

IMPERIAL COLLEGE LONDON

DEPARTMENT OF ELECTRICAL AND ELECTRONIC ENGINEERING
EXAMINATIONS 2011

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

VHDL AND LOGIC SYNTHESIS

Friday, 13 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
	Second Marker(s) :	G.A. Constantinides, G.A. Constantinides

Special Information for Invigilators: none.

Information for Candidates

VHDL language reference can be found in the booklet VHDL Exam Notes.

Unless otherwise specified assume VHDL 1993 compiler.

All packages that must be explicitly referenced with USE, e.g. IEEE.numeric_std, must be explicitly noted in each answer: semantically correct LIBRARY and USE statements may be omitted where this is done.

The Questions

Question 1 is compulsory and carries 40% of marks.

1.

- a) Write a compact VHDL process without using table lookup which implements the combinational logic function q of x and y shown in Figure 1.1. [8]
- b) Write an architecture for entity *count* in Figure 1.2 such that y changes to 0 when *reset* is 1 and y counts upwards by 1 as a two's complement signed number from -7 to 17: -7,-6, ..., 16,17. After 17 the next y value is -7 again and the sequence repeats. All changes are on the positive edge of *clk*. [8]
- c) Architecture *deltadelay* in Figure 1.3 drives signals x, y, z, q, w from a . For each driven signal indicate all transitions and corresponding delta delays caused by a $0 \rightarrow 1$ transition at delta 0 on a , assuming that before this transition a is stable. [8]
- d) Figure 1.4 shows entity *fsm*. Write an architecture for *fsm* which implements the state diagram in Figure 1.5, assuming that p, q inputs and y output are unsigned numbers, and synchronously setting the state equal to a on reset. [8]
- e) Figure 1.6 shows a testbench *tb* which drives internal signals *clk, x, y, z*. Draw a timing diagram showing the *std_logic* value of these signals in the first 40ns of the simulation (delta delays not required). Comment on whether process *P1* could be made synthesisable by rewriting the code, and if so how. [8]

x(4)	x(3)	x(2)	x(1)	x(0)	q(4)	q(3)	q(2)	q(1)	q(0)
0	0	0	0	0	y(4)	y(3)	y(2)	y(1)	y(0)
1	X	X	X	X	0	0	0	1	1
0	1	X	X	X	0	0	0	0	0
0	X	1	X	X	0	0	0	0	0
0	X	X	1	X	0	0	0	0	0
0	X	X	X	1	0	0	0	0	0

Figure 1.1

```

ENTITY count IS
PORT(
  reset, clk: IN std_logic;
  y: OUT std_logic_vector(6 DOWNTO 0));
END ENTITY count;

```

Figure 1.2

```

ENTITY dl IS
  PORT (  u: IN std_logic;
          v : OUT std_logic);
END dl;

ARCHITECTURE behav OF dl IS
BEGIN
  v <= u;
END behav;

ARCHITECTURE deltadelay OF test IS
  SIGNAL x,y,z,w,q,a: std_logic;
BEGIN
  x <= a;
  y <= x xor a;

  P1: PROCESS(y)
  BEGIN
    z <= y;
    q <= y;
  END PROCESS P1;

  E1: ENTITY WORK.dl
    PORT MAP(u=>a,v=>w);
END deltadelay;

```

Figure 1.3

```

ENTITY fsm IS
PORT(
  reset, clk: IN std_logic;
  p,q:      IN std_logic_vector(3 DOWNTO 0);
  y:        OUT std_logic_vector(1 DOWNTO 0));
END ENTITY fsm;

