52

Modula-3 Report (revised)

Luca Cardelli, James Donahue,
Lucille Glassman, Mick Jordan,
Bill Kalsow, Greg Nelson

November 1, 1989

Systems Research Center
130 Lytton Avenue
Palo Alto, California 94301

Systems Research Center

DEC's business and technology objectives require a strong research program. The Systems Research Center (SRC) and three other research laboratories are committed to filling that need.

SRC began recruiting its first research scientists in 1984 — their charter, to advance the state of knowledge in all aspects of computer systems research. Our current work includes exploring high-performance personal computing, distributed computing, programming environments, system modelling techniques, specification technology, and tightly-coupled multiprocessors.

Our approach to both hardware and software research is to create and use real systems so that we can investigate their properties fully. Complex systems cannot be evaluated solely in the abstract. Based on this belief, our strategy is to demonstrate the technical and practical feasibility of our ideas by building prototypes and using them as daily tools. The experience we gain is useful in the short term in enabling us to refine our designs, and invaluable in the long term in helping us to advance the state of knowledge about those systems. Most of the major advances in information systems have come through this strategy, including time-sharing, the ArpaNet, and distributed personal computing.

SRC also performs work of a more mathematical flavor which complements our systems research. Some of this work is in established fields of theoretical computer science, such as the analysis of algorithms, computational geometry, and logics of programming. The rest of this work explores new ground motivated by problems that arise in our systems research.

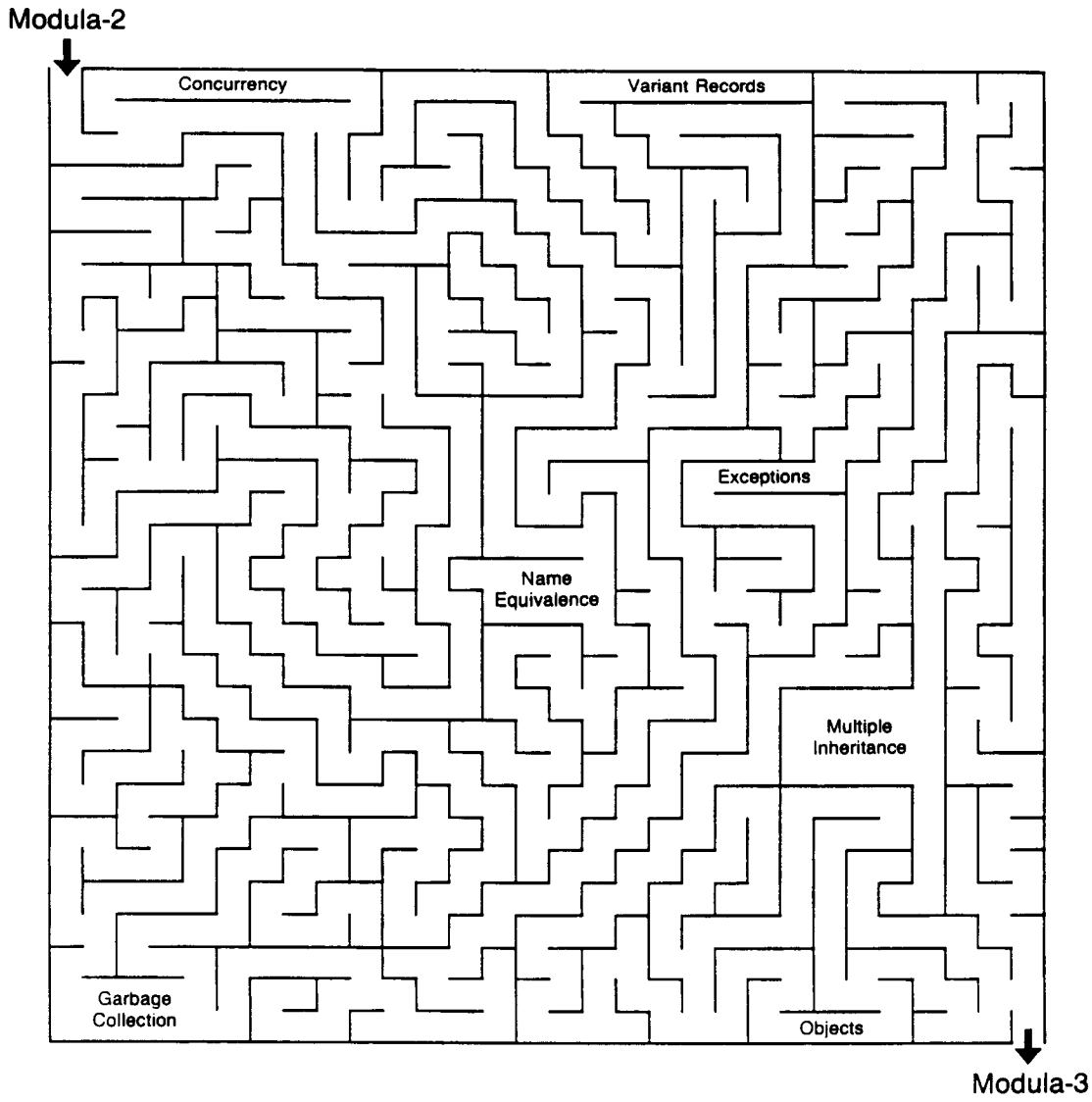
DEC has a strong commitment to communicating the results and experience gained through pursuing these activities. The Company values the improved understanding that comes with exposing and testing our ideas within the research community. SRC will therefore report results in conferences, in professional journals, and in our research report series. We will seek users for our prototype systems among those with whom we have common research interests, and we will encourage collaboration with university researchers.

Robert W. Taylor, Director

Modula-3 Report (revised)

Luca Cardelli, James Donahue, Lucille Glassman, Mick Jordan, Bill Kalsow, Greg Nelson

November 1, 1989



See the end of this report for "Twelve changes to Modula-3, 19 December 1990".

Contents

Preface

The goal of Modula-3 is to be as simple and safe as it can be while meeting the needs of modern systems programmers. Instead of exploring new features, we studied the features from the Modula family of languages that have proven themselves in practice and tried to simplify them and fit them into a harmonious language. We found that most of the successful features were aimed at one of two main goals: greater robustness, and a simpler, more systematic type system.

Modula-3 descends from Mesa[6], Modula-2[10], Cedar[3], and Modula-2+[8, 7]. It also resembles its cousins Object Pascal[5], Oberon[9], and Euclid[4].

Modula-3 retains one of Modula-2's most successful features, the provision for explicit interfaces between modules. It adds objects and classes, exception handling, garbage collection, lightweight processes (or *threads*), and the isolation of unsafe features.

The Modula-3 report was published by Olivetti and Digital in August 1988. Implementation efforts followed shortly at both companies. In January 1989, the committee revised the language to reflect the experiences of these implementation teams. The main changes were the introduction of branded reference types, the requirement that opaque types be branded, the legalization of opaque supertypes, and the new flexibility in revealing information about an opaque type.

Modula-3 Report

He that will not apply new remedies must expect new evils: for time is the greatest innovator, and if time of course alter things to the worse, and wisdom and counsel shall not alter them to the better, what shall be the end?
—Francis Bacon

1 Definitions

A Modula-3 program specifies a computation that acts on a sequence of digital components called *locations*. A *variable* is a set of locations that represents a mathematical value according to a convention determined by the variable's *type*. If a value can be represented by some variable of type T, then we say that the value is a *member* of T and T *contains* the value.

An *identifier* is a symbol declared as a name for a variable, type, procedure, etc. The region of the program over which a declaration applies is called the *scope* of the declaration. Scopes can be nested. The meaning of an identifier is determined by the smallest enclosing scope in which the identifier is declared.

An *expression* specifies a computation that produces a value or variable. Expressions that produce variables are called *designators*. A designator can denote either a variable or the value of that variable, depending on the context. Some designators are *readonly*, which means that they cannot be used in contexts that might change the value of the

variable. A designator that is not readonly is called *writable*. Expressions whose values can be determined statically are called *constant expressions*; they are never designators.

A *static error* is an error that the implementation must detect before program execution. Violations of the language definition are static errors unless they are explicitly classified as runtime errors.

A *checked runtime error* is an error that the implementation must detect and report at runtime. The method for reporting such errors is implementation-dependent. (If the implementation maps them into exceptions, then a program could handle these exceptions and continue.)

An *unchecked runtime error* is an error that is not guaranteed to be detected, and can cause the subsequent behavior of the computation to be arbitrary. Unchecked runtime errors can occur only in unsafe modules.

2 Types

I am the voice of today, the herald of tomorrow...
I am the leaden army that conquers the world—I am TYPE.
—Frederic William Goudy

Modula-3 uses structural equivalence, instead of the name equivalence of Modula-2. Two types are the same if their definitions become the same when expanded; that is, when all constant expressions are replaced by their values and all type names are replaced by their definitions. In the case of recursive types, the expansion is the infinite limit of the partial expansions. A type expression is allowed wherever a type is required.

In any scope, a type name is either *opaque* or *concrete*. An opaque type name denotes a reference type with an unknown referent type. A concrete type name denotes a type that is known in the scope (except for the referent types of opaque types that occur within it). The `REVEAL` statement can be used to make an opaque type name concrete within a scope by making its referent type known (Section 4, page 31).

A type is *empty* if it contains no values. For example, `[1..0]` is an empty type. Empty types can be used to build non-empty types (for example, `SET OF [1..0]`, which is not empty because it contains the empty set). It is a static error to declare a variable of an empty type.

Every expression has a statically-determined type, which contains every value that the expression can produce. The type of a designator is the type of the variable it produces.

Assignability and type compatibility are defined in terms of a single syntactically spec-

ified subtype relation with the property that if T is a subtype of U, then every member of T is a member of U.

Every expression has a unique type, but a value can be a member of many types. For example, the value 6 is a member of both [0..9] and INTEGER. It would be ambiguous to talk about "the type of a value". Thus the phrase "type of x" means "type of the expression x", while "x is a member of T" means "the value of x is a member of T".

However, there is one sense in which a value can be said to have a type: every object or traced reference value includes a code for a type, called the *allocated type* of the reference value. The allocated type is tested by TYPECASE (Section 3, page 27).

Ordinal types

There are three kinds of ordinal types: enumerations, subranges, and INTEGER. An enumeration type is declared like this:

```
TYPE T = {id1, id2, ..., idn}
```

where the id's are distinct identifiers. The type T is an ordered set of n values; the expression $T.id_i$ denotes the i'th value of the type in increasing order. The empty enumeration { } is allowed.

Integers and enumeration elements are collectively called *ordinal values*. The *base type* of an ordinal value v is INTEGER if v is an integer, otherwise it is the unique enumeration type that contains v.

A subrange type is declared like this:

```
TYPE T = [Lo..Hi]
```

where Lo and Hi are two ordinal values with the same base type, called the base type of the subrange. The values of T are all the values from Lo to Hi inclusive. Lo and Hi must be constant expressions (Section 6, page 48). If Lo exceeds Hi, the subrange is empty.

The operators ORD and VAL convert between enumerations and integers. The operators FIRST, LAST, and NUMBER applied to an ordinal type return the first element, last element, and number of elements, respectively (Section 6, page 46).

Here are the predeclared ordinal types:

INTEGER	All integers represented by the implementation
CARDINAL	The subrange [0..LAST(INTEGER)]
BOOLEAN	The enumeration {FALSE, TRUE}
CHAR	An enumeration containing at least 256 elements

The first 256 elements of type CHAR represent characters in the ISO-Latin-1 code, which is an extension of ASCII. The language does not specify the names of the elements of the CHAR enumeration. FALSE and TRUE are predeclared synonyms for BOOLEAN.FALSE and BOOLEAN.TRUE.

Each distinct enumeration type introduces a new collection of values, but a subrange type reuses the values from the underlying type. For example:

```
TYPE
  T1 = {A, B, C};
  T2 = {A, B, C};
  U1 = [T1.A..T1.C];
  U2 = [T1.A..T2.C]; (* sic *)
  V =  {A, B}
```

T1 and T2 are the same type, since they have the same expanded form. In particular, T1.C = T2.C and therefore U1 and U2 are also the same type. But the types T1 and U1 are distinct, although they contain the same values, because the expanded form of T1 is an enumeration while the expanded form of U1 is a subrange. The type V is a third type whose values V.A and V.B are not related to the values T1.A and T1.B.

Floating-point types

There are two built-in floating point types:

REAL	Contains all single-precision floating point values
LONGREAL	Contains all double-precision floating point values

Arrays

An *array* is an indexed collection of component variables, called the *elements* of the array. The indexes are the values of an ordinal type, called the *index type* of the array. The elements all have the same size and the same type, called the *element type* of the array.

There are two kinds of array types, *fixed* and *open*. The length of a variable with a fixed array type is determined at compile time. The length of a variable with an open array type is determined at runtime, when the variable is allocated or bound. It cannot be changed thereafter.

The *shape* of a multi-dimensional array is the sequence of its lengths in each dimension. More precisely, the shape of an array is its length followed by the shape of any of its elements; the shape of a non-array is the empty sequence.

Arrays are assignable if they have the same element type and shape. If either the source or target of the assignment is an open array, a runtime shape check is required (Section 3, page 17).

A fixed array type declaration has the form:

```
TYPE T = ARRAY Index OF Element
```

where `Index` is an ordinal type and `Element` is any type other than an open array type. The values of type `T` are arrays whose element type is `Element` and whose length is the number of elements of the type `Index`.

If `a` has type `T`, then `a[i]` designates the element of `a` whose position corresponds to the position of `i` in `Index`. For example, consider the declarations:

```
VAR a: ARRAY [0..2] OF REAL
VAR b: ARRAY [5..7] OF REAL
```

The variables `a` and `b` range over the same set of values, namely the set of real sequences of length three. But `a[i]` and `b[i]` are interpreted differently; for example, the first element of `a` is designated `a[0]` while the first element of `b` is designated `b[5]`. This interpretation is unchanged by the assignment `a := b`, since assignment changes a variable's value but not its type.

An expression of the form:

```
ARRAY Index1, ..., Indexn OF Element
```

is shorthand for:

```
ARRAY Index1 OF ... OF ARRAY Indexn OF Element
```

This shorthand is eliminated from the expanded form of the type.

An expression of the form $a[i_1, \ldots, i_n]$ is shorthand for $a[i_1] \ldots [i_n]$.

An open array type declaration has the form:

```
TYPE T = ARRAY OF Element
```

where `Element` is any type. The values of `T` are arrays whose element type is `Element` and whose length is arbitrary. The index set of an open array variable is the integer subrange `[0..n-1]`, where `n` is the length of the array.

An open array type can be used only as the type of a formal parameter, the referent of a reference type, the element type of another open array type, or as the type in an array constructor.

Examples of array types:

```
TYPE
  Transform = ARRAY [1..3], [1..3] OF REAL;
  Vector = ARRAY OF REAL;
  Priority = {Background, Normal, High};
  ReadyQueue = ARRAY Priority OF Queue.T
```

Records

A *record* is a sequence of named variables, called the *fields* of the record. Different fields can have different types. The name and type of each field is statically determined by the record's type. The expression `r.f` designates the field named `f` in the record `r`.

A record type declaration has the form:

```
TYPE T = RECORD FieldList END
```

where `FieldList` is a list of field declarations, each of which has the form:

```
fieldName: Type := default
```

where `fieldName` is an identifier, `Type` is any non-empty type other than an open array type, and `default` is a constant expression. The field names must be distinct. A record is a member of `T` if it has fields with the given names and types, in the given order, and no other fields. Empty records are allowed.

The constant `default` is a default value used when a record is constructed (page 41) or allocated (page 42). Either "`:= default`" or "`: Type`" can be omitted, but not both. If `Type` is omitted, it is taken to be the type of `default`. If both are present, the value of `default` must be a member of `Type`.

When a series of fields shares the same type and default, any `fieldName` can be a list of identifiers separated by commas. Such a list is shorthand for a list in which the type and default are repeated for each identifier. That is:

f_1, ..., f_m`: Type := default`

is shorthand for:

f_1`: Type := default; ...;` f_m`: Type := default`

The shorthand is eliminated from the expanded form of the type. The default values are included in the expanded form.

Examples of record types:

```
TYPE
  Time = RECORD seconds: INTEGER; milliseconds: [0..999] END;
  Alignment = {Left, Center, Right};
  TextWindowStyle = RECORD
    align := Alignment.Center;
    font := Font.Default;
    foreground := Color.Black;
    background := Color.White;
    margin, border := 2
  END
```

Packed types

A declaration of a packed type has the form:

```
TYPE T = BITS n FOR Base
```

where `Base` is a type and `n` is an integer-valued constant expression. The values of type `T` are the same as the values of type `Base`, but variables of type `T` that occur in records, objects, or arrays will occupy exactly `n` bits and be packed adjacent to the preceding field or element. For example, a variable of type

```
ARRAY [0..255] OF BITS 1 FOR BOOLEAN
```

is an array of 256 booleans, each of which occupies one bit of storage.

