4. VHDL Describes Behaviour

In Section 1.2 we stated that the behaviour of a digital system could be described in terms of programming language notation. The familiar sequential programming language aspects of VHDL were covered in detail in Chapter 2. In this chapter, we describe how these are extended to include statements for modifying values on signals, and means of responding to the changing signal values.

4.1. Signal Assignment

A signal assignment schedules one or more transactions to a signal (or port). The syntax of a signal assignment is:

signal_assignment_statement ::= target <= [**transport**] waveform ;

target ::= name | aggregate

waveform ::= waveform_element { , waveform_element }

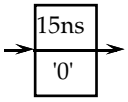
waveform_element ::=
*value*_expression [**after** *time*_expression]
| **null** [**after** *time*_expression]

The target must represent a signal, or be an aggregate of signals (see also variable assignments, Section 2.4.1). If the time expression for the delay is omitted, it defaults to 0 fs. This means that the transaction will be scheduled for the same time as the assignment is executed, but during the next simulation cycle.

Each signal has associated with it a *projected output waveform*, which is a list of transactions giving future values for the signal. A signal assignment adds transactions to this waveform. So, for example, the signal assignment:

```
s <= '0' after 10 ns;
```

will cause the signal enable to assume the value true 10 ns after the assignment is executed. We can represent the projected output waveform graphically by showing the transactions along a time axis. So if the above assignment were executed at time 5 ns, the projected waveform would be:

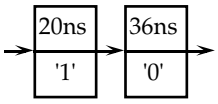


When simulation time reaches 15 ns, this transaction will be processed and the signal updated.

Suppose then at time 16 ns, the assignment:

```
s <= '1' after 4 ns, '0' after 20 ns;
```

were executed. The two new transactions are added to the projected output waveform:

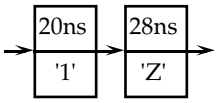


Note that when multiple transactions are listed in a signal assignment, the delay times specified must be in ascending order.

If a signal assignment is executed, and there are already old transactions from a previous assignmenton the projected output waveform, then some of the old transactions may be deleted. The way this is done depends on whether the word **transport** is included in the new assignment. If it is included, the assignment is said to use *transport delay*. In this case, all old transactions scheduled to occur after the first new transaction are deleted before the new transactions are added. It is as though the new transactions supercede the old ones. So given the projected output waveform shown immediately above, if the assignment:

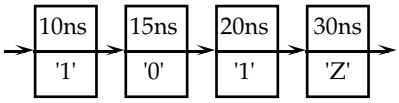
```
s <= transport '2' after 10 ns;
```

were executed at time 18 ns, then the transaction scheduled for 36 ns would be deleted, and the projected output waveform would become:



The second kind of delay, *inertial delay*, is used to model devices which do not respond to input pulses shorter than their output delay. An intertial delay is specified by omitting the word **transport** from the signal assignment. When an inertial delay transaction is added to a projected output waveform, firstly all old transactions scheduled to occur after the new transaction are deleted, and the new transaction is added, as in the case of transport delay. Next, all old transactions scheduled to occur before the new transaction are examined. If there are any with a different value from the new transaction, then all transactions up to the last one with a different value are deleted. The remaining transactions with the same value are left.

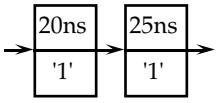
To illustrate this, suppose the projected output waveform at time 0 ns is:



and the assignment:

```
s <= '1' after 25 ns;
```

is executed also at 0 ns. Then the new projected ouptut waveform is:



When a signal assignment with multiple waveform elements is specified with intertial delay, only the first transaction uses inertial delay; the rest are treated as being transport delay transactions.

4.2. Processes and the Wait Statement

The primary unit of behavioural description in VHDL is the *process*. A process is a sequential body of code which can be activated in response to changes in state. When more than one process is activated at the same

time, they execute concurrently. A process is specified in a process statement, with the syntax:

```
process_statement ::=
    [ process_label : ]
        process [ ( sensitivity_list ) ]
            process_declarative_part
        begin
            process_statement_part
        end process [ process_label ] ;
process_declarative_part ::= { process_declarative_item }
process_declarative_item ::=
    subprogram_declaration
    | subprogram_body
    | type_declaration
    | subtype_declaration
    | constant_declaration
    | variable_declaration
    | alias_declaration
    | use_clause
process_statement_part ::= { sequential_statement }
sequential_statement ::=
    wait_statement
    | assertion_statement
    | signal_assignment_statement
    | variable_assignment_statement
    | procedure_call_statement
    | if_statement
    | case_statement
    | loop_statement
    | next_statement
    | exit_statement
    | return_statement
    | null_statement
```

A process statement is a concurrent statement which can be used in an architecture body or block. The declarations define items which can be used locally within the process. Note that variables may be defined here and used to store state in a model.

A process may contain a number of signal assignment statements for a given signal, which together form a *driver* for the signal. Normally there may only be one driver for a signal, and so the code which determines a signals value is confined to one process.

A process is activated initially during the initialisation phase of simulation. It executes all of the sequential statements, and then repeats, starting again with the first statement. A process may suspended itself by executing a wait statement. This is of the form:

```
wait_statement ::=
    wait [ sensitivity_clause ] [ condition_clause ] [ timeout_clause ] ;
sensitivity_clause ::= on sensitivity_list
sensitivity_list ::= signal_name { , signal_name }
condition_clause ::= until condition
timeout_clause ::= for time_expression
```

The sensitivity list of the wait statement specifies a set of signals to which the process is sensitive while it is suspended. When an event occurs

on any of these signals (that is, the value of the signal changes), the process resumes and evaluates the condition. If it is true or if the condition is omitted, execution procedes with the next statement, otherwise the process resuspends. If the sensitivity clause is omitted, then the process is sensitive to all of the signals mentioned in the condition expression. The timeout expression must evaluate to a positive duration, and indicates the maximum time for which the process will wait. If it is omitted, the process may wait indefinitely.

