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18. Procedure call, orphans, exception handling.
Argus Reference Manual

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Guide to the Manual

This document serves both as a reference manual and as an introduction to Argus. Sections 1 through 3 present an overview of the language. These sections highlight the essential features of Argus. Sections 4 through 15 and the appendices form the reference manual proper. These sections describe each aspect of Argus in detail, and discuss the proper use of various features. Appendices I and II provide summaries of Argus's syntax and data types. Appendix III summarizes some of the pragmatic rules for using Argus.


An overview and rationale for Argus is presented in Liskov, B. and Scheifler, R., "Guardians and Actions: Linguistic Support for Robust, Distributed Programs" (*ACM Transactions on Programming Languages and Systems*, volume 5, number 3 (July 1983), pages 381-404).

The *Preliminary Argus Reference Manual* appeared as Programming Methodology Group Memo 39 in October 1983. Since that time several new features have been added to the language; the most significant of these are closures (see Section 9.8), a fork statement (see Section 10.4), equate modules (see Section 12.4), and a more flexible instantiation mechanism (see Section 12.6). An earlier version of this document appeared as Programming Methodology Group Memo 54 in March 1987; this version is essentially identical, except that the locking policy for the built-in type generator atomic_array has been simplified.

We would greatly appreciate receiving comments on both the language and this manual. Comments should be sent to: Professor Barbara Liskov, Laboratory for Computer Science, Massachusetts Institute of Technology, 545 Technology Square, Cambridge, MA 02139.

The authors thank all the members of the Programming Methodology group at MIT for their help and suggestions regarding the language and this manual, with special thanks going to Elliot Kolodner, Deborah Hwang, Sharon Perl, and the authors of the *CLU Reference Manual*. 
Though her unhappy rival was hers to keep
Queen Juno also had a troubled mind:
What would Jove turn to next? Better, she thought,
To give the creature to Arestor’s son,
The frightful Argus whose unnatural head
Shone with a hundred eyes, a perfect jailer
For man or beast: the hundred eyes took turns
At staring wide awake in pairs, and two
At falling off to sleep; no matter how or
Where he stood he gazed at Io; even when
His back was turned, he held his prisoner
In sight and in his care.

— Ovid, *The Metamorphoses*, Book 1
Translated by H. Gregory
The Viking Press, Inc., New York, 1958
1 Overview

Argus is an experimental language/system designed to support the construction and execution of distributed programs. Argus is intended to support only a subset of the applications that could benefit from being implemented by a distributed program. Two properties distinguish these applications: they make use of on-line data that must remain consistent in spite of concurrency and hardware failures, and they provide services under real-time constraints that are not severe. Examples of such applications are office automation systems and banking systems.

Argus is based on CLU. It is largely an extension of CLU, but there are number of differences (see Appendix IV). Like CLU, Argus provides procedures for procedural abstraction, iterators for control abstraction, and clusters for data abstraction. In addition, Argus provides guardians that encapsulate and control access to one or more resources. These are discussed in more detail in Section 2. Argus also provides equate modules as a convenient way to refer to constants (see Section 12.4). As in CLU, modules may be parameterized, so that a single module can define a class of related abstractions.

1.1. Objects and Variables

The semantics of Argus deal with objects and variables. Objects are the data entities that are created and manipulated by applications. Variables are the names used in a program to refer to objects.

Every object has a type that characterizes its behavior. A type defines a set of primitive operations to create and manipulate objects of that type.

An object may refer to other objects or even to itself. It is also possible for an object to be referred to or shared by several objects. Objects exist independently of procedure and iterator invocations.

There are several categories of objects in Argus. An object that exhibits time-varying behavior is called a mutable object. A mutable object has state that may be modified by operations without changing the object's identity. A mutable object can thus exhibit behavior that varies with time. An immutable object's state is inseparable from its identity. An immutable object cannot exhibit time-variant behavior. Objects are atomic if they provide synchronization and recovery for actions that manipulate them (see Section 2.2.2). Objects are transmissible if they can be sent as arguments or results of remote procedure calls (see Section 2.4). Since guardian, handler, creator, and node objects can be shared among guardians, these objects are said to be global objects. All other objects, such as characters, integers, or procedures, can only be shared within a single guardian and are called local objects.

Variables are names used in programs to denote particular objects at execution time. It is possible for two variables to denote the same object. Variables are not objects; they cannot be denoted by other variables or referred to by objects.

Variables in guardian modules can be declared to be stable. The objects denoted by stable variables survive crashes (see Section 2) and are called stable objects.
1.2. Assignment and Calls

The basic events in Argus are assignments and calls. The assignment statement \( x := E \), where \( x \) is a variable and \( E \) is an expression, causes \( x \) to denote the object resulting from the evaluation of \( E \). The object is not copied.

A call involves passing argument objects from the caller to the called routine and returning result objects from the routine to the caller. For local calls, argument passing is defined in terms of assignment, or call by sharing; for remote calls, call by value is used. In a local call, the formal arguments of a routine are considered to be local variables of the routine and are initialized, by assignment, to the objects resulting from the evaluation of the argument expressions. In a remote call (see Section 2.3), a copy of the objects resulting from the evaluation of the argument expressions is made and transmitted to the called handler or creator (see Section 2.4). These copies are then used to initialize the formal arguments as before. Local objects are shared between the caller and a called procedure or iterator, but local objects are never shared between the caller and a called handler or creator.

1.3. Type Correctness

The declaration of a variable specifies the type of the objects which the variable may denote. In a legal assignment statement, \( x := E \), the type of the expression \( E \) must be included in the type of the variable \( x \). Type inclusion is essentially equality of types (see Section 12.6), except for routine types. (A routine type with fewer exceptions is included in an otherwise identical routine type with more exceptions. See Section 6.1 for details.)

Argus is a type-safe language, in that it is not possible to treat an object of type \( T \) as if it were an object of some other type \( S \) (the one exception is when \( T \) is a routine type and \( S \) includes \( T \)). The type safety of Argus, plus the restriction that only the code in a cluster may convert between the abstract type and the concrete representation (see Section 12.3), ensure that the behavior of an object can be characterized completely by the operations of its type.

1.4. Rules and Guidelines

Throughout this manual, and especially in the discussions of atomicity, there are pragmatic rules and guidelines for the use of the language. Certain properties that the language would like to guarantee, for example that atomic actions are really atomic, are difficult or impossible for the language to guarantee completely. As in any useful programming language, programmers have enough rope to hang themselves. The rules and guidelines noted throughout the manual (and collected in Appendix III) try to make the responsibilities of the language and the programmer clear.
1.5 Program Structure

1.5. Program Structure

An Argus distributed application consists of one or more guardians, defined by guardian modules. Guardian modules may in turn use all the other kinds of modules that Argus provides. Argus programmers may also write single-machine programs with no stable state, using Argus as essentially a "concurrent CLU." Such programs may be used to start up multi-guardian applications. Each module is a separate textual unit, and is compiled independently of other modules. Compilation is discussed in Section 3.
2. Concepts for Distributed Programs

In this chapter we present an overview of the new concepts in Argus that support distributed programs. In Section 2.1, we discuss guardians, the module used in Argus to distribute data. Next, in Section 2.2, we present atomic actions, which are used to cope with concurrency and failure. In Section 2.3 we describe remote calls, the inter-guardian communication mechanism. In Section 2.4 we discuss transmissible types: types whose objects can be sent as arguments or results of remote calls. Finally, in Section 2.4 we discuss orphans.

2.1. Guardians

Distributed applications are implemented in Argus by one or more modules called guardians. A guardian abstraction is a kind of data abstraction, but it differs from the data abstractions supported by clusters (as found in CLU). In general, data abstractions consist of a set of operations and a set of objects. In a cluster the operations are considered to belong to the abstraction as a whole. However, guardian instances are objects and their handlers are their operations. Guardian abstraction is similar to the data abstractions in Simula and Smalltalk-80; guardians are like class instances.

A node is a single physical location, which may have multiple processors. A guardian instance resides at a single node, although a node may support several guardians. A guardian encapsulates and controls access to one or more resources, such as data or devices. Access to the protected resource is provided by a set of operations called handlers. Internally, a guardian consists of a collection of data objects and processes that can be used to manipulate those objects. In general, there will be many processes executing concurrently in a guardian: a new process is created to execute each handler call, processes may be explicitly created, and there may be other processes that carry out background activity of the guardian.

The data objects encapsulated by a guardian are local: they cannot be accessed directly by a process in another guardian. In contrast, guardians are global objects: a single guardian may be shared among processes at several different guardians. A process with a reference to a guardian can call the guardian’s handlers, and these handlers can access the data objects inside the guardian. Handler calls allow access to a guardian’s local data, but the guardian controls how that data can be manipulated.

When a node fails, it crashes. A crash is a “clean” failure, as opposed to a “Byzantine” failure. A guardian survives crashes of its node (with as high a probability as needed). A guardian’s state consists of stable and volatile objects. When a guardian’s node crashes, all processes running inside the guardian at the time of the crash are lost, along with the guardian’s volatile objects, but the guardian’s stable objects survive the crash. Upon recovery of the guardian’s node, the guardian runs a special recovery process to reconstruct its volatile objects from its stable objects. Since the volatile objects are lost in a crash, they typically consist only of redundant data that is used to improve performance (for example, an index into a database). The persistent state of an application should be kept in stable objects.

Guardians are implemented by guardian definitions. These define:
1. The creators. These are operations that can be called to create new guardian instances that perform in accordance with the guardian definition.

2. The guardian's stable and volatile state.

3. The guardian's handlers.

4. The background code. This is code that the guardian executes independent of any handler calls, for example, to perform some periodic activity.

5. The recover code. This is code that is executed after a crash to restore the volatile objects.

Guardians and guardian definitions are discussed in Section 13.

2.2. Actions

The distributed data in an Argus application can be shared by concurrent processes. A process may attempt to examine and transform some objects from their current states to new states, with any number of intermediate state changes. Interactions among concurrent processes can leave data in an inconsistent state. Failures (for example, node crashes) can occur during the execution of a process, raising the additional possibility that data will be left in an inconsistent intermediate state. To support applications that need consistent data, Argus permits the programmer to make processes atomic.

We call an atomic process an action. Actions are atomic in that they are both serializable and recoverable. By serializable, we mean that the overall effect of executing multiple concurrent actions is as if they had been executed in some sequential order, even though they actually execute concurrently. By recoverable, we mean that the overall effect of an action is "all-or-nothing:" either all changes made to the data by the action happen, or none of these changes happen. An action that completes all its changes successfully commits; otherwise it aborts, and objects that it modified are restored to their previous states.

Before an action can commit, new states of all modified, stable objects must be written to stable storage\textsuperscript{1}: storage that survives media crashes with high probability. Argus uses a two-phase commit protocol\textsuperscript{2} to ensure that either all of the changes made by an action occur or none of them do. If a crash occurs after an action modifies a stable object, but before the new state has been written to stable storage, the action will be aborted.

2.2.1. Nested Actions

Actions in Argus can be nested: an action may be composed of several subactions. Subactions can be used to limit the scope of failures and to introduce concurrency within an action.

An action may contain any number of subactions, some of which may be performed sequentially, some


2.2.1 Nested Actions

concurrently. This structure cannot be observed from outside the action; the overall action is still atomic. Subactions appear as atomic actions with respect to other subactions of the same parent. Thus, subactions can be executed concurrently.

Subactions can commit and abort independently, and a subaction can abort without forcing its parent action to abort. However, the commit of a subaction is conditional: even if a subaction commits, aborting its parent action will abort it.

The root of a tree of nested actions is called a topaction. Topactions have no parent; they cannot be aborted once they have committed. Since the effects of a subaction can always be undone by aborting its parent, the two-phase commit protocol is used only when topactions attempt to commit.

In Argus, an action (e.g., a handler call) may return objects through either a normal return or an exception and then abort. The following rule should be followed to avoid violating serializability: a subaction that aborts should not return any information obtained from data shared with other concurrent actions.

2.2.2. Atomic Objects and Atomic Types

Atomicity of actions is achieved via the data objects shared among those actions. Shared objects must be implemented so that actions using them appear to be atomic. Objects that support atomicity are referred to as atomic objects. Atomic objects provide the synchronization and recovery needed to ensure that actions are atomic. An atomic type is a type whose objects are all atomic. Some objects do not need to be atomic: for example, objects that are local to a single process. Since the synchronization and recovery needed to ensure atomicity may be expensive, we do not require that all types be atomic. (For example, Argus provides all the built-in mutable types of CLU; these types are not atomic.) However, it is important to remember that atomic actions must share only atomic objects.

Argus provides a number of built-in atomic types and type generators. The built-in scalar types (null, node, bool, char, Int, real, and string) are atomic. Parameterized types can also be atomic. Typically, an instance of a type generator will be atomic only if any actual type parameters are also atomic. The built-in immutable type generators (sequence, struct, and oneof) are atomic if their parameter types are atomic. In addition, Argus provides three mutable atomic type generators: atomic_array, atomic_record, and atomic_variant. The operations on these types are nearly identical to the normal array, record, and variant types of CLU. Users may also define their own atomic types (see Section 15).

The implementation of the built-in mutable atomic type generators is based on a simple locking model. There are two kinds of locks: read locks and write locks. When an action calls an operation on an atomic object, the implementation acquires a lock on that object in the appropriate mode: it acquires a write lock if it mutates the object, or a read lock if it only examines the object. The built-in types allow multiple concurrent readers, but only a single writer. If necessary, an action is forced to wait until it can obtain the appropriate lock. When a write lock on an object is first obtained by an action, the system makes a copy
of the object's state in a new version, and the operations called by the action work on this version. If, ultimately, the action commits, this version will be retained, and the old version discarded. A subaction's locks are given to its parent action when it commits. When a topaction commits, its locks are discarded and its effects become visible to other actions. If the action aborts, the action's locks and the new version will be discarded, and the old version retained (see Figure 2-1).

Figure 2-1: Locking and Version Management Rules for a Subaction S, on Object X

---

**Acquiring a read lock:**
All holders of write locks on X must be ancestors of S.

**Acquiring a write lock:**
All holders of read and write locks on X must be ancestors of S.
If this is the first time S has acquired a write lock on X, push a copy of X on the top of its version stack.

**Commit:**
S's parent acquires S's lock on X.
If S holds a write lock on X, then S's version becomes S's parent's version.

**Abort:**
S's lock and version (if any) are discarded.

---

More precisely, an action can obtain a read lock on an object if every action holding a write lock on that object is an ancestor of the requesting action. An action can obtain a write lock on an object if every action holding a (read or write) lock on that object is an ancestor. When a subaction commits, its locks are inherited by its parent and its new versions replace those of its parent; when a subaction aborts, its locks and versions are discarded (see Figure 2-1). Because Argus guarantees that parent actions never run concurrently with their children, these rules ensure that concurrent actions never hold write locks on the same object simultaneously.

The ancestors of a subaction are itself, its parent, its parent's parent, and so on; a subaction is a descendant of its ancestors. A subaction commits to the top if it and all its ancestors, including the topaction, commit. A subaction is a committed descendant of an ancestor action if the subaction and all intervening ancestors have committed. When a topaction attempts to commit, the two-phase commit protocol is used to ensure that the new versions of all objects modified by the action and all its committed descendants are copied to stable storage. After the new versions have been recorded stably, the old versions are thrown away.

User-defined atomic types can provide greater concurrency than built-in atomic types. An

---

3 This operational description (and others in this manual) is not meant to constrain implementors. However, this particular description does reflect our current implementation.

4 An example can be found in Weihl, W. and Liskov, B., "Implementation of Resilient, Atomic Data Types," ACM Transactions on Programming Languages and Systems, volume 7, number 2 (April 1985), pages 244-269.
2.2.2 Atomic Objects and Atomic Types

Implementation of a user-defined atomic type must address several issues. First, it must provide proper synchronization so that concurrent calls of its operations do not interfere with each other, and so that the actions that call its operations are serialized. Second, it must provide recovery for actions using its objects so that aborted actions have no effect. Finally, it must ensure that changes made to its objects by actions that commit to the top are recorded properly on stable storage. The built-in atomic types and the mutex type generator are useful in coping with these issues. User-defined atomic types are discussed further in Section 15.

2.2.3 Nested Topactions

In addition to nesting subactions inside other actions, it is sometimes useful to start a new topaction inside another action. Such a nested topaction, unlike a subaction, has no special privileges relative to its "parent"; for example, it is not able to read an atomic object modified by its "parent". Furthermore, the commit of a nested topaction is not relative to its "parent"; its versions are written to stable storage, and its locks are released, just as for normal topactions.

Nested topactions are useful for benevolent side effects that change the representation of an object without affecting its abstract state. For example, in a naming system a name look-up may cause information to be copied from one location to another, to speed up subsequent look-ups of that name. Copying the data within a nested topaction that commits ensures that the changes remain in effect even if the "parent" action aborts.

A nested topaction is used correctly if it is serializable before its "parent". This is true if either the nested topaction performs a benevolent side effect, or if all communication between the nested topaction and its parent is through atomic objects.

2.3 Remote Calls

An action running in one guardian can cause work to be performed at another guardian by calling a handler provided by the latter guardian. An action can cause a new guardian to be created by calling a creator. Handler and creator calls are remote calls. Remote calls are similar to local procedure calls; for example, the calling process waits for the call to return. Remote calls differ from local procedure calls in several ways, however.

First, the arguments and results of a remote call are passed by value (see below and also Section 14) rather than by sharing. This ensures that the local objects of one guardian remain local to that guardian, even if their values are used as arguments or results of remote calls to other guardians. The only objects that are passed by sharing in remote calls are the global objects: guardians, handlers, creators, and nodes.

Second, any remote call can raise the exceptions failure and unavailable. (Unlike CLU, not all local calls can raise failure, see Appendix IV.) The occurrence of failure means that the call is unlikely to ever succeed, so there is no point in retrying the call in the future. Unavailable, on the other hand, means that
the call should succeed if retried in the future, but is unlikely to succeed if retried immediately. For example, failure can arise because it is impossible to transmit the arguments or results of the call (see Section 14); unavailable can arise if the guardian being called has crashed, or if the network is partitioned.

Third, a handler or creator can be called only from inside an action, and the call runs as a subaction of the calling action. This ensures that a remote call succeeds at most once: either a remote call completes successfully and commits, or it aborts and all of its modifications are undone (provided, of course, that the actions involved are truly atomic). Although the effect of a remote call occurs at most once, the system may need to attempt it several times; this is why remote calls are made within actions.

2.4. Transmissible Types

Arguments and results of remote calls are passed by value. This means that the argument and result objects must be copied to produce distinct objects. Not all objects can be copied like this; those that can are called transmissible objects, and their types are called transmissible types. Only transmissible objects may be used as arguments and results of a remote call. In addition, Image objects (see Section 6.6) can contain only transmissible objects. Parameterized types may be transmissible in some instances and not in others; for example, instantiations of the built-in type generators are transmissible only if their parameter types are transmissible. While guardians, creators, and handlers are always transmissible, procedures and iterators are never transmissible.

Users can define new transmissible types. For each transmissible type \( T \) the external representation type of \( T \) must be defined; this describes the format in which objects of type \( T \) are transmitted. Each cluster that implements a transmissible type \( T \) must contain two procedures, encode and decode, to translate objects of type \( T \) to and from their external representation. More information about defining transmissible types can be found in Section 14.

2.5. Orphans

An orphan is an action that has had some ancestor "perish" or has had the pertinent results of some relative action lost in a crash. Orphans can arise in Argus due to crashes and explicit aborts. For example, when a parent action is aborted, the active descendents it leaves behind become orphans. Crashes also cause orphans: when a guardian crashes, all active actions with an ancestor at the crashed guardian and all active actions with committed descendants that ran at the crashed guardian become orphans. However, having a descendent that is an orphan does not necessarily imply that the parent is an orphan; as previously described, actions may commit or abort independently of their subactions.

Argus programmers can largely ignore orphans. Argus guarantees that orphans are aborted before

---

2.5 Orphans

they can view inconsistent data (provided actions are written so that they only communicate through atomic data). Remote calls that fail for any reason may be retried by the system, including some cases where the call action becomes an orphan due to crashes (see Section 8.3).

Orphans always abort. They may abort voluntarily or they may be forced to abort by the run-time system; however, an orphan that is in a critical section (executing a `seize` statement, see Section 10.16) may not be forcibly aborted by the run-time system, except by crashing the guardian. On the other hand, the system may encourage orphans (especially topactions that are orphans) to abort themselves by having their remote calls signal `unavailable`.

2.6. Deadlocks

Actions in Argus programs may become deadlocked. For example, if action A is waiting for a lock that B holds and B is waiting for a lock that A holds, then A and B are deadlocked. Although implementations may provide some form of deadlock detection or avoidance, they are not required to do so. This is because detecting deadlocks is difficult in a language with user-defined atomic types, since it is not always clear when actions are "waiting" for each other.

If an implementation of Argus chooses to do deadlock detection (presumably for the built-in atomic types), it may only break deadlocks by aborting actions or by crashing guardians.
3. Environment

The Argus environment ensures complete static type checking of programs. It also supports separate compilation and the independence of guardians.

3.1. The Library

Argus modules are compiled in the context of a library that gives meaning to external identifiers and allows inter-module type checking. The Argus library contains type information about abstractions; for each abstraction, the library contains a *description unit* (DU), describing that abstraction and its implementations. Each DU has a unique name and these names form the basis of type checking.

3.2. Independence of Guardian Images

The code run by a guardian comes from some guardian image. A guardian image contains all the code needed to carry out any local activity of the guardian; any procedure, iterator or cluster used by that guardian will be in its guardian image. Any handler calls made by the guardian, however, are carried out at the called guardian, which contains the code that performs the call. Thus a guardian is independent of the implementations of the guardians it calls and the implementation of a guardian can be changed without affecting the implementations of its clients.

3.3. Guardian Creation

When a guardian is created, it is necessary to select the guardian image that will supply the code run by the new guardian. To this end, each guardian has an associated *creation environment* that specifies the guardian images for other guardians it may create. The creation environment is a mapping from guardian types to information that can be used to select a guardian image appropriate for each kind of node. For greater flexibility, this information can be associated with particular creator objects.

3.4. The Catalog

Somehow, guardians must be able to find other guardians to call for services. A guardian usually has a reference to any guardian it creates. Also, if a guardian can call some other server guardian, it can learn about the guardians that the server "knows", because guardians can be passed in remote calls. In addition, Argus provides a built-in subsystem known by all guardians. This subsystem is called the *catalog*. The catalog provides an atomic mapping from names to transmissible objects. For example, when a new guardian is created, it can be catalogued under some well-known name, so that other guardians can find it in the future. Since we are currently experimenting with various interfaces to the catalog, we do not include an interface specification here.
4. Notation

We use an extended BNF grammar to define the syntax of Argus. The general form of a production is:

```
nonterminal ::= alternative
  | alternative
  | ...
  | alternative
```

The following extensions are used:

- **a, ...** a list of one or more a's separated by commas: "a" or "a, a" or "a, a, a" etc.
- **{a}** a sequence of zero or more a's: " " or "a" or "a a" etc.
- **[a]** an optional a: " " or "a".

Nonterminal symbols appear in normal face. Reserved words appear in bold face. All other terminal symbols are non-alphabetic, and appear in normal face.

Full productions are not always shown in the body of this manual; often alternatives are presented and explained individually. Appendix I contains the complete syntax.
5 Lexical Considerations

A module is written as a sequence of tokens and separators. A token is a sequence of "printing" ASCII characters (values 40 octal through 176 octal) representing a reserved word, an identifier, a literal, an operator, or a punctuation symbol. A separator is a "blank" character (space, vertical tab, horizontal tab, carriage return, newline, form feed) or a comment. Any number of separators may appear between tokens.

5.1. Reserved Words

The following character sequences are reserved word tokens:

Table 5-1: Reserved Words

<table>
<thead>
<tr>
<th>reserved word tokens</th>
</tr>
</thead>
<tbody>
<tr>
<td>abort</td>
</tr>
<tr>
<td>action</td>
</tr>
<tr>
<td>any</td>
</tr>
<tr>
<td>array</td>
</tr>
<tr>
<td>atomic_array</td>
</tr>
<tr>
<td>atomic_record</td>
</tr>
<tr>
<td>atomic_variant</td>
</tr>
<tr>
<td>background</td>
</tr>
<tr>
<td>begin</td>
</tr>
<tr>
<td>bind</td>
</tr>
<tr>
<td>bool</td>
</tr>
<tr>
<td>break</td>
</tr>
<tr>
<td>cand</td>
</tr>
<tr>
<td>char</td>
</tr>
<tr>
<td>cluster</td>
</tr>
<tr>
<td>coenter</td>
</tr>
<tr>
<td>continue</td>
</tr>
<tr>
<td>cor</td>
</tr>
<tr>
<td>creator</td>
</tr>
<tr>
<td>creatortype</td>
</tr>
<tr>
<td>cvt</td>
</tr>
<tr>
<td>do</td>
</tr>
<tr>
<td>down</td>
</tr>
<tr>
<td>else</td>
</tr>
<tr>
<td>elseif</td>
</tr>
<tr>
<td>end</td>
</tr>
<tr>
<td>enter</td>
</tr>
<tr>
<td>equates</td>
</tr>
<tr>
<td>except</td>
</tr>
<tr>
<td>exit</td>
</tr>
<tr>
<td>false</td>
</tr>
<tr>
<td>for</td>
</tr>
<tr>
<td>foreach</td>
</tr>
<tr>
<td>guardian</td>
</tr>
<tr>
<td>handler</td>
</tr>
<tr>
<td>handles</td>
</tr>
<tr>
<td>has</td>
</tr>
<tr>
<td>if</td>
</tr>
<tr>
<td>image</td>
</tr>
<tr>
<td>in</td>
</tr>
<tr>
<td>int</td>
</tr>
<tr>
<td>is</td>
</tr>
<tr>
<td>iter</td>
</tr>
<tr>
<td>leave</td>
</tr>
<tr>
<td>mutex</td>
</tr>
<tr>
<td>node</td>
</tr>
<tr>
<td>null</td>
</tr>
<tr>
<td>oneof</td>
</tr>
<tr>
<td>others</td>
</tr>
<tr>
<td>own</td>
</tr>
<tr>
<td>pause</td>
</tr>
<tr>
<td>proc</td>
</tr>
<tr>
<td>process</td>
</tr>
<tr>
<td>proctype</td>
</tr>
<tr>
<td>record</td>
</tr>
<tr>
<td>recover</td>
</tr>
<tr>
<td>rep</td>
</tr>
<tr>
<td>resignation</td>
</tr>
<tr>
<td>return</td>
</tr>
<tr>
<td>returns</td>
</tr>
<tr>
<td>signal</td>
</tr>
<tr>
<td>sequence</td>
</tr>
<tr>
<td>self</td>
</tr>
<tr>
<td>sequence</td>
</tr>
<tr>
<td>yield</td>
</tr>
<tr>
<td>yields</td>
</tr>
</tbody>
</table>

Reserved words appear in bold face in this document.

5.2. Identifiers

An identifier is a sequence of letters, digits, and underscores (_) that begins with a letter or underscore, and that is not a reserved word. Upper and lower case letters are not distinguished in identifiers.

In the syntax there are two different nonterminals for identifiers. The nonterminal idn is used when the identifier has scope (see Section 7.1); idns are used for variables, parameters, module names, and as abbreviations for constants. The nonterminal name is used when the identifier is not subject to scope rules; names are used for record and structure selectors, oneof and variant tags, operation names, and exceptional condition names.
5.3. Literals

There are literals for naming objects of the built-in types null, bool, int, real, char, and string. Their forms are described in Appendix I.

5.4. Operators and Punctuation Tokens

The following character sequences are used as operators and punctuation tokens.

Table 5-2: Operator and Punctuation Tokens

<p>| | | | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
</table>
| ( | ) | $ | ** | || | <= | ~=< | ~=
| { | } | := | // | + | >= | =>= | &
|   |   | @ | / | - | > | -> | |

5.5. Comments and Other Separators

A comment is a sequence of characters that begins with a percent sign (%), ends with a newline character, and contains only printing ASCII characters (including blanks) and horizontal tabs in between. For example:

\[
\text{z} := \text{a[i]} + \% \text{ a comment in an expression} \\
\text{b[i]}
\]

A separator is a blank character (space, vertical tab, horizontal tab, carriage return, newline, form feed) or a comment. Zero or more separators may appear between any two tokens, except that at least one separator is required between any two adjacent non-self-terminating tokens: reserved words, identifiers, integer literals, and real literals. This rule is necessary to avoid lexical ambiguities.
6. Types, Type Generators, and Type Specifications

A type consists of a set of objects together with a set of operations used to manipulate the objects. Types can be classified according to whether their objects are mutable or immutable, and atomic or non-atomic. An immutable object (e.g., an integer) has a value that never varies, while the value (state) of a mutable object can vary over time. Objects of atomic types provide serializability and recovery for accessing actions. Non-atomic types may provide synchronization by specifying that particular operations are executed indivisibly on objects of the type. An operation is indivisible if no other process may affect or observe intermediate states of the operation's execution. Indivisibility properties will be described for all the built-in non-atomic types of Argus.

A type generator is a parameterized type definition, representing a (usually infinite) set of related types. A particular type is obtained from a type generator by writing the generator name along with specific values for the parameters; for every distinct set of legal values, a distinct type is obtained (see Section 12.6). For example, the array type generator has a single parameter that determines the element type; array[int], array[real], and array[array[int]] are three distinct types defined by the array type generator. Types obtained from type generators are called parameterized types or instantiations of the type generator; others are called simple types.

In Argus code, a type is specified by a syntactic construct called a type_spec. The type specification for a simple type is just the identifier (or reserved word) naming the type. For parameterized types, the type specification consists of the identifier (or reserved word) naming the type generator, together with the actual parameter values.

To be used as arguments or results of handler and creator calls, or as image objects (see Section 6.6), objects must be transmissible. Most of the built-in Argus types are transmissible, that is, they have transmissible objects. However, procedures and iterators are never transmissible. For type generators, transmissibility of a particular instantiation of the generator may depend upon transmissibility of any type parameters. A transmissible type provides the pseudo-operation transmit and two internal operations encode and decode. Generally, encode and decode are hidden from clients of the type. They are called implicitly during message transmission (see Section 14) and in creating and decomposing image objects (see Section 6.6). Transmissibility is discussed further in Section 14.

Argus provides all the built-in types of CLU as well as some new types and type generators. This section gives an informal introduction to the built-in types and type generators provided by Argus. Many details are not discussed here, but a complete definition of each type and type generator is given in Appendix II.
6.1. Type Inclusion

The notion of type inclusion in Argus is different from that in CLU. The type any is a type like every other type, and there is no implicit coercion to type any, so there is no need to make a special case for it in the type inclusion rule. Type inclusion in Argus is the same as type equality (see Section 12.6), except for procedure, iterator, handler, and creator types. A routine type $O$ is included in another routine type $V$, when the number and types of arguments, and the number and types of normal results, are equal, and for each exception in $O$ there is a corresponding exception in $V$ of the same name with the same number and types of results. Note that $V$ may have more exceptions than does $O$, and that this rule is not recursive, that is, when comparing types of arguments and results, type equality is used. For example, if we have the following declarations in effect:

```
p : proctype(real, real) returns(real) signals(overflow, underflow)
q : proctype(real, real) returns(real)
```

then the type of $q$ is included in the type of $p$ but not vice versa. Thus the assignment $p := q$ is legal.

6.2. The Sequential Built-in Types and Type-generators

In this section, we introduce the sequential built-in types of Argus. These types are generally the same as types in CLU. This section concentrates on their new characteristics.

Recovery from aborted actions is trivial for immutable objects, since the aborted actions cannot have modified these objects. In particular the built-in scalar types null, bool, Int, real, char, and string are immutable, atomic, and transmissible. The built-in mutable type generators inherited from CLU are not atomic.

6.2.1. Null

The type null has exactly one immutable object, represented by the literal nil, which is atomic and transmissible. See Section II.1 for details.

6.2.2. Bool

The two immutable objects of type bool, with literals true and false, represent logical truth values. The binary operations equal (=), and (&), and or (|), are provided, as well as unary not (¬). Objects of type bool are atomic and transmissible. See Section II.3 for details.

6.2.3. Int

The type Int models (a range of) the mathematical integers. The exact range is not part of the language definition.Integers are immutable, atomic, transmissible, and their literals are written as a sequence of one or more decimal digits. (There are also octal and hexadecimal literals, see Appendix I.)

---

However, implementations are encouraged to provide this and other information about the limits of the built-in types in an equate module.
The binary operations \(\text{add}(+)\), \(\text{sub}(-)\), \(\text{mul}(\cdot)\), \(\text{div}(/)\), \(\text{mod}(\mod)\), \(\text{power}(\power)\), \(\text{max}\), and \(\text{min}\) are provided, as well as unary \(\text{minus}(-)\) and \(\text{abs}\). There are binary comparison operations \(\text{lt}(<)\), \(\text{le}(\leq)\), \(\text{equal}(=)\), \(\text{ge}(\geq)\), and \(\text{gt}(>)\). There are two operations, \(\text{from}_\text{to}\) and \(\text{from}_\text{to}_\text{by}\), for iterating over a range of integers. See Section II.4 for details.

6.2.4. Real

The type \text{real} models (a subset of) the mathematical real numbers. The exact subset is not part of the language definition. Reals are immutable, atomic, and transmissible, although transmission of real objects between heterogeneous machine architectures may not be exact. Real literals are written as a 
\(\text{mantissa}\) with an optional \(\text{exponent}\). A 
\(\text{mantissa}\) is either a sequence of one or more decimal digits, or two sequences (one of which may be empty) joined by a period. The mantissa must contain at least one digit. An exponent is ‘E’ or ‘e’, optionally followed by ‘+’ or ‘-’, followed by one or more decimal digits. An exponent is required if the mantissa does not contain a period. As is usual, \(mE0 = m\times10^0\). Examples of real literals are:

\[
\begin{align*}
3.14 & \quad 3.14E0 & \quad 314e-2 & \quad 0.0314E+2 & \quad 3. & \quad .14 \\
\end{align*}
\]

As with integers, the operations \(\text{add}(+)\), \(\text{sub}(-)\), \(\text{mul}(\cdot)\), \(\text{div}(/)\), \(\text{mod}(\mod)\), \(\text{power}(\power)\), \(\text{max}\), \(\text{min}\), \(\text{minus}(-)\), \(\text{abs}\), \(\text{lt}(<)\), \(\text{le}(\leq)\), \(\text{equal}(=)\), \(\text{ge}(\geq)\), and \(\text{gt}(>)\), are provided. It is important to note that there is no form of \text{implicit} conversion between types. The \(i2r\) operation converts an integer to a real, \(r2i\) rounds a real to an integer, and \(\text{trunc}\) truncates a real to an integer. See Section II.5 for details.

6.2.5. Char

The type \text{char} provides the alphabet for text manipulation. Characters are immutable, atomic, transmissible, and form an ordered set. Every implementation must provide at least 128, but no more than 512, characters; the first 128 characters are the ASCII characters in their standard order.

Literals for the printing ASCII characters (octal 40 through octal 176), other than single quote (‘) or backslash (\), can be written as that character enclosed in single quotes. Any character can be written by enclosing one of the escape sequences listed in Table 6-1 in single quotes. The escape sequences may be written using upper case letters, but note that escape sequences of the form \(\text{\&}^*\) are case sensitive. A table of literals is given at the end of Appendix I. Examples of character literals are:

\[
\begin{align*}
\text{\&}' & \quad \text{\&}' & \quad \text{\&}'' & \quad \text{\&}'' & \quad \text{\&}'' & \quad \text{\&}'' & \quad \text{\&}''.
\end{align*}
\]

There are two operations, \(i2c\) and \(c2i\), for converting between integers and characters: the smallest character corresponds to zero, and the characters are numbered sequentially. Binary comparison operations exist for characters based on this numerical ordering: \(\text{lt}(<)\), \(\text{le}(\leq)\), \(\text{equal}(=)\), \(\text{ge}(\geq)\), and \(\text{gt}(>)\). For details, see Section II.6.
Table 6-1: Character Escape Sequence Forms

<table>
<thead>
<tr>
<th>escape sequence</th>
<th>character</th>
</tr>
</thead>
<tbody>
<tr>
<td>'</td>
<td>' (single quote)</td>
</tr>
<tr>
<td>&quot;</td>
<td>&quot; (double quote)</td>
</tr>
<tr>
<td>\</td>
<td>\ (backslash)</td>
</tr>
<tr>
<td>\n</td>
<td>NL (newline)</td>
</tr>
<tr>
<td>\t</td>
<td>HT (horizontal tab)</td>
</tr>
<tr>
<td>\p</td>
<td>FF (form feed, newpage)</td>
</tr>
<tr>
<td>\b</td>
<td>BS (backspace)</td>
</tr>
<tr>
<td>\r</td>
<td>CR (carriage return)</td>
</tr>
<tr>
<td>\v</td>
<td>VT (vertical tab)</td>
</tr>
<tr>
<td>***</td>
<td>specified by octal value (exactly three octal digits)</td>
</tr>
<tr>
<td>#**</td>
<td>specified by hexadecimal value (exactly two hex digits)</td>
</tr>
<tr>
<td>*</td>
<td>characters numbered 0-31 (with * a printing character)</td>
</tr>
<tr>
<td>&amp;*</td>
<td>characters numbered 128-159 (with * a printing character)</td>
</tr>
</tbody>
</table>

6.2.6. String

The type string is used for representing text. A string is an immutable, atomic, and transmissible sequence of zero or more characters. Strings are lexicographically ordered, based on the ordering for characters. A string literal is written as a sequence of zero or more characters or character escape sequences (see Table 6-1), enclosed in double quotes (").

