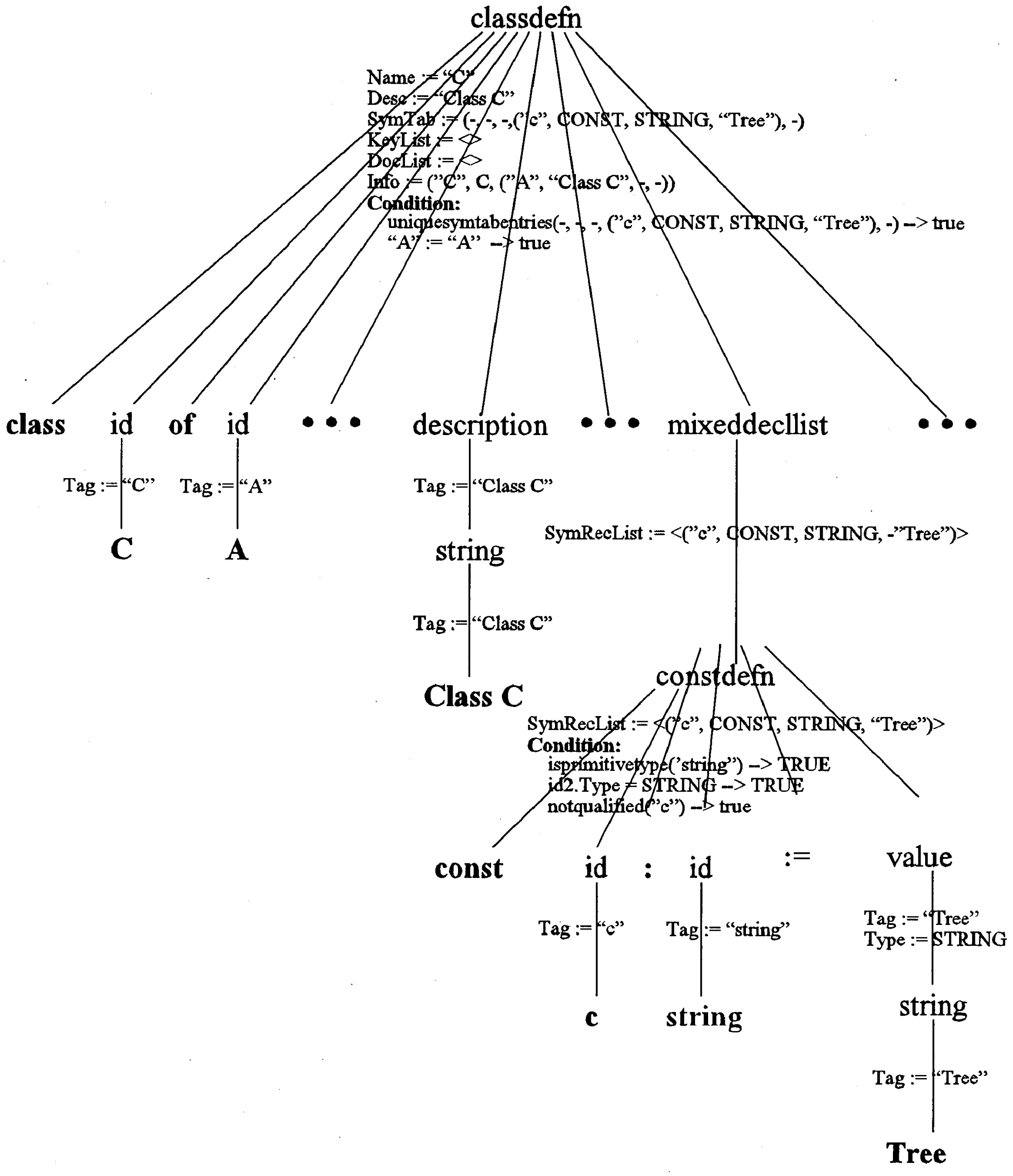


Figure 4.11 Attributed Tree for class "C"

Figure 4.12 shows the attributed derivation tree for the upper part of the EIS hierarchy in our example.

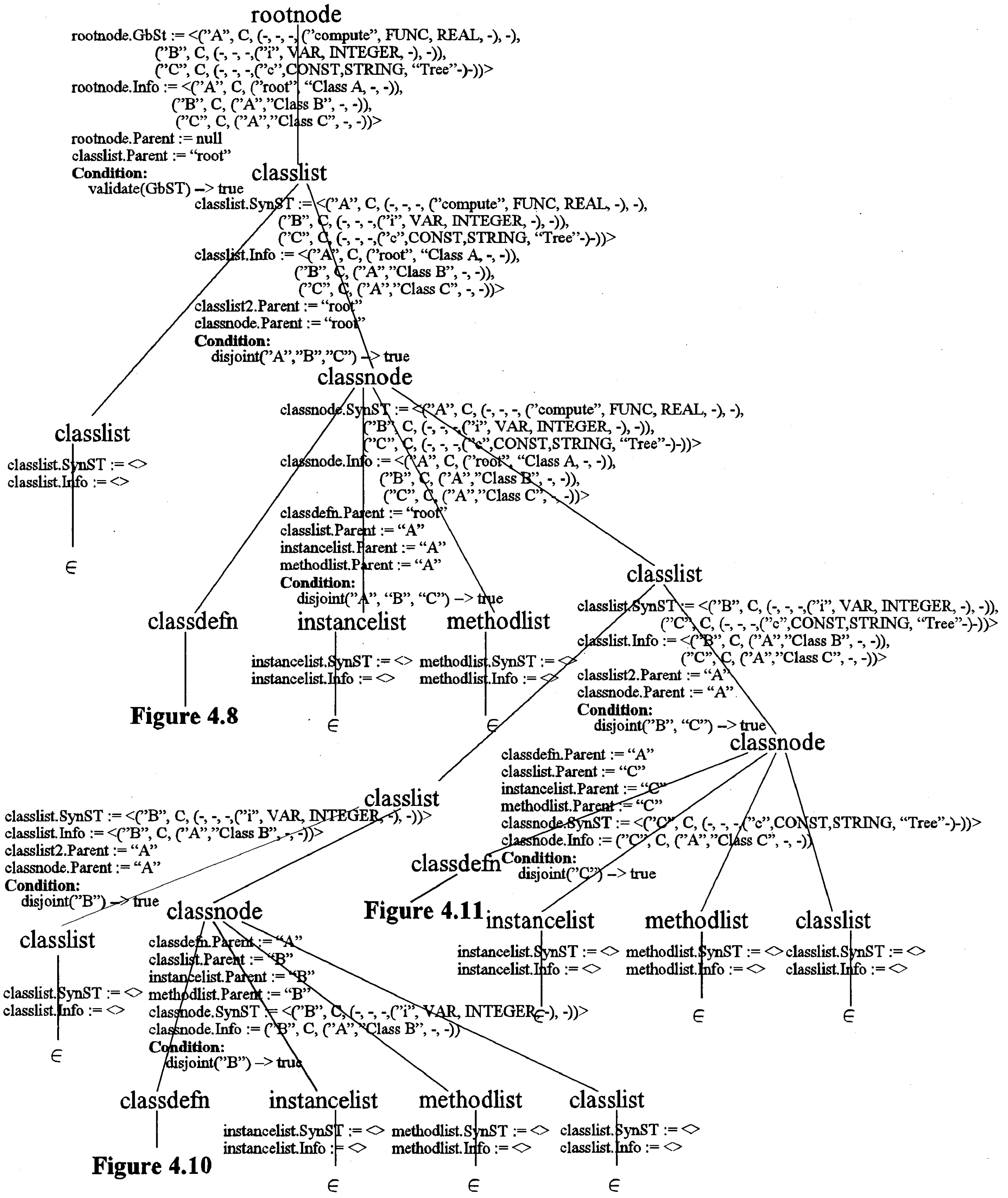


Figure 4.12 Attributed Tree for Upper Part of EIS Hierarchy

Chapter 5

Execution Results

5.1 A Simple Example

The simple attribute grammar listed in Appendix B was taken from Pagan [4]. The grammar defines an integer constant. With the single attribute "val", the attribute grammar ensures that no syntactically correct numeral can exceed 32 bits. The grammar has twelve productions, two symbols, one attribute, and three symbol/attribute occurrences.

The visit sequences for the attribute grammar are listed below. For each production in the grammar, a visit sequences is given. There are three possible actions in a visit sequence, move to a nonterminal, evaluate a symbol/attribute occurrence, or evaluate a condition. Moving to a nonterminal is indicated by the word "MOVE" followed by the nonterminal to be visited, followed by the number of times that nonterminal has been visited within that particular sequence. Evaluating a symbol/attribute occurrence is indicated by the word "EVAL" followed by the symbol/attribute occurrence. Evaluating a condition is indicated by the word "COND" followed by the number of the condition to be evaluated.

```
Sat Sep 12 19:39:46 PDT 1998
***VISIT SEQUENCES***
Production: 0
MOVE DIGIT 1
EVAL NUMERAL.VAL
MOVE NUMERAL 1
Production: 1
MOVE DIGIT 1
MOVE NUMERAL2 1
EVAL NUMERAL.VAL
COND 1
MOVE NUMERAL 1
Production: 2
EVAL DIGIT.VAL
MOVE DIGIT 1
Production: 3
EVAL DIGIT.VAL
```

```
MOVE DIGIT 1
Production: 4
EVAL DIGIT.VAL
MOVE DIGIT 1
Production: 5
EVAL DIGIT.VAL
MOVE DIGIT 1
Production: 6
EVAL DIGIT.VAL
MOVE DIGIT 1
Production: 7
EVAL DIGIT.VAL
MOVE DIGIT 1
Production: 8
EVAL DIGIT.VAL
MOVE DIGIT 1
Production: 9
EVAL DIGIT.VAL
MOVE DIGIT 1
Production: 10
EVAL DIGIT.VAL
MOVE DIGIT 1
Production: 11
EVAL DIGIT.VAL
MOVE DIGIT 1
Sat Sep 12 19:39:47 PDT 1998
```

It is easy to look at this grammar and the results and determine the visit sequences are correct. That is, they provide a way to correctly evaluate all attributes for any valid derivation tree. The runtime for this particular attribute grammar was approximately 1 second.

5.2 A More Complicated Example

The attribute grammar listed in Appendix A was taken directly from Kastens [2]. The grammar is a simple expression language with nine productions, eight attributes, eight symbols, and twenty-three symbol/attribute occurrences. This grammar provides us a means to verify that our implementation is correct, since the visit sequences (listed after the attribute grammar in Appendix A) match up with those derived by Kastens [2]. The runtime for this particular attribute grammar was approximately one minute and twenty seconds, a significant increase over the attribute grammar in Appendix B. This is due to the greater number of symbol/attribute occurrences. As the number of symbol/attribute occurrences increase the time to manipulate the datasets increases exponentially.