The values allowed for `n` are implementation-dependent. An illegal value for `n` is a static error. The legality of a packed type can depend on its context; for example, an implementation could prohibit packed integers from spanning word boundaries.

Sets

A *set* is a collection of values taken from some ordinal type. A set type declaration has the form:

```
TYPE T = SET OF Base
```

where `Base` is an ordinal type. The values of `T` are all sets whose elements have type `Base`. For example, a variable whose type is `SET OF [0..1]` can assume the following values:

```
{}    {0}    {1}    {0,1}
```

Implementations are expected to use the same representation for a `SET OF T` as for an `ARRAY T OF BITS 1 FOR BOOLEAN`. Hence, programmers should expect `SET OF [0..1023]` to be practical, but not `SET OF INTEGER`.

References

A *reference* value is either NIL or the address of a variable, called the referent.

A reference type is either *fixed*, *open*, or an object type. The members of a fixed reference type address variables of some fixed type; the members of an open reference type address variables of any type. An object type is intermediate between a fixed and open reference type: all variables addressed by a member of an object type share a common set of fields and methods. This section describes fixed and open reference types; Section 2, page 11, describes object types.

A reference type is either *traced* or *untraced*. When all traced references to a piece of allocated storage are gone, the implementation reclaims the storage. Two reference types are of the same *reference class* if they are both traced or both untraced.

There are exactly three open reference types (NULL is included by convention):

REFANY	Contains all traced references
ADDRESS	Contains all untraced references
NULL	Contains only NIL

The TYPECASE statement (Section 3, page 27) can be used to determine the referent type of a variable of type REFANY or of an object, but there is no such operation for variables of type ADDRESS.

A declaration for a fixed traced reference type has the form:

```
TYPE T = REF Type
```

where Type is any type. The values of T are traced references to variables of type Type, which is called the *referent type* of T.

Untraced reference types are similar, but with the restriction that it is unsafe for an untraced reference to point at a type that the garbage collector must trace. We thus extend the definition of "traced": a type is *traced* if it is a traced reference type, a record type any of whose field types is traced, an array type whose element type is traced, or a packed type whose underlying unpacked type is traced. Otherwise a type is *untraced*.

A declaration for a fixed untraced reference type has the form:

```
TYPE T = UNTRACED REF Type
```

where Type is any untraced[1] type. The values of T are the untraced references to variables of type Type.

In both the traced and untraced cases, the keyword REF can optionally be preceded by "BRANDED b" where b is a text literal called the *brand*. Brands distinguish types

[1] This restriction is lifted in unsafe modules.

that would otherwise be the same; they have no other semantic effect. All brands in a program must be distinct. If BRANDED is present and b is absent, the implementation automatically supplies a unique value for b.

Examples of reference types:

```
TYPE
  TextLine = REF ARRAY OF CHAR;
  ControllerHandle = UNTRACED REF RECORD
    status: BITS 8 FOR [0..255];
    filler: BITS 12 FOR [0..0];
    pc: BITS 12 FOR [0..4095]
  END;
  T = BRANDED "ANSI-M3-040776" REF INTEGER;
  Apple = BRANDED REF INTEGER;
  Orange = BRANDED REF INTEGER;
```

Procedures

A *procedure* is either NIL or a triple consisting of:

- the *body*, which is a statement,
- the *signature*, which specifies the procedure's formal arguments, result type, and raises set (the set of exceptions that the procedure can raise),
- the *environment*, which is the scope with respect to which variable names in the body will be interpreted.

A procedure that returns a result is called a *function procedure*; a procedure that does not return a result is called a *proper procedure*. A *top-level* procedure is a procedure declared in the outermost scope of a module. Any other procedure is a *local* procedure. (A local procedure can be passed as a parameter but not assigned, since in a stack implementation a local procedure becomes invalid when the frame for the procedure containing it is popped.)

A *procedure constant* is an identifier declared as a procedure. (As opposed to a procedure variable, which is a variable declared with a procedure type.)

A procedure type declaration has the form:

```
TYPE T = PROCEDURE sig
```

where sig is a signature specification, which has the form:

```
(mode1 name1: type1 := default1;
...;
moden namen: typen := defaultn): R RAISES {S}
```

where:

- Each `mode`$_i$ is a parameter mode, which can be `VALUE`, `VAR`, or `READONLY`. If `mode`$_i$ is omitted, it defaults to `VALUE`.
- Each `name`$_i$ is an identifier, the name of parameter `i`. The parameter names must be distinct.
- Each `type`$_i$ is a type, the type of parameter `i`.
- Each `default`$_i$ is a constant expression to be used as a default value for parameter `i`. If `mode`$_i$ is `VAR`, it is a static error to include "`:= default`$_i$". If `mode`$_i$ is `READONLY` or `VALUE`, either "`:= default`$_i$" or "`: type`$_i$" can be omitted, but not both. If `default`$_i$ is omitted, calls to procedures of type `T` must include a value for parameter `i`. If `type`$_i$ is omitted, it is taken to be the type of `default`$_i$. If both are present, the value of `default`$_i$ must be a member of `type`$_i$.
- `R` is the result type, which can be any type but an open array type. The "`: R`" can be omitted, making the signature that of a proper procedure.
- `S` is a set of exceptions, the raises set. If "`RAISES {S}`" is omitted, `S` defaults to the set of all exceptions. "`RAISES {}`" means that `S` is the empty set.

A procedure value `P` is a member of the type `T` if it is `NIL` or its signature is *covered* by the signature of `T`, where `signature`$_1$ covers `signature`$_2$ if:

- They have the same number of parameters, and corresponding parameters have the same type and mode.
- They have the same result type, or neither has a result type.
- The raises set of `signature`$_1$ contains the raises set of `signature`$_2$.

The parameter names and defaults affect the type of a procedure variable, but not its value. For example, consider the declarations:

```
VAR p: PROCEDURE(n: INTEGER)
VAR q: PROCEDURE(m: INTEGER)
```

The variables p and q range over the same set of values, namely the proper procedures with one `VALUE` parameter of type `INTEGER`. But calls that use keyword parameters are interpreted differently; for example, `p(n := 0)` is a valid call, but `p(m := 0)` is not. This interpretation is unchanged by the assignment `p := q`, since assignment changes a variable's value but not its type.

When a series of parameters share the same mode, type, and default, `name`$_i$ can be a list of identifiers separated by commas. Such a list is shorthand for a list in which the mode, type, and default are repeated for each identifier. That is:

```
mode v1, ..., vn: type := default
```

is shorthand for:

```
mode v1: type := default; ...; mode vn: type := default
```

This shorthand is eliminated from the expanded form of the type. The default values are included in the expanded form.

Examples of procedure types:

```
TYPE
  Integrand = PROCEDURE (x: REAL): REAL;
  Integrator = PROCEDURE(f: Integrand; lo, hi: REAL): REAL;
  TokenIterator = PROCEDURE(VAR t: Token) RAISES {TokenError};
  RenderProc = PROCEDURE(
    scene: REFANY;
    READONLY t: Transform := Identity)
```

In a procedure type, `RAISES` binds to the closest preceding `PROCEDURE`. That is, the parentheses are required in:

```
TYPE T = PROCEDURE (): (PROCEDURE ()) RAISES {}
```

Objects

An *object* is either `NIL` or a reference to a data record paired with a method suite, which is a record of procedures that will each accept the object as a first argument.

The object type determines the types of a prefix of the fields of the data record, as if "`OBJECT`" were "`REF RECORD`". But the data record can contain additional fields not mentioned in the object type. Similarly, the object type determines the signatures of a prefix of the method suite, but the suite can contain additional methods.

The only way to call a procedure in a method suite is to pass the object itself as the first argument. Consequently, the first parameter to the procedure can be of any type that contains the object. The rest of the procedure signature must be covered by the method declaration in the object type. More precisely, a procedure `p` *satisfies* a method declaration with signature `sig` for an object `x` if `p` is `NIL` or if:

- `p` is a top-level procedure whose first parameter has mode `VALUE` and a type that contains `x`, and
- if `p`'s first parameter is dropped, the resulting signature is covered by `sig`.

If o is an object, then `o.f` designates the data field named `f` in o's data record. If `m` is one of o's methods, an invocation of the form `o.m( ... )` denotes an execution of o's `m` method (Section 3). Such invocations are the only way to access methods.

There are two built-in object types:

`ROOT`	The traced object type with no fields or methods
`UNTRACED ROOT`	The untraced object type with no fields or methods

The declaration of an object type has the form:

```
TYPE T = ST OBJECT FieldList METHODS MethodList END
```

where `ST` is an optional supertype, `FieldList` is a list of field declarations, exactly as in a record type, and `MethodList` is a list of *method declarations* and *method overrides*, which are defined below. The names introduced in `FieldList` and `MethodList` must be distinct. If `ST` is omitted, it defaults to `ROOT`. If `ST` is untraced, then the fields must not include traced types.[2]

In both the traced and untraced cases, the keyword `OBJECT` can optionally be preceded by "`BRANDED`" or by "`BRANDED b`", where `b` is a text literal. The meaning is the same as in non-object reference types.

A method declaration has the form:

```
m sig := proc
```

where `m` is an identifier, `sig` is a procedure signature, and `proc` is a top-level procedure constant.

The "`:= proc`" is optional. If present, it specifies a default method value used when allocating objects of type `T`; if absent, the default method value is `NIL`. A procedure is a legal default value for method `m` in type `T` if it satisfies the method signature for any object of type `T`; that is, if its first parameter has mode `VALUE` and type some supertype of `T` and if dropping its first parameter results in a signature that is covered by `sig`.

A method override has the form:

```
m := proc
```

where `m` is the name of a method of the supertype and `proc` is a top-level procedure constant that is a legal default for method `m` in type `T`. Each method override specifies that `proc` is the default value used for method `m` when allocating objects of type `T`. If a method is not overridden, its default in `T` is the same as its default in the supertype.

An object `x` is a member of the type `T` if its data record contains the fields of the supertype, followed by the fields declared in `FieldList`, possibly followed by other fields;

[2] This restriction is lifted in unsafe modules.

its method suite contains procedures that satisfy the method declarations in the supertype, followed by procedures that satisfy the method declarations in `MethodList`, possibly followed by other procedures; its reference class is the same as the reference class of the supertype; and the allocated type of `x` is a subtype of `T`. All fields and methods must appear in the declared order.

Note that the method signatures are statically determined by an object's type (except for the first argument), but the method values are not determined until the object is allocated. They cannot be changed thereafter.

If `T` is an object type and `m` is the name of one of `T`'s methods, then `T.m` denotes `T`'s default `m` method. This notation makes it convenient for a subtype method to invoke the corresponding method of one of its supertypes.

A field or method in a subtype masks any field or method with the same name in the supertype. To access such a masked field, use `NARROW` to view the subtype variable as a member of the supertype.

Examples. Consider the following declarations:

```
TYPE
  A = OBJECT a: INTEGER; METHODS p() END;
  AB = A OBJECT b: INTEGER END;

  PROCEDURE Pa(self: A) = ... ;
  PROCEDURE Pab(self: AB) = ... ;
```

Since neither `A` nor `AB` has a default value for the `p` method, the method value should be specified when the objects are allocated. The procedures `Pa` and `Pab` are suitable values for the `p` method of objects of types `A` and `AB`. For example:

```
NEW(AB, p := Pab)
```

allocates an object with an `AB` data record and a method that expects an `AB`; it is an example of an object of type `AB`. Similarly,

```
NEW(A, p := Pa)
```

allocates an object with an `A` data record and a method that expects an `A`; it is an example of an object of type `A`. A more interesting example is:

```
NEW(AB, p := Pa)
```

which allocates an object with an `AB` data record and a method that expects an `A`. Since every `AB` is an `A`, the method is not too choosy for the object in which it is placed. The result is a valid object of type `AB`. In contrast,

```
NEW(A, p := Pab)
```

attempts to allocate an object with an `A` data record and a method that expects an `AB`; since not every `A` is an `AB`, the method is too choosy for the object in which it is placed. The result would not be a member of the type `AB`, so this call to `NEW` is a static error.

Here is an example of default method values and method overrides:

```
TYPE Window =
  OBJECT
    extent: Rectangle
  METHODS
    mouse(e: ClickEvent) := IgnoreClick;
    repaint(e: RepaintEvent) := IgnoreRepaint
  END;

TYPE TextWindow =
  Window OBJECT
    text: TEXT;
    style: TextWindowStyle
  METHODS
    repaint := RepaintTextWindow
  END;
```

`TextWindow` overrides the repaint method but not the mouse method. So if no methods are specified when an object of type `TextWindow` is allocated, its mouse method will be `IgnoreClick` and its repaint method will be `RepaintTextWindow`. The procedure `RepaintTextWindow` can demand a `TextWindow` as its first parameter, but `IgnoreRepaint` and `IgnoreClick` must accept any `Window`.

Finally, an example that uses objects for reusable queues. First, the interface:

```
TYPE
  Queue = RECORD head, tail: QueueElem END;
  QueueElem = OBJECT link: QueueElem END;

PROCEDURE Insert(VAR q: Queue; x: QueueElem);
PROCEDURE Delete(VAR q: Queue): QueueElem;
PROCEDURE Clear(VAR q: Queue);
```

Then an example client:

```
TYPE
  IntQueueElem = QueueElem OBJECT val: INTEGER END;
VAR
  q: Queue;
  x: IntQueueElem;

  ...
  Clear(q);
  x := NEW(IntQueueElem, val := 6);
  Insert(q, x);
  ...
  x := Delete(q)
```

Passing `x` to `Insert` is safe, since every `IntQueueElem` is a `QueueElem`. Assigning the result of `Delete` to `x` cannot be guaranteed valid at compile-time, but the assignment will produce a checked runtime error if the source value is not a member of the target type. Thus `IntQueueElem` bears the same relation to `QueueElem` as `[0..9]` bears to `INTEGER`. Notice that the runtime check on the result of `Delete(q)` is not redundant, since other subtypes of `QueueElem` can be inserted into `q`.

Subtyping rules

We write `T <: U` to indicate that `T` is a subtype of `U` and `U` is a supertype of `T`.

If `T <: U`, then every value of type `T` is also a value of type `U`. The converse does not hold: for example, a record or array type with packed fields contains the same values as the corresponding type with unpacked fields, but there is no subtype relation between them. This section presents the rules that define the subtyping relation.

`[u..v] <: B`	if u and v have basetype `B`
`[u..v] <: [u'..v']`	if `[u..v]` is a (possibly empty) subset of `[u'..v']`

That is, subtyping on ordinal types reflects the subset relation on the value sets.

$$\texttt{(ARRAY OF)}^{m}\ \texttt{ARRAY}\ J_1, \ldots, J_n\ \texttt{OF ARRAY}\ K_1, \ldots, K_p\ \texttt{OF T}$$
$$<:\ \texttt{(ARRAY OF)}^{m+n}\ \texttt{ARRAY}\ I_1, \ldots, I_p\ \texttt{OF T}$$
if $\texttt{NUMBER}(I_i) = \texttt{NUMBER}(K_i)$ for $i = 1, \ldots, p$.

That is, an array type `A` is a subtype of an array type `A'` if they have the same ultimate element type, the same number of dimensions, and, for each dimension, either both are open, or `A` is fixed and `A'` is open, or they are both fixed and have the same size.

```
NULL <: REF T <: REFANY
NULL <: UNTRACED REF T <: ADDRESS
```

That is, REFANY and ADDRESS contain all traced and untraced references, respectively, and NIL is a member of every reference type.

```
NULL <: PROCEDURE(A): R RAISES S for any A, R, and S.
```

That is, NIL is a member of every procedure type.

```
PROCEDURE(A): Q RAISES E <: PROCEDURE(B): R RAISES F
if signature (B): R RAISES F  covers  (A): Q RAISES E.
```

That is, for procedure types, T <: T′ if they are the same except for parameter names, defaults, and the raises set, and the raises set for T is contained in the raises set for T′.

```
ROOT <: REFANY
UNTRACED ROOT <: ADDRESS
NULL <: T OBJECT ... END <: T
```

That is, every object is a reference, NIL is a member of every object subtype (and therefore of every object type), and every subtype is included in its supertype.

```
BITS n FOR T <: T and T <: BITS n FOR T
```

That is, BITS FOR T has the same values as T.

```
T <: T for all T
T <: U and U <: V implies T <: V for all T, U, V.
```

That is, <: is reflexive and transitive.

Note that T <: U and U <: T does not imply that T and U are the same, since the subtype relation is unaffected by parameter names, default values, and packing.

For example, consider:

```
TYPE
  T = [0..255];
  U = BITS 8 FOR [0..255];
  AT = ARRAY OF T;
  AU = ARRAY OF U;
```

The types T and U are subtypes of one another but are not the same; so the types AT and AU are unrelated by the subtype relation.

Predeclared opaque types

The language predeclares the two types:

```
TEXT <: REFANY
MUTEX <: ROOT
```

which represent text strings and mutual exclusion semaphores, respectively. These are opaque types as defined in Section 4, page 31. Their properties are specified in the required interfaces `Text` and `Thread` (Section 8).

