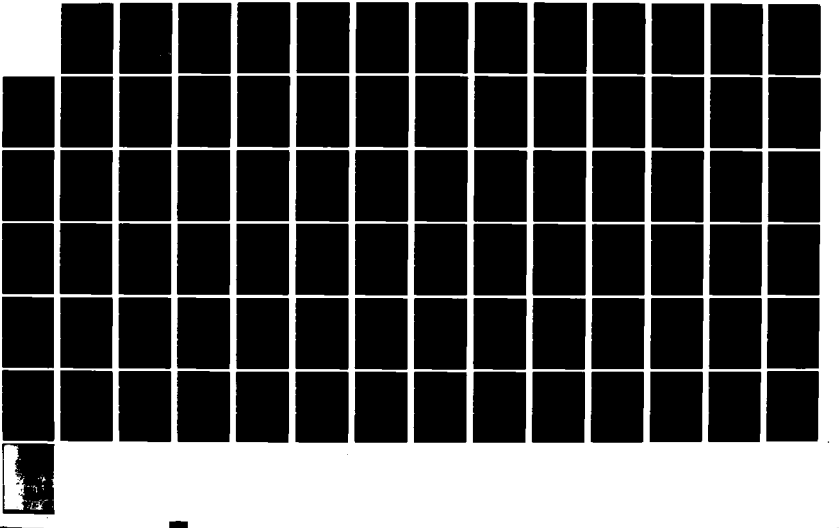
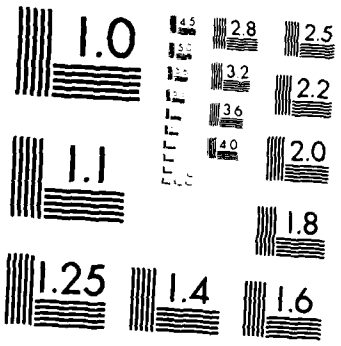
AD-A129 818 TOOLS FOR TESTING DENOTATIONAL SEMANTIC DEFINITIONS OF PROGRAMMING LANGUA..(U) UNIVERSITY OF SOUTHERN CALIFORNIA MARINA DEL REY INFORMATION S.. 1/1

UNCLASSIFIED V KINI ET AL. MAY 83 ISI/RR-83-112 F/G 9/2 NL





ISI/RR-83-112
May 1983

University of Southern California

Vittal Kini
David F. Martin
Allen Stoughton

Tools for Testing Denotational Semantic Definitions of Programming Languages

INFORMATION SCIENCES INSTITUTE

213/822-1511
4676 Admiralty Way/Marina del Rey/California 90291-6695

This research is supported by the Defense Advanced Research Projects Agency under Contract No. MDA903 81 C 0335. Views and conclusions contained in this report are the authors' and should not be interpreted as representing the official opinion or policy of DARPA, the U.S. Government, or any person or agency connected with them.

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE *(When Data Entered)*

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER ISI/RR-83-112	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE *(and Subtitle)* Tools for Testing Denotational Semantic Definitions of Programming Languages		5. TYPE OF REPORT & PERIOD COVERED Research Report 6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR*(s)* Vittal Kini, David F. Martin, and Allen Stoughton		8. CONTRACT OR GRANT NUMBER*(s)* MDA903 81 C 0335
9. PERFORMING ORGANIZATION NAME AND ADDRESS USC/Information Sciences Institute 4676 Admiralty Way Marina del Rey, CA 90291		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS .....
11. CONTROLLING OFFICE NAME AND ADDRESS Defense Advanced Research Projects Agency 1400 Wilson Blvd. Arlington, VA 22209		12. REPORT DATE May 1983 13. NUMBER OF PAGES 81
14. MONITORING AGENCY NAME & ADDRESS*(if different from Controlling Office)*		15. SECURITY CLASS. *(of this report)* Unclassified 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT *(of this Report)*

This document is approved for public release and sale: distribution is unlimited.

17. DISTRIBUTION STATEMENT *(of the abstract entered in Block 20, if different from Report)*

.....

18. SUPPLEMENTARY NOTES

19. KEY WORDS *(Continue on reverse side if necessary and identify by block number)*

Ada, denotational semantics, semantic interpreter, software tools

20. ABSTRACT *(Continue on reverse side if necessary and identify by block number)*

(OVER)

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE
S/N 0102-014-6601

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE *(When Data Entered)*

20. ABSTRACT (continued)

The Department of Defense commissioned the design and implementation of the Ada programming language with the intention of requiring most future military systems to be programmed in Ada. To ensure the quality of systems written in Ada, it is necessary that Ada be precisely understood by both its users and implementers. To this end a denotational formal semantic definition (FSD) of Ada was developed at the Institut National de Recherche en Informatique et en Automatique (INRIA), in France. Its intent is to provide the precise meaning of the language and its constructs via the mathematical formalism which underlies the denotational semantic descriptive technique. Due to the complexity of Ada, however, and despite the power and elegance of the denotational semantics method, the FSD itself is quite large: both the static (compile-time) and dynamic (run-time) phases of the definition consist of hundreds of mutually recursive functions. As a result of this inherent complexity, it is difficult for a person to understand the definition or to attempt symbolic execution of the definition without machine assistance. This report describes the work of the ISI Formal Semantics project in developing and constructing tools to aid the understanding and validation of the Ada FSD. First we briefly describe the INRIA meta-language, AFDL, and the extensions we were forced to make to it. Next we describe the various tools we have built and their application to the interpreting of the FSD. Finally, we describe the outcome of the project. The appendices contain an informal specification of our enhanced version of AFDL (AFDL+), a definition of the toy programming language TINY in AFDL+, and a transcript of an example use of our tools to process the TINY definition.

ISI/RR-83-112
May 1983

University of Southern California

Vittal Kini
David F. Martin
Allen Stoughton

Tools for Testing Denotational Semantic Definitions of Programming Languages

INFORMATION SCIENCES INSTITUTE

213/822-1511
4676 Admiralty Way/Marina del Rey/California 90291-6695

This research is supported by the Defense Advanced Research Projects Agency under Contract No MDA903 81 C 0335 Views and conclusions contained in this report are the authors' and should not be interpreted as representing the official opinion or policy of DARPA, the U S Government, or any person or agency connected with them

CONTENTS

1. TESTING THE INRIA ADA FORMAL DEFINITION: THE ISI FORMAL SEMANTICS PROJECT

1.1 INTRODUCTION

The design and implementation of the Ada [1] programming language were commissioned by DoD with the intention of requiring most future military systems to be programmed in Ada. It is therefore necessary that Ada be precisely understood by both its users and implementers, in order to ensure the quality of systems written in Ada. In particular, since DoD must control Ada compiler implementations, a precise, well-structured, and validated formal definition of Ada can provide one of the principal standards to which these implementations must adhere. Beyond such considerations pertaining to particular programming languages such as Ada, good generic research toward the design and implementation of tools and methodologies for supporting the development of precise, readable, and accurate formal definitions has considerable relevance to the broader goals of understanding large programs and verifying their correctness.

A denotational formal semantic definition (FSD) of Ada has been developed at INRIA [10]. Due to the complexity of Ada, and despite the power and elegance of the denotational semantics method, the FSD itself is quite large: both the static (compile-time) and dynamic (run-time) phases of the definition consist of hundreds of mutually recursive functions. As a result of this inherent complexity, it is difficult for a human to understand the definition. One approach to understanding a denotational definition is to symbolically execute the definition on specific example programs. Attempting to do this without machine assistance will likely result in a great many errors and is, in a practical sense, impossible. Unaided human application of this FSD to understanding Ada programs is at best an arduous task.

It is therefore imperative to construct appropriate tools to aid the understanding and validation of the Ada FSD. Such tools can be used in two ways. Initially, Ada test cases whose semantics are well understood can be used to test the correctness of the FSD. Subsequently, after confidence in the correctness of the Ada FSD has increased, the tools can be used to answer very specific questions about specific parts of the FSD as they relate to example Ada programs whose semantics are not readily apparent. This report describes work done at USC-Information Sciences Institute in constructing tools that may be used in these ways to exercise and validate the INRIA Ada FSD.

The Ada FSD is written in a typed lambda calculus expressed in an "Ada-like" syntax; we shall henceforth call this language AFDL, an acronym for Ada Formal Definition Language. We have written tools to

- translate the functions and data types of the Ada FSD into an equivalent directly executable intermediate language (AFDL-IL),
- transform candidate Ada test programs (such as the Softech compiler test cases [8]) into corresponding abstract syntax trees, and
- apply the translated FSD to the abstract syntax trees to obtain via interpretation the static and dynamic semantics of the corresponding programs.

The semantics thus obtained can be compared to the expected meaning. In addition we have built tools to generate useful items such as cross reference listings of the FSD's components.

In this report, we describe in more detail our approach to validating the Ada FSD. First, we briefly describe the INRIA meta-language and the extensions we were forced to make to it, and give an overview of the structure of the INRIA Ada FSD. Next, we describe the various tools we have built and their application to the FSD. And finally, we describe the current state of our project and its expected outcome.

1.2 ADA FORMAL SEMANTIC DEFINITION

1.2.1 The Meta-Language of the Ada FSD

AFDL, the meta-language in which the FSD is written, is an applicative language with an Ada-like syntax. The language contains function, block, conditional, and case statements, simple expressions, and packages (for modularity and information hiding) as in Ada. AFDL's basic data types are the integers and the booleans, and its data type constructors are enumerated types and (unlike Ada) function types. Conspicuously absent from AFDL are the sum (union), product (record), and sequence (array) types; these types are basic to the denotational semantics method. As a result, the data types upon which the FSD is based are only defined informally in plain language, and are not formally defined in AFDL (or any other language). The absence of formal explication of the entire base-level of the definition is one of the major impediments to the human reader who wishes to understand the formal definition (the task is akin to trying to understand a large software system in which the data type declarations were only cursorily outlined in English). This deficiency must be remedied before the FSD can be tested.

Our approach to this problem was to extend AFDL, in an upward compatible way, to include sum, product and sequence types, along with their associated operations. This approach provides a meta-language capable of conveying the entire definition in a formal manner, and thus facilitates both human understanding and machine execution of the definition. We call this extension AFDL+. Further details of AFDL+ are provided in Appendix I. Appendix II of the report contains a definition of Gordon's example programming language "TINY" [9]. The definition is essentially a transliteration of the *continuation*-style semantic definition of TINY that Gordon provides. In this definition, all of the static and semantic domains are defined in terms of the basic types *INTEGER* and *BOOLEAN* and the various domain constructors.

1.2.2 Structure of the Ada FSD

The Ada FSD basically consists of a collection of mutually recursive functions together with a repertoire of intrinsic basic data types. The Ada Reference Manual [1] is divided into a number of chapters, each devoted to a specific aspect or component of the language. None of the FSD appears in this manual. The Ada FSD ([10] and later versions), however, is organized by "folding" it into the Reference Manual so that each chapter contains the pertinent components of the Ada FSD. The intrinsic FSD data types and operations on them are intended to be described in Appendices to the Ada FSD in order to separate these base-level concerns from the rest of the FSD.

From an operational point of view, the Ada FSD is organized into three "phases", one of which is syntactic and the others semantic. The syntactic phase establishes a relationship between the concrete and abstract syntax of Ada by providing a specification of both the concrete and abstract

syntactic domains together with a (constructive) mapping from the former to the latter. In practice, this mapping is implemented as a parse-driven construction of Ada abstract syntax trees from corresponding Ada program strings. There are two semantic phases which process abstract syntax trees. The first, called static semantics, performs what are generally considered to be "compile-time" functions such as static type-checking and overloading resolution. This phase produces what we term an *annotated abstract syntax tree* which is a modified form of the tree input to the phase. The annotations consist of error messages and static environment information gathered by the phase such as the overloading resolutions, visibility calculations, normalizations, etc. The final semantic phase, called dynamic semantics, determines the "run-time" semantics (the meaning of procedures, expressions, etc.) of error-free annotated abstract syntax trees output from the static semantics phase.

1.2.3 Status of the Ada FSD -- June 1982

At this time, the Ada FSD is incomplete in that (excluding the semantics of Tasking in Ada) many of the semantic functions in the chapters of the FSD document are either missing or contain errors (both type and logical), and the data types and functions in appendices of the document are largely unspecified. The functions missing from the FSD have been identified, and type errors have been detected by the use of type-checking tools developed at ISI. The burden of defining these missing types and functions and of correcting these errors necessarily falls upon INRIA.

In the FSD document, the concrete and abstract syntaxes of Ada are defined, the latter less explicitly than the former. In fact, there exist two abstract syntaxes: a post-parse abstract syntax (which is input to the static semantics phase) and a post-static-semantics abstract syntax (which is input to the dynamic semantics phase). The correspondence between the (post-parse) abstract syntax and the concrete syntax in the document is implicit; it must be given explicitly or else the reader must be given enough information to deduce the exact correspondence, as this is necessary for a detailed understanding of the FSD. However, INRIA has supplied an LR(1) syntax for a superset of Ada, together with a correspondence between it and the Ada abstract syntax.

1.3 MECHANICAL INTERPRETATION OF THE ADA FSD

In this section we shall describe the processes whereby the Ada FSD is translated into suitable intermediate forms that may then be interpreted. The interpretive execution of the FSD will allow the testing and validation of the FSD and, subsequently, the accurate determination of the semantics of given example Ada programs. Figures 1, 2, 3, and 4 illustrate these processes.

The boxes in these figures represent abstract machines that accept inputs and produce outputs in certain forms. Boxes subdivided vertically into two compartments represent abstract machines that are constructed by loading what is represented by the upper compartment into the abstract machine represented by the lower compartment. Compartments may themselves be vertically subdivided into compartments in a hierarchical manner (see Figure 4 for example). Numbers above the top left corner of a box uniquely identify an abstract machine and two boxes labeled with the same number therefore represent the same abstract machine.

Parser Generation

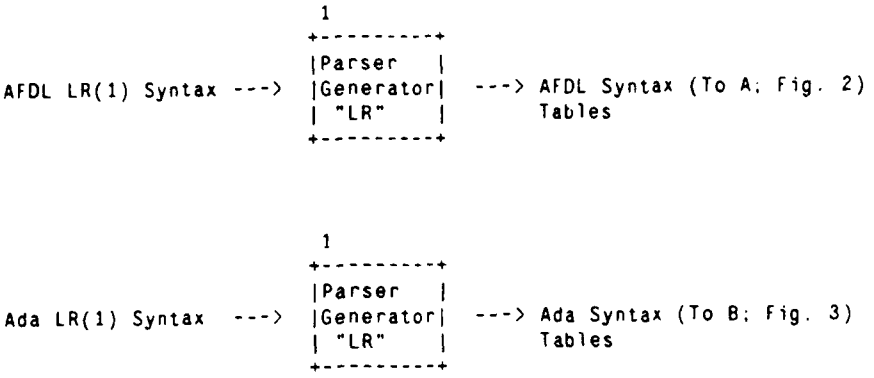
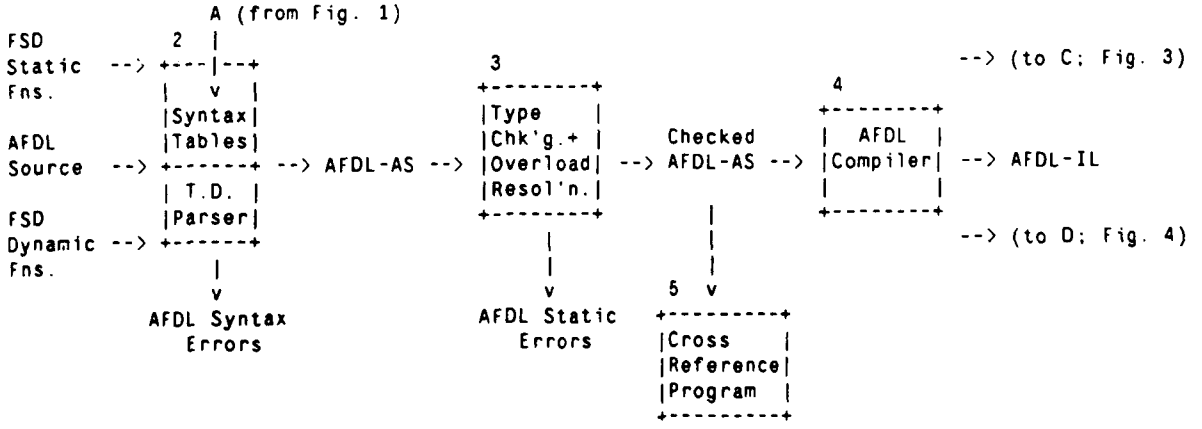


Figure 1

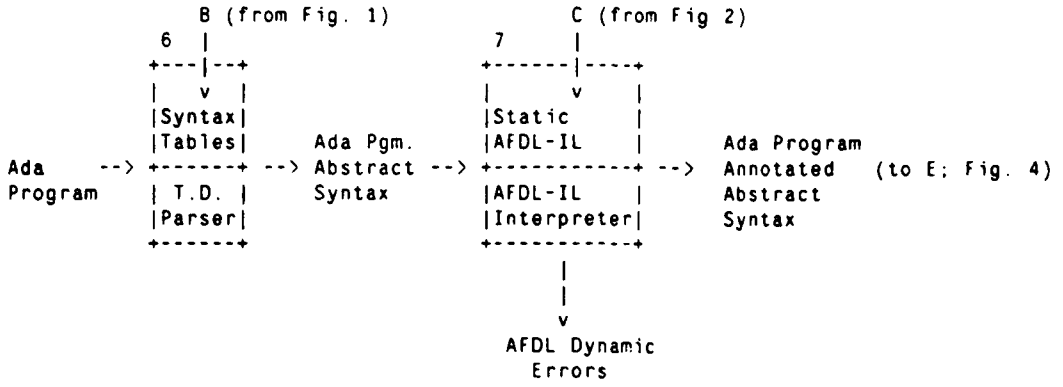
Processing FSD Semantic Functions



Key: T.D. Parser = Table Driven Parser

Figure 2

Static Semantics (PASS 1)



Key: T.D. Parser = Table Driven Parser

Figure 3

Dynamic Semantics (PASS 2)

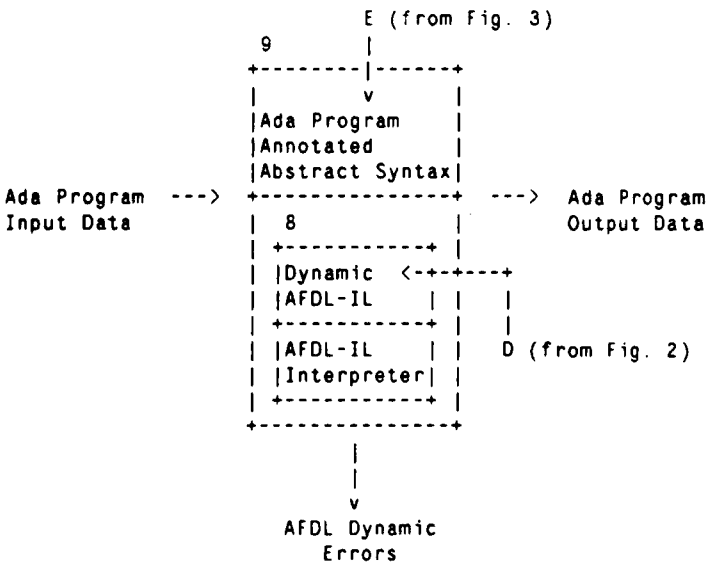


Figure 4

1.3.1 Generation of Parsers

To generate parsers for the Ada and AFDL languages we use the LR program [12] which accepts an LR(1) syntax for a language and outputs syntax tables. These tables are used to control a table-driven LR parser. Figure 1 shows this process for Ada and AFDL. Abstract Machine 1 is the LR program referred to above. The table-driven parser (bottom half, Abstract Machines 2 and 6) was constructed in Interlisp.

1.3.2 Processing of FSD Semantic Functions

The static and dynamic semantic functions of the FSD, written in AFDL, are translated to a directly executable intermediate language, AFDL-IL, by the process depicted in Figure 2. Abstract Machine 2 parses the AFDL text of the functions and produces the AFDL abstract syntax (AFDL-AS) form of those functions (the AFDL text is first extracted from the surrounding prose in the FSD source document, using a SNOBOL program). Errors discovered at this stage include AFDL syntax errors arising from misspelled or missing keywords or delimiters, or from improperly constructed syntactic forms. The syntax tables generated by the LR program in the process of Figure 1 are loaded into the table-driven LR(1) parser to yield Abstract Machine 2.

