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Preface

The OCCAM programming language is a high level language, designed to express concurrent algorithms and their implementation on a network of processing components.

The OCCAM reference manual serves to provide a single reference, and definition of the language OCCAM. The manual describes each aspect of the language, starting with the most primitive components of an OCCAM program, and moving on to cover the whole language in detail. The manual is addressed to the wider audience, including not only the computer scientist, software engineer and programmer, but also the electronics engineer and system designer.

Programming in OCCAM is easy. OCCAM enables an application to be described as a collection of processes, where each process executes concurrently, and communicates with other processes through channels. Each process in such an application describes the behaviour of a particular aspect of the implementation, and each channel describes the connection between each of the processes. This approach has two important consequences. Firstly, it gives the program a clearly defined and simple structure. Secondly, it allows the application to exploit the performance of a system which consists of many parts.

Concurrency and communication are the prime concepts of the OCCAM model. OCCAM captures the hierarchical structure of a system by allowing an interconnected set of processes to be regarded as a unified, single process. At any level of detail, the programmer is only concerned with a small, manageable set of processes.

OCCAM is an ideal introduction to a number of key methodologies in modern computer science. OCCAM programs can provide a degree of security unknown in conventional programming languages such as C, FORTRAN or Pascal. OCCAM simplifies the task of program verification, by allowing application of mathematical proof techniques to prove the correctness of programs. Transformations, which convert a process from one form to a directly equivalent form, can be applied to the source of an OCCAM program to improve its efficiency in any particular environment. OCCAM makes an ideal language for specification and behavioural description. OCCAM programs are easily configured onto the hardware of a system or indeed, may specify the hardware of a system.

The founding principle of OCCAM is a minimalist approach which avoids unnecessary duplication of language mechanism, and is named after the 14th century philosopher William of Occam who proposed that invented entities should not be duplicated beyond necessity. This proposition has become known as "Occam's razor".

The OCCAM programming language arises from the concepts founded by David May in EPL (Experimental Programming Language) and Tony Hoare in CSP.(Communicating Sequential Processes). Since its conception in 1982 OCCAM has been, and continues to be under development at INMOS Ltd, in the United Kingdom, under the direction of David May. The development of the INMOS transputer, a device which places a microcomputer on a single chip, has been closely related to OCCAM, its design and implementation. The transputer reflects the OCCAM architectural model, and may be considered an OCCAM machine. OCCAM is the language of the transputer and as such, when used to program a single transputer or a network of transputers, provides the equivalent efficiency to programming a conventional computer at assembler level. However, this manual does not make any assumptions about the hardware implementation of the language or the target system.

OCCAM is a trademark of the INMOS group of companies.
Introduction

This manual describes the programming language [OCCAM 2](#), which differs in a number of ways from the prototype language [OCCAM 1](#). The prototype language gave programmers and designers an early introduction to the concepts of concurrency in programming and design. OCCAM 2 introduces a number of new aspects to the language that extend both its use and facility. In particular, OCCAM 2 introduces floating point representation of real numbers, functions and a data typing system.

This manual was completed during 1986 and 1987 as a part of the final development of OCCAM 2 at the INMOS Microcomputer Centre, Bristol, UK.

Using this manual

This book is designed primarily to be used as a reference text for the programming language [OCCAM](#). However, the manual should also serve as an introduction to the language for someone with a reasonable understanding of programming languages. The primitive aspects of the language are presented at the start of the manual, with as few forward references as possible. It is therefore possible to read the manual from cover to cover, giving the reader an insight into the language as a whole. The manual is cross referenced throughout, and a full index and glossary of terms are provided at the end of the manual.

Keywords and example program fragments appear in a **bold program font** throughout, for example:

```
-- example program fragment
IF
  occam
  programming := easy
```

Words which appear in **italic** indicate a syntactic object, but may also serve to emphasise a need to cross reference and encourage referral to the index. Mathematical symbols and names referring to a mathematical values use a *roman italic font*.

Figures are used in a number of places to illustrate examples, they use the following conventions: an arrowed line represents a **channel**, a round cornered box represents a **process** (refered to here as a **process box**), a lighter coloured process box combines a number of smaller processes. The conventions are illustrated in figure I.1.

![Figure I.1 Figure conventions](image-url)
Syntax and program format

Syntactic notation

The syntax of OCCAM programs is described in a modified Backus-Naur Form (BNF). As an example, the following shows the syntax of assignment, discussed on page 5:

\[ \text{assignment} = \text{variable} := \text{expression} \]

This means "An assignment is a variable followed by the symbol :=, followed by an expression". A vertical bar (|) means "or", so for example:

\[
\begin{align*}
\text{action} &= \text{assignment} \\
&\quad \text{| input} \quad \text{is the same as} \quad \text{action} = \text{input} \\
&\quad \text{| output} \quad \text{action} = \text{output}
\end{align*}
\]

The meaning of this syntax is "An action is an assignment, an input, or an output".

The written structure of OCCAM programs is specified by the syntax. Each statement in an OCCAM program normally occupies a single line, and the indentation of each statement forms an intrinsic part of the syntax of the language. The following example shows the syntax for sequence discussed on page 9:

\[
\text{sequence} = \quad \text{SEQ} \quad \{ \text{process} \}
\]

The syntax here means "A sequence is the keyword SEQ followed by zero or more processes, each on a separate line, and indented two spaces beyond SEQ". Curly brackets { and } are used to indicate the number of times some syntactic object occurs. { process } means, "zero or more processes, each on a separate line". Similarly, {0 , expression}, means "A list of zero or more expressions, separated by commas", and {1 , expression}, means "A list of one or more expressions, separated by commas".

A complete summary of the syntax of the language is given at the end of the main body of the manual (starting on page 80).

Continuation lines

A long statement may be broken immediately after one of the following:

| an operator: | i.e. +, -, *, / etc.. |
| a comma: | ; |
| a semi-colon: | ; |
| assignment: | := |
| the keyword: | IS, FROM or FOR |

A statement can be broken over several lines providing the continuation is indented at least as much as the first line of the statement.

The annotation of occam programs

As the format of OCCAM programs is significant, there are a number of rules concerning how programs are annotated. A comment is introduced by a double dash symbol (--) and extends to the end of the line.
Consider the following sequence:

```occam
SEQ
   -- This example illustrates the use of comments
   -- A comment may not be indented less than
      -- the following statement
   ...
SEQ   -- A sequence
   ...
```

Comments may not be indented less than the following statement.

**Names and keywords used in occam programs**

Names used in OCCAM programs must begin with an alphabetic character. Names consist of a sequence of alphanumeric characters and dots. There is no length restriction. OCCAM is sensitive to the case of names, i.e. `Say` is considered different from `say`. With the exception of the names of channels protocols, names in the examples presented in this manual are all lower case. However, the following are all valid names in occam:

```
PACKETS
vector6
LinkOut
NOT.A.NUMBER
transputer
terminal.in
terminalOut
```

All keywords are upper case (e.g. `SEQ`). All keywords are reserved, and thus may not be used by the programmer. A full list of the keywords appear on page 91. The names of library routines are given in the appendix starting on page 94.
1 Primitive processes

1.1 Assignment

OcCam programs are built from processes. The simplest process in an OcCam program is an action. An action is either an assignment, an input or an output. Consider the following example:

\[ x := y + 2 \]

This simple example is an assignment, which assigns the value of the expression \( y + 2 \) to the variable \( x \). The syntax of an assignment is:

\[
\text{assignment} = \text{variable} := \text{expression}
\]

The variable on the left of the assignment symbol (:=) is assigned the value of the expression on the right of the symbol. The value of the expression must be of the same data type as the variable to which it is to be assigned, otherwise the assignment is not valid.

Variables are discussed on page 26, data types are discussed on page 23, and expressions on page 43.

A multiple assignment assigns values to several variables, as illustrated in the following example:

\[ a, b, c := x, y + 1, z + 2 \]

This assignment assigns the values of \( x \), \( y + 1 \) and \( z + 2 \) to the variables \( a \), \( b \) and \( c \) respectively. The expressions on the right of the assignment are evaluated, and the assignments are then performed in parallel. Consider the following example:

\[ x, y := y, x \]

The effect of this multiple assignment is to swap the values of the variables \( x \) and \( y \).

The syntax of multiple assignment extends the syntax for assignment:

\[
\begin{align*}
\text{assignment} &= \text{variable.list} := \text{expression.list} \\
\text{variable.list} &= \{ 1, \text{variable} \} \\
\text{expression.list} &= \{ 1, \text{expression} \}
\end{align*}
\]

A list of expressions appearing to the right of the assignment symbol (:=) are evaluated in parallel, and then each value is assigned (in parallel) to the corresponding variable of the list to the left of the symbol. The rules which govern the names used in a multiple assignment therefore follow from those for names used in parallel constructions (see page 54). Practically, this means that no name may appear twice on the left side of a multiple assignment, as the name of a variable or as the name of a variable and the name of a subscript expression which selects a component from an array (arrays are explained in chapter 6 which starts on page 39).

The expression on the right of the assignment symbol (:=) may be a function. A multiple result function can be an expression list in a multiple assignment. Functions are discussed in chapter 11 starting on page 65.
1.2 Communication

Communication is an essential part of OCCAM programming. Values are passed between concurrent processes by communication on channels. Each channel provides unbuffered, unidirectional point-to-point communication between two concurrent processes. The format and type of communication on a channel is specified by a channel protocol given in the declaration of a channel. Channel protocols are discussed in chapter 4, which starts on page 29, and channel declarations are discussed in the same chapter on page 29.

Two actions exist in OCCAM which perform communication on a channel. They are: input and output.

1.2.1 Input

An input receives a value from a channel and assigns the received value to a variable. Consider the following example:

```
keyboard ? char
```

This simple example receives a value from the channel named keyboard and assigns the value to the variable char. The input waits until a value is received.

The syntax of an input is:

```
input = channel ? variable
```

An input receives a value from the channel on the left of the input symbol (?), and assigns that value to the variable on the right of the symbol. The value input must be of the same data type as the variable to which it is assigned, otherwise the input is not valid. Variables are discussed on page 26, and data types are discussed on page 23.

1.2.2 Output

An output transmits the value of an expression to a channel. Consider the following example:

```
screen ! char
```

This simple example transmits the value of the variable char to the channel named screen. The output waits until the value has been received by a corresponding input.

The syntax of an output is:

```
output = channel ! expression
```

An output transmits the value of the expression on the right of the output symbol (!) to the channel named on the left of the symbol.

Variables are discussed on page 26 and expressions on page 43.
1.3 **SKIP and STOP**

The primitive process **SKIP** starts, performs no action and terminates.

The primitive process **STOP** starts, performs no action and never terminates.

To explain how **SKIP** behaves, consider the following sequence:

```
SEQ
  keyboard ? char
  SKIP
  screen ! char
```

This sequence executes the input `keyboard ? char`, then executes **SKIP**, which performs no action. The sequence continues, and the output `screen ! char` is executed. The behaviour of **STOP** is illustrated by the following sequence:

```
SEQ
  keyboard ? char
  STOP
  screen ! char
```

This sequence performs the input `keyboard ? char` before, then executes **STOP**, which starts but does not terminate and so does not allow the sequence to continue. The output `screen ! char` is never executed.
Combining processes

OCCAM programs are built from processes. Primitive processes are described in the previous chapter. Larger processes are built by combining smaller processes in a construction. A construction builds a process of one of the following kind:

<table>
<thead>
<tr>
<th>SEQ</th>
<th>IF</th>
<th>CASE</th>
<th>WHILE</th>
<th>PAR</th>
<th>ALT</th>
</tr>
</thead>
<tbody>
<tr>
<td>sequence</td>
<td>conditional</td>
<td>selection</td>
<td>loop</td>
<td>parallel</td>
<td>alternation</td>
</tr>
</tbody>
</table>

A sequential process is built by combining processes in a sequence, conditional or selection construction. A loop is built by combining processes in a WHILE loop. Concurrent processes are built with parallel and alternation constructions, and communicate using channels, inputs and outputs.

The constructions SEQ, IF, PAR and ALT can all be replicated. A replicated construction replicates the constructed process, choice or alternative a specified number of times. Details of replication applied to each of these constructions is given in the following sections.

2.1 Sequence

A sequence combines processes into a construction in which one process follows another. Consider the following example:

```
SEQ
keyboard ? char
screen ! char
```

This process combines two actions which are performed sequentially. The input `keyboard ? char` receives a value which is assigned to the variable `char`, then the following output `screen ! char` is performed.

Programs are built by constructing larger processes from smaller ones. Thus a construction may contain other constructions, as shown in the following example:

```
SEQ
  SEQ
    screen ! '?'
    keyboard ? char
  SEQ
    screen ! char
    screen ! cr
    screen ! lf
```

This simple example combines five actions, and suggests how embedded sequences may be used to show the hierarchical structure of a program. Embedding constructions of the same kind has no effect on the behaviour of the process. This example is equivalent to the following:

```
SEQ
  screen ! '?'
  keyboard ? char
  screen ! char
  screen ! cr
  screen ! lf
```
The syntax for a sequence is:

\[
\text{sequence} = \text{SEQ} \\
\quad \{ \text{process} \}
\]

The keyword \text{SEQ} is followed by zero or more processes at an indentation of two spaces.

### 2.1.1 Replicated sequence

A sequence can be \textit{replicated} to produce a number of similar processes which are performed in sequence, and behave like a conventional counted loop. Consider the following:

\[
\text{SEQ} \quad i = 0 \text{ FOR array.size} \\
\quad \text{stream ! data.array}[i]
\]

This process performs the output \text{stream ! data.array}[i] the number of times specified by the value of \text{array.size}. The initial value of the index \(i\) is specified by a base value (in this case 0). In the above sequence the value of \(i\) for the first output is 0, and for each successive output performed the value of the index is an increment of its previous value. If \text{array.size} has the value 2, the example can be expanded to show the effect of the replication as follows:

\[
\text{SEQ} \\
\quad \text{stream ! data.array}[0] \\
\quad \text{stream ! data.array}[1]
\]

Consider the following example in which the base value is 14:

\[
\text{SEQ} \quad i = 14 \text{ FOR 2} \\
\quad \text{stream ! data.array}[i]
\]

This example may also be expanded to show the value of the index for each replication, as follows:

\[
\text{SEQ} \\
\quad \text{stream ! data.array}[14] \\
\quad \text{stream ! data.array}[15]
\]

This example uses an \textit{array}; arrays (page 39) are explained later in the manual.

The syntax for a replicated sequence extends the syntax for sequences:

\[
\text{sequence} = \text{SEQ} \quad \text{replicator} \\
\quad \{ \text{process} \}
\]

\[
\text{replicator} = \text{name} = \text{base} \text{ FOR } \text{count}
\]

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

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

The keyword \text{SEQ} and a replicator are followed by a process which is indented two spaces. The replicator appears to the right of the keyword \text{SEQ}. The replicator specifies a name for the index (i.e. the name does not need to be declared elsewhere). The value of the index for the first replication is the value of the \text{base} expression, and the number of times the process is replicated is the value of the \text{count} expression at the start of the sequence.

The index may be used in expressions but cannot be assigned to by an input or assignment. The index has a value of \textit{type INT}. The base and count expressions must also be of data type \text{INT}. Data types (page 23) are explained later in the manual. A negative value count expression is \textit{invalid}. See appendix E, page 78 for an explanation of how \textit{invalid processes} behave. If the value of the count expression is zero, the replicated sequence behaves like the primitive process \text{SKIP} (page 7).
2.2 Conditional

A conditional combines a number of processes each of which is guarded by a boolean expression. The conditional evaluates each boolean expression in sequence; if a boolean expression is found to be true the associated process is performed, and the conditional terminates. If none of the boolean expressions are true the conditional behaves like the primitive process *STOP* (page 7), for example:

```
IF
  x < y
  x := x + 1
  x >= y
  SKIP
```

Consider this example in detail: if \(x < y\) is true, the associated process \(x := x + 1\) is performed, however if the expression \(x < y\) is false, the next boolean expression \(x >= y\) is evaluated. If \(x >= y\) is true, then the associated process *SKIP* is performed. In this example, one of the boolean expressions must be true. However, consider the next example:

```
IF
  x < y
  x := x + 1
```

This conditional has a single component. If the expression \(x < y\) is false then the conditional will behave like the primitive process *STOP* (page 7). It is often convenient to use a form of conditional where the final choice is guaranteed to be performed, as illustrated by the following example:

```
IF
  x > y
  order := gt
  x < y
  order := lt
  TRUE
  order := eq
```

The expressions \(x > y\) and \(x < y\) will each be either true or false. The final expression uses the boolean constant *TRUE* which is always true, and acts as a catch-all which causes the associated process to be performed if none of the previous boolean expressions are true. In this context *TRUE* may be read as "otherwise".

The syntax for a conditional is:

```
conditional   =   IF
  { choice }
choice        =   guarded.choice | conditional
guarded.choice =   boolean
  process
boolean      =   expression
```

The keyword *IF* is followed by zero or more choices, indented two spaces. A choice is either a guarded choice or another conditional. A guarded choice is a boolean expression followed by a process, indented two spaces.

A choice which is itself a conditional has the same behaviour if “flattened out” in a similar way to the embedded sequences shown earlier (page 9). Consider the following example:

```
IF
  IF
    x > y
    x := x + 1
  TRUE
  SKIP
```
This has the same effect as:

```
IF
  x > y
  x := x + 1
TRUE
SKIP
```

Boolean expressions (page 48) are discussed later in the manual.

### 2.2.1 Replicated conditional

A conditional may also be replicated, just as a sequence may (page 10). A replicated conditional constructs a number of similar choices. The following example compares the two strings `string` and `object`:

```
IF
  IF i = 1 FOR length
    string[i] <> object[i]
    found := FALSE
  TRUE
  found := TRUE
```

The first choice in this example is a replicated conditional. This has created a number of similar choices each guarded by a boolean expression comparing a component of the array `string` and the array `object`. The replication may be expanded to show its meaning. If `length` has a constant value 2, this example has the same effect as:

```
IF
  IF
    string[1] <> object[1]
    found := FALSE
    found := FALSE
  TRUE
  found := TRUE
```

The syntax for the replicated conditional is:

```plaintext
conditional  =  IF replicator
choice
replicator   =  name = base FOR count
base         =  expression
count        =  expression
```

The keyword `IF` and a replicator are followed by a choice which is indented two spaces. The replicator appears to the right of the keyword `IF`. The replicator specifies a name for the index. The value of the index for the first replication is the value of the `base` expression, and the number of times the choice is replicated is the value of the `count` expression.

The index may be used in expressions but cannot be assigned to by an input or assignment. The index is of data type `INT`. The data type of the base and the count expressions must also be of type `INT`. Data types (page 23) are explained later in the manual. A negative value count expression is invalid. See appendix E, page 78 for an explanation of how invalid processes behave. If the value of the count expression is zero, the replicated conditional behaves like the primitive process `STOP` (page 7).
2.3 Selection

A selection combines a number of options, one of which is selected by matching the value of a selector with the value of a constant expression (called a case expression) associated with the option. Consider the following example:

```
CASE direction
  up
    x := x + 1
  down
    x := x - 1
```

In this example the value of `direction` is compared to the value of the case expressions `up` and `down`. If `direction` has a value equal to `up` then `x := x + 1` is performed, if `direction` has a value equal to `down` then `x := x - 1` is performed, however if no match is found, the selection behaves like the primitive process `STOP` (page 7). Several case expressions may be associated with a single option, for example:

```
CASE letter
  'a', 'e', 'i', 'o', 'u'
    vowel := TRUE
ELSE
    vowel := FALSE
```

If `letter` has the value 'a', 'e', 'i', 'o', or 'u', then the variable `vowel` is assigned the value `TRUE`, otherwise the selection behaves like the primitive process `STOP`. Here it is useful to use a special form of selection where one of the options is guaranteed to be performed, as illustrated below:

```
CASE letter
  'a', 'e', 'i', 'o', 'u'
    vowel := TRUE
ELSE
    vowel := FALSE
```

The process associated with `ELSE` in a selection will be performed if none of the case expressions match the selector.

The syntax for a selection is:

```
selection = CASE selector
  { option }
option = {1, case.expression }
  process
    | ELSE
      process
selector = expression
case.expression = expression
```

The keyword `CASE` is followed by zero or more options, indented two spaces. An option starts with either a list of case expressions or the keyword `ELSE`. This is followed by a process, indented two spaces. All case expressions used in a selection must have distinct constant values (that is, each must be a different value from the other expressions used). The selector and the case expressions must be the same data type, which may be either an integer or a byte data type. A selection can have only one `ELSE` option.

Constant expressions may be given a name in an abbreviation (page 57). Data types (page 23) and expressions (page 43) are also discussed later.
2.4 Loop

A loop repeats a process while an associated boolean expression is true. Consider the following example:

```plaintext
WHILE buffer <> eof
SEQ
  in  ? buffer
  out ! buffer
```

This loop repeatedly copies a value from the channel `in` to the channel `out`. The copying continues while the boolean expression `buffer <> eof` is true. The sequence is not performed if the boolean expression is initially false.

To further illustrate how processes combine, consider the following process:

```plaintext
SEQ
  -- initialise variables
  pointer := 0
  finished := FALSE
  found := FALSE
  -- search until found or end of string
  WHILE NOT finished
    IF
      string[pointer] <> char
        IF
          pointer < end.of.string
            pointer := pointer + 1
          pointer = end.of.string
            finished := TRUE
        string[pointer] = char
      SEQ
        found := TRUE
        finished := TRUE
```

This example searches the array `string` for a character (`char`). Note how the process is built from primitive processes and constructions. In fact it is simpler and easier to write this example using a replicated conditional (page 12) as follows:

```plaintext
IF
  IF i = 0 FOR string.size
    string[i] = char
    found := TRUE
  TRUE
    found := FALSE
```

The syntax for a loop is:

```
loop = WHILE boolean
       process
boolean = expression
```

The keyword `WHILE` and a boolean expression are followed by a process which is indented two spaces. The boolean expression appears to the right of the keyword `WHILE`. 

2.5 Parallel

The parallel is one of the most useful constructs of the OCCAM language. A parallel combines a number of processes which are performed concurrently. Consider the following example:

```
PAR
  editor (term.in, term.out)
  keyboard (term.in)
  screen (term.out)
```

This parallel combines three named processes (known as procedures, page 61), which are performed together. They start together and terminate when all three processes have terminated. The editor and keyboard process communicate using channel `term.in`, the screen and editor communicate using channel `term.out`.

Values are passed between concurrent processes by communication on channels (page 29) using input and output (page 6). Each channel provides unbuffered unidirectional point-to-point communication between two concurrent processes. Figure 2.1 illustrates the channels connecting the three processes in the above example.

The example above shows the parallel being used to tie together the major components of a system. However, a parallel may also be used simply to allow communication and computation to proceed together, as in the following example:

```
WHILE next <> eof
  SEQ
    x := next
  PAR
    in ? next
    out ! x * x
```

The parallel in this example inputs the next value to be processed from one channel while the last value is being processed and output on another.

The syntax of a parallel is similar to that of a sequence:

```
parallel = PAR
  { process }
```

The keyword `PAR` is followed by zero or more processes at an indentation of two spaces.

Parallels may be nested to form the hierarchical structure of a program. The behaviour of the following
process is the same as the earlier example:

```
PAR
  editor (term.in, term.out)
PAR
  keyboard (term.in)
  screen (term.out)
```

Writing a parallel like this helps later in program development when a program must be configured to its environment (when its processes are allocated to physical devices).

A parallel construction which specifies a priority of execution on a single processing device able to perform several tasks (i.e. a multi-tasking processor) is described in appendix A.2.1, page 71.

Rules concerning the use of names in parallels are given in chapter 8 on scope starting on page 53, and are summarised in the appendix (page 75).

### 2.5.1 Replicated parallel

A parallel can be replicated, in the same way as sequences and conditionals described earlier. A replicated parallel constructs a number of similar concurrent processes, as shown in the following example:

```
PAR i = 3 FOR 4
  user[i] ! message
```

This replication performs the four outputs concurrently, and is equivalent to

```
PAR
  user[3] ! message
  user[4] ! message
  user[5] ! message
  user[6] ! message
```

Now consider the following example:

```
PAR
  farmer ()
PAR i = 0 FOR 4
  worker (i)
```

The replicated parallel in this example starts 4 processes, each a copy of the procedure `worker`, and terminates when all four processes are finished. Figure 2.2 shows the structure of this process, which is elaborated upon in the following section. Unlike sequence and conditional replications, the base and count values (here 0 and 4) must be constant. The procedure `worker` takes a single parameter (page 61), for

![Figure 2.2 A farm of parallel processes](image-url)
each instance (page 61) of the procedure the value of the index $i$ is passed. Expanding the replication shows that the above example is equivalent to the following:

```plaintext
PAR
  farmer ()
PAR
  worker (0)
  worker (1)
  worker (2)
  worker (3)
```

The syntax of a replicated parallel is similar to that of the replicated sequence shown earlier in the manual:

```plaintext
parallel = PAR replicator
  process
replicator = name = base FOR count
base = expression
count = expression
```

The keyword `PAR` and a replicator are followed by a process, indented two spaces. The replicator appears to the right of the keyword `PAR`. The replicator specifies a name for the index. The value of the index for the first replication is the value of the base expression, and the number of times the process is replicated is the value of the count expression.

The index may be used in expressions but cannot be assigned to by an input or assignment. A negative value count expression is invalid (see appendix E, page 78 for an explanation of how invalid processes behave). If the value of the count expression is zero, the parallel replication behaves like the primitive process `SKIP` (page 7). The base and count expressions of a replicated `PAR` must be constant values.

The index has a value of type `INT`. The data type of the base and the count expressions must also be of type `INT`. Data types (page 23) are explained later in the manual.
2.6 Alternation

An alternation combines a number of processes guarded by inputs. The alternation performs the process associated with a guard which is ready. Consider the following example:

\[
\begin{align*}
\text{ALT} & \\
\text{left} & \ ? \ \text{packet} \\
& \text{stream} ! \ \text{packet} \\
\text{right} & \ ? \ \text{packet} \\
& \text{stream} ! \ \text{packet}
\end{align*}
\]

The effect of this example is to merge the input from the two channels named left and right, onto the channel stream. The alternation (illustrated in figure 2.3) receives an input from either channel left or channel right. A ready input is selected, and the associated process is performed. Consider this example in detail. If the channel left is ready, and the channel right is not ready, then the input left ? packet is selected. If the channel right is ready, and the channel left is not ready, then the input right ? packet is selected. If neither channel is ready then the alternation waits until an input becomes ready. If both inputs are ready, only one of the inputs and its associated process are performed.

![Figure 2.3 Merging the flow of data](image)

A boolean expression may be included in an alternation to selectively exclude inputs from being considered ready, as shown in the following example:

\[
\begin{align*}
\text{ALT} & \\
\text{left.enabled} & \ & \text{left} & \ ? \ \text{packet} \\
& \text{stream} ! \ \text{packet} \\
\text{right} & \ ? \ \text{packet} \\
& \text{stream} ! \ \text{packet}
\end{align*}
\]

This alternation places the boolean variable (page 26) left.enabled before the second input. If left.enabled is true, the input is included for consideration by the alternation. If left.enabled is false, the input is excluded. To clarify this behaviour, consider the following example:

```plaintext
-- Regulator: 
-- regulate flow of work into a networked farm 
SEQ
idle := processors
WHILE running
    ALT
    from.workers ? result
    SEQ
    from.farm ! result
    idle := idle + 1
    (idle >= 1) & to.farm ? packet
    SEQ
    to.workers ! packet
    idle := idle - 1
```


This is an example (part of the farmer process first illustrated in figure 2.2 and fully illustrated in figure 2.4) of a process which regulates the flow of work into a processor farm. A processor farm can be thought of as a number of machines (worker processes), microcomputers perhaps, each able to perform some task and output a result. The above example controls the amount of work (as packets of data) given to a farm which consists of a network of worker processes. Work may be received by the input to.farm ? packet, and is only considered if a member of the farm is idle (i.e. (idle >= 1)). As a packet of work is sent to the farm, the counter idle is decremented to indicate the number of worker processes which are idle. The worker processes are sent work on the channel to.workers (see figure 2.2), and the variable idle is decremented to keep a count of the idle machines in the farm. If a worker is busy, the work packet is passed on until a non-busy worker is found.