3 Statements

Look into any carpenter's tool-bag and see how many different hammers, chisels, planes and screw-drivers he keeps there—not for ostentation or luxury, but for different sorts of jobs.
—Robert Graves and Alan Hodges

Executing a statement produces a computation that can halt (normal outcome), raise an exception, cause a checked runtime error, or loop forever. If the outcome is an exception, it can optionally be paired with an argument.

We define the semantics of `RETURN` and `EXIT` with exceptions called the *exit-exception* and the *return-exception*. The exit-exception takes no argument; the return-exception takes an argument of arbitrary type. Programs cannot name these exceptions explicitly.

Implementations should speed up normal outcomes at the expense of exceptions (except for the return-exception and exit-exception). Expending ten thousand instructions per exception raised to save one instruction per procedure call would be defensible.

If an expression is evaluated as part of the execution of a statement, and the evaluation raises an exception, then the exception becomes the outcome of the statement.

The empty statement is a no-op. In this report, empty statements are written `(*skip*)`.

Assignment

To specify the typechecking of assignment statements we need to define "assignable", which is a relation between types and types, between expressions and variables, and between expressions and types.

A type `T` is *assignable* to a type `U` if:

- `T <: U`, or
- `U <: T` and `T` is an array or a reference type other than `ADDRESS`[3], or
- `T` and `U` are ordinal types with at least one member in common.

[3] This restriction is lifted in unsafe modules.

An expression `e` is *assignable* to a variable `v` if:

- the type of `e` is assignable to the type of `v`, and
- the value of `e` is a member of the type of `v`, is not a local procedure, and if it is an array, then it has the same shape as `v`.

The first point can be checked statically; the others generally require runtime checks. Since there is no way to determine statically whether the value of a procedure parameter is local or global, assigning a local procedure is a runtime rather than a static error.

An expression `e` is *assignable* to a type `T` if `e` is assignable to a variable of type `T`. (If `T` is not an open array type, it follows that `e` is assignable to any variable of type `T`.)

An assignment statement has the form:

```
v := e
```

where `v` is a writable designator and `e` is an expression assignable to the variable designated by `v`. The statement sets `v` to the value of `e`. The order of evaluation of `v` and `e` is undefined, but `e` will be evaluated before `v` is updated. In particular, if `v` and `e` are overlapping subarrays (Section 6, page 39), the assignment is performed in such a way that no element is used as a target before it is used as a source.

Examples of assignments:

```
VAR
  x: REFANY;
  a: REF INTEGER;
  b: REF BOOLEAN;

  a := b; (* static error *)
  x := a; (* no possible error *)
  a := x (* possible checked runtime error *)
```

The same comments would apply if `x` had an ordinal type with non-overlapping subranges `a` and `b`, or if `x` had an object type and `a` and `b` had incompatible subtypes. The type `ADDRESS` is treated differently from other reference types, since a runtime check cannot be performed on the assignment of raw addresses. For example:

```
VAR
  x: ADDRESS;
  a: UNTRACED REF INTEGER;
  b: UNTRACED REF BOOLEAN;

  a := b; (* static error *)
  x := a; (* no possible error *)
  a := x (* static error in safe modules *)
```

Procedure call

A procedure call has the form:

```
P(Bindings)
```

where P is a procedure-valued expression and Bindings is a list of *keyword* or *positional* bindings. A keyword binding has the form `name := actual`, where `actual` is an expression and `name` is an identifier. A positional binding has the form `actual`, where `actual` is an expression. When keyword and positional bindings are mixed in a call, the positional bindings must precede the keyword bindings. If the list of bindings is empty, the parentheses are still required.

The list of bindings is rewritten to fit the signature of P's type as follows: First, each positional binding `actual` is converted into a keyword binding by supplying the name of the i'th formal parameter, where `actual` is the i'th binding in Bindings. Second, for each parameter that has a default and is not bound after the first step, the binding `name := default` is added to the list of actuals, where `name` is the name of the parameter and `default` is its default value.

The rewritten list of actuals must bind only formal parameters and must bind each formal parameter exactly once.

For a READONLY or VALUE parameter, the actual can be any expression assignable to the type of the formal (except that the prohibition against assigning local procedures is relaxed). For a VAR parameter, the actual must be a writable designator whose type is the same as that of the formal, or, in case of a VAR array parameter, assignable to that of the formal.

A VAR formal is bound to the variable designated by the corresponding actual; that is, it is aliased. A VALUE formal is bound to a variable with an unused location and initialized to the value of the corresponding actual. A READONLY formal is treated as a VAR formal if the actual is a designator and the type of the actual is the same as the type of the formal (or an array type that is assignable to the type of the formal); otherwise it is treated as a VALUE formal.

Implementations are allowed to forbid VAR or READONLY parameters of packed types.

To execute the call, the procedure P and its arguments are evaluated, the formal parameters are bound, and the body of the procedure is executed. The order of evaluation of P and its actual arguments is undefined. It is a checked runtime error to call an undefined or NIL procedure.

It is a checked runtime error for a procedure to raise an exception not listed in its RAISES clause[4] or for a function procedure to fail to return a result.

[4] If an implementation maps this runtime error into an exception, the exception is implicitly included in all RAISES clauses.

A procedure call is a statement only if the procedure is proper. To call a function procedure and discard its result, use EVAL.

A procedure call can also have the form:

```
o.m(Bindings)
```

where o is an object and m names one of o's methods. This is equivalent to:

```
(o's m method) (o, Bindings)
```

For examples of procedure calls, suppose that the type of P is

```
PROCEDURE(ch: CHAR; n: INTEGER := 0)
```

Then the following calls are all equivalent:

```
P('a', 0)
P('a')
P(n := 0, ch := 'a')
P('a', n := 0)
```

The call P() is illegal, since it doesn't bind ch. The call P(n := 0, 'a') is illegal, since it has a keyword parameter before a positional parameter.

EVAL

An EVAL statement has the form:

```
EVAL e
```

where e is an expression. The effect is to evaluate e and ignore the result. For example:

```
EVAL Thread.Fork(p)
```

Block statement

A block statement has the form:

```
Decls BEGIN S END
```

where Decls is a sequence of declarations and S is a statement. The block introduces the constants, types, variables, and procedures declared in Decls and then executes S. The scope of the declared names is the block. (See Section 4, page 28.)

Sequential composition

A statement of the form:

```
S1 ; S2
```

executes S_1, and then if the outcome is normal, executes S_2. If the outcome of S_1 is an exception, S_2 is ignored.[5]

RAISE

A `RAISE` statement without an argument has the form:

```
RAISE e
```

where `e` is an exception that takes no argument. The outcome of the statement is the exception `e`. A `RAISE` statement with an argument has the form:

```
RAISE e(x)
```

where `e` is an exception that takes an argument and `x` is an expression assignable to `e`'s argument type. The outcome of the statement is the exception `e` paired with the argument `x`.

TRY EXCEPT

A `TRY-EXCEPT` statement has the form:

```
TRY
  Body
EXCEPT
  id1 (v1) => Handler1
| ...
| idn (vn) => Handlern
ELSE Handler0
END
```

where `Body` and each `Handler` are statements, each `id` names an exception, and each `v` is an identifier. The "`ELSE Handler`$_0$" and each "`(v`$_i$`)`" are optional. It is a static error for an exception to be named more than once in the list of `id`'s.

The statement executes `Body`. If the outcome is normal, the except clause is ignored. If `Body` raises any listed exception `id`$_i$, then `Handler`$_i$ is executed. If `Body` raises any other exception and "`ELSE Handler`$_0$" is present, then it is executed. In either case,

[5] Some programmers use the semicolon as a statement terminator, some use it as a statement separator. Similarly, some use the vertical bar in case statements as a prefix operator, some use it as a separator. Modula-3 allows both styles. This report uses both operators as separators.

the outcome of the TRY statement is the outcome of the selected handler. If Body raises an unlisted exception and "ELSE $\texttt{Handler}_0$" is absent, then the outcome of the TRY statement is the exception raised by Body.

Each $(\texttt{v}_i)$ declares a variable whose type is the argument type of the exception $\texttt{id}_i$ and whose scope is $\texttt{Handler}_i$. When an exception $\texttt{id}_i$ paired with an argument x is handled, $\texttt{v}_i$ is initialized to x before $\texttt{Handler}_i$ is executed. It is a static error to include $(\texttt{v}_i)$ if exception $\texttt{id}_i$ does not take an argument.

If $(\texttt{v}_i)$ is absent, then $\texttt{id}_i$ can be a list of exceptions separated by commas, as shorthand for a list in which the rest of the handler is repeated for each exception. That is:

$\texttt{id}_1$, ..., $\texttt{id}_n$ => Handler

is shorthand for:

$\texttt{id}_1$ => Handler; ...; $\texttt{id}_n$ => Handler

It is a checked runtime error to raise an exception outside the dynamic scope of a handler for that exception. A "TRY EXCEPT ELSE" counts as a handler for all exceptions.

TRY FINALLY

A statement of the form:

TRY $\texttt{S}_1$ FINALLY $\texttt{S}_2$ END

executes statement $\texttt{S}_1$ and then statement $\texttt{S}_2$. If the outcome of $\texttt{S}_1$ is normal, the TRY statement is equivalent to $\texttt{S}_1$; $\texttt{S}_2$. If the outcome of $\texttt{S}_1$ is an exception and the outcome of $\texttt{S}_2$ is normal, the exception from $\texttt{S}_1$ is re-raised after $\texttt{S}_2$ is executed. If both outcomes are exceptions, the outcome of the TRY is the exception from $\texttt{S}_2$.

LOOP

A statement of the form:

LOOP S END

repeatedly executes S until it raises the exit-exception. The statement is equivalent to:

TRY S; S; S; ... EXCEPT exit-exception => (*skip*) END

EXIT

The statement

```
EXIT
```

raises the exit-exception. An EXIT statement must be textually enclosed by a LOOP, WHILE, REPEAT, or FOR statement.

We define EXIT and RETURN in terms of exceptions in order to specify their interaction with the exception handling statements. As a pathological example, consider the following code, which is an elaborate infinite loop:

```
LOOP
  TRY
    TRY EXIT FINALLY RAISE(E) END
  EXCEPT
    E: (*skip*)
  END
END
```

RETURN

A RETURN statement for a proper procedure has the form:

```
RETURN
```

The statement raises the return-exception without an argument. It is allowed only in the body of a proper procedure.

A RETURN statement for a function procedure has the form:

```
RETURN Expr
```

where Expr is an expression assignable to the result type of the procedure. The statement raises the return-exception with the argument Expr. It is allowed only in the body of a function procedure.

Failure to return a value from a function procedure is a checked runtime error.

The effect of raising the return exception is to terminate the current procedure activation. To be precise, a call on a proper procedure with body B is equivalent (after binding the arguments) to:

```
TRY B EXCEPT return-exception => (*skip*) END
```

A call on a function procedure with body B is equivalent to:

```
TRY
   B; (error: no returned value)
EXCEPT
   return-exception (v) => (the result becomes v)
END
```

IF

An IF statement has the form:

```
IF    B1 THEN S1
ELSIF B2 THEN S2
  ...
ELSIF Bn THEN Sn
ELSE S0
END
```

where the B's are boolean expressions and the S's are statements. The "ELSE S_0" and each "ELSIF B_i THEN S_i" are optional.

The statement evaluates the B's in order until some B_i evaluates to TRUE, and then executes S_i. If none of the expressions evaluates to TRUE and "ELSE S_0" is present, it is executed. If none of the expressions evaluates to TRUE and "ELSE S_0" is absent, the statement is a no-op (except for any side-effects of the B's).

WHILE

If B is an expression of type BOOLEAN and S is a statement:

```
WHILE B DO S END
```

is shorthand for:

```
LOOP IF B THEN S ELSE EXIT END END
```

REPEAT

If B is an expression of type BOOLEAN and S is a statement:

```
REPEAT S UNTIL B
```

is shorthand for:

```
LOOP S; IF B THEN EXIT END END
```

WITH

A WITH statement has the form:

```
WITH id = e DO S END
```

where id is an identifier, e an expression, and S a statement. The statement declares id with scope S as an alias for the variable e or as a readonly name for the value e. The expression e is evaluated once, at entry to the WITH statement. The statement is equivalent to a procedure call of the form P(e), where P is declared as:

```
PROCEDURE P(mode id: type of e) = BEGIN S END P;
```

If e is a writable designator, mode is VAR; otherwise, mode is READONLY. Free variables in S are interpreted in the context of the WITH statement. Any RETURN or EXIT statements in S are also interpreted in the context of the WITH.

A single WITH can contain multiple bindings, which are evaluated sequentially. Thus:

```
WITH id1 = e1, id2 = e2, ...
```

is equivalent to:

```
WITH id1 = e1 DO WITH id2 = e2 DO ...
```

FOR

A FOR statement has the form:

```
FOR id := first TO last BY step DO S END
```

where id is an identifier, first and last are ordinal expressions with the same base type, step is an integer-valued expression, and S is a statement. "BY step" is optional; if omitted, step defaults to 1.

The identifier id denotes a readonly variable whose scope is S and whose type is the common basetype of first and last.

If id is an integer, the statement steps id through the values first, first+step, first+2*step, ..., stopping when the value of id passes last. S executes once for each value; if the sequence of values is empty, S never executes. The expressions first, last, and step are evaluated once, before the loop is entered. If step is negative, the loop iterates downward.

The case in which id is an element of an enumeration is similar. In either case, the semantics are defined precisely by the following rewriting, in which T is the type of id and in which i, done, and delta stand for variables that do not occur in the FOR statement:

```
VAR
  i := ORD(first);
  done := ORD(last);
  delta := step;
BEGIN
  IF delta >= 0 THEN
    WHILE i <= done DO
      WITH id = VAL(i, T) DO S END;
      INC(i, delta)
    END
  ELSE
    WHILE i >= done DO
      WITH id = VAL(i, T) DO S END;
      INC(i, delta)
    END
  END
END
```

CASE

A CASE statement has the form:

```
CASE Expr OF
  L1 => S1
| ...
| Ln => Sn
ELSE S0
END
```

where Expr is an expression whose type is an ordinal type and each L is a list of constant expressions or ranges of constant expressions denoted by "e_1 . . e_2", which represent the values from e_1 to e_2 inclusive. If e_1 exceeds e_2, the range is empty. It is a static error if the sets represented by any two L's overlap or if the value of any of the constant expressions is not a member of the type of Expr. The "ELSE S_0" is optional.

The statement evaluates Expr. If the resulting value is in any L_i, then S_i is executed. If the value is in no L_i and "ELSE S_0" is present, then it is executed. If the value is in no L_i and "ELSE S_0" is absent, a checked runtime error occurs.

TYPECASE

A TYPECASE statement has the form:

```
TYPECASE Expr OF
  T1 (v1) => S1
| ...
| Tn (vn) => Sn
ELSE S0
END
```

where Expr is an expression whose type is a reference type, the S's are statements, the T's are reference types, and the v's are identifiers. It is a static error if Expr has type ADDRESS or if any T is not a subtype of the type of Expr. The "ELSE S_0" and each "(v)" are optional.

The statement evaluates Expr. If the resulting reference value is a member of any listed type T_i, then S_i is executed, for the minimum such i. (Thus a NULL case is useful only if it comes first.) If the value is a member of no listed type and S_0 is present, then it is executed. If the value is a member of no listed type and S_0 is absent, a checked runtime error occurs.

Each (v_i) declares a variable whose type is T_i and whose scope is S_i. If v_i is present, it is initialized to the value of Expr before S_i is executed.

If (v_i) is absent, then T_i can be a list of type expressions separated by commas, as shorthand for a list in which the rest of the branch is repeated for each type expression. That is:

```
T1, ..., Tn => S
```

is shorthand for:

```
T1 => S | ... | Tn => S
```

For example:

```
PROCEDURE ToText(r: REFANY): TEXT =
    (* Assume r = NIL or r^ is a BOOLEAN or INTEGER. *)
  BEGIN
    TYPECASE r OF
      NULL => RETURN "NIL"
    | REF BOOLEAN (rb) => RETURN Fmt.Bool(rb^)
    | REF INTEGER (ri) => RETURN Fmt.Int(ri^)
    END
  END ToText;
```

LOCK

A LOCK statement has the form:

```
LOCK mu DO S END
```

where S is a statement and mu is an expression whose type is MUTEX (Section 2, page 16). It is equivalent to:

```
WITH m = mu DO
  Thread.Acquire(m);
  TRY S FINALLY Thread.Release(m) END
END
```

where m stands for a variable that does not occur in S.

INC and DEC

INC and DEC statements have the form:

```
INC(v, n)
DEC(v, n)
```

where v designates a variable of an ordinal type[6] and n is an optional integer-valued argument. If omitted, n defaults to 1. The statements increment and decrement v by n, respectively. The statements are equivalent to:

```
WITH x = v DO x := VAL(ORD(x) + n, T) END
WITH x = v DO x := VAL(ORD(x) - n, T) END
```

where T is the type of v and x stands for a variable that does not appear in n. As a consequence, the statements check for range errors.