The output of Abstract Machine 2 is then fed to Abstract Machine 3 which checks for incorrect AFDL data type usage and resolves any overloading of function names. Errors trapped at this stage consist of improper type usage, unresolvable function name overloading due to ambiguity, missing declarations, misspelled declaration names leading to the appearance of missing declarations, etc. The output of Abstract Machine 3 is the AFDL-AS form of the static and dynamic semantic functions in which such errors have been eliminated. The actual output of the type-checker/overloading-resolver is a symbol table that relates all symbols in the global scope of the definition to their type-checked values. Thus, for example, the value of a symbol representing a typename will be the definition of that type and the value of a symbol representing a function will be the type of that function along with the abstract syntactic form of the function body.

For efficiency, the abstract syntax tree forms of the semantic functions are not directly executed during the interpretation process. A compiled form is used instead. Abstract Machine 4 compiles the AFDL-AS functions, producing instruction sequences for the AFDL-IL interpreters depicted in Abstract Machines 7 and 8. The AFDL-IL interpreter is a virtual stack machine implemented in Interlisp with a retention strategy for storage to model the static binding of variables which is possible in AFDL.

1.3.3 Cross Reference Facility

Abstract Machine 5 in Figure 2 represents the cross reference facility. This program accepts the AFDL-AS output from Abstract Machine 3 and produces a listing of attributes for each symbol in the global scope of the FSD. Thus, for instance, if a symbol represents a semantic function, the attributes include a list of functions it calls and a list of functions that call it. These cross reference lists are a useful tool in checking the FSD for irregularities.

1.3.4 Static Semantics, PASS 1

The Ada FSD is constructed to provide the semantics of an Ada program in two passes that evaluate, respectively, the static and dynamic semantics of the program. The process of Figure 3 depicts the first or static semantics phase. The Ada programs whose semantics are to be evaluated are first rendered into an abstract syntactic form by an LR(1) Ada parser (Abstract Machine 6). This abstract machine is constructed by loading the syntax tables for Ada, produced by the LR program, into the table-driven parser mentioned in Section 1.3.1.

The Ada program abstract syntax is fed into Abstract Machine 7 which does the actual static semantic evaluation. Abstract Machine 7 is constructed by loading the compiled AFDL-IL form (symbol table) of the static semantic functions of the FSD (output from Abstract Machine 4, Figure 2) into an interpreter for AFDL-IL. As mentioned earlier, the interpreter is a stack machine programmed in Interlisp. Abstract Machine 7 is, therefore, the static semantics evaluator and embodies the corresponding part of the FSD.

The output of Abstract Machine 7 is an annotated abstract syntactic representation of the Ada program that was input to the process of Figure 3. The annotations correspond to the error messages and static environment information that were obtained from the program and checked for correctness by the static semantic functions of the FSD. By using this annotated abstract syntax representation, the dynamic semantic functions in PASS 2 need not re-analyze the Ada program to obtain static environment information.

During the running of Abstract Machine 7, AFDL dynamic (run-time) errors may occur (e.g. selection of a non-existent element of a sequence type (array)). Such errors are defects in the FSD and must be corrected. In addition, various errors may also be detected by the *FSD itself* and recorded as annotations in the Ada abstract syntax tree it produces. For instance, unresolvable overloading of Ada function or operator names, ambiguities due to importation of declarations by means of **use** clauses, improper data-type usage, etc., are errors that may be statically determined to exist in a program. The flagging of such errors, however, may signify different things depending on the intended use of Abstract Machine 7. In initial phases when the FSD is being validated, it is supposed that the semantics of the test-case input Ada programs are well understood and are known to conform to program specifications. In such cases, the errors flagged by Abstract Machine 7 will in all likelihood be caused by errors in the FSD static semantic functions themselves. In latter phases, subsequent to the validation of the FSD, such errors flagged by Abstract Machine 7 will point to errors in the Ada programs themselves. In such cases, the FSD static semantic functions will have fulfilled their purpose.

1.3.5 Dynamic Semantics, PASS 2

The second pass of the Ada FSD, the dynamic semantics phase, is depicted in the process of Figure 4. It is seen from the figure that Abstract Machine 8 is constructed in a manner similar to that of Abstract Machine 7. This is done by loading the compiled AFDL-IL (symbol table) form of the FSD dynamic semantic functions (output of Abstract Machine 4 in Figure 2) into the AFDL-IL interpreter. The result is an abstract machine with the capability to evaluate Ada program annotated abstract syntax trees.

The dynamic semantics interpreter (Abstract Machine 9) is obtained by loading Abstract Machine 8 with the annotated abstract syntax representation of the Ada program that is the output of the static semantics evaluator (Abstract Machine 7). Machine 9 is an executable object that embodies the semantics of these Ada programs. It accepts representations of the input data that the Ada programs would have accepted and through a process of interpretation produces the output data of those programs (assuming they terminate). In addition to viewing the output data produced by Ada test programs, it is also possible to view the internal computation states of those programs. Both the external and internal behavior can be used in judging the correctness of the FSD and Ada programs.

In a manner similar to that described in Section 1.3.4, AFDL dynamic (run-time) errors can occur during the execution of Abstract Machine 9. These are FSD errors. In addition, the FSD dynamic semantic functions themselves may detect run-time errors in the Ada test programs. These errors are indicated as part of the output data of those programs, and may represent errors either in the dynamic functions of the FSD or in the Ada programs themselves. Furthermore, the program output data produced by Abstract Machine 9 may be examined to determine whether it is as expected. Again, in the case of test-case Ada programs with well understood semantics, incorrect output data is symptomatic of errors in the FSD which will require identification and correction.

1.3.6 Summary

It may be observed from the foregoing description that the processes depicted in Figures 1 and 2 are performed once for each version of the Ada FSD. (Except for the process in Figure 1 which generates the syntax tables for the LR(1) Ada grammar. This is done precisely once, unless the grammar for Ada changes, a much less likely event.) Here, a new version of the Ada FSD is created each time errors detected in the FSD are corrected. Therefore, these processes are "constructor processes" in that they are used to construct the Ada FSD validation tools. When errors in the FSD are detected during the running of these constructor processes, they must be terminated prematurely, a new version of the FSD generated, and these processes restarted.

The processes depicted in Figures 3 and 4, on the other hand, are run for each test-case Ada program whose semantics is to be evaluated, or whose known semantics is to be used to validate the FSD. As such, these processes may be viewed as "validation processes".

In summary, the processes of Figures 1 and 2 are used to parse, type-check and prepare intermediate forms of the FSD static and dynamic semantic functions. The checked intermediate forms are then loaded into the AFDL-IL interpreter to produce the static and dynamic semantics interpreters. These interpreters are used in the processes of Figures 3 and 4 to evaluate the semantics of test-case Ada programs and validate the FSD.

1.4 STATUS AS OF JUNE 1982

The software tools we have described in this report have been constructed and are fully operational at USC-Information Sciences Institute. An exception is the user-interface to the AFDL-IL interpreter which must perforce remain in a rudimentary state until experience with exercising the complete INRIA Ada FSD is gained. For the moment we have the capability to set conditional breakpoints upon entries to and/or exits from semantic functions and also at the level of individual instructions in the compiled forms of the semantic functions. The full power of Interlisp is available at a breakpoint and thus it is possible to observe the static and dynamic chains, variable bindings and continuations in the

interpreter. This ability to intervene interactively in the interpretation is a feature that distinguishes our work from that of Mosses [11].

An extensive list of type errors generated by the type checker (Abstract Machine 3), and cross reference listings have been supplied to INRIA for the entire FSD. Unfortunately, because the FSD is currently incomplete, it has not yet been possible to test the static and dynamic interpreters on the FSD, or to begin validating the FSD. It is hoped that efforts at INRIA will soon remedy this situation. In the meantime we are employing the denotational definition of TINY (provided in Appendix II of this report) to exercise our tools.

We have succeeded in processing the TINY definition through the parser, type-checker and compiler. The compiled definition has been run on the interpreter with several examples meant to test the various paths in the definition. The biggest TINY program we have executed under the AFDL interpretation of the definition has been one that accepts integers in the input stream and produces the corresponding factorials in the output stream. Since the TINY language does not have a multiplication operation, this was implemented via iterative addition! While such a program is quite small, the work done by the interpreter in terms of semantic function applications and the corresponding manipulation of static and dynamic chains is not trivial. Thus it has proven to be a fairly good test of the software.

Since AFDL+ contains the necessary idioms for writing denotational semantic definitions, we expect that our software could also be useful to the scientific community at large.

2. A DESCRIPTION OF AFDL+: THE ADA FSD METALANGUAGE

2.1 OVERVIEW

The purpose of this chapter is to describe the semantic metalanguage in which the formal definition of Ada [1, 10] is written. This language, called AFDL (Ada Formal Definition Language) is essentially a typed lambda calculus with Ada syntactic sugaring.

The original version of AFDL was conceived by the INRIA team that wrote the Ada formal definition [10]. Certain enhancements of AFDL were found to be desirable by the ISI group whose goal is to build tools to test the Ada FSD; this enhanced version of AFDL is called "AFDL+". AFDL is a proper subset of AFDL+, and therefore AFDL programs are completely "upward compatible" with AFDL+. It is this enhanced version of AFDL that will be described in this chapter.

AFDL+ and AFDL are purely applicative languages intended for writing denotational semantic definitions in an Ada-like syntax. AFDL contains functions, blocks, conditional and case "statements" (which are actually expressions), simple expressions, and packages (for modularity and information hiding). AFDL's basic data types are the integers and booleans, and its data type constructors are enumeration of types and (unlike Ada) function types. Conspicuously absent from AFDL are sum (union), product (record), and sequence (array) types; these types are basic to the denotational semantics method. As a result, the data types upon which the Ada FSD is based are only defined *informally in plain* language, and are not formally defined in AFDL (or in any other language). This situation is an obstacle to full understanding of the Ada FSD; moreover, it must be remedied before the FSD can be tested. AFDL+ is an upward compatible extension of AFDL designed to overcome these shortcomings by including sum, product, and sequence types together with their associated operations. This allows the entire FSD to be formally defined, by writing it in AFDL+. This will facilitate human undestanding of the FSD, and will also render it machine executable.

2.1.1 Style of this Description

The description of AFDL+ presented in this chapter deals with two principal aspects of AFDL+: its syntax and semantics.

The syntax of AFDL+ is given in two forms: (1) an LR(1) *concrete syntax*, which is used to parse AFDL+ programs and translate them into equivalent abstract syntactic form, and (2) an *abstract syntax*, which is the target representation of this translation, and which is used as an intermediate form for type checking and compiling AFDL+ programs into equivalent AFDL machine programs for execution of semantic descriptions written in AFDL+. The correspondence between concrete and abstract syntax is in most cases quite straightforward and requires no additional explanation. Those occasional cases that are not so clear are briefly explained in accompanying comments.

A summary of the AFDL+ abstract syntax is given in Appendix III. A precise specification of the correspondence between AFDL+ concrete and abstract syntax is given in Appendix IV. The correspondence consists of a specification input to the grammar analysis program LR; this kind of specification is explained in the documentation of the AFDL/Ada syntax tools [4]. Appendix IV presents the output from LR.

The semantics of AFDL + is given in plain English. A more precise, though complex, operational semantics of AFDL + is defined by the combination of the AFDL + parser, compiler, and the LISP code that implements the AFDL virtual machine. These processors are documented in [4, 5, 6], respectively.

2.1.2 Abstract Syntax Notation

The notation used to describe AFDL + abstract syntax is similar to BNF, except ":" is used instead of "::=". Lower case names denote syntactic categories or classes, and upper case names denote syntactic constants that are used as node names or labels. The suffix "_s" denotes a *list* of syntactic objects of the class to which the suffix is appended (e.g., id_s denotes a list of objects of class id). Most comments appear at the end of lines, and are prefixed by "--".

Abstract syntax constructs are basically trees implemented in a simple list structure of the form

```
(NAME son1 son2 ... sonN)
```

where NAME is the root node label and son1, ..., sonN are trees that are the immediate successors of the root node. When N = 0, the tree is simply represented as NAME rather than (NAME).

Several syntax classes are terminal, in that they represent sets of syntactic constants in AFDL + . These are

`var_id`	variable identifier; corresponds to "`.varname`" in concrete syntax.
`fun_id`	function or package identifier; corresponds to "`.procname`" in concrete syntax.
`type_id`	type identifier; corresponds to "`.typemark`" in concrete syntax.
`const_id`	(enumerated type) constant name; corresponds to "`.etconst`" in concrete syntax.
`integer`	integer; corresponds to "`.integer`" in concrete syntax.
`string`	string; corresponds to "`.string`" in concrete syntax.

2.2 LEXICAL ELEMENTS

AFDL has a simple set of lexical elements [4]. In addition to the usual delimiters such as parentheses, operators, etc., AFDL has four major disjoint classes of lexical elements:

- keywords
- names
- (positive) integer constants
- strings

Basically, keywords and names are identifiers of various kinds. In order to define their representations precisely, the following definitions are useful. A *word* is a nonempty sequence of letters; an *upper (lower) case word* is a word in which all the letters are upper (lower) case. An *identifier* is a nonempty sequence of letters, decimal digits, and underscore characters that must begin with a letter and not end with an underscore.

An AFDL *keyword* is a lower case word prefixed by an underscore; this representation of keywords causes them to be printed as boldface in the Ada FSD.

An AFDL *integer constant* is a nonempty sequence of decimal digits.

AFDL names are partitioned into four classes:

- names of packages and main functions
- names of values and auxiliary functions
- names of syntactic constructs and selectors
- type names

AFDL *package names* and *function names* are upper case identifers; these constitute the lexical class ".procname" in the concrete syntax. AFDL *value names* and *auxiliary function names* are lower case identifiers; these constitute the lexical class ".varname" in the concrete syntax. AFDL *syntactic construct names* and *selector names* are lower case identifiers prefixed with a tilde (~); these constitute the lexical class ".etconst" in the concrete syntax. Syntactic construct and selector names print as lower case italic in the Ada FSD. An AFDL *type name* is an upper case identifier prefixed by a tilde (~); these constitute the lexical class ".typemark" in the concrete syntax. In order that type names be easily distinguishable, the leading tilde of a type name is changed to "#" by the AFDL parser (during formation of AFDL abstract syntax trees), and therefore in the AFDL abstract syntax, type names are upper case identifiers prefixed by a "#".

2.3 DECLARATIONS AND TYPES

A *declaration* is an entity used to associate a name with an object that it represents. Most AFDL + declarations have two parts: a required *specification* part and an optional *initialization* or *body* part. In addition, AFDL has several kinds of type declarations; these are necessary to support the denotational semantics application for which AFDL is used.

2.3.1 Declarations

In AFDL, four kinds of items are declared: variables ("objects" in Ada), functions (Ada value-returning subprograms), packages (of data types together with associated functions) to support the formal definition, and types.

2.3.1.1 Variable declarations

AFDL has a standard kind of variable declaration, consisting of the variable's name, type, and an optional initial value to be assigned to that variable. A variable's type may be regarded as its

"signature". Variables declared within functions are generally initialized, whereas those declared within packages are not. Variable declarations without initializations are called *variable specifications*.

CONCRETE SYNTAX

```
variable_specification :: = .varname : type_id
                          | 2_var_id_list : type_id

variable declaration :: = .varname : type_id : = expression

2_var_id_list :: = .varname , .varname
                 | 2_var_id_list , .varname
```

ABSTRACT SYNTAX

```
var_spec: (VSPEC var_id_s type_id)

var_decl: (VDECL var_id type_id expr)
```

2.3.1.2 Function declarations

AFDL function declarations consist of at least a *function specification*, which consists of the function's name and result type together with the names and types of its formal parameters, plus an optional "initialization", the function's body. Function specifications are used to provide their names and "signature" (i.e., their argument and result types) in packages and also in situations where specifications are necessary to satisfy the "prior declaration" requirement of Ada when functions are declared to be mutually recursive.

CONCRETE SYNTAX

```
function_specification :: = function id formal_part return_type

function_declaration :: = function_specification is function_body

formal_part :: =                        -- empty
               | ( parameter_declaration_list )

parameter_declaration_list :: = parameter_declaration
                              | parameter_declaration_list , parameter_declaration

parameter_declaration :: = name_list : type_id

return_type :: = return type_id

function body :: = declaration_list block_body
                 | block_body

declaration_list :: = declaration ;
                    | declaration_list declaration ;
```

declaration :: = variable_declaration
| function_specification
| function_declaration

ABSTRACT SYNTAX

fun_spec: (FSPEC fun_id fun_type)

fun_decl: (FDECL fun_id fun_type fun_def)

fun_type: (MAP type_id_s type_id)

fun_def: (LAM id_s expr)

In the above abstract syntax, the fun_type is a function's "signature", i.e., the types of its formal parameters and the type of its result. In addition, a function declaration (in contrast to a function specification) has a fun_def, which is similar to a lambda calculus abstraction, whose bound variables are the function's formal parameters and whose body is the function's body.

Like Ada, but unlike lambda calculus, AFDL functions have their actual parameters transmitted *by value*. This causes difficulties when AFDL is used to express certain common denotational semantics idioms that assume evaluation (or parameter transmission) by name. *As a result, "programming" denotational semantics in AFDL must be done with due recognition of this fundamental difference between AFDL and lambda calculus.*

2.3.1.3 Package declarations

Packages are used in AFDL to encapsulate data types (domains and associated functions) that serve as "utility support" for the FSD. There are packages that define the Ada abstract syntax (Appendix G of the Ada FSD [10]), support for the Ada static semantics (Appendix H), support for the dynamic semantics (Appendix I), and basic denotational semantics notions such as environments, a store, and continuations (Appendices J and K). Packages are made visible to one another by means of **use** clauses. As in Ada, package declarations can have only a specification part (called a *package specification*) and an optional body part (a *package body*).

Packages are only syntactic sugar. The package structure cannot be used to resolve ambiguity. All package declarations should be viewed as being global.

CONCRETE SYNTAX

package_specification :: = **package** .procname **is** declarative_item_list **end** function_name_option

package_body :: = **package body** .procname **is** declarative_part **end** function_name_option

declarative_item_list :: = declarative_item ;
| declarative_item_list declarative_item ;

declarative_part :: = declarative_item ;
| package_body ;
| declarative_part declarative_item ;
| declarative_part package_body ;

```
declarative_item :: = variable_specification
                    | variable_declaration
                    | function_specification
                    | function_declaration
                    | type_declaration
                    | function_type_declaration
                    | sum_type_declaration
                    | product_type_declaration
                    | sequence_type_declaration
                    | package_specification
                    | use_clause

type_declaration :: = type type_id is type_definition

use_clause :: = use pkg_id_list
```

ABSTRACT SYNTAX

```
pkg_spec: (PSPEC pkg_id decl_item_s)

pkg_body: (PBODY pkg_id decl_item_s)

decl_item: var_spec
         | var_decl
         | fun_spec
         | fun_decl
         | type_decl
         | fun_type_decl
         | prod_type_decl
         | sum_type_decl
         | seq_type_decl
         | pkg_spec
         | pkg_body
         | use_clause

type_decl: (TDECL type_id type_def)

use_clause: (USE pkg_id_s)
```

2.3.1.4 Type declarations

AFDL + has several kinds of type declarations: those for enumerated, private, function, sum, product, and sequence types. In addition, AFDL + provides a type equivalence declaration to permit certain kinds of type conversions to be expressed.

Enumerated Types

An enumerated type definition is a list of constants. This kind of type is used in the Ada FSD primarily to denote sets, such as the set of node labels in Ada abstract syntax trees, where these

labels control the selection of alternatives in an AFDL **case** statement contained in a semantic function of the Ada FSD.

CONCRETE SYNTAX

type_definition :: = enumerated_type definition

enumerated_type definition :: = (const_id_list)
| (var_id_list)

ABSTRACT SYNTAX

type_def: enum_type

enum_type: const_id_s
| var_id_s

Private Type

The **private** type is present in AFDL packages to indicate those data types whose detailed structure has been left unspecified, in order "not to portray superfluous or extraneous details".

CONCRETE SYNTAX

type_definition :: = **private**

ABSTRACT SYNTAX

type_def: PRIVATE

Function Types

Function types are present in AFDL, but not in Ada. Unlike Ada, AFDL can have function-valued parameters and return function-valued results, and function types are necessary to indicate this. In particular, denotational semantics notions that are intrinsically function-typed, such as continuations, are declared to have function types in AFDL.