5.3 The EIS Attribute Grammar

The EIS Attribute Grammar (listed in Appendix C) contains twenty-one attributes, seventy-nine symbols, one hundred productions, and one hundred twenty-nine symbol/attribute occurrences. A machine with one hundred twenty-eight megabytes of RAM could not meet the memory requirements of running the analyzer with the EIS attribute grammar.

A second version of the analyzer was written to accommodate very large attribute grammars. In the new version, data originally stored in three-dimensional Vectors in memory is now written as a group of files, where each file contains a two-dimensional Vector. This version of the analyzer works correctly, however the runtime increases dramatically. For example, the simple attribute grammar listed in Appendix B took one minute and twenty seconds to run with this version, i.e., approximately one minute and nineteen seconds longer than the first version.

The more complex attribute grammar listed in Appendix A took eight hours, forty-one minutes and fifty-one seconds with the new version, approximately eight hours, forty minutes and thirty-one seconds longer than the original version. By looking at the results it was obvious the EIS attribute grammar would take weeks to run through the analyzer. The time to produce the needed visit sequences was not practical. Therefore a third version of the analyzer was written.

As mentioned before, version 2 stores data as a two dimensional Vector in file. To reduce the amount of time needed to maintain a two dimensional Vector, version 3 stores data as a one dimensional Vector. All the information is still maintained, just in a different data structure. The simple attribute grammar listed in Appendix B took one minute and two seconds to run. The more complex attribute grammar listed in Appendix A took seven hours, thirty-three minutes and fifty seconds to run. The performance of version 3 is significantly better than that of version 1, yet not enough to be used for practical purposes on large attribute grammars. Figure 5.1 summarizes the execution results.

	Version 1	**Version 2**	**Version 3**
Appendix B	1 sec.	1 min. 20 sec.	1 min. 2 sec.
Appendix A	1 min. 20 sec.	8 hours 41 min. 51 sec.	7 hours 33 min. 50 sec.

Figure 5.1 Summary of Execution Results

Due to time constraints, a fourth implementation was never written. After analyzing the dependency relations of several attribute grammars it is noted that only a small portion of the dependency graphs are marked with a dependency. A possible solution to the memory problem could be to just keep track of the marked dependencies. A large portion of the analyzer would have to be rewritten if a new data structure was used. Most of the procedures in the analyzer access or manipulate the data structures that represent the dependency relations.

5.4 Dividing the EIS Attribute Grammar

The EIS attribute grammar was divided into four sections. Each section was run through the analyzer individually. The break points were productions that contained only sythesized attributes and control only needed to be passed to descendants once. Dividing a grammar up in such a way has no affect on the final visit sequences, decreases the run time exponentially, and allows us to analyze a large attribute grammar. Each section of the EIS attribute grammar was successfully run through the analyzer. The visit sequences for each section are listed after the attribute grammar in Appendix C.

Chapter 6

Analysis of Results

6.1 The EIS Attribute Grammar

The EIS hierarchy in Figure 4.7 was derived and attributes were evaluated according to the visit sequences produced by the analysis algorithm. Figures 6.1, 6.2, 6.3, and 6.4 show the evaluation order from left to right. For example, in Figure 6.1 a move is made from the symbol *classdefn* to it's descendant *id*. Another move is made from *id* to the terminal *A*. When *id* receives control again attribute *id.Tag* is evaluated and a move is made up to it's ancestor *classdefn*. The attribute *classdefn.Name* is evaluated and control is passed down to the nonterminal *mixeddecllist*. Attributes listed in the figures without a symbol are assumed to be synthesized.

Every attribute and condition in the derivation tree is evaluated correctly. All dependencies are reflected in the visit sequences. All constraints (listed in section 4.3) intended for the hierarchy are met: all class names are unique, each property defined locally within a class is locally unique, the arguments and return value of a function is a class, basic type or constructed type.

6.2 Attribute Evaluator

An attribute evaluator must be implemented to efficiently evaluate the attributes for any given derivation. The work from this thesis provides a critical piece of data for an

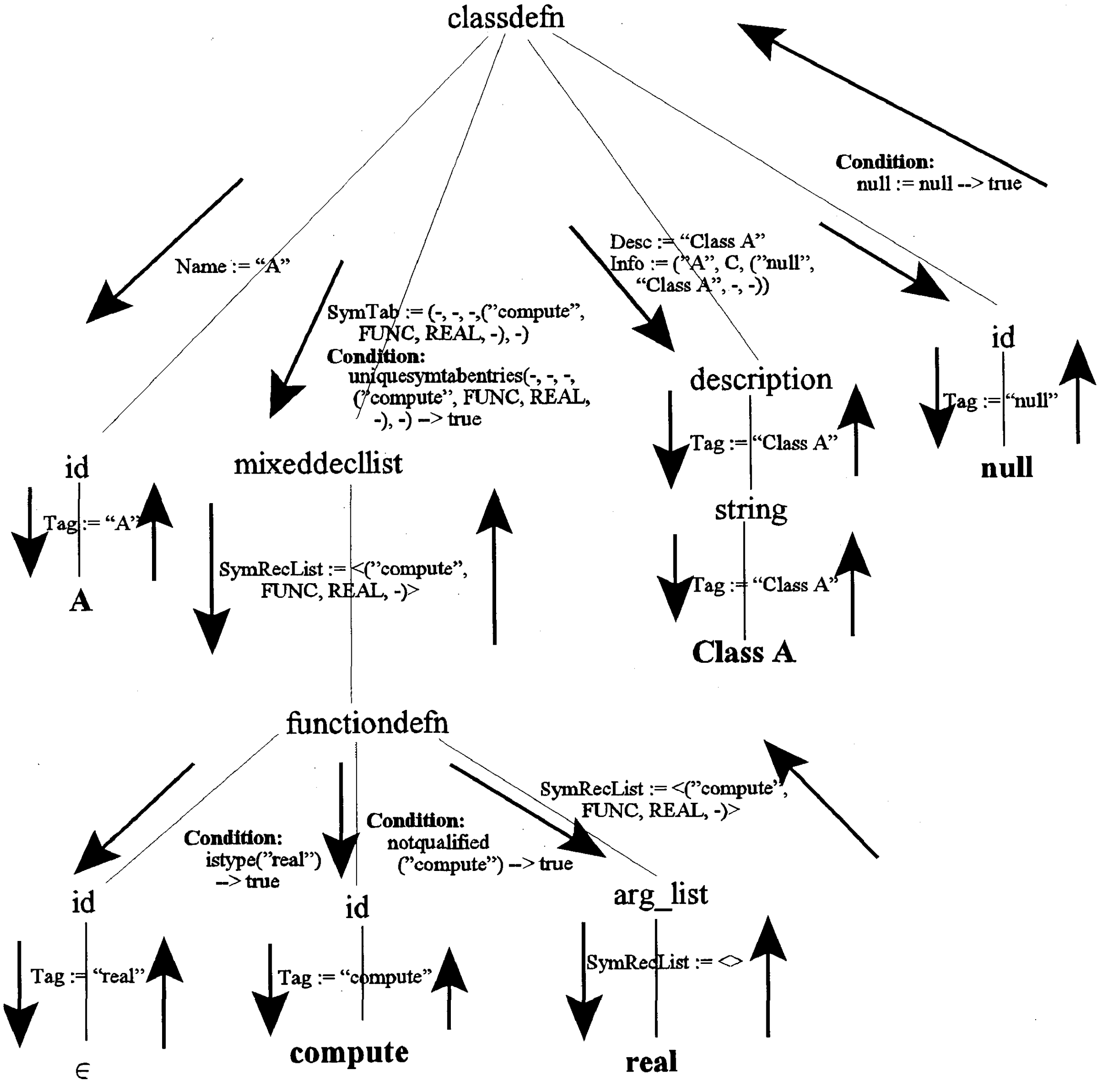


Figure 6.1 Evaluation of class "A"

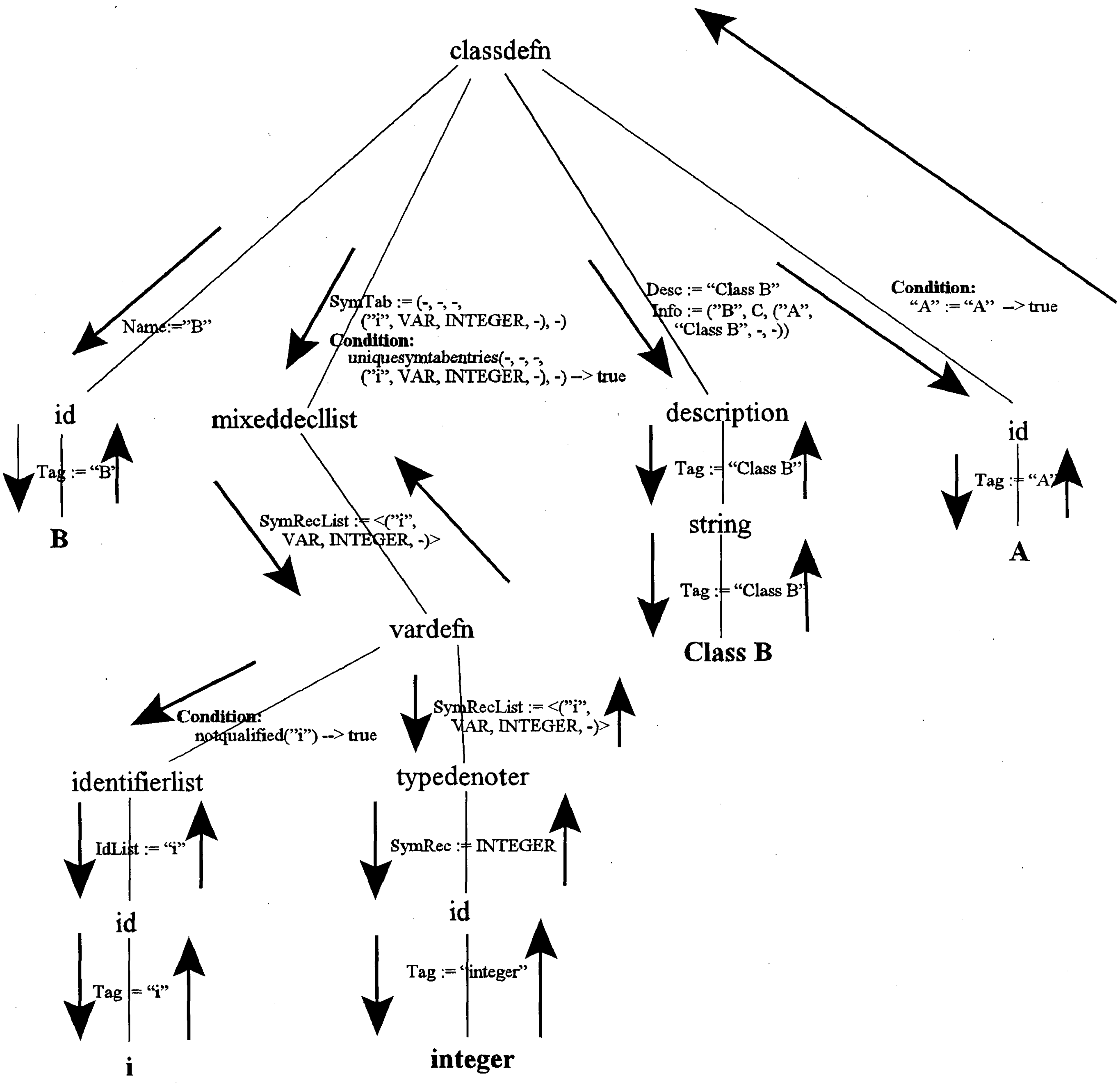


Figure 6.2 Evaluation of class "B"