The syntax for alternation is:

```
alternation = ALT
alternative = guarded.alternative | alternation
guarded.alternative = guard
\[\]\护\[\]
process
\[\]\护\[\]
input | boolean & input
| boolean & SKIP
```

The keyword ALT is followed by zero or more alternatives, indented two spaces. An alternative is either a guarded alternative or another alternation. A guarded alternative is an input, or a boolean expression to the left of an ampersand (&) with an input or SKIP on the right. SKIP can take the place of an input in a guard which includes a boolean expression, as shown in the following example:

```
ALT
  in ? data
  out ! data
  monday & SKIP
  out ! no.data
```

If the boolean monday is true then SKIP is treated as though it where a ready input, and may be selected immediately. If the input in ? data is also ready, only one of the processes is performed, which process will be performed is undefined.

Alternation with priority selection is explained in appendix A.2.1, page 72. Delayed inputs explained on page 38 will delay before they become ready, and may be used in guards wherever an input may be used.

Inputs (page 6) and SKIP (page 7) are discussed in chapter 1. Expressions (page 43) are discussed later in the manual. Details of boolean expressions are given on page 48.
2.6.1 Replicated alternation

An alternation can be replicated in the same way as sequences, conditionals and parallels described earlier in the manual. A replicated alternation constructs a number of similar alternatives. Consider the following example:

\[
\text{ALT} \\
\text{ALT } i = 0 \text{ FOR number.of.workers} \\
\quad \text{free.worker}[i] \land \text{to.farm} \ ? \ packet \\
\quad \text{SEQ} \\
\quad \text{to.worker}[i] \ ! \ packet \\
\quad \text{free.worker}[i] := \text{FALSE} \\
\]

\[
\text{ALT } i = 0 \text{ FOR number.of.workers} \\
\quad \text{from.worker}[i] \ ? \ result \\
\quad \text{SEQ} \\
\quad \text{from.farm} \ ! \ result \\
\quad \text{free.worker}[i] := \text{TRUE}
\]

This example presents an alternate version of the process \text{farmer} discussed in the previous section and is illustrated in figure 2.5. This version also regulates the flow of work into the farm, but does so by maintaining an array of booleans (\text{free.worker}) which indicate when a worker is busy. This version of the farmer process is most suitable where several worker processes in the farm are able to input directly from the process. Work packets are input on the channel \text{to.farm} and distributed to an array of worker processes. The completed result is returned to the farmer process via the channel \text{from.worker}. Consider first the upper half of this alternation. Each alternative is guarded by a boolean \text{free.worker}[i] (which has the value true if the worker process is idle), and an input \text{to.farm} \ ? \ packet which inputs packets of work. A selected component of this replication will, after completing the input of a packet, perform the output \text{to.worker}[i] \ ! \ packet (i.e. pass work to an idle worker process), and then set the boolean \text{free.worker}[i] to false, indicating the worker is no longer idle.

Now consider the lower half of this example, which handles the results returning from worker processes. Each component of the replication is guarded by an input \text{from.worker}[i] \ ? \ result which receives results from a worker process. A selected component of this replication will, after completing the input from the worker process, perform the output \text{from.farm} \ ! \ result (i.e. pass the result back to the process which sent the work), and reset the boolean \text{free.worker} to true to indicate the worker is now idle.

A number of these farmer processes in parallel can form a tree of worker processes (see figure 2.5), enabling large and effective farms to be built.
If `number.of.workers` has the value 2, the example has the same effect as:

```
ALT
  ALT
  free.worker[0] & to.farm ? packet
    SEQ
    to.worker[0] ! packet
    free.worker[0] := FALSE
  free.worker[1] & to.farm ? packet
    SEQ
    to.worker[1] ! packet
    free.worker[1] := FALSE

ALT
  from.worker[0] ? result
    SEQ
    from.farm ! result
    free.worker[0] := TRUE
  from.worker[1] ? result
    SEQ
    from.farm ! result
    free.worker[1] := TRUE
```

As for the earlier descriptions of replication, the value of the index for the first replication is the value of the base expression, and the number of replications is the value of the count expression. The syntax for the replicated alternation is:

```
alternation  =  ALT replicator
  alternative
replicator    =  name = base FOR count
base           =  expression
count          =  expression
```

The keyword `ALT` and a replicator are followed by an alternative which is indented two spaces. The replicator appears to the right of the keyword `ALT`. The replicator specifies a name for the index.

The index may be used in expressions but cannot be assigned to by an input or assignment. A negative value count expression is `invalid`. See appendix E, page 78 for an explanation of how `invalid processes` behave. If the value of the count expression is zero, the replicated alternation behaves like the primitive process `STOP` (page 7).

The index has a value of `data type INT`. The data type of the base and the count expressions must also be an integer of type `INT`. Data types (page 23) are explained later in the manual.
3 Data types

**OCCAM** programs act upon variables, channels and timers. A variable has a value, and may be assigned a value in an assignment or input. Channels communicate values. Timers produce a value which represents the time.

This chapter describes the data type of values, also literal representations of known values, and the declaration of variables.

Channels are discussed on page 29 and timers are discussed on page 37.

### 3.1 Data types

Values are classified by their data type. A data type determines the set of values that may be taken by objects of that type.

These are the primitive data types available in **OCCAM**:

<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>BOOL</td>
<td>Boolean values true and false.</td>
</tr>
<tr>
<td>BYTE</td>
<td>Integer values from 0 to 255.</td>
</tr>
<tr>
<td>INT</td>
<td>Signed integer values represented in twos complement form using the word size most efficiently provided by the implementation.</td>
</tr>
<tr>
<td>INT16</td>
<td>Signed integer values in the range (-32768) to (32767), represented in twos complement form using 16 bits.</td>
</tr>
<tr>
<td>INT32</td>
<td>Signed integer values in the range (-2^{31}) to ((2^{31} - 1)), represented in twos complement form using 32 bits.</td>
</tr>
<tr>
<td>INT64</td>
<td>Signed integer values in the range (-2^{63}) to ((2^{63} - 1)), represented in twos complement form using 64 bits.</td>
</tr>
<tr>
<td>REAL32</td>
<td>Floating point numbers stored using a sign bit, 8 bit exponent and 23 bit fraction in ANSI/IEEE Standard 754-1985 representation. The value is positive if the sign bit is 0, negative if the sign bit is 1. The magnitude of the value is:</td>
</tr>
</tbody>
</table>
|      | \[ (2^{(exponent-127)}) \times 1.fraction \]
|      | \[ (2^{-126}) \times 0.fraction \]
|      | 0 if exponent = 0 and fraction = 0
|      | if 0 < exponent and exponent < 255
| REAL64| Floating point numbers stored using a sign bit, 11 bit exponent and 52 bit fraction in ANSI/IEEE Standard 754-1985 representation. The value is positive if the sign bit is 0, negative if the sign bit is 1. The magnitude of the value is: |
|      | \[ (2^{(exponent-1023)}) \times 1.fraction \]
|      | \[ (2^{-1022}) \times 0.fraction \]
|      | 0 if exponent = 0 and fraction = 0
|      | if 0 < exponent and exponent < 2047
|      | if exponent = 0 and fraction ≠ 0

As the above list shows, all signed integer values are represented in twos complement form using the number of bits indicated by the type. All real values are represented according to the representation specified by the ANSI/IEEE standard 754-1985, for binary floating-point arithmetic.

Objects which have values in **OCCAM** have one of the following forms:

<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Literals</td>
<td>Textual representation of known values</td>
</tr>
<tr>
<td>Constants</td>
<td>Symbolic names which have a constant value</td>
</tr>
<tr>
<td>Variables</td>
<td>Symbolic names which have a value, and may be assigned to by input or assignment</td>
</tr>
<tr>
<td>Index</td>
<td>Replication index value</td>
</tr>
</tbody>
</table>
A literal is a known value (1, 2, ‘H’, "Hello", etc.). A variable has a value of a specified type, and may be assigned a new value by an input or assignment. Names with a constant value are specified by an abbreviation (page 57). Expressions (page 43) and functions (page 65) also have a data type and value. The name specified as the index of a replication has a different value for each component of the replication.

The syntax of primitive data types is:

\[
\text{primitive.type} = \begin{cases} 
\text{BOOL} \\
\text{BYTE} \\
\text{INT} \\
\text{INT16} \\
\text{INT32} \\
\text{INT64} \\
\text{REAL32} \\
\text{REAL64} 
\end{cases}
\]

**Rounding of real values**

An accepted limitation in the use of floating point representations of real values is that only a finite set of all possible real values can be represented, thus any real value will be rounded to produce a result which is the nearest value that can be represented by the type. For example, where the type is \text{REAL32}, the next representable value after 1.0 is the value 1.00000019209 (to the nearest 11 digits past the decimal point), any value lying between 1.0 and this value cannot be exactly represented using the representation of type \text{REAL32}. Thus, values which do lie between 1.0 and 1.00000019209 which are of type \text{REAL32} must be rounded to one of these values.

The rounding of real numbers occurs in arithmetic expression evaluation (page 43), in explicit type conversions (page 49), and also when literals are converted to the IEEE representation. An explanation of the IEEE rounding modes, is given in the appendix (page 79).

**3.1.1 Arrays**

The previous section describes primitive types. Non-primitive data types are array types. Arrays and their declaration are described in detail in chapter 6 on page 39. Arrays are briefly described here for completeness, as an understanding of them is necessary in the following chapter which describes channel protocols. An array has a number of components of the same primitive type. An example of an array type is:

\[
[5]\text{INT}
\]

Arrays of this type have components each of type \text{INT}. The components are numbered 0, 1, 2, 3, 4. Arrays may have several dimensions. The following example is an array type with two dimensions:

\[
[4][5]\text{INT}
\]

An array of this type has four components each of type \text{[5]INT}. Array types with any number of dimensions may be constructed. Here are some further examples of array types:

\[
\begin{align*}
[\text{n}]\text{BYTE} & & \text{byte arrays with n components} \\
[3][3][3]\text{REAL32} & & \text{arrays of real numbers, with three dimensions} \\
[50]\text{BOOL} & & \text{arrays with boolean components.}
\end{align*}
\]

The syntax for array types is:

\[
\text{array.type} = [\text{expression}] \text{type}
\]

The syntax for array types shows that any type can be preceded by a value (of type \text{INT}) in square brackets, that value specifying the number of components of the type. Primitive and non-primitive types are collectively called types (types include channels and timers, as shown later). The above syntax is recursive, and this
allows it to cater for multidimensional arrays, as illustrated in the examples above.

3.2 Literals

A literal is a textual representation of a known value, and has a data type. For example, the following are all valid literals:

| 42  | an integer literal in decimal |
| #2A | an integer literal in hexadecimal |
| 'T' | a byte literal |
| "zen" | a string literal |
| TRUE | a boolean literal |

A number (e.g. 42) representing a decimal value, or a hexadecimal value introduced by the hash symbol (#), is an integer of type INT. A character enclosed within a pair of quotation marks (e.g. 'z') has a value of type BYTE. A string is an array of bytes, thus the string "zen" is an array of type [3]BYTE.

Literal values of other types are expressed by stating the type explicitly, for example:

| 42 (BYTE) | a byte value |
| 'T' (INT) | an integer value |
| 42 (INT64) | an integer value with 64 bit representation |
| 42.0 (REAL32) | a 32 bit floating point value |
| 386.54 (REAL64) | a 64 bit floating point value |
| 587.0E-20 (REAL64) | a 64 bit floating point value |
| +1.0E+123 (REAL64) | a 64 bit floating point value |
| 16777217.0 (REAL32) | a 32 bit floating point value |

The type of all real number literals must be stated explicitly in parentheses after the real number. A literal of type REAL32 or REAL64 will be rounded (page 24) when the value is converted into the representation of the type. The effect of this rounding can be seen particularly in the last example shown here. The value 16777216.0 is $2^{24}$ and can be represented precisely in the representation of 32 bit real numbers with a fraction of 23 bits. However, the value 16777217.0 is $(2^{24} + 1)$ and cannot be represented precisely in this representation, and will round to the value 16777216.0. The nearest unique value of a conversion of a literal of type REAL32 can be determined from the first 9 significant digits, and from the first 17 significant digits of a literal of type REAL64. The routines which perform these conversions will use all the digits given in a literal, but further digits will have no affect on the value, for example:

| 54321765439.54 (REAL32) | has a nearest representable value of 54321766400.0 |
| 54321765400.00 (REAL32) | also has a nearest representable value of 54321766400.0 |

An explanation of the IEEE rounding is given in the appendix (page 79).
The syntax for literals is:

\[
\begin{align*}
\text{literal} & = \text{integer} \\
& \quad | \text{byte} \\
& \quad | \text{integer (type)} \\
& \quad | \text{byte (type)} \\
& \quad | \text{real (type)} \\
& \quad | \text{string} \\
& \quad | \text{TRUE | FALSE} \\
\text{integer} & = \text{digits | #hex.digits} \\
\text{byte} & = \text{‘ character’} \\
\text{real} & = \text{digits . digits | digits . digits E exponent} \\
\text{exponent} & = \text{+digits | -digits} \\
\text{digit} & = \text{0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9} \\
\text{hex . digit} & = \text{digit | A | B | C | D | E | F}
\end{align*}
\]

All characters are coded according to their ASCII code. The character A, for example, has a value 65, and so on. A table of the ASCII character set is given in the appendix (appendix I, page 92). A character enclosed in a pair of quotes (e.g. “T”) is a byte value, unless explicitly stated otherwise by placing a type in parentheses to the right of the enclosing quotes.

Strings are a sequence of characters enclosed by double quotes (e.g. "zen"). The type of a string is a table of type BYTE. Each component of the table is the ASCII value of the corresponding character in the string. Special character sequences allow control values such as Tabulation and Carriage Return values to be included in strings. Full details of the OCCAM character set and special characters are given in the appendix (page 92).

A string may be broken over several lines by terminating broken lines with an asterisk, and starting the continuation on the following line with another asterisk. The indentation of the continuation should be no less than the current indentation, as illustrated in the following example:

```plaintext
occam := "Beware the jabberwock my son, the jaws that bite, the* 
* claws that catch, beware the jubjub bird, and shun the* 
* frumious bandersnatch."
```

The literals TRUE and FALSE represent the boolean values true and false respectively.

### 3.3 Variables

The declaration of a variable declares the data type and name of the variable. Consider the following example:

```plaintext
INT n :
```

This declaration declares an integer variable of type INT, and identifies the variable with the name n. The variable is not initialised, and therefore the value of the variable is unspecified until assigned to by an input or assignment. An assignment or input to a variable is valid only if the value to be assigned is the same data type as the variable. Here is a sequence of variable declarations:

```plaintext
BOOL flag :
BYTE char :
INT64 big :
REAL32 x :
```

The syntax for a declaration is:

\[
\text{declaration} = \text{type | ; | name} :
\]

This syntax applies also to the declaration of channels (page 29) and timers (page 37). A variable declaration
consists of the data type, and a name to identify the variable. The declaration appears on a single line, and is terminated by a colon. Where a number of variables of the same type need to be declared, OCCAM permits a single declaration for several names, as shown in the following example:

```
REAL64 a, b, c :
```

The type of the declaration is determined, and then the declarations are performed. This declaration is equivalent to the following sequence of declarations:

```
REAL64 a :
REAL64 b :
REAL64 c :
```

The variable names specified in a multiple declaration are separated by commas. A line break is permitted after a comma. Here are a few more multiple declarations:

```
BOOL flag, switch :
INT16 i, j, k :
REAL64 x, y :
INT64 chains,
    more.chains :
```

Details of arrays and their declaration are given on page 39.
4 Channels

occam programs act upon variables, channels and timers. A variable has a value, and may be assigned a value in an assignment or input. Channels communicate values. Timers produce a value which represents the time.

This chapter describes channels, the declaration of channels, and the specification of the format and data type of communication.

Variables (page 23) and timers (page 37) are discussed elsewhere in the manual.

Channels provide unbuffered, unidirectional point-to-point communication of values between two concurrent processes. The format and type of values passed on a channel is specified by the channel protocol. The name and protocol of a channel are specified in a channel declaration.

4.1 Channel type

The type of a channel is:

CHAN OF protocol

As the syntax shows, channels are a primitive type, just like data types and timers:

primitive.type  =  CHAN OF protocol

4.2 Declaring a channel

A channel is declared in just the same way as variables are declared. Consider the following example:

CHAN OF BYTE screen :

This declaration declares a channel named screen with a protocol of type BYTE. The protocol in this example specifies that each communication on this channel must be a value of type BYTE. An output on this channel could be:

screen ! 'H'

Several channels with the same protocol can be declared together, for example:

CHAN OF BYTE screen, keyboard :

The type of the declarations is determined, and then the declarations are made.

Arrays are described in chapter 6 which starts on page 39.

4.3 Channel protocol

A channel communicates values between two concurrent processes. The format and data type of these values is specified by the channel protocol. The channel protocol is specified when the channel is declared. Each input and output must be compatible with the protocol of the channel used. Channel protocols enable the compiler to check the usage of channels.
4.3.1 Simple protocols

The simplest protocols consist of a primitive data type, or an array data type. An example of a channel with a byte protocol has already been given. A protocol with an array type can be declared in the same way, for example:

CHAN OF [36]BYTE message :

This declaration declares a channel with a byte array protocol which is identified by the name message. The protocol of this channel specifies that the channel is able to pass byte arrays with 36 components. For example, consider this output:

message ! "The vorpal blade went snicker-snack."

It is often desirable to have a channel that will pass arrays of values, where the number of components in the array is not known until the output occurs. A special protocol, called a counted array protocol, enables this kind of array communication by passing a length first, and then that number of components from the array. A declaration for such a channel looks like this:

CHAN OF INT::[](BYTE message :

This declaration declares a channel which passes an integer value first, then that number of components from the array. An output on this channel will look like this:

message ! 16::"The vorpal blade went snicker-snack."

This has the effect of outputting the string "The vorpal blade"; the first 16 characters of the array. The associated input could look like this:

message ? len::buffer

This input will first receive an integer value (16 in this example) which is assigned to the variable len, then that number of components are input and assigned to the first components of the array buffer. The input is invalid if the number of components in buffer is less than len.

All the above protocols are called simple protocols, their syntax is:

```
simple.protocol = type
  | primitive.type::[]type
input = channel ? input.item
input.item = variable
  | variable::variable
output = channel!output.item
output.item = expression
  | expression::expression
protocol = simple.protocol
```

This syntax has extended the syntax for input and output (see page 6). A simple protocol is either a data type or a counted array as described above, and is specified by the data type of the count (which may be either an integer or byte), followed by a double colon, square brackets (::[]), and the specifier indicating the type of the components.
### 4.3.2 Naming a protocol

A protocol can be given a name in a *protocol definition*, as shown in the following example:

```
PROTOCOL CHAR IS BYTE :
```

A channel can now be declared with the protocol `CHAR`, for example:

```
CHAN OF CHAR screen :
```

A protocol definition must be used if more complex protocols, like the *sequential protocol* described in the following section are required. The syntax for protocol definition is:

```
definition = PROTOCOL name IS simple.protocol :
    | PROTOCOL name IS sequential.protocol :
protocol = name
```

A protocol definition defines a name for the simple protocol or sequential protocol (described in the following section) which appears to the right of the keyword `IS`. A protocol definition appears on a single line, and is terminated by a colon. The line may be broken after the keyword `IS` or after a semi-colon in a sequential protocol. It is recommended that the names of protocols be uppercase.

### 4.3.3 Sequential protocol

Simple protocols have been discussed earlier. Sequential protocols specify a protocol for communication which consists of a sequence of simple protocols. Consider the following example:

```
PROTOCOL COMPLEX IS REAL64; REAL64 :
```

Channels declared with this protocol (`CHAN OF COMPLEX`) pass pairs of values. An input or output on a channel with sequential protocol is a sequence of distinct inputs or outputs. An input on a channel with the above protocol `complex` is shown below:

```
items ? real.part; imaginary.part
```

Each value is input in sequence and assigned to each variable in turn. Here are some more examples of sequential protocol definitions:

```
PROTOCOL DIR.ENTRY IS INT16; [14]BYTE :
PROTOCOL INODE IS INT16;INT16;INT32;INT32;INT16;[7]INT16;INT16;INT16 :
PROTOCOL RECORD IS INT16:[]BYTE :
```

Declarations of channels with these protocols would look like this:

```
CHAN OF DIR.ENTRY directory :
CHAN OF INODE sys :
CHAN OF RECORD blocks :
```

The syntax for sequential protocol is:

```
sequential.protocol = {1 ; simple.protocol }
input = channel ? {1 ; input.item }
output = channel ! {1 ; output.item }
```

A sequential protocol is one or more simple protocols separated by semi-colons. The communication on a channel with a sequential protocol is valid provided the type of each item input or output is compatible with the corresponding component of the protocol.
4.3.4 Variant protocol

It is often convenient to use a single channel to communicate messages with different formats. A variant protocol specifies a number of possible formats for communication on a single channel. Consider the following example:

```
PROTOCOL FILES
  CASE
    request;  BYTE
    filename; [14]BYTE
    word;     INT16
    record;   INT32; INT16::[]BYTE
    error;    INT16; BYTE::[]BYTE
    halt;
```

This example defines a variant protocol named FILES. CASE combines a number of tags, each of which may identify a sequential protocol. The variant protocol defined here has six variants. It is important to note that this protocol definition defines seven new names, the name of the protocol FILES, and the names of the six tags, request, filename, word, record, error, halt. A channel declared with this protocol would look like this:

```
CHAN OF FILES to.dfs :
```

A communication on this channel first sends a tag to inform the receiving process of the format for the rest of the communication. So, for example

```
to.dfs ! request; get.record
```

first sends the tag request followed by a BYTE value (get.record). Consider the output:

```
to.dfs ! halt
```

This output sends only the tag halt and according to the above variant protocol definition requires no further output.

The syntax for a variant protocol and the associated output is:

```
definition  =  PROTOCOL name
              CASE
                { tagged.protocol }
             :

tagged.protocol =  tag
                  |  tag ; sequential.protocol

tag
output =  channel ! tag
          |  channel ! tag ; {1 ; output.item }
```

In a definition of a variant protocol the name which identifies the protocol appears to the right of the keyword PROTOCOL, this is followed at an indentation of two spaces by the keyword CASE, which in turn is followed at a further indentation of two spaces by a number of tagged protocols. The definition of a variant protocol is terminated by a colon, which appears on a line by itself, at the same level of indentation as the \texttt{P} of the keyword \texttt{PROTOCOL}. A tagged protocol is either a tag by itself or a tag followed by a semi-colon, and sequential protocol. Tags are a name like any other name, they must be distinct and are specified (that is, brought into existence) by the variant protocol definition.

An output on a channel of variant protocol is a tag by itself or a tag followed by a number of output items separated by semi-colons. The output is valid only if the tag and the associated output items are compatible with one of the tagged protocols specified in the definition.
Input on a channel with variant protocol

So far only output on a channel with variant protocol has been shown. A special form of input is required (called case input) to provide for input on channels with a variant protocol. The previous example is suggestive of a conversation with a disc filing system, and is a reminder that channels are unidirectional. So, for a user process to "listen to" the other side of this conversation, another channel must be declared, as shown below:

```plaintext
CHAN OF FILES from.dfs :
```

This example declares another channel with the protocol FILES. The process which outputs request; get.record, might reasonably expect to receive a reply on a channel with this protocol. Consider a more complete example of this conversation:

```plaintext
SEQ
to.dfs ! request; get.record
from.dfs ? CASE
    record; rnumber; rlen::buffer
    ... do whatever
    error; enumber; elen::buffer
    ... handle error
```

Illustrated in the above example is a case input on the channel from.dfs. This accepts a variant input with either the tag record or the tag error, any other tag would be invalid and the input would behave like the primitive process STOP.

A special form of case input simply receives a tag from the channel named on the left of the case input symbol (? CASE), and then compares the tag for equality with the tag of the tagged list which appears to the right of the symbol. A tag is input, then if the tags match the process next inputs the remainder of the tagged list, if the tags do not match the process next behaves like the primitive process STOP, for example:

```plaintext
from.dfs ? CASE filename; name.buffer
```

This process inputs a tag, if the tag is filename the input is completed, and a value assigned to the variable name.buffer. Otherwise, no further input is performed, and the input behaves like the primitive process STOP (page 7). A case input is valid only if the tagged lists are compatible with one of the tagged protocols specified in the definition.

Consider the following:

```plaintext
PROTOCOL COMMS
    CASE
        packet;INT::[]BYTE
        sync :
        CHAN OF COMMS route :
    PAR
        SEQ
            route ! packet; 11::"Hello world"
            R ()
        SEQ
            route ? CASE sync
            S ()
```

In this example the input route ? CASE sync will behave like the primitive process STOP as the tags do not match. The associated output will also behave like STOP, for although the output of the tag packet succeeds, the output 11::"Hello world" does not. In this example the procedures R() and S() will
not be performed. Also consider the following:

```
PAR
  SEQ
    route ! sync
  P ()
SEQ
    route ? CASE packet; length::message
    Q ()
```

Each communication of sequential protocol, or of a tagged sequential protocol is in fact a sequence of separate communications. So, in the above example, the input `route ? CASE packet; length::message` will behave like the primitive process `STOP` because the tags do not match. However, the associated output `route ! sync` will succeed as the output of the tag has completed, and the variant requires no further output. Thus, the `procedure (page 61)` `P ()` will be performed, and the procedure `Q ()` will not be performed.

The syntax for case input is:

```
case,input         =    channel ? CASE
    { variant }  
variant           =    tagged.list
            process
    | specification
        variant
tagged.list       =    tag
            | tag ; {, ; input.item }  
process           =    case,input
input             =    channel ? CASE tagged.list
```

A case input receives a tag from the channel named on the left of the case input symbol (`? CASE`), and then the tag is used to select one of the variants. These appear on the following lines, indented by two spaces. A tag is input, then if a variant with that tag is present the process next inputs the remainder of the tagged list, and an associated process, indented a further two spaces, is performed. If no variant with that tag is found the process next behaves like the primitive process `STOP`.

A case input may consist of a tagged list only, as shown in the earlier examples.

**Variants in alternatives**

Case inputs may also be used as an input in an alternation (chapter 2, page 18). Consider the following example:

```
ALT
  from.dfs ? CASE
    request; query
    ... do query
    error; enumber; eelen::buffer
    ... handle dfs error
    record; rnumber; rlen::buffer
    ... accept record

from.network ? CASE
  request; query
  ... do query
  error; enumber; eelen::buffer
  ... handle network error
  record; rnumber; rlen::buffer
  ... accept record
```

This alternation accepts input from either of the two channels (`from.dfs` and `from.network`). These inputs are explained in the previous section. This alternation could have included a mix of case inputs, and
the alternatives described on page 18. The syntax for case inputs in an alternative is:

\[
\text{alternative} = \quad \text{channel} \ ? \ \text{CASE} \\
\hspace{1cm}\{ \ \text{variant} \ \} \\
\hspace{1cm}\mid \ \text{boolean} \ & \ \text{channel} \ ? \ \text{CASE} \\
\hspace{1cm}\{ \ \text{variant} \ \}
\]

A case input as an alternative is either a case input with variants as described in the earlier syntax, or such a case input preceded by a boolean guard and an ampersand (&) to the left of the channel name. The case input is not considered by the alternation if the boolean guard is false.

4.3.5 Anarchic protocol

In some situations it may be necessary to specify a channel protocol where the format of the protocol for some reason cannot be defined. Such situations are rare, and are likely to occur only when communicating with an external device such as a printer, terminal or other device controller. Such a device can be considered an alien process where the protocol for communication with that process is dictated by the nature of the device. A special protocol exists which allows the input and output of any format without checking. The protocol is specified by the keyword ANY, as illustrated in the following example:

\[
\text{CHAN OF ANY printer :}
\]

A channel with this protocol can only input or output values of data type. The effect of an output on a channel with the ANY protocol is that the value is mapped down into its constituent bytes, and output as an array of bytes. An input on a channel with the ANY protocol inputs the array of bytes and converts (by retyping conversion, see page 77) the value to the type of the receiving variable.
5 Timers

OCCAM programs act upon variables, channels and timers. A variable has a value, and may be assigned a value in an assignment or input. Channels communicate values. Timers produce a value which represents the time.

This chapter describes timers, the declaration of timers, and access to them.

Channels are discussed on page 29 and variables are discussed on page 23.

A timer provides a clock which can be accessed by any number of concurrent processes.

5.1 Timer type

The type of a timer is:

```plaintext
TIMER
```

Timers are a primitive type, just like channels and data types. Here is the syntax:

```plaintext
primitive.type = TIMER
```

5.2 Declaring a timer

A timer is declared in a manner similar to channels and variables. Consider the following example:

```plaintext
TIMER clock :
```

This declaration declares a timer which is identified by the name `clock`. Several timers may be declared together, for example:

```plaintext
TIMER clockA, clockB :
```

The type of the declarations are determined, and then the declarations are made. Arrays of timers are discussed later in the manual (page 40).

