

DEPARTMENT OF ELECTRICAL AND ELECTRONIC ENGINEERING  
EXAMINATIONS 2007

MSc and EEE/ISE PART III/IV: MEng, BEng and ACGI

**VHDL AND LOGIC SYNTHESIS**

Wednesday, 9 May 10:00 am

Time allowed: 3:00 hours

**There are FOUR questions on this paper.****Question 1 is COMPULSORY****Answer question 1 and any TWO of questions 2-4****Question 1 carries 40% of the marks, questions 2-4 each carry 30% of the marks.****Any special instructions for invigilators and information for candidates are on page 1.**

Examiners responsible	First Marker(s) :	T.J.W. Clarke, T.J.W. Clarke
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**Special Information for Invigilators: none.**

### **Information for Candidates**

*VHDL language reference and course notes can be found in the booklet VHDL Exam Notes.*

*Unless otherwise specified assume VHDL 1993 compiler.*

*Library functions from the VHDL package **utility\_pack** from the coursework may be used freely in your implementations.*

## The Questions

*Question 1 is COMPULSORY*

1. a)
- (i) Determine the precise behaviours of processes P1 & P2 in *Figure 1.1*, assuming that z is initially '0'. Is P1 synthesisable?
  - (ii) You may assume that synthesis of a VHDL process depends only on its precise behaviour in simulation. State, giving reasons, whether P2 is synthesisable?
- [4]
- b) *Figure 1.2* shows a random access memory entity *ram* with data output *dout* and control input *write*, address input *addr* and data input *din*. In *ram* what is the width of one memory location and the number of memory locations? Write a synthesisable architecture for entity *ram* implementing the function shown in *Figure 1.2*.
- [4]
- c) Calculate the ROBDD for the Boolean expression:  
 $X \text{ xor } Y \text{ xor } Z \text{ xor } W$   
with variable order X, Y, Z, W
- [4]
- d) You may assume that *a*, *b*, *c*, *d* in *Figure 1.3* are all '0' at the start of simulation. Draw the first 20ns of the waveforms on these signals when driven by process P3, annotating each signal transition with its physical time and indicating the simulation  $\Delta$  of the transition if this is not 0.
- [4]
- e) Entity *iobuff* in *Figure 1.4* has ports *za*, *zb* which are both inputs and (tri-state) clocked outputs. Its behaviour is described in *Figure 1.5* where the notation  $x_i$  denotes the value on signal *x* during clock cycle *i*. Write an architecture for *iobuff* consistent with *Figure 1.5*.
- [4]

```

P1:PROCESS
BEGIN
    WAIT UNTIL clk'EVENT;
    z <= not z;
END PROCESS P1;

```

```

P2:PROCESS
BEGIN
    WAIT UNTIL clk'EVENT;
    IF clk='1' THEN
        z <= not z;
    END IF;
END PROCESS P2;

```

Figure 1.1

```

ENTITY ram IS
PORT(
    write, clk: IN std_logic;
    addr: IN std_logic_vector(3 DOWNTO 0);
    din: IN std_logic_vector(7 DOWNTO 0);
    dout: OUT std_logic_vector(7 DOWNTO 0)
);
END ram;

```

write	Operation on next clock positive edge	Dout in current cycle
1	ramloc[addr] := din	ramloc[addr]
0	n/a	ramloc[addr]

Figure 1.2

```

P3:PROCESS
    VARIABLE xv : std_logic;
BEGIN
    WAIT FOR 10 ns;
    xv := a;
    a <= not xv;
    b <= not a;
    WAIT FOR 0 ns;
    c <= b;
    d <= b AFTER 5 ns;
END PROCESS P3;

```

Figure 1.3

```

ENTITY iobuf IS
PORT(dir,clk:IN std_logic;
    za,zb:INOUT std_logic
);
END iobuf;

```

Figure 1.4

$dir_n$	$za_n$	$zb_n$
1	$zb_{n-1}$	High impedance
0	High impedance	$za_{n-1}$

Figure 1.5

Students must answer TWO out of Questions 2-4.

2. Figure 2.2 shows an implementation of entity *transpose* in Figure 2.1. This uses a 16 word RAM *tram* to implement 4X4 matrix transposition. The circuit is synchronous with the *negative* edge of *clk*. The operation is initiated by a '1' on *reset* and controlled by finite state machine *fsm* with three states as in Figure 2.3. Note that the double vertical lines indicate where clock cycles have been omitted.