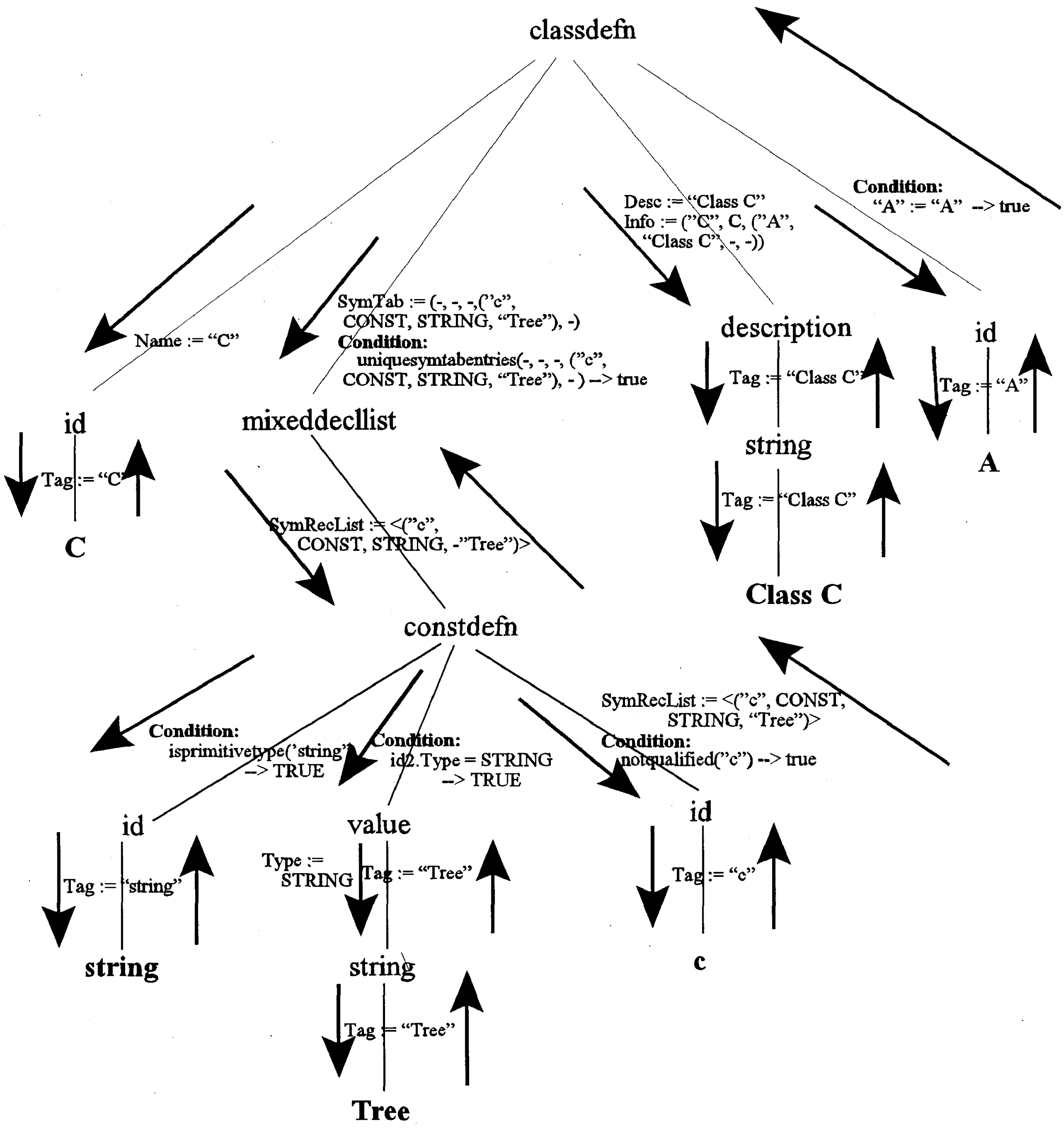


Figure 6.3 Evaluation of class "C"

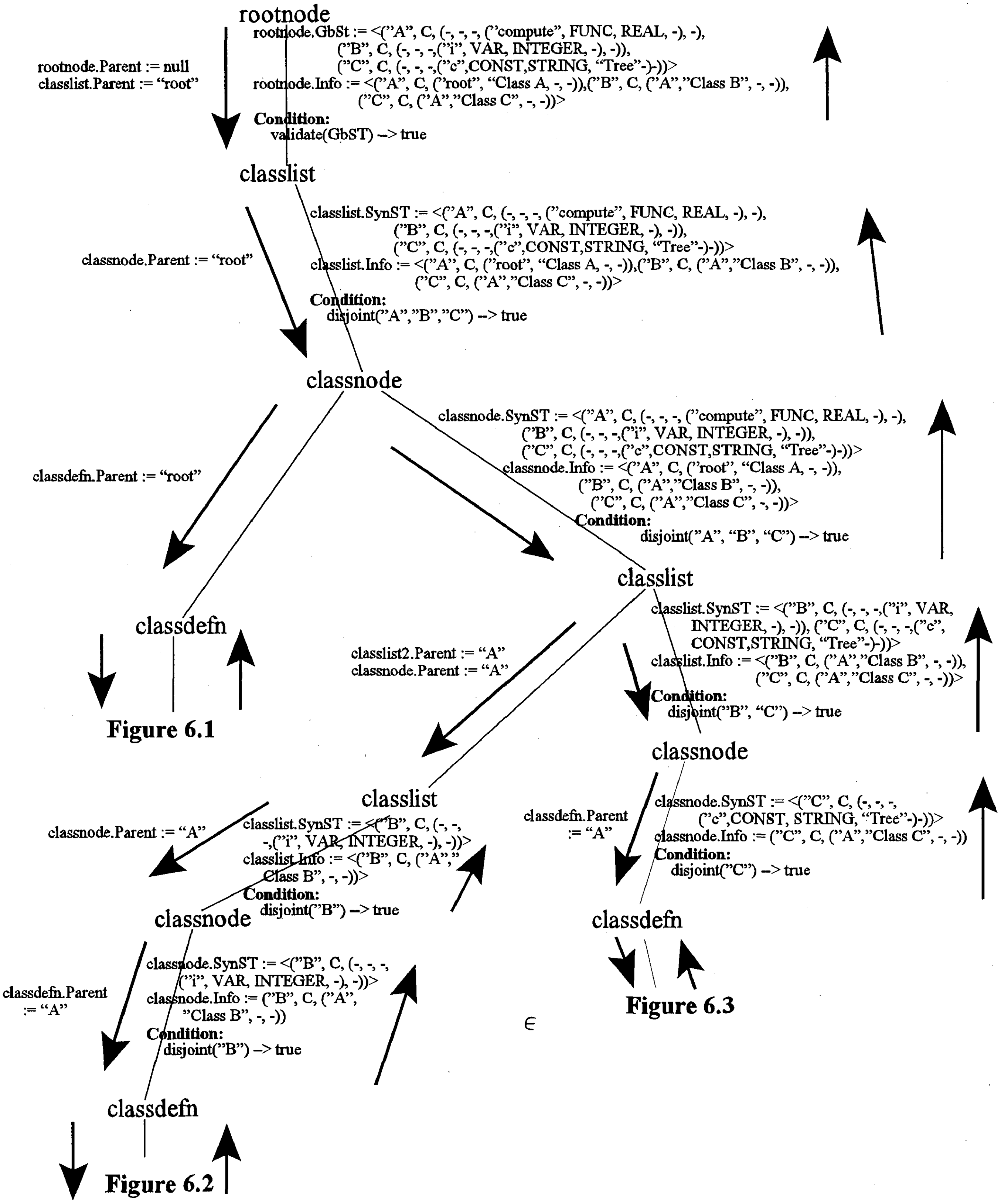


Figure 6.4 Evaluation of Upper Part of EIS Hierarchy

attribute evaluator, the visit sequences. Kastens [2] explains four ways an attribute evaluator could be implemented: using coroutines, recursive procedures, stack automaton, or finite automaton. Constructing an attribute evaluator can be a possible thesis project for a future computer science student.

6.3 Conclusion

In conclusion, the EIS attribute grammar gives a formal definition of both the syntactic and semantic checking that must be done to process the EIS object description language. With an efficient attribute evaluator the formal specification can be used for implementation of EIS language processing tools. The EIS attribute grammar is well-defined, ordered, and meets the intent of the EIS user.