4 Declarations

There are two basic methods of declaring high or low before the showdown in all High-Low Poker games. They are (1) simultaneous declarations, and (2) consecutive declarations . . . . It is a sad but true fact that the consecutive method spoils the game.
—John Scarne's Guide to Modern Poker

A declaration introduces a name for a constant, type, variable, exception, or procedure. The scope of the name is the block containing the declaration. A block has the form:

```
Decls BEGIN S END
```

[6] In unsafe modules, INC and DEC are extended to ADDRESS.

where `Decls` is a sequence of declarations and `S` is a statement, the executable part of the block. A block can appear as a statement or as the body of a module or procedure. The declarations of a block can introduce a name at most once, though a name can be redeclared in nested blocks, and a procedure declared in an interface can be redeclared in a module exporting the interface (Section 5, page 32). Except for variable initializations, the order of declarations in a block does not matter.

Types

If `T` is an identifier and `U` a type (or type expression, since a type expression is allowed wherever a type is required), then:

```
TYPE T = U
```

declares `T` to be the type `U`.

Constants

If `id` is an identifier, `T` a type, and `C` a constant expression, then:

```
CONST id: T = C
```

declares `id` as a constant with the type `T` and the value of `C`. The ": `T`" can be omitted, in which case the type of `id` is the type of `C`. If present, `T` must contain `C`.

Variables

If `id` is an identifier, `T` a non-empty type other than an open array type, and `E` an expression, then:

```
VAR id: T := E
```

declares `id` as a variable of type `T` whose initial value is the value of `E`. Either ":= `E`" or ": `T`" can be omitted, but not both. If `T` is omitted, it is taken to be the type of `E`. If `E` is omitted, the initial value is an arbitrary value of type `T`. If both are present, `E` must be assignable to `T`.

The initial value is a shorthand that is equivalent to inserting the assignment `id := E` at the beginning of the executable part of the block. If several variables have initial values, their assignments are inserted in the order they are declared. For example:

```
VAR i: [0..5] := j; j: [0..5] := i; BEGIN S END
```

initializes `i` and `j` to the same arbitrary value in `[0..5]`; it is equivalent to:

```
VAR i: [0..5]; j: [0..5]; BEGIN i := j; j := i; S END
```

If a sequence of identifiers share the same type and initial value, `id` can be a list of identifiers separated by commas. Such a list is shorthand for a list in which the type and initial value are repeated for each identifier. That is:

```
VAR v1, ..., vn: T := E
```

is shorthand for:

```
VAR v1: T := E; ...; VAR vn: T := E
```

This means that `E` is evaluated `n` times.

Procedures

There are two forms of procedure declaration:

```
PROCEDURE id sig = B id

PROCEDURE id sig
```

where `id` is an identifier, `sig` is a procedure signature, and `B` is a block. In both cases, the type of `id` is the procedure type determined by `sig`. The first form is allowed only in modules; the second form is allowed only in interfaces.

The first form declares `id` as a procedure constant with signature `sig`, body `B`, and environment the scope containing the declaration. The parameter names are treated as if they were declared at the outer level of `B`; the parameter types and initial values are evaluated in the scope containing the procedure declaration. The procedure name `id` must be repeated after the `END` that terminates the body.

The second form declares `id` to be a procedure constant whose signature is `sig`. The procedure body is specified in a module exporting the interface, by a declaration of the first form.

Exceptions

If `id` is an identifier and `T` a type other than an open array type, then:

```
EXCEPTION id(T)
```

declares `id` as an exception with argument type `T`. If "`(T)`" is omitted, the exception takes no argument. Exception declarations are allowed only at the top level of interfaces and modules. All declared exceptions are distinct.

Opaque types

An opaque type declaration has the form:

```
TYPE T <: U
```

where T is an identifier and U an expression denoting a reference type. It declares T as a name for some unspecified subtype of U.

Revelations

A *revelation* provides information about an opaque type. Unlike other declarations, revelations introduce no new names.

There are two kinds of revelations, *definitive* and *partial*. There can be any number of partial revelations for an opaque type; there must be exactly one definitive revelation.

A definitive revelation has the form:

```
REVEAL T = V
```

where V is a type expression (not just a name) whose outermost type constructor is a branded reference or object type, T is an identifier (possibly qualified by a module name) that has been declared as an opaque subtype of some type U, and V <: U. Within the scope of the revelation, T is known to be the concrete type V. The requirement that V be branded guarantees that all opaque types in a program are distinct.

A partial revelation has the form:

```
REVEAL T <: V
```

where V is a type expression, T is a (possibly qualified) identifier that has been declared as an opaque subtype of some type U, and V <: U. Within the scope of this revelation, T is known to be a subtype of V. It is a static error if this is not the case.

Revelations are allowed only at the top level of interfaces and modules. A revelation in an interface can be imported into any scope where it is required.

Recursive declarations

A constant, type, or procedure declaration N = E, a variable declaration N : E, an exception declaration N(E), or a revelation N = E is *recursive* if N occurs in any partial expansion of E. A variable declaration N := I where the type is omitted is recursive

if N occurs in any partial expansion of the type E of I. Such declarations are allowed if every occurrence of N in any partial expansion of E is (1) within some occurrence of the type constructor REF or PROCEDURE, (2) within a field or method type of the type constructor OBJECT, or (3) within a procedure body.

Examples of legal declarations:

```
TYPE
  List = REF RECORD x: REAL; link: List END;
  T = PROCEDURE(n: INTEGER; p: T);
  XList = X OBJECT link: XList END;
CONST
  N = BYTESIZE(REF ARRAY [0..N] OF REAL);
PROCEDURE P(b: BOOLEAN) = BEGIN IF b THEN P(NOT b) END END P;
EXCEPTION E(PROCEDURE () RAISES {E});
VAR v: REF ARRAY [0..BYTESIZE(v)] OF INTEGER;
VAR v := BITSIZE(v)
```

Examples of illegal declarations:

```
TYPE
  T = RECORD u: U END; U = RECORD t: T END;
  X = X OBJECT END;
CONST
  N = N+1;
TYPE
  T <: ROOT; U <: ROOT;
REVEAL T = U OBJECT END; U = T OBJECT END;
VAR v := P();
PROCEDURE P(): ARRAY [0..NUMBER(v)] OF INTEGER
```

5 Modules and interfaces

Art, it seems to me, should simplify. That, indeed, is very nearly the whole of the higher artistic process; finding what conventions of form and what detail one can do without and yet preserve the spirit of the whole.
—Willa Cather

A *module* is like a block, except for the visibility of names. A name is visible in a block only if it is declared in the block or in some enclosing block; a name is visible in a module only if it is declared in the module or in an interface that is imported or exported by the module.

An *interface* is a group of declarations. Declarations in interfaces are the same as in blocks, except that any variable initializations must be constant and procedure declarations must specify only the signature, not the body.

A module `X` *exports* an interface `I` to supply bodies for one or more of the procedures declared in the interface. A module or interface `X` *imports* an interface `I` to make the names in `I` visible in `X`.

Import statements

There are two forms of `IMPORT` statement:

```
IMPORT I1, ..., In
FROM I IMPORT N1, ..., Nm
```

where the `I`'s are names of interfaces and the `N`'s are names of entities declared in the interface `I`.

The first form makes the names of the interfaces I_1, ..., I_n visible. To refer to an entity named `N` in any I_j the importer must use the qualified identifier I_j`.N`.

The second form makes the names N_1, ..., N_m from interface `I` visible. It does not make the name `I` visible; the importer must refer to N_i and not `I.`N_i.

The same interface can be imported using both forms, in which case both the interface name and the explicitly imported names are visible. Importing an interface provides access to the names and revelations it declares, but not to those it imports.

Interfaces

An interface has the form:

```
INTERFACE id; Imports; Decls END id.
```

where `id` is an identifier that names the interface, `Imports` is a sequence of import statements, and `Decls` is a sequence of declarations that contains no procedure bodies or non-constant variable initializations. The names declared in `Decls` and the visible imported names must be distinct. It is a static error for two or more interfaces to form an import cycle.

Modules

A module has the form:

```
MODULE id EXPORTS Interfaces; Imports; Block id.
```

where `id` is an identifier that names the module, `Interfaces` is a list of distinct names of interfaces exported by the module, `Imports` is a list of import statements, and `Block` is a block, the *body* of the module. The name `id` must be repeated after the `END` that terminates the body. "`EXPORTS Interfaces`" can be omitted, in which case `Interfaces` defaults to `id`.

If module `M` exports interface `I`, then all declared names in `I` are visible without qualification in `M`. Any procedure declared in `I` can be redeclared in `M`, with a body. The signature in `M` must be covered by the signature in `I` (as defined in Section 2, page 9.) To determine the interpretation of keyword bindings in calls to the procedure, the signature in `M` is used within `M`; the signature in `I` is used everywhere else.

Except for the redeclaration of exported procedures, the names declared at the top level of `Block`, the visible imported names, and the names declared in the exported interfaces must be distinct.

For example, the following is illegal, since two names in exported interfaces coincide:

```
INTERFACE I;          INTERFACE J;          MODULE M EXPORTS I, J;
  PROCEDURE X();        PROCEDURE X();        PROCEDURE X();
```

The following is also illegal, since the visible imported name `X` coincides with the top-level name `X`:

```
INTERFACE I;          MODULE M EXPORTS I; FROM I IMPORT X;
  PROCEDURE X();        PROCEDURE X() = ...;
```

But the following is legal, although peculiar:

```
INTERFACE I;            MODULE M EXPORTS I; IMPORT I;
  PROCEDURE X(...);       PROCEDURE X(...) = ...;
```

since the only visible imported name is `I`, and the coincidence between `X` as a top-level name and `X` as a name in an exported interface is allowed, assuming the interface signature covers the module signature. (Within `M`, the interface declaration determines the signature of `I.X` and the module declaration determines the signature of `X`.)

Initialization

A *program* is a collection of modules in which no procedure is multiply defined. The effect of executing a program is to execute the bodies of each of its modules. The order of execution of the modules in a program is constrained by the following rule:

If module M depends on module N and N does not depend on M, then N's body will be executed before M's body, where:

- A module M *uses* an interface I if M imports or exports I or if M uses an interface that imports I.
- A module M *depends on* a module N if M uses an interface that N exports or if M depends on a module that depends on N.

Except for this constraint, the order of execution is implementation-dependent.

The module whose body is executed last is called the *main module*. Implementations are expected to provide a way to specify the main module, in case the import dependencies do not determine it uniquely. The recommended rule is that the main module be the one that exports the interface Main, whose contents are implementation-dependent.

Program execution terminates when the body of the main module terminates, even if concurrent threads of control are still executing.

Safety

The keyword UNSAFE can precede the declaration of any interface or module to indicate that it is *unsafe*; that is, that it uses unsafe features of the language (Section 7, page 48). An interface or module not explicitly labeled UNSAFE is called *safe*.

An interface is *intrinsically safe* if there is no way to produce an unchecked runtime error by using the interface in a safe module. If all modules that export a safe interface are safe, the compiler guarantees the intrinsic safety of the interface. If any of the modules that export a safe interface are unsafe, it is the programmer, rather than the compiler, who makes the guarantee.

It is a static error for a safe interface to import an unsafe one or for a safe module to import or export an unsafe interface.

Example module and interface

Here is the canonical example of a public stack with hidden representation:

```
INTERFACE Stack;
  TYPE T <: REFANY;
  PROCEDURE Push(VAR s: T; x: REAL);
  PROCEDURE Pop(VAR s: T): REAL;
  PROCEDURE Create(): T;
END Stack.

MODULE Stack;
  REVEAL T = BRANDED OBJECT item: REAL; link: T END;
  PROCEDURE Push(VAR s: T; x: REAL) =
    BEGIN
      s := NEW(T, item := x, link := s)
    END Push;
  PROCEDURE Pop(VAR s: T): REAL =
    VAR res: REAL;
    BEGIN
      res := s.item; s := s.link; RETURN res
    END Pop;
  PROCEDURE Create(): T = BEGIN RETURN NIL END Create;
BEGIN
END Stack.
```

If the representation of stacks is required in more than one module, it should be moved to a private interface, so that it can be imported wherever it is required:

```
INTERFACE Stack (* ... as before ... *) END Stack.

INTERFACE StackRep; IMPORT Stack;
  REVEAL Stack.T = BRANDED OBJECT item: REAL; link: Stack.T END
END StackRep.

MODULE Stack; IMPORT StackRep;
  (* Push, Pop, and Create as before *)
BEGIN
END Stack.
```

6 Expressions

The rules of logical syntax must follow of themselves,
if we only know how every single sign signifies.
—Ludwig Wittgenstein

An expression prescribes a computation that produces a value or variable. Syntactically, an expression is either an operand or an operation applied to arguments, which are

themselves expressions. Operands can be identifiers, literals, or types. An expression is evaluated by recursively evaluating its arguments and performing the operation. The order of argument evaluation is undefined for all operations except `AND` and `OR`.

Conventions for describing operations

To describe the argument and result types of operations, we use a notation like procedure signatures. But since most operations are too general to be described by a true procedure signature, we extend the notation in several ways.

The argument to an operation can be required to have a type in a particular class, such as an ordinal type, set type, etc. In this case the formal specifies a type class instead of a type. For example:

```
ORD (x: Ordinal): INTEGER
```

A single operation name can be overloaded, which means that it denotes more than one operation. In this case, we write a separate signature for each of the operations. For example:

```
ABS (x: INTEGER)  : INTEGER
    (x: REAL)     : REAL
    (x: LONGREAL) : LONGREAL
```

The particular operation will be selected so that each actual argument type is a subtype of the corresponding formal type or a member of the corresponding formal type class.

The argument to an operation can be an expression denoting a type. In this case, we write `Type` as the argument type. For example:

```
BYTESIZE (T: Type): CARDINAL
```

The result type of an operation can depend on its argument values (although the result type can always be determined statically). In this case, the expression for the result type contains the appropriate arguments. For example:

```
FIRST (T: FixedArrayType): IndexType(T)
```

`IndexType(T)` denotes the index type of the array type `T` and `IndexType(a)` denotes the index type of the array `a`. The definitions of `ElemType(T)` and `ElemType(a)` are similar.

Operation syntax

The operators that have special syntax are classified and listed in order of decreasing binding power in the following table:

`x.a`	infix dot
`f(x) a[i] T{x}`	applicative (, [, {
`p^`	postfix ^
`+ -`	prefix arithmetics
`* / DIV MOD`	infix arithmetics
`+ - &`	infix arithmetics
`= # < <= >= > IN`	infix relations
`NOT`	prefix `NOT`
`AND`	infix `AND`
`OR`	infix `OR`

All infix operators are left associative. Parentheses can be used to override the precedence rules. Here are some examples of expressions together with their fully parenthesized forms:

`M.F(x)`	`(M.F)(x)`	dot before application
`Q(x)^`	`(Q(x))^`	application before ^
`- p^`	`- (p^)`	^ before prefix -
`- a * b`	`(- a) * b`	prefix - before *
`a * b - c`	`(a * b) - c`	* before infix -
`x IN s - t`	`x IN (s - t)`	infix - before `IN`
`NOT x IN s`	`NOT (x IN s)`	`IN` before `NOT`
`NOT p AND q`	`(NOT p) AND q`	`NOT` before `AND`
`A OR B AND C`	`A OR (B AND C)`	`AND` before `OR`

Operators without special syntax are *procedural*. An application of a procedural operator has the form `op(args)`, where `op` is the operation and `args` is the list of argument expressions. For example, `MAX` and `MIN` are procedural operators.

Designators

An identifier is a writable designator if it is declared as a variable, is a `VAR` or `VALUE` parameter, is a local of a `TYPECASE` or `TRY EXCEPT` statement, or is a `WITH` local that is bound to a writable designator. An identifier is a readonly designator if it is a `READONLY` parameter, a local of a `FOR` statement, or a `WITH` local bound to a non-designator or readonly designator.

The only operations that produce designators are dereferencing, subscripting, selection, and SUBARRAY.[7] This section defines these operations and specifies the conditions under which they produce designators.

`r^` denotes the the referent of `r`; this operation is called *dereferencing*. The expression `r^` is always a writable designator. It is a static error if the type of `r` is an open reference type, object type, or opaque type, and a checked runtime error if `r` is `NIL`. The type of `r^` is the referent type of `r`.

`a[i]` denotes element `i - FIRST(a)` of the array `a`. The expression `a[i]` is a designator if `a` is, and is writable if `a` is. The expression `i` must be assignable to the index type of `a`. The type of `a[i]` is the element type of `a`.

An expression of the form $a[i_1, \ldots, i_n]$ is shorthand for $a[i_1]\ldots[i_n]$. If `a` is a reference to an array, then `a[i]` is shorthand for `a^[i]`.