A value input from a timer provides an integer value of type INT representing the time. The value is derived from a clock, which changes by an increment at regular intervals. The value of the clock is cyclic (i.e. when the value reaches the most positive integer value, an increment results in the most negative integer value). The special operator `AFTER` can be used to compare times even though the value may have crossed from most positive to most negative, just as one o'clock pm may be considered later than eleven o'clock am. If t1 and t2 are successive inputs from the same timer, then the expression `t1 AFTER t2` is true if t1 is later than t2. This behaviour is only sensible if the second value (t2) is input within one cycle of the timer. `AFTER` is also explained in the chapter on expressions (page 43).

The rate at which a timer is incremented is implementation dependent.
5.3 Timer input

Timers are accessed by special forms of input called timer inputs, which are similar to channel inputs, for example:

```plaintext
clock ? t
```

This example inputs a value from the timer `clock` and assigns the value to the variable `t`. Unlike channels, inputs from the same timer may appear in any number of components of a parallel.

Another special input (called a delayed input) specifies a time, after which the input terminates, for example:

```plaintext
clock ? AFTER t
```

This input waits until the value of the timer `clock` is later than the value of `t`. In other words, if `c` is the value of the timer `clock`, then the input will wait until `(c AFTER t)` is true. The value of `t` is unchanged.

More usefully perhaps, a delay can be caused by this sequence:

```plaintext
SEQ
  clock ? now
  clock ? AFTER now PLUS delay
```

This sequence inputs a value representing the current time and assigns it to the variable `now`. The following delayed input waits until the value input from `clock` is later than the value of `now PLUS delay`. PLUS (page 46) is a modulo operator.

The syntax for timer inputs is:

```plaintext
input = timer input | delayed input
timer input = timer ? variable
delayed input = timer ? AFTER expression
```

A timer input receives a value from the timer named on the left of the input symbol (?), and assigns that value to the variable named on the right of the symbol. A delayed input waits until the value of the timer named on the left of the input symbol (?) is later than the value of the expression on the right of the keyword `AFTER`. 
6 Arrays and elements

Previous chapters have described types in OCCAM and the declaration of variables, channels and timers. This chapter describes arrays, and the syntactic components of a program which describe elements of these types.

An array has a number of consecutively numbered components of the same primitive type. Elements enable channels, timers, variables or arrays to be selected from arrays. An element is either a name, a subscripted name, or a segment. An element which is a name identifies a variable or array of variables, a channel or array of channels, a timer or array of timers.

6.1 Data type arrays

Primitive types have already been discussed in some detail. Non-primitive data types are array types. An example of an array type is:

\[ [5] \text{INT} \]

Arrays of this type have components each of type \text{INT}. The components are numbered 0, 1, 2, 3, 4. The declaration of an array follows the same form as other declarations, for example:

\[ [5] \text{INT} \ x : \]

This declaration declares an integer array \( \text{x} \) with five components. Arrays may have further dimensions specified by simply adding the size of the dimension, enclosed in square brackets, to the type. The following is an array type with two dimensions:

\[ [4][5] \text{INT} \]

An array of this type has four components each of type \[5\] \text{INT}. Equally, an array of type \[3][4][5] \text{INT} \] is an array with three components of type \[4][5] \text{INT} \], and so on. In this way, arrays with any number of dimensions may be constructed. The declaration of an array with multiple dimensions is similar to other declarations, as shown in the following example:

\[ [4][5] \text{INT} \ x : \]

In theory there is no limit to the number of dimensions an array type may have. In practice however, arrays of data type require memory, and therein lies the limit. Here are some more array types:

<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>[n]\text{BYTE}</td>
<td>a byte array with ( n ) components</td>
</tr>
<tr>
<td>[3][3][3]\text{REAL32}</td>
<td>a three dimensional array of real numbers</td>
</tr>
<tr>
<td>[50]\text{BOOL}</td>
<td>an array with boolean components</td>
</tr>
</tbody>
</table>

The size of each dimension in an array declaration must be specified by a value of type \text{INT}, and be a value greater than zero. Two arrays of data type are considered to have the same type if they have the same number and type of components. An array may be assigned to by input or assignment. An input or assignment to an array is valid only if the value to be assigned is of the same type as the array. Here are a few more examples of array declarations:

\[ [4]\text{BOOL} \ flag : \]

\[ [5]\text{INT} \ v1, \ v2 : \]

\[ [\text{maxlen}]\text{BYTE} \ \text{string} : \]

\[ [\text{xsize}][\text{ysize}]\text{REAL64} \ \text{matrix} : \]

\[ [3][3][3]\text{INT16} \ \text{cube} : \]
The syntax for array types is:

\[
\begin{align*}
\text{type} & = \quad \text{primitive.type} \\
\text{array.type} & = \quad [\text{expression}] \text{ type}
\end{align*}
\]

The syntax for array types shows that any type can be preceded by a value (of type \text{INT}) in square brackets, that value specifying the number of components of the type. Primitive and non-primitive types are collectively called \textit{types} (types include channels and timers, as shown in the next section). The syntax is defined recursively, and this allows the syntax to cater for multidimensional arrays, as illustrated in the examples above.

The declaration of arrays follows from the syntax for declaration described on page 26. Several arrays of the same type can be declared together, for example:

\begin{verbatim}
[users]INT id, privilege ;
\end{verbatim}

The type of the declarations are determined, and then the declarations are made. This is especially important in the declaration of arrays. Consider the following rather silly declaration:

\begin{verbatim}
[forms]INT forms, teachers :
\end{verbatim}

This example is therefore equivalent to the following sequence:

\begin{verbatim}
SEQ
 t := forms
 [t]INT forms :
 [t]INT teachers :
\end{verbatim}

\section{6.2 Channel arrays and timer arrays}

The previous section has described arrays of data type. Arrays of channels and arrays of timers can be declared in the same way. The following, for example, declares an array of channels:

\begin{verbatim}
[4]CHAN OF BYTE screens :
\end{verbatim}

This declaration declares an array \textit{screens} of four channels. The following declares an array of timers:

\begin{verbatim}
[4]TIMER clock :
\end{verbatim}

This declaration declares an array \textit{clock} of four timers.

Multidimensional arrays of channels and timers are built in the same way as multidimensional arrays of variables, for example:

\begin{verbatim}
[3][4]TIMER clock.clock :
[5][5]CHAN OF PACKETS node :
\end{verbatim}

There is a subtle semantic distinction to be made between an array of data type and arrays of channels and timers. An array of variables is itself a variable (it may be assigned to by assignment or input), however, an array of channels is not itself a channel (that is, only single components of the array may be used in input/output) but a means of referencing a number of distinct channels identified by consecutive subscripts. The same is true for arrays of timers.

Several arrays of the same type can be declared together. Consider the following example:

\begin{verbatim}
[users]CHAN OF BYTE screen, keyboard :
\end{verbatim}

The type of the declarations are determined, and then the declarations are made.
6.3 Elements

Elements have a type. Elements which have a data type are variables, and also have a value. Elements of channel type are used for input and output (page 6). Elements of timer type are used in a timer input or delayed input (page 37).

Subscripted names select a component of an array. Suppose clock, user.in and data are declared as follows:

\[
\begin{align*}
\text{[9]} & \text{TIMER clock :} \\
\text{[12]} & \text{CHAN OF MESSAGES user.in :} \\
\text{[8][8][8]} & \text{REAL32 data :}
\end{align*}
\]

Consider these examples:

<table>
<thead>
<tr>
<th>Subscripted Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>\text{clock[0]}</td>
<td>the first component of the array clock, of type TIMER.</td>
</tr>
<tr>
<td>\text{user.in[9]}</td>
<td>the tenth component of the array user.in, of type CHAN OF MESSAGES.</td>
</tr>
<tr>
<td>\text{data[0]}</td>
<td>the first component of a dimension of data, of type [8][8]\text{REAL32}.</td>
</tr>
<tr>
<td>\text{data[3][0]}</td>
<td>the first component of another dimension of data, of type [8]\text{REAL32}.</td>
</tr>
</tbody>
</table>

A subscript appears in square brackets after the name of an array. The component selected has one dimension less than its type for each subscript. Subscripts must be an expression of integer type INT. A subscript is valid only if the value of the expression is within the bounds of the array, and so a negative value subscript is always invalid. That is, the value of a subscript must be in the range 0 to \((n - 1)\), where \(n\) is the number of components in the array.

A segment of an array is itself an array. The segment has zero or more components, as shown in the following examples:

<table>
<thead>
<tr>
<th>Segment</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>\text{[clock FROM 0 FOR 1]}</td>
<td>the first component of the array clock, of type [1]\text{TIMER}.</td>
</tr>
<tr>
<td>\text{[user.in FROM 9 FOR 1]}</td>
<td>the tenth component of the array user.in, of type [1]\text{CHAN OF MESSAGES}.</td>
</tr>
<tr>
<td>\text{[user.in FROM 9 FOR 3]}</td>
<td>the tenth, eleventh and twelfth components of the array user.in, of type [3]\text{CHAN OF MESSAGES}.</td>
</tr>
<tr>
<td>\text{[data FROM 0 FOR n]}</td>
<td>the first (n) components of data, of type [n][8][8]\text{REAL32}.</td>
</tr>
<tr>
<td>\text{[data FROM n FOR 6]}</td>
<td>six components of the array data from (n), of type [6][8][8]\text{REAL32}.</td>
</tr>
<tr>
<td>\text{[data FROM 1 FOR 0]}</td>
<td>an “empty” segment, compatible with a specifier [ ] [8][8]\text{REAL32}.</td>
</tr>
</tbody>
</table>

A segment of an array has the same number of dimensions as the array.

The syntax for elements is:

\[
\text{element} = \begin{cases} 
\text{element [ subscript ]} \\
\text{[ element FROM subscript FOR count ]} \\
\text{name} \\
\text{expression}
\end{cases}
\]

The syntax is defined recursively, and shows how more complex elements can be built. The simplest subscripted element is a name followed by a single subscript in square brackets to the right of the name. This is itself an element and may also be followed by a subscript in square brackets, and so on, limited by the number of dimensions in the array. A segment begins with a square bracket, followed on the right by an element and the keyword FROM. This is followed by a subscript, which must be an integer of type INT, indicating the first component of the segment, this in turn is followed by the keyword FOR and a count, which is a value of type INT which specifies the number of components in the segment. Line breaks are permitted.
immediately after the keyword **FROM** and the keyword **FOR**. The segment is valid only if the value of the count is not negative, and does not violate the bounds of the array. That is, the value must be in the range 0 to 
\((\text{subscript} + \text{count}) - 1\). Here is another example to consider:

```
[[c FROM j FOR i] FROM 0 FOR 5]
```

This complex looking segment selects the first five components of an element which is itself a segment, it is in fact equivalent to `[c FROM j FOR 5]` provided `i \geq 5`. Segments may also be subscripted, for example:

```
[x FROM n FOR 8][3]
```

The subscript in this example selects component number 3 from the associated segment.

An assignment to a variable selected by a subscript is an assignment to that component of the array, and has no effect on any other component in the array. Consider the following example:

```
x[3] := 42
```

Assignment to a segment of a variable which is an array, is not valid if a component of the expression is also a component of the array to which it is to be assigned. Thus, the following assignment is not valid:

```
[x FROM 6 FOR 6] := [x FROM 8 FOR 6] -- INVALID!
```

Both these segments share the component `x[8]`. The effect of an assignment to an array or a segment of an array, is to assign to each component the value of the corresponding component of the expression.

The combined effect of an input and output on a channel of an array or a segment of an array is equivalent to an assignment from the outputting process to the inputting process. Consider the following example:

```
[x FROM 0 FOR 10] := [y FROM 0 FOR 10]
```

This is a valid assignment, and has the same effect as the following:

```
PAR
  c ! [y FROM 0 FOR 10]
  c ? [x FROM 0 FOR 10]
```

Also consider the following assignment of `v1` to `v2`, where both are arrays of type `[12]`**INT**:

```
v1 := v2
```

This assignment assigns each component of the array `v2` to each respective component of the array `v1`, and has the same effect as the following communication:

```
PAR
  c ! v1
  c ? v2
```

Assignment is discussed earlier on page 5, input and output are also described earlier on page 6. See the appendix (page 78) to discover how invalid processes behave.
This chapter is about expressions, and describes the range of operators provided by OCCAM. The chapter also describes data type conversions and tables.

An expression is evaluated and produces a result. The result of an expression has a value and a data type. The simplest expressions are literals and variables. More complex expressions are constructed from operands, operators and parentheses. An operand is either an element (page 39) of data type, a literal, a table, or another expression enclosed in parentheses. An operator performs an operation, for example an addition, upon its operand(s). The following are all valid expressions:

<table>
<thead>
<tr>
<th>Expression</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 (INT64)</td>
<td>a literal value</td>
</tr>
<tr>
<td>x</td>
<td>a variable</td>
</tr>
<tr>
<td>6 * 4</td>
<td>multiplication of two literal operands</td>
</tr>
<tr>
<td>x * y</td>
<td>multiplication of two variable operands</td>
</tr>
<tr>
<td>NOT TRUE</td>
<td>a boolean expression</td>
</tr>
</tbody>
</table>

An expression may itself be an operand in an expression. In this way larger expressions are built, as shown in the following examples:

<table>
<thead>
<tr>
<th>Expression</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1 + 2) - 1</td>
<td>subtract 1 from the result of (1 + 2)</td>
</tr>
<tr>
<td>(x * y) * (w * z)</td>
<td>multiply the results of the expressions (x * y) and (w * z)</td>
</tr>
</tbody>
</table>

There is no operator precedence as the hierarchical structure of a large expression is clearly defined by parentheses. With the exception of shift operations, where the number of bits shifted is indicated by a value of type INT, the data type of the two operands in a dyadic expression must be of the same type. In an assignment the value of the expression must be of the same data type as the variable to which it is to be assigned. Consider in detail the following example:

\[ y := (m \times x) + c \]

Each of the elements in this expression (y, m, x and c) must be of the same data type. The result of an expression is of the same type as its operand(s). The expression in this example - (m \times x) + c - has two operators. The parentheses indicate that the expression (m \times x) is an operand of the operator +, and thus must be evaluated before the + operation can be performed.

The syntax for expressions is:

\[
\begin{align*}
expression &= \text{monadic.operator operand} \\
&\quad|\text{operand dyadic.operator operand} \\
&\quad|\text{conversion} \\
&\quad|\text{operand} \\
operand &= \text{element} \\
&\quad|\text{literal} \\
&\quad|\text{table} \\
&\quad|\text{(expression)}
\end{align*}
\]

Tables, operators and conversions are detailed in the following sections. Elements (page 39) and literals (page 25) have been explained earlier.
7.1 Tables

A table constructs an array of values from a number of expressions which must yield values of the same data type. The value of each component of the array is the value of the corresponding expression. Consider the following example:

\[ [1, 2, 3] \]

This example constructs an array with three components, each of type INT. Here are some more examples:

<table>
<thead>
<tr>
<th>Expressions</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>['a', 'b', 'c']</td>
<td>a table of three bytes (equivalent to &quot;abc&quot;)</td>
</tr>
<tr>
<td>[x, y, z]</td>
<td>a table of three values</td>
</tr>
<tr>
<td>[x * y, x + 4]</td>
<td>a table with two component values</td>
</tr>
<tr>
<td>[(a * b) + c]</td>
<td>a table with a single component</td>
</tr>
<tr>
<td>[6(INT64), 8888(INT64)]</td>
<td>a table of two INT64 integers</td>
</tr>
</tbody>
</table>

If the variables a, b and c are of type INT, then the table \[ (a * b) + c \] is an expression whose type is \[ 1 \] INT. \['a', 'b', 'c'\] is an expression whose type is \[ 3 \] BYTE, and so on.

The syntax for tables is:

```
table = table [ subscript ]
| [ {1, expression} ]
| [ table FROM subscript FOR count ]
```

A table is one or more expressions of the same data type, separated by commas, and enclosed in square brackets. Line breaks are permitted after a comma. The meanings of subscript and count are given earlier in the description of elements (page 39).

7.2 Operations

An operation evaluates its operand(s) and produces a result. The result of an operation has a value and a data type.

<table>
<thead>
<tr>
<th>Operation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>+</td>
<td>addition</td>
</tr>
<tr>
<td>-</td>
<td>subtraction</td>
</tr>
<tr>
<td>*</td>
<td>multiplication</td>
</tr>
<tr>
<td>/</td>
<td>division</td>
</tr>
<tr>
<td>REM</td>
<td>remainder</td>
</tr>
<tr>
<td>\</td>
<td>remainder</td>
</tr>
<tr>
<td>PLUS</td>
<td>modulo addition</td>
</tr>
<tr>
<td>MINUS</td>
<td>modulo subtraction</td>
</tr>
<tr>
<td>TIMES</td>
<td>modulo multiplication</td>
</tr>
<tr>
<td>MOSTNEG</td>
<td>most negative</td>
</tr>
<tr>
<td>MOSTPOS</td>
<td>most positive</td>
</tr>
<tr>
<td>/\</td>
<td>bitwise and</td>
</tr>
<tr>
<td>/</td>
<td>bitwise or</td>
</tr>
<tr>
<td>&gt;&gt;</td>
<td>bitwise not</td>
</tr>
<tr>
<td>&lt;&lt;</td>
<td>shift right</td>
</tr>
<tr>
<td>AND</td>
<td>boolean and</td>
</tr>
<tr>
<td>OR</td>
<td>boolean or</td>
</tr>
<tr>
<td>NOT</td>
<td>boolean not</td>
</tr>
<tr>
<td>=</td>
<td>equal</td>
</tr>
<tr>
<td>&lt;=</td>
<td>less than</td>
</tr>
<tr>
<td>&gt;=</td>
<td>greater than</td>
</tr>
<tr>
<td>&lt;&gt;</td>
<td>not equal</td>
</tr>
<tr>
<td>AFTER</td>
<td>later than</td>
</tr>
<tr>
<td>SIZE</td>
<td>array size</td>
</tr>
</tbody>
</table>
7.2.1 Arithmetic operators

The arithmetic operators are:

+ addition
- subtraction
* multiplication
/ division
REM remainder

Arithmetic operators perform an arithmetic operation upon operands of the same integer or real data type (not on bytes or booleans), for example:

<table>
<thead>
<tr>
<th>Operation</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>39 + 3</td>
<td>produces a value of 42</td>
</tr>
<tr>
<td>45 - 3</td>
<td>produces a value of 42</td>
</tr>
<tr>
<td>6 * 7</td>
<td>produces a value of 42</td>
</tr>
<tr>
<td>126 / 3</td>
<td>produces a value of 42</td>
</tr>
<tr>
<td>128 REM 3</td>
<td>produces a value of 2</td>
</tr>
</tbody>
</table>

The final example in this list may also be written: 128 \ 3. The symbols REM and \ both signify the remainder operation. Except where the result is zero, the sign of an integer remainder operation is the sign of the dividend regardless of the sign of the divisor. The result of an integer division is rounded toward zero (i.e. truncated), for example:

<table>
<thead>
<tr>
<th>Operation</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 / 2</td>
<td>produces a value of 1</td>
</tr>
<tr>
<td>(-3) / 2</td>
<td>produces a value of -1</td>
</tr>
<tr>
<td>(-9) / 4</td>
<td>produces a value of -2</td>
</tr>
<tr>
<td>(-9) REM 4</td>
<td>produces a value of -1</td>
</tr>
</tbody>
</table>

Remainder operations on both integers and reals, obey the following law:

\[
((x/y) \times y) + (x \text{ REM} y) = x
\]

It is possible for the result of a real remainder operation to be negative. If \(x\) and \(y\) are real values, the result of \(x \text{ REM} y\) is \((x - (y \times n))\), where \(n\) is the result of dividing \(x\) and \(y\) rounded toward the nearest integer. Applying this to the following example, \(n\) is 0.75 rounded to the nearest integer (1.0), leaving: \((1.5 - (2.0 \times 1.0)) = (-0.5)\):

\[
1.5(\text{REAL32}) \text{ REM} 2.0(\text{REAL32})
\]

The operator – is also a monadic negation operator, which has the effect of negating the value of its operand, for example:

<table>
<thead>
<tr>
<th>Operator</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>- x</td>
<td>has the value ((0 - x))</td>
</tr>
<tr>
<td>- 5</td>
<td>minus 5</td>
</tr>
</tbody>
</table>

The result of an arithmetic operation produces a result of the same data type as the operands. An arithmetic operation is not valid if the resulting value cannot be represented by the same data type as the operands, for example where the result of a multiplication of two large integers produces a value which exceeds the range of the type (arithmetic overflow). Division by zero is also treated as invalid.

Here are some examples of real expressions, in which \(x\) is a value of 39.0 (REAL32), and \(y\) is a value of 3.0 (REAL32):

<table>
<thead>
<tr>
<th>Expression</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>(x + y)</td>
<td>produces a value of 42.0 of type REAL32</td>
</tr>
<tr>
<td>(x - y)</td>
<td>produces a value of 36.0 of type REAL32</td>
</tr>
<tr>
<td>(x \times y)</td>
<td>produces a value of 117.0 of type REAL32</td>
</tr>
<tr>
<td>(x / y)</td>
<td>produces a value of 13.0 of type REAL32</td>
</tr>
<tr>
<td>(x \text{ REM} y)</td>
<td>produces a value of 0.0 of type REAL32</td>
</tr>
</tbody>
</table>
Rounding the results of real operations

The result of a real arithmetic expression (which is considered to be infinitely precise) is rounded to the nearest value which can be represented by the type. That is, the value will be adjusted, if necessary, to fit into the representation of its type. The precision of an operation is that of the type of the operands.

Full details of IEEE rounding modes are given in the appendix (page 79).

7.2.2 Modulo arithmetic operators

The modulo arithmetic operators are:

<table>
<thead>
<tr>
<th>Operator</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>PLUS</td>
<td>modulo addition</td>
</tr>
<tr>
<td>MINUS</td>
<td>modulo subtraction</td>
</tr>
<tr>
<td>TIMES</td>
<td>modulo multiplication</td>
</tr>
</tbody>
</table>

The modulo arithmetic operators perform an operation upon operands of the same integer data type (not on reals, bytes or booleans). The operations perform modulo arithmetic (that is, modulo the range of the type) and thus no overflow can take place. For example, adding one to the most positive integer will produce a value equal to the most negative integer (i.e. (MOSTPOS PLUS 1) = MOSTNEG), and subtracting one from the most negative integer will produce a value equal to the most positive integer (i.e. (MOSTNEG MINUS 1) = MOSTPOS). Consider these examples:

<table>
<thead>
<tr>
<th>Expression</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>32767(INT16) + 1(INT16)</td>
<td>causes an arithmetic overflow. INVALID!</td>
</tr>
<tr>
<td>32767(INT16) PLUS 1(INT16)</td>
<td>produces the value -32768.</td>
</tr>
<tr>
<td>(-32768(INT16)) - 1(INT16)</td>
<td>causes an arithmetic overflow. INVALID!</td>
</tr>
<tr>
<td>(-32768(INT16)) MINUS 1(INT16)</td>
<td>produces the value 32767.</td>
</tr>
<tr>
<td>20000(INT16) * 10(INT16)</td>
<td>causes an arithmetic overflow. INVALID!</td>
</tr>
<tr>
<td>20000(INT16) TIMES 10(INT16)</td>
<td>produces the value 3392</td>
</tr>
</tbody>
</table>

MINUS is also a valid monadic operator.

7.2.3 MOSTPOS and MOSTNEG (integer range)

The operator MOSTPOS produces the most positive value of an integer type. The operator MOSTNEG produces the most negative value of an integer type. Consider the following examples:

<table>
<thead>
<tr>
<th>Expression</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>MOSTNEG INT16</td>
<td>has the value -32768</td>
</tr>
<tr>
<td>MOSTPOS INT16</td>
<td>has the value 32767</td>
</tr>
</tbody>
</table>

The syntax for these operators is:

```
expression = MOSTPOS type
             | MOSTNEG type
```

The keyword (MOSTPOS or MOSTNEG) appears to the left of a type.
7.2.4 Bit operations

Bitwise operators perform operations on the bit pattern of a value of integer type. The bitwise operators are:

<table>
<thead>
<tr>
<th>Operator</th>
<th>Description</th>
</tr>
</thead>
</table>
| /
\ | bitwise and         |
| /     | bitwise or          |
| \>     | bitwise exclusive or|
| ~      | bitwise not         |

Here are some example expressions using the bitwise operators. The results shown are true if the value of `pixel` is #1010, and the value of `pattern` is #FFFF, and their type is INT16:

<table>
<thead>
<tr>
<th>Expression</th>
<th>Result</th>
</tr>
</thead>
</table>
| pixel /
\ pattern | produces a result #1010 (INT16) |
| ~ pixel    | produces a result #EFEF (INT16) |
| pixel / pattern | produces a result #FFFF (INT16) |
| pixel \> pattern | produces a result #EFEF (INT16) |

The operands of /
\, / and \> must both be of the same integer type. The following table illustrates how each bit of the result is produced from the corresponding bits in the operand:

| Bit | /
\ | / | \> |
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

The bitwise not operator (\~) has a single operand which must be an integer type. Each bit of the result is the inverse of the corresponding bit in the operand, as shown in the following table:

<table>
<thead>
<tr>
<th>Expression</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>~ 1</td>
<td>0</td>
</tr>
<tr>
<td>~ 0</td>
<td>1</td>
</tr>
</tbody>
</table>

The result of a bitwise operation is of the same integer type as the operand(s). The keywords BITAND, BITOR and BITNOT are equivalent to /
\, / and \~, respectively, and are included especially for implementations which have a restricted character set.

7.2.5 Shift operations

The shift operators perform a logical shift on the value of an integer type. The shift operators are:

<table>
<thead>
<tr>
<th>Operator</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt;&gt;</td>
<td>shift right</td>
</tr>
<tr>
<td>&lt;&lt;</td>
<td>shift left</td>
</tr>
</tbody>
</table>

The shift operators shift the bit pattern of a value of any integer type by a number of places determined by a count value of type INT. For example, if the value of `n` is #FFFF, and of type INT16:

<table>
<thead>
<tr>
<th>Expression</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>n &lt;&lt; 4</td>
<td>produces a result #FFFF0 (INT16)</td>
</tr>
<tr>
<td>n &gt;&gt; 4</td>
<td>produces a result #OFFF (INT16)</td>
</tr>
</tbody>
</table>

The result is of the same integer type as `n`. The bits vacated by the shift become zero, the bits shifted out of the pattern are lost. The left shift operator shifts toward the most significant end of the pattern, the right shift operator shifts toward the least significant end of the pattern.
Consider these further examples, where \( n \) is a value of type \texttt{INT32}:

<table>
<thead>
<tr>
<th>Operation</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>( n &lt;&lt; 0 )</td>
<td>produces the value ( n )</td>
</tr>
<tr>
<td>( n &gt;&gt; 0 )</td>
<td>produces the value ( n )</td>
</tr>
<tr>
<td>( n &gt;&gt; 32 )</td>
<td>produces the value 0</td>
</tr>
<tr>
<td>( n &lt;&lt; 32 )</td>
<td>produces the value 0</td>
</tr>
</tbody>
</table>

A shift by a negative value, or by a value which exceeds the number of bits in the representation, is invalid.