Appendix A

```
access          set
description     strseq
primode         string
postmode        string
evaluable       boolean
value           string
id              string
val             string
%

include
identify
isdefined
widen
add
%

rule program : primary;
semantic
        primary.access := 0;
        primary.postmode := primary.primode;
end;

rule primary : '(' declaration ';' assignment ')';
semantic
        declaration.access := primary.access;
        assignment.access := include(primary.access,declaration.description);
        primary.primode := assignment.primode;
        assignment.postmode := primary.postmode;
        primary.evaluable := false;
        primary.value := undefined;
end;

rule primary : identifier;
semantic
        primary.primode := identify(identifier.id,primary.access);
        primary.evaluable := false;
        primary.value := undefined;
condition
        isdefined(identifier.id,primary.access);
end;

rule primary : intconstant;
semantic
        primary.primode := int;
        primary.evaluable := true;
        primary.value := if primary.postmode = real
                         then widen(intconstant.value) else intconstant.value fi;
end;
```

```
rule primary : realconstant;
semantic
        primary.primode := real;
        primary.evaluable := true;
        primary.value := realconstant.value;
end;

rule assignment : identifier ':=' expression;
semantic
        expression.access := assignment.access;
        assignment.primode := identify(identifier.id, assignment.access);
        expression.postmode := assignment.primode;
condition
        isdefined(identifier.id, assignment.access) and not (expression.primode = real and
expression.postmode = int);
end;

rule expression : expression2 '+' primary;
semantic
        expression2.access := expression.access;
        primary.access := expression.access;
        expression.primode := if expression2.primode = int and primary.primode = int then int else real
fi;
        expression2.postmode := expression.primode;
        primary.postmode := expression.primode;
        expression.evaluable := expression2.evaluable and primary.evaluable;
        expression.value := if expression.evaluable then add(expression2.value, primary.value) else
undefined fi;
end;

rule expression : primary;
semantic
        primary.access := expression.access;
        primary.postmode := expression.postmode;
        expression.primode := primary.primode;
        expression.evaluable := primary.evaluable;
        expression.value := primary.value;
end;

rule declaration : 'new' identifier ':=' expression;
semantic
        expression.access := declaration.access;
        declaration.description := (identifier.id, expression.primode);
        expression.postmode := expression.primode;
end;
```

```
Sat Sep 12 19:40:51 PDT 1998
***VISIT SEQUENCES***
Production: 0
EVAL PRIMARY.ACCESS
MOVE PRIMARY 1
EVAL PRIMARY.POSTMODE
MOVE PRIMARY 2
MOVE PROGRAM 1
Production: 1
EVAL DECLARATION.ACCESS
MOVE DECLARATION 1
EVAL ASSIGNMENT.ACCESS
MOVE ASSIGNMENT 1
EVAL PRIMARY.PRIMODE
MOVE PRIMARY 1
EVAL ASSIGNMENT.POSTMODE
EVAL PRIMARY.EVALUABLE
EVAL PRIMARY.VALUE
MOVE ASSIGNMENT 2
MOVE PRIMARY 2
Production: 2
MOVE IDENTIFIER 1
EVAL PRIMARY.PRIMODE
COND 1
MOVE PRIMARY 1
EVAL PRIMARY.EVALUABLE
EVAL PRIMARY.VALUE
MOVE PRIMARY 2
Production: 3
EVAL PRIMARY.PRIMODE
MOVE PRIMARY 1
EVAL PRIMARY.EVALUABLE
MOVE INTCONSTANT 1
EVAL PRIMARY.VALUE
MOVE PRIMARY 2
Production: 4
EVAL PRIMARY.PRIMODE
MOVE PRIMARY 1
EVAL PRIMARY.EVALUABLE
MOVE REALCONSTANT 1
EVAL PRIMARY.VALUE
MOVE PRIMARY 2
Production: 5
EVAL EXPRESSION.ACCESS
MOVE IDENTIFIER 1
EVAL ASSIGNMENT.PRIMODE
MOVE EXPRESSION 1
EVAL EXPRESSION.POSTMODE
COND 1
MOVE ASSIGNMENT 1
MOVE EXPRESSION 2
```

```
MOVE ASSIGNMENT 2
Production: 6
EVAL PRIMARY.ACCESS
EVAL EXPRESSION2.ACCESS
MOVE PRIMARY 1
MOVE EXPRESSION2 1
EVAL EXPRESSION.PRIMODE
EVAL PRIMARY.POSTMODE
EVAL EXPRESSION2.POSTMODE
MOVE PRIMARY 2
MOVE EXPRESSION 1
MOVE EXPRESSION2 2
EVAL EXPRESSION.EVALUABLE
EVAL EXPRESSION.VALUE
MOVE EXPRESSION 2
Production: 7
EVAL PRIMARY.ACCESS
MOVE PRIMARY 1
EVAL EXPRESSION.PRIMODE
MOVE EXPRESSION 1
EVAL PRIMARY.POSTMODE
MOVE PRIMARY 2
EVAL EXPRESSION.EVALUABLE
EVAL EXPRESSION.VALUE
MOVE EXPRESSION 2
Production: 8
EVAL EXPRESSION.ACCESS
MOVE EXPRESSION 1
EVAL EXPRESSION.POSTMODE
MOVE IDENTIFIER 1
EVAL DECLARATION.DESCRIPTION
MOVE EXPRESSION 2
MOVE DECLARATION 1
Sat Sep 12 19:42:11 PDT 1998
```

Appendix B

```
val          string
%
%
rule numeral : digit;
semantic
      numeral.val := digit.val;
end;

rule numeral : numeral2 digit;
semantic
      numeral.val := 10 * numeral2.val + digit.val;
condition
      numeral.val <= 2147483647;
end;

rule digit : '0';
semantic
      digit.val := 0;
end;

rule digit : '1';
semantic
      digit.val := 1;
end;

rule digit : '2';
semantic
      digit.val := 2;
end;

rule digit : '3';
semantic
      digit.val := 3;
end;

rule digit : '4';
semantic
      digit.val :=4;
end;

rule digit : '5';
semantic
      digit.val := 5;
end;

rule digit : '6';
semantic
      digit.val := 6;
end;
```

```
rule digit : '7';
semantic
      digit.val := 7;
end;

rule digit : '8';
semantic
      digit.val := 8;
end;

rule digit : '9';
semantic
      digit.val := 9;
end;
```

```
Sat Sep 12 19:39:46 PDT 1998
***VISIT SEQUENCES***
Production: 0
MOVE DIGIT 1
EVAL NUMERAL.VAL
MOVE NUMERAL 1
Production: 1
MOVE DIGIT 1
MOVE NUMERAL2 1
EVAL NUMERAL.VAL
COND 1
MOVE NUMERAL 1
Production: 2
EVAL DIGIT.VAL
MOVE DIGIT 1
Production: 3
EVAL DIGIT.VAL
MOVE DIGIT 1
Production: 4
EVAL DIGIT.VAL
MOVE DIGIT 1
Production: 5
EVAL DIGIT.VAL
MOVE DIGIT 1
Production: 6
EVAL DIGIT.VAL
MOVE DIGIT 1
Production: 7
EVAL DIGIT.VAL
MOVE DIGIT 1
Production: 8
EVAL DIGIT.VAL
MOVE DIGIT 1
Production: 9
EVAL DIGIT.VAL
MOVE DIGIT 1
Production: 10
EVAL DIGIT.VAL
MOVE DIGIT 1
Production: 11
EVAL DIGIT.VAL
MOVE DIGIT 1
Sat Sep 12 19:39:47 PDT 1998
```

Appendix C

EIS Attribute Gramamr

GbST	setseq
Info	strseq
Parent	string
SynST	setseq
SymTab	set
Name	string
Desc	strseq
KeyList	set
Doc	set
DocList	setseq
SymRec	set
SymRecList	setseq
Tag	string
IdList	set
PType	string
InList	setseq
InPair	set
Type	string
Val	string
SVal	int
Len	int

