- Various Descriptions of Majority Gate
- When-else
- If-else
- Concurrent Statements versus Processes
- Priority Circuits and Multiplexers
- Ripple Carry Adders

Introduction To VHDL for Combinational Logic

- VHDL is a language used for simulation and synthesis of digital logic.
- A VHDL description of a digital system can be transformed into a gate level implementation.
- This process is know as **synthesis**.
- It is important to understand how statements are **compiled** by VHDL tools to combinational logic

A Sample Model

Description

Implementation

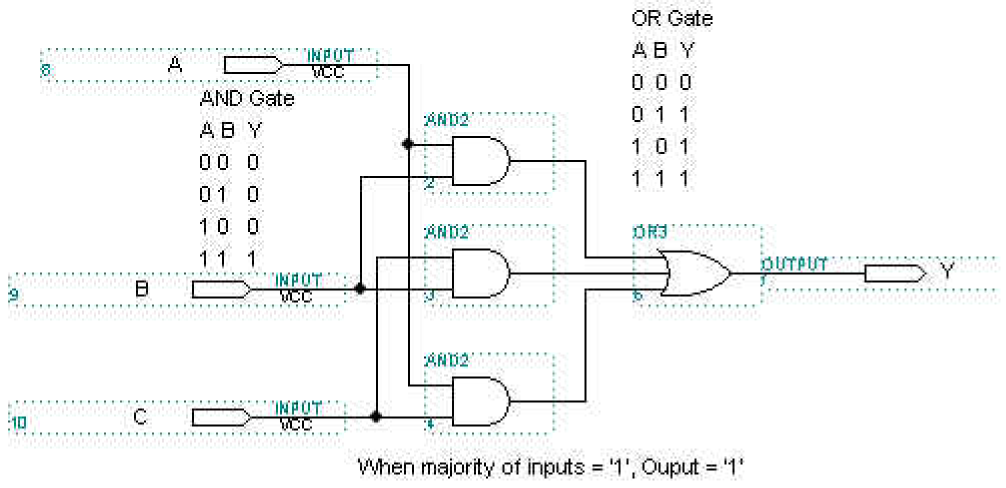
```
library ieee;
use ieee.std_logic_1164.all;

entity majconc is
    port ( A, B, C : in std_logic;
              Y: out std_logic
           );
end majconc;

ARCHITECTURE a of majconc is

begin

Y <= (A and B) or (A and C) or (B and C);
end a;
```



AND Gate

A	B	Y
0	0	0
0	1	0
1	0	0
1	1	1

OR Gate

A	B	Y
0	0	0
0	1	1
1	0	1
1	1	1

When majority of inputs = '1', Ouput = '1'

Majority gate: Variant 1

VHDL Statements

- VHDL has a reputation as a complex language (it is!)
- We will use a subset of the language for our purposes
- Some VHDL constructs:
  - Signal Assignment: A <=   B;
  - Comparisons   = (equal), > (greater than), < (less than), etc.
  - Boolean operations   AND, OR, NOT, XOR
  - Sequential statements (CASE, IF, FOR)
  - Concurrent statements (when-else)
- READ YOUR BOOK. We will cover VHDL by 'example'; will explain VHDL constructs as we get to them.   The book has many examples.
- SPIRAL APPROACH.

VHDL Combinational Template

- Every VHDL model is composed of an entity and at least one architecture .
- *Entity* describes the interface to the model (inputs, outputs)
- Architecture describes the behavior of the model
- Can have multiple architectures for one entity (we will only use one in this class).

A VHDL Template for Combinational Logic

```
entity  model_name is
      port  (
               list of inputs and outputs );
    end model_name;
  architecture  arch_name  of model_name is
    begin
        concurrent statement 1
        concurrent statement 2
         ... concurrent statement N;

    end  arch_name ;
```

Order of these statements is not important

- All of the text not in **italics** are VHDL keywords.
- VHDL is NOT case sensitive.
    - (ENTITY is same as entity is same as EnTiTy).

Majority Gate Example

The following is an example of a three input XOR gate (majority gate) implemented in VHDL

```
library ieee;
use ieee.std_logic_1164.all;

entity majority is
    port ( A, B, C : in std_logic;      -- two dashes is a COMMENT in VHDL
              Y: out std_logic
            );
end majority;
-- this is the architecture declaration, uses only one concurrent statement.

ARCHITECTURE concurrent of majority is

begin

Y <= (A and B) or (A and C) or (B and C);
end concurrent;
```

This is a style of one big expression

Majority Gate with Temporary Signals

The following version of the majority gate uses some **temporary signals** (entity has been left out, is same).

```
-- the architecture now uses 4 concurrent statements

ARCHITECTURE  newconc of majority is
   signal t1, t2, t3 : std_logic ;

begin
  t1 <=  A and B;
  t2 <=  A and C;
  t3 <=  B and C;
  Y <=  t1 or t2 or t3;
end newconc;
```

Majority gate: Variant 2

Explain why this style is often more convenient to use

Note that temporary signals are declared between architecture statement and begin statement.