```

Figure 1.4

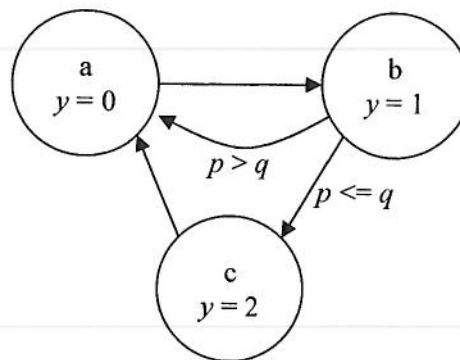


Figure 1.5

```

ENTITY tb IS
END ENTITY tb;

LIBRARY IEEE; USE IEEE.std_logic_1164.ALL;
ARCHITECTURE behav OF tb IS
  SIGNAL clk: std_logic := '0';
  SIGNAL x: std_logic := '0';
  SIGNAL y, z: std_logic;
BEGIN
  clk <= not clk AFTER 10 ns;
  x <= not x AFTER 25 ns;

  P1: PROCESS
  BEGIN
    WAIT UNTIL clk'EVENT and clk='1';
    y <= x;
    WAIT UNTIL clk'EVENT and clk='0';
    z <= y;
  END PROCESS P1;
END ARCHITECTURE behav;

```

Figure 1.6

Answer two of questions 2 - 4. Each question carries 30% of marks.

2. Figure 2.2 displays a block diagram of structural hardware using the saturated arithmetic entities defined in Figure 2.1. The three arithmetic entities *add_sat*, *mult_sat* and *power_sat* are denoted in blocks B1-B5 by labels +, * and Pow respectively. Generic inputs are specified by numbers. The VHDL bit numbers on a signal *z* are indicated *z(a:b)* for the range *z(a DOWNT0 b)*. **All unconnected block input signals should be assumed connected to 0.** Input and output connections to the hardware are specified by signal lines that intersect the bounding box, and the output *s* is driven as stated in Figure 2.2.

- a) Assuming that the three entities implement combinational unsigned integer $p+q$ (*add_sat*), $p*q$ (*mult_sat*) and p^n (*power_sat*) functions respectively, what, ignoring overflows, is the multivariate polynomial implemented by this hardware?

[5]

- b) You may assume that the entities in Figure 2.1 have synthesisable implementations which you need not write. Write a VHDL entity and synthesisable architecture which implements the Figure 2.2 hardware with all ports appropriately chosen vectors.

[25]

```
ENTITY mult_sat IS -- unsigned multiplication with arithmetic saturation
```

```
    GENERIC( w_in, w_out: INTEGER);
    PORT(    p,q: IN unsigned(w_in-1 DOWNT0 0);
           x: OUT unsigned(w_out-1 DOWNT0 0);
           saturated: OUT std_logic );
```

```
END ENTITY mult_sat;
```

```
ENTITY add_sat IS -- unsigned addition with arithmetic saturation
```

```
    GENERIC( w_in, w_out: INTEGER);
    PORT(    p,q: IN unsigned(w_in-1 DOWNT0 0);
           sum: OUT unsigned(w_out-1 DOWNT0 0);
           saturated: OUT std_logic );
```

```
END ENTITY add_sat;
```

```
ENTITY power_sat IS -- unsigned integer exponentiation with arithmetic saturation
```

```
    GENERIC( w_in, w_out, n: INTEGER); -- n is exponent
    PORT(    p: IN unsigned(w_in-1 DOWNT0 0);
           x: OUT unsigned(w_out-1 DOWNT0 0);
           saturated: OUT std_logic );
```

```
END ENTITY power_sat;
```