The characters of a string are indexed sequentially starting from one. The fetch operation is used to obtain a character by index. The substr operation is used to obtain a substring. The tail of a string can be gotten by using rest. Searching in strings is provided by the indexc and indexs operations.

Two strings can be concatenated together with concat (||), and a single character can be appended to the end of a string with append. C2s converts a character to a single-character string. The size of a string can be determined with size. Chars iterates over the characters of a string, from the first to the last character. There are also the usual lexicographic comparison operations: lt (<), le (<=), equal (=), ge (>=), and gt (>). For details, see Section II.7.

6.2.7. Any

Objects of type any may contain objects of any type, and thus provide an escape from compile-time type checking. Unlike CLU, which treats any differently from all other types, any is a normal type in Argus. To this end there is an explicit create operation generator, and the force procedure is also an operation generator of type any.

An object of type any can be thought of as containing an object and its type. Since there are no operations provided by type any that change this state, any objects can be considered to be immutable. However, the state of the contained object may change if that object is shared, so from this point of view,
6.2.7 Any

The mutability and atomicity of an any object depend on the mutability and atomicity of the contained object. Objects of type any are not transmissible.

The create operation is parameterized by a type; create takes a single argument of that type and returns an any object containing the argument. The force operation is also parameterized by a type; it takes an any and extracts an object of that type, signalling wrong_type if the contained object's type is not included in the parameter type. The is_type operation is parameterized by a type and checks whether its argument contains an object whose type is included in the parameter type. The detailed specification is found in Section II.19.

6.2.8. Sequence Types

Sequences are immutable and they are atomic or transmissible when instantiated with atomic or transmissible type parameters. Although an individual sequence can have any length, the length and members of a sequence are fixed when the sequence is created. The elements of a sequence are indexed sequentially, starting from one. A sequence type specification has the form:

```
sequence [ type_actual ]
```

where a type_actual is a type_spec, possibly augmented with operation bindings (see Section 12.6).

The new operation returns an empty sequence. A sequence constructor has the form:

```
type_spec $ [ [ expression , ... ] ]
```

and can be used to create a sequence with the given elements.

Although a sequence, once created, cannot be changed, new sequences can be constructed from existing ones by means of the addh, addl, remh, and reml operations. Other operations include fetch, replace, top, bottom, size, the elements and indexes iterators, and subseq. Invocations of the fetch operation can be written using a special form:

```
q[i] % fetch the element at index i of q
```

Two sequences with equal elements are equal. The equal (=) operation tests if two sequences have equal elements, using the equal operation of the element type. Similar tests if two sequences have similar elements, using the similar operation of the element type.

All operations are indivisible except for fill_copy, equal, similar, copy, encode, and decode, which are divisible at calls to the operations of the type parameter.

For the detailed specification, see Section II.8.

6.2.9. Array Types

Arrays are one-dimensional, and mutable but not atomic. They are transmissible only if their type parameter is transmissible. The number of elements in an array can vary dynamically. There is no notion of an "uninitialized" element.
The state of an array consists of an integer called the low bound, and a sequence of objects called the elements. The elements of an array are indexed sequentially, starting from the low bound. All of the elements must be of the same type; this type is specified in the array type specification, which has the form:

```
array [ type_actual ]
```

There are a number of ways to create a new array, of which only two are mentioned here. The create operation takes an argument specifying the low bound, and creates a new array with that low bound and no elements. Alternately, an array constructor can be used to create an array with an arbitrary number of initial elements. For example,

```
array[int] $ [5: 1, 2, 3, 4]
```
creates an integer array with low bound 5, and four elements, while

```
array[bool] $ [true, false]
```
creates a boolean array with low bound 1 (the default), and two elements.

An array type specification states nothing about the bounds of an array. This is because arrays can grow and shrink dynamically, using the addh, addl, remh, and reml operations. Other operations include fetch, store, top, bottom, high, low, the elements and indexes iterators, and size. Invocations of fetch and store can be written using special forms:

```
a[i] % fetch the element at index i of a
a[i] := 3 % store 3 at index i of a (by calling store)
```

Every newly created array has an identity that is distinct from all other arrays; two arrays can have the same elements without being the same array object. The identity of arrays can be distinguished with the equal (=) operation. The similar operation tests if two arrays have the same state, using the equal operation of the element type. Similar tests if two arrays have similar states, using the similar operation of the element type.

All operations are indivisible, except fill_copy, similar, similar1, copy, encode, and decode, which are divisible at calls to operations of the type parameter.

For the detailed specification, see Section II.9.

### 6.2.10. Structure Types

A structure is an immutable collection of one or more named objects. An instantiation is atomic or transmissible only if the type parameters are all atomic or all transmissible. The names are called selectors, and the objects are called components. Different components may have different types. A structure type specification has the form:

```
struct [ field_spec , ... ]
```

where

```
field_spec ::= name , ... : type_actual
```

Selectors must be unique within a specification, but the ordering and grouping of selectors is unimportant.
A structure is created using a structure constructor. For example, assuming that "info" has been equated to a structure type:

```plaintext
info = struct[last, first, middle: string, age: Int]
```

the following is a legal structure constructor:

```plaintext
info $(last: "Scheffler", first: "Robert", age: 32, middle: "W.")
```

An expression must be given for each selector, but the order and grouping of selectors need not resemble the corresponding type specification.

For each selector "sel", there is an operation `get sel` to extract the named component, and an operation `replace sel` to create a new structure with the named component replaced with some other object. Invocations of the `get` operations can be written using a special form:

```plaintext
st.age % get the 'age' component of st
```

As with sequences, two structures with equal components are in fact the same object. The `equal (=)` operation tests if two structures have equal components, using the `equal` operations of the component types. `Similar` tests if two structures have similar components, using the `similar` operations of the component types.

All operations are indivisible except for `equal`, `similar`, `copy`, `encode`, and `decode`, which are divisible at calls to the operations of the type parameter.

For the detailed specification, see Section 11.11.

6.2.11. Record Types

A record is a mutable collection of one or more named objects. Records are never atomic, and are transmissible only if the parameter types are all transmissible. A record type specification has the form:

```plaintext
record [ field_spec , ... ]
```

where (as for structures)

```plaintext
field_spec ::= name , ... : type_actual
```

Selectors must be unique within a specification, but the ordering and grouping of selectors is unimportant.

A record is created using a record constructor. For example:

```plaintext
professor $(last: "Herlihy", first: "Maurice", age: 32, middle: "P.")
```

For each selector "sel", there is an operation `get sel` to extract the named component, and an operation `set sel` to replace the named component with some other object. Invocations of these operations can be written using a special form:

```plaintext
r.middle % get the 'middle' component of r
r.age := 33 % set the 'age' component of r to 33 (by calling set_age)
```

As with arrays, every newly created record has an identity that is distinct from all other records; two records can have the same components without being the same record object. The identity of records
can be distinguished with the `equal (=)` operation. The `similar1` operation tests if two records have equal components, using the `equal` operations of the component types. `Similar` tests if two records have similar components, using the `similar` operations of the component types.

All operations are indivisible, except `similar`, `similar1`, `copy`, `encode`, and `decode`, which are divisible at calls to operations of the type parameters.

For the detailed specification, see Section II.12.

**6.2.12. Oneof Types**

A oneof type is a *tagged, discriminated union*. A oneof is an immutable labeled object, to be thought of as "one of" a set of alternatives. The label is called the *tag*, and the object is called the *value*. A oneof type specification has the form:

```plaintext
oneof [ field_spec , ... ]
```

where (as for structures)

```plaintext
field_spec ::= name , ... : type_actual
```

Tags must be unique within a specification, but the ordering and grouping of tags is unimportant. An instantiation is atomic or transmissible if and only if all the type parameters are atomic or transmissible.

For each tag "t" of a oneof type, there is a `make_t` operation which takes an object of the type associated with the tag, and returns the object (as a oneof) labeled with tag "t".

To determine the tag and value of a oneof object, one normally uses the `tagcase` statement (see Section 10.14).

The `equal (=)` operation tests if two oneofs have the same tag, and if so, tests if the two value components are equal, using the `equal` operation of the value type. `Similar` tests if two oneofs have the same tag, and if so, tests if the two value components are similar, using the `similar` operation of the value type.

All operations are indivisible, except `equal`, `similar`, `similar1`, `copy`, `encode`, and `decode`, which are divisible at calls to operations of the type parameters.

For the detailed specification, see Section II.14.

**6.2.13. Variant Types**

A variant is a mutable oneof. Variants are never atomic and are transmissible if and only if their type parameters are all transmissible. A variant type specification has the form:

```plaintext
variant [ field_spec , ... ]
```

where (as for oneofs)

```plaintext
field_spec ::= name , ... : type_actual
```
The state of a variant is a pair consisting of a label called the tag and an object called the value. For each tag "t" of a variant type, there is a make_t operation which takes an object of the type associated with the tag, and returns the object (as a variant) labeled with tag "t". In addition, there is a change_t operation, which takes an existing variant and an object of the type associated with "t", and changes the state of the variant to be the pair consisting of the tag "t" and the given object. To determine the tag and value of a variant object, one normally uses the tagcase statement (see Section 10.14).

Every newly created variant has an identity that is distinct from all other variants; two variants can have the same state without being the same variant object. The identity of variants can be distinguished using the equal (=) operation. The similar1 operation tests if two variants have the same tag, and if so, tests if the two value components are equal, using the equal operation of the value type. Similar tests if two variants have the same tag, and if so, tests if the two value components are similar, using the similar operation of the value type.

All operations are indivisible, except similar, similar1, copy, encode, and decode, which are divisible at calls to operations of the type parameters.

For the detailed specification, see Section II.15.

6.2.14. Procedure and Iterator Types

Procedures and iterators are created by the Argus system or by the bind expression (see Section 9.8). They are not transmissible. As the identity of a procedure or iterator is immutable, they can be considered to be atomic. However, their atomicity can be violated if a procedure or iterator has own data and thus a mutable state. The immutability and atomicity of a procedure or iterator with own data depends on that operation's specified semantics.

The type specification for a procedure or iterator contains most of the information stated in a procedure or iterator heading; a procedure type specification has the form:

procedure ( [type_spec, ...] ) [returns] [signals]

and an iterator type specification has the form:

iterator ( [type_spec, ...] ) [yields] [signals]

where

returns ::= returns ( type_spec, ... )
yields ::= yields ( type_spec, ... )
signals ::= signals ( exception, ... )
exception ::= name ( [ type_spec, ... ] )

The first list of type specifications describes the number, types, and order of arguments. The returns or yields clause gives the number, types, and order of the objects to be returned or yielded. The signals clause lists the exceptions raised by the procedure or iterator; for each exception name, the number, types, and order of the objects to be returned is also given. All names used in a signals clause must be unique. The ordering of exceptions is not important.
Procedure and iterator types have an \texttt{equal(=)} operation. Invocation is not an operation, but a primitive in Argus. For the detailed specification of \texttt{proctype} and \texttt{Itertype}, see Section II.17.

6.3. Atomic\_Array, Atomic\_Record, and Atomic\_Variant

Having described the types that Argus inherited from CLU, we now describe the new types in Argus. The mutable atomic type generators of Argus are \texttt{atomic\_array}, \texttt{atomic\_record}, and \texttt{atomic\_variant}. Types obtained from these generators provide the same operations as the analogous types obtained from \texttt{array}, \texttt{record}, and \texttt{variant}, but they differ in their synchronization and recovery properties. Conversion operations are provided between each atomic type generator and its non-atomic partner (for example, \texttt{atomic\_array}[t]\$aa2a converts from an atomic array to a (non-atomic) array).

An operation of an atomic type generator can be classified as a reader or writer depending on whether it examines or modifies its principal argument, that is, the argument or result object of the operation's type. (For binary operations, such as \texttt{argets\_ar}, the operation is classified with respect to each argument.) Intuitively, a reader only examines (reads) the state of its principal argument, while a writer modifies (writes) its principal argument. Operations that create objects of an atomic type are classified as readers. Reader/writer exclusion is achieved by locking: readers acquire a read lock while writers acquire a write lock. The locking rules are discussed in Section 2.2.2.

If one or more of the type parameters is non-atomic, then the resulting type is not atomic because modifications to component objects are not controlled. However, read/write locking still occurs, as described above. Thus, an atomic type generator instantiated with a non-atomic parameter incurs the expense of atomic types without gaining any benefit; such an instantiation is unlikely to be a correct solution to a problem. Atomic type generators yield transmissible types only if the type parameters are all transmissible.

Special operations are provided for each atomic type generator to test and manipulate the locks associated with reader/writer exclusion. These operations are useful for implementing user-defined atomic types (see Section 15). The \texttt{tagtest} and \texttt{tagwait} statements (see Section 10.15) provide additional structured support for atomic\_variants. The operations \texttt{can\_read}, \texttt{can\_write}, \texttt{Test\_and\_read}, and \texttt{test\_and\_write} provide relatively unstructured access to lock information. For complete definitions of these operations, see Sections II.10, II.13, and II.16.

Assuming normal termination, the following operations acquire read locks on their principal arguments or the objects that they create.

\begin{itemize}
  \item \texttt{atomic\_array:} create, new, predict, fill, fill\_copy, size, low, high, empty, top, bottom, fetch, similar, similar1, copy, copy1, elements, indexes, test\_and\_read, a2aa, aa2a, encode, decode
  \item \texttt{atomic\_record:} create, get\_, similar, similar1, copy, copy1, test\_and\_read, ar\_gets\_ar (second argument), r2ar, ar2r, encode, decode
  \item \texttt{atomic\_variant:} make\_, is\_, value\_, av\_gets\_av (second argument), similar, similar1, copy, copy1, test\_and\_read, v2av, av2v, encode, decode
\end{itemize}
The operations `similar` and `similar!` acquire read locks on both arguments. The operations `copy` and `copy!` acquire a read lock on the value returned as well as their principal argument. `Test_and_read` is a reader only if it returns `true`; otherwise it is neither a reader nor a writer.

Assuming normal termination, the following operations acquire write locks on their principal arguments:

- **atomic_array:** `set_low`, `trim`, `store`, `addh`, `addl`, `remh`, `reml`, `test_and_write`
- **atomic_record:** `set_ar`, `ar_gets_ar` (first argument), `test_and_write`
- **atomic_variant:** `change_av`, `av_gets_av` (first argument), `test_and_write`

`Test_and_write` is a writer only if it returns `true`; otherwise it is neither a reader nor a writer.

The `equal`, `can_read`, and `can_write` operations are neither readers nor writers.

When an operation of `atomic_array` terminates with an exception, its principal argument is never modified; however, the `atomic_array` operations listed above as writers always obtain a write lock before the principal argument is examined, hence there are cases in which they will obtain a write lock and only read, but not modify their principal argument. For example, `atomic_array[]!$trim` is a writer when it signals `bounds`. On the other hand, when an `atomic_array` operation raises a signal because of an invalid argument, no locks are obtained. For example, when `atomic_array[]!$trim` signals `negative_size`, it is neither a reader nor a writer since the array's state is neither examined nor modified (only the integer argument is examined).

For the detailed specification of atomic arrays, see Section II.10; for atomic records, see Section II.13; and for atomic variants, see Section II.16.

### 6.4. Guardian Types

Guardian types are user-defined types that are implemented by guardian definitions (see Section 13). A guardian definition has a header of the form:

```
   idn = guardian [ parms ] Is idn , ... [ handlers idn , ... ] [ where ]
```

The creators are the operations named in the identifier list following `Is`; a creator is a special kind of operation that can be called to create new guardians that behave in accordance with the guardian definition. Each guardian optionally provides `handlers` that can be called to interact with it; the names of these handlers are listed in the identifier list following `handlers`. (See Section 13 for more details.)

A guardian definition named `g` defines a guardian interface type `g`. An object of the guardian interface type provides an interface to a guardian that behaves in accordance with the guardian definition. An interface object is created whenever a new guardian is created, and then the interface object can be used to access the guardian's handlers. Interface objects are transmissible, and after transmission they still give access to the same guardian. In this manual a "guardian interface object" is often called simply a "guardian object".

The guardian type `g` for the guardian definition named `g` has the following operations.
1. The creators listed in the Is list of the guardian definition.

2. For each handler name $h$ listed in the handles list, an operation $get\_h$ with type: 
   \[\text{proctype}(g) \text{ returns } (h),\] where $h$ is the type of $h$.

3. Equal and similar, both of type: \[\text{proctype}(g, g) \text{ returns } (\text{bool}),\] which return true only if both arguments are the same guardian object.

4. Copy, of type: \[\text{proctype}(g) \text{ returns } (g),\] which simply returns its argument.

5. transmit.

A creator may not be named equal, similar, copy, print, or $get\_h$ where $h$ is the name of a handler.

Thus if $x$ is a variable denoting a guardian interface object of type $g$, and $h$ is a handler of $g$, then $g$\$get\_h(x)$ will return this handler. As usual with $get\_h$ operations, this call can be abbreviated to $x.h$. Note that the handlers themselves are not operations of the guardian interface type; thus $g$\$h$ would be illegal.

A guardian interface type is somewhat like a structure type. Its objects are constructed by the creators, and decomposed by the $get\_h$ operations. Guardian interface objects are immutable and atomic.

### 6.5. Handler and Creator Types

Creators are operations of guardian types. Handler objects are created as a side-effect of guardian creation. Unlike procedures and iterators, handlers and creators are transmissible.

The types of handlers and creators resemble the types of procedures:

- \[\text{handlertype}([\text{type spec}, \ldots])\ [\text{returns}][\text{signals}]\]
- \[\text{creatortype}([\text{type spec}, \ldots])\ [\text{returns}][\text{signals}]\]

The argument, normal result, and exception result types must all be transmissible. The signals list for a handlertype or creatortype cannot include either failure or unavailable, as these signals are implicit in the interface of all creators and handlers.

Handler and creator types provide equal and similar operations which return true if and only if both arguments are the same object, and copy operations which simply return their argument. For the detailed specification of handlertype and creatortype, see Section I.I.18.

### 6.6. Image

The Image type provides an escape from compile-time type checking. The main difference between Image and any is that Image objects are transmissible. An Image object can be thought of as a portion of an undecoded message or as the information needed to recreate an object of some type. Image objects are immutable and atomic.

The create operation is parameterized by a transmissible type; it takes a single argument of that type and encodes it (using the encode operation of that type) into an Image object. The force operation is also
parameterized by a transmissible type; it takes an \texttt{Image} object and decodes it (using the \texttt{decode} operation of that type) to an object of that type, signalling \texttt{wrong_type} if the encoded object's type is not included in the parameter type. The \texttt{is_type} operation is parameterized by a type and checks whether its argument is an encoded object of a type included in the parameter type. See Section II.20 for the detailed specification.

6.7. Mutex

Mutex objects are mutable containers for information. They are not atomic, but they provide synchronization and control of writing to stable storage for their contained object. Mutex itself does not provide operations for synchronizing the use of mutex objects. Instead, mutual exclusion is achieved using the \texttt{seize} statement (see Section 10.16), which allows a sequence of statements to be executed while a process is in exclusive possession of the mutex object. Mutex objects are transmissible if the contained object is transmissible.

The type generator \texttt{mutex} has a single parameter that is the type of the contained object. A mutex type specification has the form:

\begin{verbatim}
mutex [type_actual]
\end{verbatim}

Mutex types provide operations to create and decompose mutex objects, and to notify the system of modifications to the mutex object or its contained object.

The \texttt{create} operation takes a single argument of the parameter type and creates a new mutex object containing the argument object. The \texttt{get_value} operation obtains the contained object from its mutex argument, while \texttt{set_value} modifies a mutex object by replacing its contained object. As with records, these operations can be called using special forms, for example:

\begin{verbatim}
m: mutex[Int] := mutex[Int]$create (0)
x: Int := m.value % extract the contained object
m.value := 33 % change the contained object
\end{verbatim}

\texttt{Set_value} and \texttt{get_value} are indivisible.

Mutexes can be distinguished with the \texttt{equal (=)} operation. There are no operations that could cause or detect sharing of the contained object by two mutexes. Such sharing is dangerous, since two processes would not be synchronized with each other in their use of the contained object if each possessed a different mutex. In general, if an object is contained in a mutex object, it should not be contained in any other object, nor should it be referred to by a variable except when in a \texttt{seize} statement that has possession of the containing mutex.

There are some mutex operations that seize the mutex object automatically. \texttt{Copy} seizes its single argument object. \texttt{Similar} seizes its two argument objects; the first argument object is seized first and then the second. In both cases possession is retained until the operations return. Also, when a mutex object is encoded (for a message or when making an \texttt{Image}), the object is seized automatically. See Section II.21 for the detailed specification of \texttt{mutex}. 
Mutexes are used primarily to provide process synchronization and mutual exclusion on shared data, especially to implement user-defined atomic types. In such implementations, it is important to control writing to stable storage. The mutex operation `changed` provides the necessary control. `Changed` informs the system that the calling action requires that the argument object be copied to stable storage before the commit of the action's top-level parent (topaction). Any mutex is asynchronous: its contained object is written to stable storage independently of objects that contain that mutex. See Section 15 for further discussion of user-defined atomic objects.

### 6.8. Node

Objects of type `node` stand for physical nodes. The operation `here` takes no arguments and returns the `node` object that denotes its caller's node. `Equal`, `similar`, and `copy` operations are also provided.

The main use of `node` objects is in guardian creation (see Section 13), where they are used to cause a newly created guardian to reside at a particular node. Objects of type `node` are immutable, atomic, and transmissible. For the detailed specification, see Section 11.2.

### 6.9. Other Type Specifications

A type specification for a user-defined type has the form of a `reference`:

```
reference ::= idn
           | idn [ actual_parm, ... ]
           | reference $ name
```

where each `actual_parm` must be a compile-time computable constant (see Section 7.2) or a `type_actual` (see Section 12.6). A reference must denote a data abstraction to be used as a type specification; this syntax is provided for referring to a data abstraction that is named in an equate module (see Section 12.4). For type generators, actual parameters of the appropriate types and number must be supplied. The order of parameters is always significant for user-defined types (see Section 12.5).

There are two special type specifications that are used when implementing new abstractions: `rep`, and `cvt`. These forms may only be used within a cluster; they are discussed further in Section 12.3.

Within an implementation of an abstraction, formal parameters declared with `type` can be used as type specifications. Finally, identifiers that have been equated to type specifications can also be used as type specifications.
7. Scopes, Declarations, and Equates

This section describes how to introduce and use constants and variables, and the scope of constant and variable names. Scoping units are described first, followed by a discussion of variables, and finally constants.

7.1. Scoping Units

Scoping units follow the nesting structure of statements. Generally, a scoping unit is a body and an associated "heading". The scoping units are as follows (see Appendix I for details of the syntax).

1. From the start of a module to its end.
2. From a cluster, proc, iter, equates, guardian, handler, or creator to the matching end.
3. From a for, do, begin, background, recover, enter, coenter, or seize to the matching end.
4. From a then or else in an if statement to the end of the corresponding body.
5. From a tag, wtag, or others in a tagcase, tagwalt, or tagtest statement to the end of the corresponding body.
6. From a when or others in an except statement to the end of the corresponding body.
7. From the start of a type_set to its end.
8. From an action or topaction to the end of the corresponding body.

The structure of scoping units is such that if one scoping unit overlaps another scoping unit (textually), then one is fully contained in the other. The contained scope is called a nested scope, and the containing scope is called a surrounding scope.

New constant and variable names may be introduced in a scoping unit. Names for constants are introduced by equates, which are syntactically restricted to appear grouped together at or near the beginning of scoping units (except in type sets). For example, equates may appear at the beginning of a body, but not after any statements in the body.

In contrast, declarations, which introduce new variables, are allowed wherever statements are allowed, and hence may appear throughout a scoping unit. Equates and declarations are discussed in more detail in the following two sections.

In the syntax there are two distinct nonterminals for identifiers: idn and name. Any identifier introduced by an equate or declaration is an idn, as is the name of the module being defined, and any operations it has. An idn names a specific type or object. The other kind of identifier is a name. A name is generally used to refer to a piece of something, and is always used in context; for example, names are used as record selectors. The scope rules apply only to idns.

The scope rules are simple:

1. An idn may not be redefined in its scope.
2. Any idn that is used as an external reference in a module may not be used for any other purpose in that module.
Unlike other "block-structured" languages, Argus prohibits the redefinition of an identifier in a restricted scope. An identifier used as an external reference names a module or constant the reference is resolved using the compilation environment.

7.1.1. Variables

Objects are the fundamental "things" in the Argus universe, variables are a mechanism for denoting (i.e., naming) objects. A variable has three properties: its type, whether it is stable or not, and the object that it currently denotes (if any). A variable is said to be uninitialized if it does not denote any object. Attempts to use uninitialized variables are programming errors and (if not detected at compile-time) cause the guardian to crash.

There are only three things that can be done with variables:

1. New variables can be introduced. Declarations perform this function, and are described below.
2. An object may be assigned to a variable. After an assignment the variable denotes the object assigned.
3. A variable may be used as an expression. The value of a variable is the object that the variable denotes at the time the expression is evaluated.

7.1.2. Declarations

Declarations introduce new variables. The scope of a variable is from its declaration to the end of the smallest scoping unit containing its declaration; hence, variables must be declared before they are used.

There are two sorts of declarations: those with initialization, and those without. Simple declarations (those without initialization) take the form

\[ \text{decl} ::= \text{idn}, \ldots: \text{type spec} \]

A simple declaration introduces a list of variables, all having the type given by the type spec. This type determines the types of objects that can be assigned to the variable. The variables introduced in a simple declaration initially denote no objects, i.e., they are uninitialized.

A declaration with initialization combines declarations and assignments into a single statement. A declaration with initialization is entirely equivalent to one or more simple declarations followed by an assignment statement. The two forms of declaration with initialization are:

\[ \text{idn} : \text{type spec} = \text{expression} \]

and

\[ \text{decl}_1, \ldots, \text{decl}_n := \text{call} [@ \text{primary}] \]

These are equivalent to (respectively):

\[ \text{idn} : \text{type spec} \]

\[ \text{idn} = \text{expression} \]

and
7.2 Equates and Constants

An equate allows an identifier to be used as an abbreviation for a constant, type set, or equate module name that may have a lengthy textual representation. An equate also permits a mnemonic identifier to be used in place of a frequently used constant, such as a numerical value. We use the term constant in a very narrow sense here: constants, in addition to being immutable, must be computable at compile-time. Constants are either types (built-in or user-defined), or objects that are the results of evaluating constant expressions. (Constant expressions are defined below.)

The syntax of equates is:

\[
\text{equate} ::= \text{idn} = \text{constant} \\
| \text{idn} = \text{type\_set} \\
| \text{idn} = \text{reference}
\]

\[
\text{constant} ::= \text{type\_spec} \\
| \text{expression}
\]

\[
\text{type\_set} ::= \{ \text{idn} \mid \text{idn has oper\_decl, ...} \{ \text{equate} \} \}
\]

\[
\text{reference} ::= \text{idn} \\
| \text{idn [ actual\_parm, ... ]} \\
| \text{reference \$ name}
\]

References can be used to name equate modules.

An equated identifier may not be used on the left-hand side of an assignment statement.

The scope of an equated identifier is the smallest scoping unit surrounding the equate defining it; here we mean the entire scoping unit, not just the portion after the equate. All the equates in a scoping unit must appear grouped near the beginning of the scoping unit. The exact placement of equates depends on the containing syntactic construct; usually equates appear at the beginnings of bodies.

Equates may be in any order within the a scoping unit. Forward references among equates in the same scoping unit are allowed, but cyclic dependencies are illegal. For example,

\[
x = y \\
y = z \\
z = 3
\]

is a legal sequence of equates, but
x = y
y = z
z = x

is not. Since equates introduce idns, the scoping restrictions on idns apply (i.e., the idns may not be defined more than once).

7.2.1. Abbreviations for Types

Identifiers may be equated to type specifications, giving abbreviations for type names.

7.2.2. Constant Expressions

We define the subset of objects that equated identifiers may denote by stating which expressions are constant expressions. (Expressions are discussed in detail in Section 9.) A constant expression is an expression that can be evaluated at compile-time to produce an immutable object of a built-in type. This includes:

1. Literals.
2. Identifiers equated to constants.
3. Formal parameters.
4. Procedure, iterator, and creator names.
5. Bind expressions (see Section 9.8), where the routine bound and the explicit arguments are all constants.
6. Invocations of procedure operations of the built-in immutable types, provided that all operands are constant expressions that are not formal parameters.

The built-in immutable types are: null, int, real, bool, char, string, sequence types, oneof types, structure types, procedure types, iterator types, and creator types.

We explicitly forbid the use of formal parameters as operands to calls in constant expressions, since the values of formal parameters are not known at compile-time. If the evaluation of a constant expression would signal an exception, the constant defined by that expression is illegal.
8 Assignment and Calls

8. Assignment and Calls

The two fundamental activities of Argus programs are calls and assignment of computed objects to variables.

Argus programs should use mutual exclusion or atomic data to synchronize access to all shared variables, because Argus supports concurrency and thus processes can interfere with each other during assignments. For example,

\[ i := 1 \]
\[ j := 2 \]

is not equivalent to

\[ i, j := 1, 2 \]

in the presence of concurrent assignments to the same variables, because any interleaving of indivisible events is possible in the presence of concurrency.

Argus is designed to allow complete compile-time type-checking. The type of each variable is known by the compiler. Furthermore, the type of objects that could result from the evaluation of any expression is known at compile time. Hence, every assignment can be checked at compile time to ensure that the variable is only assigned objects of its declared type. An assignment \( v := E \) is legal only if the type of \( E \) is included the type of \( v \). The definition of type inclusion is given in Section 6.1.

8.1. Assignment

Assignment causes a variable to denote an object. Some assignments are implicitly performed as part of the execution of various mechanisms of the language (in exception handling, and the tagcase, tagtest, and tagwalt statements). All assignments, whether implicit or explicit, are subject to the type inclusion rule.

8.1.1. Simple Assignment

The simplest form of assignment statement is:

\[ idn := \text{expression} \]

In this case the expression is evaluated, and then the resulting object is assigned to the variable named by the idn in an indivisible event. Thus no other process may observe a "half-assigned" state of the variable, but another process may observe various states during the expression evaluation and between the evaluation of the expression and the assignment. The expression must return a single object (whose type must be included in that of the variable).

8.1.2. Multiple Assignment

There are two forms of assignment statement that assign to more than one variable at once:

\[ idn, \ldots := \text{expression}, \ldots \]

and
The first form of multiple assignment is a generalization of simple assignment. The first variable is assigned the first expression, the second variable the second expression, and so on. The expressions are all evaluated (from left to right) before any assignments are performed. The assignment of multiple objects to multiple variables is an indivisible event, but evaluation of the expressions is divisible from the actual assignment. The number of variables in the list must equal the number of expressions, no variable may occur more than once, and the type of each variable must include the type of the corresponding expression.

The second form of multiple assignment allows one to retain the objects resulting from a call returning two or more objects. The first variable is assigned the first object, the second variable the second object, and so on, but all the assignments are carried out indivisibly. The order of the objects is the same as in the return statement executed in the called routine. The number of variables must equal the number of objects returned, no variable may occur more than once, and the type of each variable must include the corresponding return type of the called procedure.

8.2. Local Calls

In this section we discuss procedure calls; iterator calls are discussed in Section 10.12. However, argument passing is the same for both procedures and iterators.

Local calls take the form:

\`
primary([expression, ...])
\`

The sequence of activities in performing a local call are as follows:

1. The primary is evaluated.
2. The expressions are evaluated, from left to right.
3. New variables are introduced corresponding to the formal arguments of the routine being called (i.e., a new environment is created for the called routine to execute in).
4. The objects resulting from evaluating the expressions (the actual arguments) are assigned to the corresponding new variables (the formal arguments). The first formal is assigned the first actual, the second formal the second actual, and so on. The type of each expression must be included in the type of the corresponding formal argument.
5. Control is transferred to the routine at the start of its body.

A call is considered legal in exactly those situations where all the (implicit) assignments are legal.

A routine may assign an object to a formal argument variable; the effect is just as if that object were assigned to any other variable. From the point of view of the called routine, the only difference between its formal argument variables and its other local variables is that the formals are initialized by its caller.

Procedures can terminate in two ways: they can terminate normally, returning zero or more objects, or they can terminate exceptionally, signalling an exception.
8.2 Local Calls

normally, any result objects become available to the caller, and can be assigned to variables or passed as arguments to other routines. When a procedure terminates exceptionally, the flow of control will not go to the point of return of the call, but rather will go to an exception handler (see Section 11).

8.3. Handler Calls

As explained in Section 2 and in Section 13, a handler is an operation that belongs to some guardian. A handler call causes an activation of the called handler to run at the handler's guardian; the activation is performed at the called handler's guardian by a new subaction created solely for this purpose. Usually the handler's guardian is not the same as the one in which the call occurs, and the called handler's guardian is likely to reside at a different node in the network than the calling guardian. However, it is legal to call a handler that belongs to a guardian residing at the caller's node, or even to call a handler belonging to the caller's guardian.

Although the form of a handler call looks like a procedure call:

    primary ([ expression, ... ])

its meaning is very different. Among other things, a handler is called remotely, with the arguments and results being transmitted by value in messages, and the call is run as a subaction of its calling action. Below we present an overview of what happens when executing a handler call and then a detailed description.

A handler call runs as a subaction of the calling action. We will refer to this subaction as the call action. The first thing done by the call action is the transmission of the arguments of the call. Transmission is accomplished by encoding each argument object, using the encode operation of its type. The arguments are decoded at the called guardian by a subaction of the call action called the activation action. Each argument is decoded by using the decode operation of its type. The effect of transmission is that the arguments are passed by value from the caller to the handler activation: new objects come into existence at the handler's guardian that are copies of the argument objects. Object values are transmitted in such a way as to preserve the internal sharing structure of each argument object is preserved⁸, as well as any sharing structure between the argument objects in a single call. See Section 14 for further discussion of transmission.

After the arguments have been transmitted, the activation action performs the handler body. When the handler body terminates, by executing a return, abort return, signal, or abort signal statement, the result objects are transmitted to the caller by encoding them at the handler's guardian, and committing or aborting the activation action (as it specified). The call action then decodes the results at the caller's guardian. Once the results have been transmitted to the caller, the call action commits and execution continues in the caller as indicated by the caller's code. (Note that the call action will commit even if the activation action aborts.)

---

⁸This is only strictly true for the built-in types. A user-defined type might not preserve internal sharing structure.
The above discussion has ignored the possibility of several problems that may arise in executing a handler call. These problems either cause the call action or the activation action to abort or result in the crash of the calling guardian. A handler call attempted from outside a topaction or subaction is a programming error, and so if this happens the calling guardian is crashed. Other problems cause the call action or the activation action to be aborted, and this is reflected back to the caller as an exception raised by the Argus system. Two such exceptions can be raised: failure(string) and unavailable(string). The string exception results summarize the problem that has occurred.

The meaning of a failure exception generated by the Argus system is that this particular call did not succeed, and furthermore it is unlikely to succeed if repeated. There are two reasons why failure is raised: an error occurred in transmitting an argument or result, or the handler's guardian no longer exists.

The Argus system raises the unavailable exception when it is unable to communicate with the handler's guardian. Reasons why communication may fail include network partitions and a crashes of the called guardian or its node. The Argus system raises the unavailable exception only if communication seems impossible at that time; it may try many times to establish communication. Therefore, when a call terminates with the unavailable exception, there is little point in retrying the call immediately. However, unlike a call terminated by the failure exception, a call terminated by the unavailable exception may complete successfully if retried later. Note that the arguments and results may be encoded several times as the system tries to establish communication.

For example, suppose we have a handler call:

```
m.send_mail(user, my-message)
```

where \( m \) is a mailer guardian, and the send_mail handler has the header

```
send_mail = handler (u: user_id, msg: message) signals (no_such_user)
```

Then \( user \) and \( my\_message \) are encoded using the encode operations of types user_id and message, respectively, and the encoded values are decoded at the called guardian using the decode operations of these types. If \( user \) is actually registered to receive mail, then send_mail will return normally; otherwise it signals no_such_user. In either case no encoding or decoding of the reply is needed since there is no result.

Possible exceptions from this call are no_such_user, failure, and unavailable. So the call might be performed in an except statement:

```
m.send_mail(user, my_message)
    except when no_such_user: ...
    when unavailable (s: string): ...
    when failure (s: string): ...
end
```
8.3.1. Semantics of Handler Calls

In this section we describe the semantics of a handler call in detail. A handler call causes activity at both the calling guardian and at the called guardian. At the calling guardian, the sequence of activities in performing a handler call is as follows:

1. The *primary* is evaluated.
2. The argument *expressions* are evaluated from left to right.
3. A subaction, which we will refer to as the *call action*, is created for the remote call. All subsequent activity on behalf of the call will be performed by the call action or one of its descendants. For it to be possible to create the call action, the caller must already be running as an action. Remote calls by non-actions are programming errors and cause the calling guardian to crash.
4. A call message is constructed. As part of constructing this message, *encode* operations are performed on the argument objects. If any of the *encode* operations terminates with a *failure* exception, then the remote call will terminate with the same exception, and the call action will be aborted.
5. The call message is sent to the guardian of the called handler, and the call action waits for the completion of the call.
6. If the call message arrives at the node of the target guardian, and the target guardian does not exist, then the call action is aborted with the *failure* exception having the string "guardian does not exist" as its exception result.
7. If the system determines that it cannot communicate with the called guardian, it aborts the call action. The call action may be retried several times (beginning at step 3) in attempts to communicate. If repeated communication failures are encountered, the system aborts the call action and causes the call to terminate with the *unavailable* exception. The system will cause this kind of termination only when it is extremely unlikely that retrying the call immediately will succeed.
8. Ordinarily, a call completes when a reply message containing the results is received. When the reply message arrives at the caller, it is decoded using the *decode* operation for each result object. If any *decode* terminates with a *failure* exception, the call action is aborted, and the call terminates with the same exception. Otherwise, the call action commits.
9. The call will terminate normally if the result message indicates that the handler activation returned (instead of signalled); otherwise it terminates with whatever exception was signalled.