CONCRETE SYNTAX

function_type_declaration :: = **function type** type_id (parameter_declaration_list) return_type

ABSTRACT SYNTAX

fun_type_decl: (FNTDECL type_id fun_type)

fun_type: (MAP type_id_s type_id)

A function type declaration specifies the signature of a functional type; its abstract syntactic structure is similar to that of a function specification.

Sum, Product, and Sequence Types

These types, present in AFDL + but not in AFDL, were added to permit the complete specification of the Ada FSD to be done in AFDL + itself. The inclusion of sum, product, and sequence types in AFDL + make it possible to express in the semantic metalanguage essential details currently concealed in private types. A sum (product) type is declared as the sum (product) of a finite number of other types; a sequence type is declared as a finite sequence of another type. In addition to these type-formation operations, other operations are provided. For sum types, projection, injection, and domain query operations are provided. For product types, selection and tupling operations are provided. For sequence types, "head", "tail", concatenation, and sequence construction operations are provided.

CONCRETE SYNTAX

sum_type_declaration :: = **sum type** type_id (2_type_id_list)

product_type_declaration :: = **product type** type_id (2_type_id_list)

sequence_type_declaration :: = **sequence type** type_id type_id

2_type_id_list :: = type_id , type_id
| 2_type_id_list , type_id

ABSTRACT SYNTAX

sum_type_decl: (SMTDECL type_id type_id_s)

prod_type_decl: (PRTDECL type_id type_id_s)

seq_type_decl: (SQTDECL type_id type_id)

Sum and product types T with component types $T_1, ..., T_n$, where $n \geq 2$, are declared via

sum type T ($T_1, ..., T_n$)

product type T ($T_1, ..., T_n$)

where the type identifiers T_i are all distinct.

A sequence type T with components of type S is declared via

sequence type T S

Type Equivalence Declarations

A type T may be declared *equivalent* to a type S by the declaration

type T **is** S .

See Section 2.4.3 for a discussion of the application of type equivalence declarations.

CONCRETE SYNTAX

type_definition :: = type_id

ABSTRACT SYNTAX

type_def: type_id

2.3.1.5 Order of declarations

At the global level, the order of declarations is irrelevant, except that specifications for variables or functions may not occur after the definitions of those objects. Thus "forward declarations" are legal, but unnecessary at this level.

At the local level (i.e., inside functions and variables), the order is relevant. Names are only visible once they are declared. The name of a variable is NOT visible within its own declaration, but the name of a function is. Forward declarations for functions (i.e., occurrences of function specifications (FSPECs)) are legal and *necessary* to effect mutual recursion at a local level. Forward declarations for variables (VSPECs) are not legal. A name may not be declared (with the same type) twice within the same block.

At the global level, variables must not be mutually recursive, i.e., there must be some partial ordering on which variables require the values of other variables in order to produce their own value. This is allowed to be value dependent -- it is as liberal as possible, and is not (and could not be) checked statically. (At present, infinite recursion would result if the value of a variable that was recursively defined in terms of other variables were requested (unless shielded properly with function bodies).)

At the local level, functions must be defined (FDECLed) before they are "used". This is only a problem when variable declarations and function specifications/declarations are intermixed. The actual restriction here is conservative in that it outlaws some programs that could be legal at runtime. A function is considered "used" at the point when a reference to it (not necessarily a call) is contained in the body of a variable declaration (even if shielded within a function declaration that occurs within that variable declaration), or if it occurs within another function that itself has been "used" by this definition. Note the recursion in this definition. If the initialization for a variable *x* contains a reference to a function *f*, and *f* contains a reference to *g*, and *g* contains a reference to *h*, and *h* is not defined before the declaration of *x*, then the program is illegal. These rules allow mutually recursive functions to be declared. Note the distinction between visibility of function names (forward declarations make a function name visible) and the definition of the corresponding functions (only FDECLs do that).

The general idea is that order is not required at the global level, and it is not checked statically that variables do not depend, in a mutually recursive manner, on one another; where at the local level, proper order is required, and some (necessarily conservative) static checking is performed. These choices are largely pragmatic: we found that the global level of the Ada FSD was NOT properly ordered, and performing static checking appeared to be expensive. The checking at the local level catches some errors and allows the linear elaboration of declarations in the compiled code.

2.4 EXPRESSIONS

AFDL + is purely applicative, and thus expressions are the principal computational mechanism in the language. AFDL has two kinds of expressions: "simple" expressions, which are an extended subset of Ada expressions, and "compound" expressions, most of which correspond to certain Ada compound statements. Thus blocks, case "statements", conditional "statements", etc., all yield values. Requiring the **return** expression to be used to return a value from a function as in AFDL is excessively verbose. and thus **return** expressions are treated as comments in AFDL + . Finally, semicolons are made optional in AFDL + where they were formerly required as statement terminators in blocks, case expressions, and conditional expressions in AFDL. These changes are "upward compatible" in the sense that syntactically legal AFDL programs are still syntactically legal in AFDL + .

CONCRETE SYNTAX

```
expression :: = return_expr
              | relation
              | and_expression
              | or_expression
              | xor_expression
              | andthen_expression
              | orelse_expression

and_expression :: = relation and relation
                  | and_expression and relation

or_expression :: = relation or relation
                 | or_expression or relation

xor_expression :: = relation xor relation
                  | xor_expression xor relation

andthen_expression :: = relation and then relation
                      | andthen_expression and then relation

orelse_expression :: = relation or else relation
                     | orelse_expression or else relation

relation :: = simple_expression
            | simple_expression relop simple_expression
            | simple_expression elt type_id

simple_expression :: = sum
                     | simple_expression seq_op sum
                     | simple_expression dom_op type_id
```

```
sum :: = term
        | un_op term
        | sum add_op term

term :: = primary
        | term * primary

primary : = id
          | .integer
          | .string
          | ( expression )
          | ( 2_expression_list )
          | [ 2_expression_list ]
          | [ ]
          | type_coercion
          | if_expr
          | case_expr
          | type_case_expr
          | block
          | function_call
```

ABSTRACT SYNTAX

```
expr: simple_expr
    | (CAST type_id expr)          -- type coercion
    | (IF expr expr expr)          -- conditional
    | (CASE expr alt_s)            -- case
    | (TCASE expr t_alt_s)         -- type case
    | (LET decl_s expr)            -- block
    | (APPLY expr expr_s)          -- function call
    | (WARNING expr msg)           -- from static type checker

simple_expr: (binop expr expr)
           | (unop expr)
           | (ELT expr type_id)
           | (INJ expr type_id)
           | (INJ expr type_id (FROM type_id))
           | (PRO expr type_id)
           | id
           | integer
           | string
           | (PRDEN expr_s)
           | (SQDEN expr_s)
```

Return, type coercion, conditional, case, type case, block, and function call expressions are considered to be "compound" expressions; their concrete syntax is given in Section 2.4.4.

2.4.1 Names

CONCRETE SYNTAX

```
name :: = .varname
        | .procname

id :: = name
      | const_id

function_name_option :: =          -- empty
                        | id

const_id :: = .etconst

type_id :: = .typemark
```

ABSTRACT SYNTAX

```
id: var_id
  | fun_id
  | const_id
  | type_id
```

2.4.2 Operators

The equality comparison of "infinite" values, i.e., values that include closure objects, is illegal.[1] All other values may be compared for equality (this currently is a run-time check in the AFDL virtual machine, although it could be done statically).

CONCRETE SYNTAX

```
relop :: = =
         | / =
         | >
         | > =
         | <
         | < =

un_op :: = -
         | not
         | length

add_op :: = +
          | -
```

[1] Closure objects are representations of function objects. A closure object is a pair of pointers; the first pointer points to a corpus to be executed within an environment pointed to by the second pointer (see [6]). Closure objects can result in circular list structures in their Lisp representations.

```
dom_op ::= inj
         | pro

seq_op ::= :
         | ::
         | &
```

ABSTRACT SYNTAX

```
binop: AND | OR | XOR | ANDTHEN | ORELSE
     | EQ | NE | GT | GE | LT | LE
     | HEAD | TAIL | CAT
     | PLUS | MINUS | TIMES

unop: UMINUS
    | NOT
    | LENGTH
```

2.4.3 Simple Expressions

Simple expressions in AFDL + are used to indicate the application of basic operations to appropriate operands. The standard basic operations in AFDL are

integer arithmetic — binary addition, subtraction, and multiplication; unary negation

boolean operations — conjunction, disjunction, exclusive or, complement, **andthen**, **orelse**

integer relations — equal (=), not equal (/=), greater than (>), greater than or equal (>=), less than (<), less than or equal (<=)

Additional domain operations added in AFDL + for sum, product, and sequence types are

sum types — domain injection (**inj**), projection (**pro**), membership test (**elt**)

product types — domain element selection, tupling

sequence types — "head" (:), "tail" (::), concatenation (&), length (**length**), sequence formation

AFDL + provides several sum domain operations. If T is declared via

sum type T (T_1, ..., T_n),

then x **inj** T injects an element of component type T_i into the sum type T; x **elt** T_i tests whether an element x of sum type T was injected from component type T_i; x **pro** T_i projects an element x of sum type T into component type T_i if x **elt** T_i is true, and otherwise causes a fatal error in the AFDL + virtual machine.

If the product type T is declared via

product type T (T_1, ..., T_n),

then an element of T is constructed from elements x_i of type T_i by the tupling operation (x_1, ..., x_n). The i-th component of a value x of product type T is selected by the operation x:i, where i must be a constant (iiteral).

A sequence type T with components of type S is declared via

sequence type T S.

An element of sequence type T is constructed from elements x_i of type S by the operation [x_1, ..., x_n], $n \geq 0$. [ ] denotes the empty element of any sequence type. The i-th component (head) of an element x of sequence type T is selected by the operation x:i, where i may be any integer expression. The i-th *tail* of x = [x_1, ..., x_n] is selected by the operation x::i, and is equal to [x_{i+1}, ..., x_n] (if i = n then x::i is equal to [ ]). If i is "out of range" (≤ 0 or $> n$) for : or ::, then a fatal error occurs in the AFDL + virtual machine.

A type T may be declared *equivalent* to a type S by the declaration

type T **is** S .

This permits an element x of type T to be converted to type S by applying the *cast* S(x); conversely, an element y of type S can be converted to type T via the cast T(y). Type conversions must be explicit and have no run-time significance. Equivalent types provide a way of declaring a sum type T with multiple components T_i that are equivalent to some type S. If x **elt** T_i, then S(x **pro** T_i) is type S, and if y is an element of type S, then (T_i(y)) **inj** T is an element of type T.

2.4.4 Compound Expressions

Compound expressions in AFDL provide return expressions, conditional (**if-then-else**) expressions, "case" expressions, blocks and local declaration of variables (similar to the "**let** variable = expression **in** expression" capability in lambda calculus), and function application. An additional compound expression in AFDL + is a "type case" expression, in which the case selection expression must evaluate to a value in a sum domain, and a case alternative is selected on the basis of which particular constituent type the case expression possesses.

CONCRETE SYNTAX

return_expr :: = **return** expression

if_expr :: = **if** expression **then** expression semi if_expr_tail

if_expr_tail :: = **else** expression semi **end if**
| **elsif** expression **then** expression semi if_expr_tail

case_expr :: = **case** expression **is** alternative_list **end case**

alternative_list :: = alternative
| alternative_list alternative

```
alternative :: = when choice_list => expression semi

choice_list :: = choice
               | choice_list | choice

choice :: = const_id
          | .varname
          | others

type_case_expr :: = tcase expression is type_alt_list end tcase

type_alt_list :: = type_alt
                 | type_alt_list type_alt

type_alt :: = when .varname : type_id => expression semi
            | when_others .varname : type_id => expression semi

when_others :: = when others

block :: = declare declaration_list block_body
         | block_body

block_body :: = begin expression semi end function_name_option

type_coercion :: = type_id ( expression )

semi :: =                          -- empty
         | ;
```

ABSTRACT SYNTAX

```
expr: (IF expr expr expr)          -- conditional
    | (CASE expr alt_s)            -- case
    | (TCASE expr t_alt_s)         -- type case
    | (LET decl_s expr)            -- block
    | (CAST type_id expr)          -- type coercion
    | (WARNING expr msg)           -- constructed by static type checker

alt: (choice_s expr)

choice: id
      | OTHERS

t_alt: (ALT var_id type_id expr)
     | (OTHERS var_id type_id expr)
```

The AFDL *type case* expression is a variant of the usual case construct and is provided to simplify the manipulation of sum types. The **tcase** (type case) expression

```
tcase expr is
        when t1: T1 => expr1 ;
        ...
        when tn: Tn => exprn ;
        when others t: T => default
end tcase
```

evaluates $expr_i$ in a new scope in which t_i is bound to expr **pro** T_i if expr **elt** T_i, and yields the resulting value as the value of the type case expression. If a **when** clause for the appropriate T is not provided, then if the **others** clause is present, "default" is evaluated in a scope in which t is bound to expr, and the resulting value is yielded as the value of the type case expression; otherwise, a fatal error occurs.

2.5 FUNCTIONS

Functions in AFDL + are like those in Ada, except that AFDL + functions can take function-valued parameters and return function-valued results. This enhancement enables AFDL + to be used for programming denotational semantic definitions. Actual parameters of AFDL + functions are bound to corresponding formal parameters *by value*; consequently, programming denotational semantic definitions in AFDL + must be done carefully, in order to avoid using lambda calculus idioms whose correctness depends upon parameter binding by name.

A common situation in which transmission of actual parameters by value would lead to nontermination whereas transmission by name would not, is the evaluation of the semantics of a recursively defined construct such as a **while** loop, using continuation semantics. The evaluation of the semantics of a **while** loop requires evaluation of the value of the test expression followed by the semantic evaluation of the loop body if the test value is *true*. This latter semantic evaluation invokes a function that takes as an actual parameter the continuation (a function) that continues the computation after the traversal of the body. This continuation (recursively) computes the semantics of the *entire* **while** loop (given a new state). If an attempt is made to first evaluate this continuation (which represents the entire possible future behavior of the **while** loop), then an infinite semantic computation will result. The usual way to avoid this phenomenon is to simulate parameter transmission by name by "encapsulating" the offending actual parameter inside a function literal (sometimes called a "thunk"), producing a closure object as an actual parameter value and thereby "suspending" further evaluation involving this parameter until it is later applied to a state.

A detailed illustration of this situation, in the context of the formal semantic definition of Gordon's pedagogical programming language TINY [9], is given in [2].

CONCRETE SYNTAX

```
function_call :: = id ( )
                 | id ( expression_list )
                 | curried_function_call ( )
                 | curried_function_call ( expression_list )
```

```
curried_function_call :: = id ( )
                         | id ( expression_list )
                         | curried_function_call ( )
                          | curried_function_call ( expression_list )
```

ABSTRACT SYNTAX

```
expr: (APPLY expr expr_s)
```

AFDL + functions have their actual parameters bound *by value*, as previously mentioned. To facilitate the programming of denotational semantics, AFDL + functions are *curried*.

2.6 PACKAGES

AFDL + packages, like those in Ada, are used to specify collections of logically related entities. In the Ada FSD, packages are used to define abstract data types that support the functions that comprise the main portion of the FSD. In particular, the Ada FSD contains packages that define the Ada abstract syntax, the static and dynamic environments, and continuations and an abstract store.

The syntax of packages is described in Section 2.3.1.3.

2.7 PROGRAM STRUCTURE

AFDL + program structure reflects that of the Ada FSD. The main corpus of the FSD consists of a nonempty sequence of (mutually recursive) function declarations. The "support" for the FSD, contained in appendices, consists of nonempty sequences of package declarations and package bodies. An AFDL + "compilation unit", therefore, is a function declaration, a package declaration, or a package body; an AFDL + program is a nonempty sequence of compilation units.

CONCRETE SYNTAX

```
afdl_program :: = compilation_unit_list

compilation_unit_list :: = compilation_unit ;
                         | compilation_unit_list compilation_unit ;

compilation_unit :: = function_declaration
                    | package_specification
                    | package_body
```

ABSTRACT SYNTAX

```
program: comp_unit_s

comp_unit: fun_decl
         | fun_spec
         | pkg_spec
         | pkg_body
```

3. AFDL+ TRANSCRIPTS

This chapter consists of several AFDL + [3] transcripts in which a definition of Gordon's example programming language "TINY" ([9]. pp. 57-61) is "debugged." Three versions of the Tiny definition are used for illustration as follows:

- Version 1 of the Tiny definition contains a type error that is detected statically by the AFDL + Typechecker.
- Version 2 of the definition, in which this type error has been corrected, contains no type errors, but results in infinite recursion due to AFDL + 's *call-by-value* parameter passing rule.
- Version 3, the final version of the definition, in which an expression that yields a functional value has been "shielded" by a function definition, executes correctly on a sample Tiny program.

We have made efforts to include enough comments in the transcripts so that this chapter stands on its own. However, if more than a superficial understanding of the contents is desired, we expect the reader to be familiar with the Interlisp language. the AFDL + Typechecker [7], Compiler [5], and Virtual-Machine [6] documentation.

We first present the third and *final* version of the AFDL + definition of Tiny. This is the version without errors. The differences between the correct Version 3 and the incorrect Versions 1 and 2 will be discussed subsequently.

```
package TINY is

-- Syntactic Domains

sum type EXPR (INTEGER, BOOLEAN, IDENT, READ, NOT, EQUAL, PLUS);

type IDENT is STRING;
type READ is private;
type NOT is EXPR;
product type EQUAL (EXPR, EXPR);
product type PLUS (EXPR, EXPR);

sum type COM (ASSIGN, OUTPUT, IF, WHILE, SEQ);

product type ASSIGN (IDENT, EXPR);
type OUTPUT is EXPR;
product type IF (EXPR, COM, COM);
product type WHILE (EXPR, COM);
product type SEQ (COM, COM);


-- Semantic Domains

product type STATE (MEMORY, INPUT);
```

```
function type MEMORY (id: IDENT) return VALUE_OR_UNBOUND;
sum type VALUE_OR_UNBOUND (VALUE, UNBOUND_VALUE);
type UNBOUND_VALUE is (unbound);

sequence type INPUT VALUE;

sum type VALUE (INTEGER, BOOLEAN);

function type CONT (state: STATE) return ANS;
function type ECONT (value: VALUE) return CONT;

sum type ANS (FINAL_ANSWER, PARTIAL_ANSWER);
type FINAL_ANSWER is (error, stop);
product type PARTIAL_ANSWER (VALUE, ANS);


-- Auxiliary Functions

function update (memory: MEMORY; value: VALUE; id: IDENT)
          return MEMORY is
  function new_memory (ident: IDENT) return VALUE_OR_UNBOUND is
    begin
      if ident = id
      then value inj VALUE_OR_UNBOUND
      else memory(ident)
      end if
    end new_memory;
begin
  new_memory
end update;

function value_of (memory: MEMORY; id: IDENT) return VALUE_OR_UNBOUND is
begin
  memory(id)
end value_of;

function error (state: STATE) return ANS is
begin
  error inj ANS
end error;

function final (state: STATE) return ANS is
begin
  stop inj ANS
end final;

function initial_memory (id: IDENT) return VALUE_OR_UNBOUND is
begin
  unbound inj VALUE_OR_UNBOUND
end intitial_memory;
```

```
-- Semantic Functions

function EVAL_EXPR (expr: EXPR; econt: ECONT) return CONT is
begin
  tcase expr is
    when integer: INTEGER => econt(integer inj VALUE);
    when boolean: BOOLEAN => econt(boolean inj VALUE);
    when ident: IDENT =>
      declare
        function cont (state: STATE) return ANS is
          value: VALUE_OR_UNBOUND := value_of(state:1, ident);
        begin
          if value elt UNBOUND_VALUE
          then error inj ANS
          else econt(value pro VALUE)(state)
          end if
        end cont;
      begin
        cont
      end;
    when read: READ =>
      declare
        function cont (state: STATE) return ANS is
        begin
          if state:2 = [ ]
          then error inj ANS
          else econt(state:2:1)((state:1, state:2::1))
          end if
        end cont;
      begin
        cont
      end;
    when not: NOT =>
      EVAL_EXPR
      ( EXPR(not),
        declare
          function new_econt (value: VALUE)
                        return CONT is
          begin
            if value elt BOOLEAN
            then econt((not (value pro BOOLEAN))
                                inj VALUE)
            else error
            end if
          end new_econt;
        begin
          new_econt
        end);
```

```
        when equal: EQUAL =>
          EVAL_EXPR
          ( equal:1,
            declare
              function econt1 (value1: VALUE) return CONT is
                begin
                  EVAL_EXPR
                  ( equal:2,
                    declare
                      function econt2 (value2: VALUE)
                                return CONT is
                      begin
                        econt((value1 = value2) inj VALUE)
                      end econt2;
                    begin
                      econt2
                    end)
                end econt1;
            begin
              econt1
            end);
        when plus: PLUS =>
          EVAL_EXPR
          ( plus:1,
            declare
              function econt1 (value1: VALUE) return CONT is
                begin
                  EVAL_EXPR
                  ( plus:2,
                    declare
                      function econt2 (value2: VALUE)
                                return CONT is
                      begin
                        if value1 elt INTEGER and
                          value2 elt INTEGER
                        then econt( ((value1 pro INTEGER) +
                                     (value2 pro INTEGER))
                                       inj VALUE)
                        else error
                        end if
                      end econt2;
                    begin
                      econt2
                    end)
                end econt1;
            begin
              econt1
            end)
      end tcase
    end EVAL_EXPR;
```

```
function EVAL_COM (com: COM; cont: CONT) return CONT is
begin
  tcase com is
    when ass: ASSIGN =>
      EVAL_EXPR
      ( ass:2,
        declare
          function econt (value: VALUE) return CONT is
            function new_cont (state: STATE) return ANS is
            begin
              cont( (update(state:1, value, ass:1), state:2) )
            end new_cont;
          begin
            new_cont
          end econt;
        begin
          econt
        end);
    when out: OUTPUT =>
      EVAL_EXPR
      ( EXPR(out),
        declare
          function econt (value: VALUE) return CONT is
          begin
            declare
              function new_cont (state: STATE)
                        return ANS is
              begin
                (value, cont(state)) inj ANS
              end new_cont;
            begin
              new_cont
            end
          end econt;
        begin
          econt
        end);
    when if: IF =>
      EVAL_EXPR
      ( if:1,
        declare
          function econt (value: VALUE) return CONT is
          begin
            if value elt BOOLEAN
            then
              if value pro BOOLEAN
              then EVAL_COM(if:2, cont)
              else EVAL_COM(if:3, cont)
              end if
```

```
                else error
                end if
              end econt;
            begin
              econt
            end);
        when while: WHILE =>
          declare
          EVAL_EXPR
          ( while:1,
            declare
              function econt (value: VALUE) return CONT is
              begin
                if value elt BOOLEAN
                then
                  if value pro BOOLEAN
                  then EVAL_COM
                              (while:2,
                               declare
                                 function while_cont
                                          (state: STATE) return ANS is
                                 begin
                                   EVAL_COM(com, cont)(state)
                                 end while_cont;
                               begin
                                 while_cont
                               end
                              )
                  else cont
                  end if
                else error
                end if
              end econt;
            begin
              econt
            end
          )
        when seq: SEQ =>
          EVAL_COM(seq:1, EVAL_COM(seq:2, cont))
      end tcase
    end EVAL_COM;

    end TINY;
```