Figure 2.1 VHDL Entities using IEEE.numeric_std

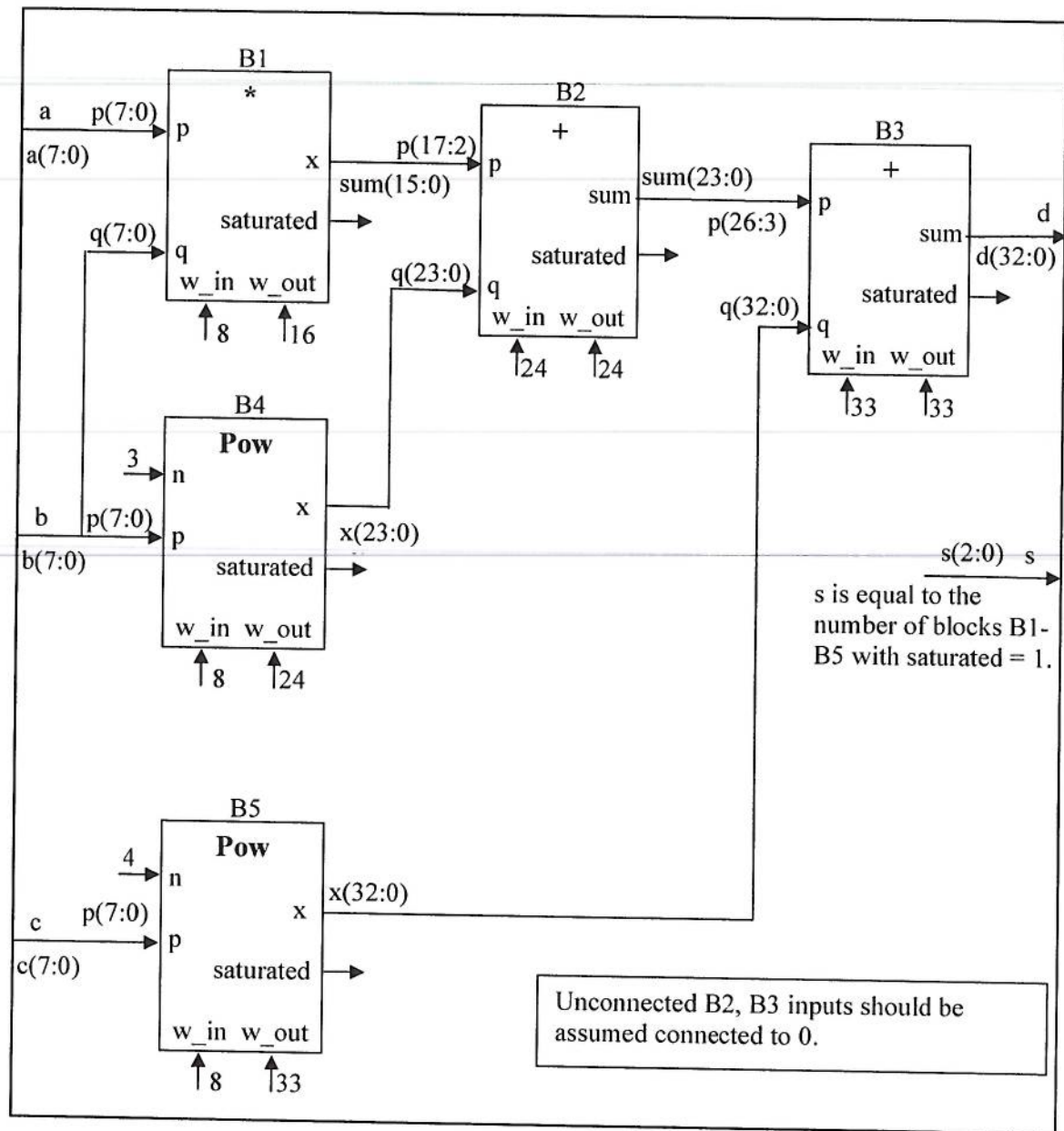


Figure 2.2

3. This question relates to the implementation of entity *power_sat_signed* as defined in Figure 3.3. The combinational outputs *x* and *saturated* of *power_sat_signed* are defined in Figure 3.1 where *X* and *P* are the signed numbers represented by ports *x* and *p* respectively.

a) Explain why this is the appropriate definition for the integer power function X^n in digital hardware.

[3]

b) Write VHDL which ensures that *w_in*, *w_out*, *n* satisfy the equations in Figure 3.2 wherever the entity *power_sat_signed* is instantiated.

[6]

c) Write a VHDL synthesisable FOR loop which implements X^n , for any positive value of *n*. Efficiency is not required. What would be the consequences of using your code with a very large value of *n*?

[6]

d) Using your answers to the above, or otherwise, write a synthesisable VHDL architecture which implements *power_sat_signed* for all non-negative values of *n*. Note that a zero length FOR loop will not compile, and therefore you may need to use one or more IF GENERATE statements.