### 7.2.6 Boolean operations

The boolean operators combine operands of boolean type, and produce a boolean result. The boolean operators are:

<table>
<thead>
<tr>
<th>Operator</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AND</td>
<td>boolean and</td>
</tr>
<tr>
<td>OR</td>
<td>boolean or</td>
</tr>
<tr>
<td>NOT</td>
<td>boolean not</td>
</tr>
</tbody>
</table>

The following table shows the results for each operation:

<table>
<thead>
<tr>
<th>left operand</th>
<th>operator</th>
<th>right operand</th>
<th>result</th>
</tr>
</thead>
<tbody>
<tr>
<td>false</td>
<td>AND</td>
<td>true</td>
<td>false</td>
</tr>
<tr>
<td>false</td>
<td>AND</td>
<td>false</td>
<td>false</td>
</tr>
<tr>
<td>true</td>
<td>AND</td>
<td>false</td>
<td>true</td>
</tr>
<tr>
<td>true</td>
<td>AND</td>
<td>true</td>
<td>true</td>
</tr>
<tr>
<td>false</td>
<td>OR</td>
<td>false</td>
<td>true</td>
</tr>
<tr>
<td>true</td>
<td>OR</td>
<td>false</td>
<td>true</td>
</tr>
<tr>
<td>true</td>
<td>OR</td>
<td>true</td>
<td>true</td>
</tr>
<tr>
<td>false</td>
<td>NOT</td>
<td>false</td>
<td>true</td>
</tr>
<tr>
<td>true</td>
<td>NOT</td>
<td>true</td>
<td>false</td>
</tr>
</tbody>
</table>

The operand to the left of a boolean operator is evaluated, and if the result of the operation can be determined evaluation ceases. This differs from the behaviour of other expressions. Consider the following example:

```c
IF
  ((ch >= 'a') AND (ch <= 'z')) OR ((ch >= 'A') AND (ch <= 'Z'))
  (ch = cr) OR (ch = down) OR (ch = up)
  ((ch = escape) AND shift)) OR ((ch = escape) AND control))
```

Note that parentheses may be omitted between expressions containing adjacent AND or OR operators. The evaluation of the boolean expression \(((ch >= 'a') \text{ AND } (ch <= 'z'))\) ceases if the expression \((ch >= 'a')\) is false, the evaluation of the expression \((ch <= 'z')\) does not take place. If the result is true, the expression \(((ch >= 'A') \text{ AND } (ch <= 'Z'))\) to the right of OR is not evaluated. The rule is that evaluation of a boolean expression will cease if the operand to the left of AND is false, or if the operand to the left of OR is true.

### 7.2.7 Relational operations

The relational operators perform a comparison of their operands, and produce a boolean result. The relational operators are:

<table>
<thead>
<tr>
<th>Operator</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>=</td>
<td>equal</td>
</tr>
<tr>
<td>&lt;&gt;</td>
<td>not equal</td>
</tr>
<tr>
<td>&lt;</td>
<td>less than</td>
</tr>
<tr>
<td>&gt;</td>
<td>greater than</td>
</tr>
<tr>
<td>&lt;=</td>
<td>less than or equal</td>
</tr>
<tr>
<td>&gt;=</td>
<td>greater than or equal</td>
</tr>
</tbody>
</table>
Here are examples of relational expressions using = and <>. In these examples the operands, \(x\) and \(y\), can be any primitive data type:

| \(x = y\) | is true if the value of \(x\) is equal to the value of \(y\)  
| \(x <> y\) | is true if the value of \(x\) is not equal to the value of \(y\) |

The following are examples using the other relational operators. In these examples the operands, \(x\) and \(y\), can be an integer, byte or real type, but may not be a boolean:

| \(x < y\) | is true if the value of \(x\) is less than the value of \(y\)  
| \(x > y\) | is true if the value of \(x\) is greater than the value of \(y\)  
| \(x <= y\) | is true if the value of \(x\) is less than or equal to the value of \(y\)  
| \(x >= y\) | is true if the value of \(x\) is greater than or equal the value of \(y\) |

\(\text{AFTER}\) (later than)

The special modulo operator \(\text{AFTER}\) performs a comparison operation, and returns a boolean result, for example:

\((a \ \text{AFTER} \ b)\)

This expression is true if \(a\) is later in a cyclic sequence than \(b\), just as one o'clock pm can be considered later than eleven o'clock am. The first operand is considered the starting point on a "clock face" of integer values. If the shortest route to the value of the second operator is clockwise, then the value is later than the first operand and the result of the expression is true. If the shortest route to the value of the second operand is anticlockwise, then the value of the second operand is earlier, and the result of the expression is false.

\((a \ \text{AFTER} \ b)\) produces the same value as \((a \ \text{MINUS} \ b) > 0\).

\(7.2.8\) \(\text{SIZE}\) (number of components in an array)

The special operator \(\text{SIZE}\) has a single operand of array type, and produces an integer value of type \(\text{INT}\), equal to the number of components in the array. For example, if \(a\) is an array of type \([8]\ \text{INT}\), then:

\(\text{SIZE } a\) produces the value \(8\)

If \(a\) is of type \([8][4]\ \text{INT}\), then:

\(\text{SIZE } a\) produces the value \(8\)

\(\text{SIZE } a[1]\) produces the value \(4\)

\(7.3\) Data type conversion

With the exception of logical shifts (where the number of bits to shift must be of type \(\text{INT}\)), the types of the operands in an expression must be of the same type. Operands may explicitly have their data type converted. A data type conversion permits a value of a primitive data type (not array types) to be converted to a numerically similar value of another primitive data type. A data type conversion produces the value of its
operand as a value of the specified data type, for example:

\[ j := (k \times 4.5\text{ (REAL64)}) \times \text{(REAL64 n)} \]

The value of \( n \) in this example is converted to a value of type \text{REAL64}. Note that \( 4.5\times\text{REAL64} \) is a literal value of type \text{REAL64}, whereas \( \text{REAL64 n} \) is a data type conversion of the value of \( n \).

The syntax for data type conversions is:

\[
\text{conversion} = \frac{\text{primitive.type operand}}{
| \text{primitive.type ROUND operand} \quad | \text{primitive.type TRUNC operand}
}
\]

The type must be a primitive data type, and appears to the left of the operand. A data type conversion which includes the keyword \text{ROUND} as described by the syntax, produces a value rounded to the nearest value of the specified type. Where two values are equally near, the value is rounded toward the nearest even number. A data type conversion which includes the keyword \text{TRUNC} as described by the syntax, produces a value truncated (rounded toward zero) to a value of the specified type.

A conversion between any of the integer types, and conversions between those types and type \text{BYTE}, is valid only if the value produced is within the range of the receiving type. Byte and integer values may be converted to boolean values if their value is one or zero. The boolean value is true if the value is one, and false if the value is zero. That is:

| \text{BOOL 1} | evaluates to \text{TRUE} |
| \text{BOOL 0} | evaluates to \text{FALSE} |
| \text{INT TRUE} | evaluates to 1 |
| \text{INT FALSE} | evaluates to 0 |

Conversions from integer values to real values, and vice versa, must specify whether the result is to be rounded or truncated. A value of type \text{REAL32} can be extended to an exact value of type \text{REAL64}. Values of type \text{REAL64} can be converted to values of type \text{REAL32}, providing the value is in the range of the \text{REAL32} type. The conversion must specify if the value is to be rounded or truncated. Consider these examples, where \( n \), and \( m \) are integers of type \text{INT64}, and \( n \) has a value 255 and \( m \) has a value 3:

| \text{BYTE n} | produces a byte value 255 |
| \text{REAL32 ROUND n} | produces a \text{REAL32} value 255.0 |
| \text{REAL64 TRUNC n} | produces a \text{REAL64} value 255.0 |
| \text{REAL64 ROUND (n \times m)} | produces a \text{REAL64} value 765.0 |
| \text{(REAL64 ROUND n) \times (REAL64 ROUND m)} | produces a \text{REAL64} value 765.0 |

Conversions may be applied to operands of the same type, but will have no effect. The truncation and rounding of integer types to real types occurs where the integer cannot be exactly represented as a value of the real type. Consider the following example:

```plaintext
SEQ
  i := 33554435 \text{ (INT32)} -- hex #2000003
  a := \text{REAL32 ROUND i}
  b := \text{REAL32 TRUNC i}
```

The value in this example has been chosen specifically to illustrate the behaviour of explicitly rounding an integer value which cannot be directly represented in the floating point representation of \text{REAL32}. The value of \( a \) after this sequence is 33554436.0, and the value of \( b \) is 33554432.0. For \( b \), the two least significant bits of the integer representation have been lost they had held the value 3. For \( a \) the value of those bits has been rounded to the next nearest representable value. Further detail of rounding is given in the appendix on page 79.
Conversion of real values to integers has the effect illustrated by the following examples:

<table>
<thead>
<tr>
<th>Expression</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>INT32 ROUND 0.75(REAL32)</code></td>
<td>produces a value of 1</td>
</tr>
<tr>
<td><code>INT32 ROUND 0.25(REAL32)</code></td>
<td>produces a value of 0</td>
</tr>
<tr>
<td><code>INT32 TRUNC 0.75(REAL32)</code></td>
<td>produces a value of 0</td>
</tr>
<tr>
<td><code>INT32 TRUNC 0.25(REAL32)</code></td>
<td>produces a value of 0</td>
</tr>
</tbody>
</table>

Consider these examples, where `x` and `y` are type `REAL32`, `x` has a value 3.5, `y` has a value 2.5:

<table>
<thead>
<tr>
<th>Expression</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>INT16 TRUNC y</code></td>
<td>produces the value 2, <code>y</code> truncated</td>
</tr>
<tr>
<td><code>INT16 ROUND y</code></td>
<td>produces the value 2, <code>y</code> rounded (even)</td>
</tr>
<tr>
<td><code>INT32 ROUND x</code></td>
<td>produces the value 4, <code>x</code> rounded (even)</td>
</tr>
<tr>
<td><code>INT16 TRUNC (x / y)</code></td>
<td>produces the value 1</td>
</tr>
<tr>
<td><code>(INT ROUND x) * 10</code></td>
<td>produces the value 40</td>
</tr>
<tr>
<td><code>REAL64 x</code></td>
<td>produces the value 3.5</td>
</tr>
</tbody>
</table>

A full explanation of the IEEE rounding modes is given in the appendix (page 79).
8 Scope

Earlier chapters of this manual describe how OCCAM programs are built from processes (page 9), and how smaller processes are combined to form larger processes. The manual has also described ways that names may be specified. A name in an OCCAM program denotes one of the following:

<table>
<thead>
<tr>
<th>Name</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Variable</td>
<td>26</td>
</tr>
<tr>
<td>Channel</td>
<td>29</td>
</tr>
<tr>
<td>Timer</td>
<td>37</td>
</tr>
<tr>
<td>Protocol</td>
<td>31</td>
</tr>
<tr>
<td>Tag</td>
<td>32</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>57</td>
</tr>
<tr>
<td>Procedure</td>
<td>61</td>
</tr>
<tr>
<td>Function</td>
<td>65</td>
</tr>
<tr>
<td>Replication index</td>
<td>9</td>
</tr>
</tbody>
</table>

Associated with each name is a region of the program in which the name is valid, called the scope, for example:

```
INT n :
SEQ
n := 0
WHILE n < 10
   n := n + 1
```

This example performs a count of ten using the variable n which is declared for the sequence. This variable exists only within the associated scope (illustrated by the comments), and has no existence outside that scope. In the following example two unrelated variables are given the same name (x), each variable exists independently within its own scope.

```
TIMER t :
PAR
REAL32 x :
SEQ
x := y + 1
...
INT x :
SEQ
t ? x
...
```

The scope of a name is illustrated by the level of program indentation. The scope of a name includes any other specification which may immediately follow at the same level of indentation, and encompasses all greater levels of indentation in the program. The illustrated scope concludes when the level of indentation returns to the same or lesser level, as the following example shows:

```
SEQ
INT max :
INT min :
SEQ
c ? max; min
   IF
   p < max
      p := p + 1
   p = max
      p := min
SEQ
...```
This example increments \( p \) if it is less than the value specified by \( \text{max} \). The scope associated with the variable \( p \) in this example begins at the declaration of \( p \) earlier in the program. The association of a name with any particular scope is either \textit{local}, that is, it is specified at the start of the scope under consideration, or the name is \textit{free} of local association. That is, the name is specified at an outer level of scope (as for \( p \) in the above example) which includes the scope under consideration. If a specification is made which uses an existing name then the new meaning supersedes the old meaning for the duration of the scope of the new specification, as illustrated by the following example:

```
INT x :                      -- integer variable x
SEQ
  dm ? x                     -- scope
ALT
  REAL32 x :                 -- real x hides integer variable x
  rs ? x                    -- scope
  ...
  dm ? y
  ...
```

The second declaration of \( x \) in the above example, has the effect of “hiding” the earlier use of the name \( x \) for the duration of its scope. All names within a scope in OCCAM are distinct. That is, a name may only have one meaning within any scope.

Names of keywords may not be used in specifications.

The following syntax specifies at which point in a program a declaration, abbreviation, or definition may occur, and the scope associated with each:

```
process = specification
  process
choice = specification
  choice
option = specification
  option
alternative = specification
  alternative
variant = specification
  variant
valof = specification
  valof
specification = declaration
  abbreviation
  definition
```

A specification is a declaration, an abbreviation (page 57) or a definition (e.g. Protocol definition, page 29). A specification may appear before a process, choice, option, alternative, variant, or valof (See \textit{functions} page 65). The region of the program in which a specified name is valid includes any other specification that may immediately follow at the same level of indentation, and the corresponding process, choice, option, alternative, variant or valof.

\subsection{8.1 Names in the scope of parallel constructs}

Component processes of a parallel must not violate the rules which govern the use of variables and channels. This section describes the usage rules which are checked by the OCCAM compiler.

Variables which are assigned to by input or assignment in one of the processes of a parallel may not appear in any other process in the parallel. Also, an array can be used in only one component of a parallel if components of the array are selected by a variable subscript, i.e. a subscript which is dependent on a variable, or a replication index with a variable base or count. A variable may appear in an expression in
any component of a parallel, provided the variable is not assigned to by input or assignment in any other component in the parallel. Consider the following example:

```
INT mice : PAR
    SEQ
    mice := 42 -- cannot assign to the same variable
    c ! 42
    c ? mice -- in more than one process in a parallel
```

This process is invalid because it assigns to the variable `mice` in the assignment `mice := 42` in one component of the parallel, and also in the input `c ? mice` in a second component. Also consider the following example:

```
PAR
    c1 ? data[i]
    c2 ? data[j]
```

The validity of this parallel is dependent upon `i` and `j`. If the value of either `i` or `j` may change, for example if one is a variable or a replicator index with a variable base or count, then the parallel is invalid. If the value of both are constant, the parallel is valid provided `i` and `j` select different components of the array `data`. This ensures that no component of an array is misused. An array may be divided between several parallel processes, and components of those disjoint parts may be selected using variable subscripts, provided each part of the array is referenced by an abbreviation discussed in the following chapter.

A check list of the usage rules which apply to parallel processes is given in the appendix on page 75.
This chapter describes OCCAM abbreviations. There are two kinds of abbreviations: abbreviations which specify a name for an expression (page 43), and abbreviations which specify a name for an element (page 39). The name specified in an abbreviation is an alias for the expression or element.

### 9.1 Abbreviation of expressions

The first kind of abbreviation to consider is the abbreviation of an expression. This kind of abbreviation can be used to specify a name for a constant value. Consider the following example:

```plaintext
VAL INT days.in.week IS 7 :
```

This abbreviation specifies the name `days.in.week` for the constant value 7. Here are some more abbreviations for expressions:

- `VAL REAL32 y IS (m * x) + c :` specifies a name for the current value of an expression
- `VAL INT n IS m :` specifies a name for the current value of the element `m`
- `VAL []BYTE vowels IS ['a', 'e', 'i', 'o', 'u'] :` specifies a name for a table of constant values

The abbreviated expression must be a valid expression, that is, it must not overflow, and all subscripts must be in range. Variables used in an abbreviated expression may not be assigned to by an input or assignment within the scope (page 53, the region of a program where a name is valid) of the abbreviation. This ensures that the value of the expression remains constant for the scope of the abbreviation. For example, in the following abbreviation:

```plaintext
VAL REAL32 y IS (m * x) + c :
```

no assignment or input may be made to `m`, `x`, or `c` within the scope of `y` of this abbreviation. The effect of the abbreviation is the same as each instance of `y` being replaced by the abbreviated expression. Similarly for the following abbreviation of the expression `[screen FROM line FOR length]`:

```plaintext
VAL []INT scan IS [screen FROM line FOR length] :
```

no assignment or input may be made to `screen`, `line`, or `length`, within the scope of `scan`. The effect of the abbreviation is the same as each instance of `scan` being replaced by the abbreviated expression, thus:

```plaintext
VAL []INT scan IS [screen FROM line FOR length] :
  SEQ
  row := scan
  ...
```

is equivalent to

```plaintext
SEQ
  row := [screen FROM line FOR length]
  ...
```

The syntax for abbreviations of expressions is:

- `abbreviation = VAL specifier name IS expression :`
- `specifier = VAL name IS expression :`
- `primitive.type`
- `[]specifier`
- `[] expression specifier`

The abbreviation of a value begins with the keyword `VAL`. An optional specifier, (which specifies the data type of the abbreviation,) appears to the right of `VAL`, followed by the name, and the keyword `IS`. The abbreviated
expression appears to the right of the keyword IS. Line breaks are permitted after the keyword IS. The type of the expression must be of the same data type as the specifier. The specifier can usually be omitted from the abbreviation, as the type can be inferred from the type of the expression. A specifier [ ] type simply defines the abbreviation as being an array with components of the specified type.

9.2 Abbreviation of elements

OCCAM abbreviations may also specify a name for an element of any type. A variable, channel, timer, or array that is within the current scope may be given a name in an abbreviation of this kind, for example:

    INT n IS m :

This abbreviation specifies the name n as the new name for m. Also, consider the following example:

    CHAN OF INT user IS lines[8] :

This abbreviation specifies the name user for a component of the array lines. All subscript expressions used in an abbreviation must be valid. The type of the abbreviated element must be the same as the specifier, so in this example, lines has to be an array of CHAN OF INT. Other components of the array lines may be used only in abbreviations within the scope (page 53) of user, but they must not include the component lines[8]. Here are some more examples of abbreviations:

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>x IS y :</td>
<td>specifies a new name x for y</td>
</tr>
<tr>
<td>[]REAL32 s IS [a FROM 8 FOR n] :</td>
<td>specifies a name for a component of the array a</td>
</tr>
<tr>
<td>TIMER my.time IS clock[me] :</td>
<td>specifies a name for an element of an array of timers</td>
</tr>
</tbody>
</table>

An abbreviation simply provides a name to identify an existing element. The name my.time in the above example identifies the existing element clock[me]. In the scope of the abbreviation, my.time ? t is a timer input from the original timer clock[me]. A variable used in a subscript to select a component or components of an array may not be assigned to within the scope of the abbreviation. For example, no assignment or input can be made to me within the scope of my.time. As a result the abbreviation always refers to the same variable throughout its scope. This allows various optimisations to be provided, such as evaluating any expression within the abbreviated element only once. The original element clock[me] may not be used within the scope of the abbreviation my.time. Where the abbreviation is of an element of an array no other reference may be made to any other part of that array, except in a further abbreviation. Consider the following example:

    [60][72]INT page :
    ...
    first.line IS page[0] :
    last.line IS page[59] :
    SEQ
    first.line := last.line
    last.line := page[58] -- This assignment is INVALID!
    ...
    next.to.last.line IS page[58] : -- This abbreviation is valid
    last.line := next.to.last.line -- and so too, this assignment ...
    ...

Also consider the following example:

    WHILE i < limit
    this.line IS page[i] :
    next.line IS page[i+1] :
    SEQ
    this.line := next.line
    ...
    i = i + 1 -- this assignment is INVALID!
The assignment in the above example is invalid as \( i \) is used to select components of the array \( \text{page} \) in an abbreviation within the scope of the assignment. This is how the above should be written:

\[
\begin{align*}
\text{WHILE} & \quad i < \text{limit} \\
\text{SEQ} & \\
\text{this}. \text{line} & \text{IS} \quad \text{page}[i] : \\
\text{next}. \text{line} & \text{IS} \quad \text{page}[i+1] : \\
\text{SEQ} & \\
\text{this}. \text{line} & := \text{next}. \text{line} \\
\vdots & \\
i & := i + 1
\end{align*}
\]

It is important to ensure that all the components of an array remain identified by a single name within any given scope. Identification of any component of an array by more than one name constitutes an invalid usage of the component, and it is especially important to be aware of when abbreviating components of an array. Once any component of an array is abbreviated then reference to other components of the array must be made by further abbreviation. Checks are made to ensure that two abbreviations which identify segments from the same array do not overlap. Further discussion on abbreviation is given in the chapter on procedures (page 61).

The syntax for abbreviations of elements is:

```
abbreviation = specifier name IS element :
| name IS element :
specifier = primitive.type
| []specifier
| [ expression ]specifier
```

The abbreviation of an element begins with an optional specifier. The name specified appears to the right of the optional specifier followed by the keyword IS, the abbreviated element appears to the right of the keyword IS. The line on which the abbreviation occurs may be broken after the keyword IS or at some valid point in the element. The type of the element must be the same as the type of the specifier. As for abbreviations of values, the specifier can usually be omitted from the abbreviation, as the type can be inferred from the type of the element. A specifier [] type simply defines the abbreviation as being an array with components of the specified type.

### 9.3 Disjoint arrays in parallels

Abbreviations may be used to decompose an array into a number of disjoint parts, so that each part may have a unique name in all or several processes in parallel. Components of each disjoint part may then be selected by a variable subscript (a subscript whose value is dependent on a procedure parameter, a variable, or a replicator index whose base or count is not a constant value), for example:

```
frame1 IS [page FROM 0 FOR 512] :
frame2 IS [page FROM 512 FOR 512] :
PAR
  INT i :
  SEQ 
    \ldots
    c1 ? frame1[i]
    \ldots
  INT j :
  SEQ 
    \ldots
    c2 ? frame2[j]
    \ldots
```

This example divides the array \( \text{page} \) into two parts, and provides a name for those parts in each of the two parallel processes. These parts may then be selected by using variable subscripts.
10 Procedures

This chapter describes procedures in OCCAM. A procedure definition in OCCAM defines a name for a process. Consider the following example:

```
PROC increment (INT x)
  x := x + 1
:
```

This example defines `increment` as the name for the process. \( x := x + 1 \). Formal parameters of a procedure are specified in parentheses after the procedure name. In this example, \( x \) is a formal parameter, and is of type INT. The procedure `increment` may be used as shown in the following example:

```
INT y :
SEQ
  ...
  increment (y)
  ...
```

A formal parameter is an abbreviation (page 57) of the actual parameter used in an instance of a procedure. An instance of a procedure has the same effect as the substitution of the process named in the procedure's definition. This instance of `increment` can be expanded to show its effect:

```
INT y :
SEQ
  ...
  x IS y :
  x := x + 1
  ...
```

Here is a further example:

```
PROC writes (CHAN OF BYTE stream, VAL []BYTE string)
  SEQ i = 0 FOR SIZE string
    stream! string[i]
:
```

This procedure takes a channel (`stream`) and an array (`string`) as parameters, and outputs the components of the array to the channel. An instance of the procedure looks like this:

```
SEQ
  ...
  writes (screen, "Hello world")
  ...
```

Again, this instance can be expanded to show the effect:

```
SEQ
  ...
  CHAN OF BYTE stream IS screen :
  VAL []BYTE string IS "Hello world" :
  SEQ i = 0 FOR SIZE string
    stream! string[i]
  ...
```

The rules for procedure parameters follow from those for abbreviations. There are two kinds of abbreviation: abbreviations which specify a name for the value of an expression (page 43), and abbreviations which specify a name for an element (page 39) of an existing variable, channel, timer, or array. Abbreviations have already been discussed in chapter 9 which starts on page 57. A name which is free in the body of the procedure is
statically bound to the name used in the procedure definition, for example:

```plaintext
INT step :
SEQ
  step := 39
PROC next.item (INT next, VAL INT present)
  next := present + step :
INT g, step :
SEQ
  step := 7
  next.item (g, 3)
... -- at this point the value of g is 42
```

The free variable `step`, in scope when the procedure `next.item` was defined, is bound to the procedure `next.item`. The rules of OCCAM state that all names identify distinct objects. In the example, the scope and binding of the elements can be seen more clearly by making systematic changes of name. Once this is done, the example is equivalent to:

```plaintext
INT step :
SEQ
  step := 39
INT g, curb : -- name changed
SEQ
  curb := 7
  next IS g : -- expand instance of next.item
  VAL present IS 3 :
  next := present + step
... -- at this point the value of g is 42
```

In this transformation of the earlier example, it can be seen that the variable used in the instance of `next.item` is the variable named `step` declared before the procedure definition of `next.item`, and not the second variable declared with the same name. Consider this example:

```plaintext
INT x, y, step :
PROC next.item (INT next, VAL INT present)
  next := present + step :
```

And now consider the following equivalences of instances that may appear in the scope of the procedure:

```plaintext
next.item (x, y) is equivalent to: INT next IS x :
  VAL INT present IS y :
  next := present + step

next.item (x, step) is equivalent to: INT next IS x :
  VAL INT present IS step :
  next := present + step

next.item (step, x) is equivalent to: INT next IS step :
  which is INVALID!
  VAL INT present IS x :
  next := present + step

next.item (x, x) is equivalent to: INT next IS x :
  which is INVALID!
  VAL INT present IS x :
  next := present + step
```

Here it can be seen how the meaning of each procedure parameter is defined in terms of an abbreviation, the ordering of parameters corresponds to a sequence of abbreviations. `next.item (step, x)` is invalid because the element `step` is used in the expression `next := present + step`, after it has been
abbreviated, and the example \texttt{next.item (x, x)} is invalid as \texttt{x} has already been used in the previous abbreviation of the element \texttt{x} (and the rules state [abbreviations on page 57] that an element used in such an abbreviation may not be used within the associated scope). Notice also the effect with the order of parameters used in \texttt{next.item} changed:

```plaintext
INT x, y, step :
PROC next.item (VAL INT present, INT next)
  next := present + step
:
```

With this re-ordering, \texttt{next.item (x, x)} is still invalid, although now for a different reason, as follows:

\texttt{next.item (x, x)} is equivalent to:

\begin{verbatim}
VAL INT present IS x :
which is INVALID!
INT next IS x :
next := present + step
\end{verbatim}

\texttt{next.item (x, x)} is invalid here as there is an assignment to \texttt{x} (via \texttt{next}) within the scope of the first abbreviation. Now consider the following example:

```plaintext
PROC nonsense (INT x, VAL INT y)
SEQ 
x := x + y
x := x - y
:
```

This procedure should leave the value of the variable used as the actual parameter for \texttt{x}, unchanged, as the following expansion shows:

\texttt{nonsense (n, 3)} is equivalent to:

\begin{verbatim}
INT x IS n :
VAL INT y IS 3 :
SEQ
  x := x + y
  x := x - y
and by substitution
SEQ
  n := n + 3
  n := n - 3
\end{verbatim}

The value of \texttt{n} after this instance is \texttt{n}, as might be expected. However, the following instance is invalid, which is just as well, as the effect is non-intuitive:

\texttt{nonsense (n, n)} is equivalent to:

\begin{verbatim}
INT x IS n :
which is INVALID!
VAL INT y IS n :
SEQ
  x := x + y
  x := x - y
and by substitution
SEQ
  n := n + n
  n := n - n
\end{verbatim}

The value of \texttt{n} after this instance, if it were valid, would be 0, which is counter intuitive. The following example
highlights the problem further.

\[
\text{nonsense} \ (i, \ v[i]) \quad \text{is equivalent to:} \quad \begin{align*}
\text{INT} \ x \ &\text{ IS } \ i : \\
\text{VAL} \ \text{INT} \ y \ &\text{ IS } \ v[i] : \\
\text{SEQ} \\
x \ := \ x + y \\
x \ := \ x - y
\end{align*}
\]

and by substitution

\[
\text{SEQ} \\
i \ := \ i + v[i] \\
i \ := \ i - v[i]
\]

If this instance were valid, the value of \(i\) after the instance of \text{nonsense} would be difficult to predict, as in each of the assignments \(v[i]\) will probably reference a different component of \(v\), as the value of the subscript \(i\) may be changed by the first assignment.

The syntax for a procedure definition is:

\[
\begin{align*}
\text{definition} \quad &\quad \text{PROC } \text{name} \ (\{0, \ formal\} \ ) \\
&\quad \text{procedure.body} \\
\text{formal} \quad &\quad \text{specifier} \ \{1, \ name\} \\
&\quad | \quad \text{VAL specifier} \ \{1, \ name\} \\
\text{procedure.body} \quad &\quad \text{process}
\end{align*}
\]

The keyword \text{PROC}, the name of the procedure, and a formal parameter list enclosed in parentheses is followed by a process, indented two spaces, which is the body of the procedure. The procedure definition is terminated by a colon which appears on a new line at the same indentation level as the start of the definition.

The syntax for procedure instance is:

\[
\begin{align*}
\text{instance} \quad &\quad \text{name} \ (\{0, \ actual\} \ ) \\
\text{actual} \quad &\quad \text{element} \\
&\quad | \quad \text{expression}
\end{align*}
\]

An instance of a procedure is the procedure name followed by a list of zero or more actual parameters in parentheses. An actual parameter is either an element or expression. The list of actual parameters must correspond directly to the list of formal parameters used in the definition of the procedure. The actual parameter list must have the same number of entries, each of which must be the compatible with the kind (\text{VAL} or non-\text{VAL}) and type of the corresponding formal parameter. In a program in which all names are distinct, an instance of a procedure behaves like the substitution of the procedure body. Notice that all programs can be expressed in a form in which all names are made distinct by systematic changes of name. Procedures in \text{OCCAM} 2 are not recursive. A channel parameter or free channel may only be used for input or output (not both) in the procedure.

An instance of a procedure defined with zero parameters must be followed by empty parentheses. Where a number of parameters of the same type appear in the parameter list, a single specifier may specify several names. For example:

\[
\text{PROC snark} \ (\text{VAL INT butcher, beaver, REAL64 boojum, jubjub})
\]

\[
\quad \ldots
\]

This example, is equivalent to:

\[
\text{PROC snark} \ (\text{VAL INT butcher, VAL INT beaver, REAL64 boojum, REAL64 jubjub})
\]

\[
\quad \ldots
\]
11 Functions

The previous chapter discusses named processes (called procedures). This chapter describes functions in OCCAM. A function defines a name for a special kind of process, called a value process. A value process produces a result of primitive data type (but not of array type), and may appear in expressions. Value processes may also produce more than one result, which may be assigned in a multiple assignment. OCCAM functions are side effect free, as they are forbidden to communicate or assign to free variables. This helps to ensure that programs are clear and easy to maintain.

A value process, performs an enclosed process, and produces a result. Consider the following example:

```
total := subtotal + (INT sum :
VALOF
SEQ
    sum := 0
    SEQ i = 0 FOR SIZE v
    sum := sum + v[i]
RESULT sum )
```

In the example shown here, the value process produces the sum of the array v, and is equivalent to

\[
\sum_{i=0}^{SIZE} v[i]
\]

More commonly however, the value process is the body of a function definition, as illustrated in the following example:

```
INT FUNCTION sum (VAL []INT values)
    INT accumulator :
    VALOF
    SEQ
        accumulator := 0
        SEQ i = 0 FOR SIZE values
        accumulator := accumulator + values[i]
    RESULT accumulator :
```

This function definition defines the name `sum` for the associated value process. The type of the result is INT, specified by `INT FUNCTION`. Just as the behaviour of procedures is defined by the substitution of the procedure body, functions behave like the substitution of the function body. It follows that the example which starts this chapter is an expansion of the following:

```
total := subtotal + sum (v)
```

A function definition may also define a name for an expression list, so that simple, single line, functions can be defined in the following fashion:

```
BOOL FUNCTION lowercase (VAL BYTE ch) IS (ch >= 'a') AND (ch <= 'z') :
BOOL FUNCTION uppercase (VAL BYTE ch) IS (ch >= 'A') AND (ch <= 'Z') :
BOOL FUNCTION ischar (VAL BYTE ch) IS uppercase (ch) OR lowercase (ch) :
```

Each of these functions returns a single boolean result. The definition of the function `ischar` is equivalent to the following:

```
BOOL FUNCTION ischar (VAL BYTE ch)
VALOF
SKIP
RESULT uppercase (ch) OR lowercase (ch)
```
A number of rules apply to functions to ensure they are side effect free. As for procedures, the correspondence between the formal and actual parameters of a function is defined in terms of abbreviations, and follows the associated scope rules. However, an argument of a function may only be a value parameter. Only variables declared within the scope of a value process or function may be assigned to. Also, value processes may not contain inputs or outputs, nor may they contain alternations, or parallels. The body of any procedure used within a function must also obey the above rules. A name which is free within the value process (Scope, page 53) can be used only in expressions within the value process or function body, they may not be assigned to by input or assignment. Consider the following:

```plaintext
INT FUNCTION read.top.of.stack () IS stack[stack.pointer] :
  stack[stack.pointer] :=

BOOL FUNCTION empty () IS stack.pointer = 0 :
  stack.pointer := 0 :
```

A value process may produce more than one result, which may then be assigned using a multiple assignment. Consider the following example:

```plaintext
point, found := (VAL BYTE char IS 'g' :
  VAL []BYTE string IS message :
  BOOL ok :
  INT ptr :
  VALOF IF
    IF i = 0 FOR SIZE string
      string[i] = char
      seq
        ok := TRUE
        ptr := i
    TRUE
    seq
    ok := FALSE
    ptr := -1
  RESULT ptr, ok
)```
This value process searches the byte array \texttt{string} for the character ‘\texttt{g}’. The result is produced from the expression list which follows \texttt{RESULT}, and is then assigned to \texttt{point}, and \texttt{found}. This value process can be given a name in a function definition, as follows:

\begin{verbatim}
INT, BOOL FUNCTION instr (VAL BYTE char, VAL [ ]BYTE string)
  BOOL ok : INT ptr :
  VALOF
    IF
      IF i = 0 FOR SIZE string
        string[i] = char
        ok := TRUE
        ptr := i
      TRUE
      SEQ
        ok := FALSE
        ptr := -1
      RESULT ptr, ok :
    VAL message IS "Twas brillig and the slithy toves" :
    INT point :
    BOOL found :
    SEQ
      point, found := instr ("g", message)
    ... 
\end{verbatim}

This example finds the position of \texttt{g} in the string \texttt{message}. After the multiple assignment in this example, the value of \texttt{point} will be 11, and the value of \texttt{found} will be \texttt{TRUE}. Single line functions with multiple results may also be defined:

\begin{verbatim}
INT, INT FUNCTION div.rem (VAL INT x, y) IS x / y, x REM y :
\end{verbatim}

This function produces the division, and remainder of \texttt{x} and \texttt{y}. If an error occurs within a function or value process, it will behave like the primitive process \texttt{STOP}. This behaviour is equivalent to the behaviour of a mathematical overflow in an arithmetic expression (see page 78 for details of the behaviour of invalid processes). Consider the behaviour of an instance of the following partial function:

\begin{verbatim}
INT FUNCTION factorial (VAL INT n)
  INT product :
  VALOF
    IF
      n >= 0
      SEQ
        product := 1
        SEQ i = 1 FOR n
          product := product * i
    RESULT product
\end{verbatim}

This function will behave like the primitive process \texttt{STOP} if \texttt{n} is less than zero, or if an overflow occurs in the evaluation of the factorial. In either case the behaviour is equivalent to the behaviour of any other invalid expression (page 78).
The syntax for functions is:

\[
\begin{align*}
\text{value.process} & = \text{valof} \\
\text{valof} & = \text{VALOF} \\
& \quad \text{process} \\
& \quad \text{RESULT} \text{ expression.list} \\
& \quad \text{specification} \\
& \quad \text{valof} \\
\text{operand} & = ( \text{value.process} \\
& \quad ) \\
\text{expression.list} & = ( \text{value.process} \\
& \quad ) \\
\text{definition} & = \{1, \text{primitive.type} \} \text{ FUNCTION } \text{name} ( \{0, \text{formal} \}) \\
& \quad \text{function.body} \\
\text{function.body} & = \text{value.process} \\
\text{operand} & = \text{name} ( \{0, \text{expression} \}) \\
\text{expression.list} & = \text{name} ( \{0, \text{expression} \}) \\
\text{definition} & = \{1, \text{primitive.type} \} \text{ FUNCTION } \text{name} ( \{0, \text{formal} \}) \text{ IS expression.list} :
\end{align*}
\]

A value process consists of zero or more specifications which precede the keyword VALOF, followed by a process at an indentation of two spaces, and the keyword RESULT at the same indentation. The keyword RESULT is followed by an expression list on the same line. The line may be broken after a comma, or at a valid point in an expression. An operand of an expression may consist of a left parentheses, a value process, followed by a right parentheses. The structured parentheses appear at the same indentation as each other, and are equivalent to the left hand and right hand parentheses of a bracketed expression respectively. So, where the value process produces a single result, the upper bracket may be preceded by an operator, or the lower bracket may be followed by an operator.

The heading of a function definition consists of the keyword FUNCTION, preceded by the type(s) of the result(s) produced by the function. The name of the function and a formal parameter list enclosed by parentheses follows the keyword FUNCTION on the same line. This is followed by a value process, indented two spaces, which forms the body of the function. The function definition is terminated by a colon which appears on a new line at the same indentation level as the start of the definition. Alternatively, a function definition may consist of the function heading followed by the keyword IS, an expression list, and a colon, on the same line. The line may be broken after the keyword IS, a comma, or at a valid point in an expression.

An instance of a function defined to have zero parameters must be followed by empty parentheses. Where a number of parameters of the same type appear in the parameter list, a single specifier may specify several names. For example:

\[
\text{INT FUNCTION alice (VAL REAL64 tweedle.dum, tweedle.dee,} \\
\text{VAL INT cheshire.cat)}
\]

\[
\text{...}
\]

This example, is equivalent to:

\[
\text{INT FUNCTION alice (VAL REAL64 tweedle.dum,} \\
\text{VAL REAL64 tweedle.dee,} \\
\text{VAL INT cheshire.cat)}
\]

\[
\text{...}
\]
Appendices
This appendix describes the aspects of OCCAM which specify the configuration of an OCCAM program. Configuration associates the components of an OCCAM program with a set of physical resources. During configuration the processes which make up an OCCAM program are distributed over the number of interconnected processing devices available in the environment in which the program will execute. The processes which execute on a single processor may be given a priority of execution, and the channels which interconnect the distributed processes may be mapped onto the physical communication links between processing devices. It is expected that the program is logically correct before configuration is used to optimise performance. Configuration does not affect the logical behaviour of a program.

A.1 Execution on multiple processors

The component processes of a parallel may each be executed on an individual processor. This can be specified by a placed parallel which assigns a process for execution on a specified processor. Consider the following example:

```
PLACED PAR
  PROCESSOR 1
    terminal (term.in, term.out)
  PROCESSOR 2
    editor (term.in, term.out, files.in, files.out)
  PROCESSOR 3
    network (files.in, files.out)
```

In this example, the processes terminal, editor and network, are placed on three individual processors numbered 1, 2 and 3. Each process is executed on the assigned processor, each process uses local memory, and communicates with the other processes via channels.

The syntax for a placed par is:

```
placedpar = PLACED PAR
  { placedpar }
| PLACED PAR replicator
      placedpar
| PROCESSOR expression
    process
parallel = placedpar
```

The keywords PLACED PAR are followed by zero or more processor allocations. A processor allocation is the keyword PROCESSOR, and an expression of type INT which serves to identify the processor on which the associated process is to be placed. As for normal parallels (page 16), the placed parallel may be replicated. An implementation may extend this syntax to identify the type of processor on which the process is placed. All variables and timers used within the placement must be declared within it.

A.2 Execution priority on a single processor

A.2.1 Priority parallel

The component processes of a parallel (page 15) executing on a single processor may be assigned a priority of execution. Consider the following example:

```
PRI PAR
  terminal (term.in, term.out)
  editor (term.in, term.out)
```

This process will always execute the process terminal in preference to the process editor. Each process executes at a separate priority, the first process is the highest priority, the last is the lowest. Lower priority processes may only continue when all higher priority processes are unable to. The process may also
be replicated, as shown in the following example:

```
PRI PAR i = 0 FOR 8
users (term.in[i], term.out[i])
```

The process with the highest index is executed at the lowest priority.

The syntax for priority execution is:

```
parallel = PRI PAR { process } | PRI PAR replicator process
```

The keywords **PRI PAR** are followed by zero or more processes at an indentation of two spaces. As for parallels detailed in the main body of the manual (page 16), the process may be replicated.

### A.2.2 Priority alternation

The inputs which guard alternatives in an alternation (page 18) may also be given a selection priority. Consider the following example:

```
PRI ALT
disk ? block
d ()
keyboard ? char
k ()
```

This priority alternation will input values from the channel **disk** in preference to inputs from the channel **keyboard**. If both channels **disk** and **keyboard** become ready then **disk** will be selected as it has the highest priority.

Consider the following example:

```
PRI ALT
stream ? data
P ()
busy & SKIP
Q ()
```

This process inputs **data** if an input from **stream** is ready, and performs the process **P**, otherwise if the boolean **busy** is true the process **Q** is performed.

The syntax for priority alternation is:

```
alternation = PRI ALT { alternative } | PRI ALT replicator alternative
```

The keywords **PRI ALT** are followed by zero or more processes at an indentation of two spaces. As for alternations detailed earlier in the manual (page 20) the alternative may be replicated.
A.3 Allocation to memory

This section explains how a variable, channel, timer or array may be placed at an absolute location in memory. OCCAM presents a consistent view of a processor's memory map. Memory is considered to be an array of type INT, each address in memory is considered a subscript into that array. Consider the following example:

\[
\text{PLACE term.in AT linklin :}
\]

This allocation places the element term.in at the location specified by linklin. Here are some further examples:

\[
\begin{align*}
[80]\text{INT buffer :} \\
&\text{PLACE buffer AT #0400 :}
\end{align*}
\]

\[
\begin{align*}
[5]\text{REAL32 points :} \\
&\text{PLACE points AT #0800 :}
\end{align*}
\]

\[
\begin{align*}
\text{CHAN OF INT term.out :} \\
&\text{PLACE term.out AT 3 :}
\end{align*}
\]

The syntax for allocation is:

\[
\begin{align*}
\text{process} & = \text{allocation} : \\
& \text{process} \\
\text{allocation} & = \text{PLACE name AT expression} :
\end{align*}
\]

An allocation begins with the keyword `PLACE`, followed by the name of the variable, channel, timer or array to be placed. This in turn is followed by an expression of type INT which indicates the absolute location in memory.

An allocation must allocate an element to a compatible location. That is, a timer should be placed at a location which acts as a timer, and a channel should be placed at the location which implements a channel. Also, arrays must not be placed so that the components of an array overlap other allocations.
This appendix describes how memory mapped devices may be addressed in OCCAM. A process may communicate with external devices which are mapped into the processor's memory map, using a special input or output in a way similar to communication on channels. A special type declares a port which must then be placed using an allocation (page 73). Consider the following example:

```
PORT OF INT16 status :
PLACE status AT uart.status :
SEQ
  ...
  status ? state
  status ! reset
  ...
```

This example declares a port which is then allocated to a location uart.status in memory. The following sequence includes an input which reads the value of the port, and also an output which writes a value reset to the port location. Consider the following examples of port declarations:

```
PORT OF [8]INT uart :
PORT OF [8]BYTE transducer :
```

A port declaration is similar to a channel declaration, and must obey the same rules of scope (page 53). That is, a port may not be used for input or output in more than one component process in a parallel.

The syntax for ports is:

- `primitive.type` = `PORT OF type`
- `port` = `element`
- `input` = `port ? variable`
- `output` = `port ! expression`

The syntax shows that ports are a primitive type, just like data types, channels and timers. A port is declared in just the same way as a channel. Instead of a defined protocol (page 29) the port definition specifies a type, which must be a data type, as the type for communication.
This appendix summarises the rules which govern the use of variables, channels, timers, ports (page 74) and arrays in parallel constructions, and the rules which govern abbreviations and parameters. These rules are discussed in context throughout the manual, and are gathered here as a check list.

C.1 Usage in parallel

The purpose of these rules is to prevent parallel processes from sharing variables, to ensure that each channel connects only two parallel processes, and to ensure that the connection of channels is unidirectional. The rules allow most of the checking for valid usage to be performed by a compiler, thus reducing runtime overheads.

A channel implements a point-to-point communication between two parallel processes. The name of a channel may only be used in one component of a parallel for input, and in one other component of the parallel for output.

A timer may be used for input by any number of components of a parallel.

A variable or component of an array of variables, which is assigned to in a component of a parallel, may not appear in any other component of the parallel.

An array may be used in more than one component of a parallel, if and only if the subscripts used to select components of the array can be determined at compile time. Otherwise the array may only be used in one component of the parallel.

Several abbreviations can decompose an array into non-overlapping disjoint parts; components of these parts may then be selected using variable subscripts.

A port may be used in only one component of a parallel.

C.2 The rules for abbreviations

The purpose of these rules is to ensure that each name identifies a unique object, and that the substitution semantics are maintained.

All reference to an abbreviated element must be via the abbreviation only, with the exception that array elements may be further abbreviated providing the later abbreviations do not include components of the array already abbreviated.

Variables used in an abbreviated expression may not be assigned to by input or assignment within the scope of the abbreviation.

The abbreviated expression must be valid, i.e. in range and not subject to overflow, and all subscript expressions must be in range.

All subscript expressions used in an element abbreviation must be valid, i.e. not subject to overflow and in range.

All reference to a retyped element must be via the new name only, with the exception that array elements may be further retyped providing the later retyping conversions do not include components of the array already retyped.

Variables used in a retyping conversion may not be assigned to by input or assignment within the scope of the new name.
C.3 The rules for procedures

The rules for procedure parameters follow from those for abbreviations, but in addition a channel parameter or free channel may not be used for both input or output in a procedure.

C.4 The rules for value processes and functions

Functions may only have value parameters.

Only variables declared within the scope of a value process may be assigned to. Free names may be used in expressions.

A value process may not contain inputs, outputs, parallels or alternations.

The body of a procedure used within a function must also obey these rules.
This appendix describes retyping conversion. A retyping conversion changes the data type of a bit pattern, from one data type to another. There are two kinds of retyping conversions: conversions which convert an element, and conversions which convert the value of an expression. The length (i.e. the number of bits) of the new type specified must be the same as the length of the bit pattern. A retyping conversion has no effect upon the bit pattern, and differs from type conversion (page 49) where the value of one type is represented as an equivalent value of another type.

The retyping conversion of a value may be used to specify a name for a particular bit pattern described by a hexadecimal constant. Consider the following example:

```
VAL REAL32 root.NaN RETYPES #7F840000(INT32)
```

The advantage of the above conversion is that it has been possible to specify the exact representation of a value otherwise difficult to represent. Consider also the following example:

```
VAL INT64 pattern RETYPES 42.0(REAL64)
```

The bit pattern for the real representation of the value 42.0 is mapped to a name pattern of type INT64. As for the abbreviations (page 57) of expressions, no variable used in the expression may be assigned to by input or assignment within the scope of the conversion.

The retyping conversion may also specify a name of a new type for an existing element of the same length. For example:

```
INT64 condition :
...[8]BYTE state RETYPES condition :
...
```

In this example, condition, a variable of type INT64, is converted into an array of 8 bytes. Each byte is accessible via subscript, any change to the bit pattern as a result of an assignment or input will directly affect the value of the original element.

The same rules apply to names specified by retyping conversions as apply to abbreviations. That is, no variable used in a subscript or count expression which selects a component or segment of an array may be assigned to by an input or assignment within the scope (page 53, the region of a program where a name is valid) of the conversion. The element converted may not be be used within the scope of the conversion. See the rules which affect abbreviations on page 58.

The syntax for retyping conversion is:

```
definition = specifier name RETYPES element :
  | VAL specifier name RETYPES expression :
```

The retyping conversion of a value begins with the keyword VAL, a specifier appears to the right of VAL, followed by the name specified, and the keyword RETYPES, the expression appears to the right of the keyword RETYPES. The line on which the conversion occurs may not be broken after the keyword RETYPES, but may be broken at some valid point in the expression.

As word alignment tends to vary between machines, the use of retyping conversion will normally result in implementation dependent processes.
Processes which become invalid during program execution may behave in one of three ways, determined by a compiler option. An invalid process may behave in one of these ways: the process may stop, the system may halt, or the behaviour of the process may be undefined.

The three modes of existence in detail are:

**Stop process mode** In this mode, processes which become invalid behave like the primitive process STOP, thus allowing other processes to continue. The invalid process stops, and in particular does not make erroneous outputs to other processes. Other processes continue until they become dependent upon data from the stopped process. In this mode it is therefore possible to write communications which will timeout to warn of a stopped process, and to construct a system with redundancy in which a number of processes performing the same task may be used to enable the system to continue after one of the processes has failed.

**Halt system mode** In this mode an invalid process may cause the whole system to halt, and is useful for the development of programs, particularly when debugging concurrent systems. In this mode the primitive process STOP will also cause the whole system to halt.

**Undefined mode** In this mode, an invalid process may have an arbitrary effect, and is only useful for optimising programs known to be correct!
Earlier sections of this manual have discussed rounding and the possibility of rounding errors. These occur because the types **REAL32** and **REAL64** only contain a subset of the real numbers. This is because it is not possible to store all the possible real values in the format for real numbers available on a machine. Rounding takes a value, which is considered infinitely precise and, if necessary, modifies it to a value which is representable by the type. By default, values are rounded to the nearest value of the type, if the nearest greater value and the nearest smaller value are equally near, then the result which has the least significant bit zero is chosen. Other modes of rounding are selectable using the **IEEEOP** library routine, these modes round values toward plus infinity, minus infinity or toward zero. A value rounded to plus infinity is the value nearest to and not less than the value to be represented, a value rounded to minus infinity is the value nearest to and not greater than the value to be represented, a value rounded toward zero is the value no greater in magnitude than the value to be represented.

A value is rounded to the precision of its type. A value of type **REAL32** is equivalent to IEEE single precision, and a value of type **REAL64** is equivalent to IEEE double precision.

Values in the **REAL32** and **REAL64** formats are stored in the following formats

```
[s] exp  frac
```

where *s* is the sign bit, *exp* is the exponent and *frac* is the fraction. For the **REAL32** type *s* is 1 bit wide, *exp* is 8 bits wide and *frac* is 23 bits wide. For the **REAL64** type *s* is 1 bit wide, *exp* is 11 bits wide and *frac* is 52 bits wide. Whenever the *exp* field is not 0 the actual fraction of the number represented has an "implied" 1 placed on the left of the *frac* value.

The value of finite **REALs** is given by

```
val [s] exp  frac = \begin{cases} (-1)^s \times 1 \cdot \text{frac} \times 2^{\exp-bias}, & \text{if } \exp \neq 0; \\
(-1)^s \times 0 \cdot \text{frac} \times 2^{1-bias}, & \text{if } \exp = 0; 
\end{cases}
```

where *bias* is 127 for **REAL32** and 1023 for **REAL64**

In the **REAL32** type the value 1.0 is represented by an unset sign bit *s*, an *exp* equal to 127, and a *frac* of 0. The next larger number has an unset signbit, *exp* of 127 and a *frac* of 1. This has the value 1.00000019209... Hence any number lying between 1.0 and this value cannot be exactly represented in the **REAL32** type – such values have to be rounded to one of these values. Now consider the assignment:

```
X := 1.0(REAL32) + 1.0E-7(REAL32)
```

The previous sections show that the result of this operation cannot be exactly represented by the type **REAL32**. The exact result has to be rounded to "fit" the type. Here the exact result will be rounded to the nearest **REAL32** value 1.00000019209...

Other rounding modes – Round to Zero (truncation), Round to Plus infinity and Round to Minus infinity – can be obtained through the use of the **IEEEOP** function. Because of the presence of rounding, programmers should be wary of using equality tests on real types. Consider the following example:

```
SEQ
  X := 1.0(REAL32)
  WHILE X <> 1.000001(REAL32)
  X := X + 0.0000005(REAL32)
```

never terminates as rounding errors cause 1.000001 and 1.0 + 0.0000005 + 0.0000005 to differ.

The nearest unique value of a conversion of a literal of type **REAL32** can be determined from the first 9 significant digits, and from the first 17 significant digits of a literal of type **REAL64**. Complete details of the IEEE Standard for Binary Floating-Point Arithmetic can be found in the published ANSI/IEEE Std 754-1985 standard.
G.1 Syntax in context

The following tables present the syntax of OCCAM 2. Each syntactic object appears in context. However, the following BNF should not be read in isolation. The syntactic objects are kept to a minimum, and must be considered in association with the semantic rules given in the definition. Thus, for example, the use of primitive.type and type in the syntax

\( \text{simple.protocol} = \text{primitive.type: : [ ] type} \)

is clarified by the semantics which point out that the primitive.type must be an integer or byte type, and that type must be a data type.

G.1.1 Processes

\[
\begin{align*}
\text{process} & = \text{SKIP} | \text{STOP} \\
& \quad | \text{action} \\
& \quad | \text{construction} \\
& \quad | \text{instance} \\
\text{action} & = \text{assignment} | \text{input} | \text{output} \\
\text{assignment} & = \text{variable} : = \text{expression} \\
\text{input} & = \text{channel} ? \text{variable} \\
\text{output} & = \text{channel} ! \text{expression} \\
\text{process} & = \text{sequence} | \text{conditional} | \text{selection} | \text{loop} \\
& \quad | \text{parallel} | \text{alternation} \\
\text{sequence} & = \text{SEQ} \\
& \quad \{ \text{process} \} \\
\text{conditional} & = \text{IF} \\
& \quad \{ \text{choice} \} \\
\text{choice} & = \text{guarded.choice} | \text{conditional} \\
\text{guarded.choice} & = \text{boolean} \\
& \quad \text{process} \\
\text{boolean} & = \text{expression} \\
\text{selection} & = \text{CASE} \text{selector} \\
& \quad \{ \text{option} \} \\
\text{option} & = \{ \text{case.expression} \} \\
& \quad \text{process} \\
& \quad | \text{ELSE} \\
& \quad \text{process} \\
\text{selector} & = \text{expression} \\
\text{case.expression} & = \text{expression} \\
\text{loop} & = \text{WHILE} \text{boolean} \\
& \quad \text{process} \\
\text{parallel} & = \text{PAR} \\
& \quad \{ \text{process} \}
\end{align*}
\]
Syntax summary

G

alternation = ALT
       { alternative }
alternative = guarded.alternative | alternation
guarded.alternative = guard
       process
guard = input
       | boolean & input
       | boolean & SKIP

G.1.3 Replicator

sequence = SEQ replicator
       process
conditional = IF replicator
       choice
parallel = PAR replicator
       choice
alternation = ALT replicator
       alternative
replicator = name = base FOR count
base = expression
count = expression

G.1.4 Types

type = primitive.type
       | array.type
primitive.type = CHAN OF protocol
       | TIMER
       | BOOL
       | BYTE
       | INT
       | INT16
       | INT32
       | INT64
       | REAL32
       | REAL64
array.type = [ expression ] type

G.1.5 Literal

literal = integer
       | byte
       | integer (type)
       | byte (type)
       | real (type)
       | string
       | TRUE | FALSE
integer = digits | #hex.digits
byte = ' character'
real = digits.digits | digits.digitsEexponent
exponent = +digits | -digits
digit = 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9
hex.digit = digit | A | B | C | D | E | F
G.1.6 Declaration

declaration = type {1 , name } :

G.1.7 Protocol

definition = PROTOCOL name IS simple.protocol :
                 | PROTOCOL name IS sequential.protocol :
protocol = name

simple.protocol = type
                 | primitive.type : [ ] type
input = channel ? input.item
input.item = variable
                 | variable : : variable
output = channel ! output.item
output.item = expression
                 | expression : : expression
protocol = simple.protocol

sequential.protocol = {1 ; simple.protocol }
input = channel ? {1 ; input.item }
output = channel ! {1 ; output.item }
definition = PROTOCOL name
            CASE { tagged.protocol }
            :
tagged.protocol = tag
            | tag ; sequential.protocol
tag = name
output = channel ! tag
         | channel ! tag ; {1 ; output.item }
case.input = channel ? CASE { variant }
variant = tagged.list
          process specification
          variant
tagged.list = tag
             | tag ; {1 ; input.item }
process = case.input
input = channel ? CASE tagged.list

alternative = channel ? CASE { variant }
             | boolean & channel ? CASE { variant }

G.1.8 Timer access

input = timer.input
       | delayed.input
timer.input = timer ? variable
delayed.input = timer ? AFTER expression
G.1.9  Element

\[
\text{element} = \begin{align*}
\text{element} & \mid \text{subscript} \\
& \mid [ \text{element FROM subscript FOR count} ] \\
& \mid \text{name}
\end{align*}
\]

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

\[
\text{variable} = \text{element}
\]

\[
\text{channel} = \text{element}
\]

\[
\text{timer} = \text{element}
\]

G.1.10  Expression

\[
\text{operand} = \begin{align*}
\text{element} & \mid \text{literal} \\
& \mid \text{table} \\
& \mid (\text{expression})
\end{align*}
\]

\[
\text{expression} = \begin{align*}
\text{operand} & \mid \text{dyadic.operator operand} \\
& \mid \text{conversion} \\
& \mid \text{operator}
\end{align*}
\]

\[
\text{table} = \begin{align*}
\text{table} & \mid \text{subscript} \\
& \mid \{, \text{expression} \} \\
& \mid \text{table FROM subscript FOR count}
\end{align*}
\]

\[
\text{expression} = \begin{align*}
\text{MOSTPOS} & \text{type} \\
& \text{MOSTNEG} & \text{type}
\end{align*}
\]

\[
\text{conversion} = \begin{align*}
\text{primitive.type operand} & \mid \text{ROUND operand} \\
& \text{TRUNC operand}
\end{align*}
\]