Version 1 of the definition differs from Version 3, shown above, in two respects. First, the "*IDENT*" alternative of the "**tcase**" of "EVAL_EXPR" consists of the following, in which the curried application of a continuation to "state" in the 8th line has been omitted (i.e., commented out). This results in a type mismatch since a value of type "*CONT*" is yielded where "*ANS*" is required.

```
    when ident: IDENT =>
```

```
declare
  function cont (state: STATE) return ANS is
    value: VALUE_OR_UNBOUND := value_of(state:1, ident);
  begin
    if value elt UNBOUND_VALUE
    then error inj ANS
    else econt(value pro VALUE)   -- (state)
    end if
  end cont;
begin
  cont
end;
```

Second, the "*WHILE*" alternative of the "**tcase**" in "EVAL_COM" consists of the following, in which the continuation-valued actual parameter "EVAL_COM(com, cont)" (passed by *value* to the invocation of "EVAL_COM" that evaluates the effect of traversing the body of a "**while**" loop) is not "shielded" by the function "while_cont". This will result in infinite recursion when the Tiny definition is applied to Tiny programs that contain "**while**" loops in which the boolean expression parts do not reference or modify the state (i.e., contain no variable references or "**read**" expressions). The introduction of "while_cont" simulates passing "EVAL_COM(com, cont)" by *name*.

```
when while: WHILE =>
  EVAL_EXPR
  ( while:1,
    declare
      function econt (value: VALUE) return CONT is
      begin
        if value elt BOOLEAN
        then
          if value pro BOOLEAN
          then EVAL_COM
                    (while:2,
                     EVAL_COM(com, cont)
                    )
          else cont
          end if
        else error
        end if
      end econt;
    begin
      econt
    end)
```

Version 2 of the Tiny definition contains only the "*WHILE*" alternative error (i.e., it was obtained from Version 1 by correcting the "*IDENT*" error).

The Tiny program that was used to test the Tiny definition appears next. This program reads integers from the input stream, and outputs the corresponding factorials to the output stream. Since Tiny does not contain a multiplication operation, iterative addition is used instead. The program halts with an error when the input stream is exhausted.

```
while true
  do
    num := read; res := 1; i := 2;

    while not (i = (num + 1))
      do
        x := res; j := 1;

        while not (j = i)
          do
            res := res + x; j := j + 1
          od;

        i := i + 1
      od;

    output res
  od
```

In the following we present five transcripts of operations on the TINY definition and the above program in the TINY language. In Transcript I we present the parsing of the TINY definition. For illustrative purposes, two syntax errors were introduced into Version 3 of the TINY definition. These are detected during the parse. In Transcript II the static semantic error in Version 1 of the TINY definition is detected. In Transcript III Version 2 of the TINY definition passes the static semantic check and is compiled and run on the virtual-machine. During the run an error is detected in the definition. Transcript IV, shows the interpretation of Version 3 the TINY definition after this "infinite recursion" error has been corrected. In this transcript the TINY definition is made to interpret the TINY program shown above. In the final transcript, Transcript V, we illustrate the capability of the virtual-machine to optimize tail recursion. This capability can be turned on or off by the user at run time by setting or resetting a flag and is expected to be useful in improving efficiency during interpretation of large semantic definitions. The correct version of the TINY definition, Version 3, is used for Transcript V.

NOTE: Comments appear in *italics* in all of the transcripts.

Transcript I: Parsing and Storage of Abstract Syntax Trees

In this transcript we show the process of parsing Version 3 of the TINY definition into which two minor syntax errors were deliberately introduced.

> *We first try to parse the text of the TINY definition without generating the abstract syntax trees. This is done by making the second parameter to the parse* command be NIL i.e., by omitting it. The parsing is faster as a result. The first error found is a semicolon where a colon should appear.*

```
1_parse* TINY-DEFINITION.TXT
Parsing file <AU-ADA>TINY-DEFINITION.TXT.1

    _function new_memory (ident; ~IDENT) _return ~VALUE_OR_UNBOUND _is
*********************************
```

```
***ERROR*** LINE 47: Syntax error in state 39
help!

(HELP broken)
2:quit
NIL
```

The parse error puts us in a Lisp break. We exit Lisp, fix up the parse error just found, and return to Lisp. We exit the break by typing a ↑ and then redo the parse command. The next error found is a misspelled type identifier; all type identifiers in AFDL are upper-case identifiers prefixed with a tilde.*

```
3:↑

3_redo parse*
Parsing file <AU-ADA>TINY-DEFINITION.TXT.2

_function error (state: ~STaTE) _return ~ANS _is
******************************

***ERROR*** LINE 63: Syntax error in state 112
help!

(HELP broken)
4:quit
NIL
```

Again exit, fix up the error and return. The next redo of the parse command finds no errors.*

```
5:↑

5_redo parse*
Parsing file <AU-ADA>TINY-DEFINITION.TXT.3
End of file <AU-ADA>TINY-DEFINITION.TXT.3
Done.
```

We do the parse again, this time providing T as the second parameter to the parse command. This causes the abstract syntax trees to be generated. As each program unit is parsed (in this case only one, the package TINY), its name is printed out by the semantic action appended to the topmost concrete syntax production of the AFDL+ language. During parsing the Control-L character is defined as an interrupt character. Typing a ↑L prints out the index of the line in the file on which the lexer is currently working, along with the load average.*

```
6_parse* TINY-DEFINITION.TXT T
Parsing file <AU-ADA>TINY-DEFINITION.TXT.3
PARSING AT LINE 98, LOAD 10.9
PARSING AT LINE 126, LOAD 9.9
PARSING AT LINE 137, LOAD 10.0
PARSING AT LINE 194, LOAD 10.2
TINY
End of file <AU-ADA>TINY-DEFINITION.TXT.3
Done.
```

Next we use the saveafdl command to save the generated abstract syntax trees in a structuredfile. The property list (CHAPTER SMALL) is given to each unit being stored. This is used by the Typechecker in reporting the full name of contexts in which errors exist (see Transcript II). The CHAPTER property is particularly useful in processing the Ada FSD; it enables each semantic function to be located to within a Chapter of the FSD. The third parameter T ensures that a new version of the output file is created. If it had been omitted or NIL, the abstract syntax trees being saved would have been added to the contents of the latest version of the output file.*

```
7_saveafdl* TINY-DEFINITION.AS (CHAPTER SMALL)
...T
<AU-ADA>TINY-DEFINITION.AS.1
8_
```

Transcript II: Static Semantic Error
Tiny Definition, Version 1

The transcript of the application of the AFDL + tools to Version 1 of the Tiny definition appears next. Not shown are the stages in which Version 1 of the AFDL + Tiny definition and the Tiny program are parsed and output to structuredfiles (see Transcript I above). (A parser for Tiny was generated in the same way that AFDL + and Ada parsers have been generated.) Since a type-error is uncovered, the Compiler and Virtual-machine are not run in this example.

```
1_(TCTypeCheck 'TINY-DEFINITION.AS 'TINY-DEFINITION-SYMTAB]
?TC:  "[TypeIf:]" "[in:]" SMALL.TINY.EVAL_EXPR.ident.cont Incompatible then
                  and else expressions
?TC:  "[3Fun:]" "[in:]" SMALL.TINY Invalid function declaration "[name:]"
                EVAL_EXPR "[type:]" (FUN (#EXPR #ECONT)
                                         #CONT)
?TC:  "[Pass3:]" Error during Pass 3
?TC:  "[TypeCheck:]" Fatal error
NIL
```

*Run the Typechecker on the structuredfile "TINY-DEFINITION.AS" produced by the parser, producing a symboltable "TINY-DEFINITION-SYMTAB". An error is detected: the "**then**" and "**else**" parts of a conditional, in "ident.cont", in function "EVAL_EXPR", in package "TINY", and in chapter "SMALL", yield incompatible types.*

```
2_(NILL (symtab _ (SYMOpenTable 'TINY-DEFINITION-SYMTAB]
NIL
```

Open the symboltable produced by the Typechecker. The function "NILL" is used to prevent values yielded by expressions from being printed.

```
3_(NILL (evalexpr _ (SYMGetValue symtab NIL T 'EVAL_EXPR):1]
NIL
```

Extract the body of "EVAL_EXPR" from the symboltable.

```
4_(EV evalexpr]
edit
```

Edit the function body. Travel to the "IDENT" alternative.

```
1*p
(LAM (expr econt) (TCASE expr &))

2*-1 p
(TCASE expr (& & & & & &))

4*-1 p
((ALT integer #INTEGER &) (ALT boolean #BOOLEAN &) (ALT ident #IDENT &)
(ALT read #READ &) (ALT not #NOT &) (ALT equal #EQUAL &) (ALT plus #PLUS &))

6*F ident

7*pp
(ident
  #IDENT
  (LET
    [(FDECL
       cont
       (MAP (#STATE)
            #ANS)
       (LAM
         (state)
         (TYPE
           NIL
           (LET
             ((VDECL value #VALUE_OR_UNBOUND
                     (APPLY value_of
                            ((HEAD state 1)
                             ident))))
             (TYPE
               NIL
               (ERROR [IF (TYPE (#BOOLEAN)
                                (ELT (TYPE (#VALUE_OR_UNBOUND)
                                           value)
                                     #UNBOUND_VALUE))
                          (TYPE (#ANS)
                                (INJ (TYPE (#FINAL_ANSWER)
                                           ~error)
                                     #ANS))
                          (TYPE (#CONT)
                                (APPLY (TYPE (#ECONT)
                                             econt)
                                       ((TYPE (#VALUE)
                                              (PRO (TYPE (#VALUE_OR_UNBOUND)
                                                         value)
                                                   #VALUE]
                       ("[TypeIf:]" "[in:]" SMALL.TINY.EVAL_EXPR.ident.cont
                                    Incompatible then and else expressions]
    cont))
```

*Print the "IDENT" alternative. It can be seen that a conditional is annotated with the error message that was printed above, and that the "**then**" part of that conditional yields a value of type "ANS" whereas the "**else**" part yields "CONT". Since a value of type "ANS" is required, the "**else**" part must be in error.*

```
8*OK
evalexpr
```

Exit the editor.

```
5_(SYMCloseTable symtab]
T
```

Close the symboltable.

Transcript III: Dynamic Semantic Error
Tiny Definition, Version 2

The transcript of the application of the AFDL + tools to the *second* version of the Tiny definition, in which the above error had been corrected, appears next. Again, the parsing stages are not shown.

In this transcript, as well as in Transcript IV (following), certain compiler-generated unique compound names appear. The AFDL compiler [5] generates these names to uniquely identify contexts and declared objects within AFDL programs. For example, these unique names are useful in specifying which of several continuations, declared with the same name "continue1" (as is done in the Ada FSD), is being designated in a discussion or program trace. These unique names consist of several sections separated by periods, where each section is either an AFDL identifier or a non-negative decimal integer, e.g., `EVAL_COM.4.1.econt.1.while_cont`. These names are formed in the following way. The scope that is the entire body of a top-level AFDL function is named with the name of that top-level function itself. This scope is the one in which (conceptually) only formal parameters of the function are declared. Each subsequent nesting of a block within a scope introduces an additional period and section in the unique name. Blocks at the same nesting level are named by numbering them in order of occurrence, beginning with 1. The compiler produces code that introduces a new block (and hence nesting level) for

1. each LET (AFDL **declare-begin-end** construct), and
2. each alternative of a TCASE

in the AFDL abstract syntax.

Thus the compound name `EVAL_COM.4.1.econt.1.while_cont` is the *fully-qualified name* of a unique object that is possibly one of many objects declared with the same name `while_cont`. The fully-qualified name of an object provides a way of unambiguously locating it within an AFDL program. Thus in the above name, `while_cont` is located by going into the body of the top-level function `EVAL_COM`, then proceeding to the fourth block within it and to the first block within that block. A function `econt` will be found to be declared at this point. The designated object `while_cont` is located (declared) in the first block within `econt`.

The compiler-generated fully-qualified names are particularly useful for locating the body (program) part of a closure object. Internally, a typical closure object is of the form

```
(INT#ClosureObject (EVAL_COM 142) (INT#Frame ...))
```

where the body part `(EVAL_COM 142)` points to a location within `EVAL_COM` via an offset `142`. This particular example corresponds to a closure object formed from a continuation declared within the body of the function `EVAL_COM`. Since there may be several such continuations the offset is a poor indication of which particular continuation is being pointed to. Therefore, a more readable form of

this pointer is the corresponding fully-qualified name. Accordingly, closure objects are displayed together with the fully-qualified name that designates their body part. Thus the above closure object would be displayed as (see step 12 of Transcript III below)

```
("EVAL_COM.4.1.econt" : (INT#ClosureObject ( ... ) ( ... ))).
```

Transcript III now follows.

```
1_(TCTypeCheck 'TINY-DEFINITION.AS 'TINY-DEFINITION-SYMTAB]
T
```

Type-check the structuredfile "TINY-DEFINITION.AS", producing the symboltable "TINY-DEFINITION-SYMTAB". No errors.

```
2_compile* TINY-DEFINITION-SYMTAB
update                    21        (FUN (#MEMORY #VALUE #IDENT) #MEMORY)
value_of                  7         (FUN (#MEMORY #IDENT) #VALUE_OR_UNBOUND)
error                     6         (FUN (#STATE) #ANS)
final                     6         (FUN (#STATE) #ANS)
initial_memory            6         (FUN (#IDENT) #VALUE_OR_UNBOUND)
EVAL_EXPR                 242       (FUN (#EXPR #ECONT) #CONT)
EVAL_COM                  200       (FUN (#COM #CONT) #CONT)

      0 Warnings
      0 Fatal Errors

TINY-DEFINITION-SYMTAB -- Compilation complete.
NIL
```

Compile the symboltable. The compile Lispxmacro calls the function COM#CompileSymbolTable and if given a second argument of T would produce a compiler listing file. The integers in the second column are the number of instructions compiled for the corresponding symbol.*

```
3_(tinystf _ (STFOpenFile 'TINY-TEST-AS.TXT]
Loading directory of TINY-TEST-AS.TXT
  Last updated 10-Jun-82 11:50:18
TINY-TEST-AS.TXT#STFDIR
```

Open the structured file that contains the abstract syntax form of the Tiny program.

```
4_(NILL (tinyprogram _ (STFGetObject tinystf 'TinyProgram):1:1]
NIL
```

Extract the tiny program from the structuredfile. The ":1:1" CLISP selection on the value returned by STFGetObject reflects the structure of the abstract syntax of the TINY language. The first :1 is necessary because STFGetObject returns a list of items that are stored in the structuredfile on the key given as an argument to the function. An item is of the form (object prop1 value1 prop2 value2 ...). Therefore, the following :1 selects the body of the tiny program as pretty printed below.

```
5_(PP tinyprogram]

  [#WHILE
    ((#BOOLEAN true)
     (#SEQ
       ([#SEQ
          ((#SEQ ((#SEQ ((#ASSIGN ("num" (#READ NIL)))
                         (#ASSIGN ("res" (#INTEGER 1)))))
                  (#ASSIGN ("i" (#INTEGER 2)))))
           (#WHILE
             ([#NOT (#EQUAL ((#IDENT "i")
                             (#PLUS ((#IDENT "num")
                                     (#INTEGER 1]
              (#SEQ
                ([#SEQ
                   ((#SEQ ((#ASSIGN ("x" (#IDENT "res")))
                           (#ASSIGN ("j" (#INTEGER 1)))))
                    (#WHILE ((#NOT (#EQUAL ((#IDENT "j")
                                            (#IDENT "i"))))
                             (#SEQ ((#ASSIGN ("res" (#PLUS ((#IDENT "res")
                                                            (#IDENT "x")))))
                                    (#ASSIGN ("j" (#PLUS ((#IDENT "j")
                                                          (#INTEGER 1]
                  (#ASSIGN ("i" (#PLUS ((#IDENT "i")
                                        (#INTEGER 1]
        (#OUTPUT (#IDENT "res"]
(tinyprogram)
```

Pretty-print the Tiny program. The program has AFDL+ type "COM". Note the sum-type tags such as "#SEQ".

```
6_(NILL (ms _ (INT#CreateMachineState (SYMOpenTable 'TINY-DEFINITION-SYMTAB]
NIL
```

Create a Virtual-machine machine-state that contains a compiled-code pointer to the open symboltable "TINY-DEFINITION-SYMTAB".

```
7_(INT#LoadApply ms
      (INT#TopLevelClosureObject 'EVAL_COM)
      < tinyprogram
        (INT#TopLevelClosureObject 'final) >]
T
```

Prepare the machine to apply "EVAL_COM" to the command "tinyprogram" and continuation "final".

```
8_(INT#Break ms (INT#ApplyBreak 'EVAL_COM) (INT#ApplyBreak 'EVAL_EXPR)
                (INT#ApplyBreak 'cont) (INT#ApplyBreak 'econt]
T
```

Set breakpoints on calls to and returns from "EVAL_COM", "EVAL_EXPR", "cont" and "econt".

```
9_Run ms
Broken after *BINDF* in EVAL_COM
          (Broken before EVAL_COM)
NIL
```

Begin running the initialized machine. Machine breaks upon entry to "EVAL_COM".

```
10_CF
EVAL_COM
     com       (#WHILE ((#BOOLEAN true) (#SEQ ((#SEQ ((#SEQ ((#SEQ (& &))
(#ASSIGN ("i" &)))) (#WHILE ((#NOT (#EQUAL &)) (#SEQ (& &)))))) (#OUTPUT
(#IDENT "res"))))))
     cont      ("final" : (INT#ClosureObject (final 1) NIL))
Dynamic chain:  NIL
NIL
```

*View the current frame of the machine. The values of the command "com" and continuation "cont" are displayed. "com" is a "**while**" loop, and is the entire tiny program.*

```
11_Run
Broken after *BINDF* in EVAL_EXPR
          (Broken before EVAL_EXPR)
T
```