During *state1*, the 16 matrix elements each of width 16 bits are input sequentially on *din* in row order and written to the RAM. In *state2* the 16 matrix elements are output in column order. As this happens all 16 elements are summed in block *alureg*. In *state3*, lasting 1 cycle, the sum is output. The address inputs of *tram* are driven by a block *amux* which permutes address inputs in state 2 to implement the transposed element order. Block *muxd* selects the appropriate signal for *dout*.

- a) Write appropriate VHDL to define type *word* as a 16 bit vector which can be used in entities instantiating *transpose* as well as the entity and architecture of *transpose* and *tram*.

[3]

- b) The RAM *tram* is implemented as a separate entity. Write an appropriate entity declaration for *tram*. You do not need to write an architecture for *tram*.

[2]

- c) Write an architecture for *transpose* which instantiates *tram* and implements blocks *amux*, *muxd*, *fsm*, *alureg*, and *count*.

[15]

```

ENTITY transpose IS
  PORT (
    clk, reset : IN STD_LOGIC;
    datain : IN word;
    dataout : OUT word
  );
END transpose;

```

Figure 2.1

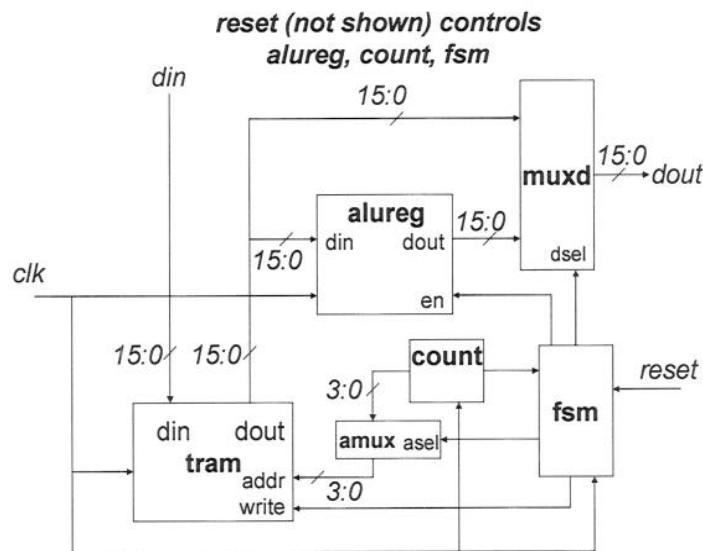


Figure 2.2

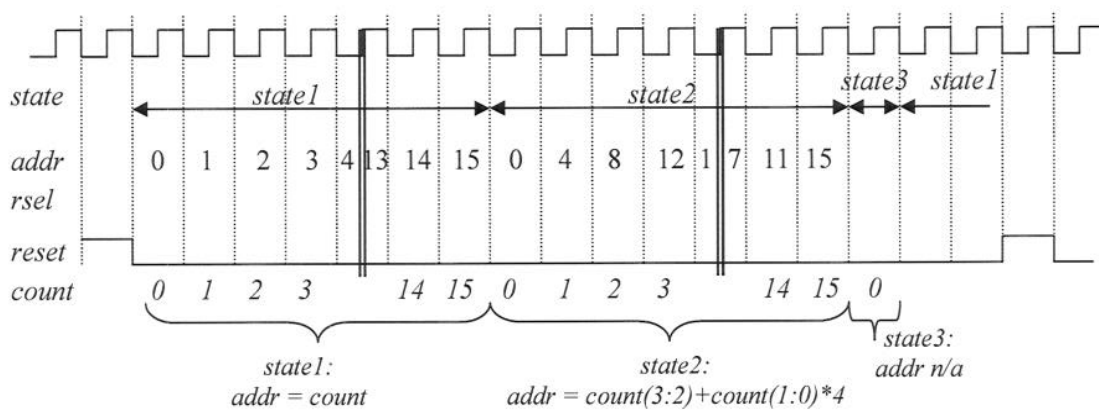


Figure 2.3

3. Figure 3.1 illustrates a hardware engine to compute the Mandelbrot fractals which implements repeatedly two complex number iterations each of the form:

$$\begin{aligned} z'_r &:= \text{round}\{(z_r * z_r - z_i * z_i) * 2^{-n}\} + c_r \\ z'_i &:= \text{round}\{2z_i * z_r * 2^{-n}\} + c_i \end{aligned} \quad (3.1)$$

where  $z_i, c_i, z_r, c_r$  are two's complement  $m$ -bit signed integers representing imaginary and real parts of (fixed point) complex numbers  $z$  and  $c$  respectively, and  $z'$  is the new value of  $z$ . The function **round** implements rounding to the nearest signed integer.