%
add
exp
div
validate
append
disjoint
uniquesymtabentries
addfwddcllist
notqualified
addintuselist
addparamdecl
addbindparams
addbindstvars
addtypedefn
addvardefn
findtype
addconstantdefn
addfunctiondefn
getentry
istype
isprimitivetype
addargdcl
addenumeratedtype
addarraytype
addrecordtype
addsettype

```
addenumvalid
addidtypefromidlist
isdiscretetype
notnull
concat
lookup
%
rule rootnode : classlist;
semantic
        rootnode.GbST := classlist.SynST;
        rootnode.Info := classlist.Info;
        rootnode.Parent := null;
        classlist.Parent := root;
condition
        validate(rootnode.GbST);
end;

rule classlist : classlist2 classnode;
semantic
        classlist.SynST := append(classlist2.SynST,classnode.SynST);
        classlist.Info := append(classlist2.Info,classnode.Info);
        classlist2.Parent := classlist.Parent;
        classnode.Parent := classlist.Parent;
condition
        disjoint(classlist2.SynST,classnode.SynST);
end;

rule classlist : ' ';
semantic
        classlist.SynST := <>;
        classlist.Info := <>;
end;

rule instancelist : instancelist2 instancenode;
semantic
        instancelist.SynST := append(instancelist2.SynST,instancenode.SynST);
        instancelist.Info := append(instancelist2.Info,instancenode.Info);
        instancelist2.Parent := instancelist.Parent;
        instancenode.Parent := instancelist.Parent;
condition
        disjoint(instancelist2.SynST,instancenode.SynST);
end;

rule instancelist : ' ';
semantic
        instancelist.SynST := <>;
        instancelist.Info := <>;
end;

rule methodlist : methodlist2 methodnode;
semantic
        methodlist.SynST := append(methodlist2.SynST,methodnode.SynST);
```

```
        methodlist.Info := append(methodlist2.Info,methodnode.Info);
        methodlist2.Parent := methodlist.Parent;
        methodnode.Parent := methodlist.Parent;
condition
        disjoint(methodlist2.SynST,methodnode.SynST);
end;

rule methodlist : ' ';
semantic
        methodlist.SynST := <>;
        methodlist.Info := <>;
end;

rule classnode : 'classnode' classdefn instancelist methodlist classlist 'endclassnode';
semantic
        classnode.SynST := append((classdefn.Name,C,classdefn.SymTab),
                        instancelist.SynST,methodlist.SynST,classlist.SynST);
        classnode.Info := append(classdefn.Info,instancelist.Info,methodlist.Info,classlist.Info);
        classdefn.Parent := classnode.Parent;
        classlist.Parent := classdefn.Name;
        instancelist.Parent := classdefn.Name;
        methodlist.Parent := classdefn.Name;
condition
        disjoint((classdefn.Name,C,classdefn.SymTab),instancelist.SynST,
                methodlist.SynST,classlist.SynST);
end;

rule instancenode : instancedefn;
semantic
        instancenode.SynST := (instancedefn.Name,I,instancedefn.SymTab);
        instancenode.Info := instancedefn.Info;
condition
        instancenode.Parent = instancedefn.Parent;
end;

rule methodnode : methoddefn;
semantic
        methodnode.SynST := (methoddefn.Name,M,-);
        methodnode.Info := methoddefn.Info;
condition
        methodnode.Parent := methoddefn.Parent;
end;

rule classdefn : 'class' id 'of' id2 interfaceusessection forwarddeclsection bindparamsection
declparamsection description mixeddecllist bindstvarsection keywordssection documentsection 'endclass';
semantic
        classdefn.Name := id.Tag;
        classdefn.Desc := description.Tag;
        classdefn.SymTab := append((bindparamsection.SymRecList,declparamsection.SymRecList),
                forwarddeclsection.SymRecList,interfaceusessection.SymRecList,
                mixeddecllist.SymRecList,bindstvarsection.SymRecList);
        classdefn.KeyList := keywordssection.KeyList;
```

```
        classdefn.DocList := documentsection.DocList;
        classdefn.Info := (classdefn.Name,C,(classdefn.Parent,classdefn.Desc,
                classdefn.KeyList,classdefn.DocList));
condition
        uniquesymtabentries(classdefn.SymTab);
        classdefn.Parent = id2.Tag;
end;

rule instancedefn : 'instance' id 'of' id2 bindparamsection description bindstvarsection keywordssection
documentsection;
semantic
        instancedefn.Name := id.Tag;
        instancedefn.Parent := id2.Tag;
        instancedefn.Desc := description.Tag;
        instancedefn.SymTab := append(bindparamsection.SymRecList,bindstvarsection.SymRecList);
        instancedefn.KeyList := keywordssection.KeyList;
        instancedefn.DocList := documentsection.DocList;
        instancedefn.Info := (instancedefn.Name, I, (instancedefn.Parent,
                instancedefn.Desc,instancedefn.KeyList,instancedefn.DocList));
end;

rule methoddefn : 'method' id 'of' id2 description keywordssection documentsection;
semantic
        methoddefn.Name := id.Tag;
        methoddefn.Parent := id2.Tag;
        methoddefn.Desc := description.Tag;
        methoddefn.KeyList := keywordssection.KeyList;
        methoddefn.DocList := documentsection.DocList;
        methoddefn.Info := (methoddefn.Name, M, (methoddefn.Parent,
                        methoddefn.Desc,methoddefn.KeyList,methoddefn.DocList));
end;

rule forwarddeclsection : ' ';
semantic
        forwarddeclsection.SymRecList := <>;
end;

rule forwarddeclsection : 'forwarddecl' identifierlist 'endforwarddecl';
semantic
        forwarddeclsection.SymRecList := addfwddcllist(identifierlist.IdList);
condition
        notqualified(identifierlist.IdList);
end;

rule interfaceusessection : ' ';
semantic
        interfaceusessection.SymRecList := <>;
end;

rule interfaceusessection : 'interfaceuses' identifierlist 'endinterfaceuses';
semantic
        interfaceusessection.SymRecList := addintuselist(identifierlist.IdList);
```

```
condition
          notqualified(identifierlist.IdList);
end;

rule declparamsection : ' ';
semantic
          declparamsection.SymRecList := <>;
end;

rule declparamsection : 'paramdecl' paramdecllist 'endparamdecl';
semantic
          declparamsection.SymRecList := paramdecllist.SymRecList;
end;

rule paramdecllist : id ':' paramtype;
semantic
          paramdecllist.SymRecList := addparamdecl(id.Tag,paramtype.PType);
end;

rule paramdecllist : paramdecllist2 ':' id ':' paramtype;
semantic
          paramdecllist.SymRecList := append(paramdecllist2.SymRecList,
                                    addparamdecl(id.Tag,paramtype.PType));
condition
          disjoint(paramdecllist2.SymRecList,addparamdecl(id.Tag,paramtype.PType));
end;

rule paramtype : 'CLASS';
semantic
          paramtype.PType := CLASS;
end;

rule paramtype : 'TYPE';
semantic
          paramtype.PType := TYPE;
end;

rule paramtype : 'CONST';
semantic
          paramtype.PType := CONST;
end;

rule paramtype : 'FUNCTION';
semantic
          paramtype.PType := FUNCTION;
end;

rule bindparamsection : ' ';
semantic
          bindparamsection.SymRecList := <>;
end;
```

```
rule bindparamsection : 'parambind' bindparamlist 'endparambind';
semantic
        bindparamsection.SymRecList := bindparamlist.SymRecList;
end;

rule bindparamlist : id ':=' id2;
semantic
        bindparamlist.SymRecList := addbindparams(id.Tag,getentry(id2.Tag));
end;

rule bindparamlist : bindparamlist2 ';' id ':=' id2;
semantic
        bindparamlist.SymRecList := append(bindparamlist2.SymRecList,
                        addbindparams(id.Tag,getentry(id2.Tag)));
end;

rule mixeddecllist : ' ';
semantic
        mixeddecllist.SymRecList := <>;
end;

rule mixeddecllist : mixeddecl ';' mixeddecllist2;
semantic
        mixeddecllist.SymRecList := append(mixeddecllist2.SymRecList,mixeddecl.SymRecList);
condition
        disjoint(mixeddecllist2.SymRecList,mixeddecl.SymRecList);
end;

rule mixeddecl : typedefn;
semantic
        mixeddecl.SymRecList := typedefn.SymRecList;
end;

rule mixeddecl : vardefn;
semantic
        mixeddecl.SymRecList := vardefn.SymRecList;
end;

rule mixeddecl : constantdefn;
semantic
        mixeddecl.SymRecList := constantdefn.SymRecList;
end;

rule mixeddecl : functiondefn;
semantic
        mixeddecl.SymRecList := functiondefn.SymRecList;
end;

rule bindstvarsection : ' ';
semantic
        bindstvarsection.SymRecList := <>;
end;
```

```
rule bindstvarsection : 'bindstvar' bindstvarlist 'endbindstvar';
semantic
        bindstvarsection.SymRecList := bindstvarlist.SymRecList;
end;

rule bindstvarlist : bindstvarlist2 ';' id ':=' value;
semantic
        bindstvarlist.SymRecList := append(bindstvarlist2.SymRecList,
                addbindstvars(id.Tag,value.Tag,getentry(value.Type)));
end;

rule bindstvarlist : id ':=' value;
semantic
        bindstvarlist.SymRecList := addbindstvars(id.Tag,value.Tag,getentry(value.Type));
end;

rule typedefn : 'type' id ':=' typedenoter;
semantic
        typedefn.SymRecList := addtypedefn(id.Tag,typedentoer.SymRec);
condition
        notqualified(id.Tag);
end;

rule vardefn : 'var' identifierlist 'of' typedenoter;
semantic
        vardefn.SymRecList := addvardefn(identifierlist.IdList,typedenoter.SymRec);
condition
        notqualified(identifierlist.IdList);
end;

rule constantdefn : 'const' id ':' id2 ':=' value;
semantic
        constantdefn.SymRecList := addconstantdefn(id.Tag,findtype(id2.Tag),value.Tag);
condition
        isprimitivetype(id2.Tag);
        id2.Type = value.Type;
        notqualified(id.Tag);
end;

rule functiondefn : 'function' id '(' arglist ')' ':' id2;
semantic
        functiondefn.SymRecList := addfunctiondefn(id.Tag,arglist.SymRecList,getentry(id2.Tag));
condition
        istype(id2.Tag);
        notqualified(id.Tag);
end;

rule arglist : ' ';
semantic
        arglist.SymRecList := <>;
end;
```

```
rule arglist : argdcl;
semantic
        arglist.SymRecList := argdcl.SymRec;
end;

rule arglist : arglist2 ',' argdcl;
semantic
        arglist.SymRecList := append(arglist2.SymRecList,argdcl.SymRec);
end;

rule argdcl : typedenoter;
semantic
        argdcl.SymRec := addargdcl(typedenoter.SymRec);
end;

rule typedenoter : id;
semantic
        typedenoter.SymRec := if (lookup(id.Tag) = FALSE)
          then (id.Tag,UNRSLVD,NULL,NULL) else getentry(id.Tag) fi;
end;

rule typedenoter : newtype;
semantic
        typedenoter.SymRec := newtype.SymRec;
end;

rule newtype : enumeratedtype;
semantic
        newtype.SymRec := addenumeratedtype(enumeratedtype.SymRecList);
end;

rule newtype : arraytype;
semantic
        newtype.SymRec := addarraytype(arraytype.SymRec,arraytype.InList);
end;

rule newtype : recordtype;
semantic
        newtype.SymRec := addrecordtype(recordtype.SymRecList);
end;

rule newtype : settype;
semantic
        newtype.SymRec := addsettype(settype.SymRec);
end;

rule enumeratedtype : '(' identifierlist ')';
semantic
        enumeratedtype.SymRecList := addenumvalid(identifierlist.IdList);
condition
        notqualified(identiferlist.IdList);
end;
```

```
rule recordtype : 'recordstart' fieldlist 'recordend';
semantic
        recordtype.SymRecList := fieldlist.SymRecList;
end;

rule fieldlist : recordsection;
semantic
        fieldlist.SymRecList := recordsection.SymRecList;
end;

rule fieldlist : fieldlist2 ';' recordsection;
semantic
        fieldlist.SymRecList := append(fieldlist2.SymRecList, recordsection.SymRecList);
condition
        disjoint(fieldlist2.IdList,recordsection.IdList);
end;

rule recordsection : identifierlist ':' typedenoter;
semantic
        recordsection.SymRecList := addidtypefromidlist(identifierlist.IdList,typedenoter.SymRec);
condition
        notqualified(identifierlist.IdList);
end;

rule arraytype : 'array' '[' indextypelist ']' 'of' typedenoter;
semantic
        arraytype.SymRec := typedenoter.SymRec;
        arraytype.InList := indextypelist.InList;
end;

rule indextypelist : indextype;
semantic
        indextypelist.InList := indextype.InPair;
end;

rule indextypelist : indextypelist2 ',' indextype;
semantic
        indextypelist.InList := append(indextypelist2.InList,indextype.InPair);
end;

rule indextype : lowerbound '..' upperbound;
semantic
        indextype.InPair := (lowerbound.Tag,upperbound.Tag);
end;

rule lowerbound : value;
semantic
        lowerbound.Tag := value.Tag;
condition
        isdiscretetype(value.Tag);
end;
```

```
rule lowerbound : id;
semantic
        lowerbound.Tag := id.Tag;
condition
        isdiscretetype(id.Tag);
end;

rule upperbound : value;
semantic
        upperbound.Tag := value.Tag;
condition
        isdiscretetype(value.Tag);
end;

rule upperbound : id;
semantic
        upperbound.Tag := id.Tag;
condition
        isdiscretetype(id.Tag);
end;

rule settype : 'set' 'of' basetype;
semantic
        settype.SymRec := basetype.SymRec;
end;

rule basetype : id;
semantic
        basetype.SymRec := getentry(id.Tag);
end;

rule basetype : enumeratedtype;
semantic
        basetype.SymRec := addenumeratedtype(enumeratedtype.SymRecList);
end;

rule keywordssection : 'keywords' keywordslist 'endkeywords';
semantic
        keywordssection.KeyList := keywordslist.KeyList;
end;

rule keywordssection : ' ';
semantic
        keywordssection.KeyList := <>;
end;

rule keywordslist : string;
semantic
        keywordslist.KeyList := string.Tag;
end;
```

```
rule keywordslist : keywordslist2 ';' string;
semantic
        keywordslist.KeyList := append(keywordslist2.KeyList,string.Tag);
condition
        disjoint(keywordslist2.KeyList,string.Tag);
end;

rule documentsection : ' ';
semantic
        documentsection.DocList := <>;
end;

rule documentsection : 'documents' documentdefnlist 'enddocuments';
semantic
        documentsection.DocList := documentdefnlist.DocList;
end;

rule documentdefnlist : documentdefn;
semantic
        documentdefnlist.DocList := documentdefn.Doc;
end;

rule documentdefnlist : documentdefnlist2 ';' documentdefn;
semantic
        documentdefnlist.DocList := append(documentdefnlist2.DocList,documentdefn.Doc);
condition
        disjoint(documentdefnlist2.Doclist,documentdefn.Doc);
end;

rule documentdefn : 'documentnameloc' id string;
semantic
        documentdefn.Doc := (id.Tag,string.Tag);
end;

rule documentdefn : 'documentation' string;
semantic
        documentdefn.Doc := (NULL,string.Tag);
end;

rule value : sign unsignednumber;
semantic
        value.Tag := concat(sign.Tag,unsignednumber.Tag);
        value.Type := unsignednumber.Type;
        value.Val := sign.SVal * unsignednumber.Val;
end;

rule value : unsignednumber;
semantic
        value.Tag := unsignednumber.Tag;
        value.Type := unsignednumber.Type;
        value.Val := unsignednumber.Val;
end;
```

```
rule value : string;
semantic
        value.Tag := string.Tag;
        value.Type := STR;
end;

rule value : character;
semantic
        value.Tag := character.Tag;
        value.Type := CHAR;
end;

rule value : boolean;
semantic
        value.Tag := boolean.Tag;
        value.Type := BOOL;
        value.Val := boolean.Val;
end;

rule unsignednumber : unsignedinteger;
semantic
        unsignednumber.Tag := unsignedinteger.Tag;
        unsignednumber.Val := unsignedinteger.Val;
        unsignednumber.Type := INT;
end;

rule unsignednumber : unsignedreal;
semantic
        unsignednumber.Tag := unsignedreal.Tag;
        unsignednumber.Val := unsignedreal.Val;
        unsignednumber.Type := REAL;
end;

rule unsignedreal : unsignedinteger '.' fractionalpart;
semantic
        unsignedreal.Tag := concat(unsignedinteger.Tag,concat(".",fractionalpart.Tag));
        unsignedreal.Val := add(unsignedinteger.Val,div(fractionalpart.Val,exp(fractionalpart.Len)));
end;

rule unsignedinteger : DIGITSEQUENCE;
semantic
        unsignedinteger.Tag := DIGITSEQUENCE.Tag;
        unsignedinteger.Val := DIGITSEQUENCE.Val;
end;

rule fractionalpart : DIGITSEQUENCE;
semantic
        fractionalpart.Tag := DIGITSEQUENCE.Tag;
        fractionalpart.Len := DIGITSEQUENCE.Len;
        fractionalpart.Val := DIGITSEQUENCE.Val;
end;
```

```
rule sign : PLUS;
semantic
        sign.Tag := "+";
        sign.SVal := 1;
end;

rule sign : MINUS;
semantic
        sign.Tag := "-";
        sign.SVal := -1;
end;

rule identifierlist : id;
semantic
        identifierlist.IdList := id.Tag;
end;

rule identifierlist : identifierlist2 ',' id;
semantic
        identifierlist.IdList := append(identifierlist2.IdList,id.Tag);
condition
        disjoint(identifierlist2.IdList.id.Tag);
end;

rule description : string;
semantic
        description.Tag := string.Tag;
condition
        notnull(string.Tag);
end;

rule id : id2 '.' IDENTIFIER;
semantic
        id.Tag := concat(id2.Tag,concat(".",IDENTIFIER.Tag));
end;

rule id : IDENTIFIER;
semantic
        id.Tag := IDENTIFIER.Tag;
end;

rule string : STRINGTOKEN;
semantic
        string.Tag := STRINGTOKEN.Tag;
end;

rule character : CHARACTERTOKEN;
semantic
        character.Tag := CHARACTERTOKEN.Tag;
end;
```

```
rule boolean : TRUETOKEN;
semantic
        boolean.Tag := TRUETOKEN.Tag;
        boolean.Val := TRUE;
end;

rule boolean : FALSETOKEN;
semantic
        boolean.Tag := FALSETOKEN.Tag;
        boolean.Val := FALSE;
end;
```

```
Sat Sep 12 20:43:33 PDT 1998
***VISIT SEQUENCES***
Production: 0
EVAL ROOTNODE.PARENT
EVAL CLASSLIST.PARENT
MOVE CLASSLIST 1
EVAL ROOTNODE.GBST
EVAL ROOTNODE.INFO
COND 1
MOVE ROOTNODE 1
Production: 1
EVAL CLASSLIST2.PARENT
EVAL CLASSNODE.PARENT
MOVE CLASSLIST2 1
MOVE CLASSNODE 1
EVAL CLASSLIST.SYNST
EVAL CLASSLIST.INFO
COND 1
MOVE CLASSLIST 1
Production: 2
EVAL CLASSLIST.SYNST
EVAL CLASSLIST.INFO
MOVE CLASSLIST 1
Production: 3
EVAL INSTANCELIST2.PARENT
EVAL INSTANCENODE.PARENT
MOVE INSTANCELIST2 1
MOVE INSTANCENODE 1
EVAL INSTANCELIST.SYNST
EVAL INSTANCELIST.INFO
COND 1
MOVE INSTANCELIST 1
Production: 4
EVAL INSTANCELIST.SYNST
EVAL INSTANCELIST.INFO
MOVE INSTANCELIST 1
Production: 5
EVAL METHODLIST2.PARENT
EVAL METHODNODE.PARENT
MOVE METHODLIST2 1
MOVE METHODNODE 1
EVAL METHODLIST.SYNST
EVAL METHODLIST.INFO
COND 1
MOVE METHODLIST 1
Production: 6
EVAL METHODLIST.SYNST
EVAL METHODLIST.INFO
MOVE METHODLIST 1
Production: 7
EVAL CLASSDEFN.PARENT
MOVE CLASSDEFN 1
```

```
EVAL CLASSLIST.PARENT
EVAL INSTANCELIST.PARENT
EVAL METHODLIST.PARENT
MOVE CLASSLIST 1
MOVE INSTANCELIST 1
MOVE METHODLIST 1
EVAL CLASSNODE.SYNST
EVAL CLASSNODE.INFO
COND 1
MOVE CLASSNODE 1
Production: 8
MOVE INSTANCEDEFN 1
EVAL INSTANCENODE.SYNST
EVAL INSTANCENODE.INFO
COND 1
MOVE INSTANCENODE 1
Production: 9
MOVE METHODDEFN 1
EVAL METHODNODE.SYNST
EVAL METHODNODE.INFO
COND 1
MOVE METHODNODE 1
Production: 10
MOVE ID 1
EVAL CLASSDEFN.NAME
MOVE INTERFACEUSESSECTION 1
MOVE FORWARDDECLSECTION 1
MOVE BINDPARAMSECTION 1
MOVE DECLPARAMSECTION 1
MOVE MIXEDDECLLIST 1
MOVE BINDSTVARSECTION 1
EVAL CLASSDEFN.SYMTAB
COND 1
MOVE DESCRIPTION 1
EVAL CLASSDEFN.DESC
MOVE KEYWORDSSECTION 1
EVAL CLASSDEFN.KEYLIST
MOVE DOCUMENTSECTION 1
EVAL CLASSDEFN.DOCLIST
EVAL CLASSDEFN.INFO
MOVE ID2 1
COND 2
MOVE CLASSDEFN 1
Production: 11
EVAL FORWARDDECLSECTION.SYMRECLIST
MOVE FORWARDDECLSECTION 1
Production: 12
MOVE IDENTIFIERLIST 1
EVAL FORWARDDECLSECTION.SYMRECLIST
COND 1
MOVE FORWARDDECLSECTION 1
Production: 13
```

```
EVAL INTERFACEUSESSECTION.SYMRECLIST
MOVE INTERFACEUSESSECTION 1
Production: 14
MOVE IDENTIFIERLIST 1
EVAL INTERFACEUSESSECTION.SYMRECLIST
COND 1
MOVE INTERFACEUSESSECTION 1
Production: 15
EVAL DECLPARAMSECTION.SYMRECLIST
MOVE DECLPARAMSECTION 1
Production: 16
MOVE PARAMDECLLIST 1
EVAL DECLPARAMSECTION.SYMRECLIST
MOVE DECLPARAMSECTION 1
Production: 17
MOVE ID 1
MOVE PARAMTYPE 1
EVAL PARAMDECLLIST.SYMRECLIST
MOVE PARAMDECLLIST 1
Production: 18
MOVE ID 1
MOVE PARAMTYPE 1
MOVE PARAMDECLLIST2 1
EVAL PARAMDECLLIST.SYMRECLIST
COND 1
MOVE PARAMDECLLIST 1
Production: 19
EVAL PARAMTYPE.PTYPE
MOVE PARAMTYPE 1
Production: 20
EVAL PARAMTYPE.PTYPE
MOVE PARAMTYPE 1
Production: 21
EVAL PARAMTYPE.PTYPE
MOVE PARAMTYPE 1
Production: 22
EVAL PARAMTYPE.PTYPE
MOVE PARAMTYPE 1
Production: 23
EVAL BINDPARAMSECTION.SYMRECLIST
MOVE BINDPARAMSECTION 1
Production: 24
MOVE BINDPARAMLIST 1
EVAL BINDPARAMSECTION.SYMRECLIST
MOVE BINDPARAMSECTION 1
Production: 25
MOVE ID 1
MOVE ID2 1
EVAL BINDPARAMLIST.SYMRECLIST
MOVE BINDPARAMLIST 1
Production: 26
MOVE ID 1
```

```
MOVE ID2 1
MOVE BINDPARAMLIST2 1
EVAL BINDPARAMLIST.SYMRECLIST
MOVE BINDPARAMLIST 1
Production: 27
EVAL BINDSTVARSECTION.SYMRECLIST
MOVE BINDSTVARSECTION 1
Production: 28
MOVE BINDSTVARLIST 1
EVAL BINDSTVARSECTION.SYMRECLIST
MOVE BINDSTVARSECTION 1
Production: 29
MOVE ID 1
MOVE BINDSTVARLIST2 1
MOVE VALUE 1
EVAL BINDSTVARSECTION.SYMRECLIST
MOVE BINDSTVARLIST 1
Production: 30
MOVE ID 1
MOVE VALUE 1
EVAL BINDSTVARLIST.SYMRECLIST
MOVE BINDSTVARLIST 1
Production: 31
MOVE KEYWORDSLIST 1
EVAL KEYWORDSSECTION.KEYLIST
MOVE KEYWORDSSECTION 1
Production: 32
EVAL KEYWORDSSECTION.KEYLIST
MOVE KEYWORDSSECTION 1
Production: 33
MOVE STRING 1
EVAL KEYWORDSLIST.KEYLIST
MOVE KEYWORDSLIST 1
Production: 34
MOVE STRING 1
MOVE KEYWORDSLIST2 1
EVAL KEYWORDSLIST.KEYLIST
COND 1
MOVE KEYWORDSLIST 1
Production: 35
EVAL DOCUMENTSECTION.DOCLIST
MOVE DOCUMENTSECTION 1
Production: 36
MOVE DOCUMENTDEFNLIST 1
EVAL DOCUMENTSECTION.DOCLIST
MOVE DOCUMENTSECTION 1
Production: 37
MOVE DOCUMENTDEFN 1
EVAL DOCUMENTDEFNLIST.DOCLIST
MOVE DOCUMENTDEFNLIST 1
Production: 38
MOVE DOCUMENTDEFN 1
```

```
MOVE DOCUMENTDEFNLIST2 1
EVAL DOCUMENTDEFNLIST.DOCLIST
COND 1
MOVE DOCUMENTDEFNLIST 1
Production: 39
MOVE ID 1
MOVE STRING 1
EVAL DOCUMENTDEFN.DOC
MOVE DOCUMENTDEFN 1
Production: 40
MOVE STRING 1
EVAL DOCUMENTDEFN.DOC
MOVE DOCUMENTDEFN 1
Sat Sep 12 20:59:02 PDT 1998
```

```
Sat Sep 12 19:43:50 PDT 1998
***VISIT SEQUENCES***
Production: 0
MOVE ID 1
EVAL INSTANCEDEFN.NAME
MOVE ID2 1
EVAL INSTANCEDEFN.PARENT
MOVE DESCRIPTION 1
EVAL INSTANCEDEFN.DESC
MOVE BINDPARAMSECTION 1
MOVE BINDSTVARSECTION 1
EVAL INSTANCEDEFN.SYMTAB
MOVE KEYWORDSSECTION 1
EVAL INSTANCEDEFN.KEYLIST
MOVE DOCUMENTSECTION 1
EVAL INSTANCEDEFN.DOCLIST
EVAL INSTANCEDEFN.INFO
MOVE INSTANCEDEFN 1
Production: 1
EVAL BINDPARAMSECTION.SYMRECLIST
MOVE BINDPARAMSECTION 1
Production: 2
MOVE BINDPARAMLIST 1
EVAL BINDPARAMSECTION.SYMRECLIST
MOVE BINDPARAMSECTION 1
Production: 3
MOVE ID 1
MOVE ID2 1
EVAL BINDPARAMLIST.SYMRECLIST
MOVE BINDPARAMLIST 1
Production: 4
MOVE ID 1
MOVE ID2 1
MOVE BINDPARAMLIST2 1
EVAL BINDPARAMLIST.SYMRECLIST
MOVE BINDPARAMLIST 1
Production: 5
EVAL BINDSTVARSECTION.SYMRECLIST
MOVE BINDSTVARSECTION 1
Production: 6
MOVE BINDSTVARLIST 1
EVAL BINDSTVARSECTION.SYMRECLIST
MOVE BINDSTVARSECTION 1
Production: 7
MOVE ID 1
MOVE BINDSTVARLIST2 1
MOVE VALUE 1
EVAL BINDSTVARSECTION.SYMRECLIST
MOVE BINDSTVARLIST 1
Production: 8
MOVE ID 1
MOVE VALUE 1
```

```
EVAL BINDSTVARLIST.SYMRECLIST
MOVE BINDSTVARLIST 1
Production: 9
MOVE KEYWORDSLIST 1
EVAL KEYWORDSSECTION.KEYLIST
MOVE KEYWORDSSECTION 1
Production: 10
EVAL KEYWORDSSECTION.KEYLIST
MOVE KEYWORDSSECTION 1
Production: 11
MOVE STRING 1
EVAL KEYWORDSLIST.KEYLIST
MOVE KEYWORDSLIST 1
Production: 12
MOVE STRING 1
MOVE KEYWORDSLIST2 1
EVAL KEYWORDSLIST.KEYLIST
COND 1
MOVE KEYWORDSLIST 1
Production: 13
EVAL DOCUMENTSECTION.DOCLIST
MOVE DOCUMENTSECTION 1
Production: 14
MOVE DOCUMENTDEFNLIST 1
EVAL DOCUMENTSECTION.DOCLIST
MOVE DOCUMENTSECTION 1
Production: 15
MOVE DOCUMENTDEFN 1
EVAL DOCUMENTDEFNLIST.DOCLIST
MOVE DOCUMENTDEFNLIST 1
Production: 16
MOVE DOCUMENTDEFN 1
MOVE DOCUMENTDEFNLIST2 1
EVAL DOCUMENTDEFNLIST.DOCLIST
COND 1
MOVE DOCUMENTDEFNLIST 1
Production: 17
MOVE ID 1
MOVE STRING 1
EVAL DOCUMENTDEFN.DOC
MOVE DOCUMENTDEFN 1
Production: 18
MOVE STRING 1
EVAL DOCUMENTDEFN.DOC
MOVE DOCUMENTDEFN 1
Production: 19
MOVE UNSIGNEDNUMBER 1
EVAL VALUE.TYPE
MOVE SIGN 1
EVAL VALUE.TAG
EVAL VALUE.VAL
MOVE VALUE 1
```

```
Production: 20
MOVE UNSIGNEDNUMBER 1
EVAL VALUE.TAG
EVAL VALUE.TYPE
EVAL VALUE.VAL
MOVE VALUE 1
Production: 21
EVAL VALUE.TYPE
MOVE STRING 1
EVAL VALUE.TAG
MOVE VALUE 1
Production: 22
EVAL VALUE.TYPE
MOVE CHARACTER 1
EVAL VALUE.TAG
MOVE VALUE 1
Production: 23
EVAL VALUE.TYPE
MOVE BOOLEAN 1
EVAL VALUE.TAG
EVAL VALUE.VAL
MOVE VALUE 1
Production: 24
EVAL UNSIGNEDNUMBER.TYPE
MOVE UNSIGNEDINTEGER 1
EVAL UNSIGNEDNUMBER.TAG
EVAL UNSIGNEDNUMBER.VAL
MOVE UNSIGNEDNUMBER 1
Production: 25
EVAL UNSIGNEDNUMBER.TYPE
MOVE UNSIGNEDREAL 1
EVAL UNSIGNEDNUMBER.TAG
EVAL UNSIGNEDNUMBER.VAL
MOVE UNSIGNEDNUMBER 1
Production: 26
MOVE UNSIGNEDINTEGER 1
MOVE FRACTIONALPART 1
EVAL UNSIGNEDREAL.TAG
EVAL UNSIGNEDREAL.VAL
MOVE UNSIGNEDREAL 1
Production: 27
MOVE DIGITSEQUENCE 1
EVAL UNSIGNEDINTEGER.TAG
EVAL UNSIGNEDINTEGER.VAL
MOVE UNSIGNEDINTEGER 1
Production: 28
MOVE DIGITSEQUENCE 1
EVAL FRACTIONALPART.TAG
EVAL FRACTIONALPART.VAL
EVAL FRACTIONALPART.LEN
MOVE FRACTIONALPART 1
Production: 29
```