Begin running again. Machine breaks upon entry to "EVAL_EXPR".

```
12_CF
EVAL_EXPR
     expr      (#BOOLEAN true)
     econt     ("EVAL_COM.4.1.econt" : (INT#ClosureObject (EVAL_COM 142)
(INT#Frame EVAL_COM.4.1 & & &)))
Dynamic chain:  EVAL_COM.4
NIL
```

*The expression being evaluated is the boolean expression "true", which is the boolean expression of the outer "**while**" loop. The state is not required to evaluate it.*

```
13_Run
Broken after *BINDF* in EVAL_COM.4.1.econt
          (Broken before econt)
T
```

*The value "true" is supplied to the expression continuation "econt" of step 12. "econt" was passed by the "WHILE" "**tcase**" alternative of "EVAL_COM" to "EVAL_EXPR".*

```
14_CF
EVAL_COM.4.1.econt
     value     (#BOOLEAN true)
Dynamic chain:  EVAL_EXPR.2
NIL

15_Run
Broken after *BINDF* in EVAL_COM
          (Broken before EVAL_COM)
T
```

*Since "value" was "true", "EVAL_COM" should now be called with the statement part of the "**while**" statement and a continuation that will evaluate the loop again. Since*

AFDL + has call-by-value semantics, these arguments are first computed. The statement part is evaluated and pushed on the stack, and then "EVAL_COM" is called to produce the continuation. Unfortunately, this process repeats forever, as the following steps show.

```
16_CF
EVAL_COM
     com       (#WHILE ((#BOOLEAN true) (#SEQ ((#SEQ ((#SEQ ((#SEQ (& &))
(#ASSIGN ("i" &)))) (#WHILE ((#NOT (#EQUAL &)) (#SEQ (& &)))))) (#OUTPUT
(#IDENT "res"))))))
     cont      ("final" : (INT#ClosureObject (final 1) NIL))
Dynamic chain:  EVAL_COM.4.1.econt
NIL
```

The invocation of "EVAL_COM" that must produce the continuation is entered.

```
17_Stk
1         (#SEQ ((#SEQ ((#SEQ ((#SEQ ((#ASSIGN ("num" &)) (#ASSIGN
("res" &)))) (#ASSIGN ("i" (#INTEGER 2))))) (#WHILE ((#NOT (#EQUAL
((#IDENT "i") (#PLUS &)))) (#SEQ ((#SEQ (& &)) (#ASSIGN ("i" &))))))))
(#OUTPUT (#IDENT "res"))))
NIL
```

*The stack now contains the statement part of the "**while**" loop.*

```
18_Run
Broken after *BINDF* in EVAL_EXPR
          (Broken before EVAL_EXPR)
T
```

"EVAL_EXPR" is called again on the loop's boolean expression "true".

```
19_CF
EVAL_EXPR
     expr      (#BOOLEAN true)
     econt     ("EVAL_COM.4.1.econt" : (INT#ClosureObject (EVAL_COM 142)
(INT#Frame EVAL_COM.4.1 & & &)))
Dynamic chain:  EVAL_COM.4
NIL

20_Run
Broken after *BINDF* in EVAL_COM.4.1.econt
          (broken before econt)
T
```

The expression continuation in "EVAL_COM" is called again with "true".

```
21_CF
EVAL_COM.4.1.econt
     value     (#BOOLEAN true)
Dynamic chain:  EVAL_EXPR.2
NIL

22_Run
Broken after *BINDF* in EVAL_COM
```

```
          (Broken before EVAL_COM)
T
```

And yet another attempt is made to produce a continuation to the evaluation of the statement part.

```
23_CF
EVAL_COM
     com       (#WHILE ((#BOOLEAN true) (#SEQ ((#SEQ ((#SEQ ((#SEQ (& &))
(#ASSIGN ("i" &)))) (#WHILE ((#NOT (#EQUAL &)) (#SEQ (& &)))))) (#OUTPUT
(#IDENT "res"))))))
     cont      ("final" : (INT#ClosureObject (final 1) NIL))
Dynamic chain:  EVAL_COM.4.1.econt
NIL

24_Stk
1          (#SEQ ((#SEQ ((#SEQ ((#SEQ ((#ASSIGN ("num" &)) (#ASSIGN
("res" &)))) (#ASSIGN ("i" (#INTEGER 2))))) (#WHILE ((#NOT (#EQUAL
((#IDENT "i") (#PLUS &)))) (#SEQ ((#SEQ (& &)) (#ASSIGN ("i" &))))))))
(#OUTPUT (#IDENT "res"))))
2          (#SEQ ((#SEQ ((#SEQ ((#SEQ ((#ASSIGN ("num" &)) (#ASSIGN
("res" &)))) (#ASSIGN ("i" (#INTEGER 2))))) (#WHILE ((#NOT (#EQUAL
((#IDENT "i") (#PLUS &)))) (#SEQ ((#SEQ (& &)) (#ASSIGN ("i" &))))))))
(#OUTPUT (#IDENT "res"))))
NIL
```

*The statement part of the "**while**" loop has now been pushed onto the stack twice.*

```
25_DC
+  EVAL_COM
+  EVAL_COM.4.1.econt
   EVAL_EXPR.2
+  EVAL_EXPR
   EVAL_COM.4
+  EVAL_COM
+  EVAL_COM.4.1.econt
   EVAL_EXPR.2
+  EVAL_EXPR
   EVAL_COM.4
+  EVAL_COM
NIL
```

*Display the dynamic chain. An obvious pattern can be seen, and would continue forever. The statement part of the "**while**" loop will never be evaluated, because its continuation can never be produced. Note that the "+" signs mark frames that have explicit dynamic chain pointers, i.e., were created by "call" instructions.*

Transcript IV: Successful Interpretation Tiny Definition, Version 3

The transcript of the application of the AFDL+ tools to Version 3, the *final* version of the Tiny definition, appears next. In this version the recursive continuation "EVAL_COM(com, cont)" of the "*WHILE*" alternative of "EVAL_COM" has been "shielded" by the function "new_cont", in order to simulate passing the continuation to "EVAL_COM" by name.

```
1_tc* TINY-DEFINITION.AS TINY-DEFINITION-SYMTAB
T
```

We use the tc* *command here which is exactly equivalent to calling the function* TCTypeCheck *as in Transcripts II and III. This command is provided as a user convenience.*

```
2_compile* TINY-DEFINITION-SYMTAB
update                    21        (FUN (#MEMORY #VALUE #IDENT) #MEMORY)
value_of                  7         (FUN (#MEMORY #IDENT) #VALUE_OR_UNBOUND)
error                     6         (FUN (#STATE) #ANS)
final                     6         (FUN (#STATE) #ANS)
initial_memory            6         (FUN (#IDENT) #VALUE_OR_UNBOUND)
EVAL_EXPR                 242       (FUN (#EXPR #ECONT) #CONT)
EVAL_COM                  210       (FUN (#COM #CONT) #CONT)

      0 Warnings
      0 Fatal Errors

TINY-DEFINITION-SYMTAB -- Compilation complete.
NIL
```

The definition is compiled. The integers in the second column are the number of virtual-machine instructions compiled for the corresponding AFDL object.

```
3_(NILL (tinystf _ (STFOpenFile 'TINY-TEST-AS.TXT]
Loading directory of TINY-TEST-AS.TXT
  Last updated 10-Jun-82 11:50:18
NIL

4_(NILL (tinyprogram _ (STFGetObject tinystf 'TinyProgram):1:1]
NIL

5_(NILL (ms _ (INT#CreateMachineState (SYMOpenTable 'TINY-DEFINITION-SYMTAB]
(ms reset)
NIL

6_(INT#LoadApply ms
      (INT#TopLevelClosureObject 'EVAL_COM)
      < tinyprogram
        (INT#TopLevelClosureObject 'final) >]
T

7_Run ms
Halted
NIL
```

Since no break points were set, the machine halts with a continuation on the top of the stack.

```
8_Stk
1         ("EVAL_EXPR.4.1.cont" : (INT#ClosureObject (EVAL_EXPR 75)
(INT#Frame EVAL_EXPR.4.1 & NIL & &)))
NIL
```

"EVAL_EXPR.4.1.cont" represents the return of the continuation "cont" by the "READ" **tcase** *of "EVAL_EXPR", which corresponds to the factorial program's attempt to* **read** *the first datum from the input stream. Interpretation of the factorial program cannot*

proceed until this continuation, suspended in a closure object, is applied to a machine state. This is done in the following steps.

```
9_(INT#LoadApply ms
      (INT#PopVMSTACK ms)
      < < (INT#TopLevelClosureObject 'initial_memory)
          < '(#INTEGER 1) '(#INTEGER 2) '(#INTEGER 3) '(#INTEGER 4) > > >]
T
```

Prepare the machine to apply the continuation closure object that is on the top of the stack to an initial state. The "MEMORY" component of that state is the closure object "initial_memory". The "INPUT" component is a sequence of elements of type "VALUE", each of which was injected from type "INTEGER".

```
10_Stk
1         ("EVAL_EXPR.4.1.cont" : (INT#ClosureObject (EVAL_EXPR 75)
(INT#Frame EVAL_EXPR.4.1 & NIL & &)))
2         ((("initial_memory : (INT#ClosureObject (initial_memory 1) NIL))
((#INTEGER 1) (#INTEGER 2) (#INTEGER 3) (#INTEGER 4))))
NIL
```

View the stack before the continuation is applied to the initial state.

```
11_(INT#Break ms (INT#ApplyBreak 'update)(INT#ApplyBreak 'value_of))
T
```

Break the memory manipulation functions "update" and "value_of".

```
12_Run
Broken after *BINDF* in update
          (Broken before update)
T

13_CF
update
     memory  ("initial_memory" : (INT#ClosureObject (initial_memory 1) NIL))
     value   (#INTEGER 1)
     id      "num"
Dynamic chain:  EVAL_COM.1.1.econt.1.new_cont
NIL
```

"update" is called to yield a new memory function that associates "id" with "value" (in this case '"num"' with "(#INTEGER 1)") and otherwise calls "memory". "memory" is the "initial_memory" closure object.

```
Run
Broken before *RETURN* in update
          (Broken after update)
T
```

Broken before the return from "update".

```
15_Stk
1         ("update.1.new_memory" : (INT#ClosureObject (update 5)
(INT#Frame update.1 & NIL & &)))
NIL
```

New memory function closure object is now on the stack; '"num"' has been assigned the value "(#INTEGER 1)", which is the datum read from the input stream.

```
16_Run
Broken after *BINDF* in update
          (Broken before update)
T

17_CF
update
     memory    ("update.1.new_memory" : (INT#ClosureObject (update 5)
(INT#Frame update.1 & NIL & &)))
     value     (#INTEGER 1)
     id        "res"
Dynamic chain:  EVAL_COM.1.1.econt.1.new_cont
NIL
```

The "memory" argument of this invocation of "update" is now the closure object that was computed by the previous invocation of "update".

```
18_Run
Broken before *RETURN* in update
          (Broken after update)
T
```

'"res"' has been assigned the (constant) value "(# INTEGER 1)".

```
19_Run
Broken after *BINDF* in update
          (Broken before update)
T

20_Run
Broken before *RETURN* in update
          (Broken after update)
T
```

'"i"' has been assigned the (constant) value "(# INTEGER 2)".

```
21_Run
Broken after *BINDF* in value_of
          (Broken before value_of)
T
```

The first memory access occurs.

```
22_CF
value_of
     memory    ("update.1.new_memory" : (INT#ClosureObject (update 5)
 (INT#Frame update.1 & NIL & &)))
     id        "i"
Dynamic chain:  EVAL_EXPR.3.1.cont.1
NIL
```

The value of '"i"' is requested.

```
23_Run
Broken before *RETURN* in value_of
          (Broken after value_of)
T

24_Stk
1         (#VALUE (#INTEGER 2))
NIL
```

The value of '"i"' was "(# VALUE (# INTEGER 2))", of type "VALUE_OR_UNBOUND".

```
25_(INT#UnBreak ms (INT#ApplyBreak 'update]
T
```

Unbreak "update".

```
26_(INT#Break ms (INT#ApplyBreak 'new_memory]
T
```

Break "new_memory", which is the function of type "MEMORY" yielded by "update".

```
27_Run
Broken after *BINDF* in value_of
          (Broken before value_of)
T

28_CF
value_of
     memory    ("update.1.new_memory" : (INT#ClosureObject (update 5)
 (INT#Frame update.1 & NIL & &)))
     id        "num"
Dynamic chain:  EVAL_EXPR.3.1.cont.1
NIL
```

The value of '"num"' is requested. The last value associated with '"num"' is "(# INTEGER 1)" (see steps 12 and 13).

```
29_Run
Broken after *BINDF* in update.1.new_memory
          (Broken before new_memory)
T
```

"value_of" calls its argument "memory", which is an instance of "new_memory" yielded by "update".

```
30_SC
update.1.new_memory
     ident     "num"

update.1
     new_memory
               ("update.1.new_memory" : (INT#ClosureObject (update 5)
 (INT#Frame update.1 & NIL & &)))

update
     memory    ("update.1.new_memory" : (INT#ClosureObject (update 5)
 (INT#Frame update.1 & NIL & &)))
     value     (#INTEGER 2)
     id        "i"
NIL
```

View the static chain of "new_memory". "ident" is bound to '"num"', the identifier whose value is needed. This instance of the closure object "new_memory" is itself visible. The arguments to the invocation of "update" that created this instance of "new_memory" are also visible. '"i"' is associated with the value "(# INTEGER 2)". "memory" is the remainder of the memory that was supplied to that invocation of "update".

```
31_Run
Broken after *BINDF* in update.1.new_memory
          (Broken before new_memory)
T
```

Since '"i"' is not '"num"', "new_memory" calls "memory".

```
32_SC
update.1.new_memory
     ident     "num"

update.1
     new_memory
               ("update.1.new_memory" : (INT#ClosureObject (update 5)
 (INT#Frame update.1 & NIL & &)))

update
     memory    ("update.1.new_memory" : (INT#ClosureObject (update 5)
 (INT#Frame update.1 & NIL & &)))
     value     (#INTEGER 1)
     id        "res"
NIL
```

This instance of "new_memory" knows about the value of '"res"'.

```
33_Run
Broken after *BINDF* in update.1.new_memory
          (Broken before new_memory)
T
```

The next "deeper" instance of "new_memory" is called.

```
34_SC
update.1.new_memory
     ident     "num"

update.1
     new_memory
               ("update.1.new_memory" : (INT#ClosureObject (update 5)
 (INT#Frame update.1 & NIL & &)))

update
     memory  ("initial_memory" : (INT#ClosureObject (initial_memory 1) NIL))
     value   (#INTEGER 1)
     id      "num"
NIL
```

This instance does "know about" the most recent binding of '"num"', and was yielded by the invocation of "update" that began in step 12.

```
35_Run
Broken before *RETURN* in update.1.new_memory
          (Broken after new_memory)
T
```

The value of '"num"' will now be yielded by each of the instances of "new_memory" that are active, and finally by "value_of" itself.

```
36_Stk
1         (#VALUE (#INTEGER 1))
```

```
NIL

37_Run
Broken before *RETURN* in update.1.new_memory
          (Broken after new_memory)
T

38_Stk
1         (#VALUE (#INTEGER 1))
NIL

39_Run
Broken before *RETURN* in update.1.new_memory
          (Broken after new_memory)
T

40_Stk
1         (#VALUE (#INTEGER 1))
NIL

41_Run
Broken before *RETURN* in value_of
          (Broken after value_of)
T

42_Stk
1         (#VALUE (#INTEGER 1))
NIL
```

The value of '"num"' is finally yielded by "value_of".

```
43_UBA
T
```

Remove all break points.

```
44_(INT#Break ms (INT#ApplyBreak 'EVAL_EXPR.4.1.cont]
T
```

*Break the function "cont" of the "**tcase**" of "EVAL_EXPR". This function will be called with the "current" state each time a "**read**" expression is evaluated, which will occur on each successive traversal of the outer "**while true**" loop.*

```
45_Run
Broken after *BINDF* in EVAL_EXPR.4.1.cont
          (Broken before EVAL_EXPR.4.1.cont)
T

46_SC
EVAL_EXPR.4.1.cont
     state     (("update.1.new_memory" : (INT#ClosureObject (update 5)
(INT#Frame update.1 & NIL & &))) ((#INTEGER 2) (#INTEGER 3) (#INTEGER 4)))

EVAL_EXPR.4.1
     cont      ("EVAL_EXPR.4.1.cont" : (INT#ClosureObject (EVAL_EXPR 75)
 (INT#Frame EVAL_EXPR.4.1 & NIL & & )))

EVAL_EXPR.4
      read      NIL
```

```
EVAL_EXPR
     expr       (#READ NIL)
     econt      ("EVAL_COM.1.1.econt" : (INT#ClosureObject (EVAL_COM 14)
 (INT#Frame EVAL_COM.1.1 & NIL & &)))
NIL
```

*A "**read**" expression is evaluated (see the value of "expr") and the second element of the original input stream is about to be read. "econt" is the expression continuation that will be called with the value read, resulting in a continuation that will be called with the new state.*

```
47_DC
+  EVAL_EXPR.4.1.cont
+  EVAL_COM.4.1.econt.1.while_cont
+  EVAL_COM.2.1.econt.1.new_cont
   EVAL_EXPR.3.1.cont.1
+  EVAL_EXPR.3.1.cont
   EVAL_EXPR.3.1.cont.1
+  EVAL_EXPR.3.1.cont
   EVAL_EXPR.3.1.cont.1
+  EVAL_EXPR.3.1.cont
+  EVAL_COM.1.1.econt.1.new_cont
+  EVAL_COM.1.1.econt.1.new_cont
+  EVAL_COM.1.1.econt.1.new_cont
+  EVAL_EXPR.4.1.cont
NIL
```

*The "+" signs mark those frames that have explicit dynamic chain pointers, i.e., were created by "call" instructions. "while_cont" is the continuation that continues the computation after this traversal of the "**while true**" loop.*

```
48_Run
Broken after *BINDF* in EVAL_EXPR.4.1.cont
          (Broken before EVAL_EXPR.4.1.cont)
T
```

```
49_CF
EVAL_EXPR.4.1.cont
     state      (("update.1.new_memory" : (INT#ClosureObject (update 5)
(INT#Frame update.1 & NIL & &))) ((#INTEGER 3) (#INTEGER 4)))
Dynamic chain:  EVAL_COM.4.1.econt.1.while_cont
NIL
```

*The third "**read**" occurs.*

```
50_Stk
1          (#INTEGER 2)
2          (#INTEGER 1)
NIL
```

The results of computing the first two factorials are now on the stack These values were pushed onto the stack by the "OUTPUT" alternative of "EVAL_COM" and, together with the third and fourth factorials, will be combined into a value of type "ANS", working from the top of the stack downward, when the input stream is exhausted and "error" is produced as the value of type "FINAL_ANSWER".

```
51_Run
Broken after *BINDF* in EVAL_EXPR.4.1.cont
          (Broken before EVAL_EXPR.4.1.cont)
T

52_CF
EVAL_EXPR.4.1.cont
     state     (("update.1.new_memory" : (INT#ClosureObject (update 5)
(INT#Frame update.1 & NIL & &))) ((#INTEGER 4)))
Dynamic chain:  EVAL_COM.4.1.econt.1.while_cont
NIL
```

*The fourth "**read**" occurs. The final integer will now be removed from the input stream.*

```
53_Stk
1         (#INTEGER 6)
2         (#INTEGER 2)
3         (#INTEGER 1)
NIL
```

The third factorial has now been output, and is on the stack.

```
54_Run
Broken after *BINDF* in EVAL_EXPR.4.1.cont
          (Broken before EVAL_EXPR.4.1.cont)
T

55_CF
EVAL_EXPR.4.1.cont
     state     (("update.1.new_memory" : (INT#ClosureObject (update 5)
(INT#Frame update.1 & NIL & &))) NIL)
Dynamic chain:  EVAL_COM.4.1.econt.1.while_cont
NIL
```

*The final "**read**" occurs. An attempt to read past the end of the input stream will now occur.*

```
56_Stk
1         (#INTEGER 24)
2         (#INTEGER 6)
3         (#INTEGER 2)
4         (#INTEGER 1)
NIL
```

The fourth and final factorial has now been output.

```
57_Run
Broken before *RETURN* in EVAL_EXPR.4.1.cont
          (Broken after EVAL_EXPR.4.1.cont)
T
```