At the called guardian, the following activities take place.

1. A subaction of the call action is created at the target guardian to run the call. We will refer to this subaction as the *activation action*. All activity at the target guardian occurs on behalf of the activation action or one of its descendants.
2. The call message is decomposed into its constituent objects. As part of this process *decode* operations are performed on each argument. If any *decode* terminates with a *failure* exception, then the activation action is aborted, and the call terminates with the same exception.
3. The called handler is called within the activation action. This call is like a regular procedure call. The objects obtained from decoding the message are the actual arguments, and they are bound to the formals via implicit assignments.
4. If the handler terminates by executing an *abort return* or an *abort signal* statement (see Section 11.1), then all committed descendents of the activation action are aborted. Then the reply message is constructed by encoding the result objects, the activation action is
aborted, and the reply message is sent to the caller. Otherwise, when the handler terminates, the reply message is constructed by encoding the result objects, the activation action commits, and the reply message is sent to the caller. If one of the calls of encode terminates with a failure exception, then the activation action is aborted, and the call terminates with the same exception.

When the Argus system terminates a call with the unavailable exception, it is possible that the activation action and/or some of its descendants are actually running. This could happen, for example, if the network partitions. These running processes are called "orphans". The Argus system makes sure that orphans will be aborted before they can view inconsistent data (see Section 2.5).

8.4. Creator Calls

Creators are called to cause new guardians to come into existence. As part of the call, the node at which the newly created guardian will be located may be specified. If the node is not specified, then the new guardian is created at the same node as the caller of the creator. The form of a creator call is:

```plaintext
primary ([expression, ...]) [@ primary]
```

The `primary` following the at-sign (@) must be of type node.

A creator call causes two activities to take place. First, a new guardian is created at the indicated node. Second, the creator is called as a handler at the newly created guardian. This handler call has basically the same semantics as the regular handler call described above.

The Argus system may also cause a creator call to abort with the failure or unavailable exceptions. The reasons for such terminations are the same as those for handler calls, and the meanings are the same: the failure exception means that the call should not be retried, while the unavailable exception means that the call should not be retried immediately.

8.4.1. Semantics of Creator Calls

The activities carried out in executing a creator call are as follows.

1. The (first) `primary` is evaluated.
2. The argument expressions are evaluated from left to right.
3. The optional `primary` following the at-sign is evaluated to obtain a node object. If this `primary` is missing, the node at which the call is taking place is used.
4. A subaction, which we will refer to as the call action, is created. All subsequent activity takes place within this subaction. As was the case for handler calls, creators can be called only from within actions. A creator call by a non-action is a programming error and causes the calling guardian to crash.
5. A new guardian is created at the indicated node. The creator obtained in step 1 will indicate the type of this guardian. The selection of a particular load image for this type will occur as discussed in Section 3.3.
6. As was the case for handler calls, if the system cannot communicate with the indicated node, the creator call will terminate with the unavailable exception. If the system is unable
8.4.1 Semantics of Creator Calls

to determine what implementation to load, or if there is no implementation of the type that
can run on the indicated node, or if the manager of the node refuses to allow the new
guardian to be created, the creator call will terminate with the failure exception. In either
case the call action will be aborted.

7. A remote call is now performed to the creator. This call has the same semantics as
described for handler calls above in steps 4 through 9 of the activities at the calling node
and also steps 1 through 4 of activities at the called node. However, if either the call action
or the activation action aborts, the newly created guardian will be destroyed.

For example, suppose we execute the creator call
\[
x: G := G\$create(3) @ n
\]
where \(G\) is a guardian type, \(n\) denotes an object of type node, and \(create\) has header
\[
create = creator (n: int) returns (G) signals (not_possible(string))
\]
The system will select an implementation of \(G\) that is suitable for use at node \(n\), and will then create a
guardian at node \(n\) running that implementation. Next \(create\) (3) is performed as a handler call at that
new guardian. If \(create\) returns, then the assignment to \(x\) will occur, causing \(x\) to refer to the new
guardian that \(create\) returned; now we can call the handlers provided by \(G\). The exceptions that can be
signalled by this call are not_possible, failure, and unavailable. An example of a call that handles all
these exceptions is:
\[
x: G := G\$create (3) @ n
\]
\[
\text{except when not_possible (s: string): ...}
\]
\[
\text{when failure (s: string): ...}
\]
\[
\text{when unavailable (s: string): ...}
\]
end

Creators are described in more detail in Section 13.
9. Expressions

An expression evaluates to an object in the Argus universe. This object is said to be the result or value of the expression. Expressions are used to name the object to which they evaluate. The simplest forms of expressions are literals, variables, parameters, equated identifiers, equate module references, procedure, iterator, and creator names, and self. These forms directly name their result object. More complex expressions are built up out of nested procedure calls. The result of such an expression is the value returned by the outermost call.

9.1. Literals

Integer, real, character, string, boolean and null literals are expressions. The type of a literal expression is the type of the object named by the literal. For example, true is of type bool, "abc" is of type string, etc. (see the end of Appendix I for details).

9.2. Variables

Variables are identifiers that denote objects of a given type. The type of a variable is the type given in the declaration of that variable. An attempt to use an uninitialized variable as an expression is a programming error and causes the guardian to crash.

9.3. Parameters

Parameters are identifiers that denote constants supplied when a parameterized module is instantiated (see Section 12.5). The type of a parameter is the type given in the declaration of that parameter. Type parameters cannot be used as expressions.

9.4. Equated Identifiers

Equated identifiers denote constants. The type of an equated identifier is the type of the constant which it denotes. Identifiers equated to types, type_sets, and equate modules cannot be used as expressions.

9.5. Equate Module References

Equate modules provide a named set of equates (see Section 12.4). To use a name defined in an equate module as an expression, one writes:

reference $ name

where

\[ \text{reference} ::= \text{idn} \]

\[ | \text{idn} [ \text{actual_parm} \ , \ ... \ ] \]

\[ | \text{reference} \$ \text{name} \]

The type of a reference is the type of the constant which it denotes. Identifiers equated to types, type_sets, and equate modules cannot be used as expressions.
9.6. Self

The expression `self` evaluates to the object (of guardian type) corresponding to the guardian instance within which the expression is evaluated. A `self` expression may only appear textually within the body of a guardian. See Section 13 for further discussion.

9.7. Procedure, Iterator, and Creator Names

Procedures and iterators may be defined either as separate modules, or within a cluster. Creators may only be defined within a guardian module. Those defined as separate modules are named by expressions of the form:

```
  idn \[\[ actual_parm , ... \] \]
```

The actual parameters of a parameterized procedure or iterator can be either constants or type actuals (see Section 12.6).

When a procedure, iterator, or creator is defined as an operation of a type, that type is part of the name of the routine. The form for naming an operation of a type is:

```
  type_spec $ name \[\[ actual_parm , ... \] \]
```

The type of this expression is just the type of the named routine.

9.8. Bind

Closures may be created by the `bind` expression:

```
  bind entity \[ bind_arg , ... \]
```

where

```
  bind_arg ::= *
          | expression

definition ::= reference
             | entity . name
             | entity [ expression ]
             | bind entity \[ bind_arg , ... \]
             | type_spec $ name \[\[ actual_parm , ... \] \]
             | type_spec $ \{ field , ... \}
             | type_spec $ \{ [ expression : ] [ expression , ... ] \}
             | up ( expression )
             | down ( expression )
```

An `entity` is a simple kind of expression that is used to prevent syntactic ambiguity.

The number of `bind_arg` must match the entity's number of formals. A `bind_arg` that is an asterisk (*) indicates an argument position in which no binding is made. If a `bind_arg` is an expression, the type of the expression must be included in the type of the corresponding formal. The type of the `bind` expression as a whole is a routine type obtained from the type of the `entity` by deleting argument positions that are bound.
The evaluation of a `bind` expression proceeds by first evaluating the entity and then evaluating, from left to right, any `bind_args` that are expressions. The `entity` may evaluate to a procedure, iterator, handler, or creator object. Suppose that the `entity` is a procedure or iterator object. (Creator and handler bindings are discussed below.) Then the result is formed by binding the argument objects to the corresponding formals of the entity to form a closure; note that the procedure or iterator is not called when the `bind` expression is evaluated. When the closure is called, the object denoted by the `entity` is passed all the bound objects and any actual arguments supplied in the call, all in the corresponding argument positions.

For example, suppose we have:

```
p = proc(x: T, y: Int, w: S) returns(R) signals(too_big)
```

Then

```plaintext
q := bind p(*, 3 + 4, *)
```

produces a procedure whose type is `proctype(T, S) returns(R) signals(too_big)` and assigns it to `q`. A call of `q(a, b)` is then equivalent to the call `p(a, 7, b)`.

Bound routines will be stored in stable storage if they are accessible from a stable variable (see Section 13.1). In this case the entity and the `bind_args` should denote atomic objects.

There is only one instance of a routine's `own` data for each parameterization; thus all the bindings of a routine share its `own` data, if any (see Section 12.7). Each binding is generally a new object; thus the relevant `equal` operation may treat syntactically identical bindings as distinct.

The semantics of binding a creator or handler are similar to binding a procedure or iterator; the differences arise from argument transmission. Encoding of bound argument objects happens when the `bind` expression is evaluated and sharing is only preserved among objects bound at the same time (see Section 14). In more detail, the evaluation of a `bind` expression proceeds by first evaluating the `entity` and then evaluating, from left to right, any `bind_args` that are expressions. Then the argument objects are encoded, from left to right, preserving sharing among these objects. The result is formed by binding the encoded argument objects to the corresponding formals of the entity to form a closure. Note that the entity is not called when the `bind` expression is evaluated.

When the closure is called, first any other arguments are evaluated and encoded (not sharing with the bound objects) and then the call to the entity is initiated. Decoding of the arguments at the called guardian is done in reverse of the order of encoding; that is, other arguments are decoded before bound arguments and the most recently bound arguments are decoded first. Sharing is preserved on decoding only among groups of bound arguments and among the other arguments, not between groups. Thereafter the call proceeds as normally.

For example, if we execute

```plaintext
h1 := bind h(x, y, *)
h1(z)
```
then sharing of objects between \( x \) and \( y \) will be preserved by transmission, but sharing will not be preserved between \( x \) and \( z \) or \( y \) and \( z \).

Closures can be used in equates, provided all the expressions are constants (see Section 7.2.2). However, a handler cannot appear in an equate, since it is not a constant.

### 9.9. Procedure Calls

Procedure calls have the form:

\[
\text{primary ( [ expression , ] )}
\]

The primary is evaluated to obtain a procedure object, and then the expressions are evaluated left to right to obtain the argument objects. The procedure is called with these arguments, and the object returned is the result of the entire expression. For more discussion see Section 8.

Any procedure call \( p(E_1, \ldots, E_n) \) must satisfy two constraints to be used as an expression: the type of \( p \) must be of the form:

\[
\text{proctype (} T_1, \ldots, T_n \text{ returns (} R \text{) signals (...)}
\]

and the type of each expression \( E_i \) must be included in the corresponding type \( T_i \). The type of the entire call expression is given by \( R \).

### 9.10. Handler Calls

Handler calls have the form:

\[
\text{primary ( [ expression , ] )}
\]

The primary is evaluated to obtain a handler object, and then the expressions are evaluated left to right to obtain the argument objects. The handler is then called with these arguments as discussed in Section 8.3. The following expressions are examples of handler calls:

\[
\begin{align*}
h(x) \\
\text{info.guard.who.is.user("john", "doe")} \\
\text{dow Jones.info("XYZ Corporation")}
\end{align*}
\]

Any handler call \( h(E_1, \ldots, E_n) \) must satisfy the following constraints when used as an expression. The type of \( h \) must be of the form:

\[
\text{handlertype (} T_1, \ldots, T_n \text{ returns (} R \text{) signals (...)}
\]

and the type of each expression \( E_i \) must be included in the corresponding type \( T_i \). The type of the entire call expression is given by \( R \).

As explained in Section 8.3, the execution of a handler call starts by creating a subaction. Therefore an attempt to call a handler from a process that is not running an action is a programming error and will cause the calling guardian to crash. This crash occurs after all of the component expressions have been evaluated.
9.11 Creator Calls

Creator calls have the form:

\[
\text{creator} (\left[ \text{expression}, \ldots \right]) [\mathbf{@} \text{creator}]
\]

The first \text{creator} is evaluated to obtain a creator object, the argument expressions are evaluated left to right to obtain the argument objects, and then the \text{creator} following the at-sign (@), if present, is evaluated to obtain a node object. If the \text{creator} following the at-sign is omitted, then \text{node} here is used. The guardian is then created at that node, and the creator called, as discussed in Section 8.4. The following are examples of creator calls:

\begin{itemize}
  \item \text{mailer}create0 @ n
  \item \text{spooler[devtype]}create0
\end{itemize}

A creator call \( c(E_1, \ldots, E_n)@n \) must satisfy the following constraints when used as an expression. The type of \( c \) must be of the form:

\[
\text{creator}(T_1, \ldots, T_n) \text{ returns (R) signals (...)}
\]

where each \( T_i \) includes the type of the corresponding expression \( E_i \). \( N \) must be of type node. The type of the entire call expression is given by \( R \).

As with handler calls, an attempt to call a creator from a process that is not running an action will cause the calling guardian to crash after all component expressions have been evaluated.

9.12. Selection Operations

Selection operations provide access to the individual elements or components of a collection. Simple notations are provided for calling the \text{fetch} operations of array-like types, and the \text{get} operations of record-like types. In addition, these "syntactic sugarings" for selection operations may be used for user-defined types with the appropriate properties.

9.12.1. Element Selection

An element selection expression has the form:

\[
\text{primary} [\text{expression}]
\]

This form is just syntactic sugar for a call of a \text{fetch} operation, and is computationally equivalent to:

\[
T\$fetch(\text{primary}, \text{expression})
\]

where \( T \) is the type of the \text{primary}. \( T \) must provide a procedure operation named \text{fetch}, which takes two arguments whose types include the types of \text{primary} and \text{expression}, and which returns a single result.

9.12.2. Component Selection

The component selection expression has the form:

\[
\text{primary} \cdot \text{name}
\]

This form is just syntactic sugar for a call of a \text{get name} operation, and is computationally equivalent to:

\[
T\$get\_name(\text{primary})
\]

where \( T \) is the type of \text{primary}. \( T \) must provide a procedure operation named \text{get name}, that takes one
argument and returns a single result. Of course, the type of the procedure's argument must include the type of the primary.

9.13. Constructors

Constructors are expressions that enable users to create and initialize sequences, arrays, atomic arrays, structures, records, and atomic records. There are no constructors for user-defined types.

9.13.1. Sequence Constructors

A sequence constructor has the form:

```
    typespec $ [ [ expression , ... ] ]
```

The `typespec` must name a sequence type: `sequence[7]`. This is the type of the constructed sequence. The expressions are evaluated to obtain the elements of the sequence. They correspond (left to right) to the indexes 1, 2, 3, etc. For a sequence of type `sequence[7]`, the type of each element expression in the constructor must be included in `T`.

A sequence constructor is computationally equivalent to a sequence `new` operation, followed by a number of sequence `addh` operations.

9.13.2. Array and Atomic Array Constructors

An array or atomic array constructor has the form:

```
    typespec $ [ [ expression : ] [ expression , ... ] ]
```

The `typespec` must name an array or atomic array type: `array[7]` or `atomic_array[7]`. This is the type of the constructed array. The optional expression preceding the colon `:` must evaluate to an integer, and becomes the low bound of the constructed array or atomic array. If this expression is omitted, the low bound is 1. The optional list of expressions is evaluated to obtain the elements of the array. These expressions correspond (left to right) to the indexes `low_bound`, `low_bound+1`, `low_bound+2`, etc. For an array or atomic array of type `array[7]` or `atomic_array[7]`, the type of each element expression in the constructor must be included in `T`. A constructor of the form `array[7]$[]` has a low bound of 1 and no elements.

An array constructor is computationally equivalent to a `create` operation, followed by a number of `addh` operations.

9.13.3. Structure, Record, and Atomic Record Constructors

A structure, record, or atomic record constructor has the form:

```
    typespec $ { field , ... }
```

where

```
    field ::= name , ... : expression
```

Whenever a field has more than one name, it is equivalent to a sequence of fields, one for each name. Thus, if `R = record[ a: int, b: int, c: int ]`, then the following two constructors are equivalent:


In the following we discuss only record constructors; structure and atomic record constructors are similar. In a record constructor, the type specification must name a record type: \texttt{record}[S_1:T_1, \ldots, S_n:T_n]. This is the type of the constructed record. The component names in the field list must be exactly the names \texttt{S}_1, \ldots, \texttt{S}_n, although these names may appear in any order. The expressions are evaluated left to right, and there is one evaluation per component name even if several component names are grouped with the same expression. The type of the expression for component \texttt{S}_i must be included in \texttt{T}_i. The results of these evaluations form the components of a newly constructed record. This record is the value of the entire constructor expression.


Argus allows prefix and infix notation to be used as a shorthand for the operations listed in Table 9-1. The table shows the shorthand form and the computationally equivalent expanded form for each operation. For each operation, the type \texttt{T} is the type of the first operand.

<table>
<thead>
<tr>
<th>Shorthand form</th>
<th>Expansion</th>
</tr>
</thead>
<tbody>
<tr>
<td>\texttt{expr}_1 ** \texttt{expr}_2</td>
<td>\texttt{T$power(expr_1, expr_2)}</td>
</tr>
<tr>
<td>\texttt{expr}_1 \texttt{/} \texttt{expr}_2</td>
<td>\texttt{T$div(expr_1, expr_2)}</td>
</tr>
<tr>
<td>\texttt{expr}_1 \texttt{*} \texttt{expr}_2</td>
<td>\texttt{T$mul(expr_1, expr_2)}</td>
</tr>
<tr>
<td>\texttt{expr}_1 \texttt{+} \texttt{expr}_2</td>
<td>\texttt{T$add(expr_1, expr_2)}</td>
</tr>
<tr>
<td>\texttt{expr}_1 \texttt{-} \texttt{expr}_2</td>
<td>\texttt{T$sub(expr_1, expr_2)}</td>
</tr>
<tr>
<td>\texttt{expr}_1 \texttt{&lt;} \texttt{expr}_2</td>
<td>\texttt{T$lt(expr_1, expr_2)}</td>
</tr>
<tr>
<td>\texttt{expr}_1 \texttt{=} \texttt{expr}_2</td>
<td>\texttt{T$equal(expr_1, expr_2)}</td>
</tr>
<tr>
<td>\texttt{expr}_1 \texttt{&gt;} \texttt{expr}_2</td>
<td>\texttt{T$gt(expr_1, expr_2)}</td>
</tr>
<tr>
<td>\texttt{expr}_1 \texttt{=} \texttt{expr}_2</td>
<td>\texttt{T$ge(expr_1, expr_2)}</td>
</tr>
<tr>
<td>\texttt{expr}_1 \texttt{=} \texttt{expr}_2</td>
<td>\texttt{T$le(expr_1, expr_2)}</td>
</tr>
<tr>
<td>\texttt{expr}_1 \texttt{=} \texttt{expr}_2</td>
<td>\texttt{T$lt(expr_1, expr_2)}</td>
</tr>
<tr>
<td>\texttt{expr}_1 \texttt{=} \texttt{expr}_2</td>
<td>\texttt{T$ge(expr_1, expr_2)}</td>
</tr>
<tr>
<td>\texttt{expr}_1 \texttt{=} \texttt{expr}_2</td>
<td>\texttt{T$le(expr_1, expr_2)}</td>
</tr>
<tr>
<td>\texttt{expr}_1 \texttt{=} \texttt{expr}_2</td>
<td>\texttt{T$not(expr)}</td>
</tr>
</tbody>
</table>

Operator notation is used most heavily for the built-in types, but may be used for user-defined types as well. When these operations are provided for user-defined types, they should be free of side-effects, and
Expressions

they should mean roughly the same thing as they do for the built-in types. For example, the comparison operations should only be used for types that have a natural partial or total order. Usually, the comparison operations (lt, le, equal, ge, gt) will be of type

proctype (T, T) returns (bool)

the other binary operations (e.g., add, sub) will be of type

proctype (T, T) returns (T) signals (...)

and the unary operations will be of type

proctype (T) returns (T) signals (...)

9.15. Cand and Cor

Two additional binary operators are provided. These are the conditional and operator, cand, and the conditional or operator, cor. The result of evaluating:

expression₁ cand expression₂

is the boolean and of expression₁ and expression₂. However, if expression₁ is false, expression₂ is never evaluated. The result of evaluating:

expression₁ cor expression₂

is the boolean or of expression₁ and expression₂, but expression₂ is not evaluated unless expression₁ is false. For both cand and cor, expression₁ and expression₂ must have type bool.

Because of the conditional expression evaluation involved, uses of cand and cor are not equivalent to any procedure call.

9.16. Precedence

When an expression is not fully parenthesized, the proper nesting of subexpressions might be ambiguous. The following precedence rules are used to resolve such ambiguity. The precedence of each infix operator is given in the table below. Higher precedence operations are performed first. Prefix operators always have precedence over infix operators.

Table 9-2: Precedence for Infix Operators

<table>
<thead>
<tr>
<th>Precedence</th>
<th>Operators</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>**</td>
</tr>
<tr>
<td>4</td>
<td>* / //</td>
</tr>
<tr>
<td>3</td>
<td>+ -</td>
</tr>
<tr>
<td>2</td>
<td>&lt; &lt;= = &gt;= &gt; ~&lt; ~&lt;= ~= ~&gt;</td>
</tr>
<tr>
<td>1</td>
<td>&amp; cand</td>
</tr>
<tr>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>
9.16 Precedence

The order of evaluation for operators of the same precedence is left to right, except for **, which is right to left.

9.17. Up and Down

There are no implicit type conversions in Argus. Two forms of expression exist for explicit conversions. These are:

- `up ( expression )`
- `down ( expression )`

**Up** and **down** may be used only within the body of a cluster operation (see Section 12.3). **Up** changes the type of the expression from the representation type of the cluster to the abstract type. **Down** converts the type of the expression from the abstract type to the representation type.
10. Statements

In this section, we discuss most of the statements of Argus, emphasizing the interaction of actions and the various kinds of control flow statements. We postpone discussion of the signal, exit, and except statements, which are used for signalling and handling exceptions, until Section 11. See Appendix I for the complete syntax of statements.

Atomic actions allow sequences of statements to appear to be indivisible to other actions. Sequences of statements that are not within an action are executed divisibly; that is, other processes may observe intermediate states between statements. Statements are executed for their side-effects and do not return any values. Most statements are control statements; these permit the programmer to create processes and to dictate how control flows in a process. The rest are simple statements: assignment and calls (see Section 8).

A control statement can control a group of equates, declarations, and statements rather than just a single statement. Such a group is called a body, and has the form:

\[
\text{body ::= \{ equate \}
\{ statement \}}
\]

Note that statements include declarations (see Sections 7.1.2 and Appendix I). No special terminator is needed to signify the end of a body; reserved words used in the various compound statements serve to delimit the bodies. The statements in a body are executed sequentially in textual order.

10.1. Calls

A call statement may be used to call a procedure, handler, or creator. For procedures and handlers its form is the same as a call expression:

\[
\text{primary ([ expression , ... ])}
\]

The primary must be a procedure, or handler object. The type of each actual expression must be included in the type of the corresponding formal argument. The procedure or handler may or may not return results; if it does return results, they are discarded.

For creator calls the syntax is similar, but one can optionally specify the node at which the guardian is to be created:

\[
\text{primary ([ expression , ... ])[ @ primary ]}
\]

The primary following the at-sign (@) must be of type node.

The details of procedure, handler, and creator calls are described in Sections 8.2, 8.3, and 8.4.
10.2. Update Statements

Two special statements are provided for updating components of record and array-like objects. In addition they may be used with user-defined types with the appropriate properties. These statements resemble assignments syntactically, but are actually call statements.

10.2.1. Element Update

The element update statement has the form:

```
primary [ expression1 ] := expression2
```

This form is merely syntactic sugar for a call of a store operation; it is equivalent to the call statement:

```
T$store(primary, expression1, expression2)
```

where \( T \) is the type of the primary. \( T \) must provide a procedure named store that takes three arguments whose types include those of primary, expression1, and expression2, respectively.

10.2.2. Component Update

The component update statement has the form:

```
primary . name := expression
```

This form is syntactic sugar for a call of a set operation whose name is formed by attaching set to the name given. For example, if the name is \( f \), then the statement above is equivalent to the call statement:

```
T$set_f(primary, expression)
```

where \( T \) is the type of the primary. \( T \) must provide a procedure operation named set\_f, where \( f \) is the name given in the component update statement. This procedure must take two arguments whose types include the types of primary and expression, respectively.

10.3. Block Statement

The block statement permits a sequence of statements to be grouped together into a single statement. Its form is:

```
begin body end
```

Since the syntax already permits bodies inside control statements, the main use of the block statement is to group statements together for use with the except statement (see Section 11).

10.4. Fork Statement

A fork statement creates an autonomous process. The fork statement has the form:

```
fork primary ( [ expression, ... ] )
```

where the primary is a procedure object whose type has no results or signals (see Section 12.1). The type of each actual expression must be included in the type of the corresponding formal.

Execution of the fork statement starts by evaluating the primary and actual argument expressions from left to right. Any exceptions raised by the evaluation of the primary or the expressions are raised by the fork statement. If no exceptions are raised, then a new process is created and execution resumes after
the fork statement in the old process. The new process starts by calling the given procedure with the argument objects. This new process terminates if and when the procedure call does. However, if the guardian crashes the process goes away (like any other process).

Note that the new process does not run in an action, although the procedure called can start a topaction if desired. There is no mechanism for waiting for the termination of the new process. The procedure called in a fork statement cannot return any results or signal any exceptions.

10.5. Enter Statement
Sequential actions are created by means of the enter statement, which has two forms:

\[
\text{enter topaction body end}
\]

and

\[
\text{enter action body end}
\]

The topaction qualifier causes the body to execute as a new top-level action. The action qualifier causes the body to execute as a subaction of the current action; an attempt to execute an enter action statement in a process that is not executing an action is a programming error and causes the guardian to crash. When the body terminates, it does so either by committing or aborting. Normal completion of the body results in the action committing. Statements that transfer control out of the enter statement (exit, leave, break, continue, return, signal, and resignal) normally commit the action unless are prefixed with abort (e.g., abort exit). Two-phase commit of a topaction may fail, in which case the enter topaction statement raises an unavailable exception.

10.6. Coenter Statement
Concurrent actions and processes are created by means of the coenter statement:

\[
\text{coenter coarm \{ coarm \} end}
\]

where

\[
\text{coarm} ::= \text{armtag} [ \text{foreach decl , ... In call} ] \text{body}
\]

\[
\text{armtag} ::= \text{action}
\]

| \text{topaction} |
| \text{process} |

Execution of the coenter starts by creating all of the coarm processes, sequentially, in textual order. A foreach clause indicates that multiple instances of the coarm will be created. The call in a foreach clause must be an iterator call. At each yield of the iterator, a new coarm process is created and the objects yielded are assigned to newly declared variables in that process. (This implicit assignment must be legal, see Section 6.1.) Each coarm process has separate, local instances of the variables declared in the foreach clause.
The process executing the **coenter** is suspended until after the **coenter** is finished. Once all coarm processes are created, they are started simultaneously as concurrent siblings. Each coarm instance runs in a separate process, and each coarm with an **armtag** of **topaction** or **action** executes within a new top-level action or subaction, respectively. An attempt to execute a **coenter** with a **process** coarm when in an action, or to execute a **coenter** with an **action** coarm when not in an action is an error and will cause the guardian to crash (see Table 10-1).

**Table 10-1**: Legality of **coenter** statements.

<table>
<thead>
<tr>
<th>armtag</th>
<th>process executing the <strong>coenter</strong> is:</th>
<th>not in an action</th>
<th>running an action</th>
</tr>
</thead>
<tbody>
<tr>
<td>action</td>
<td>not legal</td>
<td></td>
<td>legal</td>
</tr>
<tr>
<td>topaction</td>
<td>legal</td>
<td></td>
<td>legal</td>
</tr>
<tr>
<td>process</td>
<td>legal</td>
<td></td>
<td>not legal</td>
</tr>
</tbody>
</table>

A simple example making use of **foreach** is:

```plaintext
coenter action foreach i: Int Int$from_to (1, 5)
  p (i)
end
```

which creates five processes, each with a local variable `i`, having the value 1 in the first process, 2 in the second process, and so on. Each process runs in a newly created subaction. This statement is legal only if the process executing it is running an action.

A coarm may terminate without terminating the entire **coenter** (and sibling coarms) either by normal completion of its body, or by executing a **leave** statement (see Section 10.7). The commit of a coarm declared as a **topaction** may terminate in an **unavailable** exception if two-phase commit fails. Such an exception can only be handled outside the **coenter** statement, and thus will force termination of the entire **coenter** (as explained below).

A coarm may also terminate by transferring control outside the **coenter** statement. When such a transfer of control occurs, the following steps take place.

1. Any containing statements are terminated divisibly, to the outermost level of the coarm, at which point the coarm becomes the **controlling coarm**.

2. Once there is a controlling coarm, every other active coarm will be terminated (and abort if declared as an action) as soon as it leaves all **seize** statements; the controlling coarm is suspended until all other coarms terminate.

3. The controlling coarm then commits or aborts if declared as an action; if declared as a **topaction** and the two-phase commit fails, an **unavailable** exception is raised by the **coenter** statement.

4. Finally, the entire **coenter** terminates, and **control flow continues** outside the **coenter** statement.

Divisible termination implies, for instance, that a nested **topaction** may commit while its parent **action** aborts.
10.6 Coenter Statement

A simple example of early termination is reading from a replicated database, where any copy can supply the necessary information:

```coenter
coenter action foreach db: database in all_replicas (...)
  return( database$read (db))
end
```

When one of these coarms completes first, it tries to commit itself and abort the others. The aborts take place immediately (since there are no `seize` statements); it is not necessary for the handler calls to finish. It is possible that some descendants of an aborted coarm may be running at remote sites when the coarm aborts; the Argus system ensures that such orphans will be aborted before they can make their presence known or detect that they are in fact orphans (see Section 2.5).

10.7. Leave Statement

The `leave` statement has the form:

```
[ abort ] leave
```

Executing a `leave` statement terminates the innermost `enter` statement or `coenter` coarm in which it appears. If the process terminated is an action, then it commits unless the `abort` qualifier is present, in which case the action aborts. The `abort` qualifier can only be used textually within an `enter` statement or within an `action` or `topaction` coarm of a `coenter` statement.

Note that unlike the other control flow statements, `leave` does not affect concurrent siblings in a `coenter` (see Section 10.6).

10.8. Return Statement

The form of the `return` statement is:

```
[ abort ] return [ ( expression , ... ) ]
```

The return statement terminates execution of the containing routine. If the `return` statement occurs in an iterator no results can be returned. If the `return` statement is in a procedure, handler, or creator the type of each `expression` must be included in the corresponding return type of the routine. The `expressions` (if any) are evaluated from left to right, and the objects obtained become the results of the routine.

If no `abort` qualifier is present, then all containing actions (if any) terminated by this statement are committed. If the `abort` qualifier is present, then all terminated actions are aborted. Note that unlike the `leave` statement, `return` will abort concurrent siblings if executed within a coarm of a `coenter` statement (see Section 10.6). The `abort` qualifier can only be used textually within an `enter` statement, an `action` or `topaction` coarm of a `coenter` statement, or the body of a handler or creator.

Within a handler or creator, the result objects are encoded just before the activation action terminates, but after all control flow and nested action termination. If encoding of any result object terminates in a `failure` exception, then the activation action aborts and the handler or creator terminates with the same exception.
10.9. Yield Statement
The form of a yield statement is:

```
yield[ ( expression , ... ) ]
```

The yield statement may occur only in the body of an iterator. The effect of a yield statement is to suspend execution of the iterator invocation, and return control to the calling for statement or foreach clause. The values obtained by evaluating the expressions (left to right) are passed back to the caller. The type of each expression must be included in the corresponding yield type of the iterator. Upon resumption, execution of the iterator continues at the statement following the yield statement.

A yield statement cannot appear textually inside an enter, coenter, or seize statement.

10.10. Conditional Statement
The form of the conditional statement is:

```
If expression then body
{ elseif expression then body }
[ else body ]
end
```

The expressions must be of type bool. They are evaluated successively until one is found to be true. The body corresponding to the first true expression is executed, and the execution of the If statement then terminates. If there is an else clause and if none of the expressions is true, then the body in the else clause is executed.

10.11. While Statement
The while statement has the form:

```
while expression do body end
```

Its effect is to repeatedly execute the body as long as the expression remains true. The expression must be of type bool. If the value of the expression is true, the body is executed, and then the entire while statement is executed again. When the expression evaluates to false, execution of the while statement terminates.

10.12. For Statement
An iterator (see Section 12.2) can be called by a for statement. The iterator produces a sequence of items (where an item is a group of zero or more objects) one item at a time; the body of the for statement is executed for each item in the sequence.

The for statement has the form:

```
for [ decl , ... ] In call do body end
```
or

```
for [ idn , ... ] In call do body end
```
The call must be an iterator call. The second form (with an `idn` list) uses distinct, previously declared variables to serve as the loop variables, while the first form (with a `deci` list) form introduces new variables, local to the `for` statement, for this purpose. In either case, the type of each variable must include the corresponding yield type of the called iterator (see Section 12.2) and the number of variables must also match the yield type.

Execution of the `for` statement begins by calling the iterator, which either yields an item or terminates. If it yields an item (by executing a `yield` statement), its execution is temporarily suspended, the objects in the item are assigned to the loop variables, and the body of the `for` statement is executed. The next cycle of the loop is begun by resuming execution of the iterator after the `yield` statement which suspended it. Whenever the iterator terminates, the entire `for` statement terminates.

### 10.13. Break and Continue Statements

The `break` statement has the form:

```
[ abort ] break
```

Its effect is to terminate execution of the smallest `for` or `while` loop statement in which it appears. Execution continues with the statement following that loop.

The `continue` statement has the form:

```
[ abort ] continue
```

Its effect is to start the next cycle (if any) of the smallest `for` or `while` loop statement in which it appears.

Terminating a cycle of a loop may also terminate one or more containing actions. If no `abort` qualifier is present, then all these terminated actions (if any) are committed. If the `abort` qualifier is present, then all of the terminated actions are aborted. Unlike `leave`, `break` and `continue` will abort concurrent sibling actions when control flow leaves a containing `coenter` (see Section 10.6).

The `abort` qualifier can only be used textually within an `enter` statement or an `action` or `topaction` coarm of a `coenter` statement.

### 10.14. Tagcase Statement

The `tagcase` statement can be used to decompose `on eof` and `variant` objects; `atomic_variant` objects can be decomposed with the `tagtest` or `tagwait` statements. The decomposition is indivisible for `variant` objects; thus, use of the `tagcase` statement for variants is not equivalent to using a conditional statement in combination with `is_` and `value_` operations (see Section II.15).

The form of the `tagcase` statement is:

```
tagcase expression
    tag_arm { tag_arm }
    [ others : body ]
end
```

where
tag_arm ::= tag name , ... [ ( idn : type_spec ) ] : body

The expression must evaluate to a oneof or variant object. The tag of this object is then matched against the names on the tag arms. When a match is found, if a declaration (idn : type_spec) exists, the value component of the object is assigned to the new local variable idn. The matching body is then executed; idn is defined only in that body. If no match is found, the body in the others arm is executed.

In a syntactically correct tagcase statement, the following three constraints are satisfied:
1. The type of the expression must be some oneof or variant type, T.
2. The tags named in the tag arms must be a subset of the tags of T, and no tag may occur more than once.
3. If all tags of T are present, there is no others arm; otherwise an others arm must be present.

On any tag_arm containing a declaration (idn : type_spec), type_spec must include the type(s) of T corresponding to the tag or tags named in that tag_arm.

10.15. Tagtest and Tagwait Statements

The tagtest and tagwait statements are provided for decomposing atomic_variant objects, permitting the selection of a body based on the tag of the object to be made indivisibly with the testing or acquisition of specified locks.

10.15.1. Tagtest Statement

The form of the tagtest statement is:

```
tagtest expression
  atag_arm { atag_arm }
  [ others : body ]
end
```

where

```
tag_arm ::= tag_kind name , ... [ ( idn : type_spec ) ] : body

tag_kind ::= tag
  | wtag
```

The expression must evaluate to an atomic_variant object. If a read lock could be obtained on the atomic_variant object by the current action, then the tag of the object is matched against the names on the atag arms; otherwise the others arm, if present, is executed. If a matching name is found, then the tag_kind is considered.

- If the tag_kind is tag, a read lock is obtained on the object and the match is complete.
- If the tag_kind is wtag and the current action can obtain a write lock on the object, then a write lock is obtained and the match is complete.

When a complete match is found, if a declaration (idn : type_spec) exists, the value component of the object is assigned to the new local variable idn. The matching body is then executed; idn is defined only in that body. The entire matching process, including testing and acquisition of locks, is indivisible.
10.15.1 Tagtest Statement

If a complete match is not found, or the object was not readable by the action, then the others arm (if any) is executed; if there is no others arm, the tagtest statement terminates. If no complete match is found, then no locks are acquired.