[15]

condition	X	<i>saturated</i>
$P^n > 2^{w_out-1} - 1$	$2^{w_out-1} - 1$	1
$P^n < -2^{w_out-1}$	-2^{w_out-1}	1
$-2^{w_out} \leq P^n \leq 2^{w_out-1} - 1$	P^n	0

Figure 3.1

$w_out \leq n * w_in$
$n \geq 0$
$w_out > 0$
$w_in > 0$

Figure 3.2

```

LIBRARY IEEE;
USE IEEE.numeric_std
ENTITY power_sat_signed IS
    GENERIC( w_in, w_out, n: INTEGER); -- n is exponent
    PORT(    p: IN signed(w_in-1 DOWNTO 0);
            x: OUT signed(w_out-1 DOWNTO 0);
            saturated: OUT std_logic );
END ENTITY power_sat_signed;

```

Figure 3.3 VHDL Entities

4. The testbench architecture *zz* in Figure 4.1 implements 10 independent tests of entity *dut*. Arrays *testin* and *testout* are defined in package *testpack*.

a) Explain, with reference to the delta delay timings on which data is read and changed, why this architecture will correctly test an entity *dut* clocked synchronously by *clk*.

[5]

b) In test *i* (*i* = 0 to 9) what are the timing and data input conditions under which *dut* is tested, and what is the required output? Give your answers for data in terms of values of *testin* & *testout*. What assumption about *dut* is necessary for each test to have a definite result independent of the other tests?

[5]

c) The algorithm implemented by *dut* is known to use different equations for the cases $xin \geq 0$ and $xin < 0$, and to have maximum output +32767 at $xin = 1000$. Provide, with justification, a suitable definition of *testin* for ad-hoc testing. Write your answer in VHDL as package *testpack*, omitting *testout*.

[10]

d) Suppose that the simulation takes 1ms per simulated clock cycle. Discuss the relative merits of random sample, exhaustive, ad hoc testing for the case illustrated in Fig 4.1, and also in the case that *xin*, *xout* are both 32 bit.

[10]

```

USE IEEE.numeric_std.ALL;
ENTITY dut IS
    PORT(xin,xout: signed(15 DOWNT0 0));
END dut;

LIBRARY IEEE;
USE IEEE.std_logic_1164.ALL;
USE IEEE.numeric_std.ALL;
LIBRARY WORK;
USE WORK.testpack.ALL;

ARCHITECTURE zz OF tb IS
    SIGNAL clk,a: std_logic := '0';
    SIGNAL x, y, z: std_logic;
    SIGNAL xin_i, xout_i, r:
        signed(15 DOWNT0 0);
BEGIN

    clk <= not clk AFTER 100 ns;

    I1: ENTITY WORK.dut
        PORT MAP( xin=>xin_i,
                  xout=>xout_i );

    Pmain: PROCESS
    BEGIN
        FOR num in testarray'RANGE LOOP
            WAIT FOR 150 ns;
            WAIT UNTIL clk'EVENT and clk='1';
            a <= '1';
            xin_i <= testin(num);
            WAIT UNTIL clk'EVENT and clk='1';
            a <= '0';
            FOR i IN 0 To 9 LOOP
                WAIT UNTIL clk'EVENT and clk='1';
            END LOOP; -- 0 to 9
            r <= xout_i;
            WAIT FOR 0 ns;
            ASSERT r = testout(num) REPORT "Test " &
                INTEGER'IMAGE(num) & " failed."
                SEVERITY failure;
            END LOOP; -- numtest
            ASSERT false REPORT "test ended"
                SEVERITY failure;
        END PROCESS Pmain;
    END ARCHITECTURE zz;

```

Figure 4.1

END OF QUESTIONS

VHDL EXAM NOTES 2011

VHDL Sequential (Behavioural) Statements - inside PROCESS body

Meta-language
optional part
0 or more repetitions
grouping brackets

variable := value; -- variable assignment
 NULL; -- empty statement
 WAIT [ON signal] [UNTIL condition];
 WAIT FOR time;