`r.f, o.f, I.x, T.m, E.id`

If `r` denotes a record, `r.f` denotes its `f` field. In this case `r.f` is a designator if `r` is, and is writable if `r` is. The type of `r.f` is the declared type of the field.

If `r` is a reference to a record, then `r.f` is shorthand for `r^.f`.

If `o` denotes an object and `f` names a data field specified in the type of `o`, then `o.f` denotes that data field of `o`. In this case `o.f` is a writable designator whose type is the declared type of the field.

If `I` denotes an imported interface, then `I.x` denotes the entity named `x` in the interface `I`. In this case `I.x` is a designator if `x` is declared as a variable; such a designator is always writable.

If `T` is an object type and `m` is the name of one of `T`'s methods, then `T.m` denotes `T`'s default `m` method. In this case `T.m` is not a designator. Its type is the procedure type whose first argument has mode `VALUE` and type `T`, and whose remaining arguments are determined by the method declaration for `m` in `T`. The name of the first argument is unspecified; thus in calls to `T.m`, this argument must be given positionally, not by keyword. `T.m` is not a procedure constant.

If `E` is an enumerated type, then `E.id` denotes its value named `id`. In this case `E.id` is not a designator. The type of `E.id` is `E`.

`SUBARRAY(a: Array; from, for: CARDINAL): ARRAY OF ElemType(a)`

SUBARRAY produces a subarray of `a`. It does not copy the array; it is a designator if `a` is, and is writable if `a` is. If `a` is a multi-dimensional array, SUBARRAY applies only to the top-level array.

[7] In unsafe modules, LOOPHOLE can also produce a designator.

The operation returns the subarray that skips the first `from` elements of `a` and contains the next `for` elements. Note that if `from` is zero, the subarray is a prefix of `a`, whether the type of `a` is zero-based or not. It is a checked runtime error if `from+for` exceeds `NUMBER(a)`.

If the element type of `a` is packed, implementations may restrict or prohibit the `SUBARRAY` operation.

Numeric literals

Numeric literals denote constant non-negative integers or reals. The types of these literals are `INTEGER`, `REAL`, and `LONGREAL`.

A literal `INTEGER` has the form `base_digits`, where `base` is one of "`2`", "`3`", ..., "`16`", and `digits` is a non-empty sequence of the decimal digits `0` through `9` plus the hexadecimal digits `A` through `F`. The "`base_`" can be omitted, in which case `base` defaults to `10`. The digits are interpreted in the given base. Each digit must be less than `base`. For example, `16_ff` and `255` are equivalent integer literals.

A literal `REAL` has the form `decimal E exponent`, where `decimal` is a non-empty sequence of decimal digits followed by a decimal point followed by a non-empty sequence of decimal digits, and `exponent` is a non-empty sequence of decimal digits optionally preceded by a `+` or `-`. The literal denotes `decimal` times ten raised to the given `exponent`. If "`E exponent`" is omitted, `exponent` defaults to `0`.

A literal `LONGREAL` has the form `decimal D exponent`, and `decimal` and `exponent` are the same as in a literal `REAL`.

Case is not significant in digits, prefixes or scale factors. Embedded spaces are not allowed.

For example, `1.0` and `0.5` are valid, `1.` and `.5` are not; `6.624E-27` is a `REAL`, and `3.1415926535d0` a `LONGREAL`.

Text and character literals

A character literal is a single printing character or escape sequence enclosed in single quotes. The type of a character literal is `CHAR`.

A text literal is a sequence of zero or more printing characters or escape sequences enclosed in double quotes. The type of a text literal is `TEXT`.

Printing characters are all printing ISO-Latin-1 characters except double-quote, right single quote, and backslash (see Section 9, page 59).

The only way to include a quotation mark or non-printing character such as newline in a text or character literal is with an escape sequence. Here are the legal escape sequences:

\n	newline (linefeed)	\f	form feed
\t	tab	\\	backslash
\r	carriage return	\"	double quote
\'	single quote	\nnn	char with code 8_nnn

A \ followed by exactly three octal digits specifies the character whose code is that octal value. A \ that is not a part of one of these escape sequences is a static error.

For example, `'a'` and `'\''` are valid character literals, `'"'` and `'''` are not; `""` and `"Don\'t\n"` are valid text literals, `"'"` is not.

NIL

The literal "`NIL`" denotes the value `NIL`. Its type is `NULL`.

Function application

A procedure call is an expression if the procedure returns a result. The type of the expression is the result type of the procedure.

Set, array, and record constructors

A set constructor has the form:

$S\{e_1, \ldots, e_n\}$

where `S` is a set type and the `e`'s are expressions or ranges of the form `lo..hi`. The constructor denotes a value of type `S` containing the listed values and the values in the listed ranges. The `e`'s, `lo`'s, and `hi`'s must be assignable to the element type of `S`.

An array constructor has the form:

$A\{e_1, \ldots, e_n\}$

where `A` is an array type and the `e`'s are expressions. The constructor denotes a value of type `A` containing the listed elements in the listed order. The `e`'s must be assignable to the element type of `A`. This means that if `A` is a multi-dimensional array, the `e`'s must themselves be array-valued expressions.

If `A` is a fixed array type and `n` is at least 1, then e_n can be followed by "`..`" to indicate that the value of e_n will be replicated as many times as necessary to fill out the array. It is a static error to provide too many or too few elements for a fixed array type.

A record constructor has the form:

```
R{Bindings}
```

where R is a record type and Bindings is a list of keyword or positional bindings, exactly as in a procedure call (Section 3). The list of bindings is rewritten to fit the list of fields and defaults of R, exactly as for a procedure call; the record field names play the role of the procedure formal parameters. The expression denotes a value of type R whose field values are specified by the rewritten binding.

The rewritten binding must bind only field names and must bind each field name exactly once. Each expression in the binding must be assignable to the type of the corresponding record field.

NEW

An allocation operation has the form:

```
NEW(T, ...)
```

where T is a reference type other than REFANY, ADDRESS, or NULL. If T is a fixed reference type, the operation returns the address of a newly-allocated variable of T's referent type. If T has an object type, the operation returns a newly-allocated data record containing the data fields declared in T, paired with a method suite containing the methods declared in T. The reference returned by NEW is distinct from all existing references. The allocated type of the new reference is T.

It is a static error if T's referent type is empty. If T is declared as an opaque type, NEW(T) is legal only in the scope of a definitive revelation for T (Section 4, page 31).

The initial state of the referent generally represents an arbitrary value of its type. If T is an object type or a reference to a record or open array then NEW takes additional arguments to control the initial state of the new variable.

If T is a reference to an array with k open dimensions, the NEW operation has the form:

```
NEW(T, n1, ..., nk)
```

where the n's are integer-valued expressions that specify the lengths of the new array in its first k dimensions. The values in the array will be arbitrary values of their type.

If T is an object type or a reference to a record, the NEW operation has the form:

```
NEW(T, Bindings)
```

where Bindings is a list of keyword bindings used to initialize the new fields and methods. Positional bindings are not allowed.

Each binding `f := v` initializes the field or method `f` to the value `v`. Fields or methods for which no binding is supplied will be initialized to their defaults if they have defaults; otherwise they will be initialized to arbitrary values of their types. Note that methods always have defaults, since the "default default" is `NIL`. It is a static error if any method's signature fails to satisfy its declaration (Section 2, page 11), and a checked runtime error if any method is not a top-level procedure.

Arithmetic operations

The effect of an operation that overflows, underflows, or divides by zero is a checked runtime error. To perform arithmetic operations modulo the word size, programs should use the routines in the `Word` interface (page 53).

```
prefix   +  (x: INTEGER)      : INTEGER
            (x: REAL)         : REAL
            (x: LONGREAL)     : LONGREAL

infix    +  (x,y: INTEGER)    : INTEGER
            (x,y: REAL)       : REAL
            (x,y: LONGREAL)   : LONGREAL
            (s,t: Set)        : Set
```

As a prefix operator, `+x` returns `x`. As an infix operator on numeric arguments, `+` denotes addition. On sets, `+` denotes set union. That is, `x IN (s + t)` if and only if `(x IN s) OR (x IN t)`. The types of `s` and `t` must be the same, and the result is the same type as both. In unsafe modules, `+` is extended to `ADDRESS`.

```
prefix   -  (x: INTEGER)      : INTEGER
            (x: REAL)         : REAL
            (x: LONGREAL)     : LONGREAL

infix    -  (x,y: INTEGER)    : INTEGER
            (x,y: REAL)       : REAL
            (x,y: LONGREAL)   : LONGREAL
            (s,t: Set)        : Set
```

As a prefix operator, `-x` is the negative of `x`. As an infix operator on numeric arguments, `-` denotes subtraction. On sets, `-` denotes set difference. That is: `x IN (s - t)` if and only if `(x IN s) AND NOT (x IN t)`. The types of `s` and `t` must be the same, and the result is the same type as both. In unsafe modules, `-` is extended to `ADDRESS`.

```
infix    *  (x,y: INTEGER)    : INTEGER
            (x,y: REAL)       : REAL
            (x,y: LONGREAL)   : LONGREAL
            (s,t: Set)        : Set
```

On numeric arguments, * denotes multiplication. On sets, * denotes intersection. That is: `x IN (s * t)` if and only if `(x IN s) AND (x IN t)`. The types of `s` and `t` must be the same, and the result is the same type as both.

```
infix   /   (x,y: REAL)       : REAL
            (x,y: LONGREAL)   : LONGREAL
            (s,t: Set)        : Set
```

On reals, / denotes division. On sets, it denotes symmetric difference. In other words, `x IN (s / t)` if and only if `(x IN s) # (x IN t)`. The types of `s` and `t` must be the same, and the result is the same type as both.

```
infix   DIV  (x,y: INTEGER): INTEGER
infix   MOD  (x,y: INTEGER): INTEGER
```

The value `x DIV y` is the floor of the quotient of `x` and `y`; that is, the maximum integer not exceeding the real number `z` such that `z * y = x`. The value of `x MOD y` is defined to be `x - y * (x DIV y)`.

This means that for positive `y`, the value of `x MOD y` lies in the interval `[0 .. y-1]`, regardless of the sign of `x`. For negative `y`, the value of `x MOD y` lies in the interval `[y+1 .. 0]`, regardless of the sign of `x`.

```
ABS  (x: INTEGER)    : INTEGER
     (x: REAL)       : REAL
     (x: LONGREAL)   : LONGREAL
```

`ABS(x)` is the absolute value of `x`.

```
FLOAT      (x: INTEGER)    : REAL
           (x: LONGREAL)   : REAL

LONGFLOAT  (x: INTEGER)    : LONGREAL
           (x: REAL)       : LONGREAL
```

`FLOAT(x)` is the nearest `REAL` to `x`; `LONGFLOAT(x)` is the nearest `LONGREAL`. Ties are broken arbitrarily.

```
FLOOR    (x: REAL)       : INTEGER
         (x: LONGREAL)   : INTEGER

CEILING  (x: REAL)       : INTEGER
         (x: LONGREAL)   : INTEGER
```

`FLOOR(x)` is the greatest integer not exceeding `x`. `CEILING(x)` is the least integer not less than `x`.

```
ROUND  (r: REAL)       : INTEGER
       (r: LONGREAL)   : INTEGER

TRUNC  (r: REAL)       : INTEGER
       (r: LONGREAL)   : INTEGER
```

`ROUND(r)` is the nearest integer to `r`; ties are broken arbitrarily. `TRUNC(r)` rounds `r` toward zero; it equals `FLOOR(r)` for positive `r` and `CEILING(r)` for negative `r`.

```
MAX, MIN  (x,y: Ordinal)    : Ordinal
          (x,y: REAL)       : REAL
          (x,y: LONGREAL)   : LONGREAL
```

`MAX` returns the greater of the two values `x` and `y`; `MIN` returns the lesser. If `x` and `y` are ordinals, they must have the same base type, which is the type of the result.

Relations

infix `=, #  (x, y: Any): BOOLEAN`

The operator = returns `TRUE` if `x` and `y` have the same value. The operator # returns `TRUE` if `x` and `y` have different values. It is a static error if the type of `x` is not assignable to the type of `y` or vice versa.

References are equal if they address the same variable. Procedures are equal if they agree as closures; that is, if they refer to the same procedure body and environment. Sets are equal if they have the same elements. Arrays are equal if they have the same length and corresponding elements are equal. Records are equal if they have the same fields and corresponding fields are equal.

```
infix  <=, >=  (x,y: Ordinal)    : BOOLEAN
               (x,y: REAL)       : BOOLEAN
               (x,y: LONGREAL)   : BOOLEAN
               (x,y: ADDRESS)    : BOOLEAN
               (x,y: Set)        : BOOLEAN
```

In the first four cases, <= returns `TRUE` if `x` is not greater than `y`. In the last case, <= returns `TRUE` if every element of `x` is an element of `y`. In all cases, it is a static error if the type of `x` is not assignable to the type of `y`, or vice versa. The expression `x >= y` is equivalent to `y <= x`.

```
infix  >, <  (x,y: Ordinal)    : BOOLEAN
             (x,y: REAL)       : BOOLEAN
             (x,y: LONGREAL)   : BOOLEAN
             (x,y: ADDRESS)    : BOOLEAN
             (x,y: Set)        : BOOLEAN
```

In all cases, `x < y` means `(x <= y) AND (x # y)`, and `x > y` means `y < x`. It is a static error if the type of `x` is not assignable to the type of `y`, or vice versa.

```
infix   IN  (e: Ordinal; s: Set): BOOLEAN
```

Returns `TRUE` if `e` is an element of the set `s`. It is a static error if the type of `e` is not assignable to the element type of `s`. If the value of `e` is not a member of the element type, no error occurs, but `IN` returns `FALSE`.

Boolean operations

```
prefix   NOT  (p: BOOLEAN)     : BOOLEAN
 infix   AND  (p,q: BOOLEAN)   : BOOLEAN
 infix   OR   (p,q: BOOLEAN)   : BOOLEAN
```

`NOT p` is the complement of `p`.

`p AND q` is `TRUE` if both `p` and `q` are `TRUE`. If `p` is `FALSE`, `q` is not evaluated.

`p OR q` is `TRUE` if at least one of `p` and `q` is `TRUE`. If `p` is `TRUE`, `q` is not evaluated.

Type operations

```
ORD  (element: Ordinal): INTEGER
VAL  (i: INTEGER; T: OrdinalType): T
```

`ORD` converts an element of an enumeration to the integer that represents its position in the enumeration order. The first value in any enumeration is represented by zero. If the type of `element` is a subrange of an enumeration `T`, the result is the position of the element within `T`, not within the subrange.

`VAL` is the inverse of `ORD`; it converts from a numeric position `i` into the element that occupies that position in an enumeration. If `T` is a subrange, `VAL` returns the element with the position `i` in the original enumeration type, not the subrange. It is a checked runtime error for the value of `i` to be out of range for `T`.

If `n` is an integer, `ORD(n) = VAL(n, INTEGER) = n`.

```
NUMBER  (T: OrdinalType)      : CARDINAL
        (A: FixedArrayType)   : CARDINAL
        (a: Array)            : CARDINAL
```

For an ordinal type `T`, `NUMBER(T)` returns the number of elements in `T`. For a fixed array type `A`, `NUMBER(A)` is defined by `NUMBER(IndexType(A))`. Similarly, for an array `a`, `NUMBER(a)` is defined by `NUMBER(IndexType(a))`. In this case, the expression `a` will be evaluated only if it denotes an open array.

```
FIRST  (T: OrdinalType)      : BaseType(T)
       (A: FixedArrayType)   : BaseType(IndexType(A))
       (a: Array)            : BaseType(IndexType(a))

LAST   (T: OrdinalType)      : BaseType(T)
       (A: FixedArrayType)   : BaseType(IndexType(A))
       (a: Array)            : BaseType(IndexType(a))
```

For a non-empty ordinal type T, FIRST returns the smallest value of T and LAST returns the largest value. If T is the empty enumeration, FIRST(T) and LAST(T) are static errors. If T is any other empty ordinal type, the values returned are implementation-dependent, but they satisfy FIRST(T) > LAST(T).

For a fixed array type A, FIRST(A) is defined by FIRST(IndexType(A)) and LAST(A) by LAST(IndexType(A)). Similarly, for an array a, FIRST(a) and LAST(a) are defined by FIRST(IndexType(a)) and LAST(IndexType(a)). The expression a will be evaluated only if it is an open array. Note that if a is an open array, FIRST(a) and LAST(a) have type INTEGER.

```
ISTYPE  (x: Reference; T: RefType)  : BOOLEAN
```

ISTYPE(x, T) is TRUE if and only if x is a member of T. T must be an object type or traced reference type, and x must be assignable to T.

```
NARROW  (x: Reference; T: RefType): T
```

NARROW(x, T) returns x after checking that x is a member of T. If the check fails, a runtime error occurs. T must be an object type or traced reference type, and x must be assignable to T.

```
TYPECODE  (T: RefType)         : INTEGER
          (r: REFANY)          : INTEGER
          (r: UNTRACED ROOT)   : INTEGER
```

Every object type or traced reference type (including NULL) has an associated integer code. Different types have different codes. The code for a type is constant for any single execution of a program, but may differ for different executions. TYPECODE(T) returns the code for the type T and TYPECODE(r) returns the code for the allocated type of r. It is a static error if T is REFANY or is not an object type or traced reference type.

```
BITSIZE   (x: Any)   : CARDINAL
          (T: Type)  : CARDINAL

BYTESIZE  (x: Any)   : CARDINAL
          (T: Type)  : CARDINAL

ADRSIZE   (x: Any)   : CARDINAL
          (T: Type)  : CARDINAL
```

These operations return the size of the variable `x` or of variables of type `T`. `BITSIZE` returns the number of bits, `BYTESIZE` the number of 8-bit bytes, and `ADRSIZE` the number of addressable locations. In all cases, `x` must be a designator and `T` must not be an open array type. A designator `x` will be evaluated only if its type is an open array type.