- a) A fixed-point signed vector  $x(m-1:0)$  with  $n$  fractional bits ( $n < m$ ) may be rounded to the nearest fixed-point integer by adding bit  $x(n-1)$  onto  $x$  at bit index  $n$ , and setting the bottom  $n$  bits to 0. Write a VHDL function:

**FUNCTION roundn (n: INTEGER; x: SIGNED) RETURN SIGNED;**

which rounds a signed fixed point vector  $x$  to the nearest integer.

[4]

- b) Figure 3.1 shows hardware to implement Equation (3.1). The multiplier blocks compute products  $z_i * z_i, z_i * z_r, z_r * z_r$ , which are held in *REG1*. The block *COUNT* is a one bit counter. Block *ASR* computes the new values  $z'_i, z'_r$  from these products and the complex constant  $c$ , which is output from multiplexer *MUX*. Supposing complex inputs  $ca$  and  $cb$  are constant, determine the output of *REG2* for the first four clock cycles after reset. Hence explain how the circuit computes Equation (3.1).

[4]

- c) Define a VHDL type *complex* which implements a complex number as an array of two signed vectors, each of length  $m$ , where  $m$  is a constant.

[2]

- d) You may assume that the VHDL operator :

**\*: signed × signed → signed**

synthesises signed multipliers. The length of the result is the sum of the lengths of the two operands. Using the  $*$  operator and previous answers from this question write a VHDL architecture for the entity in Figure 3.2 which implements Figure 3.1.

[10]

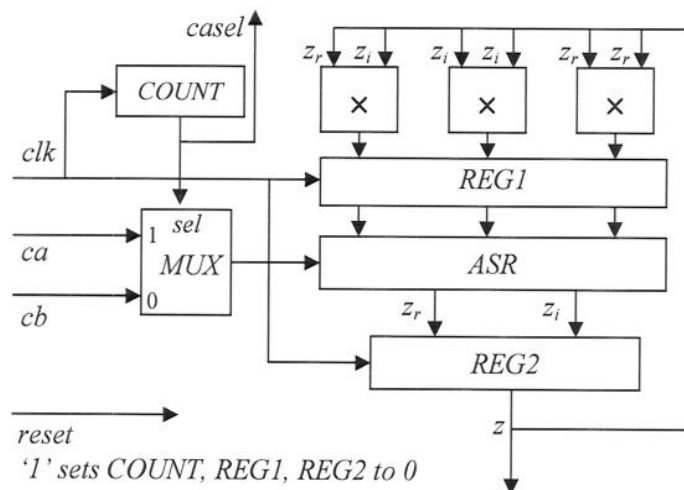


Figure 3.1

```

ENTITY mandelbrot IS
  GENERIC( n : INTEGER); -- precision
  PORT(
    ca, cb : IN complex;
    z       : OUT complex;
    reset, clk: IN std_logic;
    casel:   OUT std_logic -- '1' when ca is selected
  );
END mandelbrot;

```

Figure 3.2



4.

- (a) Explain how in VHDL constant expressions are synthesised differently from signals whose value may change:
- (i) as indexes of arrays
  - (ii) as operands of logical operators.
- Specify three distinct contexts in which VHDL identifiers can represent constant expressions.

[4]

- (b) Figure 4.1 shows VHDL entity and architecture *permute* which has  $k$  bit input  $a$  and output  $b$ . Precisely what hardware will this synthesise if
- (i)  $k = 2, m = 1$
  - (ii)  $k = 4, m = 2$

[2]

- (c) Entity *switch* in Figure 4.3 uses multiple *permute* blocks all with  $k=2, m=1$ . It connects  $2^n$  inputs  $a$  to  $2^n$  outputs  $b$  and is made up of  $n$  layers labelled 0 to  $n-1$  each containing  $2^{n-1}$  copies of *permute* with identical  $p$  input as illustrated in Figure 4.2, where the dots indicate repeated blocks which have been omitted. Between layers  $q$  and  $q+1$  there is an array of  $2^n$  signals  $x(q)$ . You are given synthesisable functions  $\mathbf{x0}(q, i)$  and  $\mathbf{x1}(q, i)$  which determine the connections of the *permute* blocks. In layer  $q$ , the  $i$ th copy of *permute* ( $i = 0, \dots, 2^{n-1}$ ) is connected as in Figure 4.4.