IF condition THEN statements
 [ELSIF condition THEN statements]
 [ELSE statements]
 END IF;

FOR var IN range LOOP
 for-statements
 END LOOP;

CASE var IS
 WHEN case1 => statements
 [WHEN case2 => statements]
 [WHEN OTHERS => statements]
 END CASE;

S.1

- ◆ See also the dataflow statements which can also occur inside a PROCESS - previous slide
- ◆ Sequential statements (except WAIT) take zero simulation time to execute

Signal Attributes & Design Units

Signal Attributes

SIGNAL x has type T

Expression	Type	Description
x'EVENT	Boolean	TRUE if event on x
x'DELAYED(del)	T	x delayed by time del
x'LAST_VALUE	T	value of x before last or current event
x'LAST_EVENT	TIME	elapsed time from last event
x'STABLE(tim)	Boolean	FALSE if event on x within time tim

Design Units

```

ENTITY myentity IS
  GENERIC( signal-list );
  PORT( port-signal-list );
END myentity;

ARCHITECTURE archname OF entityname IS
  declaration-statements
BEGIN
  dataflow-statements
END archname;

PACKAGE mypackage IS
  declarations
END [mypackage];

PACKAGE BODY mypackage IS
  function and procedure body definitions
END PACKAGE BODY mypackage;
```

S.3

(Sequential also)

signal <= [TRANSPORT] value [AFTER time];
 subprogram(para1 [, para2 [, ...]]);

[ASSERT condition] REPORT message-if-false
 [SEVERITY level];
 level ::= note | warning | error | failure

(Dataflow only)

signal <= value WHEN condition
 [ELSE value WHEN condition]
 ELSE value;

WITH sel SELECT
 signal <= value WHEN sel-case
 [, value WHEN sel-case]
 [, value WHEN OTHERS];

label : FOR var IN range GENERATE
 dataflow-statements
 END GENERATE;

IF condition GENERATE
 dataflow-statements
 END GENERATE;

S.2

VHDL array syntax

unconstrained_array_type ::= STD_LOGIC_VECTOR | SIGNED | UNSIGNED | etc
 range ::= low TO high | high DOWNTO low | array_signal 'RANGE

TYPE my_type IS ARRAY range OF base_type;
 SUBTYPE my_subtype IS unconstrained_array_type(range);

SIGNAL | VARIABLE | CONSTANT name : unconstrained_array_type(range);

my_array(range) -- array slice on LHS or RHS
 my_array(index) -- array element on LHS or RHS
 (val1, value2, value3) -- array value using element values specified via position on RHS
 (index1=>val1, index2=>val2, ..., OTHERS=>valn) -- array value on RHS

array'LEFT array'LOW
 array'RIGHT array'HIGH
 array'LENGTH
 array'RANGE (see definitions of range above)

S.4

VHDL Dataflow statements

meta-language grouping brackets - not VHDL!

label : {ENTITY entity-name} | component-name
 GENERIC MAP(gen-map [, gen-map])
 PORT MAP(port-map [, port-map]);

[label :] PROCESS [(sensitivity-list)]
 process-declarations
 BEGIN sequential statements
 END PROCESS [label];

[label :] BLOCK local-declarations
 BEGIN dataflow-statements
 END [label];

VHDL Declarations

Declarations

```
SIGNAL name : type [ := init_val ];
CONSTANT name : type := init_val;
VARIABLE name : type [ := init_val ];
SHARED VARIABLE name : type [ := init_val ];
FILE name : type [ OPEN file_open_kind IS file_name_string ];
TYPE name : type;
```

Types

```
INTEGER 1, 123, -3456
NATURAL <non-negative integer>
REAL 1.21, -0.033
CHARACTER ' ', '0',
STRING "my string"
BOOLEAN FALSE, TRUE
TIME 10.1 ns, 11 fs, 10 min (units fs, ps, ns, ms, s, min, hr) – physical time constant
INTEGER RANGE low TO high – fixed range integer type
TYPE enumeration_type IS ( value_name_1, value_name_2, ..., value_name_n ); –enumeration type
```