Concurrent statement, no process

Majority Gate with when-else statement

The following version of the majority gate uses a 'when-else' statement:

```
-- the architecture now uses a when-else statement.

ARCHITECTURE whenelse of majority is

begin
   Y <=  '1' when ( (A and B) or (A and C) or (B and C))
                 else '0';
end whenelse;
```

Majority gate: Variant 3

Concurrent statement, no process

- You will find that there are many different ways to accomplish the same result in VHDL.
- There is usually no best way; just use one that you feel most comfortable with.

Concurrent Versus Sequential Statements

- The statements we have looked at so far are called concurrent statements.
  - Each concurrent statement will synthesize to a block of logic.
- Another class of VHDL statements are called sequential statements.
  - Sequential statements can ONLY appear inside of a process block.
  - A **process block** is considered to be a single concurrent statement.
  - Can have multiple process blocks in an architecture.
  - Usually use process blocks to describe **complex** combinational or sequential logic.

Majority Gate using *process* block and *if* statement

The entity declaration has been left out (same as before).

```
ARCHITECTURE ifstate of majority is

begin
   main: process (A, B, C)
     begin
          Y <= '0';      -- default output assignment.
           if ((A = '1') and (B = '1')) then
              Y <= '1';
           end if;
           if ((A = '1') and (C = '1') ) then
              Y <= '1';
           end if;
           if ((B = '1') and (C = '1') ) then
              Y <= '1';
           end if;
      end process main;
end ifstate;
```

name of a process

Majority gate: Variant 4

name of a process

process

Comments on process block model

- The first line in the process "main: process (A, B, C)" has the **name of the process** (main) and the *sensitivity list of the process*.
  - The process name is user defined, can also be left out (unnamed process).
  - The sensitivity list should contain any signals that appear on the ***right hand side*** of an assignment (inputs) or in any boolean for a sequential control statement.
- The ***if*** **statement condition** must return a boolean value (TRUE or FALSE) so that is why the conditional is written as:

  ((A='1') and (B= '1'))

- **Cannot write** it as:

  (A and B)

  because this will return a **'std_logic'** type (more on types later).

Use of *if-else*

```
ARCHITECTURE ifelse of majority is

begin
   process (A, B, C)
     begin

          if (((A = '1') and (B = '1')) or
             ((A = '1') and (C = '1')) or
             ((B = '1') and (C = '1')) ) then
            Y <= '1';
          else
             Y <= '0';
          end if;

     end process;
end ifelse;
```

Comments:
Process is anonymous (no name)
Used an 'else' clause to specify what the output should be if the if condition test was not true.

CAREFUL!
use parenthesis to define precedence order

Majority gate: Variant 5

process

Unassigned outputs in Process blocks

```
ARCHITECTURE bad of majority is

begin
    process (A, B, C)
      begin

            if (((A = '1') and (B = '1')) or
                ((A = '1') and (C = '1')) or
                ((B = '1') and (C = '1')) ) then
              Y <= '1';
            end if;

      end process;
end bad;
```

```
else
          Y <= '0';
```

A common mistake in writing a combinational process is to leave an output unassigned.

If there is a path through the process in which an output is NOT assigned a value, then that value is unassigned.

Comments on ‘bad’ architecture

- In the above process, the ELSE clause was left out. If the 'if' statement condition is false, then the output Y is not assigned a value.
  - In synthesis terms, **this means the output Y should have a LATCH placed on it!**
  - The synthesized logic will have a latch placed on the Y output; **once Y goes to a '1', it can NEVER return to a '0'**!!!!!
- This is probably the ***#1 student mistake*** in writing processes.
- To avoid this problem do one of the following things:
  - **1.** ALL signal outputs of the process should have DEFAULT assignments right at the beginning of the process (this is my preferred method, is easiest).
  - **2.** OR, all 'if' statements that affect a signal must have ELSE clauses that assign the signal a value if the 'if' test is false.

Priority circuit example

```
library ieee;
use ieee.std_logic_1164.all;
entity priority is
   port ( y1, y2, y3, y4, y5, y6, y7 : in std_logic;
            dout: out std_logic_vector(2 downto 0)
  );
end priority;
architecture ifels of priority  is
begin
-- priority circuit, Y7 highest priority input
-- Y1 is lowest priority input
process (y1, y2,y3, y4, y5, y6, y7)
begin
if (y7 = '1') then dout <= "111";
elsif (y6 = '1') then dout <= "110";
elsif (y5 = '1') then dout <= "101";
elsif (y4 = '1') then dout <= "100";
elsif (y3 = '1') then dout <= "011";
elsif (y2 = '1') then dout <= "010";
elsif (y1 = '1') then dout <= "001";
else dout <= "000";
end process;
end ifels;
```

• This priority circuit has 7 inputs; Y7 is highest priority, Y0 is lowest priority.