Text operations

infix `& (a,b: TEXT): TEXT`

The concatenation of `a` and `b`, as defined by `Text.Cat`. (Section 8, page 50.)

Constant Expressions

Constant expressions are a subset of the general class of expressions, restricted by the requirement that it be possible to evaluate the expression statically. All operations are legal in constant expressions except for `ADR`, `LOOPHOLE`, `TYPECODE`, `NARROW`, `ISTYPE`, `SUBARRAY`, `NEW`, dereferencing (explicit or implicit), and function application. All required operations in the `Word` interface (Section 8, page 53) are allowed in constant expressions.

A variable can appear in a constant expression only as an argument to `FIRST`, `LAST`, `NUMBER`, `BITSIZE`, `BYTESIZE`, or `ADRSIZE`, and such a variable must not have an open array type. All literals are legal in constant expressions; procedure constants are not.

7 Unsafe operations

There are some cases that no law can be framed to cover.
—Aristotle

The features defined in this chapter can potentially cause unchecked runtime errors and are thus forbidden in safe modules.

An unchecked type transfer operation has the form:

```
LOOPHOLE(e, T)
```

where `e` is an expression whose type is not an open array type and `T` is a type. It denotes `e`'s bit pattern interpreted as a variable or value of type `T`. It is a designator if `e` is, and is writable if `e` is. An unchecked runtime error can occur if `e`'s bit pattern is not a legal `T`, or if `e` is a designator and some legal bit pattern for `T` is not legal for `e`.

If T is not an open array type, BITSIZE(e) must equal BITSIZE(T). If T is an open array type, its element type must not be an open array type, and e's bit pattern is interpreted as an array whose length is BITSIZE(e) divided by BITSIZE(the element type of T). The division must come out even.

The following operations are primarily used for address arithmetic:

```
ADR  (VAR x: Any)              : ADDRESS
+    (x: ADDRESS, y:INTEGER)   : ADDRESS
-    (x: ADDRESS, y:INTEGER)   : ADDRESS
-    (x,y: ADDRESS)            : INTEGER
```

ADR(x) is the address of the variable x. The actual argument must be a designator but need not be writable. The operations + and - treat addresses as integers. The validity of the addresses produced by these operations is implementation-dependent. For example, the address of a variable in a local procedure frame is probably valid only for the duration of the call. The address of the referent of a traced reference is probably valid only as long as traced references prevent it from being collected (and not even that long if the implementation uses a compacting collector).

In unsafe modules the INC and DEC statements apply to addresses as well as ordinals:

```
INC (VAR x: ADDRESS; n: INTEGER := 1)
DEC (VAR x: ADDRESS; n: INTEGER := 1)
```

These are short for x := x + n and x := x - n, except that x is evaluated only once.

A DISPOSE statement has the form:

```
DISPOSE (v)
```

where v is a writable designator with a fixed or object reference type. If v is untraced, the statement frees the storage for v's referent and sets v to NIL. Freeing storage to which active references remain is an unchecked runtime error. If v is traced, the statement is equivalent to v := NIL. If v is NIL, the statement is a no-op.

In unsafe modules the definition of "assignable" for types is extended: two reference types T and U are assignable if T <: U or U <: T. The only effect of this change is to allow a value of type ADDRESS to be assigned to a variable of type UNTRACED REF T. It is an unchecked runtime error if the value does not address a variable of type T.

In unsafe modules the type constructor UNTRACED REF T is allowed for traced as well as untraced T, and the fields of untraced objects can be traced. If u is an untraced reference to a traced variable t, then the validity of the traced references in t is implementation-dependent, since the garbage collector probably will not trace them through u.

8 Required interfaces

C++ has a host of operators that will be explained if and where needed.
—The C++ Programming Language

Modula-3 requires that every implementation provide the interfaces `Text`, `Thread`, and `Word`, as specified in this chapter. Implementations are free to extend these interfaces, as long as they do not invalidate clients of the unextended interfaces.

The Text interface

For a semantic specification of an extended version of the `Text` interface, see "The Modula-2+ Text Interface" [2].

```
INTERFACE Text;

TYPE
  T = TEXT;
  (* A zero-based sequence of characters. It is a checked runtime
     error to pass the NIL TEXT to any procedure in this interface. *)

PROCEDURE Cat(t, u: T): T;
(* The concatenation of t and u.  *)

PROCEDURE Equal(t, u: T): BOOLEAN;
(* TRUE if t and u have the same length and (case-sensitive) contents. *)

PROCEDURE GetChar(t: T; i: CARDINAL): CHAR;
(* Character i of t.  A checked runtime error if i >= Length(t). *)

PROCEDURE Length(t: T): CARDINAL;
(* The number of characters in t. *)

PROCEDURE Empty(t: T): BOOLEAN;
(* TRUE if Length(t) = 0. *)

PROCEDURE Sub(t: T; start, length: CARDINAL): T;
(* Return a subsequence of t: empty if start >= Length(t)
   or length = 0; otherwise the subsequence ranging from
   start to MIN(start+length, Length(t) - 1). *)

PROCEDURE SetChars(VAR a: ARRAY OF CHAR; t: T);
(* For each i [0..MIN(LAST(a), Length(t) - 1)], set a[i] to
   GetChar(t, i). *)
```

```
PROCEDURE FromChar(ch: CHAR): T;
(* A text containing the single character ch. *)

PROCEDURE FromChars(READONLY a: ARRAY OF CHAR): T;
(* A text containing the characters of a. *)

END Text.
```

The Thread interface

If a shared variable is written concurrently by two threads, or written by one and read concurrently by another, the effect is to set the variable to an implementation-dependent value of its type. For example, if one thread writes `a[0]` while another concurrently writes `a[1]`, one of the writes might be lost. Thus, portable programs must use the `Thread` interface to provide mutual exclusion for shared variables. The formal specification of this interface is in "Synchronization Primitives for a Multiprocessor: A Formal Specification" [1].

```
INTERFACE Thread;

TYPE
  T         <: REFANY;  (* A handle on a thread *)
  Mutex     = MUTEX;    (* Locked by some thread, or unlocked *)
  Condition <: ROOT;    (* A set of waiting threads *)

  (* Initially a Mutex is unlocked and a Condition is empty.
     It is a checked runtime error to pass the NIL Mutex,
     Condition, or T to any procedure in this interface. *)

  Closure = OBJECT METHODS apply(): REFANY RAISES {} END;

PROCEDURE NewMutex(): Mutex;
(* A newly-allocated, unlocked mutex *)

PROCEDURE NewCondition(): Condition;
(* A newly-allocated condition with no threads waiting on it. *)

PROCEDURE Fork(cl: Closure): T;
(* A handle on a newly-created thread executing cl.apply(). *)

PROCEDURE Join(t: T): REFANY;
(* Wait until t has terminated and return its result.  It is a
   checked error to call this more than once for any t. *)
```

```
PROCEDURE Wait(m: Mutex; c: Condition);
(* The calling thread must have m locked.  Atomically unlocks
   m and waits on c.  Then relocks m and returns. *)

PROCEDURE Acquire(m: Mutex);
(* Wait until m is unlocked and then lock it. *)

PROCEDURE Release(m: Mutex);
(* The calling thread must have m locked.  Unlocks m. *)

PROCEDURE Broadcast(c: Condition);
(* All threads waiting on c become eligible to run.  *)

PROCEDURE Signal(c: Condition);
(* One or more threads waiting on c become eligible to run. *)

PROCEDURE Self(): T;
(* Return the handle of the calling thread. *)

EXCEPTION Alerted; (* Approximate asynchronous interrupts *)

PROCEDURE Alert(t: T);
(* Mark t as an alerted thread. *)

PROCEDURE TestAlert(): BOOLEAN;
(* TRUE if the calling thread has been marked alerted. *)

PROCEDURE AlertWait(m: Mutex; c: Condition) RAISES {Alerted,...};
(* Like Wait, but if the thread is marked alerted at the time of
   call or sometime during the wait, lock m and raise Alerted.
   Implementations may raise additional exceptions. *)

PROCEDURE AlertJoin(t: T): REFANY RAISES {Alerted, ...};
(* Like Join, but if t is marked alerted at the time of
   call or sometime during the wait, raise Alerted.
   Implementations may raise additional exceptions. *)

CONST
  AtomicSize = ...;
(* An implementation-dependent integer constant:  the number of bits
   in a memory-coherent block.  If two components of a record or
   array fall in different blocks, they can be accessed concurrently
   by different threads without locking. *)

END Thread.
```

The Word interface

```
INTERFACE Word;

(* A Word.T w represents a sequence of Word.Size bits

                        w0, ..., wWord.Size-1.

It also represents the unsigned number

             sum of 2^i * w_i for i in 0, ..., Word.Size-1. *)

TYPE T = INTEGER;  (* encoding is implementation-dependent;
                      for example, two's complement. *)

CONST Size = BITSIZE(T);

PROCEDURE Plus (x,y: T): T;      (* (x + y) MOD 2^Word.Size *)

PROCEDURE Times (x,y: T): T;     (* (x * y) MOD 2^Word.Size *)

PROCEDURE Minus (x,y: T): T;     (* (x - y) MOD 2^Word.Size *)

PROCEDURE Divide(x,y: T): T;     (* x divided by y *)

PROCEDURE Mod (x,y: T): T;       (* x MOD y *)

PROCEDURE LT(x,y: T): BOOLEAN;   (* x < y *)

PROCEDURE LE(x,y: T): BOOLEAN;   (* x <= y *)

PROCEDURE GT(x,y: T): BOOLEAN;   (* x > y *)

PROCEDURE GE(x,y: T): BOOLEAN;   (* x >= y *)

PROCEDURE And(x,y: T): T;        (* Bitwise AND of x and y *)

PROCEDURE Or (x,y: T): T;        (* Bitwise OR of x and y *)

PROCEDURE Xor(x,y: T): T;        (* Bitwise XOR of x and y *)

PROCEDURE Not (x: T): T;         (* Bitwise complement of x *)
```

```
PROCEDURE Shift(x: T; n: INTEGER): T;
(* For all i such that both i and i - n are in the range
   [0..Word.Size - 1], bit i of the result equals bit i - n of x.
   The other bits of the result are 0.  Thus shifting by n > 0 is
   like multiplying by 2^n *)

PROCEDURE Rotate(x: T; n: INTEGER): T;
(* Bit i of the result is bit ((i - n) MOD Word.Size) of x. *)

PROCEDURE Extract(x: T; i, n: CARDINAL): T;
(* Take n bits from x, with bit i as the least significant
   bit, and return them as the least significant n bits of
   a word whose other bits are 0.  A checked runtime error
   if n + i > Word.Size. *)

PROCEDURE Insert(x: T; y: T; i, n: CARDINAL): T;
(* Result of replacing n bits of x, with bit i as the least
   significant  bit, by the least significant n bits of y.
   The other bits of x are unchanged.  A checked runtime
   error if n + i > Word.Size. *)

END Word.
```

9 Syntax

Care should be taken, when using colons and semicolons in the same sentence, that the reader understands how far the force of each sign carries.
—Robert Graves and Alan Hodges

Keywords

Here are the Modula-3 keywords:

```
AND       DO        FINALLY   METHODS   RAISES    THEN      VAR
ARRAY     ELSE      FOR       MOD       READONLY  TO        WHILE
BEGIN     ELSIF     FROM      MODULE    RECORD    TRY       WITH
BITS      END       IF        NOT       REF       TYPE
BRANDED   EVAL      IMPORT    OBJECT    REPEAT    TYPECASE
BY        EXCEPT    IN        OF        RETURN    UNSAFE
CASE      EXCEPTION INTERFACE OR        REVEAL    UNTIL
CONST     EXIT      LOCK      PROCEDURE ROOT      UNTRACED
DIV       EXPORTS   LOOP      RAISE     SET       VALUE
```

Reserved identifiers

Here are the *reserved* identifiers, which cannot be redeclared:

```
ABS       BYTESIZE  FALSE     ISTYPE    MIN       NUMBER    TEXT
ADDRESS   CARDINAL  FIRST     LAST      MUTEX     ORD       TRUE
ADR       CEILING   FLOAT     LONGFLOAT NARROW    REAL      TRUNC
ADRSIZE   CHAR      FLOOR     LONGREAL  NEW       REFANY    TYPECODE
BITSIZE   DEC       INC       LOOPHOLE  NIL       ROUND     VAL
BOOLEAN   DISPOSE   INTEGER   MAX       NULL      SUBARRAY
```

Operators

The following characters and character pairs are classified as operators:

```
+       <       #       =       ;       ..      :
-       >       {       }       |       :=      <:
*       <=      (       )       ^       ,       =>
/       >=      [       ]       .       &
```

Comments

A comment is an arbitrary character sequence opened by (* and closed by *). Comments can be nested and can extend over more than one line.

Pragmas

A pragma is an arbitrary character sequence opened by <* and closed by *>. Pragmas can be nested and can extend over more than one line. Pragmas are hints to the implementation; they do not affect the language semantics.

We recommend supporting the two pragmas <*INLINE*> and <*EXTERNAL*>. The pragma <*INLINE*> precedes a procedure declaration to indicate that the procedure should be expanded at the point of call. The pragma <*EXTERNAL L*> precedes a procedure declaration to indicate that the procedure is implemented in the language L, or precedes an interface to indicate that the entire interface is implemented in the language L.

Conventions for syntax

We use the following notation for defining syntax:

`X Y`	`X` followed by `Y`
`X|Y`	`X` or `Y`
`[X]`	`X` or empty
`{X}`	A possibly empty sequence of `X`'s
`X&Y`	`X` or `Y` or `X Y`

Parentheses are used for grouping. Non-terminals begin with an upper-case letter. Terminals are either keywords or quoted operators. The symbols `Ident`, `Number`, `TextLiteral`, and `CharLiteral` are defined in the token grammar on page 59. Each production is terminated by a period. Indented productions are used only in the productions immediately above them. The syntax does not reflect the restrictions that revelations and exceptions can only be declared at the top level; nor does it include explicit productions for `NEW`, `INC`, and `DEC`, which parse like procedure calls.