S.5

VHDL Operators

Logical (not is unary)	and, or, nand, nor, xor, xnor, not S X S -> B, B X B -> B (unary S->S, B->B)
Relational	=/= (any type) <,<=,>,>= (scalar or discrete types)
Shift	sll,srl,sla,sra,rol,ror V X l -> V Shift_Left/Right_Logical/Arithmetic Rotate_Left/Right
Addition	+, - N->N, N X N -> N (all same type) Also in <i>numeric_std</i> for V X V -> V etc
Multiply	* / N X N -> N (all same type) mod, rem Integer
Misc	** N X N -> N (all same type) a ** b = a ^b abs: absolute value N->N (both same type)
Concatenation	& V X V -> V, V X S -> V, S X V -> V

Key to Types

V: std_logic_vector
N: integer or real
l: integer
S: std_logic
B: Boolean

Vector lengths a.b:
length result
a + b -> max(a,b)
a * b -> a+b
a mod b -> b

Logical, Relational,
Shift, Additive,
Concatenation ops
are synthesisable on
vectors and fixed
range integers

S.6

VHDL Text File I/O

```
TYPE file_type IS FILE OF element_type;
FILE f : TEXT: name: IN STRING;
mode: IN FILE_OPEN_KIND := read_mode);
file_open(file_f: TEXT);
file_close(file_f: TEXT);
endfile(file_f: TEXT) RETURN boolean;
readline(file_f: TEXT; line: OUT LINE);
-- read the next line from f into line
writeln(file_f: TEXT; line: INOUT: LINE);
-- write a line from line to f, clearing line
read(line: INOUT LINE; value: OUT <any-type>);
write(line: INOUT LINE; value: IN <any-type>; justified: IN SIDE := right; field: IN WIDTH := 0);
--Defines TEXT file type, LINE linebuffer type
TYPE SIDE IS (right, left);
TYPE FILE_OPEN_KIND IS (read_mode, write_mode, append_mode);
TYPE FILE_OPEN_STATUS IS (open_ok, status_error, name_error, mode_error);
```

S.7

Functions & Procedures

```
PACKAGE mypack IS
<function header>;
END PACKAGE mypack;
<function header> ::=
[IMPURE] FUNCTION myfunc(<par> { : <par> } )
RETURN rtype;
<par> ::= [<pspec>] pname : [<fmode>] ptype;
<pspec> ::= FILE | SIGNAL | VARIABLE | CONSTANT
-- omit <pspec> for value IN parameter
-- may omit <pspec> for VARIABLE OUT mode
<fmode> ::= IN | OUT | INOUT -- default mode is IN
-- functions can only have IN parameters
PACKAGE BODY mypack IS
<function_header> IS
--<function-declarations>
BEGIN
--<function-statements>
END FUNCTION;
END PACKAGE BODY mypack;
<function-statement> ::= <sequential_statement> |
RETURN expression;
```

Meta-language
□ optional part
• 0 or more repetitions
{} grouping brackets

- ◆ PROCEDURE as for FUNCTION but
 - ❖ No RETURN *rtype* in header
 - ❖ WAIT allowed in body
 - ❖ OUT, INOUT parameters are allowed
- ◆ FUNCTIONS & PROCEDURES can be defined in package body without duplicating header in package - in this case their scope is restricted to package body.
- ◆ Functions with zero parameters have no brackets in header or function call.

Built-in functions

now -- returns current simulation time
'POS -- CHARACTER -> ASCII code
'VAL -- ASCII code -> CHARACTER
<scalar_type_name>'IMAGE(<value>)
-- <value> -> printable string

S.8

Answers 2011**Question 1.**

The 5 parts of this question test basic VHDL writing & simulation skills & understanding.

a)

marks will be deducted for less compact answers.

```
PROCESS(x,y)
BEGIN
  q <= "00000";
  IF x(0)='1' THEN
    q(1 DOWNT0 0) <= "11";
  END IF;
  IF x = "00000" THEN
    q <= y;
  END IF;
END PROCESS;
```