Using one or more **FOR GENERATE** loops, complete architecture *synth* in Figure 4.3 using synthesisable code.

[14]

	<i>index 0</i>	<i>index 1</i>
<i>xin</i>	$\mathbf{x}(q)(\mathbf{x0}(q, i))$	$\mathbf{x}(q)(\mathbf{x1}(q, i))$
<i>xout</i>	$\mathbf{x}(q+1)(\mathbf{x0}(q, i))$	$\mathbf{x}(q+1)(\mathbf{x1}(q, i))$

Figure 4.4

```

ENTITY permute IS
  GENERIC (k,m: INTEGER) ;
  PORT (
    p      : IN std_logic_vector(m-1 DOWNT0 0) ;
    xin    : IN std_logic_vector(k-1 DOWNT0 0) ;
    xout    : OUT std_logic_vector(k-1 DOWNT0 0)
  ) ;
END permute;

ARCHITECTURE behave OF permute IS
BEGIN
  G1: FOR i IN k DOWNT0 1 GENERATE
    xout(i-1) <= xin((i*(conv_integer(unsigned((p)))+1) mod k+1)-1) ;
  END GENERATE G1;
END behave;

```

Figure 4.1

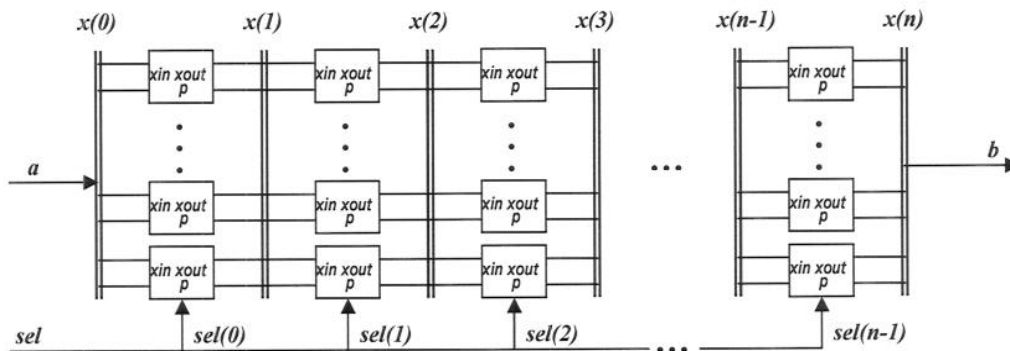


Figure 4.2

```

ENTITY switch IS
  GENERIC (n: INTEGER) ;
  PORT( a: IN std_logic_vector(2**n-1 DOWNT0 0) ;
        b: OUT std_logic_vector(2**n-1 DOWNT0 0) ;
        sel: IN std_logic_vector(n-1 DOWNT0 0) );
END switch;

ARCHITECTURE synth OF switch IS
  TYPE grid IS ARRAY (0 TO n+1) OF std_logic_vector(2**n-1 DOWNT0 0) ;
  SIGNAL x: grid;
BEGIN
  END synth;

```

Figure 4.3

# VHDL 2007 SOLUTIONS

A=Analysis, D = Design, B = Bookwork

*Question 1 is COMPULSORY, and constitutes 40% of marks, 72 minutes time, 15 minutes per part.*

## Solution to Question 1.

1.

a)

(i) P1 inverts z on every edge of clk. It is therefore not synthesisable, since flip-flops must trigger on one edge not both.

(ii) P2 has identical semantics to a positive edge triggered T flip-flop, so it synthesises.

[4A]

b)

--from question

ENTITY ram IS

PORT(

    write, clk: IN std\_logic;

    addr: IN std\_logic\_vector(3 DOWNTO 0);

    din: IN std\_logic(7 DOWNTO 0);

    dout: OUT std\_logic\_vector(7 DOWNTO 0)

);

END ram;

ARCHITECTURE synth OF ram IS

    TYPE ramtype IS ARRAY (0 TO 15) OF std\_logic\_vector( 7 DOWNTO 0);

    SIGNAL ramloc : ramtype;

BEGIN

    dout <= ramloc(conv\_integer(unsigned(addr)));

    P1: PROCESS

    BEGIN

        WAIT UNTIL clk'EVENT AND clk='1';