If a sensitivity list is included in the header of a process statement, then the process is assumed to have an implicit wait statement at the end of its statement part. The sensitivity list of this implicit wait statement is the same as that in the process header. In this case the process may not contain any explicit wait statements.

An example of a process statements with a sensitivity list:

```
process (reset, clock)
    variable state : bit := false;
begin
    if reset then
        state := false;
    elsif clock = true then
        state := not state;
    end if;
    q <= state after prop_delay;
    -- implicit wait on reset, clock
end process;
```

During the initialization phase of simulation, the process is activated and assigns the initial value of state to the signal q. It then suspends at the implicit wait statement indicated in the comment. When either reset or clock change value, the process is resumed, and execution repeats from the beginning.

The next example describes the behaviour of a synchronization device called a Muller-C element used to construct asynchronous logic. The output of the device starts at the value '0', and stays at this value until both inputs are '1', at which time the output changes to '1'. The output then stays '1' until both inputs are '0', at which time the output changes back to '0'.

```
muller_c_2 : process
begin
    wait until a = '1' and b = '1';
    q <= '1';
    wait until a = '0' and b = '0';
    q <= '0';
end process muller_c_2 ;
```

This process does not include a sensitivity list, so explicit wait statements are used to control the suspension and activation of the process. In both wait statements, the sensitivity list is the set of signals a and b, determined from the condition expression.

4.3. Concurrent Signal Assignment Statements

Often a process describing a driver for a signal contains only one signal assignment statement. VHDL provides a convenient short-hand notation, called a concurrent signal assignment statement, for expressing such processes. The syntax is:

```
concurrent_signal_assignment_statement ::=
    [ label : ] conditional_signal_assignment
    | [ label : ] selected_signal_assignment
```

For each kind of concurrent signal assignment, there is a corresponding process statement with the same meaning.

4.3.1. Conditional Signal Assignment

A conditional signal assignment statement is a shorthand for a process containing signal assignments in an if statement. The syntax is:

```
conditional_signal_assignment ::= target <= options conditional_waveforms ;

options ::= [ guarded ] [ transport ]

conditional_waveforms ::=
    { waveform when condition else }
    waveform
```

Use of the word **guarded** is not covered in this booklet. If the word **transport** is included, then the signal assignments in the equivalent process use transport delay.

Suppose we have a conditional signal assignment:

```
s <= waveform_1 when condition_1 else
        waveform_2 when condition_2 else
        ...
        waveform_n;
```

Then the equivalent process is:

```
process
    if condition_1 then
        s <= waveform_1;
    elsif condition_2 then
        s <= waveform_2;
    elsif ...

    else
        s <= waveform_n;
    wait [ sensitivity_clause ];
end process;
```

If none of the waveform value expressions or conditions contains a reference to a signal, then the wait statement at the end of the equivalent process has no sensitivity clause. This means that after the assignment is made, the process suspends indefinitely. For example, the conditional assignment:

```
reset <= '1', '0' after 10 ns when short_pulse_required else
             '1', '0' after 50 ns;
```

schedules two transactions on the signal reset, then suspends for the rest of the simulation.

On the other hand, if there are references to signals in the waveform value expressions or conditions, then the wait statement has a sensitivity list consisting of all of the signals referenced. So the conditional assignment:

```
mux_out <= 'Z' after Tpd when en = '0' else
                in_0 after Tpd when sel = '0' else
                in_1 after Tpd;
```

is sensitive to the signals en and sel. The process is activated during the initialization phase, and thereafter whenever either of en or sel changes value.

The degenerate case of a conditional signal assignment, containing no conditional parts, is equivalent to a process containing just a signal assignment statement. So:

```
s <= waveform;
```

is equivalent to:

```
process
    s <= waveform;
    wait [ sensitivity_clause ];
end process;
```

4.3.2. Selected Signal Assignment

A selected signal assignment statement is a shorthand for a process containing signal assignments in a case statement. The syntax is:

```
selected_signal_assignment ::=
    with expression select
        target <= options selected_waveforms ;
selected_waveforms ::=
    { waveform when choices , }
    waveform when choices
choices ::= choice { | choice }
```

The options part is the same as for a conditional signal assignment. So if the word **transport** is included, then the signal assignments in the equivalent process use transport delay.

Suppose we have a selected signal assignment:

```
with expression select
    s <= waveform_1 when choice_list_1,
         waveform_2 when choice_list_2,
         ...
         waveform_n when choice_list_n;
```

Then the equivalent process is:

```
process
    case expression is
        when choice_list_1=>
            s <= waveform_1;
        when choice_list_2=>
            s <= waveform_2;
        ...
        when choice_list_n=>
            s <= waveform_n;
    end case;
    wait [ sensitivity_clause ];
end process;
```

The sensitivity list for the wait statement is determined in the same way as for a conditional signal assignment. That is, if no signals are referenced in the selected signal assignment expression or waveforms, the wait statement has no sensitivity clause. Otherwise the sensitivity clause contains all the signals referenced in the expression and waveforms.

An example of a selected signal assignment statement:

```
with alu_function select
    alu_result <= op1 + op2 when alu_add | alu_incr,
                  op1 – op2 when alu_subtract,
                  op1 and op2 when alu_and,
                  op1 or op2 when alu_or,
                  op1 and not op2 when alu_mask;
```

In this example, the value of the signal alu_function is used to select which signal assignment to alu_result to execute. The statement is sensitive to the signals alu_function, op1 and op2, so whenever any of these change value, the selected signal assignment is resumed.