[8 marks]

b)

```
ARCHITECTURE behav OF count IS
  SIGNAL y_i: unsigned(6 DOWNT0 0);
BEGIN
P1:PROCESS
  BEGIN
    WAIT UNTIL clk'EVENT and clk='1';
    y_i <= y_i+1;
    IF reset = '1' THEN y_i <= (OTHERS=>'0');
  END IF;
  IF y_i = to_unsigned(17,7) THEN
    y_i <= to_unsigned(-7,7);
  END IF;
END PROCESS P1;
y <= std_logic_vector(y_i);
END behav;
```

[8 marks]

c)

	delta of 1 st transition 0->1	delta of 2 nd transition 1->0
x	1	n/a
y	1	2
z	2	3
q	2	3
w	1	n/a

1 mark for each transition correct

[8 marks]

d)

ARCHITECTURE behav OF fsm IS

TYPE state IS (a,b,c);

SIGNAL ss,ss_next: state;

BEGIN

F1: PROCESS

BEGIN

WAIT UNTIL clk = '1';

IF reset = '1' THEN ss <= a;

ELSE ss <= ss_next; END IF;

END PROCESS F1;

F2: PROCESS(p,q,ss)

BEGIN

CASE ss IS

WHEN a => ss_next <= b;

y <= "00";

WHEN b => IF unsigned(p) > unsigned(q)

THEN ss_next <= a;

ELSE ss_next <= c;

END IF;

y <= "01";

WHEN c => ss_next <= a; y <= "10";

END CASE;

END PROCESS F2;

END ARCHITECTURE behav;

[8 marks]

e)

	0-5	5-10	10-15	15-20	20-25	25-30	30-35	35-40	marks
clk	0	0	1	1	0	0	1	1	1
x	0	0	0	0	0	1	1	1	1
y	U	U	0	0	0	0	1	1	2
z	U	U	U	U	0	0	0	0	2

[6 marks]

Code could be made synthesisable by splitting P1 into two separate processes, each clocked by different clk edge, and driving y from the positive edge process, z from the negative edge process.

[2 marks]

Question 2.

Long, but straightforward, test of ability to write structural code

a) $d = 32ab + 8b^3 + c^4$

[5 marks]

b)

```

LIBRARY IEEE; USE IEEE.std_logic_1164.ALL;
USE IEEE.numeric_std.ALL;
ENTITY polynomial IS
PORT( a,b,c:IN unsigned(7 DOWNTO 0);
      d: OUT unsigned(32 DOWNTO 0);
      s: OUT unsigned(2 DOWNTO 0));
END polynomial;

ARCHITECTURE struct OF polynomial IS
-- b1-b6 are data outputs from blocks
  SIGNAL b2, b4, p_b3: unsigned(32 DOWNTO 0);
  SIGNAL b1: unsigned(15 DOWNTO 0);
  SIGNAL b5: unsigned(31 DOWNTO 0);
  SIGNAL p_b2: unsigned(23 DOWNTO 0);
  SIGNAL sat: std_logic_vector(5 DOWNTO 1); -- sat outputs
BEGIN

  p_b2 <= "000000" & b1 & "00";
  p_b3 <= resize(a,30) & "000";

PROCESS(sat) -- add the sat(i) outputs
  VARIABLE sum: unsigned(2 DOWNTO 0);
BEGIN
  sum := "000";
  FOR i in sat'RANGE LOOP
    sum := sum + unsigned('0','0',sat(i));
  END LOOP;
  s <= sum;
END PROCESS;

IB1: ENTITY WORK.mult_sat
  GENERIC MAP(w_in=>8,w_out=>16)
  PORT MAP(p=>a,q=>b,x=>b1,saturated=>sat(1));

IB2: ENTITY WORK.add_sat GENERIC MAP(w_in=>24,w_out=>24)
  PORT MAP(p=>p_b2,q=>b4,sum=>b2,saturated=>sat(2));

IB3: ENTITY WORK.add_sat
  GENERIC MAP(w_in=>33,w_out=>33)
  PORT MAP(p=>p_b3,q=>b5,sum=>d,saturated=>sat(3));

IB4: ENTITY WORK.power_sat
  GENERIC MAP(w_in=>8,w_out=>24, n=>3)
  PORT MAP(p=>b,x=>b4,saturated=>sat(4));

IB5: ENTITY WORK.power_sat
  GENERIC MAP(w_in=>8,w_out=>33, n=>4)
  PORT MAP(p=>c,x=>b1,saturated=>sat(5));

END ARCHITECTURE struct;

```

[25 marks]

Question 3.