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EVAL SIGN.TAG
EVAL SIGN.SVAL
MOVE PLUS 1
MOVE SIGN 1
Production: 30
EVAL SIGN.TAG
EVAL SIGN.SVAL
MOVE MINUS 1
MOVE SIGN 1
Production: 31
MOVE STRING 1
EVAL DESCRIPTION.TAG
COND 1
MOVE DESCRIPTION 1
Production: 32
MOVE ID2 1
MOVE IDENTIFIER 1
EVAL ID.TAG
MOVE ID 1
Production: 33
MOVE IDENTIFIER 1
EVAL ID.TAG
MOVE ID 1
Production: 34
MOVE STRINGTOKEN 1
EVAL STRING.TAG
MOVE STRING 1
Production: 35
MOVE CHARACTERTOKEN 1
EVAL CHARACTER.TAG
MOVE CHARACTER 1
Production: 36
EVAL BOOLEAN.VAL
MOVE TRUETOKEN 1
EVAL BOOLEAN.TAG
MOVE BOOLEAN 1
Production: 37
EVAL BOOLEAN.VAL
MOVE FALSETOKEN 1
EVAL BOOLEAN.TAG
MOVE BOOLEAN 1
Sat Sep 12 19:49:25 PDT 1998
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```
Sat Sep 12 20:10:03 PDT 1998
***VISIT SEQUENCES***
Production: 0
MOVE ID 1
EVAL METHODDEFN.NAME
MOVE ID2 1
EVAL METHODDEFN.PARENT
MOVE DESCRIPTION 1
EVAL METHODDEFN.DESC
MOVE KEYWORDSSECTION 1
EVAL METHODDEFN.KEYLIST
MOVE DOCUMENTSECTION 1
EVAL METHODDEFN.DOCLIST
EVAL METHODDEFN.INFO
MOVE METHODDEFN 1
Production: 1
MOVE KEYWORDSLIST 1
EVAL KEYWORDSSECTION.KEYLIST
MOVE KEYWORDSSECTION 1
Production: 2
EVAL KEYWORDSSECTION.KEYLIST
MOVE KEYWORDSSECTION 1
Production: 3
MOVE STRING 1
EVAL KEYWORDSLIST.KEYLIST
MOVE KEYWORDSLIST 1
Production: 4
MOVE STRING 1
MOVE KEYWORDSLIST2 1
EVAL KEYWORDSLIST.KEYLIST
COND 1
MOVE KEYWORDSLIST 1
Production: 5
EVAL DOCUMENTSECTION.DOCLIST
MOVE DOCUMENTSECTION 1
Production: 6
MOVE DOCUMENTDEFNLIST 1
EVAL DOCUMENTSECTION.DOCLIST
MOVE DOCUMENTSECTION 1
Production: 7
MOVE DOCUMENTDEFN 1
EVAL DOCUMENTDEFNLIST.DOCLIST
MOVE DOCUMENTDEFNLIST 1
Production: 8
MOVE DOCUMENTDEFN 1
MOVE DOCUMENTDEFNLIST2 1
EVAL DOCUMENTDEFNLIST.DOCLIST
COND 1
MOVE DOCUMENTDEFNLIST 1
Production: 9
MOVE ID 1
MOVE STRING 1
```

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EVAL DOCUMENTDEFN.DOC
MOVE DOCUMENTDEFN 1
Production: 10
MOVE STRING 1
EVAL DOCUMENTDEFN.DOC
MOVE DOCUMENTDEFN 1
Production: 11
MOVE ID 1
EVAL IDENTIFIERLIST.IDLIST
MOVE IDENTIFIERLIST 1
Production: 12
MOVE ID 1
MOVE IDENTIFIERLIST2 1
EVAL IDENTIFIERLIST.IDLIST
COND 1
MOVE IDENTIFIERLIST 1
Production: 13
MOVE STRING 1
EVAL DESCRIPTION.TAG
COND 1
MOVE DESCRIPTION 1
Production: 14
MOVE ID2 1
MOVE IDENTIFIER 1
EVAL ID.TAG
MOVE ID 1
Production: 15
MOVE IDENTIFIER 1
EVAL ID.TAG
MOVE ID 1
Production: 16
MOVE STRINGTOKEN 1
EVAL STRING.TAG
MOVE STRING 1
Sat Sep 12 20:10:34 PDT 1998
```