        IF write = '1' THEN

            ramloc(conv\_integer(unsigned(addr))) <= din;

        END IF;

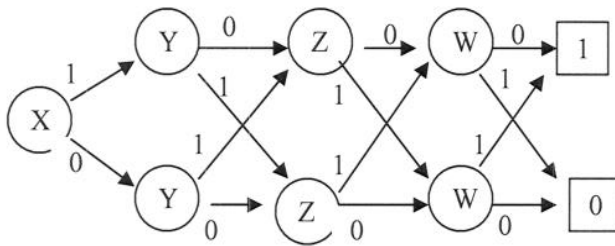
    END PROCESS P1;

END ARCHITECTURE synth;

[4D]

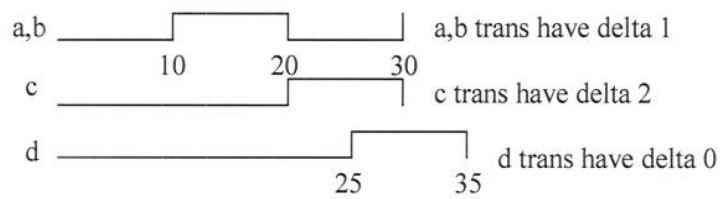
**VHDL 2007 SOLUTIONS**  
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c)



[4B]

d)



[4A]

VHDL 2007 SOLUTIONS  
A=Analysis, D = Design, B = Bookwork

e)

```
--from question
ENTITY iobuf IS
    PORT(dir,clk:IN std;
          za,zb:INOUT std_logic
    );
END iobuf;

ARCHITECTURE synth OF iobuf IS
    SIGNAL za_del, zb_del: std_logic;
BEGIN

P1: PROCESS
BEGIN
    WAIT UNTIL clk'EVENT AND clk='1';
    za_del <= za;
    zb_del <= zb;
END PROCESS P1;

P2: PROCESS(dir, za_del, zb_del)
BEGIN
    WAIT UNTIL clk'EVENT AND clk='1';
    IF dir='1' THEN
        zb <= za_del; za <= 'Z';
    ELSE
        za <= zb_del; zb <= 'Z';
    END IF;
END PROCESS P2;

END synth;
```

[4D]

**VHDL 2007 SOLUTIONS**  
**A=Analysis, D = Design, B = Bookwork**

*Students must answer two questions from questions 2-4, each question carries 30% of marks and takes 54 minutes.*

**Solution to Question 2**

3.

a)

Must be in a package, so:

```
PACKAGE mypak IS
SUBTYPE word IS std_logic_vector(15 DOWNTO 0);
END PACKAGE;
```

[3B]

b)

```
ENTITY tram IS
PORT(
    din: IN word;
    dout: OUT word;
    clk, write: IN std_logic;
    addr: In std_logic_vector(3 DOWNTO 0)
);
END tram;
```

[2B]

**VHDL 2007 SOLUTIONS**  
**A=Analysis, D = Design, B = Bookwork**

c)

```
ARCHITECTURE synth OF transpose IS
    TYPE fsmtype IS (state1, state2, state3);
    SIGNAL state: fsmtype;
    SIGNAL regs: word;
    SIGNAL write, wen, dsel, asel: std_logic;
    SIGNAL data, adata : word;
    SIGNAL count, addr : STD_LOGIC_VECTOR(3 DOWNTO 0);

BEGIN

    I1: ENTITY tram PORT MAP(datain, dataout, clk, write, addr);

    ALU : PROCESS
    BEGIN
        WAIT UNTIL clk'EVENT AND clk = '1';
        IF state=state2 THEN
            regs <= SIGNED(regs)+SIGNED(data);
        END IF;
        IF reset='1' THEN regs<= (OTHERS=>'0'); END IF;
    END PROCESS ALU;

    COUNT : PROCESS
    BEGIN
        WAIT UNTIL clk'EVENT AND clk = '1';
        IF reset='1' OR state=state3 THEN
            count <= "0000";
        ELSE
            count <= UNSIGNED(count) + 1;
        END IF;
    END PROCESS COUNT;

    MUX : PROCESS(state, data, adata, count)
    BEGIN
        IF state=state3 THEN dataout <= adata; ELSE dataout <=data; END IF;
        addr <= count;
        IF state=state2 THEN
            addr <= (count(1), count(0), count(3), count(2));
        END IF;
    END PROCESS MUX;

    FSM : PROCESS
    BEGIN
        WAIT UNTIL clk'EVENT AND clk='1';
        IF reset THEN state <= state1;
        ELSE
            IF count=std_logic_vector("1111") THEN
                CASE state IS
                    WHEN state1 => state <= state2;
                    WHEN state2 => state <= state3;
                END CASE;
            END IF;
        END IF;
    END PROCESS FSM;

END ARCHITECTURE synth; -- of transpose
```