The code written here (can be) short, but the question involves quite difficult conceptual issues.

a) The numbers are limited to the max or min two's complement value for the output bus and are thus always as close as is possible to the correct value even with overflow.

[3 marks]

d) [15 marks]

```
ARCHITECTURE behav OF power_sat_signed IS
    SIGNAL s: unsigned(n*w_in DOWNT0 0); -- long enough for result+1,
    to keep sign
BEGIN
```

--b) [6 marks]

```
    ASSERT n >= 0 and w_out <= n*w_in and w_out >0 and w_in > 0
    REPORT "n or wout invalid";
    SEVERITY failure;
```

-- end of b)

```
    IF n /= 0 GENERATE
    P1: PROCESS(p)
        VARIABLE x1: unsigned(n*w_in DOWNT0 0);
    BEGIN
        saturated <= '0';
        x1 := to_unsigned(1,w_out);
```

--c) [6 marks]

```
        FOR i IN n DOWNT0 1 LOOP
            x1 := resize(x1 * p, n*w_in+1);
        END LOOP;
-- this uses n multipliers so is expensive for large n
-- end of c)
```

```
        IF x1 >= 2**(w_out-1) THEN
            saturated <= '1';
            x <= to_unsigned(-(2**(w_out-1)),w_out);
        END IF;
        IF x1 < -2**(w_out-1) THEN
            saturated <= '1';
            x <= to_unsigned(-(2**(w_out-1)),w_out);
        END IF;
    END PROCESS P1;
```

```
END GENERATE;
```

```
    IF n = 0 GENERATE
        saturated <= '0';
        x <= to_signed(1,x'length);
    END GENERATE;
```

```
END ARCHITECTURE behav;
```

Question 4.

This question is quite easy but requires independent thinking and tests ability to reason about testbenches and test strategies.

- a) The wait on clock edge statements will result in code after executing in same delta as clk + edge, therefore dut output is read on this delta BEFORE any clk clocked outputs from dut have time to change in new cycle. Dut input is driven in clk edge + 1 delta. This is OK because the hold time for all dut f-fs clocked by clk will be met, and in a synchronous system any small delay on inputs is acceptable.

[5 marks]

- b) For ith test data in = testin(i), data out = testout(i) for test to pass. xin is set to input data during single cycle where a is pulsed 1 and stays equal to this throughout the test. The output is checked on the clock edge 10 cycles after a goes to 0. All inputs & outputs change on positive edge of clock. For tests to be independent the dut must have no internal state preserved from one test to the next - e.g. it is reset by a=1.

[5 marks]

- c) we need to test corner cases, 0,-1,1 & 1000 (since output might overflow). and max & min values: +32767, -32768. The remaining 4 values don't matter very much, choose two positive & two negative roughly even throughout range: 10000,20000,-10000,-20000. Testin() must be set with these 10 values in any order.

[6 marks]

```
PACKAGE testpack IS
  TYPE intarray IS ARRAY (0 TO 9) OF INTEGER;
  CONSTANT testin : intarray := (0,1,-1,1000,32767,-32768,10000,20000,-10000,-20000);
END PACKAGE testpack;
```

[4 marks]

- d) $1\text{ms} * 2^{16} = 64$ seconds => exhaustive testing is no problem and easier than anything else - ad hoc testing is not needed. $1\text{ms} * 2^{32} = 50$ days. Too long for sensible exhaustive testing therefore tests should be both ad hoc (to catch corner cases) and random (to catch rest. Probably a few 1000 random samples, with ad hoc samples added, would give very good test coverage.

[10 marks]