The tagtest statement will only obtain a lock if it is possible to do so without “waiting”. For example, suppose that the internal state of the atomic_variant indicates that some previous action acquired a conflicting lock. This action may have since aborted, or may have committed up to an ancestor of the action executing the tagtest, but determining such facts may require system-level communication to other guardians. In this case the tagtest statement may give misleading information, because it may not indicate a match. Apparent anomalies in testing locks may occur even if the action executing the tagtest “knows” that the lock can be acquired, so that the use of tagtest to avoid deadlocks or long delays may result in excessive aborts.

10.15.2. Tagwait Statement

The form of the tagwait statement is:

```
tagwait expression
  atag_arm { atag_arm }
end```

Execution of the tagwait statement proceeds as for the tagtest statement, but if no complete match is found, or if the object is not readable by the current action, then the entire matching process is repeated (after a system-controlled delay), until a complete match is found. Although there is no others arm in a tagwait statement, all tag names do not have to be listed.

10.15.3. Common Constraints

Tagtest and tagwait statements may be executed only within an action. An attempt to execute a tagtest or tagwait statement in a process that is not executing an action is an error and will cause the guardian to crash after evaluating the expression.

In a syntactically correct tagtest or tagwait statement, the following three constraints are satisfied:

1. The type of the expression must be some atomic variant type, T.

2. The tags named in the atag_arms must be a subset of the tags of T, and no tag may occur more than once.

3. Finally, on any atag_arm containing a declaration (idn: type_spec), type_spec must include the type(s) specified as corresponding in T to the tag or tags named in the atag_arm.

A simple example of a tagtest statement is garbage collecting the elements of an array that are in the dequeued state:
item = atomic_variant[enqueued: Int, dequeued: null]
for i: item in array[item]$elements(l) do
  tagtest i
  tag dequeued: array[item]$rem(l)
  others: break
end
end

10.16. Seize Statement

The seize statement has the form:

\[\text{seize expression do body end}\]

The expression must evaluate to a mutex object. The executing process then attempts to gain possession of that mutex object, and waits to do so if necessary. Only one process, whether user or system defined, may possess a given mutex object at one time. Once the process gains possession, the body of the seize statement is executed. When the body terminates, possession of the mutex is released. This includes termination of the body by statements that transfer control out of the body.

The body of a seize statement is considered to be a critical section; a process executing in the body of a seize statement can only be forcibly terminated by crashing the guardian at which the process is running. See Section 15 for the reasons for this and for more discussion of the use of mutex.

Multiple, nested seizes of the same mutex object are allowed, and nest properly. A process seizing a mutex that it has already seized will not deadlock with itself, and possession is not really released until the outermost seize terminates.

10.17. Pause Statement

The pause statement has the form:

\[\text{pause}\]

The pause statement must occur within an enclosing seize statement. Its effect is to release the mutex object associated with the smallest enclosing seize statement, suspend execution of the process for a system-controlled period of time, and then regain possession and continue execution.

If multiple, nested seizes on the mutex object have been performed, pause will not actually release possession. For example, possession is not released in the following:

\[\text{seize m do}
\text{seize m do}
\text{pause \% does not really release possession}
\text{end}
\text{end}\]

In general, nested seizes should be avoided when pause must be used, and pause should be avoided when nested seizes must be used.
10.18 Terminate Statement

The terminate statement may occur only within a guardian definition (see Sect 13). The form of a terminate statement is:

```
terminate
```

When executed within an action, its effect is to cause the eventual destruction of the guardian after the enclosing action commits to the top. If a process attempts to execute terminate while not running an action, a topaction is created to execute the terminate and immediately commit.

Let \( A \) be the action that is executing the terminate. The effect of this statement is the following:

1. Action \( A \) must wait until the action that created the guardian is committed relative to \( A \). In the case of a permanent guardian whose creation has committed to the top there will be no wait, but for a recently created guardian there may be a delay.

2. If multiple processes are attempting to execute terminate statements, at most one at a time may proceed to the next step.

3. If \( A \) commits to the top, the guardian will be destroyed at some time after topaction commit. If some ancestor of \( A \) aborts, however, the guardian will be unaffected. The guardian is also unaffected during the time between \( A \) executing terminate and \( A \) committing to the top.

In order to avoid serialization problems, creation or destruction of a guardian must be synchronized with use of that guardian via atomic objects such as the catalog (see Section 3.4).
11. Exception Handling and Exits

A routine is designed to perform a certain task. However, in some cases that task may be impossible to perform. In such a case, instead of returning normally (which would imply successful performance of the intended task), the routine should notify its caller by signalling an exception, consisting of a descriptive name and zero or more result objects.

The exception handling mechanism consists of two parts: signalling exceptions and handling exceptions. Signalling is the way a routine notifies its caller of an exceptional condition; handling is the way the caller responds to such notification. A signalled exception always goes to the immediate caller, and the exception must be handled in that caller. When a routine signals an exception, the current activation of that routine terminates and the corresponding call (in the caller) is said to raise the exception. When a call raises an exception, control immediately transfers to the closest applicable exception handler. Exception handlers are attached to statements; when execution of the exception handler completes, control passes to the statement following the one to which the exception handler is attached. For brevity, exception handlers will be called "handlers" in this chapter; these should not be confused with the remote call handlers of guardians (see Section 13).

11.1. Signal Statement

An exception is signalled with a signal statement, which has the form:

```
[abort] signal name [(expression, ...)]
```

A signal statement may appear anywhere in the body of a routine. The execution of a signal statement begins with evaluation of the expressions (if any), from left to right, to produce a list of exception results. The activation of the routine is then terminated. Execution continues in the caller as described in Section 11.2 below.

The exception name must be one of the exception names listed in the routine heading. If the corresponding exception specification in the heading has the form:

```
name(T1, ..., Tn)
```

then there must be exactly \( n \) expressions in the signal statement, and the type of the \( i \)th expression must be included in \( T_i \).

If no abort qualifier is present, then all containing actions (if any) terminated by this statement are committed. If the abort qualifier is present, then all terminated actions are aborted. Unlike the leave statement, signal will terminate (abort) concurrent siblings if executed within a coenter statement (see Section 10.6). The abort qualifier can only be used textually within an enter statement, an action or topaction coarm of a coenter statement, or the body of a handler or creator.

Within a handler or creator, the result objects are encoded just before the activation action terminates, but after termination of all control flow and nested actions. If encoding of any result object terminates in a failure exception, then the activation action aborts and the handler or creator terminates with the failure exception.
11.2. Except Statement

When a routine activation terminates by signalling an exception, the called routine is said to raise that exception. By attaching exception handlers to statements, the caller can specify the action to be taken when an exception is raised by a call within a statement or by the statement itself.

A statement with handlers attached is called an except statement, and has the form:

```
statement except { when_handler }
   [ others_handler ]
end
```

where

```
when_handler ::= when name , ... [ ( decl , ... ) ] : body
                   | when name , ... ( * ) : body

others_handler ::= others [ ( idn : string ) ] : body
```

Let $S$ be the statement to which the handlers are attached, and let $X$ be the entire except statement. Each `when_handler` specifies one or more exception names and a `body`. The `body` is executed if an exception with one of those names is raised by a call in $S$. Each of the names listed in the `when_handlers` must be distinct. The optional `others_handler` is used to handle all exceptions not explicitly named in the `when_handlers`. The statement $S$ can be any form of statement, and can even be another except statement. As an example, consider the following except statement:

```
m.sendmail(user, mymessage)
   except when no_such_user: ...
                 % body 1
       when unavailable, failure (s: string): ...
                 % body 2
       when others (ename: string): ...
                 % body 3
end
```

This statement handles exceptions arising from a remote call. If the call raises a `no_such_user` exception, then "body 1" will be executed. If the call raises a `failure` or `unavailable` exception, then "body 2" will be executed. Any other exception will be handled by "body 3."

If, during the execution of $S$, some call in $S$ raises an exception $E$, control transfers to the textually closest handler for $E$ that is attached to a statement containing the call. When execution of the handler completes, control passes to the statement following the one to which the handler is attached. Thus if the closest handler is attached to $S$, the statement following $X$ is executed next. If execution of $S$ completes without raising an exception, the attached handlers are not executed.

An exception raised inside a handler is treated the same as any other exception: control passes to the closest handler for that exception. Note that an exception raised in some handler attached to $S$ cannot be handled by any handler attached to $S$; the exception can be handled within the handler, or it can be handled by some handler attached to a statement containing $X$. For example, in the following except statement:
11.2 Except Statement

times3_plus1(a)
   except when limits:
      a := a + a
      when overflow: ... % body 2
   end

any overflow signal raised by the expression \(a + a\) will not be handled in "body 2," because this overflow handler is not in an except statement attached to the assignment statement \(a := a + a\).

We now consider the forms of exception handlers in more detail. The form:

```
when name, ..., [ ( decl, ... ) ] : body
```

is used to handle exceptions with the given names when the exception results are of interest. The optional declared variables, which are local to the handler, are assigned the exception results before the body is executed. Every exception potentially handled by this form must have the same number of results as there are declared variables, and the types of the variables must include the types of the results. The form:

```
when name, ..., ( * ) : body
```

handles all exceptions with the given names, regardless of whether or not there are exception results; any actual results are discarded. Using this form, exceptions with differing numbers and types of results can be handled together.

The form:

```
others [ ( idn: string ) ] : body
```

is optional, and must appear last in a handler list. This form handles any exception not handled by other handlers in the list. If a variable is declared, it must be of type string. The variable, which is local to the handler, is assigned a lower case string representing the actual exception name; any results are discarded.

Note that number and type of exception results are ignored when matching exceptions to handlers; only the names of exceptions are used. Thus the following is illegal, in that Int$div signals zero_divide without any results (see Section 11.4), but the closest handler has a declared variable:

```
begin
   y: int := 0
   x: int := 3 / y
   except when zero_divide (z: int): return end
end
```

... A call need not be surrounded by except statements that handle all potential exceptions. In many cases the programmer can prove that a particular exception will not arise; for example, the call Int$div(x, 7) will never signal zero_divide. However, if some call raises an exception for which there is no handler, then the guardian crashes due to this error.

---

9The implementation of the Argus should log unhandled exceptions in some fashion, to aid later debugging. During debugging, an unhandled exception would be trapped by the debugger before the crash.
11.3. Resignal Statement

A resignal statement is a syntactically abbreviated form of exception handling:

```
statement [ abort ] resignal name , ...
```

Each name listed must be distinct, and each must be one of the condition names listed in the routine heading. The resignal statement acts like an except statement containing a handler for each condition named, where each handler simply signals that exception with exactly the same results. Thus, if the resignal clause names an exception with a specification in the routine heading of the form:

```
name(T_1, ..., T_n)
```

then effectively there is a handler of the form:

```
when name (x_1: T_1, ..., x_n: T_n): [ abort ] signal name(x_1, ..., x_n)
```

which has an abort qualifier if and only if the resignal statement did. As for an explicit handler of this form, every exception potentially handled by this implicit handler must have the same number of results as declared in the exception specification, and the types of the results must be included in the types listed in the exception specification.

If no abort qualifier is present, then all containing actions (if any) terminated by this statement are committed. If the abort qualifier is present, then all terminated actions are aborted. Unlike the leave statement, resignal will abort concurrent siblings if executed within a coenter statement (see Section 10.6). The abort qualifier can only be used textually within an enter statement, an action or topaction coarm of a coenter statement, or the body of a handler or creator.

11.4. Exit Statement

An exit statement has the form:

```
[ abort ] exit name [ ( expression , ...) ]
```

An exit statement is similar to a signal statement except that where the signal statement signals an exception to the calling routine, the exit statement raises the exception directly in the current routine. Thus an exit causes a transfer of control within a routine but does not terminate the routine. An exception raised by an exit statement must be handled explicitly by a containing except statement with a handler of the form:

```
when name , ... [ ( decl , ...) ] : body
```

As usual, the types of the expressions in the exit statement must be included in the types of the variables declared in the handler. The handler must be an explicit one, i.e., exits to the implicit handlers of resignal statements are illegal.

If no abort qualifier is present, then all containing actions (if any) terminated by the exit statement are committed. If the abort qualifier is present, then all terminated actions are aborted. Unlike the leave statement, exit will abort concurrent siblings when control flow leaves a containing coenter statement (see Section 10.6). The abort qualifier can only be used textually within an enter statement or an action topaction coarm of a coenter statement.
11.4 Exit Statement

The exit statement and the signal statement mesh nicely to form a uniform mechanism. The signal statement can be viewed simply as terminating a routine activation; an exit is then performed at the point of invocation in the caller. (Because this exit is implicit, it is not subject to the restrictions on exits listed above.)

11.5. Exceptions and Actions

A new action is created by a handler call, creator call, enter statement, or action or topaction arm of a coenter statement. In addition, the recover code of a guardian runs as an action. When control flows out of an action, that action is committed unless action is taken to prevent its committing. To abort an action, it is necessary to qualify control flow statements such as exit, signal, resignal, and leave with the keyword abort (see Section 10.6).

However, there is an additional complication. Not only will explicit termination of actions by exit, signal, and resignal statements commit actions, but also implicit termination by flow of control out of an action body when an exception raised within that body is handled outside the action's body. Thus, if an exception which is raised by a call within an action is not to commit the action, then it is necessary to catch the exception within the action. This is particularly important when dealing with topactions. A common desire is to catch all "unexpected" exceptions, but still have the topaction abort. In this case, the catch-all exception handler must be placed inside the topaction. However, an unavailable handler must still be placed outside the topaction, since the two-phase commit may fail.

An action or topaction coarm of a coenter statement will not abort its concurrent siblings when it ends in either normal completion of its body or by a leave statement. However, if control flows otherwise out of the coenter statement from within one of the coarms, the entire coenter is terminated as described in Section 10.6. Thus, a coenter statement should must be used carefully to ensure the proper behavior in case of exceptions. There may be circumstances where a separate exception handler will have to be used for each coarm to ensure the proper behavior, even when the exception handling is identical for each coarm.

11.6. Failure Exceptions

Argus responds to unhandled exceptions differently than CLU. In CLU, an unhandled exception in some routine causes that routine to terminate with the failure exception. In Argus, however, an unhandled exception causes the guardian that is running the routine to crash. Our motivation for this change is that an unhandled exception is typically a symptom of a programming error that cannot be handled by the calling routine. Furthermore, crashing the guardian limits the damage that the programming error can cause.

Procedures and iterators in Argus no longer have an implicit failure exception associated with them. Instead, such a routine may list failure explicitly in its signals clause and failure may have any number (and type) of exception results. Failure should be used to indicate an unexpected (and possibly
catastrophic) failure of a lower-level abstraction, for example, when there is a failure in a type parameter's routines (for instance in similar or copy operations). Another example is when there is an unwanted side effect, such as a bounds exception in array[t]#elements caused by a mutation of the array argument. Various operations of the built-in types signal failure under such circumstances.

For handlers and creators, failure is used to indicate that a remote call has failed; thus the exception failure(string) is implicit in the type of every handler and creator (see Section 13.5). When a remote call terminates with the failure exception, this means that not only has this call failed, but that the call is unlikely to succeed if repeated.
12. Modules

Besides guardian modules, Argus has procedure, iterator, cluster, and equate modules.

\[
\text{module ::= } \{ \text{equate} \} \text{guardian} \\
\text{  | } \{ \text{equate} \} \text{procedure} \\
\text{  | } \{ \text{equate} \} \text{iterator} \\
\text{  | } \{ \text{equate} \} \text{cluster} \\
\text{  | } \{ \text{equate} \} \text{equates}
\]

Guardians are discussed in Section 13, the rest are described below.

12.1. Procedures

A procedure performs an action on zero or more arguments, and when it terminates it returns zero or more results. A procedure implements a procedural abstraction: a mapping from a set of argument objects to a set of result objects, with possible modification of some of the argument objects. A procedure may terminate in one of a number of conditions; one of these is the normal condition, while others are exceptional conditions. Differing numbers and types of results may be returned in the different conditions.

The form of a procedure is:

\[
\text{idn = proc [ parms ] args [ returns ] [ signals ] [ where ]} \\
\text{  routine_body} \\
\text{  end idn}
\]

where

\[
\text{args ::= ( [ decl , ... ] )} \\
\text{returns ::= returns ( type_spec , ... )} \\
\text{signals ::= signals ( exception , ... )} \\
\text{exception ::= name [ ( type_spec , ... ) ]} \\
\text{routine_body ::= \{ equate \}} \\
\text{  \{ own_var \}} \\
\text{  \{ statement \}}
\]

In this section we discuss non-parameterized procedures, in which the \text{parms} and \text{where} clauses are missing. Parameterized modules are discussed in Section 12.5. Own variables are discussed in Section 12.7.

The heading of a procedure describes the way in which the procedure communicates with its caller. The \text{args} clause specifies the number, order, and types of arguments required to call the procedure, while the \text{returns} clause specifies the number, order, and types of results returned when the procedure terminates normally (by executing a return statement or reaching the end of its body). A missing \text{returns} clause indicates that no results are returned.

The \text{signals} clause names the exceptional conditions in which the procedure can terminate, and specifies the number, order, and types of result objects returned in each condition. All names of
exceptions in the \textit{signals} clause must be distinct. The \textit{idn} following the \textbf{end} of the procedure must be the same as the \textit{idn} naming the procedure.

A procedure is an object of some procedure type. For a non-parameterized procedure, this type is derived from the procedure heading by removing the procedure name, rewriting the formal argument declarations with one \textit{idn} per \textit{decl}, deleting the \textit{idns} of all formal arguments, and finally, replacing \texttt{proc} by \texttt{proctype}.

The call of a procedure causes the introduction of the formal variables, and the actual arguments are assigned to these variables. Then the procedure body is executed. Execution terminates when a \textit{return} statement or a \textit{signal} statement is executed, or when the textual end of the body is reached. If a procedure that should return results reaches the textual end of the body, the guardian crashes due to this error. At termination the result objects, if any, are passed back to the caller of the procedure.

\section*{12.2. Iterators}

An iterator computes a sequence of \textit{items}, one item at a time, where an item is a group of zero or more objects. In the generation of such a sequence, the computation of each item of the sequence is usually controlled by information about what previous items have been produced. Such information and the way it controls the production of items is local to the iterator. The user of the iterator is not concerned with how the items are produced, but simply uses them (through a \texttt{for} statement) as they are produced. Thus the iterator abstracts from the details of how the production of the items is controlled; for this reason, we consider an iterator to implement a control abstraction. Iterators are particularly useful as operations of data abstractions that are collections of objects (e.g., sets), since they may produce the objects in a collection without revealing how the collection is represented.

An iterator has the form:

\begin{verbatim}
  idn = iter [ parms ] args [ yields ] [ signals ] [ where ]
  routine_body
end idn
\end{verbatim}

where

\begin{verbatim}
  yields ::= yields ( type_spec , ... )
\end{verbatim}

In this section we discuss non-parameterized iterators, in which the \textit{parms} and \textit{where} clauses are missing. Parameterized modules are discussed in Section 12.5. Own variables are discussed in Section 12.7.

The form of an iterator is similar to the form of a procedure. There are only two differences:

1. An iterator has a \textit{yields} clause in its heading in place of the \textit{returns} clause of a procedure. The \textit{yields} clause specifies the number, order, and types of objects yielded each time the iterator produces the next item in the sequence. If zero objects are yielded, then the \textit{yields} clause is omitted. The \textit{idn} following the \textbf{end} of the iterator must be the same as the \textit{idn} naming the iterator.

2. Within the iterator body, the \texttt{yield} statement is used to present the caller with the next item
12.2 Iterators

in the sequence. An iterator terminates in the same manner as a procedure, but it may not
return any results.

An iterator is an object of some iterator type. For a non-parameterized iterator, this type is derived from
the iterator heading by removing the iterator name, rewriting the formal argument declarations with one
*idn* per *decl*, deleting the *idns* of all formal arguments, and finally, replacing *iter* by *IterType*.

An iterator can be called only by a *for* statement or by a *foreach* clause in a *coenter* statement.

12.3. Clusters

A cluster is used to implement a new data type, distinct from any other built-in or user-defined data
type. A data type (or data abstraction) consists of a set of objects and a set of primitive operations. The
primitive operations provide the most basic ways of manipulating the objects; ultimately every
computation that can be performed on the objects must be expressed in terms of the primitive operations.
Thus the primitive operations define the lowest level of observable object behavior.\(^\text{10}\)

The form of a cluster is:

\[
\text{idn} = \text{cluster} \{ \text{parms} \} \text{Is} \text{idn}, \ldots \{ \text{where} \}
\]

\[
\text{cluster\_body}
\]

\[
\text{end idn}
\]

where

\[
\text{idn} :: \equiv \text{idn} \quad | \quad \text{transmit}
\]

\[
\text{cluster\_body} :: \equiv \{ \text{equate} \} \text{rep} = \text{type\_spec} \{ \text{equate} \}
\]

\[
\{ \text{own\_var} \}
\]

\[
\text{routine} \{ \text{routine} \}
\]

\[
\text{routine} :: \equiv \text{procedure} \quad | \quad \text{iterator}
\]

In this section we discuss non-parameterized clusters, in which the *parms* and *where* clauses are
missing. Parameterized modules are discussed in Section 12.5. Own variables are discussed in Section
12.7.

The primitive operations are named by the list of *opidns* following the reserved word *Is*. All of the
*opidns* in this list must be distinct. The *idn* following the *end* of the cluster must be the same as the *idn*
naming the cluster.

To define a new data type, it is necessary to choose a *concrete representation* for the objects of the
type. The special equate:

\[^{10}\text{Readers not familiar with the concept of data abstraction might read Liskov, B. and Guttag, J., } \text{Abstraction and Specification in} \]
\[^{10}\text{Program Development, MIT Press, Cambridge, 1986.}\]
\texttt{rep = type\_spec}

within the cluster body identifies the \texttt{type\_spec} as the concrete representation. Within the cluster, \texttt{rep}
may be used as an abbreviation for this \texttt{type\_spec}.

The identifier naming the cluster is available for use in the cluster body. Use of this identifier within the
cluster body permits the definition of recursive types.

In addition to giving the representation of objects, the cluster must implement the primitive operations
of the type. One exception to this, however, is the transmit operation. The transmit operation is not
directly implemented by a cluster; instead, the cluster must implement two operations: \texttt{encode} and
\texttt{decode} (see Section 14 for details). The primitive operations may be either procedural or control
abstractions; they are implemented by procedures and iterators, respectively. Any additional routines
implemented within the cluster are \textit{hidden}: they are private to the cluster and may not be named directly
by users of the abstract type. All the routines must be named by distinct identifiers; the scope of these
identifiers is the entire cluster.

Outside the cluster, the type's objects may only be treated abstractly (i.e., manipulated by using the
primitive operations). To implement the operations, however, it is usually necessary to manipulate the
objects in terms of their concrete representation. It is also convenient sometimes to manipulate the
objects abstractly. Therefore, inside the cluster it is possible to view the type's objects either abstractly or
in terms of their representation. The syntax is defined to specify unambiguously, for each variable that
refers to one of the type's objects, which view is being taken. Thus, inside a cluster named T, a
declaration:

\begin{verbatim}
v: T
\end{verbatim}

indicates that the object referred to by \texttt{v} is to be treated abstractly, while a declaration:

\begin{verbatim}
w: rep
\end{verbatim}

indicates that the object referred to by \texttt{w} is to be treated concretely. Two primitives, \texttt{up} and \texttt{down}, are
available for converting between these two points of view. The use of \texttt{up} permits a type \texttt{rep} object to be
viewed abstractly, while \texttt{down} permits an abstract object to be viewed concretely. For example, given
the declarations above, the following two assignments are legal:

\begin{verbatim}
v := up(w)
w := down(v)
\end{verbatim}

Only routines inside a cluster may use \texttt{up} and \texttt{down}. Note that \texttt{up} and \texttt{down} are used merely to inform
the compiler that the object is going to be viewed abstractly or concretely, respectively.

A common place where the view of an object changes is at the interface to one of the type's
operations: the user, of course, views the object abstractly, while inside the operation, the object is
viewed concretely. To facilitate this usage, a special type specification, \texttt{cvt}, is provided. The use of \texttt{cvt}
is restricted to the \texttt{args}, \texttt{returns}, \texttt{yields} and \texttt{signals} clauses of routines inside a cluster, and may be used
at the top level only (e.g., \texttt{array(cvt)} is illegal). When used inside the \texttt{args} clause, it means that the view
of the argument object changes from abstract to concrete when it is assigned to the formal argument
variable. When \texttt{cvt} is used in the \texttt{returns}, \texttt{yields}, or \texttt{signals} clause, it means the view of the result object
changes from concrete to abstract as it is returned (or yielded) to the caller. Thus cvt means abstract outside, concrete inside: when constructing the type of a routine, cvt is equivalent to the abstract type, but when type-checking the body of a routine, cvt is equivalent to the representation type. The type of each routine is derived from its heading in the usual manner, except that each occurrence of cvt is replaced by the abstract type. The cvt form does not introduce any new ability over what is provided by up and down. It is merely a shorthand for a common case.

Inside the cluster, it is not necessary to use the compound form \texttt{(type\_spec$op\_name)} for naming locally defined routines. Furthermore, the compound form cannot be used for calling hidden routines.

12.4. Equate Modules

An equate module provides a convenient way to define a set of equates for later use by other modules.

The form of an equate module is:

\[
\begin{align*}
\text{idn} & = \text{equates} \left[ \text{parms} \left[ \text{where} \right] \right] \\
& \quad \text{equate} \{ \text{equate} \} \\
& \quad \text{end idn}
\end{align*}
\]

The usual scope rules apply. The \text{idn} following the \text{end} of the equate module must be the same as the \text{idn} naming the equate module.

In this section we discuss non-parameterized equate modules. Parameterized modules are discussed in Section 12.5.

An equate module defines a set of equates, that is, it defines a set of named constants. The set of equates is also a constant, although it is not an object. Thus the name of an equate module can be used in an equate, but an equate module cannot be assigned to a variable. The equates defined by an equate module \text{E} may be referenced using the same syntax as for naming the operations of a cluster. For example, an object or type named \text{n} in equate module \text{E} can be referred to as \text{E$n$}. If equate modules contain equates that give names to other equate modules, compound names can be used. For example:

\[
A[\text{int}]B[\text{int}]C[\text{int}]$\text{name}
\]

where \text{A}, \text{B}, and \text{C} are equate modules is legal.

As always, equates to type specifications do not define new types but merely abbreviations for types. For example, in the following:

\[
\begin{align*}
\text{my\_types} & = \text{equates} \\
& \quad \text{ai} = \text{array[\text{int}]} \\
& \quad \text{float} = \text{real} \\
& \quad \text{end my\_types}
\end{align*}
\]

the types \text{my\_types$ai$} and \text{array[\text{int}]} are equivalent.
12.5. Parameterized Modules

Procedures, iterators, clusters, guardians (see Section 13), and equate modules may all be parameterized. Parameterization permits a set of related abstractions to be defined by a single module. In each module heading there is an optional \texttt{parms} clause and an optional \texttt{where} clause (see Appendix I). The presence of the \texttt{parms} clause indicates that the module is parameterized; the \texttt{where} clause declares the types of any operation parameters that are expected to accompany the formal type parameters.

The form of the \texttt{parms} clause is:

\begin{verbatim}
[ parm , ... ]
\end{verbatim}

\begin{verbatim}
where
\end{verbatim}

\begin{verbatim}
parm ::= idn , ... : type_spec
\end{verbatim}

Each parm declares some number of formal parameters. Only the following types of parameters can be declared in a \texttt{parms} clause: \texttt{int}, \texttt{real}, \texttt{bool}, \texttt{char}, \texttt{string}, \texttt{null}, and \texttt{type}. The declaration of operation parameters associated with type parameters is done in the \texttt{where} clause, as discussed below. The actual values for parameters are required to be constants that can be computed at compile-time. This requirement ensures that all types are known at compile-time, and permits complete compile-time type-checking.

In a parameterized module, the scope rules permit the parameters to be used throughout the module. Type parameters can be used freely as type specifications, and all other parameters (including the operations parameters specified in the \texttt{where} clause) can be used freely as expressions.

A parameterized module implements a set of related abstractions. A program must instantiate a parameterized module before it can be used; that is, it must provide actual, constant values for the parameters (see Section 12.6). The result of an instantiation is a procedure, iterator, type, guardian, or equate module that may be used just like a non-parameterized module of the same kind. Each distinct list of actual parameters produces a distinct procedure, iterator, type, guardian, or equate module (see Section 12.6 for details).

The meaning of a parameterized module is given by binding the actual parameters to the formal parameter names and deleting the \texttt{parms} clause and the \texttt{where} clause. That is, in an instantiation of a parameterized module, each formal parameter name denotes the corresponding actual parameter. The resulting module is a regular (non-parameterized) module. In the case of a cluster some of the operations may have additional parameters; further bindings take place when these operations are instantiated.

In the case of a type parameter, one can also declare what operation parameters must accompany the type by using a \texttt{where} clause. The \texttt{where} clause also specifies the type of each required operation parameter. The \texttt{where} clause constrains the parameterized module as well: the only operations of the type parameter that can be used are those listed in the \texttt{where} clause.
The form of the where clause is:

\[
\text{where } ::= \text{where restriction } \ldots \\
\text{restriction } ::= \text{idn has oper_decl } \ldots \\
| \quad \text{idn In type_set} \\
\text{oper_decl } ::= \text{name , } \ldots : \text{type_spec} \\
| \quad \text{transmit} \\
\text{type_set } ::= \{ \text{idn | idn has oper_decl } \ldots \{ \text{equate } \} \} \\
| \quad \text{idn} \\
| \quad \text{reference$ \text{name}}
\]

There are two forms of restrictions. In both forms, the initial idn must be a type parameter. The has form lists the set of required operation parameters directly, by means of oper_decls. The type_spec in each oper_decl must be a proctype, itertype, or creatortype (see Appendix I). The In form requires that the actual type be a member of a type_set, a set of types with the required operations. The two identifiers in the type_set must match, and the notation is read like set notation; for example,

\[
\{ t | t \text{ has } f \ldots \}
\]

means "the set of all types t such that t has f...". The scope of the identifier is the type_set.

The In form is useful because an abbreviation can be given for a type_set via an equate. If it is helpful to introduce some abbreviations in defining the type_set, these are given in the optional equates within the type_set. The scope of these equates is the entire type_set.

A routine in a parameterized cluster may have a where clause in its heading, and can place further constraints on the cluster parameters. For example, any type is permissible for the array element type, but the array similar operation requires that the element type have a similar operation. This means that array[7] exists for any type T, but that array[7]$similar exists only when an actual operation parameter is provided for T$similar (see Section 12.6). Note that a routine need not include in its where clause any of the restrictions included in the cluster where clause.

12.6. Instantiations
To instantiate a parameterized module, constants or type specifications are provided as actual parameters:

\[
\text{actual_parm } ::= \text{constant} \\
| \quad \text{type_actual} \\
\text{type_actual } ::= \text{type_spec [ with } \{ \text{opbinding } , \ldots \} \} \\
\text{opbinding } ::= \text{name } , \ldots : \text{primary}
\]

If the parameter is a type, the module's where clause may require that some routines be passed as parameters. These routines can be passed implicitly by omitting the with clause; the routine selected as a default will be the operation of the type that has the same name as that used in the where clause.
Routines may also be passed explicitly by using the with clause overriding the default. In this case, the actual routine parameter need not have the same name as is required in the where clause, and need not even be one of the type's primitive operations.

The syntactic sugar that allows default routines to be selected implicitly works as follows. If a generator requires an operation named op from a type parameter, and if the corresponding type_actual, TS with { ... }, has no explicit binding for op, then Argus adds an opbinding of op to TS$op. (It will be an error if TS$op is not defined.) Thus one only has to provide an explicit opbinding if the default is unsatisfactory.

For example, suppose a procedure generator named sort has the following heading:

\[ \text{sort} = \text{proc}[t\text{: type}](a\text{: array}[t]) \text{ where } t \text{ has } \text{gt: proctype}(t, t) \text{ returns}(\text{bool}) \]

and consider the three instantiations:

\[
\begin{align*}
\text{sort}[\text{Int with } \{ \text{gt: Int$gt} \}] \\
\text{sort}[\text{int}] \\
\text{sort}[\text{Int with } \{ \text{lt: Int$lt} \}]
\end{align*}
\]

The first two instantiations are equivalent; in the first the routine \text{Int$gt} is passed explicitly, while in the second it is passed implicitly as the default. In the third instantiation, however, \text{Int$lt} is passed in place of the default. All three instantiations result in a routine of type:

\[ \text{proctype} \text{ (array[\text{int}])} \]

and so each could be called by passing it an array[\text{int}] as an argument. However a call of the third instantiation will sort its array argument in the opposite order from a call of either the first or second instantiation.

Within an instantiation of a parameterized module, an operation of a type parameter named $op denotes the actual routine parameter bound to op in the instantiation of that module. For example, suppose we make the call:

\[
\text{sort}[\text{Int with } \{ \text{gt: Int$gt} \}] \text{ (my ints)}
\]

where my ints is an array of integers. If, in the body of sort, there is a recursive call:

\[
\text{sort}[\text{t with } \{ \text{gt: $gt} \}] \text{ (a, i, j)}
\]

then t denotes the type Int, and $gt denotes the routine \text{Int$gt}, so that the recursive sort happens in the correct order.

A cluster generator may include routines with where clauses that place additional requirements on the cluster's type parameters. A common example is to require a copy operation only within the cluster's copy implementation.

\[
\begin{align*}
\text{set} & = \text{cluster}[t\text{: type} \text{ is } ..., \text{ copy}] \\
\text{where } t & \text{ has equal: proctype}(t, t) \text{ returns}(\text{bool}) \\
\text{rep} & = \text{array}[t] \\
\text{copy} & = \text{proc}(s\text{: cvt} \text{ returns}(cvt) \text{ where } t \text{ has copy: proctype}(t) \text{ returns}(t) \\
& \text{return}(\text{rep$copy}(s))
\end{align*}
\]

The intent of these subordinate where clauses is to allow more operations to be defined if the actual type parameter has the additional required operations, but not to make the additional operations an absolute
12.6 Instantiations

Requirement for obtaining an instance of the type generator. For example, with the above definition of \textit{set}, \texttt{set[any]} would be defined, but \texttt{set[any]$copy} would not be defined because \texttt{any} does not have a \textit{copy} operation. We shall call the routine parameters required by subordinate \textit{where} clauses \textit{optional parameters}.

Like regular \textit{required parameters}, \textit{optional parameters} can be provided when the cluster as a whole is instantiated and can be provided explicitly or by default. For any \textit{optional parameter} \texttt{op} that is not provided explicitly by the \textit{type actual}, \texttt{TS with [...]}, we add an \textit{opbinding} of \texttt{op} to \texttt{TS$op} if \texttt{TS$op} exists; otherwise the \textit{opbinding} is not added. The resulting cluster contains just those operations for which \textit{opbindings} exist for all the required routine parameters. For example, as mentioned above, \texttt{set[any]} would not have a \textit{copy} operation because \texttt{any$copy} does not exist and therefore the needed \textit{opbinding} is not present. On the other hand, \texttt{set[Int]} does have a \textit{copy} operation because \texttt{Int$copy} does exist. Finally, \texttt{set[any with \{copy: \texttt{foo}\}], where \texttt{foo} is a procedure that takes an \texttt{any} as an argument and returns an \texttt{any} as a result, would have a \textit{copy} operation.

For an instantiation to be legal it must type check. Type checking is done after the syntactic sugars are applied. The \textit{types} of constant parameters must be included in the declared \textit{type}, \textit{type actuals} must be \textit{types}, and the \textit{types} of the actual routine parameters must be included in the \textit{proctype}s, \textit{itertypes}, or \textit{creatortypes} declared in the appropriate \textit{where} clauses. Of course, the number of parameters declared must match the number of actuals passed and with each \textit{type actual} parameter there must be an \textit{opbinding} for each \textit{required routine parameter}. If the generator is a cluster, then \textit{opbindings} must be provided for all operations required in the cluster's \textit{where} clause; \textit{opbindings} can (but need not) be provided for \textit{optional parameters}. Extra actual routine parameters are illegal.

Because the meaning of an instantiation may depend on the actual routine parameters, type equality makes instances with different actual routine parameters distinct types. For example, consider the \texttt{set} type generator again; the instance

\[
\texttt{set[\texttt{array[\texttt{int}] with \{equal: \texttt{array[\texttt{int]}$equal}\} ]}
\]

is not equal to

\[
\texttt{set[\texttt{array[\texttt{int}] with \{equal: \texttt{array[\texttt{int]}$similar}\} ]}
\]

Intuitively these instances should be unequal because the two \textit{equal} procedures define different equivalence classes and therefore the abstract behaviors of the two instances are different. However, \textit{optional parameters} do not effect type equality. For example,

\[
\texttt{set[\texttt{array[\texttt{int}] with \{copy: \texttt{Int$copy}\} ]}
\]

and

\[
\texttt{set[\texttt{array[\texttt{int}] with \{copy: my\_copy\} ]}
\]

are equal types. This is intuitively justified because in each case \texttt{set} objects behave the same way even though different sets are produced when sets are copied in the two cases.

Thus we have the following type equality rule, which defines when two \textit{type specs} denote equal types (after syntactic sugars are applied). A similar notion is also needed for routine equality. A formal type
identifier is equal only to itself for type checking purposes. Otherwise, two type names denote equal
types if they denote the same Description Unit (DU). Similarly, Argus compares the names of routine
formals or the DUs of routines, or checks that they are the same operation in equal types. To decide the
equality of two type generator instantiations:

\[ T[l_1 \text{ with } \{op_1; \text{ act}_1, \ldots, \text{ op}_m; \text{ act}_m\} , \ldots, l_n \text{ with } \{\ldots\}] \]

and

\[ T'[l_1' \text{ with } \{op_1'; \text{ act}_1', \ldots, \text{ op}_m'; \text{ act}_m'\} , \ldots, l_n' \text{ with } \{\ldots\}] \]

Argus first checks whether:

1. \( T \) and \( T' \) denote the same DU, and whether

2. they have the same number of type_actuals, and \( t_i \) is equal to \( t_i' \), etc.

Second, any optional parameter opbindings in either instantiation are deleted. After this step, Argus
checks that for each corresponding type_actual there is the same number of opbindings and that each
corresponding opbinding is the same. (That is, the corresponding actual routines are equal.) The order
of the actual routine parameters does not matter, since Argus matches opbindings by operation names.
(The definition of routine equality for instantiations of routine generators is similar.) This definition, for
example, tells us that

\[ \text{set[ array[int] with } \{\text{equal: array[int]$equal}\} \] 

is different from

\[ \text{set[ array[int] with } \{\text{equal: array[int]$similar}\} \] ,

(assuming \text{set} requires an equal operation from its type parameter). It also tells us that:

\[ \text{set[ int with } \{\text{equal: foo, copy: bar}\} \]

and

\[ \text{set[ int with } \{\text{equal: foo, copy: xerox}\} \]

are equal (assuming \text{copy} is required only by the \text{set[int]$copy} operation).

This type equality rule allows programmers to control what requirements affect type equality by
choosing whether to put them on a cluster or on each operation. A requirement on the cluster should be
used whenever the actuals make some difference in the abstraction. For example, in the \text{set} cluster, the
type parameter's equal operation should be required by the cluster as a whole, since using different
equality tests for a set's objects causes the set's behavior to change.

One can require that a type parameter, say \( t \), be transmissible by stating the requirement:

\[ t \text{ has transmit} \]

This requirement is regarded as a formal parameter declaration for a special "transmit actual", but Argus
does not provide syntax for passing it explicitly. The "transmit actual" is passed implicitly just when the
actual type parameter is transmissible and the generator requires it.

\[ ^{11} \text{This is name equality unless the type environment has synonyms for types} \]
12.7. Own Variables

Occasionally it is desirable to have a module that retains information internally between calls. Without such an ability, the information would either have to be reconstructed at every call, which can be expensive (and may even be impossible if the information depends on previous calls), or the information would have to be passed in through arguments, which is undesirable because the information is then subject to uncontrolled modification in other modules (but see also the binding mechanism described in Section 9.8).

Procedures, iterators, handlers, creators, and clusters may all retain information through the use of own variables. An own variable is similar to a normal variable, except that it exists for the life of the program or guardian, rather than being bound to the life of any particular routine activation. Syntactically, own variable declarations must appear immediately after the equates in a routine or cluster body; they cannot appear in bodies nested within statements. Declarations of own variables have the form:

\[
\text{own \_var} ::= \text{own \_decl} \\
\phantom{\text{own \_var}} ::= \text{own \_idn} : \text{type\_spec} ::= \text{expression} \\
\phantom{\text{own \_var}} ::= \text{own \_decl}, \ldots ::= \text{call \texttt{[@ primary]}}
\]

Note that initialization is optional.

The own variables of a module are created when a guardian begins execution or recovers from a crash, and they always start out uninitialized. The own variables of a routine (including cluster operations) are initialized in textual order as part of the first call of an operation of that routine (or the first such call after a crash), before any statements in the body of the routine are executed. Cluster own variables are initialized in textual order as part of the first call of the first cluster operation to be called (even if the operation does not use the own variables). Cluster own variables are initialized before any operation own variables are initialized. Argus insures that only one process can execute a cluster's or a routine's own variable initializations.

Aside from the placement of their declarations, the time of their initialization, and their lifetime, own variables act just like normal variables and can be used in all the same places. As with normal variables, an attempt to use an uninitialized own variable (if not detected at compile-time) will cause the guardian to crash.

Declarations of own variables in different modules always refer to distinct own variables. Several guardians never share own variables. Furthermore, own variable declarations within a module produce distinct own variables for each distinct instantiation of the module. Instantiation of a parameterized cluster, all instantiations of the type's operations, and various cluster own variables, but distinct instantiations of parameterized operations of own variables.

Declarations of own variables cannot be enclosed by an except when writing initialization expressions. It an exception is not
treated as an exception raised, but not handled, in the body of the routine whose call caused the initialization to be attempted. Thus, the guardian will crash due to this error.
13. Guardians

This section is concerned with the form and meaning of the modules used to define guardians. Such a module, called a guardian definition, declares the objects making up the guardian's stable state and volatile state, and provides implementations for the guardian's handlers. It also defines one or more creators: operations that produce new guardians that behave in accordance with the guardian definition. In addition, a guardian definition may provide background code to carry out independent activities, and recovery code to restore the volatile state when the guardian is restarted after a crash.

The syntactic form of a guardian definition is as follows:

```
 idn = guardian [ parms ] is idn , ... [ handles idn , ... ] [ where ]
 { equate }
 { state_decl }
 [ recover body end ]
 [ background body end ]
 { operation } creator { operation }
 end idn
```

where

```
 operation ::= creator
 | handler
 | routine
```

The initial `idn` names the guardian type or type generator (as explained in Section 6.4) and must agree with the final `idn`. The guardian header contains two `idn` lists. The first, following `Is`, gives the names of the creators, which can be called to create and initialize new guardians (the objects belonging to the guardian type). The second, following the handles, gives the names of the handlers that can be called on these guardian objects. The names of all operations must be distinct. Creators may not be named `equal`, `similar`, `copy`, or `get_h` where `h` is the name of a handler. See Section 6.4 for the interface type defined by a guardian definition. See Section 12.5 for the meaning of guardians having `parms` and `where` clauses.

The remaining portions of the guardian definition are discussed in the subsections below.

13.1. The Guardian State

The `state_decls` of the guardian definition declare a number of variables (with optional initialization):

```
 state_decl ::= [ stable ] decl
 | [ stable ] idn : type_spec ::= expression
 | [ stable ] decl, ... ::= call
```

The scope of these declarations is the entire guardian definition. The objects reachable from variables declared to be `stable` survive crashes of the guardian, while other objects do not.

For example, if the `state_decls` were:
stable buffer: atomic_array[int] := atomic_array[int]$new ( )
cache: array[int] := array[int]$new ( )

then the atomic_array object denoted by buffer would survive a guardian crash, but the array object denoted by cache would not. See Section 13.3 for more details of crash recovery. Volatile variables can be assigned wherever an assignment statement is legal. However, stable variables may only be assigned by an initialization when declared or in the body of a creator. The initializations of both stable and volatile variables are executed within an action, as described below. However, the stable variables are not reinitialized upon crash recovery, whereas volatile variables are reinitialized upon crash recovery.

Stable variables should denote resilient objects (see Section 15.2), because only resilient data objects (reachable from the stable variables) are written to stable storage when a topaction commits. (This can be ensured by having stable variables only denote objects of an atomic type or objects protected by mutex.) Non-resilient objects stored in stable variables are only written to stable storage once, when the guardian is created. Furthermore, the stable variables should usually denote atomic objects, because the stable variables are potentially shared by all the actions in a guardian.

13.2. Creators

A guardian definition must provide one or more creators. The names of these creators must be listed in the guardian header (internal creators are not allowed); each such name must correspond to a single creator definition appearing in the body of the guardian definition.

A creator definition has the same form as a procedure definition, except that creators cannot be parameterized, and the reserved word creator is used in place of proc:

\[ \text{idn = creator ([args]) [returns] [signals]} \]
\[ \text{routine body} \]
\[ \text{end idn} \]

The initial idn names the creator and must agree with the final idn. The types of all arguments and all results (normal and exceptional) must be transmissible.

A creator is an object of some creator type. This type is derived from the creator heading by removing the creator name, rewriting the formal argument declarations with one idn per decl, deleting the ids of all formal arguments, deleting any failure or unavailable signals, and finally, replacing creator by creatortype. The signals failure(string) and unavailable(string) are implicit in every creator type (since they can arise from any creator call). However, if these signals are raised explicitly by a creator, they must be listed in the signals clause with string result types.

The semantics of a creator call are explained in Section 8.4. Typically, the body of a creator will initialize some stable and volatile variables. It can also return the name of the guardian being created using the expression self. Since the creator (and the state initialization) runs as an action, the creator terminates by committing or aborting. If it aborts, the guardian is destroyed. If it commits, the guardian begins to accept handler calls, and runs the background code, if any (see below). If an ancestor of the creator aborts, the guardian is destroyed. If the creator and all its ancestors commit, the guardian becomes permanent, and will survive subsequent crashes.
13.3. Crash Recovery

Once a guardian becomes permanent, it will be recreated automatically after a crash with its stable variables initialized to the same state they were in at the last topaction commit before the crash. The volatile variables are then initialized (in declaration order) by a topaction. To aid in this reinitialization, the guardian definition can provide a recover section:

```
recover body end
```

to be run, as part of this topaction, after the initializations attached to the volatile variable declarations are performed. The recover section commits when control reaches the end of the body, or when a return statement is executed. The recover section may abort by executing an abort return statement or as a result of an unhandled exception. The guardian crashes if the recover section aborts.

13.4. Background Tasks

Tasks that must be performed periodically, independent of handler calls, can be defined by a background section:

```
background body end
```

The system creates a process to run this body as soon as creation or recovery commits successfully. The body of the background section does not run as an action; typically it will perform a sequence of topactions.

If the background process finishes executing its body (either by reaching the end of the block or by returning), the process terminates, but the guardian continues to execute incoming handler calls.

13.5. Handlers and Other Routines

Typically, the principal purpose of a guardian is to execute incoming handler calls. A guardian accepts handler calls as soon as creation or recovery commits.

The guardian header lists the names of the externally available handlers. Each handler listed must be defined by a handler definition. Additional handler definitions may also be given, but these handlers can be named only within the guardian to which they belong.

A handler definition has the same form as a procedure definition, except that handlers cannot be parameterized, and the reserved word handler is used in place of proc:

```
idn = handler ([args]) [returns] [signals] routine_body end idn
```

The initial idn names the handler and must agree with the final idn. The types of all arguments and all results (normal and exceptional) must be transmissible.

A handler is an object of some handler type. This type is derived from the handler heading by removing the handler name, rewriting the formal argument declarations with one idn per decl, deleting the
ids of all formal arguments, deleting any failure or unavailable signals, and finally, replacing handler by handlertype. The signals failure(string) and unavailable(string) are implicit in every handler type. However, if these signals are raised explicitly by a handler, they must be listed in the signals clause, with string as their result type.

As explained in Section 8.3, a handler call runs as a subaction of its caller, and arguments and results are passed by value. A new process is created at the handler’s guardian to run the handler activation. Since the handler activation is an action, it terminates by committing or aborting.

A guardian definition may also contain procedure and iterator definitions. These procedures and iterators may be called only within the guardian to which they belong.

13.6. Guardian Lifetime and Destruction

A guardian does not become permanent until its creating action (the creator activation that initialized the guardian) commits to the top. If the creating action or any of its ancestors aborts, the guardian will be destroyed.

Once a guardian becomes permanent, it will survive node crashes (with high probability) and thus may live forever. However, a shorter lifetime may be appropriate for some guardians. One guardian can never destroy another, but a guardian can destroy itself. Destruction is accomplished by the terminate statement (see Section 10.18). (A node’s guardian manager may also destroy guardians.)

A short-lived guardian can be implemented by using background code of the form:

background terminate end

The background code starts to run as soon as the creator returns. The terminate is delayed, however, until the creating action commits to the top, so the creating action can make use of the new guardian before it is destroyed. (If an ancestor of the creating action aborts, the guardian will be destroyed automatically.)

The following is an example of a handler for destroying a permanent guardian:

```plaintext
finish = handler (...) returns (...) signals (not_authorized)
... terminate return(...) end finish
```

Here, finish might check whether its caller is authorized to make this request, and signal not_authorized if not. Otherwise it returns its vital state information to its caller and destroys its guardian.

13.7. An Example

To illustrate how most of the components of a guardian definition are used, an example of a simple guardian is given in Figure 13-1. An action can use a spooler guardian to store objects until after the action has committed to the top. The spooler then passes those objects to other guardians for
consumption. The spooler provides an operation for adding (object, consumer) pairs, and for destroying
the guardian.

Figure 13-1: Spooler Guardian

spooler = guardian [t: type] ls create handles enq, finish
where t has transmit

utype = handle_type (t)
entry = struct [object: t, consumer: utype]
queue = semiquene [entry]

stable state: queue := queue$create ()

background
while true do
  enter topaction
  e: entry := queue$deq(state)
e.consumer(e.object)
  except when unavailable (*): abort leave end
end except when failure, unavailable (*): end
end

create = creator () returns (spooler[t])
  return(self)
end create

enq = handler (item: t, user: utype)
  queue$enq(state, entry$(object: item, consumer: user))
end enq

finish = handler ()
terminate
end finish
end spooler

The spooler guardian is parameterized by the type of object to be stored. The enq handler takes an
object of this type, and a handler for sending the object to the consumer, and adds this information to the
stable state of the spooler. This state is an object of the semiquene abstract data type. Each entry in
the semiquene is a structure containing a stored object and its corresponding consumer handler. The
background code of the guardian runs an infinite loop that starts a topaction, removes an entry from the
queue, and sends the object using the associated handler.

Note that an unavailable exception arising from this handler call is caught inside the topaction, so that
an explicit abort can be performed. If the exception were caught outside the topaction, it would cause the

\[^{12}\text{See W. Weihl and B. Liskov, "Implementation of Resilient, Atomic Data Types", in ACM Transactions on Programming}
Languages and Systems, volume 7, number 2, (April 1985), pages 244-269.\]
topaction to commit, and the entry would be removed without being consumed. Note also that failure is caught outside the topaction, since if an encode were to fail, or if the guardian did not exist, the background process might aimlessly loop forever, because it would not be able to remove that entry.

A more extended example of a distributed system appears in the paper Liskov, B. and Scheifler, R., "Guardians and Actions: Linguistic Support for Robust, Distributed Programs," ACM Transactions on Programming Languages and Systems, volume 5, number 3, (July 1983), pages 381-404.
14. Transmissibility

A type is said to be transmissible if it defines a transmit operation that allows the values of its objects to be sent in messages or stored in Image objects. Only objects of transmissible type may be used as arguments to handler calls or creator calls. This section describes how transmission is defined for the Argus built-in types and for user-defined types.

14.1. The Transmit Operation

Transmissibility is a property of a data abstraction and must be stated in the specification of that abstraction. A transmissible data type \( T \) can be thought of as having an additional operation,

\[
\text{transmit} = \text{proctype}(T) \text{ returns } (T) \text{ signals } \text{failure(string)}
\]

which is called implicitly during message transmission. Given an object, transmit produces a different object, which may even reside at a different guardian from the original. The relation between the original object and the transmitted object is defined by the specification for transmit. Although the exact specification of transmit is type dependent, the values of the two objects will typically be equal. (Value equality is also part of a type's specification; see the discussion in Section 13.3 of the CLU Reference Manual\(^{13} \).) The transmit operation for a type thus defines a call-by-value semantics for its objects.

14.2. Transmission for Built-in Types

The unstructured built-in types (Int, char, bool, ...) are transmissible, with the exception of proctype, Itertype, and any. The transmit operations of the unstructured types preserve value equality, with the exception of the real type, which, because of possible round-off errors, guarantees only that the two values differ by very little.

The structured types (instances of array, struct, atomic_variant, ...) are transmissible if and only if all their type parameters are transmissible. The transmit operation for a structured type is defined in terms of the transmit operations of the component types. For example, if an object \( x \) is an array containing elements of type \( T \), then the transmit operation for \( x \) creates a new array \( y \) with the same bounds as the original, and with elements:

\[
y[i] = T\text{transmit}(x[i])
\]

Thus transmission of the built-in structured types will preserve value equality only if transmission of the component types does.

The transmit operation for mutex[\( T \)] acquires and holds the lock during the transmission (actually, during the encoding, see below) of the contained object.

---

14.3. Transmit for Abstract Types

The type implemented by a cluster is transmissible if the reserved word `transmit` appears in the Is-list at the head of the cluster. Unlike the other operations provided by a type, the `transmit` operation cannot be called directly by users, and in fact is not implemented directly in the cluster. Instead, `transmit` is implemented indirectly in the following way. Each transmissible type is given a canonical representation, called its external representation type. The external representation type of an abstract type \( T \) is any convenient transmissible type \( XT \). This type can be another abstract type if desired; there is no requirement that \( XT \) be a built-in type. Intuitively, the meaning of the external representation is that values of type \( XT \) will be used in messages to represent values of type \( T \). The choice of external representation type is made for the abstract type as a whole and must be used in every implementation of that type. (There are currently no provisions for changing the external representation of a type once it has been established in the library.)

Each implementation of the abstract type \( T \) must provide two operations to map between values of the abstract type and values of the external representation type. There is an operation

\[
\text{encode} = \text{proc} (a: T) \text{returns} (XT) \begin{bmatrix} \text{signals} (\text{failure(string)}) \end{bmatrix}
\]

to map from \( T \) values to \( XT \) values (for sending messages) and an operation

\[
\text{decode} = \text{proc} (x: XT) \text{returns} (T) \begin{bmatrix} \text{signals} (\text{failure(string)}) \end{bmatrix}
\]

to map from \( XT \) values to \( T \) values (for receiving messages). The transmit operation for \( T \) is defined by the following identity:

\[
T$transmit (x) = T$decode (XT$transmit (T$encode(x)))]
\]

Intuitively, the correctness requirement for \( \text{encode} \) and \( \text{decode} \) is that they preserve the abstract \( T \) values: \( \text{encode} \) maps a value of type \( T \) into the \( XT \) value that represents it, while \( \text{decode} \) performs the reverse mapping\(^{14}\).

\( \text{Encode} \) and \( \text{decode} \) are called implicitly by the Argus system during handler and creator calls. If \( \text{encode} \) and \( \text{decode} \) do not appear in the cluster’s Is-list, then they will be accessible to the Argus system, but may not be named directly by users of the type. A failure exception raised by one of these operations will be caught by the Argus system and ressignalled to the caller (see Section 8.3).

An abstract type’s \( \text{encode} \) and \( \text{decode} \) operations should not cause any side effects. This is because the number of calls to \( \text{encode} \) or \( \text{decode} \) is unpredictable, since arguments or results may be encoded and decoded several times as the system tries to establish communication. In addition, verifying the correctness of transmission is easier if \( \text{encode} \) and \( \text{decode} \) are simply transformations to and from the external representation.

When defining a parameterized module (see Section 12.5), it may be necessary to require a type parameter to be transmissible. A special type restriction:

has transmit

is provided for this purpose. To permit instantiation only with transmissible type parameters, this
restriction should appear in the where clause of the cluster. Alternatively, by placing identical where
clauses in the headings of encode and decode procedures, one can ensure that an instantiation of the
cluster is transmissible only if the type parameters are transmissible (see Section 12.5).

As an example, Figure 14-1 shows part of a cluster defining a key-item table that stores pairs of values,
where one value (the key) is used to retrieve the other (the item). The key-item table type has operations
for creating empty tables, inserting pairs, retrieving the item paired with a given key, deleting pairs, and
iterating through all key-item pairs. The table is represented by a sorted binary tree, and its external
representation is an array of key-item pairs. The table type is transmissible only if both type parameters
are transmissible.

**Figure 14-1**: Partial implementation of table.

```literate
table = cluster [key, item: type] Is create, insert, lookup, allpairs, delete, transmit, ...
where key has it: proctype (key, key) returns (bool),
    equal: proctype (key, key) returns (bool)

pair = record[k: key, i: item]
nod = record[k: key, i: item, left, right: table[key, item]]
rep = variant[empty: null, some: nod]
xrep = array[pair] % the external representation type

% The internal representation is a sorted binary tree. All pairs in the table
% to the left (right) of a node have keys less than (greater than) the key in
% that node.
% ...
% other operations omitted

encode = proc (t: table[key, item]) returns (xrep)
where key has transmit, item has transmit
    xr: xrep := xrep$new0 % create an empty array
    % use allpairs to extract the pairs from the tree
    for p: pair In allpairs(t) do
        % Add the pair to the high end of the array.
        xrep$addh(xr, p)
    end
    return(xr)
end encode

decode = proc (xtbl: xrep) returns (tablelkey, item)
where key has transmit, item has transmit
    t: table[key, item] := create() % create empty table
    for p: pair In xrep$elements(xr) do
        % xrep$elements yields all elements of array xr
        insert(t, p.key, p.item) % enter pair in table
    end
    return(t)
end decode

end table
```
14.4. Sharing

When an object of structured built-in type is encoded and decoded, sharing among the object's components is preserved. For example, let a be an array[7] object such that \( a[i] \) and \( a[j] \) refer to a single object of type \( T \). If \( a2 \) is an array[7] object created by transmitting \( a \), then \( a2[i] \) and \( a2[j] \) also name a single object of type \( T \).

All sharing is preserved among all components of multiple objects of built-in type when those objects are encoded together. Thus, sharing is preserved for objects that are arguments of the same remote call or are results of the same remote call, unless the arguments are encoded at different times (see the discussion of the blind expression in Section 9.8). For example, let \( a \) and \( b \) be array[7] objects such that \( a[i] \) and \( b[j] \) refer to a single object of type \( T \). If \( a2 \) and \( b2 \) are arrays created by sending \( a \) and \( b \) as arguments in a single handler call, then \( a2[i] \) and \( b2[j] \) also refer to a single object.

Whether an abstract type's transmit operation preserves sharing is part of that type's specification, but sharing should usually be preserved for abstract types. In the key-item table implementation of Figure 14-1, there are two types of sharing that should be preserved: sharing of keys and items among multiple tables sent in a single message, and sharing of items bound to the same key in a single table. The key-item table example shows how to implement an abstract type whose transmission preserves sharing by choosing an external representation type whose transmit operation preserves sharing.

Care must be taken when the references among objects to be transmitted are cyclic, as in a circular list. Decoding such objects can result in a failure exception unless encode and decode are implemented in one of two ways:

1. the internal and external representation types are identical and encode and decode return their argument object without modifying it or accessing its components, or

2. the external representation object must be free of cycles.
15. Atomic Types

In Argus, atomicity is enforced by the objects shared among actions, rather than by the individual actions themselves. Types whose objects ensure atomicity of the actions sharing them are called atomic types; objects of atomic types are called atomic objects. In this chapter we define what it means for a type to be atomic and describe the mechanisms provided by Argus to support the implementation of atomic types.

Atomicity consists of two properties: serializability and recoverability. An atomic type's objects must synchronize actions to ensure that the actions are serializable. An atomic type's objects must also recover from actions that abort to ensure that actions appear to execute either completely or not at all.

In addition, an atomic type must be resilient: the type must be implemented so that its objects can be saved on stable storage. This ensures that the effects of an action that commits to the top (that is, an action that commits, as do all of its ancestors) will survive crashes.

This chapter provides definitions of the mechanisms used for user-defined types in Argus. For example implementations, see Weihl, W. and Liskov, B., "Implementation of Resilient, Atomic Data Types," ACM Transactions on Programming Languages and Systems, volume 7, number 2 (April 1985), pages 244-269.

The remainder of this chapter is organized as follows. In Section 15.1 and Section 15.2, we present the details of the mechanisms. Section 15.1 focuses on synchronization and recovery of actions, while Section 15.2 deals primarily with resilience. In Section 15.3, we discuss some guidelines to keep in mind when using the mechanisms described in Section 15.1 and Section 15.2. In Sections 15.4 and 15.5, we define more precisely what it means for a type to be atomic. Finally, in 15.6, we discuss some details that are important for user-defined atomic types that are implemented using multiple mutexes.

15.1. Action Synchronization and Recovery

In this section we describe the mechanisms provided by Argus to support synchronization and recovery of actions. These mechanisms are designed specifically to support implementations of atomic types that allow highly concurrent access to objects.

Like a non-atomic type, an atomic type is implemented by a cluster that defines a representation for the objects of the type, and an implementation for each operation of the type in terms of that representation. However, the implementation of an atomic type must solve some problems that do not occur for ordinary types, namely: synchronizing concurrent actions, making visible to other actions the effects of committed actions, hiding the effects of aborted actions, and providing resilience against crashes.

An implementation of a user-defined atomic type must be able to find out about the commits and aborts of actions. In Argus, implementations use objects of built-in atomic types for this purpose. The representation of a user-defined atomic type is typically a combination of atomic and non-atomic objects.
the non-atomic objects are used to hold information that can be accessed by concurrent actions, while the atomic objects contain information that allows the non-atomic data to be interpreted properly. The built-in atomic objects can be used to answer the following question: did the action that caused a particular change to the representation:

- commit (so the new information is now available to other actions),
- abort (so the change should be forgotten), or
- is it still active (so the information cannot be released yet)?

The operations available on built-in atomic objects have been extended to support this type of use; in particular, the `can_read` and `can_write` operations on atomic arrays, records and variants, and the `tagtest` and `tagwait` statements, are intended to be used for this purpose. (We do not expect user-defined atomic types to support such operations, however.)

The use of atomic objects in the representation permits operation implementations to discover what happened to previous actions and to synchronize concurrent actions. However, since part of the representation of a user-defined atomic object may be non-atomic, the implementation also needs a way to synchronize concurrent operation executions on that non-atomic data.

Synchronization for non-atomic data is provided by the `mutex` type generator. As discussed in Section 6.7, a `mutex[T]` object is essentially a container for an object of some type, T, that can be used to provide mutual exclusion for the contained object. The `seize` statement, described in Section 10.16, is used to gain possession of a mutex object. The `seize` statement ensures that a process has exclusive access to a mutex object while it executes the body of the `seize`. Sometimes a process discovers after examining an object that it needs to wait (for example, until some action completes) before it can continue. The `pause` statement, described in Section 10.17, can be used in the body of a `seize` statement to release possession of the seized object, pause for an indeterminate amount of time, and then regain possession.

15.2. Resilience

If a user-defined atomic object is accessible from the stable variables of some guardian, it should be written to stable storage whenever an action that modified it commits to the top. In this section, we discuss how user-defined atomic types can be implemented to ensure that their objects are written to stable storage properly. Such an implementation will make use of some additional properties of mutex objects.

In addition to its use for synchronizing user processes, `mutex` is used for three other functions: notifying the system when information needs to be written to stable storage, defining what information is written to stable storage, and ensuring that information is written to stable storage in a consistent state.

To minimize the amount of information that must be written to stable storage when actions commit, the Argus system only copies new information to stable storage. For built-in atomic objects, it copies accessible objects modified or made newly accessible from a stable variable by an action that commits to the top. For mutex objects, it also copies newly accessible objects to stable storage. In addition, the `mutex` operation


15.2 Resilience

\texttt{changed = proc (m: mutex[T])}

is provided for notifying the system that an existing mutex object should be written to stable storage. Calling this operation will cause the object to be written to stable storage (assuming it is accessible) by the time the action that executed the \texttt{changed} operation commits to the top. Sometimes after the action calls \texttt{changed}, and before its top-level ancestor commits, the system will copy the mutex object to stable storage. \texttt{Changed} must be called from a process running an action.

Mutex objects also define how much information must be written to stable storage. Copying a mutex object involves copying the contained object. By choosing the proper granularity of mutex objects the user can control how much data must be written to stable storage at a time. For example, a large database can be broken into partitions that are written to stable storage independently by dividing it among several mutex objects. Such a division can be used to limit the amount of data written to stable storage by calling \texttt{changed} only for those partitions actually modified by a committing action.

In copying a mutex object, the system will copy all objects reachable from it, excluding other mutex or built-in atomic objects. A contained mutex or built-in atomic object will be copied only if necessary; that is, only if it is:

- a mutex object for which (a descendant of) the completing action called the \texttt{changed} operation,
- a built-in atomic object that was modified by the action, or
- a newly accessible object for which no stable copy exists.

Furthermore, the component is copied independently of the containing mutex object; they may be copied in either order (or simultaneously), subject to the constraint that the system cannot copy a mutex object without first gaining possession of it.

Finally, mutex objects can be used to ensure that information is in a consistent state when it is written to stable storage. The system will gain possession of a mutex object before writing it to stable storage. By making all modifications to mutex objects inside \texttt{seize} statements, the user's code can prevent the system from copying a mutex object when it is in an inconsistent state.

Some details of the effect of \texttt{changed} are important for atomic types that are implemented as multiple mutexes. These details are presented in Section 15.6.

15.3. Guidelines

This section discusses some guidelines to be followed when implementing atomic types. There are additional guidelines to follow when multiple mutexes are used to implement an atomic type; those guidelines are discussed in Section 15.6.

An important concept for describing the resilience of user-defined atomic types is synchrony. An object is \texttt{synchronous} if it is not possible to observe that any portion of the object is copied to stable storage at a different time from any other portion. For example, an object of type \texttt{array[mutex[int]]} would not be
synchronous, because elements of the array can be copied at different times. A type is synchronous if all
of its objects are synchronous. Whether a type is synchronous or not is an important property of its
behavior and should be stated in its specification. The built-in atomic types are synchronous; user-
defined types must also be synchronous if they are to be atomic.

To ensure the resilience and serializability of a user-defined atomic type independently of how it is
used, the form of the rep for an atomic type should be one of the following possibilities.

1. The rep is itself atomic. Note that mutex is not an atomic type.

2. The rep is mutex[1] where t is a synchronous type. For example, t could be atomic, or it
could be the representation of an atomic type, if the operations on the this fictitious atomic
type are coded in-line so that the entire type behaves atomically.

3. The rep is an atomic collection of mutex types containing synchronous types.

4. The rep is a mutable collection of synchronous types, and objects of the representation
type are never modified after they are initialized. That is, mutation may be used to create
the initial state of such an object, but once this has been done the object must never be
modified.

When using mutex objects, there are a few rules to remember. First, changed must be called after the
last modification (on behalf of some action) to the contained object. This is true because the Argus
system is free to copy the mutex to stable storage as soon as changed has been called.

In addition, changed should be called even if the object is not accessible from the stable variables of a
guardian. In part this rule is just an example of separation of concerns: the implementation of the atomic
type should be done independently of any assumptions about how the object will be used. Therefore the
type should be implemented as if its objects were accessible from the stable variables of some guardian.
However, in addition, if this rule is not followed, it is possible that stable storage will not be updated
properly. This situation can occur if an object was accessible, then becomes inaccessible, and later
becomes accessible again. The system guarantees that no problems arise if changed is always called
after the last modification to the object.

Mutex objects should not share data with one another, unless the shared data is atomic or mutex.
One reason for this rule is that in copying mutex objects to stable storage Argus does not preserve this
kind of sharing.

A final point about mutex objects is that it is unwise to do any activity that is likely to take a long time
inside a seize statement. For example, a handler call should not be done from inside a seize statement if
possible. Also, it is unwise to wait for a lock inside a seize unless the programmer can be certain that the
lock is available or will be soon. Otherwise, a deadlock may occur. An example of where waiting for a
lock in a nested seize statement is safe is where all processes seize the two mutex objects in the same
order.
15.4 A Prescription for Atomicity

In this section, we discuss how to decide how much concurrency is possible in implementing an atomic type. In writing specifications for atomic types, we have found it helpful to pin down the behavior of the operations, initially assuming no concurrency and no failures, and to deal with concurrency and failures later. In other words, we imagine that the objects will exist in an environment in which all actions are executed sequentially, and in which actions never abort.

Although a sequential specification of this sort does not say anything explicit about permissible concurrency, it does impose limits on how much concurrency can be provided. Implementations can differ in how much concurrency is provided, but no implementation can exceed these limits. Therefore, it is important to understand what the limits are.

This section and the following section together provide a precise definition of permissible concurrency for an atomic type. This definition is based on two facts about Argus and the way it supports implementations of atomic type. First, in implementing an atomic type, it is only necessary to be concerned about active actions. Once an action has committed to the top, it is not possible for it to be aborted later, and its changes to atomic objects become visible to other actions. So, for example, an implementation of an atomic type needs to prevent one action from observing the modifications of other actions that are still active, but it does not have to prevent an action from observing modifications by actions that have already committed. Second, the only method available to an atomic type for controlling the activities of actions is to delay actions while they are executing operations of the type. An atomic type cannot prevent an action from calling an operation, although it can prevent that call from proceeding. Also, an atomic type cannot prevent an action that previously finished a call of an operation from completing either by committing or by aborting.

Given the sequential specification of the operations of a type, these facts lead to two constraints on the concurrency permitted among actions using the type. While an implementation can allow no more concurrency than permitted by these constraints, some implementations, like that for the built-in type generator atomic_array (see Section 11.10), may allow less concurrency than permitted by their sequential specifications and our concurrency constraints.

The first constraint is that

- an action can observe the effects of other actions only if those actions committed relative to the first action.

This constraint implies that the results returned by operations executed by one action can reflect changes made by operations executed by other actions only if those actions committed relative to the first action. For example, in an atomic array a, if one action performs a store(a, 3, 7), a second (unrelated) action can receive the answer “7” from a call of fetch(a, 3) only if the first action committed to the top. If the first action is still active, the second action must be delayed until the first action completes. This first constraint supports recoverability since it ensures that effects of aborted actions cannot be observed by other actions. It also supports serializability, since it prevents concurrent actions from observing one another’s changes.
However, more is needed for serializability. Thus, we have our second constraint:

- operations executed by one action cannot invalidate the results of operations executed by a concurrent action.

For example, suppose an action $A$ executes the size operation on an atomic array object, receiving $n$ as the result. Now suppose another action $B$ is permitted to execute addh. The addh operation will increase the size of the array to $n + 1$, invalidating the results of the size operation executed by $A$. Since $A$ observed the state of the array before $B$ executed addh, $A$ must precede $B$ in any sequential execution of the actions (since sequential executions must be consistent with the sequential specifications of the objects). Now suppose that $B$ commits. By assumption, $A$ cannot be prevented from seeing the effects of $B$. If $A$ observes any effect of $B$, it will have to follow $B$ in any sequential execution. Since $A$ cannot both precede and follow $B$ in a sequential execution, serializability would be violated. Thus, once $A$ executes size, an action that calls addh must be delayed until $A$ completes.

15.5. Commuting Operations

To state our requirements more precisely, consider a simple situation involving two concurrent actions each executing a single operation on a shared atomic object $X$. (The actions may be executing operations on other shared objects also, but in Argus each object must individually ensure the atomicity of the actions using it, so we focus on the operations involving a single object.) A fairly simple condition that guarantees serializability is the following. Suppose $X$ is an object of type $T$. $X$ has a current state determined by the operations performed by previously committed actions. Suppose $O_1$ and $O_2$ are two executions of operations on $X$ in its current state. ($O_1$ and $O_2$ might be executions of the same operation or different operations.) If $O_1$ has been executed by an action $A$ and $A$ has not yet committed or aborted, $O_2$ can be performed by a concurrent action $B$ only if $O_1$ and $O_2$ commute: given the current state of $X$, the effect (as described by the sequential specification of $T$) of performing $O_1$ on $X$ followed by $O_2$ is the same as performing $O_2$ on $X$ followed by $O_1$. It is important to realize that when we say "effect" we include both the results returned and any modifications to the state of $X$.

The intuitive explanation of why the above condition works is as follows. Suppose $O_1$ and $O_2$ are performed by concurrent actions $A$ and $B$ at $X$. If $O_1$ and $O_2$ commute, then the order in which $A$ and $B$ are serialized globally does not matter at $X$. If $A$ is serialized before $B$, then the local effect at $X$ is as if $O_1$ were performed before $O_2$ while if $B$ is serialized before $A$, the local effect is as if $O_2$ were performed before $O_1$. But these two effects are the same since $O_1$ and $O_2$ commute.

The common method of dividing operations into readers and writers and using read/write locking works because it allows operations to be executed by concurrent actions only when the operations commute. More concurrency is possible with our commutativity condition than with readers/writers because the meaning of the individual operations and the arguments of the calls can be considered. For example, calls of the atomic array operation addh always commute with calls of addl, yet both these operations are writers. As another example, store($X$, $i$, $e_1$) and store($X$, $j$, $e_2$) commute if $i \neq j$.

We require only that $O_1$ and $O_2$ commute when they are executed starting in the current state.
Consider a bank account object, with operations to deposit a sum of money, to withdraw a sum of money (with the possible result that it signals *insufficient funds* if the current balance is less than the sum requested), and to examine the current balance. Two withdraw operations, say for amounts \( m \) and \( n \), do not commute when the current balance is the maximum of \( m \) and \( n \): either operation when executed in this state will succeed in withdrawing the requested sum, but the other operation must signal *insufficient funds* if executed in the resulting state. They do commute whenever the current balance is at least the sum of \( m \) and \( n \). Thus if one action has executed a withdraw operation, our condition allows a second action to execute another withdraw operation while the first action is still active as long as there are sufficient funds to satisfy both withdrawal requests.

Our condition must be extended to cover two additional cases. First, there may be more than two concurrent actions at a time. Suppose \( A_1, \ldots, A_n \) are concurrent actions, each performing a single operation execution \( O_1, \ldots, O_m \) respectively, on \( X \). (As before, the concurrent actions may be sharing other objects as well.) Since \( A_1, \ldots, A_n \) are permitted to be concurrent at \( X \), there is no local control over the order in which they may appear to occur. Therefore, all possible orders must have the same effect at \( X \). This is true provided that all permutations of \( O_1, \ldots, O_m \) have the same effect when executed in the current state, where effect includes both results obtained and modifications to \( X \).

The second extension acknowledges that actions can perform sequences of operation executions. Consider concurrent actions \( A_1, \ldots, A_n \) each performing a sequence \( S_1, \ldots, S_n \) respectively, of operation executions. This is permissible if all sequences \( S_1, \ldots, S_m \) obtained by concatenating the sequences \( S_1, \ldots, S_n \) in some order, produce the same effect. For example, suppose action \( A \) executed \( addh \) followed by \( remh \) on an array. This sequence of operations has no net effect on the array. It is then permissible to allow a concurrent action \( B \) to execute \( size \) on the same array, provided the answer returned is the size of the array before \( A \) executed \( addh \) or after it executed \( remh \).

Note that in requiring certain sequences of operations to have the same effect, we are considering the effect of the operations as described by the specification of the type. Thus we are concerned with the abstract state of \( X \), and not with the concrete state of its storage representation. Therefore, we may allow two operations (or sequences of operations) that do commute in terms of their effect on the abstract state of \( X \) to be performed by concurrent actions, even though they do not commute in terms of their effect on the representation of \( X \). This distinction between an abstraction and its implementation is crucial in achieving reasonable performance.

It is important to realize that the constraints that are imposed by atomicity based on the sequential specification of a type are only an upper bound on the concurrency that an implementation may provide. A specification may contain additional constraints that further constrain implementations; these constraints may be essential for showing that actions using the type do not deadlock, or for showing other kinds of termination properties. For example, the specification of the built-in atomic types explicitly describes the locking rules used by their implementations; users of these types are guaranteed that the built-in atomic types will not permit more concurrency than allowed by these rules (for instance, actions writing different components of an array, or different fields of a record, cannot do so concurrently).
15.6. Multiple Mutexes

Section 15.2 presented a discussion of copying mutex objects to stable storage. That discussion is adequate for simple implementations that use just one mutex object. Sometimes, however, it is desirable to use more than one mutex object in representing a user-defined atomic object; for example, a partitioned data base would be implemented this way. Such implementations require an understanding of some details that could be ignored when just one mutex object was used in the representation. In particular, the implementor must understand the effects of crashes on recovery of mutex objects and some problems that can arise because copying to stable storage is incremental.

The writing of mutex objects to stable storage is recoverable for each topaction at each guardian: either all mutexes modified by an action at a guardian are installed on stable storage, or none of them are. That is, if an action modified more than one mutex object at a guardian, then after a crash either all those objects will be recovered, or none of them will be. This property makes it easier to preserve consistency among multiple mutex objects. However, even if an action aborts, the new versions of mutexes it modified may still be recovered from stable storage after a crash; Argus only guarantees that if any new versions are recovered, all of them will be. Note also that when an action aborts, it is possible that new versions will be installed at some of the guardians but not at others.

Although mutex objects modified by a single action are installed on stable storage as a group, the copies are made one at a time. Incremental copying has the following impact on programs. The true state of an object usually includes the states of all contained objects, and a predicate (the representation invariant) expressing a consistency condition on an object state would normally constrain the states of contained objects. For example, suppose we had an atomic type semiqueue that allowed concurrent actions to enqueue and dequeue different items (that is, for a semiqueue the enq and deq operations commute so long as they involve different objects in the semiqueue). Then consider an implementation of a double-queue that (for some reason) kept two copies of the semiqueue and was represented by:

```c
rep = struct [first, second: semiqueue]
```

where the representation invariant required that the states of the two semiqueues be the same. Now suppose the system is handling the top-level commit of some action A that modified both semiqueues contained in the double-queue, and while this is happening a second action B is modifying those semiqueues. Then it is possible that when the first semiqueue is written to stable storage it contains B's changes, but when the second semiqueue is written to stable storage it does not contain B's changes. Therefore, the information in stable storage appears not to satisfy the representation invariant of the double-queue.

However, the representation invariant of the double-queue really is satisfied, for the following reason. First note that the information in stable storage is only of interest after a crash. So suppose there is a crash. Now there are two possibilities:

15See Weihl, W. and Liskov, B., "Implementation of Resilient, Atomic Data Types," ACM Transactions on Programming Languages and Systems, volume 7, number 2 (April 1985), pages 244-269.
1. Before that crash, $B$ also committed to the top. In this case the data read back from stable storage is, in fact, consistent, since it must reflect $B$'s changes to both the first and second semiquotes.

2. $B$ aborted or had not yet committed before the crash. In either case, $B$ aborts. Therefore, the changes made to the first semiquue by $B$ will be hidden by the semiquue implementation: at the abstract level, the two semiquues do have the same state.

The point of the above example is that if the objects being written to stable storage are atomic, then the fact that they are written incrementally causes no problems.

On the other hand, when an atomic type is implemented with a representation consisting of several mutex objects, the programmer must be aware that these objects are written to stable storage incrementally, and care must be taken to ensure that the representation invariant is still preserved and that information is not lost in spite of incremental writing. If the implementation of a type requires that one mutex object (call it $M_1$) be written to stable storage before another (call it $M_2$), then the write of $M_1$ must be contained in an action that commits to the top before the action that writes $M_2$ is run.
Appendix I
Syntax

We use an extended BNF grammar to define the syntax. The general form of a production is

nonterminal ::= alternative
  | alternative
  | ...
  | alternative

The following extensions are used:

a , ... a list of one or more as separated by commas: "a" or "a, a" or "a, a, a", etc.
{ a } a sequence of zero or more as: " " or "a" or "a a", etc.
[ a ] an optional a: " " or "a".

Nonterminal symbols appear in normal face. Reserved words appear in bold face. All other terminal symbols are nonalphabetic and appear in normal face.

module ::= { equate } equates
  | { equate } guardian
  | { equate } procedure
  | { equate } iterator
  | { equate } cluster
equates ::= idn = equates [ parms [ where ] ]
  equate { equate }
  end idn
guardian ::= idn = guardian [ parms ] is idn , ... [ handles idn , ... ] [ where ]
  { equate }
  { state_decl }
  [ recover body end ]
  [ background body end ]
  { operation } creator { operation }
  end idn
cluster ::= idn = cluster [ parms ] is opidn , ... [ where ]
  { equate } rep = type_spec { equate }
  { own_var }
  routine { routine }
  end idn
operation ::= creator
| handler
| routine

routine ::= procedure
| iterator

procedure ::= idn = proc [ parms ] args [ returns ] [ signals ] [ where ]
  routine_body
end idn

iterator ::= idn = iter [ parms ] args [ yields ] [ signals ] [ where ]
  routine_body
end idn

creator ::= idn = creator args [ returns ] [ signals ]
  routine_body
end idn

handler ::= idn = handler args [ returns ] [ signals ]
  routine_body
end idn

routine_body ::= { equate }
  { own_var }
  { statement }

parms ::= [ parm, ... ]

parm ::= idn, ... : type
| idn, ... : type spec

args ::= ( [ decl, ... ] )

decl ::= idn, ... : type spec

returns ::= returns ( type_spec, ... )

yields ::= yields ( type_spec, ... )

signals ::= signals ( exception, ... )

exception ::= name [( type_spec, ... )]
1 Syntax

opidn ::= idn
   | transmit

where ::= where restriction, ...

restriction ::= idn has oper_decl, ...
   | idn in type_set

type_set ::= { idn | idn has oper_decl, ... { equate } }
   | idn
   | reference $ name

oper_decl ::= name, ..., : type_spec
   | transmit

constant ::= expression
   | type_spec

state_decl ::= [ stable ] decl
   | [ stable ] idn : type_spec := expression
   | [ stable ] decl, ..., := call

equate ::= idn = constant
   | idn = type_set
   | idn = reference

own_var ::= own decl
   | own idn : type_spec := expression
   | own decl, ..., := call [ @ primary ]
statement ::= decl
| idn : type_spec ::= expression
| decl , ... ::= call [@ primary ]
| idn , ... ::= call [@ primary ]
| idn , ... ::= expression , ...
| primary . name ::= expression
| primary [ expression ] ::= expression
| call [@ primary ]
| fork call
| seize expression do body end
| pause
| terminate
| enter_stmt
| coenter coarm { coarm } end
| [ abort ] leave
| while expression do body end
| for_stmt
| if_stmt
| tagcase_stmt
| tagtest_stmt
| tagwait_stmt
| [ abort ] return [ ( expression , ... ) ]
| yield [ ( expression , ... ) ]
| [ abort ] signal name [ ( expression , ... ) ]
| [ abort ] exit name [ ( expression , ... ) ]
| [ abort ] break
| [ abort ] continue
| begin body end
| statement [ abort ] resignal name , ...
| statement except { when_handler }
| [ others_handler ]
| end

enter_stmt ::= enter topaction body end
| enter action body end
I Syntax

coarm ::= armtag [ foreach decl, ... in call ] body

armtag ::= action
| topaction
| process

for_stmt ::= for [ decl, ... ] in call do body end
| for [ idn, ... ] in call do body end

if_stmt ::= if expression then body
{ elseif expression then body }
[ else body ]
end

tagcase_stmt ::= tagcase expression
tag_arm { tag_arm }
[ others : body ]
end

tagtest_stmt ::= tagtest expression
atag_arm { atag_arm }
[ others : body ]
end

tagwait_stmt ::= tagwait expression
atag_arm { atag_arm }
end

tag_arm ::= tag name, ... [ ( idn : type_spec ) ] : body

atag_arm ::= tag_kind name, ... [ ( idn : type_spec ) ] : body

tag_kind ::= tag
| wtag

when_handler ::= when name, ... [ ( decl, ... ) ] : body
| when name, ... ( * ) : body

others_handler ::= others [ ( idn : type_spec ) ] : body

body ::= { equate }
{ statement }
### Syntax

**type_spec** ::= null

<table>
<thead>
<tr>
<th>node</th>
<th>bool</th>
<th>int</th>
<th>real</th>
<th>char</th>
<th>string</th>
<th>any</th>
<th>image</th>
<th>rep</th>
<th>cvt</th>
</tr>
</thead>
<tbody>
<tr>
<td>sequence [ type_actual ]</td>
<td>array [ type_actual ]</td>
<td>atomic_array [ type_actual ]</td>
<td>struct [ field_spec , ... ]</td>
<td>record [ field_spec , ... ]</td>
<td>atomic_record [ field_spec , ... ]</td>
<td>oneof [ field_spec , ... ]</td>
<td>variant [ field_spec , ... ]</td>
<td>atomic_variant [ field_spec , ... ]</td>
<td>proctype ( [ type_spec , ... ] ) [ returns ] [ signals ]</td>
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<td>itertype ( [ type_spec , ... ] ) [ yields ] [ signals ]</td>
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<td>creatortype ( [ type_spec , ... ] ) [ returns ] [ signals ]</td>
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<td>handliertype ( [ type_spec , ... ] ) [ returns ] [ signals ]</td>
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<td>mutex [ type_actual ]</td>
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<td>reference</td>
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<td></td>
<td></td>
<td></td>
<td>reference</td>
</tr>
</tbody>
</table>

**field_spec** ::= name , ... : type_actual

**reference** ::= idn

| idn [ actual_parm , ... ] |
| reference $ name |

**actual_parm** ::= constant

| type_actual |
| type_spec [ wth { where opbinding , ... } ] |

**type_actual** ::= type_spec [ wth { where opbinding , ... } ]

**opbinding** ::= name , ... : primary
expression ::= primary
  | call @ primary
  | ( expression )
  | ~ expression
  | - expression
  | expression ** expression
  | expression // expression
  | expression / expression
  | expression * expression
  | expression || expression
  | expression + expression
  | expression - expression
  | expression < expression
  | expression <= expression
  | expression = expression
  | expression >= expression
  | expression > expression
  | expression ~< expression
  | expression ~<= expression
  | expression ~= expression
  | expression ~>= expression
  | expression ~> expression
  | expression & expression
  | expression and expression
  | expression | expression
  | expression cor expression

primary ::= entity
  | call
  | primary . name
  | primary [ expression ]

call ::= primary ( [ expression , ... ] )
entity ::= nil
  | true
  | false
  | int.literal
  | real.literal
  | char.literal
  | string.literal
  | self
  | reference
  | entity . name
  | entity [ expression ]
  | bind entity ([ bind_arg , ... ])
  | type_spec $ [ field , ... ]
  | type_spec $ [ expression : ] [ expression , ... ]
  | type_spec $ name [ [ actual_parm , ... ]]
  | up ( expression )
  | down ( expression )

field ::= name , ... : expression

bind_arg ::= .
  | expression
Comment: a sequence of characters that begins with a percent sign (%), ends with a newline character, and contains only printing ASCII characters and horizontal tabs in between.

Separator: a blank character (space, vertical tab, horizontal tab, carriage return, newline, form feed) or a comment. Zero or more separators may appear between any two tokens, except that at least one separator is required between any two adjacent non-self-terminating tokens: reserved words, identifiers, integer literals, and real literals.

Reserved word: one of the identifiers appearing in bold face in the syntax. Upper and lower case letters are not distinguished in reserved words.

Name, idn: a sequence of letters, digits, and underscores that begins with a letter or underscore, and that is not a reserved word. Upper and lower case letters are not distinguished in names and idns.

Int_l literal: a sequence of one or more decimal digits (0-9) or a backslash (\) followed by any number of octal digits (0-7) or a backslash and a sharp sign (#) followed by any number of hexadecimal digits (0-9, A-F in upper or lower case).

Real_l literal: a mantissa with an (optional) exponent. A mantissa is either a sequence of one or more decimal digits, or two sequences (one of which may be empty) joined by a period. The mantissa must contain at least one digit. An exponent is 'E' or 'e', optionally followed by '+' or '-', followed by one or more decimal digits. An exponent is required if the mantissa does not contain a period.

Char_l literal: a character representation other than single quote, enclosed in single quotes. A character representation is either a printing ASCII character (octal value 40 through 176) other than backslash, or an escape sequence consisting of a backslash (\) followed one to three printing characters as shown in Table 6-1 or Table 1-1 below.

String_l literal: a sequence of zero or more character representations other than double quote, enclosed in double quotes.

Table 1-1 shows most of the character literals supported by Argus, except for the higher numbered octal escape sequences. For each character, the corresponding octal literal, hexadecimal literal, and normal literal(s) are shown. Upper or lower case letters may be used in escape sequences of the form \n**, \n*, \n', \n, \n, \p, and \r. Note that an implementation need not support 256 characters, in which case only a subset of the literals listed will be legal.
### Table I-1: Character Escape Sequences

<table>
<thead>
<tr>
<th>Code</th>
<th>Character</th>
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<th>Character</th>
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Appendix II
Built-in Types and Type Generators

The following sections specify the built-in types and the types produced by the built-in type generators of Argus. For each type and for each instance of each type generator, the objects of the type are characterized, and all of the operations of the type are defined. (An implementation may provide additional operations on the built-in types, as long as these are operations that could be implemented in terms of those described in this section.)

All the built-in types (except for any) are transmissible. All instances of the built-in type generators (except for proctype and lertype) are transmissible if all their type parameters are transmissible. Transmission of the built-in types preserves value equality, except for objects of type real. However, in a homogeneous environment, reals can be transmitted without approximations. In a homogeneous environment, the only possible encode or decode failures are exceeding the representation limits of an Image, mutating the size of an array or atomic_array while it is being encoded or decoded, and improper decoding of cyclic objects (see Section 14.4).

All operations are indivisible except at calls to subsidiary operations (such as int$similar within array[int]$similar), at yields, and while waiting for locks.

The specifications given below are informal and are adapted from the book Abstraction and Specification in Program Development (Liskov, B. and Guttag, J., MIT Press, 1986). A specification starts out by giving a list of the operations and declarations of any formal parameters for the type. This is followed by an overview, which gives an introduction to the type and if necessary defines a way of describing the type's objects and their values. Following this the individual operations are described. For each operation there is a heading and a statement of the operation's effects. In the heading, the return values may be given names. The effects section describes the normal and exceptional behavior of the operation. The effects given are abstract, that is they are described using the vocabulary (or model) defined in the overview section. For example, objects of type Int are described using mathematical integers. Thus arithmetic expressions and comparisons used in defining Int operations are to be computed over the domain of mathematical integers.

An operation that (abstractly) mutates one of its arguments lists the arguments that it mutates in the clause following the word modifies. An operation is not allowed to mutate any objects, except for those listed in the modifies clause. (For the built-in mutable atomic type generators, modification only refers to the sequential state; it does not refer to changes in the locking information kept for each object.) When an argument, say a, is mutated, it is often necessary to describe its state at the start of the call as well as its final state at the end of the call. We use the notation $a_{\text{pre}}$ for a's state at the start of the call and the notation $a_{\text{post}}$ for its state at the end of the call.

Some operations of the built-in type generators are only defined if the type generator is passed appropriate actual routine parameters (see Section 12.6). For example, the copy operation of the array
type generator, is only defined if there is an actual parameter passed (explicitly or implicitly) for the type parameter's copy operation. Thus array[int]$copy is defined but array[any]$copy is not defined. These requirements are stated in a requires clause that precedes the description of the operation's effect. The type of the expected routine is also described; remember that the actual operation parameter can have fewer signals (see Section 6.1 and Section 12.6).

By convention, the order in which exceptions are listed in the operation type is the order in which the various conditions are checked.

Operations with the same semantics (for example, null$equal and null$similar) or that can be described in the same way (for example, int$add and int$sub) are grouped together to save space.

In defining the built-in types, we do not depend on users satisfying any constraints beyond those that can be type-checked. This decision leads to more complicated specifications. For example, the behavior of the elements iterator for arrays is defined even when the loop modifies the array.

II.1. Null
null = data type is copy, equal, similar, transmit

Overview

The type null has exactly one, immutable, atomic object, represented by the literal nil. Nil is generally used as a place holder in type definitions using oneofs or variants.

Operations

equal = proc (n1, n2: null) returns (bool)
similar = proc (n1, n2: null) returns (bool)
effects Returns true.

copy = proc (n: null) returns (null)
transmit = proc (n: null) returns (null)
effects Returns nil.

II.2. Nodes
node = data type is here, copy, equal, similar, transmit

Overview

Objects of type node are immutable and atomic, and stand for physical nodes. Implementations should provide some mechanism for translating a node "address" into a node object and vice versa. (However, these do not have to be operations of type node.)

Operations

here = proc () returns (node)
effects Returns the node object for the caller's node.

equal = proc (n1, n2: node) returns (bool)
similar = proc (n1, n2: node) returns (bool)
effects Returns true if and only if n1 and n2 are the same node.
11.2 Nodes

\[\text{copy} = \text{proc} \ (n: \text{node}) \ \text{returns} \ (\text{node})\]
\[\text{transmit} = \text{proc} \ (n: \text{node}) \ \text{returns} \ (\text{node})\]
\[\text{effects Returns } n.\]

11.3. Booleans

\[\text{bool} = \text{data type is and, or, not, equal, similar, copy, transmit}\]

**Overview**

The two immutable, atomic objects of type bool, with literals true and false, represent logical truth values.

The language also provides the operators \text{cand} and \text{cor} for conditional evaluation of boolean expressions, see Section 9.15.

**Operations**

\[\text{and} = \text{proc} \ (b1, b2: \text{bool}) \ \text{returns} \ (\text{bool})\]
\[\text{effects Returns true if } b1 \text{ and } b2 \text{ are both true; returns false otherwise.}\]

\[\text{or} = \text{proc} \ (b1, b2: \text{bool}) \ \text{returns} \ (\text{bool})\]
\[\text{effects Returns true if either } b1 \text{ or } b2 \text{ is true; returns false otherwise.}\]

\[\text{not} = \text{proc} \ (b: \text{bool}) \ \text{returns} \ (\text{bool})\]
\[\text{effects Returns false if } b \text{ is true; returns true if } b \text{ is false.}\]

\[\text{equal} = \text{proc} \ (b1, b2: \text{bool}) \ \text{returns} \ (\text{bool})\]
\[\text{similar} = \text{proc} \ (b1, b2: \text{bool}) \ \text{returns} \ (\text{bool})\]
\[\text{effects Returns true if } b1 \text{ and } b2 \text{ are both true or both false; otherwise returns false.}\]

\[\text{copy} = \text{proc} \ (b: \text{bool}) \ \text{returns} \ (\text{bool})\]
\[\text{transmit} = \text{proc} \ (b: \text{bool}) \ \text{returns} \ (\text{bool})\]
\[\text{effects Returns } b.\]

11.4. Integers

\[\text{Int} = \text{data type is add, sub, mul, minus, div, mod, power, abs, from_to_by, from_to, max, min, parse, unparse, lt, le, ge, gt, equal, similar, copy, transmit}\]

**Overview**

Objects of type Int are immutable and atomic, and are intended to model a subrange of the mathematical integers. The exact range is not part of the language definition and can vary somewhat from implementation to implementation. Each implementation is constrained to provide a closed interval \([\text{int_min}, \text{int_max}]\), with \(\text{int_min} < 0\) and \(\text{int_max} \geq \text{char_top}\) (the number of characters — see Section 11.6). An overflow exception is signalled by an operation if the result would lie outside this interval. See Appendix I for the syntax of integer literals.

**Operations**

\[\text{add} = \text{proc} \ (x, y: \text{Int}) \ \text{returns} \ (\text{Int}) \ \text{signals} \ (\text{overflow})\]
\[\text{sub} = \text{proc} \ (x, y: \text{Int}) \ \text{returns} \ (\text{Int}) \ \text{signals} \ (\text{overflow})\]
\[\text{mul} = \text{proc} \ (x, y: \text{Int}) \ \text{returns} \ (\text{Int}) \ \text{signals} \ (\text{overflow})\]
\[\text{effects} \ \text{These are the standard integer addition, subtraction, and multiplication operations.}\]
\[\text{They signal overflow if the result would lie outside the represented interval.}\]
minus = proc (x: Int) returns (Int) signals (overflow)
effects Returns the negative of \( x \); signals overflow if the result would lie outside the represented interval.

div = proc (x, y: Int) returns (q: Int) signals (zero_divide, overflow)
effects Signals zero_divide if \( y = 0 \). Otherwise returns the integer quotient of dividing \( x \) by \( y \); that is, \( x = y \times q + r \), for some integer \( q \) such that \( 0 \leq r < |y| \). Signals overflow if \( q \) would lie outside the represented interval.

mod = proc (x, y: Int) returns (r: Int) signals (zero_divide, overflow)
effects Signals zero_divide if \( y = 0 \). Otherwise returns the integer remainder of dividing \( x \) by \( y \); that is, \( r \) is such that \( 0 \leq r < |y| \), for some integer \( q \); \( x = y \times q + r \). Signals overflow if \( r \) would lie outside the represented interval.

copy = proc (x: Int) returns (Int)
effects Returns \( x \).

\( 0^0 = 1 \) by definition.
transmit = proc (x: Int) returns (y: Int) signals(failure(string))
  effects Returns y such that x = y or signals failure if x cannot be represented in the
  implementation on the receiving end.

II.5. Reals
real = data type Is add, sub, minus, mul, div, power, abs, max, min, exponent, mantissa, i2r, r2i,
  trunc, parse, unparse, lt, le, ge, gt, equal, similar, copy, transmit

Overview
The type real models a subset of the mathematical numbers. It is used for approximate or floating
point arithmetic. Reals are immutable and atomic, and are written as a mantissa with an optional
exponent. See Appendix I for the format of real literals.

Each implementation represents a subset of the real numbers in:
D = [-real_max, -real_min] U {0} U (real_min, real_max)
where
0 < real_min < 1 < real_max
Numbers in D are approximated by the implementation with a precision of p decimal digits such that:

\[
\forall r \in D \quad \text{Approx}(r) \in \text{Real} \\
\forall r \in \text{Real} \quad \text{Approx}(r) = r \\
\forall r \in D - \{0\} \quad |(\text{Approx}(r) - r)/r| < 10^{-p} \\
\forall r, s \in D \quad r \leq s \Rightarrow \text{Approx}(r) \leq \text{Approx}(s) \\
\forall r \in D \quad \text{Approx}(-r) = -\text{Approx}(r)
\]

We define Max_width and Exp_width to be the smallest integers such that every nonzero element
of real can be represented in "standard" form (exactly one digit, not zero, before the decimal
point) with no more than Max_width digits of mantissa and no more than Exp_width digits of
exponent.

Real operations signal an exception if the result of a computation lies outside of D; overflow
occurs if the magnitude exceeds real_max, and underflow occurs if the magnitude is less than
real_min.

Operations
add = proc (x, y: real) returns (real) signals (overflow, underflow)
  effects Computes the sum z of x and y; signals overflow or underflow if z is outside of D, as
  explained earlier. Otherwise returns an approximation such that:
  (x,y ≥ 0 v x,y ≤ 0) ⇒ add(x, y) = Approx(x + y)
  add(x, y) = (1 + e)(x + y) \quad |e| < 10^{-p}
  add(x, 0) = x
  add(x, y) = add(y, x)
  x ≤ x' ⇒ add(x, y) ≤ add(x', y)

sub = proc (x, y: real) returns (real) signals (overflow, underflow)
  effects Computes x - y; the result is identical to add(x, -y).

minus = proc (x: real) returns (real)
  effects Returns -x.

mul = proc (x, y: real) returns (real) signals (overflow, underflow)
  effects Returns approx(x*y); signals overflow or underflow if x*y is outside of D.

div = proc (x, y: real) returns (real) signals (zero divide, overflow, underflow)
  effects If y = 0, signals zero divide. Otherwise returns approx(x/y); signals overflow or
  underflow if x/y is outside of D.
power = proc (x, y: real) returns (real)
signals (zero_divide, complex_result, overflow, underflow)
  effects If \( x = 0 \) and \( y < 0 \), signals zero_divide. If \( x < 0 \) and \( y \) is nonintegral, signals complex_result. Otherwise returns an approximation to \( x^y \), good to \( p \) significant digits; signals overflow or underflow if \( x^y \) is outside of \( D \).

abs = proc (x: real) returns (real)
effects Returns the absolute value of \( x \).

max = proc (x, y: real) returns (real)
effects If \( x \geq y \), then returns \( x \), otherwise returns \( y \).

min = proc (x, y: real) returns (real)
effects If \( x \leq y \), then returns \( x \), otherwise returns \( y \).

exponent = proc (x: real) returns (Int) signals (undefined)
effects If \( x = 0 \), signals undefined. Otherwise returns the exponent that would be used in representing \( x \) as a literal in standard form, that is, \( \left\{ (i \mid |abs(x)| > 10^i) \right\} \) (with 0 in \( D \)).

mantissa = proc (x: real) returns (real)
effects Returns the mantissa of \( x \) when represented in standard form, that is, returns \( \approx(x/10^e) \), where \( e = \text{exponent}(x) \). If \( x = 0.0 \), returns 0.0.

i2r = proc (i: Int) returns (real) signals (overflow)
effects Returns \( \approx(i) \); signals overflow if \( i \) is not in \( D \).

r2i = proc (x: real) returns (Int) signals (overflow)
effects Rounds \( x \) to the nearest integer and toward zero in case of a tie. Signals overflow if the result lies outside the represented range of integers.

trunc = proc (x: real) returns (Int) signals (overflow)
effects Truncates \( x \) toward zero; signals overflow if the result would be outside the represented range of integers.

parse = proc (s: string) returns (real) signals (bad_format, overflow, underflow)
effects Returns \( \approx(z) \), where \( z \) is the value represented by the string \( s \) (see Appendix I). \( S \) must represent a real or integer literal with an optional leading plus or minus sign; otherwise signals bad_format. Signals underflow or overflow if \( z \) is not in \( D \).

unparse = proc (x: real) returns (string)
effects Returns a real literal such that \( \text{parse(unparse}(x)) = x \). The general form of the literal is:

\[
[ - ] i \_field . f \_field \ [ e \pm x \_field ]
\]

Leading zeros in \( i \_field \) and trailing zeros in \( f \_field \) are suppressed. If \( x \) is integral and within the range of represented integers, then \( f \_field \) and the exponent are not present. If \( x \) can be represented by a mantissa of no more than \( \text{Max\_width} \) digits and no exponent (that is, if \(-1 \leq \text{exponent}(\text{arg1}) < \text{Max\_width}\) ), then the exponent is not present. Otherwise the literal is in standard form, with \( \text{Exp\_width} \) digits of exponent.

lt = proc (x, y: real) returns (bool)
le = proc (x, y: real) returns (bool)
ge = proc (x, y: real) returns (bool)
gt = proc (x, y: real) returns (bool)
effects These are the standard ordering relations.

equal = proc (x, y: real) returns (bool)
similar = proc (x, y: real) returns (bool)
effects Returns true if \( x \) and \( y \) are the same number; returns false otherwise.
11.5 Reals

copy = proc (x: real) returns (real)
effects Returns x.

transmit = proc (x: real) returns (real) signals (failure(string))
effects Returns approx{x} where approx' is the approximation function for the receiving
implementation of Argus or signals failure if this cannot be represented on the receiving
end.

11.6. Characters

char = data type ls i2c, c2i, lt, le, ge, gt, equal, similar, copy, transmit

Overview

Type char provides the alphabet for text manipulation. Characters are immutable and atomic, and
form an ordered set. Every implementation must provide at least 128, but no more than 512,
characters; the first 128 characters are the ASCII characters in their standard order.

Operations i2c and c2i convert between Ints and chars (using the ASCII coding for the first 128
characters). The smallest character corresponds to zero, and characters are numbered
sequentially up to char_top, the integer corresponding to the largest character. This numbering
determines the ordering of the characters.

Printing ASCII characters (octal 40 through octal 176), other than single quote or backslash, can
be written as that character enclosed in single quotes. See Appendix I for the syntax of character
literals and tables of character escape sequences.

Operations

i2c = proc (x: int) returns (char) signals (illegal_char)
effects Returns the character corresponding to x; signals illegal_char if x is not in the range
[0, char_top].

c2i = proc (c: char) returns (int)
effects Returns the integer corresponding to c (using the ASCII coding if c is an ASCII
character).

lt = proc (c1, c2: char) returns (bool)
le = proc (c1, c2: char) returns (bool)
ge = proc (c1, c2: char) returns (bool)
gt = proc (c1, c2: char) returns (bool)
effects These are the standard ordering relations, where the order is consistent with the
numbering of characters. That is, c1 < c2 just when c2i(c1) < c2i(c2).

equal = proc (c1, c2: char) returns (bool)
similar = proc (c1, c2: char) returns (bool)
effects Returns true if c1 and c2 are the same character, i.e., returns (c2i(c1) = c2i(c2)).

copy = proc (c1: char) returns (char)
effects Returns c1.

transmit = proc (c1: char) returns (char) signals (failure(string))
effects Returns c1. Signals failure only if c1 is not representable by the implementation on
the receiving end.
II.7. Strings

string = data type Is c2s, concat, append, substr, rest, size, empty, fetch, chars, indexes, indexc,
s2ac, ac2s, s2sc, sc2s, lt, le, ge, gt, equal, similar, copy, transmit

Overview

Type string is used for representing text. A string is an immutable and atomic tuple of zero or more characters. The characters of a string are indexed sequentially starting from one. Strings are lexicographically ordered based on the ordering for characters.

A string literal is written as a sequence of zero or more character representations enclosed in double quotes. See Appendix I for a description of the character escape sequences that can be used within string literals. No string can have a size greater than int_max; however, an implementation may restrict string lengths to a value less than int_max. If the result of a string operation would be a string containing more than the maximum number of characters, the operation signals limits.

Operations

c2s = proc (c: char) returns (string)
  effects Returns a string containing c as its only character.

concat = proc (s1, s2: string) returns (r: string) signals (limits)
  effects Returns the concatenation of s1 and s2. That is, r[i]=s1[i] for i an index of s1 and r[i]=s2[i] for i an index of s2. Signals limits if r would be too large for the implementation.

append = proc (s: string, c: char) returns (r: string) signals (limits)
  effects Returns a new string having the characters of s in order followed by c. That is, r[size(s)+1] = c. Signals limits if the new string would be too large for the implementation.

substr = proc (s: string, at: Int, cnt: Int) returns (string) signals (bounds, negativesize)
  effects If cnt < 0, signals negative size. If at < 1 or at > size(s)+1, signals bounds. Otherwise returns a string having the characters s[at], s[at+1], ... in that order; the new string contains min(cnt, size-at+1) characters. For example,
  substr ("abcdef", 2, 3) = "bcd"
  substr ("abcdef", 2, 7) = "bcdef"
  substr ("abcdef", 7, 1) = "

  Note that if min(cnt, size-at+1) = 0, substr returns the empty string.

rest = proc (s: string, i: Int) returns (r: string) signals (bounds)
  effects Signals bounds if i < 0 or i > size(s) + 1; otherwise returns a string whose first character is s[i], whose second is s[i+1], ..., and whose size(i)th character is s[size(s)].
  Note that if i = size(s)+1, rest returns the empty string.

size = proc (s: string) returns (Int)
  effects Returns the number of characters in s.

empty = proc (s: string) returns (bool)
  effects Returns true if s is empty (contains no characters); otherwise returns false.

fetch = proc (s: string, i: Int) returns (char) signals (bounds)
  effects Signals bounds if i < 0 or i > size(s); otherwise returns the i\text{th} character of s.

chars = iter (s: string) yields (char)
  effects Yields, in order, each character of s (i.e., s[1], s[2], ...).
\textbf{indexs} = \textbf{proc} (s1, s2: string) \textbf{returns} (int)
\hspace{1em} \textbf{effects} If \textit{s1} occurs as a substring in \textit{s2}, returns the least index at which \textit{s1} occurs. Returns 0 if \textit{s1} does not occur in \textit{s2}, and 1 if \textit{s1} is the empty string. For example,
\hspace{2em} \text{indexs("abc", "abcabc") = 1}
\hspace{2em} \text{indexs("bc", "abcabc") = 2}
\hspace{2em} \text{indexs("", "abcde") = 1}
\hspace{2em} \text{indexs("bcb", "abcde") = 0}

\textbf{indexc} = \textbf{proc} (c: char, s: string) \textbf{returns} (int)
\hspace{1em} \textbf{effects} If \textit{c} occurs in \textit{s}, returns the least index at which \textit{c} occurs; returns 0 if \textit{c} does not occur in \textit{s}.

\textbf{s2ac} = \textbf{proc} (s: string) \textbf{returns} (array[char])
\hspace{1em} \textbf{effects} Stores the characters of \textit{s} as elements of a new array of characters, \textit{a}. The low bound of the array is 1, the size is \text{size(s)}, and the \textit{i}th element of the array is the \textit{i}th character of \textit{s}, for 1 \leq i \leq \text{size(s)}.

\textbf{ac2s} = \textbf{proc} (a: array[char]) \textbf{returns} (string)
\hspace{1em} \textbf{effects} This is the inverse of \textbf{s2ac}. The result is a string with characters in the same order as in \textit{a}. That is, the \textit{i}th character of the string is the \text{(array[char]$\text{low(a)}-1$)}\text{th element of } \textit{a}.

\textbf{s2sc} = \textbf{proc} (s: string) \textbf{returns} (sequence[char])
\hspace{1em} \textbf{effects} Transforms a string into a sequence of characters. The size of the sequence is \text{size(s)}. The \textit{i}th element of the sequence is the \textit{i}th character of \textit{s}, for 1 \leq i \leq \text{size(s)}.

\textbf{sc2s} = \textbf{proc} (s: sequence[char]) \textbf{returns} (string)
\hspace{1em} \textbf{effects} This is the inverse of \textbf{s2sc}. The result is a string with characters in the same order as in \textit{s}. That is, the \textit{i}th character of the string is the \textit{i}th element of \textit{s}.

\textbf{lt} = \textbf{proc} (s1, s2: string) \textbf{returns} (bool)
\textbf{le} = \textbf{proc} (s1, s2: string) \textbf{returns} (bool)
\textbf{ge} = \textbf{proc} (s1, s2: string) \textbf{returns} (bool)
\textbf{gt} = \textbf{proc} (s1, s2: string) \textbf{returns} (bool)
\hspace{1em} \textbf{effects} These are the usual lexicographic ordering relations on strings, based on the ordering of characters. For example,
\hspace{2em} "abc" < "aca"
\hspace{2em} "abc" < "abca"

\textbf{equal} = \textbf{proc} (s1, s2: string) \textbf{returns} (bool)
\textbf{similar} = \textbf{proc} (s1, s2: string) \textbf{returns} (bool)
\hspace{1em} \textbf{effects} Returns \text{true} if \textit{s1} and \textit{s2} are the same string; otherwise returns \text{false}.

\textbf{copy} = \textbf{proc} (s1: string) \textbf{returns} (string)
\hspace{1em} \textbf{effects} Returns \textit{s1}.

\textbf{transmit} = \textbf{proc} (s1: string) \textbf{returns} (string) \textbf{signals} (failure(string))
\hspace{1em} \textbf{effects} Returns \textit{s1}. Signals \text{failure} only if \textit{s1} is not representable on the receiving end.
II.8. Sequences

sequence = data type \{t: type\} is new, e2s, fill, fill_copy, replace, addh, addl, remh, reml, concat,
subseq, size, empty, fetch, bottom, top, elements, indexes, a2s, s2a,
equal, similar, copy, transmit

Overview

Sequences represent immutable tuples of objects of type t. The elements of the sequence can be
indexed sequentially from 1 up to the size of the sequence. Although a sequence is immutable,
the elements of the sequence can be mutable objects. The state of such mutable elements may
change; thus, a sequence object is atomic only if its elements are also atomic.

Sequences can be created by calling sequence operations and by means of the sequence
constructor, see Section 6.2.8.

Any operation call that attempts to access a sequence with an index that is not within the defined
range terminates with the bounds exception. The size of a sequence can be no larger than the
largest positive Int (int_max), but an implementation may restrict sequences to a smaller upper
bound. An attempt to construct a sequence which is too large results in a limits exception.

Operations

new = proc () returns (sequence[t])
effects Returns the empty sequence.

e2s = proc (elem: t) returns (sequence[t])
effects Returns a one-element sequence having elem as its only element.

fill = proc (cnt: Int, elem: t) returns (sequence[t]) signals (negative_size, limits)
effects If cnt < 0, signals negative_size. If cnt is larger than the maximum sequence size
supported by the implementation, signals limits. Otherwise returns a sequence having cnt elements each of which is elem.

fill_copy = proc (cnt: Int, elem: t) returns (sequence[t]) requires t has copy: proc type (t) returns (t)
signals (negative_size, limits, failure(string))
effects If cnt < 0, signals negative_size. If cnt is bigger than the maximum size of sequences that the
implementation supports, signals limits. Otherwise returns a new sequence having cnt elements each of which is elem,
as made by $copy. Note that $copy is called cnt times. Any failure signal raised by $copy is immediately
resignalled. This operation does not originate any failure signals by itself.

replace = proc (s: sequence[t], i: Int, elem: t) returns (sequence[t]) signals (bounds)
effects If i < 1 or i > high(s), signals bounds. Otherwise returns a sequence with the same
elements as s, except that elem is in the i-th position. For example,
replace(sequence[int][2,5], 1, 6) = sequence[int][6, 5]

addh = proc (s: sequence[t], elem: t) returns (r: sequence[t]) signals (limits)
effects Returns a sequence with the same elements as s followed by one additional
element, elem. That is, \(f[i]=s[i]\) for \(i\) an index of s, and \(f[size(s)+1]=elem\). If the resulting
sequence would be larger than the implementation supports, signals limits.

addl = proc (s: sequence[t], elem: t) returns (r: sequence[t]) signals (limits)
effects Returns a sequence having elem as the first element followed by the elements of s
in order. That is, \(f[1]=elem\) and \(f[i]=s[i-1]\) for \(i=2, \ldots, size(r)\). If the resulting sequence
would be larger than the implementation supports, signals limits.

remh = proc (s: sequence[t]) returns (r: sequence[t]) signals (bounds)
effects If s is empty, signals bounds. Otherwise returns a sequence having all elements of s
in order, except the last one. That is, \(size(r)=size(s)-1\) and \(f[i]=s[i]\) for \(i=1, \ldots, size(s)-1\).
reml = proc (s: sequence[t]) returns (r: sequence[t]) signals (bounds)
effects If s is empty, signals bounds. Otherwise returns a sequence containing all elements of s in order, except the first one. That is, \( r[i] = s[i+1] \) for \( i = 1, \ldots, \text{size}(s) - 1 \).

concat = proc (s1, s2: sequence[t]) returns (r: sequence[t]) signals (limits)
effects Returns the concatenation of s1 and s2; which is a sequence having the elements of s1 followed by the elements of s2. That is, \( r[i] = s1[i] \) for \( i \) an index of s1 and \( r[i] = s2[i-\text{size}(s1)+1] \) for \( i \) an index of s2. Signals limits if the resulting sequence would be larger than the implementation supports.

subseq = proc (s: sequence[t], at, cnt: Int) returns (string)
signals (bounds, negative_size)
effects If cnt < 0, signals negative_size. If at < 1 or at > \text{size}(s) + 1, signals bounds. Otherwise returns a sequence having the elements \( s(at), s(at+1), \ldots \) in that order; the new sequence contains \( \text{min}(|cnt|, \text{size} - at + 1) \) elements. Note that if \( \text{min}(|cnt|, \text{size} - at + 1) = 0 \), subseq returns the empty sequence.

size = proc (s: sequence[t]) returns (Int)
effects Returns the number of elements in s.

empty = proc (s: sequence[t]) returns (bool)
effects Returns true if s contains no elements; otherwise returns false.

fetch = proc (s: sequence[t], i: Int) returns (t) signals (bounds)
effects If i < 1 or i > \text{size}(s), signals bounds. Otherwise returns the \( i \)th element of s.

bottom = proc (s: sequence[t]) returns (t) signals (bounds)
effects If s is empty, signals bounds. Otherwise returns \( s[1] \).

top = proc (s: sequence[t]) returns (t) signals (bounds)
effects If s is empty, signals bounds. Otherwise returns \( s[\text{size}(s)] \).

elements = iter (s: sequence[t]) yields (t)
effects Yields the elements of s in order (i.e., \( s[1], s[2], \ldots \)).

indexes = iter (s: sequence[t]) yields (Int)
effects Yields the indexes of s from 1 to \text{size}(s).

a2s = proc (a: array[t]) returns (sequence[t])
effects Returns a sequence having the elements of a in the same order as in a.

s2a = proc (s: sequence[t]) returns (array[t])
effects Returns a new array with low bound 1 and having the elements of s in the same order as in s.

equal = proc (s1, s2: sequence[t]) returns (bool) signals (failure(string))
requires t has equal: proctype (t, t) returns (bool) signals (failure(string))
effects Returns true if s1 and s2 have equal values as determined by \$equal. The effect of this operation is equivalent to the following procedure body:

\[
\text{qt} = \text{sequence} [t] \\
\text{if qt}[\text{size}(s1)] = \text{qt}[\text{size}(s2)] \text{ then return (false) end} \\
\text{for } i: \text{Int} \text{ in qt}[\text{indexes}(s1)] \text{ do} \\
\quad \text{if } s1[i] = s2[i] \text{ then return (false) end} \\
\text{resignal failure} \\
\end
\]

return (true)

similar = proc (s1, s2: sequence[t]) returns (bool) signals (failure(string))
requires t has similar: proctype (t, t) returns (bool) signals (failure(string))
effects Returns true if s1 and s2 have similar values as determined by \$similar. Similar works in the same way as equal, except that \$similar is used instead of \$equal.
copy = proc (s: sequence[t]) returns (sequence[t]) signals (failure(string))
  requires t has copy: proctype (t) returns (t) signals (failure(string))
  effects Returns a sequence having as elements copies of the elements of s. The effect is equivalent to that of the following procedure body:
  qt = sequence[t]
  y := qt$new0
  for e: t in qt$elements(s) do
    y := qt$addh(y, t$copy(e)) resignal failure
  end
  return (y)
transmit = proc (s: sequence[t]) returns (sequence[t]) signals (failure(string))
  requires t has transmit
  effects Returns a sequence having as elements transmitted copies of the elements of s in the same order. Sharing among elements is preserved. Signals failure if this cannot be represented on the receiving end and also resignals any failures from $transmit.

II.9. Arrays

array = data type [t: type] ls create, new, predict, fill, fill_copy, addh, addl, remh, reml, set_low, trim, store, fetch, bottom, top, empty, size, low, high, elements, indexes, equal, similar, similar1, copy, copy1, transmit

Overview

Arrays are mutable objects that represent tuples of elements of type t that can grow and shrink dynamically. Each array's state consists of this tuple of elements and a low bound (or index). The elements are indexed sequentially, starting from the low bound. Each array also has an identity as an object.

Arrays can be created by calling array operations create, new, fill, fill_copy, and predict. They can also be created by means of the array constructor, which specifies the array low bound, and an arbitrary number of initial elements, see Section 6.2.9.

Operations low, high, and size return the current low and high bounds and size of the array. For array a, size(a) is the number of elements in a, which is zero if a is empty. These are related by the equation: high(a) = low(a) + size(a) - 1.

For any index i between the low and high bound of an array, there is a defined element, a[i]. The bounds exception is raised when an attempt is made to access an element outside the defined range. Any array must have a low bound, a high bound, and a size which are all legal integers. An implementation may restrict these to some smaller range of integers. A call that would lead to an array whose low or high bound or size is outside the defined range terminates with a limits exception.

Operations

create = proc (lb: Int) returns (array[t]) signals (limits)
  effects Returns a new, empty array with low bound lb. Limits occurs if the resulting array would not be supported by the implementation.

new = proc () returns (array[t])
  effects Returns a new, empty array with low bound 1. Equivalent to create(1).
predict = proc (lb, cnt: Int) returns (array[t]) signals (limits)
effects Returns a new, empty array with low bound lb. The absolute value of cnt is a prediction of how many addhs or addls are likely to be performed on this new array. If cnt > 0, addhs are expected; otherwise addls are expected. These operations may execute faster than if the array had been produced by calling create. Limits occurs if the resulting array would not be supported by the implementation because of its initial low bound (not because of its predicted size or because of the predicted high or low bound).

fill = proc (lb, cnt: Int, elem: t) returns (array[t]) signals (negative_size, limits)
effects If cnt < 0, signals negative_size. Returns a new array with low bound lb and size cnt, and with elem as each element; if this new array would not be supported by the implementation, signals limits.

fill_copy = proc (lb, cnt: Int, elem: t) returns (array[t])
  signals (negative_size, limits, failure(string))
  requires t has copy: proctype (t) returns (t) signals (failure(string))
effects The effect is like fill except that elem is copied cnt times. If cnt < 0, signals negative_size. Normally returns a new array with low bound lb and size cnt and with each element a copy of elem, as produced by $\&copy$. Any failure signal raised by $\&copy$ is immediately re-signalled. This operation does not originate any failure signals by itself. However, if the new array cannot be represented by the implementation, signals limits.

addh = proc (a: array[t], elem: t) signals (limits)
  modifies a.
effects If extending a on the high end causes the high bound or size of a to be outside the range supported by the implementation, signals limits. Otherwise extends a by 1 in the high direction and stores elem as the new element. That is, $a_{\text{post}}[\text{high}(a_{\text{pre}})+1] = \text{elem}$.

addl = proc (a: array[t], elem: t) signals (limits)
  modifies a.
effects If extending a on the low end causes the low bound or size of a to be outside the range supported by the implementation, signals limits. Otherwise extends a by 1 in the low direction and stores elem as the new element. That is, $a_{\text{post}}[\text{low}(a_{\text{pre}})-1] = \text{elem}$.

remh = proc (a: array[t]) returns (t) signals (bounds)
  modifies a.
effects If a is empty, signals bounds. Otherwise shrinks a by removing its high element and returning the removed element. That is, $\text{high}(a_{\text{post}}) = \text{high}(a_{\text{pre}}) - 1$.

reml = proc (a: array[t]) returns (t) signals (bounds)
  modifies a.
effects If a is empty, signals bounds. Otherwise shrinks a by removing its low element and returning the removed element. That is, $\text{low}(a_{\text{post}}) = \text{low}(a_{\text{pre}}) + 1$.

set_low = proc (a: array[t], lb: Int) signals (limits)
  modifies a.
effects Modifies the low and high bounds of a; the new low bound of a is lb and the new high bound is $\text{high}(a_{\text{post}}) = \text{high}(a_{\text{pre}}) + lb - \text{low}(a_{\text{pre}})$. If the new low (or high) bound is not supported by the implementation, signals limits and does not modify a.

trim = proc (a: array[t], lb, cnt: Int) signals (negative_size, bounds)
  modifies a.
effects If cnt < 0, signals negative_size. If $lb < \text{low}(a)$ or $lb > \text{high}(a)+1$, signals bounds. Otherwise modifies a by removing all elements with index < lb or greater than or equal to lb+cnt; the new low bound is lb. For example, if $a = \text{array}[\text{Int}][1,2,3,4,5]$, then:
  trim(a, 2, 2) results in a having the value of $\text{array}[\text{Int}][2: 2, 3]$
  trim(a, 4, 3) results in a having the value of $\text{array}[\text{Int}][4: 4, 5]$
store = proc (a: array[t], i: Int, elem: t) signals (bounds)
    modifies a.
    effects If $i < \text{low}(a)$ or $i > \text{high}(a)$, signals bounds; otherwise makes $elem$ the element of $a$ with index $i$.

fetch = proc (a: array[t], i: Int) returns (t) signals (bounds)
    effects If $i < \text{low}(a)$ or $i > \text{high}(a)$, signals bounds; otherwise returns the element of $a$ with index $i$.

bottom = proc (a: array[t]) returns (t) signals (bounds)
    effects If $a$ is empty, signals bounds; otherwise returns $a[\text{low}(a)]$.

top = proc (a: array[t]) returns (t) signals (bounds)
    effects If $a$ is empty, signals bounds; otherwise returns $a[\text{high}(a)]$.

empty = proc (a: array[t]) returns (bool)
    effects Returns true if $a$ contains no elements; otherwise returns false.

size = proc (a: array[t]) returns (Int)
    effects Returns a count of the number of elements of $a$.

low = proc (a: array[t]) returns (Int)
    effects Returns the low bound of $a$.

high = proc (a: array[t]) returns (Int)
    effects Returns the high bound of $a$.

elements = iter (a: array[t]) yields (t) signals (failure(string))
    effects Yields the elements of $a$, exactly once for each index, from the low bound to the high bound (i.e., $\text{bottom}(a) ... \text{top}(a)$). The elements are fetched one at a time, using the indexes that were legal at the start of the call. If, during the iteration, $a$ is modified so that fetching at a previously legal index signals bounds, then the iterator signals failure with the string "bounds". The iterator is divisible at yields.

indexes = iter (a: array[t]) yields (Int)
    effects Yields the indexes of $a$ from the low bound of $a$ to the high bound of $a$. Note that indexes is unaffected by any modifications done by the loop body. It is divisible at yields.

equal = proc (a1, a2: array[t]) returns (bool)
    effects Returns true if $a1$ and $a2$ refer to the same array object; otherwise returns false.

similar = proc (a1, a2: array[t]) returns (bool) signals (failure(string))
    requires $t$ has similar: proctype (t, t) returns (bool) signals (failure(string))
    effects Returns true if $a1$ and $a2$ have the same low and high bounds and if their elements are pairwise similar as determined by $\text{similar}$. This effect of this operation is equivalent to the following procedure body (except that this operation is only divisible at calls to $\text{similar}$):