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Sat Sep 12 20:12:01 PDT 1998
***VISIT SEQUENCES***
Production: 0
EVAL MIXEDDECLLIST.SYMRECLIST
MOVE MIXEDDECLLIST 1
Production: 1
MOVE MIXEDDECL 1
MOVE MIXEDDECLLIST2 1
EVAL MIXEDDECLLIST.SYMRECLIST
COND 1
MOVE MIXEDDECLLIST 1
Production: 2
MOVE TYPEDEFN 1
EVAL MIXEDDECL.SYMRECLIST
MOVE MIXEDDECL 1
Production: 3
MOVE VARDEFN 1
EVAL MIXEDDECL.SYMRECLIST
MOVE MIXEDDECL 1
Production: 4
MOVE CONSTANTDEFN 1
EVAL MIXEDDECL.SYMRECLIST
MOVE MIXEDDECL 1
Production: 5
MOVE FUNCTIONDEFN 1
EVAL MIXEDDECL.SYMRECLIST
MOVE MIXEDDECL 1
Production: 6
MOVE ID 1
EVAL TYPEDEFN.SYMRECLIST
COND 1
MOVE TYPEDENOTER 1
MOVE TYPEDEFN 1
Production: 7
MOVE IDENTIFIERLIST 1
COND 1
MOVE TYPEDENOTER 1
EVAL VARDEFN.SYMRECLIST
MOVE VARDEFN 1
Production: 8
MOVE ID2 1
COND 1
MOVE VALUE 1
COND 2
MOVE ID 1
EVAL CONSTANTDEFN.SYMRECLIST
COND 3
MOVE CONSTANTDEFN 1
Production: 9
MOVE ID2 1
COND 1
MOVE ID 1
```

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COND 2
MOVE ARGLIST 1
EVAL FUNCTIONDEFN.SYMRECLIST
MOVE FUNCTIONDEFN 1
Production: 10
EVAL ARGLIST.SYMRECLIST
MOVE ARGLIST 1
Production: 11
MOVE ARGDCL 1
EVAL ARGLIST.SYMRECLIST
MOVE ARGLIST 1
Production: 12
MOVE ARGDCL 1
MOVE ARGLIST2 1
EVAL ARGLIST.SYMRECLIST
MOVE ARGLIST 1
Production: 13
MOVE TYPEDENOTER 1
EVAL ARGDCL.SYMREC
MOVE ARGDCL 1
Production: 14
MOVE ID 1
EVAL TYPEDENOTER.SYMREC
MOVE TYPEDENOTER 1
Production: 15
MOVE NEWTYPE 1
EVAL TYPEDENOTER.SYMREC
MOVE TYPEDENOTER 1
Production: 16
MOVE ENUMERATEDTYPE 1
EVAL NEWTYPE.SYMREC
MOVE NEWTYPE 1
Production: 17
MOVE ARRAYTYPE 1
EVAL NEWTYPE.SYMREC
MOVE NEWTYPE 1
Production: 18
MOVE RECORDTYPE 1
EVAL NEWTYPE.SYMREC
MOVE NEWTYPE 1
Production: 19
MOVE SETTYPE 1
EVAL NEWTYPE.SYMREC
MOVE NEWTYPE 1
Production: 20
COND 1
MOVE IDENTIFIERLIST 1
EVAL ENUMERATEDTYPE.SYMRECLIST
MOVE ENUMERATEDTYPE 1
Production: 21
MOVE FIELDLIST 1
EVAL RECORDTYPE.SYMRECLIST
```