Since no input data remains, "cont" yields the "error" value of type "FINAL_ANSWER", which is then injected into type "ANS".

```
58_Stk
1         (#FINAL_ANSWER ~error)
2         (#INTEGER 24)
3         (#INTEGER 6)
4         (#INTEGER 2)
5         (#INTEGER 1)
NIL
```

```
59_UBA
T
```

Unbreak all functions.

```
60_(INT#Break ms (INT#InstrBreak '*PRDEN* 'After]
T
```

*Set a break point after all product denotation ("*PRDEN*") machine instructions. A break will thus occur each an instance of the "OUTPUT" alternative of "EVAL_COM" combines the second element of the stack (of type "VALUE") with the top element of the stack (of type "ANS") to form the new top element of the stack (of type "PARTIAL_ANSWER"; this value is then injected into type "ANS" and the process repeats).*

```
61_Run
Broken after *PRDEN* in EVAL_COM.2.1.econt.1.new_cont
T

62_Stk
1          ((#INTEGER 24) (#FINAL_ANSWER ~error))
2          (#INTEGER 6)
3          (#INTEGER 2)
4          (#INTEGER 1)
NIL

63_Run
Broken after *PRDEN* in EVAL_COM.2.1.econt.1.new_cont
T

64_Stk
1          ((#INTEGER 6) (#PARTIAL_ANSWER ((#INTEGER 24)
 (#FINAL_ANSWER ~error))))
2          (#INTEGER 2)
3          (#INTEGER 1)
NIL

65_Run
Broken after *PRDEN* in EVAL_COM.2.1.econt.1.new_cont
T
66_Stk
1          ((#INTEGER 2) (#PARTIAL_ANSWER ((#INTEGER 6)
 (#PARTIAL_ANSWER  ((#INTEGER 24) (#FINAL_ANSWER ~error))))))
2          (#INTEGER 1)
NIL

67_Run
Broken after *PRDEN* in EVAL_COM.2.1.econt.1.new_cont
T

68_Stk
1          ((#INTEGER 1) (#PARTIAL_ANSWER ((#INTEGER 2)
 (#PARTIAL_ANSWER ((#INTEGER 6) (#PARTIAL_ANSWER ((#INTEGER 24)
 (#FINAL_ANSWER ~error)))))))
NIL
```

```
69_DC
+  EVAL_COM.2.1.econt.1.new_cont
   EVAL_EXPR.3.1.cont.1
+  EVAL_EXPR.3.1.cont
   EVAL_EXPR.3.1.cont.1
+  EVAL_EXPR.3.1.cont
   EVAL_EXPR.3.1.cont.1
+  EVAL_EXPR.3.1.cont
+  EVAL_COM.1.1.econt.1.new_cont
+  EVAL_COM.1.1.econt.1.new_cont
+  EVAL_COM.1.1.econt.1.new_cont
+  EVAL_EXPR.4.1.cont
NIL

70_Run
Halted
T
```

The computation terminates.

```
71_Stk
1          (#PARTIAL_ANSWER ((#INTEGER 1) (#PARTIAL_ANSWER ((#INTEGER 2)
 (#PARTIAL_ANSWER ((#INTEGER 6) (#PARTIAL_ANSWER ((#INTEGER 24)
 (#FINAL_ANSWER ~error)))))))))
NIL
```

The resulting element of type "ANS" is on the top of the stack.

Transcript V: Optimization of Tail Recursion
Tiny Definition, Version 3

This transcript shows the effect of turning on the capability of the virtual machine to optimize tail recursion. This may be turned on or off at run time by setting the Lisp atom `INT#OptimizeTailRecursion` to `T` or `NIL` respectively. The optimization is expected to be useful in improving efficiency during interpretation of large semantic definitions.

We define a call to function X in context Y to be *tail recursive* if the value returned from the call to X is not modified before control returns from Y. Thus the return from X may as well return directly to Y's caller. The AFDL compiler detects all tail recursive calls in AFDL functions and emits special `*CALL*` instructions that behave like other `*CALL*` instructions until the flag `INT#OptimizeTailRecursion` is set at run time.

When tail recursion is being optimized it is possible for execution to continue, after a `*RETURN*` instruction, in a context that is not the normal target of the return. This may be somewhat confusing during "debugging." Hence by setting the `INT#OptimizeTailRecursion` flag the user is trading off clarity for debugging against increased execution speed.

In this transcript the machine state has already been initialized with the TINY semantic definition and the same test program written in TINY that was used in Transcript IV (see Steps 1 through 5 of Transcript IV). We first reset the machine state.

```
28_Reset ms
T
```

We prepare for the execution of the machine which is to apply `EVAL_COM` *to the entire Tiny program and the continuation* `final`.

```
29_(INT#LoadApply ms
     (INT#TopLevelClosureObject 'EVAL_COM)
     < tinyprogram (INT#TopLevelClosureObject 'final) >]
T
```

We request optimization of tail recursion by setting the atom INT#OptimizeTailRecursion *to a non-NIL value.*

```
30_(SETQ INT#OptimizeTailRecursion T)
(INT#OptimizeTailRecursion reset)
T
```

As a consequence of the call to INT#LoadApply *we have a closure object embodying the semantic function* EVAL_COM *on top of the stack. Just below it on the stack is the pair of arguments to which it will be applied, namely the Tiny program and the closure object that embodies the semantic function* final.

```
31_Stk
1       ("EVAL_COM" : (INT#ClosureObject (EVAL_COM 1) NIL))
2       ((#WHILE ((#BOOLEAN true) (#SEQ ((#SEQ ((#SEQ ((#SEQ &) (#ASSIGN &)))
 (#WHILE ((#NOT &) (#SEQ &))))) (#OUTPUT (#IDENT "res"))))))
("final" : (INT#ClosureObject (final 1) NIL)))
NIL
```

We set a break Around the semantic function EVAL_EXPR *in order to view the dynamic chain and its behavior when tail recursion is being optimized.*

```
32_(INT#Break ms (INT#ApplyBreak 'EVAL_EXPR))
T
```

We run the machine through several breaks on EVAL_EXPR.

```
33_Run
Broken after *BINDF* in EVAL_EXPR
          (Broken before EVAL_EXPR)
T
34_Run
Broken after *BINDF* in EVAL_EXPR
          (Broken before EVAL_EXPR)
T
35_Run
Broken before *RETURN* in EVAL_EXPR
          (Broken after EVAL_EXPR)
T
36_Run
Broken after *BINDF* in EVAL_EXPR
          (Broken before EVAL_EXPR)
T
37_Run
Broken after *BINDF* in EVAL_EXPR
          (Broken before EVAL_EXPR)
T
38_Run
Broken after *BINDF* in EVAL_EXPR
          (Broken before EVAL_EXPR)
T
39_Run
Broken before *RETURN* in EVAL_EXPR
          (Broken after EVAL_EXPR)
T
```

We are now in a break just before an incarnation of the semantic function EVAL_EXPR *is due to execute its* *RETURN* *instruction. We observe the dynamic chain with the* DC *command. As before we have "+" signs that identify those frames that have explicit dynamic chain pointers. However, due to setting of the flag* INT#OptimizeTailRecursion, *we now also have "*"s marking those frames that were created by tail-recursive function calls. Executing a return from such a tail-recursive frame (i.e., one marked with a "*") causes control to return from the first frame "up" the dynamic chain that has an explicit dynamic chain pointer but is not tail-recursive (i.e., has a "+" but no "*"). Hence in the dynamic chain below, returning from the tail-recursive topmost frame* EVAL_EXPR, *as we are about to do, will cause execution to continue in the topmost frame named* EVAL_COM.5.

```
40_DC
+* EVAL_EXPR
   EVAL_EXPR.6
+* EVAL_EXPR
   EVAL_EXPR.5
+* EVAL_EXPR
   EVAL_COM.4
+  EVAL_COM
   EVAL_COM.5
+* EVAL_COM
   EVAL_COM.5
+* EVAL_COM
+* EVAL_COM.4.1.econt
   EVAL_EXPR.2
+* EVAL_EXPR
   EVAL_COM.4
+  EVAL_COM
NIL
```

We step the machine now through one instruction that causes it to execute the *RETURN* *instruction it had broken before. The* Step *command (which may also be used with a positive integer argument) causes the machine to "single-step" through instructions. As each instruction is executed the instruction is printed out and, indented underneath it, is printed the value that is on top of the virtual-machine stack after the instruction execution. In this case we use the* Step *command without an argument implying that the current default machinestate is to be stepped and the lack of an integer argument is taken to imply one step.*

```
41_Step
   (*RETURN* EVAL_EXPR)
                    ("EVAL_EXPR.3.1.cont" : (INT#ClosureObject
(EVAL_EXPR 35) (INT#Frame EVAL_EXPR.3.1 & NIL & &)))
T
```

As predicted above, the return from the tail-recursive EVAL_EXPR *frame causes execution to return to the fram* EVAL_COM.5.

```
42_DC
   EVAL_COM.5
+* EVAL_COM
   EVAL_COM.5
+* EVAL_COM
```

```
+* EVAL_COM.4.1.econt
   EVAL_EXPR.2
+* EVAL_EXPR
   EVAL_COM.4
+  EVAL_COM
NIL
```

We remove all breaks on the machine and let it run until it halts.

```
43_UBA
T
44_Run
Halted
T
```

As a result of applying EVAL_COM *to the Tiny program and the continuation* final *we get a continuation deposited on top of the virtual-machine stack. This continuation (see TINY definition) expects an object of type STATE as argument and will provide an object of type ANS as result.*

```
45_Stk
1          ("EVAL_EXPR.4.1.cont" : (INT#ClosureObject (EVAL_EXPR 75)
(INT#Frame EVAL_EXPR.4.1 & NIL & &)))
NIL
```

We get ready to apply the just-computed continuation to a Tiny program state that is the initial memory and an input sequence consisting of the integer 4. We expect the factorial of 4 as the result of the next machine execution.

```
46_(INT#LoadApply ms
     (INT#PopVMSTACK ms)
     < < (INT#TopLevelClosureObject 'initial_memory)
        < '(#INTEGER 4) > > >]
T
```

We introduce a break to allow us to see the dynamic chain at a convenient point for purposes of illustration.

```
47_(INT#Break ms (INT#ApplyBreak 'new_cont 'After]
T
48_Run
Broken before *RETURN* in EVAL_COM.2.1.econt.1.new_cont
          (Broken after new_cont)
T
```

We are now poised to execute a *RETURN* *instruction from the tail-recursive frame* EVAL_COM.2.1.econt.1.new_cont *but note that all frames further "up" the dynamic chain (except the one at the bottom of the list below) are tail-recursive as well. Thus execution of this return should leave the dynamic chain empty.*

```
49_DC
+* EVAL_COM.2.1.econt.1.new_cont
   EVAL_EXPR.3.1.cont.1
+* EVAL_EXPR.3.1.cont
   EVAL_EXPR.3.1.cont.1
+* EVAL_EXPR.3.1.cont
   EVAL_EXPR.3.1.cont.1
+* EVAL_EXPR.3.1.cont
+* EVAL_COM.4.1.econt.1.while_cont
```

```
+* EVAL_COM.1.1.econt.1.new_cont
   EVAL_EXPR.3.1.cont.1
+* EVAL_EXPR.3.1.cont
   EVAL_EXPR.3.1.cont.1
+* EVAL_EXPR.3.1.cont
   EVAL_EXPR.3.1.cont.1
+* EVAL_EXPR.3.1.cont
+* EVAL_COM.4.1.econt.1.while_cont
+* EVAL_COM.1.1.econt.1.new_cont
   EVAL_EXPR.3.1.cont.1
+* EVAL_EXPR.3.1.cont
+* EVAL_COM.1.1.econt.1.new_cont
   EVAL_EXPR.3.1.cont.1
+* EVAL_EXPR.3.1.cont
   EVAL_EXPR.3.1.cont.1
+* EVAL_EXPR.3.1.cont
   EVAL_EXPR.3.1.cont.1
+* EVAL_EXPR.3.1.cont
   EVAL_EXPR.3.1.cont.1
+* EVAL_EXPR.3.1.cont
+* EVAL_COM.4.1.econt.1.while_cont
+* EVAL_COM.1.1.econt.1.new_cont
   EVAL_EXPR.3.1.cont.1
+* EVAL_EXPR.3.1.cont
+* EVAL_COM.1.1.econt.1.new_cont
   EVAL_EXPR.3.1.cont.1
+* EVAL_EXPR.3.1.cont
   EVAL_EXPR.3.1.cont.1
+* EVAL_EXPR.3.1.cont
   EVAL_EXPR.3.1.cont.1
+* EVAL_EXPR.3.1.cont
   EVAL_EXPR.3.1.cont.1
+* EVAL_EXPR.3.1.cont
+* EVAL_COM.4.1.econt.1.while_cont
+* EVAL_COM.1.1.econt.1.new_cont
   EVAL_EXPR.3.1.cont.1
+* EVAL_EXPR.3.1.cont
+* EVAL_COM.1.1.econt.1.new_cont
   EVAL_EXPR.3.1.cont.1
+* EVAL_EXPR.3.1.cont
   EVAL_EXPR.3.1.cont.1
+* EVAL_EXPR.3.1.cont
   EVAL_EXPR.3.1.cont.1
+* EVAL_EXPR.3.1.cont
   EVAL_EXPR.3.1.cont.1
+* EVAL_EXPR.3.1.cont
+* EVAL_COM.1.1.econt.1.new_cont
+* EVAL_COM.1.1.econt.1.new_cont
   EVAL_EXPR.3.1.cont.1
+* EVAL_EXPR.3.1.cont
   EVAL_EXPR.3.1.cont.1
+* EVAL_EXPR.3.1.cont
   EVAL_EXPR.3.1.cont.1
+* EVAL_EXPR.3.1.cont
+* EVAL_COM.4.1.econt.1.while_cont
```

```
+* EVAL_COM.1.1.econt.1.new_cont
   EVAL_EXPR.3.1.cont.1
+* EVAL_EXPR.3.1.cont
   EVAL_EXPR.3.1.cont.1
+* EVAL_EXPR.3.1.cont
   EVAL_EXPR.3.1.cont.1
+* EVAL_EXPR.3.1.cont
+* EVAL_COM.4.1.econt.1.while_cont
+* EVAL_COM.1.1.econt.1.new_cont
   EVAL_EXPR.3.1.cont.1
+* EVAL_EXPR.3.1.cont
+* EVAL_COM.1.1.econt.1.new_cont
   EVAL_EXPR.3.1.cont.1
+* EVAL_EXPR.3.1.cont
   EVAL_EXPR.3.1.cont.1
+* EVAL_EXPR.3.1.cont
   EVAL_EXPR.3.1.cont.1
+* EVAL_EXPR.3.1.cont
   EVAL_EXPR.3.1.cont.1
+* EVAL_EXPR.3.1.cont
+* EVAL_COM.4.1.econt.1.while_cont
+* EVAL_COM.1.1.econt.1.new_cont
   EVAL_EXPR.3.1.cont.1
+* EVAL_EXPR.3.1.cont
+* EVAL_COM.1.1.econt.1.new_cont
   EVAL_EXPR.3.1.cont.1
+* EVAL_EXPR.3.1.cont
   EVAL_EXPR.3.1.cont.1
+* EVAL_EXPR.3.1.cont
   EVAL_EXPR.3.1.cont.1
+* EVAL_EXPR.3.1.cont
   EVAL_EXPR.3.1.cont.1
+* EVAL_EXPR.3.1.cont
   EVAL_EXPR.3.1.cont.1
+* EVAL_EXPR.3.1.cont
+* EVAL_COM.1.1.econt.1.new_cont
+* EVAL_COM.1.1.econt.1.new_cont
   EVAL_EXPR.3.1.cont.1
+* EVAL_EXPR.3.1.cont
   EVAL_EXPR.3.1.cont.1
+* EVAL_EXPR.3.1.cont
   EVAL_EXPR.3.1.cont.1
+* EVAL_EXPR.3.1.cont
+* EVAL_COM.4.1.econt.1.while_cont
+* EVAL_COM.1.1.econt.1.new_cont
   EVAL_EXPR.3.1.cont.1
+* EVAL_EXPR.3.1.cont
   EVAL_EXPR.3.1.cont.1
+* EVAL_EXPR.3.1.cont
   EVAL_EXPR.3.1.cont.1
+* EVAL_EXPR.3.1.cont
+* EVAL_COM.4.1.econt.1.while_cont
+* EVAL_COM.1.1.econt.1.new_cont
   EVAL_EXPR.3.1.cont.1
+* EVAL_EXPR.3.1.cont
+* EVAL_COM.1.1.econt.1.new_cont
   EVAL_EXPR.3.1.cont.1
```

```
+* EVAL_EXPR.3.1.cont
   EVAL_EXPR.3.1.cont.1
+* EVAL_EXPR.3.1.cont
   EVAL_EXPR.3.1.cont.1
+* EVAL_EXPR.3.1.cont
   EVAL_EXPR.3.1.cont.1
+* EVAL_EXPR.3.1.cont
+* EVAL_COM.1.1.econt.1.new_cont
+* EVAL_COM.1.1.econt.1.new_cont
   EVAL_EXPR.3.1.cont.1
+* EVAL_EXPR.3.1.cont
   EVAL_EXPR.3.1.cont.1
+* EVAL_EXPR.3.1.cont
   EVAL_EXPR.3.1.cont.1
+* EVAL_EXPR.3.1.cont
+* EVAL_COM.1.1.econt.1.new_cont
+* EVAL_COM.1.1.econt.1.new_cont
+* EVAL_COM.1.1.econt.1.new_cont
+  EVAL_EXPR.4.1.cont
NIL
```

We execute the *RETURN* *with a* Step *command and note that the stack now contains the appropriate result.*

```
50_Step
   (*RETURN* EVAL_COM.2.1.econt.1.new_cont)
                    (#PARTIAL_ANSWER ((#INTEGER 24) (#FINAL_ANSWER ~error)))
T
51_DC
NIL
```

As expected, the dynamic chain is now completely clear and the next Run *command will simply cause the machine to halt.*

```
52_Run
Halted
T
```

The expected object of type ANS is left on top of the virtual-machine stack.

```
53_Stk
1          (#PARTIAL_ANSWER ((#INTEGER 24) (#FINAL_ANSWER ~error)))
NIL
```

I. ISI EXTENSIONS TO AFDL

We briefly describe here the differences between AFDL and our upward compatible extension, AFDL + . It is assumed that the reader is reasonably familiar with AFDL and the Ada FSD.

AFDL is a purely applicative language composed of a few Ada constructs such as **if-then-else**, **case**, blocks, variable declarations, **function** subprograms, etc. but no assignment. The major difference between the use of these constructs in Ada and in AFDL is that in AFDL functions may be passed as arguments to other functions. This is necessary for writing denotational style semantic definitions. Accordingly, the types of functional objects may be defined with **function type** declarations. Furthermore, in AFDL the only possible mode of function arguments is similar to the Ada **in** mode (i.e., parameter passing by value). *This is a fundamental divergence from the lambda calculus and must be duly recognized when writing semantic definitions in AFDL.*

In extending AFDL to produce AFDL + we introduced three further type declarations, ten domain operations and one compound expression construct. In addition, we have made AFDL + a pure expression language thereby rendering the **return** keyword and construct optional. In order to facilitate programming denotational semantics, AFDL + function calls may be *curried*.

If the sum type T is declared via

sum type T (T_1, ..., T_n),

where $n \geq 2$ and all T_i are unique names, then x **inj** T injects an element of component type T_i into the sum type T; x **elt** T_i tests whether an element x of sum type T was injected from component type T_i; x **pro** T_i projects an element x of sum type T into component type T_i if x **elt** T_i is true, and causes a fatal error in the AFDL + virtual machine otherwise.

If the product type T is declared via

product type T (T_1, ..., T_n),

where $n \geq 2$, then an element of T is constructed from elements x_i of type T_i by the tupling operation (x_1, ..., x_n). The i-th component of a value x of product type T is selected by the operation x:i, where i must be a constant (literal).

A sequence type T with components of type S is declared via

sequence type T S.

An element of sequence type T is constructed from elements x_i of type S by the operation [x_1, ..., x_n], $n \geq 0$. [ ] denotes the empty element of any sequence type. The i-th component (head) of an element x of sequence type T is selected by the operation x:i, where i may be any integer expression. The i-th *tail* of x = [x_1, ..., x_n] is selected by the operation x::i, and is equal to [x_{i+1}, ..., x_n] (if i = n then x::i is equal to [ ]). If i is "out of range" (≤ 0 or $> n$) for : or ::, then a fatal error occurs in the AFDL + virtual machine. Two elements of a given sequence type may be concatenated using the binary concatenation operation &. The length of an element of a sequence type may be obtained via the unary operation **length**.