G.1.11  Abbreviation

\[
\text{abbreviation} = \begin{align*}
\text{specifier name IS element :} \\
& \text{name IS element :} \\
& \text{VAL specifier name IS expression :} \\
& \text{VAL name IS expression :}
\end{align*}
\]

\[
\text{specifier} = \begin{align*}
\text{primitive.type} & \mid \text{[] specifier} \\
& \text{[ expression ] specifier}
\end{align*}
\]

G.1.12  Scope

\[
\text{process} = \text{specification process}
\]

\[
\text{choice} = \text{specification choice}
\]

\[
\text{option} = \text{specification option}
\]

\[
\text{alternative} = \text{specification alternative}
\]

\[
\text{variant} = \text{specification variant}
\]

\[
\text{valof} = \text{specification valof}
\]

\[
\text{specification} = \text{declaration} \mid \text{abbreviation} \mid \text{definition}
\]
G.1.13 Procedure

\[
\begin{align*}
\text{definition} & = \quad \text{PROC } \text{name} \ (\{0, \ \text{formal}\}) \\
& \quad \text{procedure.body} \\
\text{formal} & = \quad \text{specifier} \ \{1, \ \text{name}\} \\
\text{procedure.body} & = \quad \text{VAL} \ \text{specifier} \ \{1, \ \text{name}\} \\
\text{instance} & = \quad \text{name} \ (\{0, \ \text{actual}\}) \\
\text{actual} & = \quad \text{element} \\
& \quad \text{expression}
\end{align*}
\]

G.1.14 Function

\[
\begin{align*}
\text{value.process} & = \quad \text{valof} \\
\text{valof} & = \quad \text{VALOF} \\
& \quad \text{RESULT} \ \text{expression.list} \\
& \quad \text{specification} \\
& \quad \text{valof} \\
\text{operand} & = \quad (\ \text{value.process} \\
& \quad ) \\
\text{expression.list} & = \quad (\ \text{value.process} \\
& \quad )
\end{align*}
\]

\[
\begin{align*}
\text{definition} & = \quad \{1, \ \text{primitive.type}\} \ \text{FUNCTION} \ \text{name} \ (\{0, \ \text{formal}\}) \\
& \quad \text{function.body} \\
\text{function.body} & = \quad \text{value.process} \\
\text{operand} & = \quad \text{name} \ (\{0, \ \text{expression}\}) \\
\text{expression.list} & = \quad \text{name} \ (\{0, \ \text{expression}\}) \\
\text{definition} & = \quad \{1, \ \text{primitive.type}\} \ \text{FUNCTION} \ \text{name} \ (\{0, \ \text{formal}\}) \ \text{IS} \ \text{expression.list} :
\end{align*}
\]
G.1.15 Configuration

\[
\begin{align*}
\text{placedpar} & = \quad \text{PLACED PAR} \\
& \quad \{ \text{placedpar} \} \\
& \quad \mid \text{PLACED PAR} \text{ replicator} \\
& \quad \quad \text{placedpar} \\
& \quad \mid \text{PROCESSOR} \text{ expression} \\
& \quad \quad \text{process} \\
\text{parallel} & = \quad \text{placedpar} \\
\text{parallel} & = \quad \text{PRI PAR} \\
& \quad \{ \text{process} \} \\
& \quad \mid \text{PRI PAR} \text{ replicator} \\
& \quad \quad \text{process} \\
\text{alternation} & = \quad \text{PRI ALT} \\
& \quad \{ \text{alternative} \} \\
& \quad \mid \text{PRI ALT} \text{ replicator} \\
& \quad \quad \text{alternative} \\
\text{process} & = \quad \text{allocation} \\
& \quad \text{process} \\
\text{allocation} & = \quad \text{PLACE} \text{ name AT expression} : \\
\text{definition} & = \quad \text{specifier name RETYPES element} : \\
& \quad \mid \text{VAL} \text{ specifier name RETYPES expression} : \\
\text{primitive.type} & = \quad \text{PORT OF type} \\
\text{port} & = \quad \text{element} \\
\text{input} & = \quad \text{port} ? \text{ variable} \\
\text{output} & = \quad \text{port} ! \text{ expression} \\
\text{protocol} & = \quad \text{ANY}
\end{align*}
\]
G.2 Ordered syntax

The following tables present the syntax of OCCAM with each syntactic object placed in alphabetical order.

abbreviation = specifier name IS element :
   | name IS element :
   | VAL specifier name IS expression :
   | VAL name IS expression :

action = assignment
   | input
   | output

actual = element
   | expression

allocation = PLACE name AT expression :

alternation = ALT
   { alternative }
   | ALT replicator alternative
   | PRI ALT
   { alternative }
   | PRI ALT replicator alternative

alternative = guarded.alternative | alternation
   | specification alternative
   | channel ? CASE
   { variant }
   | boolean & channel ? CASE
   { variant }

array.type = [ expression ] type

assignment = variable := expression
   | variable.list := expression.list

base = expression

boolean = expression

byte = ' character'

case.expression = expression

case.input = channel ? CASE
   { variant }

channel = element

choice = guarded.choice | conditional
   specification choice
conditional = \text{IF} \\
\quad \{ \text{choice} \} \\
\quad | \text{IF replicator} \\
\quad \text{choice} \\
\text{construction} = \text{sequence} | \text{conditional} | \text{selection} | \text{loop} \\
\quad | \text{parallel} | \text{alternation} \\
\text{conversion} = \text{primitive.type operand} \\
\quad | \text{primitive.type ROUND operand} \\
\quad | \text{primitive.type TRUNC operand} \\
\text{count} = \text{expression} \\
\text{declaration} = \text{type} \{1, \text{name}\} : \\
\text{definition} = \text{PROTOCOL} \text{name IS simple.protocol} : \\
\quad | \text{PROTOCOL} \text{name IS sequential.protocol} : \\
\quad | \text{PROTOCOL} \text{name} \\
\quad \text{CASE} \\
\quad \quad \{ \text{tagged.protocol} \} \\
\quad | \text{PROC} \text{name} (\{0, \text{formal}\}) \\
\quad \quad \text{procedure.body} \\
\quad | \{1, \text{primitive.type} \} \text{FUNCTION} \text{name} (\{0, \text{formal}\}) \\
\quad \quad \text{function.body} \\
\quad | \{1, \text{primitive.type} \} \text{FUNCTION} \text{name} (\{0, \text{formal}\}) \text{IS expression.list} : \\
\quad | \text{specifier \text{name RETYPES element} :} \\
\quad | \text{VAL specifier \text{name RETYPES expression} :} \\
\text{delayed.input} = \text{timer}\? \text{AFTER expression} \\
\text{digit} = 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 \\
\text{element} = \text{element} [ \text{subscript} ] \\
\quad | [ \text{element FROM subscript FOR count} ] \\
\quad | \text{name} \\
\text{exponent} = +\text{digits} | -\text{digits} \\
\text{expression} = \text{monadic.operator operand} \\
\quad | \text{operand dyadic.operator operand} \\
\quad | \text{conversion} \\
\quad | \text{operand} \\
\quad | \text{MOSTPOS type} | \text{MOSTNEG type} \\
\text{expression.list} = (\text{value.process} \\
\quad | \text{name} (\{0, \text{expression}\}) \\
\quad | \{1, \text{expression}\} \\
\text{formal} = \text{specifier} \{1, \text{name}\} \\
\quad | \text{VAL specifier} \{1, \text{name}\} \\
\text{function.body} = \text{value.process}
\[
guard = \begin{array}{l}
\text{input} \\
\text{boolean} \& \text{input} \\
\text{boolean} \& \text{SKIP}
\end{array}
\]

\[
guarded.\text{alternative} = \begin{array}{l}
guard \\
\text{process}
\end{array}
\]

\[
guarded.\text{choice} = \begin{array}{l}
\text{boolean} \\
\text{process}
\end{array}
\]

\[
\text{hex.digit} = \begin{array}{l}
digit | A | B | C | D | E | F
\end{array}
\]

\[
\text{input} = \begin{array}{l}
\text{channel} ? \text{variable} \\
\text{channel} ? \text{input.item} \\
\text{channel} ? \{1 ; \text{input.item}\} \\
\text{channel} ? \text{CASE} \text{tagged.list} \\
\text{timer} . \text{input} \\
\text{delayed} . \text{input} \\
\text{port} ? \text{variable}
\end{array}
\]

\[
\text{input.item} = \begin{array}{l}
\text{variable} \\
\text{variable} : : \text{variable}
\end{array}
\]

\[
\text{instance} = \begin{array}{l}
\text{name} (\{0 , \text{actual}\})
\end{array}
\]

\[
\text{integer} = \begin{array}{l}
digits | \# \text{hex.digits}
\end{array}
\]

\[
\text{literal} = \begin{array}{l}
\text{integer} \\
\text{byte} \\
\text{integer} (\text{type}) \\
\text{byte} (\text{type}) \\
\text{real} (\text{type}) \\
\text{string} \\
\text{TRUE} | \text{FALSE}
\end{array}
\]

\[
\text{loop} = \begin{array}{l}
\text{WHILE} \text{boolean} \\
\text{process}
\end{array}
\]

\[
\text{operand} = \begin{array}{l}
\text{element} \\
\text{literal} \\
\text{table} \\
\{\text{expression}\} \\
\{\text{value} . \text{process} \} \\
\text{name} (\{0 , \text{expression}\})
\end{array}
\]

\[
\text{option} = \begin{array}{l}
\{1 , \text{case.expression}\} \\
\text{ELSE} \\
\text{process} \\
\text{specification} \\
\text{option}
\end{array}
\]

\[
\text{output} = \begin{array}{l}
\text{channel} ! \text{expression} \\
\text{channel} ! \text{output.item} \\
\text{channel} ! \{1 ; \text{output.item}\} \\
\text{channel} ! \text{tag} \\
\text{channel} ! \text{tag} ; \{1 ; \text{output.item}\} \\
\text{port} ! \text{expression}
\end{array}
\]

G Syntax summary
output.item = expression
    | expression :: expression

parallel = PAR
    { process }
    | PAR replicator
      process
    | PRI PAR
      { process }
    | PRI PAR replicator
      process
    | placedpar

placedpar = PLACED PAR
    { placedpar }
    | PLACED PAR replicator
      placedpar
    | PROCESSOR expression
      process

port = element

primitive.type = CHAN OF protocol
    | TIMER
    | BOOL
    | BYTE
    | INT
    | INT16
    | INT32
    | INT64
    | REAL32
    | REAL64
    | PORT OF type

procedure.body = process

process = SKIP | STOP
    action
    | construction
    | instance
    | case.input
    | specification
      process
    | allocation
      process

protocol = name
    | simple.protocol
    | ANY

real = digits.digits | digits.digitsEexponent

replicator = name = base FOR count

selection = CASE selector
    { option }
sequence = SEQ
  { process }
  | SEQ replicator
    process

sequential@protocol = {1 ; simple@protocol }

simple@protocol = type
  | primitive.type : [] type

specification = declaration | abbreviation | definition

specifier = primitive.type
  | [] specifier
  | [ expression ] specifier

subscript = expression

table = table [ subscript ]
  | [ {1 , expression } ]
  | [ table FROM subscript FOR count ]

tag = name

tagged.list = tag
  | tag ; {1 ; input.item }

tagged@protocol = tag
  | tag ; sequential@protocol

timer = element

timer.input = timer ? variable

type = primitive.type
  | array.type

valof = VALOF
  process
  RESULT expression.list
  | specification
    valof

value.process = valof

variable = element

variable.list = {1 , variable }

variant = tagged.list
  | process
  | specification
    variant

G Syntax summary
This section provides a complete list of OCCAM symbols and keywords.

<table>
<thead>
<tr>
<th>Arithmetic operators</th>
<th>Communication symbols</th>
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<td>Bit operators</td>
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<td>WHILE</td>
<td>loop</td>
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</table>

If an implementation adds further reserved words, then the names used must not include lower case letters.
Characters in OCCAM are represented according to the American Standard Code for Information Interchange (ASCII). Where the full character set is not available OCCAM guarantees the following subset:

```
ABCDEFGHIJKLMNOPQRSTUVWXYZ
abcdefghijklmnopqrstuvwxyz
0123456789
! " # $ % & ' () * + , - . / : ; < = > ? [ ]
```

For reference, here is a table of all printable ASCII characters, and their values:

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<th>Hex</th>
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<td>126</td>
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</table>

The characters *, ' and " may not be used directly in strings or as character constants. These and non-printable characters (such as carriage return, tab etc..) can be included in strings, or used as character constants, in the following form:

```
*c *C carriage return      = *#0D
*n *N newline              = *#0A
*t *T tab                  = *#08
*s *S space                = *#20
/ * quotations mark         
" * double quotations mark
*   asterisk
```
In addition, any byte value can be represented by *# followed by two hexadecimal digits, for example:

```
soh := '##01'  '##01' is a byte constant.
```
This appendix provides a complete list of the standard library routines. The behaviour of routines is described in detail in the following appendices. Library routines (typically the most primitive routines) may be predefined in an implementation, that is, they may be known to the compiler and do not need to be explicitly referenced by the programmer. Other libraries must be explicitly referenced by the programmer, and the name used in their specification has the same property as any other specification. However, programmers are discouraged from using the names of any library routine for any specification other than that of naming the routine in question. The following tables include the name of the routine, and a specifier which indicates the type of each of the parameters to the routine.

### J.1 Multiple length integer arithmetic functions

The arithmetic functions provide arithmetic shifts, word rotations and the primitives to construct multiple length arithmetic and multiple length shift operations.

<table>
<thead>
<tr>
<th>Result</th>
<th>Function</th>
<th>Parameter specifiers</th>
</tr>
</thead>
<tbody>
<tr>
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<td>LONGADD</td>
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<td>LONGSUB</td>
<td>(VAL INT, VAL INT, VAL INT)</td>
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<td>ASHIFTRIGHT</td>
<td>(VAL INT, VAL INT)</td>
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<td>INT, INT</td>
<td>SHIPTRIGHT</td>
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<td>INT, INT, INT</td>
<td>NORMALISE</td>
<td>(VAL INT, VAL INT)</td>
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</table>

### J.2 Floating point functions

The floating point functions provide the list of facilities suggested by the ANSI/IEEE standard 754-1985.

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<th>Function</th>
<th>Parameter specifiers</th>
</tr>
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<td>DABS</td>
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<td>DSCALEB</td>
<td>(VAL REAL64, VAL INT)</td>
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<td>(VAL REAL32, VAL REAL32)</td>
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</table>
### J Standard libraries

<table>
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<th>Function</th>
<th>Parameter specifiers</th>
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</thead>
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<tr>
<td>REAL64</td>
<td>DMULBY2</td>
<td>(VAL REAL64)</td>
</tr>
<tr>
<td>REAL32</td>
<td>DIVBY2</td>
<td>(VAL REAL32)</td>
</tr>
<tr>
<td>REAL64</td>
<td>DDIVBY2</td>
<td>(VAL REAL64)</td>
</tr>
<tr>
<td>REAL32</td>
<td>LOGB</td>
<td>(VAL REAL32)</td>
</tr>
<tr>
<td>REAL64</td>
<td>DLOGB</td>
<td>(VAL REAL64)</td>
</tr>
<tr>
<td>BOOL</td>
<td>ISNAN</td>
<td>(VAL REAL32)</td>
</tr>
<tr>
<td>BOOL</td>
<td>DISNAN</td>
<td>(VAL REAL64)</td>
</tr>
<tr>
<td>BOOL</td>
<td>NOTFINITE</td>
<td>(VAL REAL32)</td>
</tr>
<tr>
<td>BOOL</td>
<td>DNOTFINITE</td>
<td>(VAL REAL64)</td>
</tr>
<tr>
<td>BOOL</td>
<td>ORDERED</td>
<td>(VAL REAL32, VAL REAL32)</td>
</tr>
<tr>
<td>BOOL</td>
<td>DORDERED</td>
<td>(VAL REAL64, VAL REAL64)</td>
</tr>
<tr>
<td>INT, REAL32</td>
<td>FLOATING.UNPACK</td>
<td>(VAL REAL32)</td>
</tr>
<tr>
<td>INT, REAL64</td>
<td>DFLOATING.UNPACK</td>
<td>(VAL REAL64)</td>
</tr>
<tr>
<td>BOOL, INT32, REAL32</td>
<td>ARGUMENT.REDUCE</td>
<td>(VAL REAL32, VAL REAL32, VAL REAL32)</td>
</tr>
<tr>
<td>BOOL, INT32, REAL64</td>
<td>DARGUMENT.REDUCE</td>
<td>(VAL REAL64, VAL REAL64, VAL REAL64)</td>
</tr>
<tr>
<td>REAL32</td>
<td>FPINT</td>
<td>(VAL REAL32)</td>
</tr>
<tr>
<td>REAL64</td>
<td>DFPINT</td>
<td>(VAL REAL64)</td>
</tr>
</tbody>
</table>

### J.3 Full IEEE arithmetic functions

<table>
<thead>
<tr>
<th>Result</th>
<th>Function</th>
<th>Parameter specifiers</th>
</tr>
</thead>
<tbody>
<tr>
<td>REAL32</td>
<td>REAL32OP</td>
<td>(VAL REAL32, VAL INT, VAL REAL32)</td>
</tr>
<tr>
<td>REAL64</td>
<td>REAL64OP</td>
<td>(VAL REAL64, VAL INT, VAL REAL64)</td>
</tr>
<tr>
<td>BOOL, REAL32</td>
<td>IEEE32OP</td>
<td>(VAL REAL32, VAL INT, VAL INT, VAL REAL32)</td>
</tr>
<tr>
<td>BOOL, REAL64</td>
<td>IEEE64OP</td>
<td>(VAL REAL64, VAL INT, VAL INT, VAL REAL64)</td>
</tr>
<tr>
<td>REAL32</td>
<td>REAL32REM</td>
<td>(VAL REAL32, VAL REAL32)</td>
</tr>
<tr>
<td>REAL64</td>
<td>REAL64REM</td>
<td>(VAL REAL64, VAL REAL64)</td>
</tr>
<tr>
<td>BOOL, REAL32</td>
<td>IEEE32REM</td>
<td>(VAL REAL32, VAL REAL32)</td>
</tr>
<tr>
<td>BOOL, REAL64</td>
<td>IEEE64REM</td>
<td>(VAL REAL64, VAL REAL64)</td>
</tr>
<tr>
<td>BOOL</td>
<td>REAL32EQ</td>
<td>(VAL REAL32, VAL REAL32)</td>
</tr>
<tr>
<td>BOOL</td>
<td>REAL64EQ</td>
<td>(VAL REAL64, VAL REAL64)</td>
</tr>
<tr>
<td>BOOL</td>
<td>REAL32GT</td>
<td>(VAL REAL32, VAL REAL32)</td>
</tr>
<tr>
<td>BOOL</td>
<td>REAL64GT</td>
<td>(VAL REAL64, VAL REAL64)</td>
</tr>
<tr>
<td>INT</td>
<td>IEEECOMPARE</td>
<td>(VAL REAL32, VAL REAL32)</td>
</tr>
<tr>
<td>INT</td>
<td>DIEECECOMPARE</td>
<td>(VAL REAL64, VAL REAL64)</td>
</tr>
</tbody>
</table>
### J.4 Elementary function library

All the functions which begin with the letter D return a value of type `REAL64`, with the exception of `DRAN` which returns an `INT64` value. All other functions return a value of type `REAL32`, with the exception of `RAN` which returns a value of type `INT32`.

<table>
<thead>
<tr>
<th>Result</th>
<th>Function</th>
<th>Parameter specifiers</th>
</tr>
</thead>
<tbody>
<tr>
<td>REAL32</td>
<td>ALOG</td>
<td>(VAL REAL32)</td>
</tr>
<tr>
<td>REAL64</td>
<td>DALOG</td>
<td>(VAL REAL64)</td>
</tr>
<tr>
<td>REAL32</td>
<td>ALOG10</td>
<td>(VAL REAL32)</td>
</tr>
<tr>
<td>REAL64</td>
<td>DALOG10</td>
<td>(VAL REAL64)</td>
</tr>
<tr>
<td>REAL32</td>
<td>EXP</td>
<td>(VAL REAL32)</td>
</tr>
<tr>
<td>REAL64</td>
<td>DEXP</td>
<td>(VAL REAL64)</td>
</tr>
<tr>
<td>REAL32</td>
<td>TAN</td>
<td>(VAL REAL32)</td>
</tr>
<tr>
<td>REAL64</td>
<td>DTAN</td>
<td>(VAL REAL64)</td>
</tr>
<tr>
<td>REAL32</td>
<td>SIN</td>
<td>(VAL REAL32)</td>
</tr>
<tr>
<td>REAL64</td>
<td>DSIN</td>
<td>(VAL REAL64)</td>
</tr>
<tr>
<td>REAL32</td>
<td>ASIN</td>
<td>(VAL REAL32)</td>
</tr>
<tr>
<td>REAL64</td>
<td>DASIN</td>
<td>(VAL REAL64)</td>
</tr>
<tr>
<td>REAL32</td>
<td>COS</td>
<td>(VAL REAL32)</td>
</tr>
<tr>
<td>REAL64</td>
<td>DCOS</td>
<td>(VAL REAL64)</td>
</tr>
<tr>
<td>REAL32</td>
<td>ACOS</td>
<td>(VAL REAL32)</td>
</tr>
<tr>
<td>REAL64</td>
<td>DACOS</td>
<td>(VAL REAL64)</td>
</tr>
<tr>
<td>REAL32</td>
<td>SINH</td>
<td>(VAL REAL32)</td>
</tr>
<tr>
<td>REAL64</td>
<td>DSINH</td>
<td>(VAL REAL64)</td>
</tr>
<tr>
<td>REAL32</td>
<td>COSH</td>
<td>(VAL REAL32)</td>
</tr>
<tr>
<td>REAL64</td>
<td>DCOSH</td>
<td>(VAL REAL64)</td>
</tr>
<tr>
<td>REAL32</td>
<td>TANH</td>
<td>(VAL REAL32)</td>
</tr>
<tr>
<td>REAL64</td>
<td>DTANH</td>
<td>(VAL REAL64)</td>
</tr>
<tr>
<td>REAL32</td>
<td>ATAN</td>
<td>(VAL REAL32)</td>
</tr>
<tr>
<td>REAL64</td>
<td>DATAN</td>
<td>(VAL REAL64)</td>
</tr>
<tr>
<td>REAL32</td>
<td>ATAN2</td>
<td>(VAL REAL32, VAL REAL32)</td>
</tr>
<tr>
<td>REAL64</td>
<td>DATAN2</td>
<td>(VAL REAL64, VAL REAL64)</td>
</tr>
<tr>
<td>REAL32, INT32</td>
<td>RAN</td>
<td>(VAL INT32)</td>
</tr>
<tr>
<td>REAL64, INT64</td>
<td>DRAN</td>
<td>(VAL INT64)</td>
</tr>
<tr>
<td>REAL32</td>
<td>POWER</td>
<td>(VAL REAL32, VAL REAL32)</td>
</tr>
<tr>
<td>REAL64</td>
<td>DPOWER</td>
<td>(VAL REAL64, VAL REAL64)</td>
</tr>
</tbody>
</table>
J.5  Value, string conversion procedures

The library provides primitive procedures to convert a value to and from decimal or hexadecimal representations.

<table>
<thead>
<tr>
<th>Procedure</th>
<th>Parameter specifiers</th>
</tr>
</thead>
<tbody>
<tr>
<td>INTTOSTRING</td>
<td>(INT, [ ] BYTE, VAL INT)</td>
</tr>
<tr>
<td>INT16TOSTRING</td>
<td>(INT, [ ] BYTE, VAL INT16)</td>
</tr>
<tr>
<td>INT32TOSTRING</td>
<td>(INT, [ ] BYTE, VAL INT32)</td>
</tr>
<tr>
<td>INT64TOSTRING</td>
<td>(INT, [ ] BYTE, VAL INT64)</td>
</tr>
<tr>
<td>STRINGTOINT</td>
<td>(BOOL, INT, VAL [ ] BYTE)</td>
</tr>
<tr>
<td>STRINGTOINT16</td>
<td>(BOOL, INT16, VAL [ ] BYTE)</td>
</tr>
<tr>
<td>STRINGTOINT32</td>
<td>(BOOL, INT32, VAL [ ] BYTE)</td>
</tr>
<tr>
<td>STRINGTOINT64</td>
<td>(BOOL, INT64, VAL [ ] BYTE)</td>
</tr>
<tr>
<td>HEXTOSTRING</td>
<td>(INT, [ ] BYTE, VAL INT)</td>
</tr>
<tr>
<td>HEX16TOSTRING</td>
<td>(INT, [ ] BYTE, VAL INT16)</td>
</tr>
<tr>
<td>HEX32TOSTRING</td>
<td>(INT, [ ] BYTE, VAL INT32)</td>
</tr>
<tr>
<td>HEX64TOSTRING</td>
<td>(INT, [ ] BYTE, VAL INT64)</td>
</tr>
<tr>
<td>STRINGTOHEX</td>
<td>(BOOL, INT, VAL [ ] BYTE)</td>
</tr>
<tr>
<td>STRINGTOHEX16</td>
<td>(BOOL, INT16, VAL [ ] BYTE)</td>
</tr>
<tr>
<td>STRINGTOHEX32</td>
<td>(BOOL, INT32, VAL [ ] BYTE)</td>
</tr>
<tr>
<td>STRINGTOHEX64</td>
<td>(BOOL, INT64, VAL [ ] BYTE)</td>
</tr>
<tr>
<td>STRINGTORREAL32</td>
<td>(BOOL, REAL32, VAL [ ] BYTE)</td>
</tr>
<tr>
<td>STRINGTORREAL64</td>
<td>(BOOL, REAL64, VAL [ ] BYTE)</td>
</tr>
<tr>
<td>REAL32TOSTRING</td>
<td>(INT, [ ] BYTE, VAL REAL32, VAL INT)</td>
</tr>
<tr>
<td>REAL64TOSTRING</td>
<td>(INT, [ ] BYTE, VAL REAL64, VAL INT)</td>
</tr>
<tr>
<td>STRINGTOBOOL</td>
<td>(BOOL, BOOL, VAL [ ] BYTE)</td>
</tr>
<tr>
<td>BOOLEANSTRING</td>
<td>(INT, [ ] BYTE, VAL BOOL)</td>
</tr>
</tbody>
</table>
The floating point functions described in this appendix provide the list of facilities suggested by the ANSI/IEEE standard 754-1985.

Each function is specified by a skeletal function declaration, a predicate stating the relationship between the actual parameters after the function call and an informal textual description of the operation. All functions are implemented in a way which allows the same variable to be used as both the input and receiving variable in an assignment. The predicate gives the formal definition of the operation, although for most purposes the text will be an adequate explanation.

*NaN* and *Inf* are the sets of all Not-a-Numbers and all infinities in the format.

### K.1 Not-a-number values

Floating point arithmetic implementations will return the following valued Not-a-Numbers to signify the various errors that can occur in evaluations.

<table>
<thead>
<tr>
<th>Error</th>
<th>Single length value</th>
<th>Double length value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Divide zero by zero</td>
<td>#7FC00000</td>
<td>#7FF80000 00000000</td>
</tr>
<tr>
<td>Divide infinity by infinity</td>
<td>#7FA00000</td>
<td>#7FF40000 00000000</td>
</tr>
<tr>
<td>Multiply zero by infinity</td>
<td>#7F900000</td>
<td>#7FF20000 00000000</td>
</tr>
<tr>
<td>Addition of opposite signed infinities</td>
<td>#7F880000</td>
<td>#7FF10000 00000000</td>
</tr>
<tr>
<td>Subtraction of same signed infinities</td>
<td>#7F880000</td>
<td>#7FF10000 00000000</td>
</tr>
<tr>
<td>Negative square root</td>
<td>#7F840000</td>
<td>#7FF08000 00000000</td>
</tr>
<tr>
<td><strong>REAL64</strong> to <strong>REAL32</strong> NaN conversion</td>
<td>#7F820000</td>
<td>#7FF04000 00000000</td>
</tr>
<tr>
<td>Remainder from infinity</td>
<td>#7F804000</td>
<td>#7FF00800 00000000</td>
</tr>
<tr>
<td>Remainder by zero</td>
<td>#7F802000</td>
<td>#7FF00400 00000000</td>
</tr>
</tbody>
</table>
K.2  Absolute

REAL32 FUNCTION ABS(VAL REAL32 X)
  . . .
REAL64 FUNCTION DABS(VAL REAL64 X)
  . . .

\[ \text{ABS}(X) = |X| \]

This returns the absolute value of \( X \). This is implemented clearing the sign bit so that \(-0.0\) becomes \(+0.0\) and even though Not-a-Numbers (NaNs) have no signed-ness the sign bit in their representation will be cleared.