Compilation unit productions

```
Compilation = [ UNSAFE ] ( Interface | Module ).
Interface   = INTERFACE Ident ";" { Import }
                  { Declaration } END Ident ".".
Module      = MODULE Ident [ EXPORTS IDList ] ";" { Import }
                  Block Ident ".".
Import      = [ FROM Ident ] IMPORT IDList ";".
Block       = { Declaration } BEGIN Stmts END.
Declaration = CONST { ConstDecl ";" }
            | TYPE { TypeDecl ";" }
            | EXCEPTION { ExceptionDecl ";" }
            | VAR { VariableDecl ";" }
            | ProcedureHead [ "=" Block Ident ] ";"
            | REVEAL { TypeID ( "=" | "<:" ) Type ";" }.

ConstDecl     = Ident [ ":" Type ] "=" ConstExpr.
TypeDecl      = Ident ( "=" | "<:" ) Type.
ExceptionDecl = Ident [ "(" Type ")" ].
VariableDecl  = IDList (":" Type & ":=" Expr).
ProcedureHead = PROCEDURE Ident Signature.
Signature     = "(" Formals ")" [ ":" Type ] [ RAISES Raises ].

Formals = [ Formal { ";" Formal } [ ";" ] ].
Formal = [ VALUE | VAR | READONLY ] IDList ( ":" Type & ":=" ConstExpr ).
Raises = "{" [ ExceptionID { "," ExceptionID } ] "}".
```

Statement productions

```
Stmts = [ Stmt { ";" Stmt } [ ";" ] ].

Stmt = AssignStmt | Block | CallStmt | CaseStmt
     | ExitStmt | EvalStmt | ForStmt | IfStmt | LockStmt
     | LoopStmt | RaiseStmt | RepeatStmt | ReturnStmt
     | TryFinStmt | TryXptStmt | TCaseStmt | WhileStmt | WithStmt.

AssignStmt = Expr ":=" Expr.
CallStmt   = Expr "(" [ Actual { "," Actual } ] ")".
CaseStmt   = CASE Expr OF [ Case ] { "|" Case } [ELSE Stmts] END.
ExitStmt   = EXIT.
EvalStmt   = EVAL Expr.
ForStmt    = FOR Ident ":=" Expr TO Expr [ BY Expr ] DO Stmts END.
IfStmt     = IF Expr THEN Stmts {ELSIF Expr THEN Stmts} [ELSE Stmts] END.
LockStmt   = LOCK Expr DO Stmts END.
LoopStmt   = LOOP Stmts END.
RaiseStmt  = RAISE ExceptionID [ "(" Expr ")" ].
RepeatStmt = REPEAT Stmts UNTIL Expr.
ReturnStmt = RETURN [ Expr ].
TCaseStmt  = TYPECASE Expr OF [ Tcase ] { "|" Tcase } [ELSE Stmts] END.
TryXptStmt = TRY Stmts EXCEPT [Handler] {"|" Handler} [ELSE Stmts] END.
TryFinStmt = TRY Stmts FINALLY Stmts END.
WhileStmt  = WHILE Expr DO Stmts END.
WithStmt   = WITH Binding { "," Binding } DO Stmts END.

Case    = Labels { "," Labels } "=>" Stmts.
Labels  = ConstExpr [".." ConstExpr].
Handler = ExceptionID { "," ExceptionID } ["(" Ident ")"] "=>" Stmts.
Tcase   = Type { "," Type } [ "(" Ident ")" ] "=>" Stmts.
Binding = Ident "=" Expr.

Actual  = ( [ Ident ":=" ] Expr | Type ).
```

Type productions

```
Type = TypeName | ArrayType | PackedType | EnumType | ObjectType
     | ProcedureType | RecordType | RefType | SetType | SubrangeType
     | "(" Type ")".

ArrayType     = ARRAY [ Type { "," Type } ] OF Type.
PackedType    = BITS ConstExpr FOR Type.
EnumType      = "{" [ IDList ] "}".
ObjectType    = [Ancestor] [Brand] OBJECT Fields [ METHODS Methods ] END.
```

```
ProcedureType = PROCEDURE Signature.
RecordType    = RECORD Fields END.
RefType       = [ UNTRACED ] [ Brand ] REF Type.
SetType       = SET OF Type.
SubrangeType  = "[" ConstExpr ".." ConstExpr "]".

Ancestor = TypeName | ObjectType | UNTRACED.
Brand    = BRANDED [ TextLiteral ].
Fields   = [ Field { ";" Field } [ ";" ] ].
Field    = IDList ( ":" Type & ":=" ConstExpr ).
Methods  = [ Method { ";" Method } [ ";" ] ].
Method   = Ident ( Signature & ":=" ProcedureID ).
```

Expression productions

```
ConstExpr = Expr.

Expr = E1 { OR E1 }.
  E1 = E2 { AND E2 }.
  E2 = { NOT } E3.
  E3 = E4 { Relop E4 }.
  E4 = E5 { Addop E5 }.
  E5 = E6 { Mulop E6 }.
  E6 = { "+" | "-" } E7.
  E7 = E8 { Selector }.
  E8 = Ident | Number | CharLiteral | TextLiteral
    | Constructor | "(" Expr ")".

Relop = "=" | "#" | "<" | "<=" | ">" | ">=" | IN.
Addop = "+" | "-" | "&".
Mulop = "*" | "/" | DIV | MOD.

Selector = "^" | "." Ident | "[" Expr { "," Expr } "]"
    | "(" [ Actual { "," Actual } ] ")".

  Constructor = Type "{" [ SetCons | RecordCons | ArrayCons ] "}".

SetCons = SetElt { "," SetElt }.
SetElt = Expr [ ".." Expr ].
RecordCons = RecordElt { "," RecordElt }.
RecordElt = [ Ident ":=" ] Expr.
ArrayCons = Expr { "," Expr } [ "," ".." ] .
```

Miscellaneous productions

```
TypeName = Ident [ "." Ident ] | ROOT | UNTRACED ROOT.
ExceptionID = Ident [ "." Ident ].
ProcedureID = Ident [ "." Ident ].

IDList = Ident { "," Ident }.
```

Token productions

To read a token, first skip all blanks, tabs, newlines, carriage returns, vertical tabs, form feeds, comments, and pragmas. Then read the longest sequence of characters that forms an operator (as defined in Section 9, page 55) or an `Ident` or `Literal`, as defined here.

An `Ident` is a case-significant sequence of letters, digits, and underscores that begins with a letter. An `Ident` is a keyword if it appears in Section 9, a reserved identifier if it appears in Section 9, and an ordinary identifier otherwise.

In the following grammar, terminals are characters surrounded by double-quotes and the special terminal `DQUOTE` represents double-quote itself.

```
Literal = Number | CharLiteral | TextLiteral.

Ident = Letter { Letter | Digit | "_" }.

Operator = "+" | "-" | "*" | "/" | "." | "^" | ":" "=" | "=" | "#" | "<"
         | "<" "=" | ">" "=" | ">" | "&" | "<" ":"  | "=" ">" | "," | ";"
         | "|" | ":" | "." "." | "(" | ")" | "{" | "}" | "[" | "]".

CharLiteral = "'"  ( PrintingChar | Escape ) "'".

TextLiteral = DQUOTE { PrintingChar | Escape } DQUOTE.

Escape = "\" "n"   | "\" "t"     | "\" "r"     | "\" "f"
       | "\" "\"   | "\" "'"     | "\" DQUOTE
       | "\" OctalDigit OctalDigit OctalDigit.

Number = Digit { Digit }
       | Digit { Digit } "_" HexDigit { HexDigit }
       | Digit { Digit } "." Digit { Digit } [ Exponent ].

Exponent =  ("E" | "e" | "D" | "d" ) [ "+" | "-" ] Digit { Digit }.

PrintingChar = Letter | Digit | OtherChar.

HexDigit = Digit | "A" | "B" | "C" | "D" | "E" | "F"
                 | "a" | "b" | "c" | "d" | "e" | "f".
```

```
Digit = "0" | "1" | ... | "9".

OctalDigit = "0" | "1" | ... | "7".

Letter = "A"  | "B"  | ... | "Z"  | "a"  | "b"  | ... | "z".

OtherChar = " " | "!" | "#" | "$" | "%" | "&" | "(" | ")"
          | "*" | "+" | "," | "-" | "." | "/" | ":" | ";"
          | "<" | "=" | ">" | "?" | "@" | "[" | "]" | "^"
          | "_" | "`" | "{" | "|" | "}" | "~"
          | ExtendedChar

ExtendedChar = any char with ISO-Latin-1 code in [8_240..8_377].
```

Acknowledgments

Modula-3 was designed by Luca Cardelli, Jim Donahue, Mick Jordan, Bill Kalsow, and Greg Nelson, as a joint project by the Digital Systems Research Center and the Olivetti Research Center.

Paul Rovner made many contributions as a founding member of the design committee, but cannot be held responsible for the final product.

Our starting point was Modula-2+, which was designed by Paul Rovner, Roy Levin, John Wick, Andrew Birrell, Butler Lampson, and Garret Swart. We benefited from the ruthlessly complete description of Modula-2+ provided in Mary-Claire van Leunen's *Modula-2+ User's Manual.*

Niklaus Wirth made valuable suggestions and inspired us with the courage to throw things out. He also designed Modula-2, the starting point of our starting point.

Too many people provided helpful feedback to thank individually, but we especially want to thank the following people: Bob Ayers, Andrew Black, David Chase, Dan Craft, Hans Eberle, John Ellis, Stu Feldman, Jim Horning, Mike Kupfer, Butler Lampson, Trevor Morris, Eric Muller, Lyle Ramshaw, Eric Roberts, Ed Satterthwaite, Jorge Stolfi, and Garret Swart.

The report was written by Lucille Glassman and Greg Nelson, under the watchful supervision of the whole committee.

Bibliography

[1] A.D. Birrell, J.V. Guttag, J.J. Horning, and R. Levin. Synchronization primitives for a multiprocessor: a formal specification. *Operating Systems Review*, 21(5), November 1987. Also published as SRC Research Report 20, August 1987.

[2] Daniel Jackson and Jim Horning. The Modula-2+ Text interface. Unpublished manuscript available from Jim Horning at SRC.

[3] Butler W. Lampson. *A Description of the Cedar Language*. Technical Report CSL-83-15, Xerox Palo Alto Research Center, December 1983.

[4] Butler W. Lampson, James J. Horning, Ralph L. London, James G. Mitchell, and Gerald J. Popek. *Report on the Programming Language Euclid*. Technical Report CSL-81-12, Xerox Palo Alto Research Center, October 1981.

[5] Larry Tesler, Apple Computers. Object pascal report. *Structured Language World*, 9(3), 1985.

[6] James G. Mitchell, William Maybury, and Richard Sweet. *Mesa Language Manual*. Technical Report CSL-78-1, Xerox Palo Alto Research Center, February 1978.

[7] Paul Rovner. Extending modula-2 to build large, integrated systems. *IEEE Software*, 3(6), November 1986.

[8] Paul Rovner, Roy Levin, and John Wick. *On Extending Modula-2 For Building Large, Integrated Systems*. Technical Report 3, Digital Systems Research Center, January 1985.

[9] N. Wirth. *From Modula to Oberon and The Programming Language Oberon*. Technical Report 82, Institut fur Informatik, ETH Zurich, September 1987.

[10] Niklaus Wirth. *Programming in Modula-2*. Springer-Verlag, Third Edition, 1985.

Index

Twelve Changes to Modula-3
19 Dec 90

The Modula-3 committee has made twelve final changes to the language definition, described in this message.

On behalf of the Modula-3 committee I would like to thank Bob Ayers, Michel Gangnet, David Goldberg, Sam Harbison, Christian Jacobi, Nick Maclaren, Eric Muller, and Thomas Roemke for their helpful comments on these changes. ---Greg Nelson

Contents

Section 1. List of changes

1.1 The language will be extended to support generic interfaces and modules. The detailed semantics of generics are in Section 3, below.

1.2 In addition to REAL and LONGREAL the language will support the new floating point type EXTENDED. New required interfaces will allow clients to use IEEE floating point if the implementation supports it. The behavior of the interfaces is also defined for non-IEEE implementations. Listing of these interfaces, and other details, are in Section 4, below.

1.3 The default raises clause will be the empty set instead of the set of all exceptions. RAISES ANY will be used to indicate that a procedure can raise any exception.

1.4 The sentence:

> The declaration of an object type has the form
>
> TYPE T = ST OBJECT FieldList METHODS MethodList END
>
> where ST is an optional supertype, FieldList is a list of field declarations, exactly as in a record type, and MethodList is a list of "method declarations" and "method overrides".

will be changed to

> The declaration of an object type has the form
>
> TYPE T = ST OBJECT Fields METHODS Methods OVERRIDES Overrides END
>
> where ST is an optional supertype, Fields is a list of field declarations, exactly as in a record type, Methods is a list of "method declarations" and Overrides is a list of "method overrides".

The syntax for individual method declarations and individual method overrides remains the same.

1.5 The semantics of method overrides supplied at NEW time will be defined by the following rewriting:

> NEW(T, m := P)
>
> is sugar for
>
> NEW(T OBJECT OVERRIDES m := P END).

As a consequence, the method overrides are restricted to procedure constants, and the methods of an object are determined by its allocated type. It is no longer necessary to refer to "T's default m method", you can just say "T's m method".

1.6 On page 48, the last sentence in the section "Constant Expressions" will be changed from

> "All literals are legal in constant expressions; procedure constants are not"

to

> "Literals and top-level procedure constants are legal in constant expressions"

Procedure application remains illegal in constant expressions, except for the required procedures in the Word interface.

1.7 The word "not" will be removed from the sentence "T.m is not a procedure constant" on page 39, and the grammar will be changed to allow the syntax T.m as a method default.

1.8 The prohibition against NEWing an opaque object type will be removed. The procedures Thread.NewMutex and Thread.NewCondition will be removed from the Thread interface and replaced by comments to the effect that a newly-allocated Mutex is in the unlocked state and a newly-allocated Condition has no threads waiting on it.

1.9 The following sentence will be added to the "revelations" section:

> In any scope, the revealed supertypes of an opaque type must be totally ordered by the subtype relation. For example, in a scope where it is revealed that T <: S1 and that T <: S2, it must also be revealed either that S1 <: S2 or that S2 <: S1.

1.10 The sentence

> The pragma <*EXTERNAL L*> precedes a procedure declaration to indicate that the procedure is implemented in the language L, or precedes an interface to indi cate that the entire interface is implemented in the language L.

will be changed to

> The pragma <* EXTERNAL N:L *> precedes an interface or a declaration in an interface to indicate that the entity it precedes is implemented by the language L, where it has the name N. If ":L" is omitted, then the implementation's default ex ternal language is assumed. If "N" is omitted, then the external name is determined from the Modula-3 name in some implementation-dependent way.

1.11 The result type of the built-in function TYPECODE will be changed from INTEGER to CARDINAL.

1.12 Changes to the syntax of text, character, and integer literals, as follows: On page 59, "Token Productions", the lines

> CharLiteral = "'" (PrintingChar | Escape) "'"
>
> TextLiteral = DQUOTE { PrintingChar | Escape } DQUOTE

will be changed to

> CharLiteral = "'" (PrintingChar | Escape | DQUOTE) "'"
>
> TextLiteral = DQUOTE { PrintingChar | Escape | "'" } DQUOTE

The effect is to allow "Don't" instead of "Don\'t" and '"' instead of '\"'. In the section on integer literals, we will add the words

> If no base is present, the value of the literal must be at most LAST(INTEGER); if an explicit base is present, the value of the literal must be less than 2^Word.Size, and its interpretation as a signed integer is implementation-dependent. For example, on a sixteen-bit two's complement machine, 16_ffff and -1 represent the same value.

Section 2. Rationale

2.1 In regard to generics: several programmers have invented ad-hoc schemes for working around the absence of generics. We have found a simple design that seems to be in the Modula spirit, is easy to implement, and has essentially no impact on the rest of the language.

2.2 In regard to floating-point revisions: Jorge Stolfi and Stephen Harrison have reported on their use of Modula-3 for floating-point graphics computations, and David Goldberg has given us a critique of Modula-3 from the point of view of a numerical analyst. We have used this feedback to try to make Modula-3 better for floating-point computations, an issue that was not taken too seriously in the original design.

2.3 In regard to the default raises clause, RAISES {} is far more frequent than RAISES ANY, so it should be the default. This change is not backward-compatible: conversion will require

> Finding occurrences of RAISES {} and deleting them. This is easy to do, and is not essential, since RAISES {} is still meaningful and legal, although now redundant.
>
> Finding procedures without raises clauses and adding RAISES ANY (or, more likely, noticing that they were incorrectly annotated and that the correct clause is RAISES {} in which case they can be left alone). Since RAISES ANY is rare, this change should be necessary in very few places, e.g., for mapping functions.

2.4 In regard to the explicit OVERRIDES keyword: several programmers have accidentally declared a new method when they meant to override an existing one, strongly suggesting that the current syntax does not distinguish between methods and overrides strongly enough. This change is not backwards compatible, but existing programs can be converted easily, by

sorting the method declarations in front of the method overrides and adding the word "OVERRIDES" between the two groups.

2.5 In regard to defining the semantics of method overriding at NEW time by syntactic sugar: the advantage of this change is that the method suite becomes a constant function of the type. That is, we no longer have to talk about "T's default m method", we can just say "T's m method". For example, this is convenient for the implementation of type-safe persistent storage (pickles), which can recreate an object's method suite trivially, by asking the runtime system for the method suite associated with the type. (This is in fact what is done by both the Olivetti and the SRC pickles packages: adopting the rewriting semantics above will make both packages correct.)

The obvious cost of the change is that a procedure variable can no longer be used as a method override. However, no programs are known to use this facility. Furthermore, a strong argument can be made that this facility is not useful. For example, consider the following program, which does use a procedure variable as a method override:

```
PROCEDURE New(
  h: PROCEDURE(t: Table.T, k: Key.T): INTEGER)
: Table.T =
BEGIN
    ...
  NEW(Table.T, hashMethod := h)
END New.
```

This is poor code: it would be better to make the hash method a procedure-valued field in the table, since the usual argument for making something a method rather than a procedure data field doesn't apply here: New cannot be used to construct a subtype of Table.T with a hash method specific to that subtype, because New's signature requires that h accept any Table.T as an argument. Consequently there is no flexibility gained by using a method. Furthermore, if the hash procedure is stored in the data part of the object, hash tables with different hash procedures can share method suites, and thus save space.

This change is not strictly backwards-compatible, but as no programs are known to override methods at NEW time with non-constant procedures, it is expected to be backwards compatible in practice.

2.6 In regard to the change that allows procedure constants in constant expressions: this allows procedure constants as default parameters, which is a convenience. And it does not seem to be difficult for implementations, or any less principled to allow procedure constants in constant expressions than to allow TEXT literals.

2.7 In regard to allowing "T.m" as a procedure constant: you could already write T.m to denote the m method of type T, but because this expression was not considered a procedure constant, it couldn't be used as a method default. That usually meant that an interface exporting T would also have to export each of T's methods by name, since somebody defining a related class might reuse some of the methods. Thus this change allows less cluttered interfaces.