A type T may be declared *equivalent* to a type S by the declaration

type T **is** S .

This permits an element x of type T to be converted to type S by applying the *cast* $S(x)$; conversely, an element y of type S can be converted to type T via the cast $T(y)$. Type conversions must be explicit and have no run-time significance. Equivalent types provide a way of declaring a sum type T with multiple components T_i that are equivalent to some type S. If x **elt** T_i, then S(x **pro** T_i) is of type S, and if y is an element of type S, then (T_i(y)) **inj** T is an element of type T.

The AFDL + *type case* expression is a variant of the usual case construct and is provided to simplify the manipulation of sum types. The **tcase** expression

```
tcase expr is
        when t1: T1 => expr1 ;
        ...
        when tn: Tn => exprn ;
        when others t: T => default
end tcase
```

evaluates $expr_i$ in a new scope in which t_i is bound to expr **pro** T_i if expr **elt** T_i, and yields the resulting value as the value of the type case expression. If a **when** clause for the appropriate T_i is not provided, then if the **others** clause is present, "default" is evaluated in a scope in which t is bound to expr, and the resulting value is yielded as the value of the type case expression; otherwise, a fatal error occurs in the AFDL + virtual machine.

II. DENOTATIONAL SEMANTIC DEFINITION OF TINY IN AFDL+

```
package TINY is

-- Syntactic Domains

sum type EXPR (INTEGER, BOOLEAN, IDENT, READ, NOT, EQUAL, PLUS);

type IDENT is private;
type READ is private;
type NOT is EXPR;
product type EQUAL (EXPR, EXPR);
product type PLUS (EXPR, EXPR);

sum type COM (ASSIGN, OUTPUT, IF, WHILE, SEQ);

product type ASSIGN (IDENT, EXPR);
type OUTPUT is EXPR;
product type IF (EXPR, COM, COM);
product type WHILE (EXPR, COM);
product type SEQ (COM, COM);

-- Semantic Domains

product type STATE (MEMORY, INPUT);

function type MEMORY (id: IDENT) return VALUE_OR_UNBOUND;
sum type VALUE_OR_UNBOUND (VALUE, UNBOUND_VALUE);
type UNBOUND_VALUE is (unbound);

sequence type INPUT VALUE;

sum type VALUE (INTEGER, BOOLEAN);

function type CONT (state: STATE) return ANS;
function type ECONT (value: VALUE) return CONT;

sum type ANS (FINAL_ANSWER, PARTIAL_ANSWER);
type FINAL_ANSWER is (error, stop);
product type PARTIAL_ANSWER (VALUE, ANS);

-- Auxiliary Functions

function update (memory: MEMORY; value: VALUE; id: IDENT) return MEMORY is
  function new_memory (ident: IDENT) return VALUE_OR_UNBOUND is
    begin
      if ident = id then value inj VALUE_OR_UNBOUND
```

```
        else memory(ident) end if
    end new_memory;
begin new_memory end update;

function value_of (memory: MEMORY; id: IDENT) return VALUE_OR_UNBOUND is
begin memory(id) end value_of;

function error (state: STATE) return ANS is
begin error inj ANS end error;

function final (state: STATE) return ANS is
begin stop inj ANS end final;

function initial_memory (id: IDENT) return VALUE_OR_UNBOUND is
begin unbound inj VALUE_OR_UNBOUND end intitial_memory;

-- Semantic Functions

function EVAL_EXPR (expr: EXPR; econt: ECONT) return CONT is
begin
  tcase expr is
    when integer: INTEGER => econt(integer inj VALUE);
    when boolean: BOOLEAN => econt(boolean inj VALUE);
    when ident: IDENT =>
      declare function cont (state: STATE) return ANS is
              value: VALUE_OR_UNBOUND := value_of(state:1, ident);
              begin if value elt UNBOUND_VALUE then error inj ANS
                    else econt(value pro VALUE)(state) end if end cont;
      begin cont end;
    when read: READ =>
      declare function cont (state: STATE) return ANS is
              begin if state:2 = [] then error inj ANS
                    else econt(state:2:1)((state:1, state:2::1)) end if end cont;
      begin cont end;
    when not: NOT =>
      EVAL_EXPR( EXPR(not),
                 declare function new_econt (value: VALUE) return CONT is
                         begin
                           if value elt BOOLEAN then econt((not (value pro BOOLEAN)) inj VALUE)
                             else error end if
                         end new_econt;
                 begin new_econt end);
    when equal: EQUAL =>
      EVAL_EXPR
      ( equal:1,
        declare function econt1 (value1: VALUE) return CONT is
                begin
                  EVAL_EXPR
                  ( equal:2,
                    declare function econt2 (value2: VALUE) return CONT is
```

```
                        begin econt((value1 = value2) inj VALUE) end econt2;
                    begin econt2 end)
                end econt1;
        begin econt1 end);
    when plus: PLUS =>
      EVAL_EXPR
      ( plus:1,
        declare function econt1 (value1: VALUE) return CONT is
                begin
                EVAL_EXPR
                ( plus:2,
                  declare function econt2 (value2: VALUE) return CONT is
                        begin
                          if value1 elt INTEGER and value2 elt INTEGER
                          then econt( ((value1 pro INTEGER) + (value2 pro INTEGER)) inj VALUE)
                          else error end if
                        end econt2;
                  begin econt2 end)
                end econt1;
        begin econt1 end)
  end tcase
end EVAL_EXPR;

function EVAL_COM (com: COM; cont: CONT) return CONT is
begin
  tcase com is
    when ass: ASSIGN =>
      EVAL_EXPR
      ( ass:2,
        declare function econt (value: VALUE) return CONT is
                  function new_cont (state: STATE) return ANS is
                  begin cont( (update(state:1, value, ass:1), state:2) ) end new_cont;
                begin new_cont end econt;
        begin econt end);
    when out: OUTPUT =>
      EVAL_EXPR
      ( EXPR(out),
        declare function econt (value: VALUE) return CONT is
                  function new_cont (state: STATE) return ANS is
                  begin (value, cont(state)) inj ANS end new_cont;
                begin new_cont end econt;
        begin econt end);
    when if: IF =>
      EVAL_EXPR
      ( if:1,
        declare function econt (value: VALUE) return CONT is
                begin
                if value elt BOOLEAN then
                  if value pro BOOLEAN then EVAL_COM(if:2, cont)
                    else EVAL_COM(if:3, cont) end if
```

```
                else error end if
              end econt;
        begin econt end);
    when while: WHILE =>
      declare function new_cont (state: STATE) return ANS is
            begin
              EVAL_EXPR
              ( while:1,
                declare function econt (value: VALUE) return CONT is
                        begin
                         if value elt BOOLEAN then
                            if value pro BOOLEAN
                            then EVAL_COM(while:2, EVAL_COM(com, cont))
                            else cont end if
                          else error end if
                        end econt;
                begin econt end)
                 (state);          -- Curried call
            end new_cont;
      begin new_cont end;
    when seq: SEQ =>
      EVAL_COM(seq:1, EVAL_COM(seq:2, cont))
  end tcase
end EVAL_COM;

end TINY;
```

III. AFDL+ ABSTRACT SYNTAX

AFDL Abstract Syntax (List Representation)

D. Martin and A. Stoughton

17 Feb. 1982

```
program:       comp_unit_s

comp_unit:     fun_decl
             | fun_spec
             | pkg_spec
             | pkg_body

-------------------------------------------------------------------

pkg_spec:      (PSPEC pkg_id decl_item_s)

pkg_body:      (PBODY pkg_id decl_item_s)

decl_item:     var_spec
             | var_decl
             | fun_spec
             | fun_decl
             | type_decl
             | fun_type_decl
             | prod_type_decl
             | sum_type_decl
             | seq_type_decl
             | pkg_spec
             | pkg_body
             | use_clause

var_spec:      (VSPEC var_id_s type_id)

type_decl:     (TDECL type_id type_def)

type_def:      PRIVATE                          -- private type
             | enum_type                        -- enumerated type
             | type_id                          -- type equivalence

enum_type:     const_id_s
             | var_id_s

fun_type_decl:  (FNTDECL type_id fun_type)

prod_type_decl: (PRTDECL type_id type_id_s)

sum_type_decl:  (SMTDECL type_id type_id_s)
```

```
seq_type_decl:  (SQTDECL type_id type_id)

use_clause:     (USE pkg_id_s)

-----------------------------------------------------------------

fun_decl:       (FDECL fun_id fun_type fun_def)

fun_spec:       (FSPEC fun_id fun_type)

fun_type:       (MAP type_id_s type_id)

fun_def:        (LAM id_s expr)

expr:           (LET decl_s expr)
              | (APPLY expr expr_s)
              | (IF expr expr expr)
              | (CASE expr alt_s)
              | (TCASE expr t_alt_s)
              | (WARNING expr msg)
              | simple_expr

decl:           var_decl
              | fun_spec
              | fun_decl

var_decl:       (VDECL var_id type_id expr)

alt:            (choice_s expr)

choice:         id
              | OTHERS

t_alt:          (ALT    var_id type_id expr)
              | (OTHERS var_id type_id expr)

simple_expr:  (binop expr expr)
              | (unop expr)
              | (ELT expr type_id)
              | (INJ expr type_id)
              | (INJ expr type_id (FROM type_id))
              | (PRO expr type_id)
              | (PRDEN expr_s)
              | (SQDEN expr_s)
              | (CAST type_id expr)
              | id
              | integer
              | string

id:             var_id
              | fun_id
              | const_id
              | type_id
```

```
binop:      AND
          | OR
          | XOR
          | ANDTHEN
          | ORELSE
          | EQ
          | NE
          | GT
          | GE
          | LT
          | LE
          | CAT
          | HEAD
          | TAIL
          | PLUS
          | MINUS
          | TIMES

unop:       NOT
          | UMINUS
          | LENGTH
```

IV. AFDL+ CONCRETE AND ABSTRACT SYNTAX

*** OUTPUT FROM GRAMMAR ANALYSIS PROGRAM LR for the AFDL+ GRAMMAR ***

TERMINALS	NON TERMINALS
1 &	59 <2_EXPRESSION_LIST>
2 (	60 <2_TYPE_ID_LIST>
3)	61 <2_VAR_ID_LIST>
4 *	62 <ADD_OP>
5 **E*	63 <AFDL_PROGRAM>
6 +	64 <ALTERNATIVE>
7 .	65 <ALTERNATIVE_LIST>
8 -	66 <ANDTHEN_EXPRESSION>
9 .etconst	67 <AND_EXPRESSION>
10 .integer	68 <BLOCK>
11 .procname	69 <BLOCK_BODY>
12 .string	70 <CASE_EXPR>
13 .typemark	71 <CHOICE>
14 .varname	72 <CHOICE_LIST>
15 /=	73 <COMPILATION UNIT>
16 :	74 <COMPILATION UNIT LIST>
17 ::	75 <CONDITION>
18 :=	76 <CONST_ID>
19 ;	77 <CONST_ID_LIST>
20 <	78 <CURRIED_FUNCTION CALL>
21 <=	79 <DECLARATION>
22 =	80 <DECLARATION LIST>
23 =>	81 <DECLARATIVE ITEM>
24 >	82 <DECLARATIVE ITEM LIST>
25 >=	83 <DECLARATIVE PART>
26 AND	84 <DOM_OP>
27 BEGIN	85 <ENUMERATED_TYPE_DEFINITION>
28 BODY	86 <EXPRESSION>
29 CASE	87 <EXPRESSION_LIST>
30 DECLARE	88 <FORMAL_PART>
31 ELSE	89 <FUNCTION BODY>
32 ELSIF	90 <FUNCTION_CALL>
33 END	91 <FUNCTION DECLARATION>
34 END	92 <FUNCTION NAME_OPTION>
35 FUNCTION	93 <FUNCTION SPECIFICATION>
36 IF	94 <FUNCTION_TYPE_DECLARATION>
37 INJ	95 <ID>
38 IS	96 <IF_EXPR>
39 LENGTH	97 <IF_EXPR_TAIL>
40 NOT	98 <NAME>
41 OR	99 <NAME_LIST>
42 OTHERS	100 <NULL_BLOCK_BODY>
43 PACKAGE	101 <ORELSE_EXPRESSION>
44 PRIVATE	102 <OR_EXPRESSION>
45 PRO	103 <PACKAGE BODY>
46 PRODUCT	104 <PACKAGE_SPECIFICATION>
47 RETURN	105 <PARAMETER DECLARATION>
48 SEQUENCE	106 <PARAMETER_DECLARATION LIST>
49 SUM	107 <PKG_ID_LIST>
50 TCASE	108 <PRIMARY>
51 THEN	109 <PRODUCT_TYPE_DECLARATION>
52 TYPE	110 <RELATION>
53 USE	111 <RELOP>
54 WHEN	112 <RETURN EXPR>
55 XOR	113 <RETURN TYPE>
56 |	114 <SEMI>
57 |	115 <SEQUENCE_TYPE_DECLARATION>
58 |	116 <SEQ_OP>