K.3  Square root

REAL32 FUNCTION SQRT(VAL REAL32 X)
  . . .
REAL64 FUNCTION DSQRT(VAL REAL64 X)
  . . .

\[ \text{SQRT}(X) = \sqrt{X} . \]

This returns the square root of \( X \). Negative arguments produce a Negative square root Not-a-Number, and infinity produces an infinity.

K.4  Test for Not-a-Number

BOOL FUNCTION ISNAN(VAL REAL32 X)
  . . .
BOOL FUNCTION DISNAN(VAL REAL64 X)
  . . .

\[ \text{ISNAN}(X) = \text{TRUE} \iff X \in \text{NaN} \]

This returns \text{TRUE} if \( X \) is a Not-a-Number and \text{FALSE} otherwise.

K.5  Test for Not-a-Number or infinity

BOOL FUNCTION NOTFINITE(VAL REAL32 X)
  . . .
BOOL FUNCTION DNOTFINITE(VAL REAL64 X)
  . . .

\[ \text{NOTFINITE}(X) = \text{TRUE} \iff X \in \text{NaN} \cup \text{Inf} \]

This returns \text{TRUE} if \( X \) is a Not-a-Number or an infinity and \text{FALSE} otherwise.
K.6 Scale by power of two

REAL32 FUNCTION SCALEB(VAL REAL32 X, VAL INT n)
: . . .
REAL64 FUNCTION DSCALEB(VAL REAL64 X, VAL INT n)
: . . .

SCALEB(X, n) = X \times 2^n

This multiplies X by $2^n$. Overflow and underflow behaviour is as for normal multiplication under the ANSI/IEEE standard 754-1985. n can take any value as the operation will return the correct result even when $2^n$ cannot be represented in the format.

K.7 Return exponent

REAL32 FUNCTION LOGB(VAL REAL32 X)
: . . .
REAL64 FUNCTION DLOGB(VAL REAL64 X)
: . . .

LOGB (X) = result
    where X \notin \{Inf \cup NaN \land X \neq 0 \Rightarrow result = 0\exp X - Bias\}
            X = 0 \Rightarrow result = -inf
            X \in \{Inf \Rightarrow result = +inf\}
            X \in \{NaN \Rightarrow result = X\}

This returns the exponent of X as an integer valued floating point number; special cases for Infs, NaNs and zero. NOTE that all denormalised numbers return the same value — this is not equivalent to rounding the logarithm to an integer value. If X is a NaN then it is returned as the result, if X is an infinity then the result is plus infinity and if X is zero then the result is minus infinity.

K.8 Unpack floating point value

INT, REAL32 FUNCTION FLOATING.UNPACK(VAL REAL32 X)
: . . .
INT, REAL64 FUNCTION DFLOATING.UNPACK(VAL REAL64 X)
: . . .

FLOATING.UNPACK (X) = (n, r)
    where X = 0 \lor X \in \{Inf \cup NaN \Rightarrow r \in NaN \land n = RealExp - Bias\}
            "otherwise" X = r \times 2^n \land r \in [1, 2)

This "unpacks" X into a real (r) and an integer (n) so that r lies between 1 and 2 and that X = r $\times 2^n$. This is useful for reducing a value to the primary range for "exponential" type functions. If X is an infinity or a NaN then a NaN is returned in r and n holds MaxExp - the exponent of a NaN. If X is zero then a NaN is returned in r and MaxExp in n - this is because the methods used to evaluate a function in its primary range will not be defined for 0.0 which should have already been dealt with as a special case. The use of a NaN in these cases signals an error in the attempt to produce a "primary range" value and offset from X.
K.9 Negate

REAL32 FUNCTION MINUSX(VAL REAL32 X)
  ...;
REAL64 FUNCTION DMINUSX(VAL REAL64 X)
  ...;

\[
\text{MINUSX } (X) = \text{ result where result.sign = } \text{toggleX.sign, result.frac = } X.\text{frac, result.exp = } X.\text{exp}
\]

This returns \( X \) with the sign bit toggled. This is not the same as \((0 - X)\) as it has different behaviour on zero and NaNs. This should not be used as a unary negation where \((0 - X)\) should be used. As with ABS it does affect the representation of NaNs even though they have no sign in their interpretation.

K.10 Copy sign

REAL32 FUNCTION COPYSIGN(VAL REAL32 X, Y)
  ...
REAL64 FUNCTION DCOPYSIGN(VAL REAL64 X, Y)
  ...

\[
\text{COPYSIGN } (X, Y) = \text{ result where result.sign = } Y.\text{sign, result.frac = } X.\text{frac, result.exp = } X.\text{exp}
\]

This returns \( X \) with the sign bit from \( Y \).

K.11 Next representable value

REAL32 FUNCTION NEXTAFTER (VAL REAL32 X, Y)
  ...
REAL64 FUNCTION DNEXTAFTER (VAL REAL64 X, Y)
  ...

\[
\text{NEXTAFTER } (X, Y) = \text{ result where } \begin{cases} 
X \in NaN \lor Y \in NaN \Rightarrow \text{result } \in NaN \land \{X, Y\} \\
X = Y \Rightarrow X \\
X \neq Y \Rightarrow \text{"result is next real after } X \text{ in the direction of } Y" 
\end{cases}
\]

This can be specified precisely but as several subsidiary definitions are required first the informal third line of the "predicate" is used for brevity.

This returns the first floating point number from \( X \) in the direction of \( Y \). The major area where this will be used is in interval arithmetic. If either or both of \( X \) or \( Y \) is a NaN then a NaN equal to \( X \) or \( Y \) is returned. An overflow from a finite \( X \) to an infinite result is handled in the same way as an arithmetic overflow.
K.12 Test for orderability

BOOL FUNCTION ORDERED(VAL REAL32 X, Y)

... 

BOOL FUNCTION DORDERED(VAL REAL64 X, Y)

... 

ORDERED(X, Y) = TRUE ↔ X ≠ NaN ∧ Y ≠ NaN

This returns TRUE if X and Y are "orderable" as defined by the ANSI/IEEE standard 754-1985. This implements the negation of the unordered comparison in ANSI/IEEE 754-1985 §5.7 and enables the full IEEE style comparison to be derived from the standard <, >, ... comparisons of real types in OCCAM.

K.13 Perform range reduction

BOOL, INT32, REAL32 FUNCTION ARGUMENT.REDUCE(VAL REAL32 X, Y, Y.err)

... 

BOOL, INT32, REAL64 FUNCTION DARGUMENT.REDUCE(VAL REAL64 X, Y, Y.err)

... 

ARGUMENT.REDUCE(X, Y, error) = (b, n, r)

where \( X.exp \leq Y.exp + \text{maxexpdiff} \) \Rightarrow \begin{align*}
    b \wedge X &= n \times (Y + \text{error}) + r \\
    (r < (Y + \text{error})/2 \lor (r = (Y + \text{error})/2 \wedge n \text{MOD} 2 = 0))
\end{align*}

\( X.exp > Y.exp + \text{maxexpdiff} \) \Rightarrow \exists m : \mathbb{Z}

\begin{align*}
    b \wedge X &= m \times Y + r \\
    (r < Y/2 \lor (r = Y/2 \wedge m \text{MOD} 2 = 0)) \\
    n &= \text{undefined}
\end{align*}

where maxexpdiff is 20 for ARGUMENT.REDUCE and 30 for DARGUMENT.REDUCE. This performs a more accurate remainder \( X \text{ REM } Y \) by using an extended precision value for Y where possible. It is assumed that error is no larger than a last bit error in \( Y \). TRUE is returned as the boolean result \( b \) to indicate that the more accurate remainder has been done and the integer result \( n \) will then be the quotient. If the more accurate remainder cannot be done a normal remainder is performed and the quotient \( n \) must be calculated separately. This is designed to be used to reduce an argument to the primary range for cyclical functions - such as the trigonometric functions.

K.14 Fast multiply by two

REAL32 FUNCTION MULBY2(VAL REAL32 X)

... 

REAL64 FUNCTION DMULBY2(VAL REAL64 X)

... 

MULBY2(X) = X \times 2

This returns 2 times \( X \) with overflow handling as defined in the ANSI/IEEE standard 754-1985.
K.15 Fast divide by two

REAL32 FUNCTION DIVBY2(VAL REAL32 X)
    ...
REAL64 FUNCTION DDIVBY2(VAL REAL64 X)
    ...

DIVBY2(X) = X ÷ 2

This returns X divided by 2 with underflow handling as defined in the ANSI/IEEE standard 754-1985.

K.16 Round to floating point integer

REAL32 FUNCTION FPINT(VAL REAL32 X)
    ...
REAL64 FUNCTION DFPINT(VAL REAL64 X)
    ...

FPINT (X) = result
    where  |X| ≥ 2^{bits per word} ⇒ result = X
           |X| < 2^{bits per word} ⇒ result = REAL32 (INT ROUND X)

This returns X rounded to a floating point integer value.
The following arithmetic functions provide arithmetic shifts, word rotations and the primitives to construct multiple length integer arithmetic and multiple length shift operations.

<table>
<thead>
<tr>
<th>Function</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>LONGADD</td>
<td>signed addition with a carry in.</td>
</tr>
<tr>
<td>LONGSUM</td>
<td>unsigned addition with a carry in and a carry out.</td>
</tr>
<tr>
<td>LONGSUB</td>
<td>signed subtraction with a borrow in.</td>
</tr>
<tr>
<td>LONGDIFF</td>
<td>unsigned subtraction with a borrow in and a borrow out.</td>
</tr>
<tr>
<td>LONGPROD</td>
<td>unsigned multiplication with a carry in, producing a double length result.</td>
</tr>
<tr>
<td>LONGDIV</td>
<td>unsigned division of a double length number, producing a single length result.</td>
</tr>
<tr>
<td>SHIFTRIGHT</td>
<td>right shift on a double length quantity.</td>
</tr>
<tr>
<td>SHIFTLIGHT</td>
<td>left shift on a double length quantity.</td>
</tr>
<tr>
<td>NORMALISE</td>
<td>normalise a double length quantity.</td>
</tr>
<tr>
<td>ASHIFTRIGHT</td>
<td>arithmetic right shift on a double length quantity.</td>
</tr>
<tr>
<td>ASHIFTLIGHT</td>
<td>arithmetic left shift on a double length quantity.</td>
</tr>
<tr>
<td>ROTATERIGHT</td>
<td>rotate a word right.</td>
</tr>
<tr>
<td>ROTATELEFT</td>
<td>rotate a word left.</td>
</tr>
</tbody>
</table>

For the purpose of explanation imagine a new type INTEGER, and the associated conversion. This imaginary type is capable of representing the complete set of integers and is presumed to be represented as an infinite bit two's complement number. With this one exception the following are OCCAM descriptions of the various arithmetic functions.

```occam
-- constants used in the following description
VAL bitsperword IS machine.wordsze(INTEGER) :
VAL range IS storeable.values(INTEGER) :
    -- range = 2^bitsperword
VAL maxint IS INTEGER (MOSTPOS INT) :
    -- maxint = (range/2 - 1)
VAL minint IS INTEGER (MOSTNEG INT) :
    -- minint = -(range/2)

-- INTEGER literals
VAL one IS 1(INTEGER) :
VAL two IS 2(INTEGER) :
    -- mask
VAL wordmask IS range - one :
```

In OCCAM, values are considered to be signed. However, in these functions the concern is with other interpretations. In the construction of multiple length arithmetic the need is to interpret words as containing both signed and unsigned integers. In the following the new INTEGER type is used to manipulate these values, and other values which may require more than a single word to store.
The sign conversion of a value is defined in the functions \texttt{unsign} and \texttt{sign}. These are used in the description following but they are NOT functions themselves.

\texttt{INTEGER FUNCTION unsign (VAL INT operand)}

\begin{verbatim}
-- Returns the value of \texttt{operand} as an unsigned integer value.
-- for example, on a 32 bit word machine:
-- \texttt{unsign (1)} = 1
-- \texttt{unsign (-1)} = 2^{32} - 1

INTEGER operand.i
VALOF

IF
  operand < 0
  operand.i := (INTEGER operand) + range
  operand >= 0
  operand.i := INTEGER operand
RESULT operand.i

:
\end{verbatim}

\texttt{INT FUNCTION sign (VAL INTEGER result.i)}

\begin{verbatim}
-- Takes the \texttt{INTEGER result.i} and returns the signed type \texttt{INT}.
-- for example, on a 32 bit word machine:
-- 2^{31} - 1 becomes 2^{31} - 1
-- 2^{31} becomes -2^{31}

INT result :
VALOF

IF
  (result.i > maxint) AND (result.i < range)
  result := INT (result.i - range)
TRUE
  result := INT result.i
RESULT result

:
\end{verbatim}
L.1 The integer arithmetic functions

LONGADD performs the addition of signed quantities with a carry in. The function is invalid if arithmetic overflow occurs.

The action of the function is defined as follows:

```
INT FUNCTION LONGADD (VAL INT left, right, carry.in)

-- Adds (signed) left word to right word with least significant bit of carry.in.

INTEGER sum.i, carry.i, left.i, right.i :
VALOF
SEQ
   carry.i := INTEGER (carry.in \ 1)
   left.i := INTEGER left
   right.i := INTEGER right
   sum.i := (left.i + right.i) + carry.i
   -- overflow may occur in the following conversion
   -- resulting in an invalid process
RESULT INT sum.i
```

LONGSUM performs the addition of unsigned quantities with a carry in and a carry out. No overflow can occur.

The action of the function is defined as follows:

```
INT, INT FUNCTION LONGSUM (VAL INT left, right, carry.in)

-- Adds (unsigned) left word to right word with the least significant bit of carry.in.
-- Returns two results, the first value is one if a carry occurs, zero otherwise,
-- the second result is the sum.

INT carry.out :
INTEGER sum.i, left.i, right.i :
VALOF
SEQ
   left.i := unsigned (left)
   right.i := unsigned (right)
   sum.i := (left.i + right.i) + INTEGER (carry.in \ 1)
   IF
      -- assign carry
      sum.i >= range
      SEQ
         sum.i := sum.i - range
         carry.out := 1
   TRUE
      carry.out := 0
RESULT carry.out, sign (sum.i)
```
LONGSUB performs the subtraction of signed quantities with a borrow in. The function is invalid if arithmetic overflow occurs.

The action of the function is defined as follows:

```
INT FUNCTION LONGSUB (VAL INT left, right, borrow.in)

-- Subtracts (signed) right word from left word and subtracts borrow.in from the result.

INTEGER diff.i, borrow.i, left.i, right.i :
VALOF
SEQ
  borrow.i := INTEGER (borrow.in \ 1)
  left.i := INTEGER left
  right.i := INTEGER right
  diff.i := (left.i - right.i) - borrow.i
-- overflow may occur in the following conversion
-- resulting in an invalid process
RESULT INT diff.i
```

LONGDIFF performs the subtraction of unsigned quantities with borrow in and borrow out. No overflow can occur.

The action of the function is defined as follows:

```
INT, INT FUNCTION LONGDIFF (VAL INT left, right, borrow.in)

-- Subtracts (unsigned) right word from left word and subtracts borrow.in from the result.
-- Returns two results, the first is one if a borrow occurs, zero otherwise,
-- the second result is the difference.

INTEGER diff.i, left.i, right.i :
VALOF
SEQ
  left.i := unsign (left)
  right.i := unsign (right)
  diff.i := (left.i - right.i) - INTEGER (borrow.in \ 1)
  IF -- assign borrow
    diff.i < 0
    SEQ
      diff.i := diff.i + range
      borrow.out := 1
    TRUE
    borrow.out := 0
  RESULT borrow.out, sign (diff.i)
```
LONGPROD performs the multiplication of two unsigned quantities, adding in an unsigned carry word. Produces a double length unsigned result. No overflow can occur.

The action of the function is defined as follows:

\[
\text{INT, INT FUNCTION LONGPROD (VAL INT left, right, carry.in)}
\]

-- Multiplies (unsigned) left word by right word and adds carry.in.
-- Returns the result as two integers most significant word first.

\[
\text{INTEGER prod.i, prod.lo.i, prod.hi.i, left.i, right.i, carry.i : VALOF}
\]

SEQ

\[
\begin{align*}
\text{carry.i} & := \text{unsigned (carry.in)} \\
\text{left.i} & := \text{unsigned (left)} \\
\text{right.i} & := \text{unsigned (right)} \\
\text{prod.i} & := (\text{left.i} * \text{right.i}) + \text{carry.i} \\
\text{prod.lo.i} & := \text{prod.i REM range} \\
\text{prod.hi.i} & := \text{prod.i / range} \\
\text{RESULT} & \text{ sign (prod.hi.i), sign (prod.lo.i)}
\end{align*}
\]

LONGDIV divides an unsigned double length number by an unsigned single length number. The function produces an unsigned single length quotient and an unsigned single length remainder. An overflow will occur if the quotient is not representable as an unsigned single length number. The function becomes invalid if the divisor is equal to zero.

The action of the function is defined as follows:

\[
\text{INT, INT FUNCTION LONGDIV (VAL INT dividend.hi, dividend.lo, divisor)}
\]

-- Divides (unsigned) dividend.hi and dividend.lo by divisor.
-- Returns two results the first is the quotient and the second is the remainder.

\[
\text{INTEGER divisor.i, dividend.i, hi, lo, quot.i, rem.i : VALOF}
\]

SEQ

\[
\begin{align*}
\text{hi} & := \text{unsigned (dividend.hi)} \\
\text{lo} & := \text{unsigned (dividend.lo)} \\
\text{divisor.i} & := \text{unsigned (divisor)} \\
\text{dividend.i} & := (\text{hi} * \text{range}) + \text{lo} \\
\text{quot.i} & := \text{dividend.i / divisor.i} \\
\text{rem.i} & := \text{dividend.i REM divisor.i} \\
\text{RESULT} & \text{ sign (quot.i), sign (rem.i)}
\end{align*}
\]

\]
**SHIFTRIGHT** performs a right shift on a double length quantity. The function must be called with the number of places in range, otherwise the implementation can produce unexpected effects.

i.e. \( 0 \leq \text{places} \leq 2 \cdot \text{bitsperword} \)

The action of the function is defined as follows:

\[
\text{INT}, \text{INT FUNCTION SHIFTRIGHT (VAL INT hi.in, lo.in, places)}
\]

-- Shifts the value in hi.in and lo.in right by the given number of places.
-- Bits shifted in are set to zero.
-- Returns the result as two integers most significant word first.

\[
\text{INT hi.out, lo.out : VALOF}
\]

\[
\text{IF (places < 0) OR (places > (two*bitsperword))}
\]

\[
\text{SEQ}
\]

\[
\begin{align*}
\text{hi.out} & : = 0 \\
\text{lo.out} & : = 0
\end{align*}
\]

\[
\text{TRUE}
\]

\[
\text{INTEGER operand, result, hi, lo :}
\]

\[
\text{SEQ}
\]

\[
\begin{align*}
\text{hi} & : = \text{unsigh} (\text{hi.in}) \\
\text{lo} & : = \text{unsigh} (\text{lo.in}) \\
\text{operand} & : = (\text{hi} << \text{bitsperword}) + \text{lo} \\
\text{result} & : = \text{operand} >> \text{places} \\
\text{lo} & : = \text{result} /\backslash \text{wordmask} \\
\text{hi} & : = \text{result} >> \text{bitsperword} \\
\text{hi.out} & : = \text{sign} (\text{hi}) \\
\text{lo.out} & : = \text{sign} (\text{lo})
\end{align*}
\]

\[
\text{RESULT hi.out, lo.out}
\]
SHIFTLEFT performs a left shift on a double length quantity. The function must be called with the number of places in range, otherwise the implementation can produce unexpected effects.

i.e. \( 0 \leq \text{places} \leq 2 \times \text{bitsperword} \)

The action of the function is defined as follows:

```
INT, INT FUNCTION SHIFTLEFT (VAL INT hi.in, lo.in, places)

-- Shifts the value in hi.in and lo.in left by the given number of places.
-- Bits shifted in are set to zero.
-- Returns the result as two integers most significant word first.

VALOF

IF
    (places < 0) OR (places > (two*bitsperword))
    SEQ
        hi.out := 0
        lo.out := 0
    TRUE
    INTEGER operand, result, hi, lo :
    SEQ
        hi := unsign (hi.in)
        lo := unsign (lo.in)
        operand := (hi << bitsperword) + lo
        result := operand << places
        lo := result \ wordmask
        hi := result >> bitsperword
        hi.out := sign (hi)
        lo.out := sign (lo)
RESULT hi.out, lo.out
```

NORMALISE normalises a double length quantity. No overflow can occur.

The action of the function is defined as follows:

\[ \text{INT, INT, INT FUNCTION NORMALISE (VAL INT hi.in, lo.in)} \]

-- Shifts the value in hi.in and lo.in left until the highest bit is set.
-- The function returns three integer results
-- The first returns the number of places shifted.
-- The second and third return the result as two integers with the most significant word first;
-- If the input value was zero, the first result is \(2 \times \text{bitsperword}\).

\[
\begin{align*}
\text{INT places, hi.out, lo.out} : \\
\text{VALOF} \\
\text{IF} \\
(hi.in = 0) \text{ AND } (lo.in = 0) \\
\text{places} := \text{INT} (2 \times \text{bitsperword}) \\
\text{TRUE} \\
\text{VAL msb IS one} \ll ((2 \times \text{bitsperword}) - \text{one}) : \\
\text{INTEGER operand, hi, lo} : \\
\text{SEQ} \\
\text{lo} := \text{unsign(lo.in)} \\
\text{hi} := \text{unsign(hi.in)} \\
\text{operand} := (\text{hi} \ll \text{bitsperword}) + \text{lo} \\
\text{places} := 0 \\
\text{WHILE } (\text{operand} \mathbin{|}/ msb) = 0 \\
\text{SEQ} \\
\text{operand} := \text{operand} \ll \text{one} \\
\text{places} := \text{places} + 1 \\
\text{hi} := \text{operand} / \text{range} \\
\text{lo} := \text{operand REM range} \\
\text{hi.out} := \text{sign(hi)} \\
\text{lo.out} := \text{sign(lo)} \\
\text{RESULT places, hi.out, lo.out} \\
\end{align*}
\]
L.2   Arithmetic shifts

**ASHIFTRIGHT** performs an arithmetic right shift, shifting in and maintaining the sign bit. The function must be called with the number of places in range, otherwise the implementation can produce unexpected effects.

i.e. $0 \leq \text{places} \leq \text{bitsperword}$

No overflow can occur.

**N.B** the result of this function is NOT the same as division by a power of two.

i.e. $-1/2 = 0$

**ASHIFTRIGHT** $(-1, 1) = -1$

The action of the function is defined as follows:

```
-- Shifts the value in operand right by the given number of places.
-- The status of the high bit is maintained

INT FUNCTION ASHIFTRIGHT (VAL INT operand, places) IS
  INT( INTEGER(operand) >> places ) :
```

**ASHIPTLEFT** performs an arithmetic left shift. The function is invalid if significant bits are shifted out, signalling an overflow. The function must be called with the number of places in range, otherwise the implementation can produce unexpected effects.

i.e. $0 \leq \text{places} \leq \text{bitsperword}$

**N.B** the result of this function is the same as multiplication by a power of two.

The action of the function is defined as follows:

```
INT FUNCTION ASHIPTLEFT (VAL INT argument, places)

  -- Shifts the value in argument left by the given number of places.
  -- Bits shifted in are set to zero.

INTEGER result.i :
VALUE
  result.i := INTEGER(argument) << places
  -- overflow may occur in the following conversion
  -- resulting in an invalid process
RESULT INT result.i
```

L.3 Word rotation

ROTATERIGHT rotates a word right. Bits shifted out of the word on the right, re-enter the word on the left. The function must be called with the number of places in range, otherwise the implementation can produce unexpected effects.

i.e. \(0 \leq \text{places} \leq \text{bitsperword}\)

No overflow can occur.

The action of the function is defined as follows:

\[
\text{INT FUNCTION ROTATERIGHT (VAL INT argument, places)}
\]

\[
\text{-- Rotates the value in} \ \text{argument} \ \text{by the given number of} \ \text{places}.
\]

\[
\text{INTEGER high, low, argument.i : VALOF}
\]

\[
\text{SEQ}
\]

\[
\begin{align*}
\text{argument.i} & \ := \ \text{unsign(argument)} \\
\text{argument.i} & \ := \ (\text{argument.i} \ \times \ \text{range}) \ \gg \ \text{places} \\
\text{high} & \ := \ \text{argument.i} \ \div \ \text{range} \\
\text{low} & \ := \ \text{argument.i} \ \text{REM} \ \text{range}
\end{align*}
\]

RESULT INT(high \ \text{/} \ low)

:

ROTATELEFT rotates a word left. Bits shifted out of the word on the left, re-enter the word on the right. The function must be called with the number of places in range, otherwise the implementation can produce unexpected effects.

i.e. \(0 \leq \text{places} \leq \text{bitsperword}\)

The action of the function is defined as follows:

\[
\text{INT FUNCTION ROTATELEFT (VAL INT argument, places)}
\]

\[
\text{-- Rotates the value in} \ \text{argument} \ \text{by the given number of} \ \text{places}.
\]

\[
\text{INTEGER high, low, argument.i : VALOF}
\]

\[
\text{SEQ}
\]

\[
\begin{align*}
\text{argument.i} & \ := \ \text{unsign(argument)} \\
\text{argument.i} & \ := \ \text{argument.i} \ \ll \ \text{places} \\
\text{high} & \ := \ \text{argument.i} \ \div \ \text{range} \\
\text{low} & \ := \ \text{argument.i} \ \text{REM} \ \text{range}
\end{align*}
\]

RESULT INT(high \ \text{/} \ low)

:
IEEE floating point arithmetic

REALOP and REALREM are implementations of the ANSI/IEEE 754-1985 floating point arithmetic standard. An implementation should comply to the requirements of the standard in as much as all results returned by them should be correct as defined in the standard. Most programmers will not need to use these functions directly as most occam implementations will compile all real arithmetic as calls to these functions. In some applications, such as interval arithmetic, the rounding modes are needed so the functions will need to be explicitly called in those cases. Also, in some applications, the IEEE standards use of infinities and Not-a-number to handle errors and overflows may be required in preference to the standard occam treatment of them as invalid expressions.

The functions for REAL32 operands are

REAL32 FUNCTION REAL32OP (VAL REAL32 X, VAL INT Op, VAL REAL32 Y)

... :

REAL32 FUNCTION REAL32REM (VAL REAL32 X, VAL REAL32 Y)

...

REAL32OP (X, Op, Y) evaluates $X \text{ Op } Y$ according to the standard without error checking, using the conventional rounding mode. The various operations are coded in Op where:

$\text{op} = 0 +$
$\text{= 1 -}$
$\text{= 2 } \times$
$\text{= 3 } /$

REAL32REM (X, Y) evaluates $X \text{ REM } Y$ according to the standard without error checking.

REAL64OP and REAL64REM are defined in an similar manner to operate on REAL64s.

IEEEExxOP (X, Rm, Op, Y) evaluates $X \text{ Op } Y$ according to the standard. The rounding mode to be used is indicated by Rm where:

round\_mode = 0 Round to Zero
round\_mode = 1 Round to Nearest
round\_mode = 2 Round to Plus Infinity
round\_mode = 3 Round to Minus Infinity

IEEEExxREM (X, Y) evaluates $X \text{ REM } Y$ according to the standard. The functions are:

BOOL, REAL32 FUNCTION IEEE32OP (VAL REAL32 X, VAL INT Rm, Op, VAL REAL32 Y)

...

BOOL, REAL32 FUNCTION IEEE32REM (VAL REAL32 X, VAL REAL32 Y)

...

These functions return two results, a boolean which is true if an error has occurred, and false otherwise. Where an error has occurred the function will also return the appropriate NaN, otherwise the function returns the result.