```plaintext
at = array[t]
  if at[\text{low}(a1)] \neq at[\text{low}(a2)] or at[\text{size}(a1)] \neq at[\text{size}(a2)] then return (false) end
  for i: Int in at[\text{indexes}(a1)] do
    if \neg \text{similar}(a1[i], a2[i]) then return (false) end
    resignal failure
  else signal failure("bounds")
end
return (true)
```
similar1 = proc (a1, a2 : array[t]) returns (bool) signals (failure(string))
  requires t has equal: proctype (t, t) returns (bool) signals (failure(string))
  effects Returns true if a1 and a2 have the same low and high bounds and if their elements
  are pairwise equal as determined by $equal. This operation works the same way as
  similar, except that $equal is used instead of $similar.

copy = proc (a : array[t]) returns (b : array[t]) signals (failure(string))
  requires t has copy: proctype (t) returns (t) signals (failure(string))
  effects Returns a new array b with the same low and high bounds as a and such that each
  element b[i] contains $copy(a[i]). The effect of this operation is equivalent to the
  following body (except that it is only divisible at calls to $copy):
  b : array[t] := array[t]$copy1(a)
  for i : Int in array[t]$indexes(a) do
    b[i] := t$copy(a[i])
  resignal failure
  except when bounds : signal failure("bounds")
end
return (b)
copy1 = proc (a : array[t]) returns (b : array[t])
  effects Returns a new array b with the same low and high bounds as a and such that each
  element b[i] contains the same element as a[i].

transmit = proc (a : array[t]) returns (b : array[t]) signals (failure(string))
  requires t has transmit
  effects Returns a new array b with the same low and high bounds as a and such that each
  element b[i] contains a transmitted copy of a[i]. Sharing among the elements of a is
  preserved in b. Signals failure if b cannot be represented on the receiving end or if
  fetching an element at a legal index of a pre causes a bounds exception and resinals any
  failure signals raised by $transmit.

II.10. Atomic Arrays

atomic_array = data type [t : type] ls create, new, predict, fill, fill_copy, addh, addl, remh, reml,
  set_low, trim, store, fetch, bottom, top, empty, size, low, high, elements, indexes,
  a2a, a2aa, equal, similar, similar1, copy, copy1, transmit,
  test_and_read, test_and_write, can_read, can_write, read_lock, write_lock

Overview

Atomic_arrays are mutable atomic objects that represent tuples of elements of type t that can
grow and shrink dynamically. Each atomic_array's (sequential) state consists of this tuple of
elements and a low bound (or index). The elements are indexed sequentially, starting from the
low bound. Each atomic_array also has an identity as an object.

Atomic_arrays can be created by calling atomic_array operations create, new, fill, fill_copy, and
predict. They can also be created by means of the atomic_array constructor, which specifies the
array low bound, and an arbitrary number of initial elements, see Section 6.2.9.

Operations low, high, and size return the current low and high bounds and size of the
atomic_array. For an atomic_array a, size(a) is the number of elements in a, which is zero if a is
empty. These are related by the equation: high(a) = low(a) + size(a) - 1.
For any index \( i \) between the low and high bound of an atomic_array, there is a defined element, \( a[i] \). The bounds exception is raised when an attempt is made to access an element outside the defined range. Any atomic_array must have a low bound, a high bound, and a size which are all legal integers. An implementation may restrict these to some smaller range of integers. A call that would lead to an atomic_array whose low or high bound or size is outside the defined range terminates with a limits exception. limits exception.

Atomic_arrays use read/write locking to achieve atomicity. The locking rules are described in Section 2.2.2. It is an error if a process that is not in an action attempts to test or obtain a lock; when this happens the guardian running the process will crash. As defined below, the only operation that (in the normal case) does not attempt to test or obtain a lock is the equal operation.

Operations

create = proc (lb: Int) returns (a: atomic_array[[]]) signals (limits)
  effects Returns a new, empty atomic_array \( a \) with low bound \( lb \). Limits occurs if the resulting atomic_array would not be supported by the implementation. The caller obtains a read lock on \( a \).

new = proc () returns (atomic_array[])
  effects Equivalent to create(1).

predict = proc (lb, cnt: Int) returns (a: atomic_array[[]]) signals (limits)
  effects Returns a new, empty atomic_array \( a \) with low bound \( lb \). The caller obtains a read lock on \( a \). This is essentially the same as create(lb), except that the absolute value of \( cnt \) is a prediction of how many addhs or adds are likely to be performed on this new atomic_array. If \( cnt > 0 \), addhs are expected; otherwise adds are expected. These operations may execute faster than if the atomic_array had been produced by calling create. Limits occurs if the resulting atomic_array would not be supported by the implementation because of its initial low bound (not because of its predicted size or because of the predicted high or low bound).

fill = proc (lb, cnt: Int, elem: t) returns (atomic_array[])
  signals (negative_size, limits)
  effects If \( cnt < 0 \), signals negative_size. Returns a new atomic_array with low bound \( lb \) and size \( cnt \), and with \( elem \) as each element; if this new atomic_array would not be supported by the implementation, signals limits. The caller obtains a read lock on the result.

fill_copy = proc (lb, cnt: Int, elem: t) returns (atomic_array[])
  signals (negative_size, limits, failure(string))
  requires \( t \) has copy: proc type (t) returns (t) signals (failure(string))
  effects The effect is like fill except that \( elem \) is copied \( cnt \) times. If \( cnt < 0 \), signals negative_size. Normally returns a new array with low bound \( lb \) and size \( cnt \) and with each element a copy of \( elem \), as produced by \$copy. The caller obtains a read lock on the result. Any failure signal raised by \$copy is immediately resignalled. This operation does not originate any failure signals by itself. If the new array cannot be represented by the implementation, signals limits.

addh = proc (a: atomic_array[], elem: t) signals (limits)
  modifies \( a \).
  effects Obtains a write lock on \( a \). If extending \( a \) on the high end would cause the high bound or size of \( a \) to be outside the range supported by the implementation, then signals limits. Otherwise extends \( a \) by 1 in the high direction, and stores \( elem \) as the new element. That is, \( a_{post}[high(a_{pre})+1] = elem \).
addl = proc (a: atomic_array[t], elem: t) signals (limits)
modifies a.

effects Obtains a write lock on a. If extending a on the low end would cause the low bound
or size of a to be outside the range supported by the implementation, then signals limits.
Otherwise extends a by 1 in the low direction, and stores elem as the new element. That
is, \( a_{\text{post}}[\text{low}(a_{\text{pre}})-1] = \text{elem} \).

remh = proc (a: atomic_array[t]) returns (t) signals (bounds)
modifies a.

effects Obtains a write lock on a. If a is empty, signals bounds. Otherwise shrinks a by
removing its high element, and returns the removed element. That is, \( \text{high}(a_{\text{post}}) = \text{high}(a_{\text{pre}}) - 1 \).

reml = proc (a: atomic_array[t]) returns (t) signals (bounds)
modifies a.

effects Obtains a write lock on a. If a is empty, signals bounds. Otherwise shrinks a by
removing its low element, and returns the removed element. That is, \( \text{low}(a_{\text{post}}) = \text{low}(a_{\text{pre}}) + 1 \).

set_low = proc (a: atomic_array[t], lb: Int) signals (limits)
modifies a.

effects Obtains a write lock on a. If the new low (or high) bound would not be supported
by the implementation, then signals limits. Otherwise, modifies the low and high bounds of
a; the new low bound of a is \( \text{lb} \) and the new high bound is \( \text{high}(a_{\text{post}}) = \text{high}(a_{\text{pre}}) + \text{lb} - \text{low}(a_{\text{pre}}) \).

trim = proc (a: atomic_array[t], lb, cnt: Int) signals (negative_size, bounds)
modifies a.

effects If \( \text{cnt} < 0 \), signals negative_size and does not obtain any locks. Otherwise obtains a
write lock on a. If \( \text{lb} < \text{low}(a) \) or \( \text{lb} > \text{high}(a)+1 \), signals bounds. Otherwise, modifies a by
removing all elements with index \( < \text{lb} \) or greater than or equal to \( \text{lb} + \text{cnt} \); the new low
bound is \( \text{lb} \). For example, if \( a = \text{atomic_array}[\text{Int}][2, 3, 4, 5] \), then:
trim(a, 2, 2) results in a having value \( \text{atomic_array}[\text{Int}][2, 3] \)
trim(a, 4, 3) results in a having value \( \text{atomic_array}[\text{Int}][4, 5] \)

store = proc (a: atomic_array[t], i: Int, elem: t) signals (bounds)
modifies a.

effects Obtains a write lock on a. If \( i < \text{low}(a) \) or \( i > \text{high}(a) \), signals bounds; otherwise
makes elem the element of a with index i.

fetch = proc (a: atomic_array[t], i: Int) returns (t) signals (bounds)

effects If \( i < \text{low}(a) \) or \( i > \text{high}(a) \), signals bounds; otherwise returns the element of a with
index i. Always obtains a read lock on a.

bottom = proc (a: atomic_array[t]) returns (t) signals (bounds)

effects If a is empty, signals bounds; otherwise returns \( a[\text{low}(a)] \). Always obtains a read
lock on a.

top = proc (a: atomic_array[t]) returns (t) signals (bounds)

effects If a is empty, signals bounds; otherwise returns \( a[\text{high}(a)] \). Always obtains a read
lock on a.

empty = proc (a: atomic_array[t]) returns (bool)

effects Returns true if a contains no elements, returns false otherwise. In either case
obtains a read lock on a.

size = proc (a: atomic_array[t]) returns (Int)

effects Returns a count of the number of elements of a, obtains a read lock on a.
low = proc (a: atomic_array[] returns (Int)
  effects Returns the low bound of a, obtains a read lock on a

high = proc (a: atomic_array[] returns (Int)
  effects Returns the high bound of a, obtains a read lock on a.

elements = iter (a: atomic_array[]) yields (Int) signals (failure(string))
  effects Obtains a read lock on a and yields the elements of a, each exactly once for each index, from the low bound to the high bound (i.e., bottom(a) -> top(a)). The elements are fetched one at a time, using the indexes that were legal at the start of the call. If, during the iteration, a is modified so that fetching at a previously legal index signals bounds, then the iterator signals failure with the string "bounds". The iterator is divisible at yields.

indexes = iter (a: atomic_array[]) yields (Int)
  effects Obtains a read lock on a, then yields the indexes of a from the low bound of a to the high bound of a. Note that indexes is unaffected by any modifications done by the loop body. It is divisible at yields.

aa2a = proc (aa: atomic_array[]) returns (array[]
  effects Obtains a read lock on aa and returns an array a with the same (sequential) state.

a2aa = proc (array[]) returns (aa: atomic_array[]
  effects Returns an atomic-array aa with the same state as a. Obtains a read lock on aa.

equal = proc (a1, a2: atomic_array[]) returns (bool)
  effects Returns true if a1 and a2 refer to the same atomic_array object; otherwise returns false. No locks are obtained.

similar = proc (a1, a2: atomic_array[]) returns (bool) signals (failure(string))
  requires t has similar: proctype (t, t) returns (bool) signals (failure(string))
  effects Returns true if a1 and a2 have the same low and high bounds and if their elements are pairwise similar as determined by $similar. See the description of the similar operation of array for an equivalent body of code. This operation is divisible at calls to $similar. Read locks are obtained on a1 and a2, in that order.

similar1 = proc (a1, a2: atomic_array[]) returns (bool) signals (failure(string))
  requires t has equal: proctype (t, t) returns (bool) signals (failure(string))
  effects Returns true if a1 and a2 have the same low and high bounds and if their elements are pairwise equal as determined by $equal. This operation works the same way as similar, except that $equal is used instead of $similar. Read locks are obtained on a1 and a2, in that order.

copy = proc (a: atomic_array[]) returns (b: atomic_array[], signals (failure(string))
  requires t has copy: proctype (t, t) returns (bool) signals (failure(string))
  effects Returns a new atomic_array b with the same low and high bounds as a and such that each element b[i] contains $copy(a[i]). See the description of the copy operation of array for an equivalent body of code. This operation is divisible at calls to $copy, and obtains read locks on a and b.

copy1 = proc (a: atomic_array[]) returns (b: atomic_array[])
  effects Returns a new atomic_array b with the same low and high bounds as a and such that each element b[i] contains the same element as a[i]. Read locks are obtained on a and b.
transmit = proc (a: atomic_array[l]) returns (b: atomic_array[l]) signals (failure(string))
  requires t has transmit
  effects Returns a new array b with the same low and high bounds as a and such that each element b[i] contains a transmitted copy of a[i]. Read locks are obtained on a and b. Sharing among the elements of a is preserved in b. Signals failure if b cannot be represented on the receiving end or if fetching an element at a legal index of a causes a bounds exception and resinals any failure signals raised by transmit.

test_and_read = proc (aa: atomic_array[l]) returns (bool)
  effects Tries to obtain a read lock on aa. If the lock is obtained, returns true, otherwise no lock is obtained and the operation returns false. The operation does not "wait" for a lock. Even if the executing action "knows" that a lock could be obtained, false may be returned. Even if false is returned, a subsequent attempt to obtain a read lock might succeed without waiting.

test_and_write = proc (aa: atomic_array[l]) returns (bool)
  effects Tries to obtain a write lock on aa. If the lock is obtained, returns true; otherwise no lock is obtained and the operation returns false. The operation does not "wait" for a lock. Even if the executing action "knows" that a lock could be obtained, false may be returned. Even if false is returned, a subsequent attempt to obtain a write lock might succeed without waiting.

can_read = proc (aa: atomic_array[l]) returns (bool)
  effects Returns true if a read lock could be obtained on aa without waiting, otherwise returns false. No lock is actually obtained. Even if the executing action "knows" that a lock could be obtained, false may be returned. Since some concurrent action may obtain or release a lock on an atomic_array at any time, the information returned is unreliable: even if true is returned, a subsequent attempt to obtain the lock may require waiting; and even if false is returned, a subsequent attempt to obtain a read lock might succeed without waiting.

can_write = proc (aa: atomic_array[l]) returns (bool)
  effects Returns true if a write lock could be obtained on aa without waiting, otherwise returns false. No lock is actually obtained. Even if the executing action "knows" that a lock could be obtained, false may be returned. Since some concurrent action may obtain or release a lock on an atomic_array at any time, the information returned is unreliable: even if true is returned, a subsequent attempt to obtain the lock may require waiting; and even if false is returned, a subsequent attempt to obtain a write lock might succeed without waiting.

read_lock = proc (aa: atomic_array[l])
  effects Obtains a read lock on aa.

write_lock = proc (aa: atomic_array[l])
  effects Obtains a write lock on aa.
II.11. Structs

**Structs**

struct = data type $[n_1: t_1, \ldots, n_k: t_k]$ is replace$_{n_1}$, ..., replace$_{n_k}$, get$_{n_1}$, ..., get$_{n_k}$, s2r, r2s, equal, similar, copy, transmit

**Overview**

A struct (short for "structure") is an immutable collection of one or more named objects. The names are called *selectors*, and the objects are called *components*. Different components may have different types.

An instantiation of struct has the form:

```plaintext
struct [ field_spec, ... ]
```

where

field spec ::= name, ... : type_actual

(see Appendix I). Selectors must be unique within an instantiation (ignoring capitalization), but the ordering and grouping of selectors is unimportant. For example, the following name the same type:

```plaintext
struct [ last, first, middle: string, age: int ]
```

```plaintext
struct [ first, middle: string, age: int, last: string ]
```

A struct is created using a struct constructor, see Section 6.2.10.

For purposes of the certain operations, the the names of the selectors are ordered lexicographically. Lexicographic ordering of the selectors is the alphabetic ordering of the selector names written in lower case (based on the ASCII ordering of characters).

Much as with sequences, a struct is immutable but may contain mutable objects; therefore, a struct is atomic only if all its components are atomic.

In the following operation descriptions, let $st = \text{struct} [ n_1: t_1, \ldots, n_k: t_k ]$.

**Operations**

- replace$_{n_i} = \text{proc} (s: st, e: t_i) \text{ returns } (st)$
  
  effects Returns a struct object whose components are those of $s$ except that component $n_i$ is $e$. There is a replace_ operation for each selector.

- get$_{n_i} = \text{proc} (s: st) \text{ returns } (t_i)$
  
  effects Returns the component of $s$ whose selector is $n_i$. There is a get_ operation for each selector.

- s2r = \text{proc} (s: st) \text{ returns } (rt)
  
  effects Here $rt$ is a record type whose components have the same selectors and types as $st$. Returns a new record object whose components are those of $s$.

- r2s = \text{proc} (r: rt) \text{ returns } (st)
  
  effects Here $rt$ is a record type whose components have the same selectors and types as $st$. Returns a struct object whose components are the corresponding components of $r$.

- equal = \text{proc} (s1, s2: st) \text{ returns } (bool) \text{ signals } (failure(string))
  
  requires each $t_i$ has equal: \text{proctype} (t_i, t_i) \text{ returns } (bool) \text{ signals } (failure(string))
  
  effects Returns true if $s1$ and $s2$ contain equal objects for each component as determined by the $t_i$$equal$ operations. Any failure signal is immediately resignedalled. This operation does not itself originate any failure signal. The comparison is done in lexicographic order of the selectors; if any comparison returns false, false is returned immediately.
similar = proc (s1, s2: st) returns (bool) signals (failure(string))
  requires each t, has similar: proc type (t, t) returns (bool) signals (failure(string))
  effects Returns true if s1 and s2 contain similar objects for each component as determined
    by the t$similar operations. Any failure signal is immediately resignalled. This operation
do not itself originate any failure signal. The comparison is done in lexicographic order
    of the selectors; if any comparison returns false, false is returned immediately.

copy = proc (s: st) returns (st) signals (failure(string))
  requires each t, has copy: proc type (t) returns (t) signals (failure(string))
  effects Returns a struct containing a copy of each component of s; copies are obtained by
    calling the t$copy operations. Any failure signal is immediately resignalled. This
operation does not itself originate any failure signal. Copying is done in lexicographic
    order of the selectors.

transmit = proc (s: st) returns (st) signals (failure(string))
  requires each t, has transmit
  effects Returns a struct containing a transmitted copy of each component of s. Sharing is
    preserved among the components of s. Any failure signal from t$transmit is
immediately resignalled. This operation does not itself originate any failure signal.

II.12. Records

record = data type [n1: t1, ..., nk: tk] is r_gets_r, r_gets_s, set_n1, ..., set_nk, get_n1, ..., get_nk.
  equal, similar, similar1, copy, copy1, transmit

Overview

A record is a mutable collection of one or more named objects. The names are called selectors,
    and the objects are called components. Different components may have different types. A record
also has an identity as an object.

An instantiation of record has the form:
  record [ field_spec , ... ]
where
  field_spec ::= name, ... : type_actual
(see Appendix I). Selectors must be unique within an instantiation (ignoring capitalization), but the
ordering and grouping of selectors is unimportant. For example, the following name the same
type:
  record[last, first, middle: string, age: Int]
  record[last: string, age: Int, first, middle: string]

A record is created using a record constructor, see Section 6.2.11.

For purposes of the certain operations, the the names of the selectors are ordered
    lexicographically. Lexicographic ordering of the selectors is the alphabetic ordering of the selector
names written in lower case (based on the ASCII ordering of characters).

In the following definitions of record operations, let \( rt = \text{record}[n1: t1, ..., nk: tk] \).

Operations

  r_gets_r = proc (r1, r2: rt)
    modifies r1.
  effects Sets each component of r1 to be the corresponding component of r2.
r_gets_s = proc (r: rt, s: st)
    modifies r.
    effects Here st is a struct type whose components have the same selectors and types as rt.
             Sets each component of r to be the corresponding component of s.

set_n_i = proc (r: rt, e: t)
    modifies r.
    effects Modifies r by making the component whose selector is n_i be e. There is a set_ operation for each selector.

get_n_i = proc (r: rt) returns (t)
    effects Returns the component of r whose selector is n_i. There is a get_ operation for each selector.

equal = proc (r1, r2: rt) returns (bool)
    effects Returns true if r1 and r2 are the same record object; otherwise returns false.

similar = proc (r1, r2: rt) returns (bool) signals (failure(string))
    requires each t_i has similar: proctype (ti, ti) returns (bool) signals (failure(string))
    effects Returns true if r1 and r2 contain similar objects for each component as determined by the t$i$similar operations. Any failure signal is immediately resignalled. This operation does not itself originate any failure signal. The comparison is done in lexicographic order of the selectors; if any comparison returns false, false is returned immediately.

similar1 = proc (r1, r2: rt) returns (bool) signals (failure(string))
    requires each t_i has equal: proctype (t_i, t_i) returns (bool) signals (failure(string))
    effects Returns true if r1 and r2 contain equal objects for each component as determined by the t$i$equal operations. Any failure signal is immediately resignalled. This operation does not itself originate any failure signal. The comparison is done in lexicographic order of the selectors; if any comparison returns false, false is returned immediately.

copy = proc (r: rt) returns (rt) signals (failure(string))
    requires each t_i has copy: proctype (t_i) returns (t) signals (failure(string))
    effects Returns a new record obtained by performing copy1(r) and then replacing each component with a copy of the corresponding component of r. Copies are obtained by calling the t$i$copy operations. Any failure signal is immediately resignalled. This operation does not itself originate any failure signal. Copying is done in lexicographic order of the selectors.

copy1 = proc (r: rt) returns (rt)
    effects Returns a new record containing the components of r as its components.

transmit = proc (r: rt) returns (rt) signals (failure(string))
    requires each t_i has transmit
    effects Returns a new record containing a transmitted copy of each component of r. Sharing is preserved among the components of r. Any failure signal from t$i$transmit is immediately resignalled. This operation does not itself originate any failure signal.
II.12 Records

II.13. Atomic Records

atomic_record = data type [n₁ : t₁, ..., nₖ : tₖ] is ar_gets_ar, set_n₁, ..., set_nₖ, get_n₁, ..., get_nₖ, ar2r, r2ar, equal, similar, similar1, copy, copy1, transmit, test_and_read, test_and_write, can_read, can_write, read_lock, write_lock

Overview

An atomic_record is a mutable atomic collection of one or more named objects. The names are called selectors, and the objects are called components. Different components may have different types. An atomic_record also has an identity as an object.

An instantiation of atomic_record has the form:

atomic_record [ field_spec , ... ]

where

field_spec ::= name, ... : type_spec

(see Appendix I). Selectors must be unique within an instantiation (ignoring capitalization), but the ordering and grouping of selectors is unimportant. For example, the following name the same type:

atomic_record[last, first, middle: string, age: Int]
atomic_record[last: string, age: Int, first, middle: string]

An atomic_record is created using a atomic_record constructor, see Section 6.2.11.

For purposes of the certain operations, the names of the selectors are ordered lexicographically. Lexicographic ordering of the selectors is the alphabetic ordering of the selector names written in lower case (based on the ASCII ordering of characters).

Atomic_records use read/write locking to achieve atomicity. The locking rules are described in Section 2.2.2. It is an error if a process that is not in an action attempts to test or obtain a lock. when this happens the guardian running the process will crash. As defined below, the only operation that (in the normal case) does not attempt to test or obtain a lock is the equal operation.

In the following, let art = atomic_record[n₁: t₁, ..., nₖ: tₖ].

Operations

ar_gets_ar = proc (r1, r2: art)
modifies r1.
effects Obtains a write lock on r1 and a read lock on r2, then sets each component of r1 to be the corresponding component of r2.

get_n₁ = proc (r: art) returns (t₁)
effects Obtains a read lock on r and returns the component of r whose selector is n₁. There is a get_n₁ operation for each selector.

set_n₁ = proc (r: art, e: t₁)
modifies r.
effects Obtains a write lock on r and modifies r by making the component whose selector is n₁ be e. There is a set_n₁ operation for each selector.

ar2r = proc (ar: art) returns (r: art)
effects Obtains a read lock on ar and returns a record r with the same state.

r2ar = proc (r: art) returns (ar: art)
effects returns an atomic_record ar with the same state as r. Obtains a read lock on ar.
equal = proc (r1, r2: art) returns (bool)
effects Returns true if r1 and r2 are the very same atomic_record object; otherwise returns false. No locks are obtained.

similar = proc (r1, r2: art) returns (bool) signals (failure(string))
requires each t has similar: proctype (t, t) returns (bool) signals (failure(string))
effects Obtains a read lock on r1, then a read lock on r2, then compares corresponding components from r1 and r2 using the t$similar operations. Any failure signal is immediately resigalled. This operation does not itself originate any failure signal. The comparison is done in lexicographic order of the selectors; if any comparison returns false, false is returned immediately. If all comparisons return true, returns true.

similar1 = proc (r1, r2: art) returns (bool) signals (failure(string))
requires each t has equal: proctype (t, t) returns (bool) signals (failure(string))
effects This operation is the same as similar, except that $equal is used instead of $similar.

copy = proc (r: art) returns (res: art) signals (failure(string))
requires each t has copy: proctype (t) returns (t) signals (failure(string))
effects Obtains a read lock on r, then returns a new atomic_record res obtained by performing copy(r) and then replacing each component with a copy of the corresponding component of r. Copies are obtained by calling the t$copy operations. Any failure signal is immediately resigalled. This operation does not itself originate any failure signal. Copying is done in lexicographic order of the selectors. A read lock is also obtained on the new atomic_record res.

copy1 = proc (r: art) returns (res: art)
effects Obtains a read lock on r, then returns a new atomic_record res containing the components of r as its components. A read lock is also obtained on the new atomic_record res.

transmit = proc (ar: art) returns (art) signals (failure(string))
requires each t has transmit
effects Returns a new atomic_record containing a transmitted copy of each component of ar. Sharing is preserved among the components of ar. A read lock is obtained on ar and the new atomic_array. Any failure signal from t$transmit is immediately resigalled. This operation does not itself originate any failure signal.

test_and_read = proc (ar: art) returns (bool)
effects Tries to obtain a read lock on ar. If the lock is obtained, returns true; otherwise no lock is obtained and the operation returns false. The operation does not "wait" for a lock. Even if the executing action "knows" that a lock could be obtained, false may be returned. Even if false is returned, a subsequent attempt to obtain a read lock might succeed without waiting.

test_and_write = proc (ar: art) returns (bool)
effects Tries to obtain a write lock on ar. If the lock is obtained, returns true; otherwise no lock is obtained and the operation returns false. The operation does not "wait" for a lock. Even if the executing action "knows" that a lock could be obtained, false may be returned. Even if false is returned, a subsequent attempt to obtain a write lock might succeed without waiting.
1.13 Atomic Records

\texttt{can\_read = proc (ar: art) returns (bool)}
\textbf{effects} Returns \texttt{true} if a read lock could be obtained on \texttt{ar} without waiting, otherwise returns \texttt{false}. No lock is actually obtained. Even if the executing action "knows" that a lock could be obtained, \texttt{false} may be returned. Since some concurrent action may obtain or release a lock on an atomic_record at any time, the information returned is unreliable: even if \texttt{true} is returned, a subsequent attempt to obtain the lock may require waiting; and even if \texttt{false} is returned, a subsequent attempt to obtain a read lock might succeed without waiting.

\texttt{can\_write = proc (ar: art) returns (bool)}
\textbf{effects} Returns \texttt{true} if a write lock could be obtained on \texttt{ar} without waiting, otherwise returns \texttt{false}. No lock is actually obtained. Even if the executing action "knows" that a lock could be obtained, \texttt{false} may be returned. Since some concurrent action may obtain or release a lock on an atomic_record at any time, the information returned is unreliable: even if \texttt{true} is returned, a subsequent attempt to obtain the lock may require waiting; and even if \texttt{false} is returned, a subsequent attempt to obtain a write lock might succeed without waiting.

\texttt{read\_lock = proc (ar: art)}
\textbf{effects} Obtains a read lock on \texttt{ar}.

\texttt{write\_lock = proc (ar: art)}
\textbf{effects} Obtains a write lock on \texttt{ar}.

II.14. Oneofs

\texttt{oneof = data type[n_1: t_1, ... , n_k: t_k] is make\_n_1, ..., make\_n_k, is\_n_1, ..., is\_n_k, value\_n_1, ..., value\_n_k, o2v, v2o, equal, similar, copy, transmit}

Overview

A oneof is a tagged, discriminated union; that is, a labeled object, to be thought of as "one of" a set of alternatives. The label is called the \textit{tag part}, and the object is called the \textit{value} (or \textit{data part}).

An instantiation of \texttt{oneof} has the form:

\texttt{oneof [field\_spec , ... ]}

where (as for records)

\texttt{field\_spec ::= name, .... : type\_actual}

(see Appendix I). Tags must be unique within an instantiation (ignoring capitalization), but the ordering and grouping of tags is unimportant.

Although there are oneof operations for decomposing oneof objects, they are usually decomposed via the \texttt{tagcase} statement, which is discussed in Section 10.14.

A oneof is immutable but may contain a mutable object; therefore, a oneof is atomic only if all of the types of its data parts are atomic.

In the following, let \texttt{ot = oneof[n_1: t_1, ... , n_k: t_k]}.

Operations

\texttt{make\_n_i = proc (e: t_j) returns (ot)}
\textbf{effects} Returns a oneof object with tag \texttt{n_i} and value \texttt{e}. There is a make_ operation for each selector.

\texttt{is\_n_i = proc (o: ot) returns (bool)}
\textbf{effects} Returns \texttt{true} if the tag of \texttt{o} is \texttt{n_i}, else returns \texttt{false}. There is an is_ operation for each selector.
value\_n = \textproc{(o; ot) returns (t) signals (wrong\_tag)}
\begin{itemize}
\item \textbf{effects} If the tag of o is n, returns the value of o; otherwise signals wrong\_tag. There is a value\_operation for each selector.
\end{itemize}

o2v = \textproc{(o; ot) returns (vt)}
\begin{itemize}
\item \textbf{effects} Here vt is a variant type with the same selectors and types as ot. Returns a new variant object with the same tag and value as o.
\end{itemize}

v2o = \textproc{(v; vt) returns (ot)}
\begin{itemize}
\item \textbf{effects} Here vt is a variant type with the same selectors and types as ot. Returns a oneof object with the same tag and value as v.
\end{itemize}

equal = \textproc{(o1, o2: ot) returns (bool) signals (failure(string))}
\begin{itemize}
\item \textbf{requires} each t\_i has equal: \textproc{(t\_i, t\_i) returns (bool) signals (failure(string))}
\item \textbf{effects} Returns \texttt{true} if o1 and o2 have the same tag and equal values as determined by the equal operation of their data part's type. Any failure signal is immediately resigalled. This operation does not itself originate any failure signal. This operation is divisible at the call of t\$equal.
\end{itemize}

similar = \textproc{(o1, o2: ot) returns (bool) signals (failure(string))}
\begin{itemize}
\item \textbf{requires} each t\_i has similar: \textproc{(t\_i, t\_i) returns (bool) signals (failure(string))}
\item \textbf{effects} Returns \texttt{true} if o1 and o2 have the same tag and similar values as determined by the similar operation of their value's type. Any failure signal is immediately resigalled. This operation does not itself originate any failure signal. This operation is divisible at the call of t\$similar.
\end{itemize}

copy = \textproc{(o: ot) returns (ot) signals (failure(string))}
\begin{itemize}
\item \textbf{requires} each t\_i has copy: \textproc{(t\_i) returns (t) signals (failure(string))}
\item \textbf{effects} Returns a oneof object with the same tag as o and containing as a value a copy of o's value; the copy is made using the copy operation of the value's type. Any failure signal is immediately resigalled. This operation does not itself originate any failure signal. This operation is divisible at the call of t\$copy.
\end{itemize}

transmit = \textproc{(o: ot) returns (ot) signals (failure(string))}
\begin{itemize}
\item \textbf{requires} each t\_i has transmit
\item \textbf{effects} Returns a oneof object with the same tag as o and containing as a value a transmitted copy of o's value. Any failure signal is immediately resigalled. This operation does not itself originate any failure signal.
\end{itemize}

\section*{II.15. Variants}

\begin{itemize}
\item \textbf{variant = data type} [n\_1: t\_1, ..., n\_k: t\_k] is make\_n\_1, ..., make\_n\_k, change\_n\_1, ..., change\_n\_k,
\item is\_n\_1, ..., is\_n\_k, value\_n\_1, ..., value\_n\_k, v\_gets\_v, v\_gets\_o,
\item equal, similar, similar1, copy, copy1, transmit
\end{itemize}

\textbf{Overview}

A variant is a mutable, tagged, discriminated union. Its state is a oneof, that is, a labeled object, to be thought of as "one of" a set of alternatives. The label is called the tag part, and the object is called the value (or data part). A variant also has an identity as an object.

An instantiation of \texttt{variant} has the form:
\begin{verbatim}
variant [ field\_spec . . ]
\end{verbatim}
\begin{itemize}
\item \textbf{where}
\begin{itemize}
\item field\_spec ::= name, ..., type\_actual
\end{itemize}
\end{itemize}
(see Appendix I). Tags must be unique within an instantiation (ignoring capitalization), but the ordering and grouping of tags is unimportant.
Although there are variant operations for decomposing variant objects, they are usually decomposed via the \texttt{tagcase} statement, which is discussed in Section 10.14.

In the following let $\texttt{vt} = \texttt{variant}[n_1; t_1, \ldots, n_k; t_k]$.

\textbf{Operations}

\begin{verbatim}
make_\_n_1 = \textit{proc (e: t_1) returns (vt)}
   \textit{effects} Returns a new variant object with tag $n_1$ and value $e$. There is a \texttt{make\_} operation for each selector.

change_\_n_1 = \textit{proc (v: vt, e: t_1)}
   \textit{modifies v.}
   \textit{effects} Modifies $v$ to have tag $n_1$ and value $e$. There is a \texttt{change\_} operation for each selector.

is_\_n_1 = \textit{proc (v: vt) returns (bool)}
   \textit{effects} Returns true if the tag of $v$ is $n_1$; otherwise returns false. There is an \texttt{is\_} operation for each selector.

value_\_n_1 = \textit{proc (v: vt) returns (t) signals (wrong\_tag)}
   \textit{effects} If the tag of $v$ is $n_1$, returns the value of $v$; otherwise signals \texttt{wrong\_tag}. There is a \texttt{value\_} operation for each selector.

v\_gets\_v = \textit{proc (v1, v2: vt)}
   \textit{modifies v1.}
   \textit{effects} Modifies $v_1$ to contain the same tag and value as $v_2$.

v\_gets\_o = \textit{proc (v: vt, o: ot)}
   \textit{modifies v.}
   \textit{effects} Here \texttt{ot} is the oneof type with the same selectors and types as \texttt{vt}. Modifies $v$ to contain the same tag and value as $o$.

equal = \textit{proc (v1, v2: vt) returns (bool)}
   \textit{effects} Returns true if $v_1$ and $v_2$ are the same variant object.

similar = \textit{proc (v1, v2: vt) returns (bool) signals (failure(string))}
   \textit{requires \texttt{each t_i has similar: proctype (t_i, t_i) returns (bool) signals (failure(string))}}
   \textit{effects} Returns true if $v_1$ and $v_2$ have the same tag and similar values as determined by the \texttt{similar} operation of their value's type. Any \texttt{failure} signal is immediately ressignalled. This operation does not itself originate any \texttt{failure} signal. This operation is divisible at the call of $t_i\$\texttt{similar}$.

similar1 = \textit{proc (v1, v2: vt) returns (bool) signals (failure(string))}
   \textit{requires \texttt{each t_i has equal: proctype (t_i, t_i) returns (bool) signals (failure(string))}}
   \textit{effects} Same as similar, except that $t_i\$\texttt{equal}$ is used instead of $t_i\$\texttt{similar}$.

copy = \textit{proc (v: vt) returns (vt) signals (failure(string))}
   \textit{requires \texttt{each t_i has copy: proctype (t_i, t_i) returns (t_i) signals (failure(string))}}
   \textit{effects} Returns a variant object with the same tag as $v$ and containing as a value a copy of $v$'s value; the copy is made using the \texttt{copy} operation of the value's type. Any \texttt{failure} signal is immediately ressignalled. This operation does not itself originate any \texttt{failure} signal. This operation is divisible at the call of $t_i\$\texttt{copy}$.

copy1 = \textit{proc (v: vt) returns (vt)}
   \textit{effects} Returns a new variant object with the same tag as $v$ and containing $v$'s value as its value.
\end{verbatim}
transmit = proc (v: vt) returns (vt) signals (failure(string))
   requires each t has transmit
   effects Returns a variant object with the same tag as v and containing as a value a trans- 
   smitted copy of v's value. Any failure signal is immediately resignalled. This operation 
   does not itself originate any failure signal.

II.16. Atomic Variants

atomic_variant = data type [n_1; t_1, ..., n_k; t_k] is make_n_1, ..., make_n_k, change_n_1, ..., change_n_k, 
   av_gets_av, is_n_1, ..., is_n_k, value_n_1, ..., value_n_k, av2v, v2av, 
   equal, similar, similar1, copy, copy1, transmit, 
   test_and_read, test_and_write, can_read, can_write, read_lock, write_lock

Overview

An atomic_variant is a mutable, atomic, tagged, discriminated union. Its state is a oneof, that is, a 
labeled object, to be thought of as "one of" a set of alternatives. The label is called the tag part, 
and the object is called the value (or data part). An atomic_variant also has an identity as an 
object.

An instantiation of atomic_variant has the form:

   atomic_variant [ field_spec , ... ]

where

   field_spec ::= name, ..., : type_actual 
   (see Appendix I). Tags must be unique within an instantiation (ignoring capitalization), but the 
   ordering and grouping of tags is unimportant.

Although there are atomic_variant operations for decomposing atomic_variant objects, they are 
usually decomposed via the tagtest statement or tagwait statement, which are discussed in 
Section 10.15.

In the following, let avt = atomic_variant[n_1; t_1, ..., n_k; t_k].

Operations

make_n_i = proc (e: t_i) returns (av: avt)
   effects Returns a new atomic_variant object av with tag n_i and value e. Obtains a read lock
   on av. There is a make_ operation for each selector.

change_n_i = proc (v: avt, e: t_i)
   modifies v.
   effects Obtains a write lock on v, then modifies v to have tag n_i and value e. There is a 
   change_ operation for each selector.

av_gets_av = proc (v1, v2: avt)
   modifies v1.
   effects Obtains a read lock on v2 and then a write lock on v1, then modifies v1 to contain 
   the same tag and value as v2.

is_n_i = proc (v: avt) returns (bool)
   effects Obtains a read lock on v, then returns true if the tag of v is n_i; otherwise returns 
   false. There is an is_ operation for each selector.

value_n_i = proc (v: avt) returns (t_i) signals (wrong_tag)
   effects Obtains a read lock on v. Then, if the tag of v is n_i, returns the value of v; otherwise 
   signals wrong_tag. There is a value_ operation for each selector.
av2v = proc (av: avt) returns (v: vt)
effects Here vt is a variant type with the same selectors and types as avt. Obtains a read lock on av and returns a variant v with the same state.

v2av = proc (v: vt) returns (av: avt)
effects Here vt is a variant type with the same selectors and types as avt. Returns an atomic_variant av with the same state as v. Obtains a read lock on av.

equal = proc (v1, v2: avt) returns (bool)
effects Returns true if v1 and v2 are the same atomic_variant object. No locks are obtained.

similar = proc (v1, v2: avt) returns (bool) signals (failure(string))
requires each t has similar: proctype (t, t) returns (bool) signals (failure(string))
effects Obtains read locks on v1 and v2 in order, and then compares the objects; returns true if v1 and v2 have the same tag and similar values as determined by the similar operation of their type. Any failure signal is immediately resigalled. This operation does not itself originate any failure signal. This operation is divisible at the call of t$similar.

similar1 = proc (v1, v2: avt) returns (bool) signals (failure(string))
requires each t has equal: proctype (t, t) returns (bool) signals (failure(string))
effects Same as similar, except that t$equal is used instead of t$similar.

copy = proc (v: avt) returns (avt) signals (failure(string))
requires each t has copy: proctype (t,) returns (t) signals (failure(string))
effects Obtains a read lock on v, then returns an atomic_variant object with the same tag as v and containing as a value a copy of v's value; the copy is made using the copy operation of the value's type. Any failure signal is immediately resigalled. This operation does not itself originate any failure signal. This operation is divisible at the call of t$copy. A read lock is obtained on the result.

copy1 = proc (v: avt) returns (avt)
effects Obtains a read lock on v, then returns a new atomic_variant object with the same tag as v and containing v's value as its value. A read lock is obtained on the result.

transmit = proc (v: avt) returns (avt) signals (failure(string))
requires each t has transmit

effects Returns an atomic_variant object with the same tag as v and containing as a value a transmitted copy of v's value. Obtains a read lock on v. Any failure signal is immediately resigalled. This operation does not itself originate any failure signal.

test_and_read = proc (av: avt) returns (bool)
effects Tries to obtain a read lock on av. If the lock is obtained, returns true; otherwise no lock is obtained and the operation returns false. The operation does not "wait" for a lock. Even if the executing action "knows" that a lock could be obtained, false may be returned. Even if false is returned, a subsequent attempt to obtain a read lock might succeed without waiting.

test_and_write = proc (av: avt) returns (bool)
effects Tries to obtain a write lock on av. If the lock is obtained, returns true; otherwise no lock is obtained and the operation returns false. The operation does not "wait" for a lock. Even if the executing action "knows" that a lock could be obtained, false may be returned. Even if false is returned, a subsequent attempt to obtain a write lock might succeed without waiting.
can_read = proc (av: avt) returns (bool)
  effects Returns true if a read lock could be obtained on av without waiting, otherwise returns false. No lock is actually obtained. Even if the executing action "knows" that a lock could be obtained, false may be returned. Since some concurrent action may obtain or release a lock on an atomic variant at any time, the information returned is unreliable: even if true is returned, a subsequent attempt to obtain the lock may require waiting; and even if false is returned, a subsequent attempt to obtain a read lock might succeed without waiting.

can_write = proc (av: avt) returns (bool)
  effects Returns true if a write lock could be obtained on av without waiting, otherwise returns false. No lock is actually obtained. Even if the executing action "knows" that a lock could be obtained, false may be returned. Since some concurrent action may obtain or release a lock on an atomic variant at any time, the information returned is unreliable: even if true is returned, a subsequent attempt to obtain the lock may require waiting; and even if false is returned, a subsequent attempt to obtain a write lock might succeed without waiting.

read_lock = proc (av: avt)
  effects Obtains a read lock on av.

write_lock = proc (av: avt)
  effects Obtains a write lock on av.

II.17. Procedures and Iterators

proctype = data type Is equal, similar, copy
Itertype = data type Is equal, similar, copy

Overview

Procedures and iterators are objects created by the Argus system. The type specification for a procedure or iterator contains most of the information stated in a procedure or iterator heading; a procedure type specification has the form:

  proctype ( [type_spec , ...] ) [returns] [signals]

and an iterator type specification has the form:

  Itertype ( [type_spec , ...] ) [yields] [signals]

where

  returns ::= returns (type_spec , ...)
  yields ::= yields (type_spec , ...)
  signals ::= signals (exception , ...)
  exception ::= name [(type_spec , ...)]

(see Appendix I). The first list of type specifications describes the number, types, and order of arguments. The returns or yields clause gives the number, types, and order of the objects to be returned or yielded. The signals clause lists the exceptions raised by the procedure or iterator; for each exception name, the number, types, and order of the objects to be returned are also given. All names used in a signals clause must be unique. The ordering of exceptions is not important.

For example, both of the following type specifications name the procedure type for string subst:

  proctype (string, int, int) returns (string) signals (bounds, negative_size)
  proctype (string, int, int) returns (string) signals (negative_size, bounds)
II.17 Procedures and Iterators

Procedure and iterator objects are created by compiling modules (and by the bind expression, see Section 9.8). Procedure and iterator types are not transmissible and are considered to be immutable and atomic in normal use. However, some uses of own data (see Section 12.7) in procedures and iterators can violate this assumption.

In the following operation descriptions, \( t \) stands for a proctype or itertype.

Operations

\[
equal = \text{proc}(x, y: t) \text{ returns (bool)}
\]

\[
similar = \text{proc}(x, y: t) \text{ returns (bool)}
\]

**effects** These operations return \( \text{true} \) if and only if \( x \) and \( y \) are the same implementation of the same abstraction, with the same parameters (see Section 12.6).

\[
copy = \text{proc}(x: t) \text{ returns (t)}
\]

**effects** Returns \( x \).

II.18. Handlers and Creators

**handlertype** = data type is equal, similar, copy, transmit

**creatortype** = data type is equal, similar, copy, transmit

Overview

Handlers and creators are created by the Argus system. The type specification for a handler or creator contains most of the information stated in a handler or creator heading; a handler type specification has the form:

\[
\text{handlertype} ([\text{type spec}, \ldots]) [\text{returns}] [\text{signals}]
\]

and a creator type specification has the form:

\[
\text{creatortype} ([\text{type spec}, \ldots]) [\text{returns}] [\text{signals}]
\]

where

\[
\begin{align*}
\text{returns} & \quad ::= \quad \text{returns (type spec, \ldots)} \\
\text{signals} & \quad ::= \quad \text{signals (exception, \ldots)} \\
\text{exception} & \quad ::= \quad \text{name [(type spec, \ldots)]}
\end{align*}
\]

(see Appendix I). The first list of type specifications describes the number, types, and order of arguments. The **returns** clause gives the number, types, and order of the objects to be returned. The **signals** clause lists the exceptions raised by the handler or creator; for each exception name, the number, types, and order of the objects to be returned are also given. All names used in a **signals** clause must be unique; none can be **unavailable** or **failure**, which have a pre-defined meaning for remote calls (see Section 8.3). The ordering of exceptions is not important.

Creators are created by compiling modules, and handlers are created as a side-effect of guardian creation. Handlers and creators are transmissible and are considered to be immutable and atomic in normal use. Certain uses of own data in handlers can violate this assumption.

In the following operation descriptions, \( t \) stands for a handlertype or creatortype.

Operations

\[
equal = \text{proc}(x, y: t) \text{ returns (bool)}
\]

\[
similar = \text{proc}(x, y: t) \text{ returns (bool)}
\]

**effects** These operations return \( \text{true} \) if and only if \( x \) and \( y \) are the same object (see Section 12.6 for an exact definition for the case of creators in guardian generators).
II.19. Anys

any = data type is create, force, is_type

Overview

An object of type any contains a type $T$ and an object of type $T$. Anys are immutable and are not transmissible. Anys are atomic only if their contained object is atomic.

Operations

create = proc[T: type] (contents: T) returns (any)
effects Returns an any object containing contents and the type $T$.

force = proc[T: type] (thing: any) returns (T) signals (wrong_type)
effects If thing contains an object of a type included in type $T$, then that object is returned; otherwise wrong_type is signalled.

is_type = proc[T: type] (thing: any) returns (bool)
effects If thing contains an object of a type included in type $T$, then true is returned; otherwise, false is returned.

II.20. Images

Image = data type is create, force, is_type, copy, transmit

Overview

An object of type Image is the value of an arbitrary transmissible type. See Section 14 for more details. Images are immutable, atomic, and transmissible.

Operations

create = proc[T: type] (contents: T) returns (Image) signals (failure_string)
requires $T$ has transmit
effects Returns an image object obtained from contents via the encode operation of $T$. Resignals any failure signal raised by $T$'s encode operation.

force = proc[T: type] (thing: Image) returns (T) signals (wrong_type, failure_string))
requires $T$ has transmit
effects If thing encodes an object of a type included in type $T$, then that object is extracted using the decode operation of $T$ and returned. Otherwise wrong_type is signalled. Resignals any failure signal raised by $T$'s decode operation.

is_type = proc[T: type] (thing: Image) returns (bool)
requires $T$ has transmit
effects If thing encodes an object of a type included in type $T$, then true is returned; otherwise, false is returned.

copy = proc (thing: Image) returns (Image)
transmit = proc (thing: Image) returns (Image)
effects Returns thing.
11.21 Mutexes

**mutex** = data type[t: type] is create, set_value, get_value, changed, equal, similar, copy, transmit

**Overview**

A mutex is a mutable container for an object of type t. A mutex also has an identity as an object.

An object of type **mutex[t]** provides mutual exclusion for process synchronization, and allows explicit control over how information contained in the mutex is written to stable storage (see Section 15.1).

The **seize** statement is used in order to gain possession of a mutex. See section 6.7.

Although mutex objects are mutable, sharing among mutex objects is usually wrong, because the contained object should only be accessible through the mutex. Hence there is no **copy** operation, since this would introduce sharing, and there is no **similar** operation to check for sharing (see Section 6.7).

**Operations**

create = proc (thing: t) returns (mutex[t])
   effects Returns a new mutex object containing **thing**.

set_value = proc (container: mutex[t], contents: t)
   modifies **container**.
   effects Modifies **container** by replacing its contained object with **contents**.

get_value = proc (container: mutex[t]) returns (t)
   effects Returns the object contained in **container**.

changed = proc (container: mutex[t])
   effects Informs the Argus system that the calling action requires the contents of **container** to be copied to stable storage by the time the action commits, provided **container** is accessible from a stable variable. It is a programming error if a process that is not running an action calls this operation, and if this is done the guardian will crash.

equal = proc (m1, m2: mutex[t]) returns (bool)
   effects Returns true if and only if **m1** and **m2** are the same object.

similar = proc (m1, m2: mutex[t]) returns (bool) signals (failure(string))
   requires **t** has similar: proctype(t, t) returns(bool) signals (failure(string))
   effects Seizes **m1**, then seizes **m2**, and calls **similar** to determine its result; any failure signal is immediately resignalled. Possession of both mutexes is retained until **similar** terminates.

copy = proc (m1: mutex[t]) returns (m2: mutex[t]) signals (failure(string))
   requires **t** has copy: proctype(t) returns(t) signals (failure(string))
   effects Seizes **m1**, then calls **copy** to make a copy which it places in the new mutex object **m2**. Any failure signal is immediately resignalled. Possession of **m1** is retained until **copy** terminates.

transmit = proc (m1: mutex[t]) returns (mutex[t]) signals (failure(string))
   requires **t** has transmit
   effects Seizes **m1**, and returns a new mutex containing a transmitted copy of the contained object. Any failure signal is immediately resignalled. Possession of **m1** is retained until **transmit** terminates.
Appendix III
Rules and Guidelines for Using Argus

This appendix collects the rules and guidelines that should be followed when programming in Argus. Following these rules makes seize statements meaningful, actions atomic, and so on. In some rare cases there may be valid reasons for violating these guidelines, but doing so greatly increases the difficulty of building, debugging, and running the resulting system.

All of the rules listed in this appendix are based on information appearing elsewhere in the manual. Each rule is followed by a brief rationale, including a reference to the section of the manual from which it is drawn.

III.1. Serializability and Actions

- Actions should share only atomic objects.

_Rationale:_ Actions that share non-atomic data are not necessarily serializable. [Section 2.2.2]

- A subaction that aborts should not return any information obtained from data shared with other concurrent actions.

_Rationale:_ Returning such data may violate serializability. [Section 2.2.1]

- A nested topaction should be serializable before its parent. This is true if either
  1. the nested topaction performs a benevolent side effect (a change to the state of the representation that does not affect the abstract state), or
  2. all communication between the nested topaction and its parent is through atomic objects.

_Rationale:_ Other uses may violate serializability. [Section 2.2.3]

- The creation or destruction of a guardian must be synchronized with the use of that guardian via atomic objects such as the catalog.

_Rationale:_ Otherwise serializability may be violated. [Section 10.18]

III.2. Actions and Exceptions

- If an exception raised by a call should not commit an action, the exception must be handled within that action.

_Rationale:_ If an exception raised within an action body is handled outside the action, the implicit flow of control outside of the action will commit the action. [Section 11.5]
111.3. Stable Variables

- Stable variables should denote resilient data objects.

  *Rationale:* Only data objects that are (reachable from the stable variables and) resilient are written to stable storage when a topaction commits. (This can be ensured by having stable variables only denote objects of an atomic type or objects protected by mutex.) Non-resilient objects stored in stable variables are only written to stable storage when the guardian is created. [Section 13.1]

- If a bound procedure or iterator will be accessible from a stable variable,
  1. the procedure or iterator being bound must be atomic and
  2. only atomic objects should be bound as arguments.

  *Rationale:* The bound procedure or iterator may be stored in stable storage, and non-atomic data is only written to stable storage once. [Section 9.8]

111.4. Transmission and Transmissibility

- An abstract type's encode and decode operations should not cause side effects.

  *Rationale:* The number of calls to an encode or decode operation is unpredictable, since arguments or results may be encoded and decoded several times as the system tries to establish communication. In addition, verifying the correctness of transmission is easier if encode and decode are simply transformations to and from the external representation. [Section 14.3]

- If the naming relation among objects to be transmitted is cyclic (e.g., a circular list) then encode and decode must be implemented in one of two ways:
  1. The internal and external representation types must be identical, and encode and decode return their argument without modifying or accessing it, or
  2. The external representation object must be acyclic.

  *Rationale:* A circular external representation may cause decode to fail. [Section 14.4]

- Objects that share other objects should be bound into a handler or creator in the same bind expression.

  *Rationale:* Sharing is only preserved among objects bound at the same time. [Section 9.8]

111.5. Mutex

- Mutual exclusion or atomic data should be used to synchronize access to all shared objects.

  *Rationale:* In the presence of concurrency, any interleaving of indivisible events is possible. Without synchronization mechanisms, this concurrency will be visible to programs, significantly complicating coding and testing. [Section 8]
• All modifications to mutex objects should be made inside **seize** statements.

**Rationale:** The system will gain possession of a mutex object before writing it to stable storage, thus, seizing a mutex in order to modify it will prevent the system from copying a mutex object when it is in an inconsistent state. This also prevents other processes from seeing inconsistent data [Section 15.2 and Section 15.1]

• Nested seizes should be avoided when **pause** is used, and **pause** must be avoided when nested seizes are used.

**Rationale:** A **pause** in a nested seize does not actually release possession of the mutex object [Section 10.17]

• If an object is referred to by a mutex object, it should not be referred to by any other object, nor should it be denoted by a variable except when in possession of the containing mutex.

**Rationale:** If an object contained in a mutex can be reached by a method other than seizing the mutex, the mutual exclusion property of the mutex is undermined. [Section 6.7]

• No activity that is likely to take a long time should be performed while in a **seize** statement. In particular, programs should not make handler calls or wait for locks on atomic objects while in possession of a mutex.

**Rationale:** Waiting for a lock while in a mutex is likely to cause a deadlock with other actions or between the action holding the mutex and the Argus system. [Section 15.3]

• Mutex objects should not share data with one another, unless the shared data is atomic or **mutex**.

**Rationale:** Sharing of non-atomic objects between mutex objects is not preserved when the mutexes are written to stable storage. [Section 15.3]

• **Mutex[1]$$changed$$** must be called after the last modification (on behalf of some action) to the contained object of a mutex.

**Rationale:** The Argus system is free to copy the mutex to stable storage as soon as **mutex[1]$$changed$$** has been called. Changes after the last call to **mutex[1]$$changed$$** but before topaction commit may not be written to stable storage. [Section 15.3]

• **Mutex[1]$$changed$$** should be called even if the mutex object changed is not accessible from the stable variables.

**Rationale:** In a scenario where the object was accessible, becomes inaccessible, then becomes accessible again, it is possible that stable storage would not be updated properly if this rule were not followed. The system guarantees that no problems with updating stable storage will arise if **mutex[1]$$changed$$** is always called after the last modification to the object. [Section 15.3]
• An atomic type implemented with a representation consisting of several mutex objects should use separate topactions to ensure that the mutexes are written to stable storage in an order that preserves the correctness of the representation.

Rationale: Mutexes are written to stable storage incrementally. Sometimes, subtle timing problems can be caused by incremental writing if this rule is not followed. [Section 15.3]

III.6. User-Defined Atomic Objects

• If an atomic object $X$ of type $T$ provides operations $O_1$ and $O_2$, and action $A$ has executed $O_1$ but not yet committed, then operation $O_2$ can be performed by a concurrent action $B$ only if $O_1$ and $O_2$ commute given the current state of $X$, the effect (as described by the sequential specification of $T$) of performing $O_1$, then $O_2$ is the same as performing $O_2$, then $O_1$. "Effect" includes both results returned and the (abstract) state modified.

Rationale: There are two concurrency constraints for user-defined atomic objects:
1. An action can observe the effects of other actions only if those actions committed relative to the first action.
2. Operations executed by one action cannot invalidate the results of operations executed by a concurrent action.

Two operations (or sequences of operations) that commute in their effect on the abstract state of $X$ may be permitted to run concurrently, even if they do not commute in their effect on the representation of $X$. This distinction between an abstraction and its implementation is crucial in achieving reasonable performance. [Section 15.4]

• If a user-defined atomic object is accessible from the stable variables of some guardian, it should be written to stable storage whenever an action that modifies it commits to the top.

Rationale: A user-defined atomic type that is not written to stable storage on topaction commit will not be resilient. [Section 15.2]

• The form of the rep for a user-defined atomic type should be one of the following possibilities.
1. The rep is itself atomic. Note that mutex is not an atomic type.
2. The rep is $\text{mutex}[t]$ where $t$ is a synchronous type. For example, $t$ could be atomic, or it could be the representation of an atomic type, if the operations on the this fictitious atomic type are coded in-line so that the entire type behaves atomically.
3. The rep is an atomic collection of mutex types containing synchronous types.
4. The rep is a mutable collection of synchronous types, and objects of the representation type are never modified after they are initialized. That is, mutation may be used to create the initial state of such an object, but once this has been done the object must never be modified.

Rationale: In any other case it will be impossible to guarantee the resilience or serializability of the type's objects independently of how they are used. [Section 15.3]
III.7 Subordinate Where Clauses

- A *where* clause requirement on a cluster as a whole should be used whenever the actual parameters make some difference in the abstraction. For example, in a *set* cluster, the type parameter's *equal* operation must be required by the cluster as a whole, in order to preserve type safety and the representation invariant.

*Rationale:* Argus assumes that requirements that are not placed on the cluster as a whole do not affect the semantics of the abstraction or the representation. [Section 12.6]
Appendix IV
Changes from CLU

This appendix lists the changes made to Argus that are not upward compatible with CLU, that is, those which are not merely additions to CLU and that would cause a CLU program to be illegal or to run differently.

IV.1. Exception Handling

Unlike CLU, which propagated unhandled exceptions (by turning them into failure exceptions) and gave the failure exception special status, unhandled exceptions in Argus are considered errors and always cause a crash of the guardian, and failure is not given special status. All exceptions signalled in a procedure, iterator, handler, or creator must be declared in the routine's header, and there are no implicit resigals of failure exceptions. See Section 11.6 for details.

IV.2. Type Any

The type any is now a type like any other type, with parameterized routines force, create, and is_type. Thus the CLU manual's notion of "type inclusion" is no longer necessary (but there is a new notion of type inclusion in Argus, see Section 6.1). The any$force routine only signals "wrong_type" if the any object's underlying type is not included in the type parameter given, but the type of the result of any$force is its type parameter. The any$is_type routine returns false if the any object's underlying type is not included in the type parameter given. The CLU reserved word "force" was eliminated from Argus, and the creation of an any object is never implicit in an assignment in Argus.

IV.3. Built-in Types

Several changes to the interfaces of the built-in types were necessitated by the changes to exception handling. Specifically, the following changes were made to the built-in types.

1. The string operations concat, append, s2ac, ac2s, s2sc, and sc2s, can now all signal limits. A string literal that would be too large to represent will not be compiled.

2. The sequence operations fill, fill_copy, addh, addl, and concat can now all signal limits. A sequence constructor that would be too large to represent will not be compiled.

3. The array (and atomic_array) operations create, predict, set_low, fill, fill_copy, addh, and addl can now all signal limits. An array constructor that cannot be legally represented will either not be compiled (if this can be detected at compile time) or will signal limits.

4. The copy operations of the structured built-in type generators, and the fill_copy operations of sequence and array (and atomic_array), allow the copy operations of their type parameters to have a failure(string) exception. They will resignal such a failure exception. (Note that the type inclusion rule allows a type parameter to be used even if its copy operation does not have exceptions.)

5. The similar operations of the built-in structured type generators allow the similar operations of their type parameters to have a failure(string) exception. They will resignal such a failure exception.

6. The equal operations of the type generators sequence, struct, and oneof, and the similar
operations of the type generators array, record, and variant (and their atomic counterparts), allow the equal operation of their type parameters to have a failure(string) exception. They will resignal such a failure exception.

7. The elements iterator and the similar and similar1 procedures of the type generator array (and atomic array) will raise a failure(string) exception if the array argument is mutated in such a way as to cause a bounds exception when an element is fetched.

IV.4. Type Inclusion

Type inclusion (the new notion, see Section 6.1) is used in all contexts, including the decls of except and tagcase statements, where CLU had previously required type equality.

IV.5. Where Clauses

CLU had syntax in the where clause (specifically the production for op_name) that allowed one to require an instantiation of a type parameter's generator. This little used feature has been superseded by the mechanism described in Section 12.6.

IV.6. Uninitialized Variables

An uninitialized variable reference error is defined to cause a crash of the guardian, rather than raising a failure exception, which could conceivably be caught.

IV.7. Lexical Changes

Several new reserved words were added. In addition, the semicolon (;) was banished from the syntax.

IV.8. Input/Output Changes

The input/output data types (filename, stream, and istream) and the library procedures described in appendix III of the CLU manual are not furnished by the Argus system. Our current implementation of Argus provides a keyboard cluster for input and a pstream cluster for output. In addition, most of the built-in types currently have print operations defined, for pretty-printing objects onto pstreams. These I/O mechanisms, however, are still experimental, and so are not documented in this reference manual.
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