Allowing T.m as a procedure constant raises the following question:

Are U and V the same after

```
TYPE T = OBJECT METHODS m() := P END
TYPE
  U = T OBJECT METHODS m := P END;
  V = T OBJECT METHODS m := T.m END;
```

Answering "yes" would be hard on the implementation, since although in this case the identity of T.m with P is manifest, this would not be true in general.

So we will define U and V to be different, on the grounds that the expanded form of U contains "P" where the expanded form of V contains "(expanded form of T).m". With respect to structural equivalence, the implementation should treat the occurrence of "T.m" the same as it would treat a record field "m: T".

2.8 In regard to NEW(T) for opaque types T: If an opaque type requires initializations over and above what can be done with default field values, then the implementor of the type must provide a procedure for doing the initialization. He might provide a New procedure that allocates, initializes, and returns a value of the type, but this New procedure couldn't be used by anybody implementing a subtypes of the opaque type, since it allocates the wrong type of object. Thus when you declare an opaque type that is intended to be subclassed, you owe it to your clients to provide an init routine that takes an object that has already been allocated, or to comment that no initialization in necessary beyond what is automatically provided by default field values. In either case, the effect of NEWing the opaque type will be well-specified in the interface, and the old rule against it is revealed as an attempt to legislate style.

In fact, the old rule interfered with a style that seems attractive: for each object type T, define a method T.init that initializes the object and returns it. Then the call

```
NEW(T).init(args)
```

allocates, initializes, and returns an object of type T. If T is an subtype of some type S, and the implementer of S uses the same style, then within T.init(self, ...) there will be a call of the form EVAL S.init(self, ...) to initialize the supertype part of the object. Note that this style involves NEWing the opaque object type T.

2.9 In regard to the requirement that the revealed supertypes of an opaque type must be totally ordered by the subtype relation: this rule was present in the original version of the report, and somehow got deleted from the revised version, probably by an editing error, without the committee ever deliberately rescinding it. The advantage of the rule is that the information about an opaque type in a scope is determined by a single type, its "<:-least upper bound", rather than by a set of types. This simplifies the compiler; in fact, both the SRC and Olivetti compilers depend on this rule. Theoretically this is not a backwards-compatible change, but since it is bringing the language into conformance with the two compilers that are in use, obviously it won't require conversion by clients.

2.10 In regard to the EXTERNAL pragma: in producing the Modula-3 interfaces to the X library the need for renaming as part of the external declaration was acute.

2.11 Changing the result type of TYPECODE to CARDINAL is no burden on the implementation, and the guarantee that negative integers cannot be confused with typecodes is often convenient.

2.12 Allowing "Don't" instead of "Don\'t" makes programs more readable. Allowing integer literals whose high-order bit is set is useful both in graphics applications, where masks are being constructed, and in low-level systems code, where integers are being loopholed into addresses that may be in the high half of memory.

Section 3. Details of generics

Before describing the generics proposal proper, we describe two minor changes that are associated with generics: allowing renamed imports, and allowing text constants to be brands.

3.1 Allowing renamed imports.

IMPORT I AS N means "import the interface I and give it the local name N". The name I is not introduced into the importing scope.

The imported interfaces are all looked up before any of the local names are bound; thus

```
IMPORT I AS J, J AS I;
```

imports the two interfaces I and J, perversely giving them the local names J and I respectively.

It is illegal to use the same local name twice:

```
IMPORT J AS I, K AS I;
```

is a static error, and would be even if J and K were the same.

The old form IMPORT I is short for IMPORT I AS I.

FROM I IMPORT X introduces X as the local name for the entity named X in the interface I. A local binding for I takes precedence over a global binding for I. For example,

```
IMPORT I AS J, J AS I; FROM I IMPORT X;
```

simultaneously introduces local names I, J, and X for the entities whose global names are J, I, and J.X, respectively.

3.2 Allowing text constants as brands.

The words from the section on Reference types:

> ... can optionally be preceded by "BRANDED b", where b is a text literal called the "brand".

will be changed to

> ... can optionally be preceded by "BRANDED b", where b is a text constant called the "brand".

This allows generic modules to use an imported text constant as the brand.

3.3 Generics proper.

In a generic interface or module, some of the imported or exported interface names are treated as formal parameters, to be bound to actual interfaces when the generic is instantiated.

A generic interface has the form

GENERIC INTERFACE G(F_1, ..., F_n); Body END G.

where G is an identifier that names the generic, F_1, ..., F_n is a list of identifiers, called the formal imports of G, and Body is a sequence of imports followed by a sequence of declarations, exactly as in a non-generic interface. An instance of G has the form

INTERFACE I = G(A_1, ..., A_n) END I.

where I is the name of the instance and A_1, ..., A_n is a list of "actual" interfaces to which the formal imports of G are bound. The semantics are defined precisely by the following rewriting:

INTERFACE I; IMPORT A_1 AS F_1, ..., A_n AS F_n; Body END I.

A generic module has the form

GENERIC MODULE G(F_1, ..., F_n); Body END G.

where G is an identifier that names the generic, F_1, ..., F_n is a list of identifiers, called the formal imports of G, and Body is a sequence of imports followed by a block, exactly as in a non-generic module. An instance of a G has the form

MODULE I EXPORTS E = G(A_1, ..., A_n) END I.

where I is the name of the instance, E is a list of interfaces exported by I, and A_1, ..., A_n is a list of actual interfaces to which the formal imports of G are bound. "EXPORTS E" can be omitted, in which case it defaults to "EXPORTS I". The semantics are defined precisely by the following rewriting:

MODULE I EXPORTS E; IMPORT A_1 AS F_1, ..., A_n AS F_n; Body END I.

Notice that the generic module itself has no exports or UNSAFE indication; they can be supplied only when it is instantiated.

For example, consider

```
GENERIC INTERFACE Dynarray(Elem);
  (* Extendible arrays of Elem.T, which can be any type  except an open array type. *)
    TYPE T = REF ARRAY OF Elem.T;
    PROCEDURE Extend(VAR v: T);
  (* Extend v's length, preserving its current contents. *)
END Dynarray.
```

```
GENERIC MODULE Dynarray(Elem);

PROCEDURE Extend(VAR v: T) =
VAR w: T;
BEGIN
  IF v = NIL OR NUMBER(v^) = 0 THEN
        w := NEW(T, 5)
        ELSE
        w := NEW(T, NUMBER(v^) * 2);
        FOR i := 0 TO LAST(v^) DO w[i] := v[i] END
        END;
        v := w
        END Extend;

END Dynarray.
```

To instantiate these generics to produce dynamic arrays of integers:

INTERFACE Integer; TYPE T = INTEGER END Integer.

INTERFACE IntArray = Dynarray(Integer) END IntArray.

MODULE IntArray = Dynarray(Integer) END IntArray.

Implementations are not expected to share code between different instances of a generic module, since this will not be possible in general.

There is no typechecking associated with generics: implementations are expected to expand the instantiation and typecheck the result. For example, if one made the following mistake:

INTERFACE String; TYPE T = ARRAY OF CHAR END String.

INTERFACE StringArray = Dynarray(String) END StringArray.

MODULE StringArray = Dynarray(String) END StringArray.

Everything would go well until the last line, when the compiler would attempt to compile a version of Dynarray in which the element type was an open array. It would then complain that the "NEW" call in Extend does not have enough parameters.

Section 4. Details of floating-point

The new built-in floating-point type EXTENDED will be added. The character "x" will be used in place of "d" or "e" to denote EXTENDED constants.

FIRST(T) and LAST(T) will be defined for the floating point types. In IEEE implementations, these are minus and plus infinity, respectively.

MOD will be extended to floating point types by the rule

x MOD y = x - y * FLOOR(x / y).

Implementations may compute this as a Modula-3 expression, or by a method that avoids overflow if x is much greater than y.

All the built-in operations that take REAL and LONGREAL will take EXTENDED arguments as well. (To make the language specification shorter and more readable, we will use the type class "Float" to represent any floating point type. For example:

+ (x,y: INTEGER) : INTEGER

(x,y: Float) : Float

The sum of x and y. If x and y are floats, they must have the same type, and the result is the same type as both.

LONGFLOAT will be removed and FLOAT will be changed to:

FLOAT(x: INTEGER; T: Type := REAL): T

FLOAT(x: Float; T: Type := REAL): T

Convert x to have type T, which must be a floating-point type.

Thus FLOAT(x) means the same thing it means today; FLOAT(x, LONGREAL) means what LONGFLOAT(x) means today.

We will add to the expressions chapter a note that the rounding behavior of floating-point operations is specified in the required interface FloatMode, as well as a note that implementations are only allowed to rearrange computations if the rearrangement has no effect on the semantics; e.g., (x+y)+z should not in general be changed to x+(y+z), since addition is not associative. The arithmetic operators are left-associative; thus x+y+z is short for (x+y)+z. The behavior of overflows and other exceptional numeric conditions will also be determined by the interface FloatMode. Finally, we will change the definition of the built-in equality operation on floating-point numbers so that it is implementation-dependent, adding a note that in IEEE implementations, +0 equals -0 and Nan does not equal Nan.

Modula-3 systems will be required to implement the following interfaces related to floating-point numbers. The interfaces give clients access to the power of IEEE floating point if the implementation has it, but can also be implemented with other floating point systems. For definitions of the terms used in the comments, see the IEEE Standard for Binary Floating-Point Arithmetic (ANSI/IEEE Std. 754-1985).

```
INTERFACE Real;
TYPE T = REAL;
CONST
   Base: INTEGER = ...;
  (* The radix of the floating-point representation for T *)
  Precision: INTEGER;
 (* The number of digits of precision in the given Base for T. *)
  MaxFinite: T = ...;
 (* The maximum finite value in T. For non-IEEE implementations,  this is the same as
            LAST(T). *)
  MinPos: T = ...;
 (* The minimum positive value in T. *)
 MinPosNormal: T = ...;
(* The minimum positive "normal" value in T; differs from MinPos  only for implementations
            with denormalized numbers. *)

END Real.

INTERFACE LongReal;
TYPE T = LONGREAL;
CONST
   Base: INTEGER = ...;
   Precision: INTEGER = ...;
   MaxFinite: T = ...;
    MinPos: T = ...;
    MinPosNormal: T = ...;
   (* Like the corresponding constants in Real. *)
END LongReal.

INTERFACE Extended;

TYPE T = EXTENDED;
```

```
CONST
  Base: INTEGER = ...;
  Precision: INTEGER = ...;
  MaxFinite: T = ...;
  MinPos: T = ...;
  MinPosNormal: T = ...;
  (* Like the corresponding constants in Real. *)
END Extended.

INTERFACE RealFloat = Float(Real) END RealFloat.
INTERFACE LongFloat = Float(LongReal) END LongFloat.
INTERFACE ExtendedFloat = Float(Extended) END ExtendedFloat.

GENERIC INTERFACE Float(Real);

TYPE T = Real.T;
(* The purpose of the interface is to provide access to the floating-point operations required or
  recommended by the IEEE floating-point standard. Consult the standard for the
  precise specifications of the procedures, including when their arguments are NaNs,
  infinities, and signed zeros, and including what exceptions they can raise. Our
  comments specify their effect when the arguments are ordinary numbers and no ex-
  ception is raised. Implementations on non-IEEE machines that have values similar
  to NaNs and infinities should explain how those values behave for IsNaN, Finite,
  etc. in an implementation guide *)
PROCEDURE Scalb(x: T; n: INTEGER): T;
(* Return x * (2 ** n). *)

PROCEDURE Logb(x: T): T;
(* Return the exponent of x. More precisely, return the unique n such that ABS(x) / Base ** n
  is in the range [1..Base-1], unless x is denormalized, in which case return MinExp-1, where
  MinExp is the minimum exponent value for T. *)
PROCEDURE ILogb(x: T): INTEGER;
(* Like Logb, but returns an integer, never raises an exception, and always returns the n such
  that ABS(x)/Base**N is in [1..Base-1] even for denormalized numbers. *)
```

```
PROCEDURE NextAfter(x, y: T): T;
(* Return the next representable neighbor of x in the direction towards y. If x = y, return x *)

PROCEDURE CopySign(x, y: T): T;
(* Return x with the sign of y. *)

PROCEDURE Finite(x: T): BOOLEAN;
(* Return TRUE if x is strictly between -infinity and +infinity. This always returns TRUE on
   non-IEEE machines. *)

PROCEDURE IsNaN(x: T): BOOLEAN;
(* Return FALSE if x represents a numerical (possibly infinite) value, and TRUE if x does not
   represent a numerical value. For example, on IEEE implementations, returns TRUE if x is a
   NaN, FALSE otherwise; on Vaxes, returns TRUE of x is a reserved operand, FALSE other
   wise. *)

PROCEDURE Sign(x: T): [0..1];
(* Return the sign bit x. For non-IEEE implementations, this is the same as ORD(x >= 0); for
   IEEE implementations, Sign(-0) = 1, Sign(+0) = 0. *)

PROCEDURE Differs(x, y: T): BOOLEAN;
(* RETURN (x < y OR y < x). Thus, for IEEE implementations, Differs(NaN, x) is always
   FALSE; for non-IEEE implementations, Differs(x,y) is the same as x # y. *) PROCEDURE
   Unordered(x, y: T): BOOLEAN; (* Return NOT (x <= y OR y <= x). For non-IEEE imple-
   mentations, this always returns FALSE. *)

PROCEDURE Sqrt(x: T): T;
(* Return the square root of T. Must be correctly rounded if FloatMode.IEEE is TRUE. *)

TYPE IEEEClass =
    {SignalingNaN, QuietNaN, Infinity, Normal, Denormal, Zero};

PROCEDURE Class(x: T): IEEEClass;
```

```
(* Return the IEEE number class containing x. On non-IEEE systems, the result will be Nor
   mal or Zero. *)
END Float.

INTERFACE FloatMode;
(* This interface allows you to test the behavior of rounding and of numerical exceptions. On
   some implementations it also allows you to change the behavior, on a per-thread basis. *)

CONST IEEE: BOOLEAN = ...;
(* TRUE for full IEEE implementations. *)

EXCEPTION Failure;

TYPE RoundingMode =
{MinusInfinity, PlusInfinity, Zero, Nearest, Vax, IBM370, Other};
(* Mode for rounding operations. The first four are the IEEE modes. *)

CONST RoundDefault: RoundingMode = ...;
(* Implementation-dependent: the default mode for rounding arithmetic operations, used by a
   newly forked thread. This also specifies the behavior of the ROUND operation in half-way
   cases. *)

PROCEDURE SetRounding(md: RoundingMode) RAISES {Failure};
(* Change the rounding mode for the calling thread to md, or raise the exception if this cannot
   be done. This affects the implicit rounding in floating-point operations. Generally this is pos
   sible only on IEEE implementations and only if md is an IEEE mode. *)

PROCEDURE GetRounding(): RoundingMode;
(* Return the rounding mode for the calling thread. *)
TYPE Flag =
  {Invalid, Inexact, Overflow, Underflow, DivByZero, IntOverflow, IntDivByZero};
  (* Associated with each thread is a set of boolean status flag recording whether the condition
     represented by the flag has occurred in the thread since the flag has last been reset. The
     meaning of the first five flags is defined precisely in the IEEE floating point standard;
     roughly they mean:
```

```
    Invalid = invalid argument to an operation.
    Inexact = an operation produced an inexact result.
    Overflow = a floating-point operation produced a result whose absolute value is too large to
      be represented.
    Underflow = a floating-point operation produced a result whose absolute value is too small to
      be represented.
    DivByZero = floating-point division by zero.
    The meaning of the last two flags is:
    IntOverflow = an integer operation produced a result whose absolute value is too large to be
      represented.
    IntDivByZero = integer DIV or MOD by zero. *)

CONST NoFlags = SET OF Flags {};

PROCEDURE GetFlags(): SET OF Flag;
(* Return the set of flags for the current thread *)

PROCEDURE SetFlags(s: SET OF Flag): SET OF Flag;
(* Set the flags for the current thread to s, and return their previous values. *)

PROCEDURE ClearFlag(f: Flag);
(* Turn off the flag f for the current thread. *)

EXCEPTION Trap(Flag);
TYPE Behavior = {Trap, SetFlag, Ignore};
(* The behavior of an operation that causes one of the flag conditions is either
    Ignore = return some result and do nothing.
    SetFlag = return some result and set the condition flag. For IEEE implementations,
      the result will be what the standard requires.
    Trap = possibly set the condition flag; in any case raise the Trap exception with the
      appropriate flag as the argument.
*)
```

```
PROCEDURE SetBehavior(f: Flag; b: Behavior) RAISES {Failure};
(* Set the behavior of the current thread for the flag f to be b, or  raise Failure if this cannot be
done. *)

PROCEDURE GetBehavior(f: Flag): Behavior;
(* Return the behavior of the current thread for the flag f. *)

END FloatMode.
```