IEEE64OP and IEEE64REM are defined in a similar manner to operate on REAL64s.
M.1 ANSI/IEEE real comparison

The comparisons on the real types provided in the OCCAM language should suffice for most purposes. However, if the comparisons detailed in the ANSI/IEEE 754-1985 standard are required then they can be generated from the set of primitive comparisons.

```fortran
BOOL FUNCTION REAL32EQ (VAL REAL32 X, Y)
   -- result = (X = Y) in the IEEE sense
   ...

BOOL FUNCTION REAL32GT (VAL REAL32 X, Y)
   -- result = (X > Y) in the IEEE sense
   ...
```

A standard function `IEEECOMPARE` will return a value which indicates which of the relations *less than*, *greater than*, *equals* or *unordered* as defined by IEEE 754 paragraph 5.7. This procedure is

```fortran
INT FUNCTION IEEECOMPARE (VAL REAL32 X, Y)
   INT result :
   VALOF
   IF
      ORDERED (X, Y)
      IF
         REAL32EQ (X, Y)
         result := 0
         REAL32GT (X, Y)
         result := 1
         TRUE
         result := -1
      TRUE
      result := 2
   RESULT result :
```

Then, if really necessary, any of the 26 varieties of comparison suggested by the IEEE standard can be derived. For instance the \( \geq \) predicate could be implemented by

```fortran
BOOL, BOOL FUNCTION IEEE.UGE. (VAL REAL32 X,Y)
   VAL LT IS -1, EQ IS 0, GT IS 1, UN IS 2:
   INT relation:
   VALOF
      relation := IEEECOMPARE (X, Y)
      RESULT FALSE,
         (relation=GT) OR ((relation=EQ) OR (relation=UN))
```

Similarly \( \not=\) could be implemented as

```fortran
BOOL, BOOL FUNCTION IEEENOT.LG. (VAL REAL32 X,Y)
   VAL LT IS -1, EQ IS 0, GT IS 1, UN IS 2:
   INT relation:
   VALOF
      relation := IEEECOMPARE (X, Y)
      RESULT (relation=UN), (relation=EQ) OR (relation=UN)
```

In either of these cases the value returned in the first boolean is equivalent to the invalid operation flag being set according to the ANSI/IEEE standard 754-1985.

The double length version `DIEEECOMPARE` is defined in a similar manner to `IEEECOMPARE`. 
The elementary function library provides a set of routines which provide elementary functions compatible with the ANSI/IEEE standard 754-1985 for binary floating-point arithmetic.

All single length functions other than POWER, ATAN2 and RAN have one parameter which is a VAL REAL32 taking the argument of the function. POWER and ATAN2 have two parameters. They are both VAL REAL32s which receive the arguments of the function. RAN has a single parameter which is a VAL INT32. In each case the double-length version is obtained by prefixing a D onto the function name, whose parameters are VAL REAL64 or, in the case of DRAN, VAL INT64.

Accompanying the description of each function is the specification of the function's Domain and Range. The Domain specifies the range of valid inputs, i.e. those for which the output is a normal or denormal floating-point number. The Range specifies the range of outputs produced by all arguments in the Domain. The given endpoints are not exceeded. Note that some of the domains specified are implementation dependent.

Ranges are given as intervals, using the convention that a square bracket \{ or \} means that the adjacent endpoint is included in the range, whilst a round bracket \{ or \} means that it is excluded. Endpoints are given to a few significant figures only. Where the range depends on the floating-point format, single-length is indicated with an S and double-length with a D.

For functions with two arguments the complete range of both arguments is given. This means that for each number in one range, there is at least one (though sometimes only one) number in the other range such that the pair of arguments is valid. Both ranges are shown, linked by an 'x'.

In the specifications, \(X\) is used generically to designate the argument, and "result" to designate the output.

The routines will accept any value, as specified by the IEEE standard, including special values representing NaNs ('Not a Number') and Infs ('Infinity'). NaNs are copied directly to the result, whilst Infs may or may not be valid arguments. Valid arguments are those for which the result is a normal (or denormalised) floating-point number.

Arguments outside the domain (apart from NaNs which are simply copied to the result) give rise to exceptional results, which may be NaN, +inf, or -inf. Infs mean that the result is mathematically well-defined but too large to be represented in the floating-point format.

Error conditions are reported by means of three distinct NaNs:

<table>
<thead>
<tr>
<th>Error</th>
<th>Single length value</th>
<th>Double length value</th>
</tr>
</thead>
<tbody>
<tr>
<td>undefined.NaN</td>
<td>#7F800010</td>
<td>#7FF00002 00000000</td>
</tr>
<tr>
<td>unstable.NaN</td>
<td>#7F800008</td>
<td>#7FF00001 00000000</td>
</tr>
<tr>
<td>inexact.NaN</td>
<td>#7F800004</td>
<td>#7FF00000 80000000</td>
</tr>
</tbody>
</table>

In all cases, the function returns a NaN if given a NaN.
N.1 Logarithm

REAL32 FUNCTION ALOG (VAL REAL32 X)
    
REAL64 FUNCTION DALOG (VAL REAL64 X)

These compute: result = loge(X).

Domain: (0, XMAX]
Range: [MinLog, MaxLog) = [-103.28, 88.72] = [-745.2, 709.78]D

All arguments outside the domain generate an undefined. NaN.

N.2 Base 10 logarithm

REAL32 FUNCTION ALOG10 (VAL REAL32 X)
    
REAL64 FUNCTION DALOG10 (VAL REAL64 X)

These compute: result = log10(X)

Domain: (0, XMAX]
Range: [MinLog10, MaxLog10) = [-44.85, 38.53] = [-323.6, 308.25]D

All arguments outside the domain generate an undefined. NaN.

N.3 Exponential

REAL32 FUNCTION EXP (VAL REAL32 X)
    
REAL64 FUNCTION DEXP (VAL REAL64 X)

These compute: result = e^X.

Domain: [-Inf, MaxLog) = [-Inf, 88.72] = [-Inf, 709.78]D
Range: [0, XMAX]

If the result is too large to be represented in the floating-point format, Inf is returned.

N.4 X to the power of Y

REAL32 FUNCTION POWER (VAL REAL32 X, Y)
    
REAL64 FUNCTION DPOWER (VAL REAL64 X, Y)


These compute: \( \text{result} = X^Y \).

**Domain:** \([0, \text{Inf}] \times [-\text{Inf}, \text{Inf}]\)  
**Range:** \([-\text{Inf}, \text{Inf}]\)

If the result is too large to be represented in the floating-point format, \(\text{Inf}\) is returned. If \(X\) or \(Y\) is \(\text{NaN}\), \(\text{NaN}\) is returned. Other special cases are as follows:

<table>
<thead>
<tr>
<th>First Input ((X))</th>
<th>Second Input ((Y))</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>(X &lt; 0)</td>
<td>any</td>
<td>undefined.(\text{NaN})</td>
</tr>
<tr>
<td>0</td>
<td>(\leq 0)</td>
<td>undefined.(\text{NaN})</td>
</tr>
<tr>
<td>0</td>
<td>(0 &lt; Y \leq \text{XMAX})</td>
<td>0</td>
</tr>
<tr>
<td>(0 &lt; X &lt; 1)</td>
<td>(\text{Inf})</td>
<td>unstable.(\text{NaN})</td>
</tr>
<tr>
<td>(0 &lt; X &lt; 1)</td>
<td>(-\text{Inf})</td>
<td>Inf</td>
</tr>
<tr>
<td>1</td>
<td>(-\text{XMAX} \leq Y \leq \text{XMAX})</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>(\pm \text{Inf})</td>
<td>Inf</td>
</tr>
<tr>
<td>(1 &lt; X \leq \text{XMAX})</td>
<td>(\text{Inf})</td>
<td>undefined.(\text{NaN})</td>
</tr>
<tr>
<td>(1 &lt; X \leq \text{XMAX})</td>
<td>(-\text{Inf})</td>
<td>Inf</td>
</tr>
<tr>
<td>(\text{Inf})</td>
<td>(1 \leq Y \leq \text{Inf})</td>
<td>Inf</td>
</tr>
<tr>
<td>(\text{Inf})</td>
<td>(-\text{Inf} &lt; Y \leq -1)</td>
<td>Inf</td>
</tr>
<tr>
<td>(\text{Inf})</td>
<td>(-1 &lt; Y &lt; 1)</td>
<td>undefined.(\text{NaN})</td>
</tr>
<tr>
<td>otherwise</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>otherwise</td>
<td>1</td>
<td>(X)</td>
</tr>
</tbody>
</table>

**N.5 Sine**

\[\begin{align*}
\text{REAL32 FUNCTION SIN (VAL REAL32 X)}
\end{align*}\]

\[\begin{align*}
\text{REAL64 FUNCTION DSIN (VAL REAL64 X)}
\end{align*}\]

These compute: \(\text{result} = \sin(X)\) (where \(X\) is in radians).

**Domain:** \([-\text{Smax}, \text{Smax}] = [-12868.0, 12868.0]D, = [-2.1 \times 10^8, 2.1 \times 10^8]D\)

**Range:** \([-1.0, 1.0]\)

All arguments outside the domain generate an \(\text{inexact.\text{NaN}}\). Implementations may provide a larger domain.

**N.6 Cosine**

\[\begin{align*}
\text{REAL32 FUNCTION COS (VAL REAL32 X)}
\end{align*}\]

\[\begin{align*}
\text{REAL64 FUNCTION DCOS (VAL REAL64 X)}
\end{align*}\]

These compute: \(\text{result} = \cos(X)\) (where \(X\) is in radians).

**Domain:** \([-\text{Smax}, \text{Smax}] = [-12868.0, 12868.0]D, = [-2.1 \times 10^8, 2.1 \times 10^8]D\)

**Range:** \([-1.0, 1.0]\)
All arguments outside the domain generate an inexact.NaN. Implementations may provide a larger domain.

N.7  Tangent

\[
\text{REAL32 FUNCTION TAN (VAL REAL32 X)} \\
\text{REAL64 FUNCTION DTAN (VAL REAL64 X)}
\]

These compute: result = tan(X) (where X is in radians).

Domain: \([-\text{Tmax}, \text{Tmax}]=[-6434.0, 6434.0]\), \([-1.05 \times 10^8, 1.05 \times 10^8]\)
Range: \((-\text{Inf}, \text{Inf})\)

All arguments outside the domain generate an inexact.NaN. Implementations may provide a larger domain.

N.8  Arcsine

\[
\text{REAL32 FUNCTION ASIN (VAL REAL32 X)} \\
\text{REAL64 FUNCTION DASIN (VAL REAL64 X)}
\]

These compute: result = \(\sin^{-1}(X)\) (in radians).

Domain: \([-1.0, 1.0]\)
Range: \([-\pi/2, \pi/2]\)

All arguments outside the domain generate an undefined.NaN.

N.9  Arccosine

\[
\text{REAL32 FUNCTION ACOS (VAL REAL32 X)} \\
\text{REAL64 FUNCTION DACOS (VAL REAL64 X)}
\]

These compute: result = \(\cos^{-1}(X)\) (in radians).

Domain: \([-1.0, 1.0]\)
Range: \([0, \pi]\)

All arguments outside the domain generate an undefined.NaN.
N.10 Arctangent

\texttt{REAL32 FUNCTION ATAN (VAL REAL32 X)}
\hspace{1cm} \ldots

\texttt{REAL64 FUNCTION DATAN (VAL REAL64 X)}
\hspace{1cm} \ldots

These compute: \( \text{result} = \tan^{-1}(X) \) (in radians).

\textbf{Domain}: \([-\text{Inf}, \text{Inf}]

\textbf{Range}: \([-\pi/2, \pi/2] \)

N.11 Polar Angle

\texttt{REAL32 FUNCTION ATAN2 (VAL REAL32 X, Y)}
\hspace{1cm} \ldots

\texttt{REAL64 FUNCTION DATAN2 (VAL REAL64 X, Y)}
\hspace{1cm} \ldots

These compute the angular co-ordinate \( \tan^{-1}(Y/X) \) (in radians) of a point whose X and Y co-ordinates are given.

\textbf{Domain}: \([-\text{Inf}, \text{Inf}] \times [-\text{Inf}, \text{Inf}]\)

\textbf{Range}: \((-\pi, \pi] \times (0, 0) \) and \((\pm\text{Inf}, \pm\text{Inf})\) give \textit{undefined.NaN}.

N.12 Hyperbolic sine

\texttt{REAL32 FUNCTION SINH (VAL REAL32 X)}
\hspace{1cm} \ldots

\texttt{REAL64 FUNCTION DSINH (VAL REAL64 X)}
\hspace{1cm} \ldots

These compute: \( \text{result} = \sinh(X) \).

\textbf{Domain}: \([-\text{Hmax}, \text{Hmax}] = [-89.4, 89.4] \)

\textbf{Range}: \((-\text{Inf}, \text{Inf}) \)

\( X < -\text{Hmax} \) gives \(-\text{Inf} \), and \( X > \text{Hmax} \) gives \( \text{Inf} \).

N.13 Hyperbolic cosine

\texttt{REAL32 FUNCTION COSH (VAL REAL32 X)}
\hspace{1cm} \ldots

\texttt{REAL64 FUNCTION DCOSH (VAL REAL64 X)}
\hspace{1cm} \ldots

These compute: \( \text{result} = \cosh(X) \).
Elementary function library

Domain : \([-H_{\text{max}}, H_{\text{max}}] = [-89.4, 89.4], [-710.5, 710.5]D\)
Range : \([1.0, \infty)\)

\(|X| > H_{\text{max}}\) gives \(\infty\).

N.14 Hyperbolic tangent

\[
\text{REAL32 FUNCTION TANH (VAL REAL32 X)}
\]
\[
\text{REAL64 FUNCTION DTANH (VAL REAL64 X)}
\]

These compute: \(\text{result} = \tanh(X)\).

Domain : \([-\infty, \infty]\)
Range : \([-1.0, 1.0]\)

N.15 Pseudo-random numbers

\[
\text{REAL32, INT32 FUNCTION RAN (VAL INT32 N)}
\]
\[
\text{REAL64, INT64 FUNCTION DRAN (VAL INT64 N)}
\]

This function returns two results, the first is a real between 0.0 and 1.0, and the second is an integer. The integer, which must be used as the parameter in the next call to the function, carries a pseudo-random linear congruental sequence \(N_k\), and must be kept in scope for as long as the function is used. It should be initialised before the first call to the function but not modified thereafter except by the function itself. Consider the following sequence:

\[
\text{SEQ}
\]
\[
x, \text{seed} := \text{RAN}(8) \quad -- \text{initialise seed}
\]
\[
y, \text{seed} := \text{RAN}(\text{seed})
\]
\[
z, \text{seed} := \text{RAN}(\text{seed})
\]

In this example \(x, y, \) and \(z\) are each assigned a psuedo-random value.

Domain : Integers
Range : \([0.0, 1.0) \times \text{Integers} \)
This appendix describes the standard library of string to value, value to string routines. The library provides primitive procedures to convert a value to and from decimal or hexadecimal representations. High input/output routines can be easily built using these simple procedures, and a number will typically be provided in an implementation.

### 0.1 Integer, string conversions

The procedures described here provide conversion between integer values and their decimal or hexadecimal representations held as a string of characters, for example:

```c
PROC INTTOSTRING (INT len, []BYTE string, VAL INT n)
    ...

The procedure INTTOSTRING returns the decimal representation of n in string and the number of characters in the representation in len.

PROC STRINGTOINT (BOOL error, INT n, VAL []BYTE string)
    ...

The procedure STRINGTOINT returns in n the value represented by string. error is set to TRUE if a non numeric character is found in string. + or a – are allowed in the first character position. n will be the value of the portion of string up to any illegal character with the convention that the value of an empty string is 0. error is also set if the value of string overflows the range of INT, in this case n will contain the low order bits of the binary representation of string. error is set to FALSE in all other cases.

PROC HEXTOSTRING (INT len, []BYTE string, VAL INT n)
    ...

The procedure HEXTOSTRING returns the hexadecimal representation of n in string and the number of characters in the representation in len. All the nibbles (a nibble is a word 4 bits wide) of n are output so that leading zeros are included. The number of characters will be the number of bits in an INT divided by 4.

PROC STRINGTOHEX (BOOL error, INT n, VAL []BYTE string)
    ...

The procedure STRINGTOHEX returns in n the value represented by the hexadecimal string. error is set to TRUE if a non hexadecimal character is found in string. Here n will be the value of the the portion of string up to the illegal character with the convention that the value of an empty string is 0. error is also set to TRUE if the value represented by string overflows the range of INT. In this case n will contain the low order bits of the binary representation of string. In all other cases error is set to FALSE.

Similar procedures are provided for the types INT16, INT32 and INT64. These procedures use equivalent parameters of the appropriate type. The procedures are:

```
<table>
<thead>
<tr>
<th>INTTOSTRING</th>
<th>INT16TOSTRING</th>
<th>INT32TOSTRING</th>
<th>INT64TOSTRING</th>
</tr>
</thead>
<tbody>
<tr>
<td>STRINGTOINT</td>
<td>STRINGTOINT16</td>
<td>STRINGTOINT32</td>
<td>STRINGTOINT64</td>
</tr>
<tr>
<td>HEXTOSTRING</td>
<td>HEX16TOSTRING</td>
<td>HEX32TOSTRING</td>
<td>HEX64TOSTRING</td>
</tr>
<tr>
<td>STRINGTOHEX</td>
<td>STRINGTOHEX16</td>
<td>STRINGTOHEX32</td>
<td>STRINGTOHEX64</td>
</tr>
</tbody>
</table>
```
O.2 Boolean, string conversion

The procedures described here provide conversion between boolean values and their textual representation "TRUE" and "FALSE".

PROC BOOLTOSTRING (INT len, []BYTE string, VAL BOOL b)
  ...

The procedure BOOLTOSTRING returns "TRUE" in string if b is TRUE and "FALSE" otherwise. len contains the number of characters in the string returned.

PROC STRINGTOBOOL (BOOL error, b, VAL []BYTE string)
  ...

The procedure STRINGTOBOOL returns TRUE in b if first 4 characters of string are "TRUE", FALSE if first 5 characters are "FALSE" and b is undefined in other cases. TRUE is returned in error if string is not exactly "TRUE" or "FALSE".

O.3 Real, string conversion

The procedures described here provide conversion between real values and their representation as strings, for example:

PROC STRINGTOREAL32 (BOOL error, REAL32 r, VAL []BYTE string)
  ...
PROC STRINGTOREAL64 (BOOL error, REAL64 r, VAL []BYTE string)
  ...

These two procedures each take a string containing a decimal representation of a real number and convert it into the corresponding real value. If the value represented by string overflows the range of the type then an appropriately signed infinity is returned. Errors in the syntax of string are signalled by a Not-a-Number being returned and error being set to TRUE. The string is scanned from the left as far as possible while the syntax is still valid. If there any characters after the end of the longest correct string then error is set to TRUE, otherwise it is FALSE. For example if string was "12.34E+2+1.0" then the value returned would be $12.34 \times 10^2$ with error set to TRUE. Strings which represent real values are those specified by the syntax for real literals, for example:

12.34
587.0E-20
+1.0E+123
-3.05

Further examples are given in the section on literals on page 25.

PROC REAL32TOSTRING (INT len, []BYTE string, VAL REAL32 r, VAL INT m,n)
  ...
PROC REAL64TOSTRING (INT len, []BYTE string, VAL REAL64 r, VAL INT m,n)
  ...

These two procedures return a string representing the value r in the first len BYTES of string. The format of the representation is determined by m and n. Free format is selected by passing 0 in m and n into the procedure. Where possible a fixed point representation is used when this does not indicate more
accuracy than is available and does not have more than 3 "0"s after the decimal point before significant digits. Otherwise exponential form is used. The number of characters returned in string here depends on the input but will be no more than 15 in REALTOSTRING32 and 24 in REALTOSTRING64. string is left justified in free format.

If \( m \) is non-zero then if possible the procedure returns a fixed point representation of \( x \) with \( m \) digits before the decimal point and \( n \) places after with padding spaces being added when needed. If this is not possible then an exponential representation is returned with the same field width as the fixed point representation would have had. If \( m \) and \( n \) are both very small then an exponential representation may not fit in the field width so two special values "Un" and "Ov" with a sign are returned to indicate a value under or over the representable fixed point values. In all these cases string is padded with spaces so that it contains \( (m+n+2) \) characters - \( m \) before the decimal point, \( n \) after, as well as the sign and decimal point characters.

If \( m \) is zero but \( n \) is not then an exponential representation is returned where the number of digits of fraction returned is \( n \). The form of the fraction is digit.digits except when \( n \) is 1. In this case the output is not a proper representation as the fraction will be of the form 'digit' where the padding space is added due to the absence of a decimal point. For this reason the case \( m = 0, n = 1 \) should not be used in general. When \( m \) is 0 string will contain \( (n + 6) \) characters for REALTOSTRING32 and \( (n + 7) \) for REALTOSTRING64.

Each procedure returns a string "Inf" preceded by a sign character for infinities and a string "NaN" for Not-a-Numbers. In free format a leading space on either string is dropped. Both these will be padded on the right with spaces to fill the field width when free format output is not being used.
Abbreviation An abbreviation specifies a name as an alias for an existing element or for the value of an expression. The meaning of the alias is defined by substitution of the abbreviated element or expression.

Actual parameter A parameter used in an instance of a procedure.

Alias A name specified by an abbreviation.

Alias check Ensure all elements are identified by a single name within a given scope.

Allocation Place a variable, channel, timer, array or port at an absolute location in memory.

Alternation Combines a number of processes guarded by inputs, and performs the process associated with an input which is ready.

Alternative A component of an alternation.

Argument A parameter used in an instance of a function.

Array A number of components of the same type.

Assignment Evaluates an expression or list of expressions, and assigns each result to a corresponding variable.

Bitwise operation Operation on the individual bits in the representation of a value.

Boolean operation Logical evaluation of truth values.

Case input Selects the protocol of an input on a single channel with variant protocol.

Channel Unbuffered, uni-directional point-to-point connection for communication between two processes executing in parallel.

Channel protocol The format of communication on a channel. Communication is valid only if the output and input are compatible; i.e. each communication is of the type specified by the channel protocol.

Choice A component of a conditional.

Communication The communication of values between concurrent processes.

Concurrency Processes acting and existing together.

Conditional A construction (IF) which combines a number of processes each of which is guarded by a boolean.

Configuration Configuration associates the components of an OCCAM program with a set of physical resources.

Construction A construction combines processes. OCCAM programs are built from processes, by combining primitive processes and other constructions to form constructions of sequence (SEQ), conditional (IF), selection (CASE), loop (WHILE), parallel (PAR) or alternation (ALT).

Deadlock A state in which two or more concurrent processes can no longer proceed due to a communication interdependency.

Declaration Specifies the name, type and scope of a variable, channel, timer or array.

Delayed input A special timer input which will wait until the timer has incremented beyond a specified time before terminating. Useful for adding a simple delay in a process.

Element A syntactic structure (a name, subscripted name or segment) which selects variables, channels, timers or arrays.

Expression list A list of expressions separated by commas; used in multiple assignment and functions.

Formal parameter Parameter specified in the definition of a procedure or function. A formal parameter acts as an abbreviation for the actual parameter used in an instance of a procedure.

Free channel A abbreviation for the actual parameter used in an instance of a procedure.

Free name A variable whose name is free name.
Free variable A variable whose name is a free name.

Function definition Specifies a name for a value process or expression list.

Guard Determines the execution of an associated process in a choice (boolean guard) or alternative (input guard).

Indentation An offset from the left hand edge of the page. In OCCAM indentation is critical, and serves to define the structure of processes.

Input Receive a value from a channel and assign the value to a variable.

Input guard An input which guards an alternative in an alternation.

Instance The occurrence of a procedure or application of a function.

Invalid process A process whose behaviour has for some reason become undefined, and as a result may lead to the failure of a system. Most invalid processes will be found by the compiler, and may be corrected during program development. The behaviour of an invalid process not detected by the compiler may be set to behave in one of three ways; the process may behave like the primitive process STOP, allowing other processes to continue, or the process may cause the whole system to halt, or the process may behave in an undefined way.

Literal A literal is a textual representation of a known value, and has a data type.

Livelock A divergent process, one which remains internally active but does not perform further communication, i.e. it behaves like the following process:

\[
\text{WHILE TRUE}
\]
\[
\text{SKIP}
\]

Modulo operator A modulo operator performs its operation (PLUS, MINUS, TIMES) with no check for overflow. The value returned as a result is the cyclic value within the range of the operand type.

Network A network consists of a number of processing devices, microcomputers perhaps, with the facility to communicate with each other.

Operand Yields a value in an expression.

Operator (monadic or dyadic) performs an operation on its operand(s).

Output Send the value of an expression to a channel.

Placement A configuration statement which places a process on a particular processing device.

Primitive type A primitive type is a channel, timer, integer, boolean, byte or real type. A port is also a primitive type.

Priority Priority can be given to a parallel executing on a single processing device. Lower priority processes on such a device may only continue when all higher priority processes are unable to. The inputs which guard alternatives in an alternation may be given a selection priority. If two or more inputs are ready, the the input with the highest priority is selected.

Procedure definition A procedure definition specifies a name for a process.

Procedure instance An instance of a procedure is a use of the procedure, and behaves like a substitution of the process named in the procedure definition. The phrase "procedure call" is used in many other languages, to indicate the use of a procedure, and has a similar meaning. Although the behaviour of an OCCAM procedure is clearly defined as the substitution of the procedure body, a procedure may be implemented as either a substitution or as a call to a closed subroutine.

Process A process starts, performs a number of actions, and then either stops without completing or terminates complete. OCCAM programs are built from the primitive processes assignment (:=), input (?), output (!), SKIP and STOP. These primitives are combined in SEQ, IF, CASE, WHILE, PAR and ALT constructions.

Protocol The format and type of values passed on a channel.
Real time The actual time taken for a physical process to occur.

Relational operation A relational operation compares its operands and yields a boolean result.

Repetitive process A repetitive process (WHILE) executes the associated process as long as the specified condition is true; if the condition is initially false the associated process is not executed.

Replication A replicator produces a number of similar components of a construction.

Retyping conversion A retyping conversion changes the data type of a bit pattern, from one data type to another. There are two kinds of retyping conversions: conversions which convert an element, and conversions which convert the value of an expression. Such a conversion has no effect upon the bit pattern, and differs from type conversion where the value of one type is represented as an equivalent value of another type.

Scope The region of a program associated with the specification of a name.

Segment A segment is one or more components of an array.

Selection A selection process (CASE) executes a process from a list of associated options. The options are selected by matching a selector with a constant expression associated with the option.

Sequence A sequential process (SEQ) is one where one action follows another.

Sequential protocol A sequential protocol specifies a sequence of simple protocols as the format of communication on a channel.

Shift operation Perform logical shift of the bit pattern of a value.

Skip Start, perform no action and terminate immediately.

Specification A specification is either a declaration, an abbreviation or a definition and specifies a name which may be used within the associated scope.

Specifier Identifies the type of an alias given in an abbreviation or definition.

Stop Start, perform no further action and do not terminate.

String A sequence of ASCII characters equivalent to a table of bytes.

Subscript An expression which selects a component of an array.

Table An array of values of the same type, used in expressions.

Tag Identifier of a protocol variant specified in a variant protocol definition.

Timer A timer is a clock which can accessed by any number of concurrent processes.

Timer input A timer input inputs a value from a timer.

Type conversion A type conversion converts the value of an expression of one data type into a similar value of another data type.

Value process A value process produces one or more results, each of primitive data type.

Variable A variable is an element of data type which may be assigned to by input or assignment.

Variable list A list of variables used in a multiple assignment.

Variable subscript A variable subscript is a subscript whose value depends on a variable, a procedure parameter, or the index of a replicator with a base or count which is not a constant or constant expression.

Variant protocol Specifies a list of possible protocols for communication on a single channel.
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occam\textsuperscript{\textregistered} 2 Reference Manual

The occam 2 Reference Manual is designed as a single reference, and definition of the language occam. The manual describes each aspect of the language, starting with the most primitive components of an occam program, and moving on to cover the whole language in detail. The manual addresses the computer scientist, software engineer, programmer, electronics engineer and system designer.

Programming in occam is easy and natural. occam is a high level language, designed to express concurrent algorithms and their implementation on a network of processing components. occam is an ideal introduction to a number of key methodologies in modern computer science. occam programs can provide a degree of security unknown in conventional programming languages such as C, FORTRAN or Pascal.

This manual was completed during 1986 and 1987 as part of the final development of occam 2 at the INMOS Microcomputer Centre, Bristol, UK. The development of the INMOS transputer, a device which places a microcomputer on a single chip, has been closely related to occam, its design and implementation. The transputer reflects the occam architectural model, and may be considered an occam machine.

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