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MOVE RECORDTYPE 1
Production: 22
MOVE RECORDSECTION 1
EVAL FIELDLIST.SYMRECLIST
MOVE FIELDLIST 1
Production: 23
MOVE RECORDSECTION 1
MOVE FIELDLIST2 1
EVAL FIELDLIST.SYMRECLIST
COND 1
MOVE FIELDLIST 1
Production: 24
MOVE IDENTIFIERLIST 1
COND 1
MOVE TYPEDENOTER 1
EVAL RECORDSECTION.SYMRECLIST
MOVE RECORDSECTION 1
Production: 25
MOVE TYPEDENOTER 1
EVAL ARRAYTYPE.SYMREC
MOVE INDEXTYPELIST 1
EVAL ARRAYTYPE.INLIST
MOVE ARRAYTYPE 1
Production: 26
MOVE INDEXTYPE 1
EVAL INDEXTYPELIST.INLIST
MOVE INDEXTYPELIST 1
Production: 27
MOVE INDEXTYPE 1
MOVE INDEXTYPELIST2 1
EVAL INDEXTYPELIST.INLIST
MOVE INDEXTYPELIST 1
Production: 28
MOVE LOWERBOUND 1
MOVE UPPERBOUND 1
EVAL INDEXTYPE.INPAIR
MOVE INDEXTYPE 1
Production: 29
MOVE VALUE 1
EVAL LOWERBOUND.TAG
COND 1
MOVE LOWERBOUND 1
Production: 30
MOVE ID 1
EVAL LOWERBOUND.TAG
COND 1
MOVE LOWERBOUND 1
Production: 31
MOVE VALUE 1
EVAL UPPERBOUND.TAG
COND 1
MOVE UPPERBOUND 1
```

```
Production: 32
MOVE ID 1
EVAL UPPERBOUND.TAG
COND 1
MOVE UPPERBOUND 1
Production: 33
MOVE BASETYPE 1
EVAL SETTYPE.SYMREC
MOVE SETTYPE 1
Production: 34
MOVE ID 1
EVAL BASETYPE.SYMREC
MOVE BASETYPE 1
Production: 35
MOVE ENUMERATEDTYPE 1
EVAL BASETYPE.SYMREC
MOVE BASETYPE 1
Production: 36
MOVE UNSIGNEDNUMBER 1
EVAL VALUE.TYPE
MOVE SIGN 1
EVAL VALUE.TAG
EVAL VALUE.VAL
MOVE VALUE 1
Production: 37
MOVE UNSIGNEDNUMBER 1
EVAL VALUE.TAG
EVAL VALUE.TYPE
EVAL VALUE.VAL
MOVE VALUE 1
Production: 38
EVAL VALUE.TYPE
MOVE STRING 1
EVAL VALUE.TAG
MOVE VALUE 1
Production: 39
EVAL VALUE.TYPE
MOVE CHARACTER 1
EVAL VALUE.TAG
MOVE VALUE 1
Production: 40
EVAL VALUE.TYPE
MOVE BOOLEAN 1
EVAL VALUE.TAG
EVAL VALUE.VAL
MOVE VALUE 1
Production: 41
EVAL UNSIGNEDNUMBER.TYPE
MOVE UNSIGNEDINTEGER 1
EVAL UNSIGNEDNUMBER.TAG
EVAL UNSIGNEDNUMBER.VAL
MOVE UNSIGNEDNUMBER 1
```

```
Production: 42
EVAL UNSIGNEDNUMBER.TYPE
MOVE UNSIGNEDREAL 1
EVAL UNSIGNEDNUMBER.TAG
EVAL UNSIGNEDNUMBER.VAL
MOVE UNSIGNEDNUMBER 1
Production: 43
MOVE UNSIGNEDINTEGER 1
MOVE FRACTIONALPART 1
EVAL UNSIGNEDREAL.TAG
EVAL UNSIGNEDREAL.VAL
MOVE UNSIGNEDREAL 1
Production: 44
MOVE DIGITSEQUENCE 1
EVAL UNSIGNEDINTEGER.TAG
EVAL UNSIGNEDINTEGER.VAL
MOVE UNSIGNEDINTEGER 1
Production: 45
MOVE DIGITSEQUENCE 1
EVAL FRACTIONALPART.TAG
EVAL FRACTIONALPART.VAL
EVAL FRACTIONALPART.LEN
MOVE FRACTIONALPART 1
Production: 46
EVAL SIGN.TAG
EVAL SIGN.SVAL
MOVE PLUS 1
MOVE SIGN 1
Production: 47
EVAL SIGN.TAG
EVAL SIGN.SVAL
MOVE MINUS 1
MOVE SIGN 1
Production: 48
MOVE ID 1
EVAL IDENTIFIERLIST.IDLIST
MOVE IDENTIFIERLIST 1
Production: 49
MOVE ID 1
MOVE IDENTIFIERLIST2 1
EVAL IDENTIFIERLIST.IDLIST
COND 1
MOVE IDENTIFIERLIST 1
Production: 50
MOVE STRING 1
EVAL DESCRIPTION.TAG
COND 1
MOVE DESCRIPTION 1
Production: 51
MOVE ID2 1
MOVE IDENTIFIER 1
EVAL ID.TAG
```

```
MOVE ID 1
Production: 52
MOVE IDENTIFIER 1
EVAL ID.TAG
MOVE ID 1
Production: 53
MOVE STRINGTOKEN 1
EVAL STRING.TAG
MOVE STRING 1
Production: 54
MOVE CHARACTERTOKEN 1
EVAL CHARACTER.TAG
MOVE CHARACTER 1
Production: 55
EVAL BOOLEAN.VAL
MOVE TRUETOKEN 1
EVAL BOOLEAN.TAG
MOVE BOOLEAN 1
Production: 56
EVAL BOOLEAN.VAL
MOVE FALSETOKEN 1
EVAL BOOLEAN.TAG
MOVE BOOLEAN 1
Sat Sep 12 20:26:17 PDT 1998
```

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