[15D]

**VHDL 2007 SOLUTIONS**  
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**Solution to Question 3**

a)

```
FUNCTION roundn(n: INTEGER; x: SIGNED) RETURN SIGNED IS
VARIABLE xx:SIGNED(x'LENGTH DOWNT0 1);
CONSTANT zeros: SIGNED(N DOWNT0 1) := (OTHERS => '0');
BEGIN
  xx := x;
  xx := signed(xx)+ unsigned(xx(n) & zeros);
  FOR i IN n DOWNT0 1 LOOP xx(i) := '0'; END LOOP;
  RETURN xx;
END;
```

[4D]

b)  $cb$ ,  $ca$ ,  $cb+cb^2$ ,  $ca+ca^2$ . The circuit computes the Mandelbrot recurrence for two values of  $c$  in parallel.

[4D]

c)

```
TYPE complex IS ARRAY (1 DOWNT0 0) OF SIGNED(m-1 DOWNT0 0);
(Element type could be std_logic_vector)
```

[2B]



**VHDL 2007 SOLUTIONS**  
**A=Analysis, D = Design, B = Bookwork**

d)

```
ARCHITECTURE synth OF mandelbrot IS
    SIGNAL z_int, c : complex;
    SIGNAL zii, zir, zrr : SIGNED(2*m-1 DOWNT0 0);
    SIGNAL count
        : STD_LOGIC;

    FUNCTION roundn(n: INTEGER; x: SIGNED) return SIGNED IS
    VARIABLE xx:SIGNED(x'LENGTH DOWNT0 1);
    CONSTANT zeros: SIGNED(N DOWNT0 1):= (OTHERS => '0');
    BEGIN
        xx := x;
        xx := signed(xx)+ unsigned(xx(n) & zeros);
        FOR i IN n DOWNT0 1 LOOP xx(i) := '0'; END LOOP;
        RETURN xx;
    END;

BEGIN
    P1: PROCESS
    BEGIN
        zrr <= z_int(0)*z_int(1);
        zii <= z_int(1)*z_int(1);
        zir <= z_int(1)*signed(z_int(0));
        z_int(0) <= roundn(zrr-zii)+c(0);
        z_int(1) <= roundn(zir)+c(1);
        count <= NOT count;
        IF reset = '1' THEN
            z_int(0) <= (OTHERS=>'0');
            z_int(1) <= (OTHERS=> '0');
            count <= '0';
        END IF;
    END PROCESS P1;

    P2: PROCESS(count,ca,cb)
    BEGIN
        IF count='1' THEN c <= ca; ELSE c <= cb; END IF;
    END PROCESS P2;

    z <= z_int;

END ARCHITECTURE synth;
```

[10D]

VHDL 2007 SOLUTIONS  
A=Analysis, D = Design, B = Bookwork

Solution to Question 4

a)

A constant index selects a bit at zero cost. A variable index turns into a multiplexer to select the given bit.

As operand of a logical operator constant values simplify to '0', '1' or straight connection, or (XOR & XNOR only) an inverter. Variable values must invoke the relevant operator.

Constant expressions can be derived from:

CONSTANTS

FOR indexes

GENERICs

[4B]

b)

(i) 2 X 2-input multiplexers

(ii) 4 X 4-input multiplexers

[2B]

c)

ARCHITECTURE synth OF switch IS

  TYPE grid IS ARRAY (0 TO n) OF std\_logic\_vector(n-1 DOWNT0 0);

  SIGNAL x: grid;

BEGIN

  G1: FOR a IN 0 TO n-1 GENERATE

    G2: FOR b IN 0 TO 2\*\*(N-1)-1 GENERATE

      P: ENTITY permute GENERIC MAP(n=>n, m=>1)

        PORT MAP( p=>sel(a DOWNT0 a),

          xin =>(x(a)(x0(a,b)), x(a)(x1(a,b))),

          xout =>(x(a+1)(x0(a,b)), x(a+1)(x1(a,b))) );

    END GENERATE G2;

  END GENERATE G1;

END synth;

[14D]