117 <SIMPLE EXPRESSION>
118 <SUM>
119 <SUM TYPE DECLARATION>
120 <SYSTEM GOAL SYMBOL>
121 <TERM>
122 <TYPE ALT>
123 <TYPE ALT LIST>
124 <TYPE CASE EXPR>
125 <TYPE COERCION>
126 <TYPE DECLARATION>
127 <TYPE DEFINITION>
128 <TYPE ID>
129 <UN OP>
130 <USE CLAUSE>
131 <VARIABLE DECLARATION>
132 <VARIABLE SPECIFICATION>
133 <VAR ID LIST>
134 <WHEN OTHERS>
135 <XOR EXPRESSION>

```
                    I N I T   P R O D U C T I O N S

1 <SYSTEM GOAL SYMBOL> ::= *E* <AFDL_PROGRAM> *F*

  --
  -- LR(1) Grammar for Ada Formal Definition Language (AFDL)
  -- This version includes Appendices G, H, I, J, and K of the Ada ISD
  -- as well as the static and dynamic functions of Chapters 3, 4, 5, 6,
  -- 7, 8, 9, 10, 11, and 12.
  --
  --

2 <AFDL_PROGRAM> ::= <COMPILATION_UNIT_LIST>     S> [SEIQ AbstractSyntaxTrees STAR:1]

3 <COMPILATION_UNIT_LIST> ::= <COMPILATION_UNIT_LIST> <COMPILATION_UNIT> ;
                                                 S> [PRINTDEF STAR:1:2] TERPRI[] <<
4                           | <COMPILATION_UNIT> ; S> [PRINTDEF STAR:1:2] TERPRI[] <>

5 <COMPILATION_UNIT> ::= <FUNCTION_DECLARATION>
6                      | <PACKAGE_SPECIFICATION>
7                      | <PACKAGE_BODY>

  --
  --
  -- **********   A P P E N D I C E S   G  through  K   **********
  --
  --

8 <PACKAGE_SPECIFICATION> ::= PACKAGE .procname IS <DECLARATIVE_ITEM_LIST> END <FUNCTION_NAME_OPTION>
                                                 S> - :PSPEC!2

9 <PACKAGE_BODY> ::= PACKAGE BODY .procname IS <DECLARATIVE_PART> END <FUNCTION_NAME_OPTION>
                                                 S> - :PBODY!2

10 <DECLARATIVE_ITEM_LIST> ::= <DECLARATIVE_ITEM> ; S> <>
11                           | <DECLARATIVE_ITEM_LIST> <DECLARATIVE_ITEM> ;
                                                 S> <<

12 <DECLARATIVE_PART> ::= <DECLARATIVE_ITEM> ;    S> <>
13                      | <PACKAGE_BODY> ;        S> <>
14                      | <DECLARATIVE_PART> <DECLARATIVE_ITEM> ; S> <<
15                      | <DECLARATIVE_PART> <PACKAGE_BODY> ; S> <<

16 <DECLARATIVE_ITEM> ::= <VARIABLE_SPECIFICATION>
17                      | <VARIABLE_DECLARATION>
18                      | <FUNCTION_SPECIFICATION> S> SWAP[1 2] - :FSPEC!2
19                      | <FUNCTION_DECLARATION>
20                      | <TYPE_DECLARATION>
21                      | <FUNCTION_TYPE_DECLARATION>
22                      | <PRODUCT_TYPE_DECLARATION>
23                      | <SUM_TYPE_DECLARATION>
24                      | <SEQUENCE_TYPE_DECLARATION>
25                      | <PACKAGE_SPECIFICATION>
26                      | <USE_CLAUSE>

27 <VARIABLE_SPECIFICATION> ::= .varname : <TYPE_ID> S> SWAP[1 2] <> SWAP[1 2] :VSPEC!2
28                            | <2_VAR_ID_LIST> : <TYPE_ID> S> :VSPEC!2

29 <TYPE_DECLARATION> ::= TYPE <TYPE_ID> IS <TYPE_DEFINITION> S> :TDECL!2
30 <TYPE_DEFINITION> ::= <ENUMERATED_TYPE_DEFINITION>
31                     | PRIVATE                   S> LOAD[PRIVATE]
32                     | <TYPE_ID>                              -- type "equivalence"

33 <ENUMERATED_TYPE_DEFINITION> ::= ( <CONST_ID_LIST> )
34                                | ( <VAR_ID_LIST> )

35 <CONST_ID_LIST> ::= <CONST_ID>                 S> <>
36                   | <CONST_ID_LIST> , <CONST_ID> S> <<

37 <VAR_ID_LIST> ::= .varname                     S> <>
38                 | <VAR_ID_LIST> , .varname     S> <<
```

```
39 <2 VAR ID LIST> ::= .varname , .varname          S> MAKETUPLE[2]
40                   | <2 VAR ID LIST> , .varname  S> <<

41 <2 TYPE ID LIST> ::= <TYPE ID> , <TYPE ID>      S> MAKETUPLE[2]
42                    | <2 TYPE ID LIST> , <TYPE ID> S> <<

43 <FUNCTION TYPE DECLARATION> ::= FUNCTION TYPE <TYPE ID> ( <PARAMETER DECLARATION LIST> ) <RETURN TYPE>
                                                   S> SWAP[1 2] BURST[] SWAP[1 2] - SWAP[1 2] :MAP!2 :FNTDECL!2

44 <PRODUCT TYPE DECLARATION> ::= PRODUCT TYPE <TYPE ID> ( <2 TYPE ID LIST> )
                                                   S> :PRTDECL!2

45 <SUM TYPE DECLARATION> ::= SUM TYPE <TYPE ID> ( <2 TYPE ID LIST> ) S> :SMTDECL!2

46 <SEQUENCE TYPE DECLARATION> ::= SEQUENCE TYPE <TYPE ID> <TYPE ID> S> :SQTDECL!2

47 <USE CLAUSE> ::= USE <PKG ID LIST>              S> :USE!1

48 <PKG_ID_LIST> ::= .procname                     S> <>
49                 | <PKG_ID_LIST> , .procname     S> <<


   --
   -- **********   C H A P T E R S   3  through  12   **********
   --
   --

50 <FUNCTION DECLARATION> ::= <FUNCTION SPECIFICATION> IS <FUNCTION BODY>
                                                   S> SWAP[2 3] :LAM!2 :FDECL!3
51                          | <FUNCTION SPECIFICATION> IS <NULL BLOCK BODY>
                                                   S> SWAP[1 2] - :FSPEC!2

52 <FUNCTION SPECIFICATION> ::= FUNCTION <ID> <FORMAL PART> <RETURN TYPE>
                                                   S> :MAP!2

53 <FORMAL PART> ::=                               S> LOAD[NIL] --  <EMPTY>
                                                                -- additional NIL for a total of 2
54                 | ( <PARAMETER DECLARATION LIST> ) S> BURST[] -- burst parameter list

55 <PARAMETER DECLARATION LIST> ::= <PARAMETER DECLARATION LIST> ; <PARAMETER DECLARATION>
                                                   S> <<
56                                 | <PARAMETER DECLARATION> S> <>

57 <PARAMETER DECLARATION> ::= <NAME LIST> : <TYPE ID> S> MAKETUPLE[2]

58 <RETURN TYPE> ::= RETURN <TYPE ID>

59 <NULL BLOCK BODY> ::= BEGIN END <FUNCTION NAME OPTION> S>    -- for incomplete procedures

60 <FUNCTION BODY> ::= <DECLARATION LIST> <BLOCK BODY> S> :LET!2
61                   | <BLOCK_BODY>

62 <DECLARATION LIST> ::= <DECLARATION LIST> <DECLARATION> ; S> <<
63                      | <DECLARATION> ;          S> <>

64 <DECLARATION> ::= <VARIABLE DECLARATION>
65                 | <FUNCTION_DECLARATION>
66                 | <FUNCTION_SPECIFICATION>     S> SWAP[1 2] - :FSPEC!2

67 <VARIABLE DECLARATION> ::= .varname : <TYPE ID> := <EXPRESSION> S> :VDECL!3

68 <NAME_LIST> ::= <NAME_LIST> , <NAME>            S> <<
69              | <NAME>                           S> <>

70 <NAME> ::= .varname
71         | .procname

72 <CONST_ID> ::= .etconst                         S> [RPLACA STAR (PACK* '~ STAR:1)]

73 <TYPE ID> ::= .typemark                         S> [RPLACA STAR (PACK* '# STAR:1)]
```

```
74 <EXPRESSION> ::= <RETURN_EXPR>
75                | <RELATION>
76                | <AND_EXPRESSION>
77                | <OR_EXPRESSION>
78                | <XOR_EXPRESSION>
79                | <ANDTHEN_EXPRESSION>
80                | <ORELSE_EXPRESSION>

81 <SEMI> ::=                                          S> -        -- <EMPTY>  &C optional semicolon
                                                                   -- discard stacked NIL
82         | ;                                                     -- nothing stacked here

83 <RETURN_EXPR> ::= RETURN <EXPRESSION>

84 <IF_EXPR> ::= IF <CONDITION> THEN <EXPRESSION> <SEMI> <IF_EXPR_TAIL>
                                                       S> :IF!3

85 <CONDITION> ::= <EXPRESSION>

86 <IF_EXPR_TAIL> ::= ELSIF <CONDITION> THEN <EXPRESSION> <SEMI> <IF_EXPR_TAIL>
                                                       S> :IF!3
87                  | ELSE <EXPRESSION> <SEMI> END IF

88 <CASE_EXPR> ::= CASE <EXPRESSION> IS <ALTERNATIVE_LIST> END CASE S> :CASE!2

89 <ALTERNATIVE_LIST> ::= <ALTERNATIVE_LIST> <ALTERNATIVE> S> <<
90                      | <ALTERNATIVE>           S> <>

91 <ALTERNATIVE> ::= WHEN <CHOICE_LIST> => <EXPRESSION> <SEMI> S> MAKETUPLE[2]

92 <CHOICE_LIST> ::= <CHOICE_LIST> | <CHOICE>      S> <<
93                 | <CHOICE>                      S> <>

94 <CHOICE> ::= <CONST_ID>
95           | .varname
96           | OTHERS                              S> LOAD[OTHERS]

97 <TYPE_CASE_EXPR> ::= TCASE <EXPRESSION> IS <TYPE_ALT_LIST> END TCASE
                                                       S> :TCASE!2

98 <TYPE_ALT_LIST> ::= <TYPE_ALT>                     S> <>
99                   | <TYPE_ALT_LIST> <TYPE_ALT> S> <<

100 <TYPE_ALT> ::= WHEN .varname : <TYPE_ID> => <EXPRESSION> <SEMI> S> :ALT!3
101              | <WHEN_OTHERS> .varname : <TYPE_ID> => <EXPRESSION> <SEMI>
                                                       S> MAKETUPLE[4]

102 <WHEN_OTHERS> ::= WHEN OTHERS                     S> LOAD[OTHERS]

103 <TYPE_COERCION> ::= <TYPE_ID> ( <EXPRESSION> ) S> :CAST!2

104 <BLOCK> ::= DECLARE <DECLARATION_LIST> <BLOCK_BODY> S> :BLK!2
105           | <BLOCK_BODY>

106 <BLOCK_BODY> ::= BEGIN <EXPRESSION> <SEMI> END <FUNCTION_NAME_OPTION>
                                                       S> -

107 <FUNCTION_NAME_OPTION> ::=                                 -- <EMPTY>
108                          | <ID>

109 <AND_EXPRESSION> ::= <RELATION> AND <RELATION> S> :AND!2
110                    | <AND_EXPRESSION> AND <RELATION> S> :AND!2

111 <OR_EXPRESSION> ::= <RELATION> OR <RELATION>   S> :OR!2
112                   | <OR_EXPRESSION> OR <RELATION> S> :OR!2

113 <XOR_EXPRESSION> ::= <RELATION> XOR <RELATION> S> :XOR!2
114                    | <XOR_EXPRESSION> XOR <RELATION> S> :XOR!2

115 <ANDTHEN_EXPRESSION> ::= <RELATION> AND THEN <RELATION> S> :ANDTHEN!2
116                       | <ANDTHEN_EXPRESSION> AND THEN <RELATION> S> :ANDTHEN!2

117 <ORELSE_EXPRESSION> ::= <RELATION> OR ELSE <RELATION> S> :ORELSE!2
118                      | <ORELSE_EXPRESSION> OR ELSE <RELATION> S> :ORELSE!2
```

```
119 <RELATION> ::= <SIMPLE_EXPRESSION>
120              | <SIMPLE_EXPRESSION> <RELOP> <SIMPLE_EXPRESSION> S> !2
121              | <SIMPLE_EXPRESSION> ELT <TYPE_ID> S> :ELT!2

122 <RELOP> ::= =                                    S> :EQ
123          | /=                                    S> :NE
124          | >                                     S> :GT
125          | >=                                    S> :GE
126          | <                                     S> :LT
127          | <=                                    S> :LE

128 <SIMPLE_EXPRESSION> ::= <SUM>
129                       | <SIMPLE_EXPRESSION> <SEQ OP> <SUM> S> !2
130                       | <SIMPLE_EXPRESSION> <DOM OP> <TYPE_ID> S> !2

131 <SUM> ::= <TERM>
132         | <UN_OP> <TERM>                          S> !1
133         | <SUM> <ADD_OP> <TERM>                   S> !2

134 <TERM> ::= <PRIMARY>
135          | <TERM> * <PRIMARY>                     S> :TIMES!2

136 <PRIMARY> ::= <ID>
137             | .integer                                        -- integer
138             | .string                                         -- string
139             | <FUNCTION_CALL>
140             | ( <EXPRESSION> )
141             | <IF_EXPR>
142             | <CASE_EXPR>
143             | <TYPE_CASE_EXPR>
144             | <TYPE_COERCION>
145             | <BLOCK>
146             | ( <2_EXPRESSION_LIST> )             S> :PRDEN!1 -- product denotation
147             | [ <EXPRESSION_LIST> ]               S> :SQDEN!1 -- nonempty sequence denotation
148             | [ ]                                 S> LOAD[NIL] :SQDEN!1
                                                                  -- empty sequence denotation

149 <ID> ::= .varname                                             -- variable identifier
150        | .procname                                            -- function identifier
151        | <CONST_ID>                                           -- tree construct identifier

152 <FUNCTION_CALL> ::= <ID> ( )                     S> LOAD[NIL] :APPLY!2
153                   | <ID> ( <EXPRESSION_LIST> )  S> :APPLY!2
154                   | <CURRIED_FUNCTION_CALL> ( ) S> LOAD[NIL] :APPLY!2
155                   | <CURRIED_FUNCTION_CALL> ( <EXPRESSION_LIST> ) S> :APPLY!2

156 <CURRIED_FUNCTION_CALL> ::= <ID> ( )              S> LOAD[NIL] :APPLY!2
157                           | <ID> ( <EXPRESSION_LIST> ) S> :APPLY!2
158                           | <CURRIED_FUNCTION_CALL> ( ) S> LOAD[NIL] :APPLY!2
159                           | <CURRIED_FUNCTION_CALL> ( <EXPRESSION_LIST> )
                                                    S> :APPLY!2

160 <SEQ OP> ::= :                                  S> :HEAD      -- sequence operators
                                                                  -- product or sequence element selection
161            | ::                                 S> :TAIL      -- sequence tail selection
162            | &                                  S> :CAT       -- sequence concatenation

163 <DOM OP> ::= INJ                                S> :INJ       -- domain operators
                                                                  -- injection
164            | PRO                                S> :PRO       -- projection

165 <UN_OP> ::= -                                   S> :UMINUS
166           | NOT                                 S> :NOT
167           | LENGTH                              S> :LENGTH

168 <ADD_OP> ::= +                                  S> :PLUS
169            | -                                  S> :MINUS

170 <EXPRESSION_LIST> ::= <EXPRESSION_LIST> , <EXPRESSION> S> <<
171                     | <EXPRESSION>              S> <>

172 <2_EXPRESSION_LIST> ::= <2_EXPRESSION_LIST> , <EXPRESSION> S> <<
173                       | <EXPRESSION> , <EXPRESSION> S> MAKETUPLE[2]
```

A VOCABULARY CROSS-REFERENCE

```
&          162
(           33   34   43   44   45   54  103  140  146  152  153  154  155  156  157  158  159
)           33   34   43   44   45   54  103  140  146  152  153  154  155  156  157  158  159
*          135
**           1    1
+          168
.           36   38   39   40   41   42   49   68  170  172  173
-          165  169
.etconst    72
.integer   137
.procname            8    9   48   49   71  150
.string    138
.typemark            73
.varname    27   37   38   39   39   40   67   70   95  100  101  149
/=         123
:           27   28   57   67  100  101  160
::         161
:=          67
;            3    4   10   11   12   13   14   15   55   62   63   82
<          126
<=         127
=          122
=>          91  100  101
>          124
>=         125
AND        109  110  115  116
BEGIN       59  106
BODY         9
CASE        88   88
DECLARE    104
ELSE        87  117  118
ELSIF       86
ELT        121
END          8    9   59   87   88   97  106
FUNCTION    43   52
IF          84   87
INJ        163
IS           8    9   29   50   51   88   97
LENGTH     167
NOT        166
OR         111  112  117  118
OTHERS      96  102
PACKAGE      8    9
PRIVATE     31
PRO        164
PRODUCT     44
RETURN      58   83
SEQUENCE    46
SUM         45
TCASE       97   97
THEN        84   86  115  116
TYPE        29   43   44   45   46
USE         47
WHEN        91  100  102
XOR        113  114
|          147  148
]          147  148
|           92
<? EXPRESSION_LIST>          146  172 -172 -173
<2_TYPE_ID_LIST>      -41    42  -42   44   45
<2_VAR_ID_LIST>        28   -39   40  -40
<ADD_OP>      133 -168 -169
<AFDL_PROGRAM>           1   -2
<ALTERNATIVE>          89   90  -91
<ALTERNATIVE_LIST>     88   89  -89  -90
<ANDTHEN_EXPRESSION>         79 -115  116 -116
<AND_EXPRESSION>       76 -109  110 -110
```

```
<BLOCK>  -104 -105  145
<BLOCK_BODY>     60   61  104  105 -106
<CASE_EXPR>     -88  142
<CHOICE>    92   93  -94  -95  -96
<CHOICE_LIST>    91   92  -92  -93
<COMPILATION_UNIT>     3    4   -5   -6   -7
<COMPILATION_UNIT_LIST>     2    3   -3   -4
<CONDITION>     84  -85   86
<CONST_ID>      35   36  -72   94  151
<CONST_ID_LIST>      33  -35   36  -36
<CURRIED_FUNCTION_CALL>  154  155 -156 -157  158 -158  159 -159
<DECLARATION>    62   63  -64  -65  -66
<DECLARATION_LIST>    60   62  -62  -63  104
<DECLARATIVE_ITEM>    10   11   12   14  -16  -17  -18  -19  -20  -21  -22  -23  -24  -25  -26
<DECLARATIVE_ITEM_LIST>     8  -10   11  -11
<DECLARATIVE_PART>     9  -12  -13   14  -14   15  -15
<DOM_OP>  130 -163 -164
<ENUMERATED_TYPE_DEFINITION>    30  -33  -34
<EXPRESSION>     67  -74  -75  -76  -77  -78  -79  -80   83   84   85   86   87   88   91   97  100  101  103
                106  140  170  171  172  173  173
<EXPRESSION_LIST>   147  153  155  157  159  170 -170 -171
<FORMAL_PART>    52  -53  -54
<FUNCTION_BODY>      50  -60  -61
<FUNCTION_CALL>     139 -152 -153 -154 -155
<FUNCTION_DECLARATION>      5   19  -50  -51   65
<FUNCTION_NAME_OPTION>      8    9   59  106 -107 -108
<FUNCTION_SPECIFICATION>       18   50   51  -52   66
<FUNCTION_TYPE_DECLARATION>    21  -43
<ID>       52  108  136 -149 -150 -151  152  153  156  157
<IF_EXPR>      -84  141
<IF_EXPR_TAIL>       84   86  -86  -87
<NAME>     68   69  -70  -71
<NAME_LIST>     57   68  -68  -69
<NULL_BLOCK_BODY>     51  -59
<ORELSE_EXPRESSION>       80 -117  118 -118
<OR_EXPRESSION>       77 -111  112 -112
<PACKAGE_BODY>        7   -9   13   15
<PACKAGE_SPECIFICATION>     6   -8   25
<PARAMETER_DECLARATION>    55   56  -57
<PARAMETER_DECLARATION_LIST>    43   54   55  -55  -56
<PKG_ID_LIST>    47  -48   49  -49
<PRIMARY>      134  135 -136 -137 -138 -139 -140 -141 -142 -143 -144 -145 -146 -147 -148
<PRODUCT_TYPE_DECLARATION>     22  -44
<RELATION>      75  109  109  110  111  111  112  113  113  114  115  115  116  117  117  118 -119 -120 -121
<RELOP>   120 -122 -123 -124 -125 -126 -127
<RETURN_EXPR>    74  -83
<RETURN_TYPE>    43   52  -58
<SEMI>     -81  -82   84   86   87   91  100  101  106
<SEQUENCE_TYPE_DECLARATION>     24  -46
<SEQ_OP>  129 -160 -161 -162
<SIMPLE_EXPRESSION>       119  120  120  121 -128  129 -129  130  130
<SUM>      128  129 -131 -132  133 -133
<SUM_TYPE_DECLARATION>     23  -45
<SYSTEM_GOAL_SYMBOL>       -1
<TERM>     131  132  133 -134  135 -135
<TYPE_ALT>       98   99 -100 -101
<TYPE_ALT_LIST>       97  -98   99  -99
<TYPE_CASE_EXPR>     -97  143
<TYPE_COERCION>     -103  144
<TYPE_DECLARATION>     20  -29
<TYPE_DEFINITION>     29   30  -31  -32
<TYPE_ID>        27   28   29   32   41   41   42   43   44   45   46   46   57   58   67  -73  100  101  103
                121  130
<UN_OP>   132 -165 -166 -167
<USE_CLAUSE>     26  -47
<VARIABLE_DECLARATION>     17   64  -67
<VARIABLE_SPECIFICATION>       16  -27  -28
<VAR_ID_LIST>    34  -37   38  -38
<WHEN_OTHERS>  101 -102
<XOR_EXPRESSION>      78 -113  114 -114
```

REFERENCES

1. *Reference Manual for the Ada Programming Language (Proposed Standard Document)*. United States Department of Defense. 1980.

2. Stoughton, A., V. Kini, and D. Martin. *AFDL + Transcripts*. Transcripts of Interlisp sessions during which the definition of the TINY language is processed through AFDL + tools.

3. Kini, V., D. Martin, and A. Stoughton, *A Description of AFDL + : The Ada FSD Metalanguage*. An informal specification of ISI's enhanced version of the Ada FSD Metalanguage.

4. Martin, D., *Documentation for Syntax Analysis Tools*. Documentation for algorithms and Interlisp code for syntax analysis tools.

5. Kini, V., *Documentation for <AU-ADA>AFDL-COMPILER*. Documentation for algorithms and Interlisp code for the AFDL + compiler.

6. Kini, V., and A. Stoughton, *Documentation for <AU-ADA>VIRTUAL-MACHINE*. Documentation for structure of and Interlisp code for the AFDL + virtual machine.

7. Stoughton, A., *Documentation for <AU-ADA>TYPECHECK*. Documentation of algorithms and Interlisp code for AFDL + typechecker.

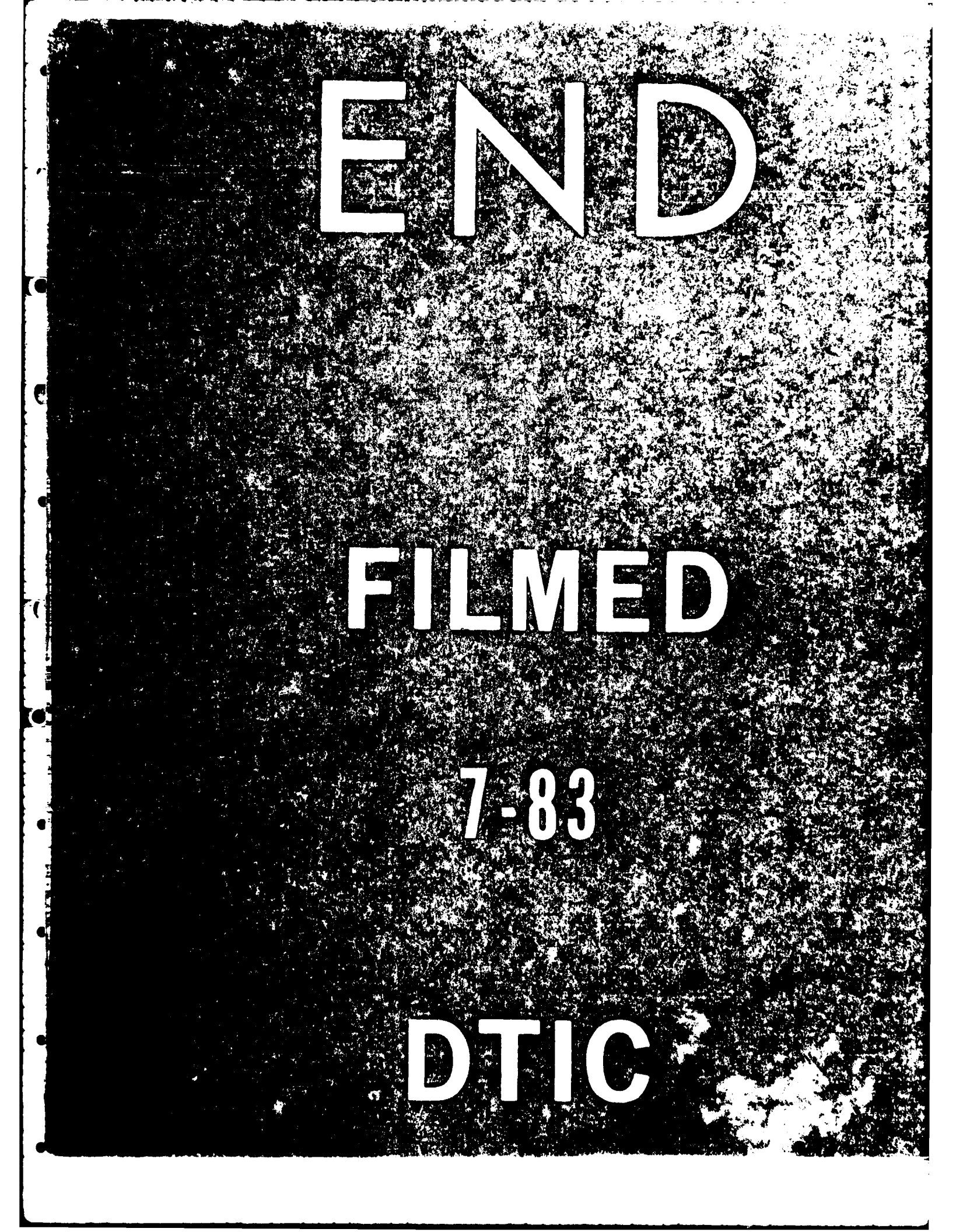
8. Goodenough, J. B., and J. R. Kelly, *Ada Compiler Validation Capability: Long Range Plan*, Defense Advanced Research Projects Agency, Waltham, Mass., Technical Report 1067-1.1, February 1980.

9. Gordon, M. J. C., *The Denotational Description of Programming Languages: An Introduction*, Springer-Verlag, New York, 1979.

10. Donzeau-Gouge, V., et al., *Formal Definition of the Ada Programming Language (Preliminary Version for Public Review)*, INRIA, Le Chesnay, France, November 1980.

11. Mosses, P. D., *SIS: A Compiler-Generator System Using Denotational Semantics (Reference Manual)*, Department of Computer Science, Aarhus University, Denmark, Draft Report 78-4-3, June 1978.

12. Wetherell, C., and A. Shannon, "LR -- Automatic parser generator and LR(1) parser," *IEEE Transactions on Software Engineering* SE-7, (3), May 1981, 274-278.


END
FILMED
7-83
DTIC