• Three bit output should indicate the highest priority input that is a '1' (ie. if Y6 ='1' and Y4 = '1', then output should be "110").

•If no input is asserted, output should be "000".

Y7 is highest priority so it is checked first

This is inside the process so order is important

Comments on Priority Example

- This is the first example that used a **bus**.
- The DOUT signal is a **3 bit output bus**.
  - std_logic_vector**(2 downto 0)** describes a 3 bit bus where dout(2) is most significant bit, dout(0) is least significant bit.
  - std_logic_vector (0 to 2) is also a 3 bit bus, but dout(0) is MSB, dout(2) is LSB. We will usually use 'downto' in this class.
- A **bus assignment** can be done in **many ways**:
  - dout <= "110"; assigns all three bits
  - dout(2) <= '1'; assigns only bit #2
  - dout(1 downto 0) <= "10"; assigns two bits of the bus.
- This architecture used the 'elsif' form of the 'if' statement
  - Note that it is 'elsif', NOT 'elseif'.
  - This called an **elsif chain.**

```
library ieee;
use ieee.std_logic_1164.all;
entity priority is
   port ( y1, y2, y3, y4, y5, y6, y7 : in
std_logic;
            dout: out std_logic_vector(2
downto 0)
  );
end priority;
architecture ifels of priority  is
begin
-- priority circuit, Y7 highest priority
input
-- Y1 is lowest priority input
process (y1, y2,y3, y4, y5, y6, y7)
begin
if (y7 = '1') then dout <= "111";
elsif (y6 = '1') then dout <= "110";
elsif (y5 = '1') then dout <= "101";
elsif (y4 = '1') then dout <= "100";
elsif (y3 = '1') then dout <= "011";
elsif (y2 = '1') then dout <= "010";
elsif (y1 = '1') then dout <= "001";
else dout <= "000";
end process;
end ifels;
```

Priority Circuit with just IF statements.

```
architecture plainif of priority  is
begin
-- priority circuit, Y7 highest priority input
-- Y1 is lowest priority input
process (y1, y2,y3, y4, y5, y6, y7)
begin
dout <= "000;
if (y1 = '1') then dout <= "001"; end if;
if (y2 = '1') then dout <= "010"; end if;
if (y3 = '1') then dout <= "011"; end if;
if (y4 = '1') then dout <= "100"; end if;
if (y5 = '1') then dout <= "101"; end if;
if (y6 = '1') then dout <= "110"; end if;
if (y7 = '1') then dout <= "111"; end if;
end process;
end plainif;
```

By **reversing** the order of the assignments, we can accomplish the same as the elsif priority chain.

In a process, the LAST assignment to the output is what counts.

Y7 is highest priority so it is **checked last**

Because in process the last value assigned wins!!

Priority Circuit with when-else statements.

```
architecture whenelse of priority  is
begin
-- priority circuit, Y7 highest priority input
-- Y1 is lowest priority input
-- uses just one when-else concurrent statement.
dout <= "111"   when (y7 = '1') else
           "110"   when (y6 = '1') else
           "101"   when (y5 = '1') else
           "100"   when (y4  = '1') else
           "011"   when (y3  = '1') else
           "010"   when (y2  = '1') else
           "001"   when (y1  = '1') else
           "000";

end process;
end whenelse;
```

- **No process;**
- just one concurrent *when-else* statement.

A Bad attempt at a Priority Circuit

```
architecture bad of priority  is
begin
-- priority circuit, Y7 highest priority input
-- Y1 is lowest priority input
-- uses just one when-else concurrent statement.
dout <= "111"   when (y7 = '1') else "000";
dout <= "110"   when (y6 = '1') else "000";
dout <= "101"   when (y5 = '1') else "000";
dout <= "100"   when (y4 = '1') else "000";
dout <= "011"   when (y3 = '1') else "000";
dout <= "010"   when (y2 = '1') else "000";
dout <= "001"   when (y1 = '1') else "000";
dout <= "000" ;

end process;
end bad;
```

You cannot assign to the same signal **dout** on left, repeated many times in concurrent statements!!

Comments on “bad” Priority Circuit

- There are TWO things wrong with this description.
- *1. There are multiple concurrent statements <u>driving the DOUT</u> signal.*
  - This means MULTIPLE GATE output are tied to dout signal!
  - Physically, this will create an unknown logic condition on the bus.

This is a bad attempt by a neophyte VHDL writer at a priority circuit.

```
architecture bad of priority  is
begin
-- priority circuit, Y7 highest priority input
-- Y1 is lowest priority input
-- uses just one when-else concurrent statement.
dout <= "111"   when (y7 = '1') else "000";
dout <= "110"   when (y6 = '1') else "000";
dout <= "101"   when (y5 = '1') else "000";
dout <= "100"   when (y4 = '1') else "000";
dout <= "011"   when (y3 = '1') else "000";
dout <= "010"   when (y2 = '1') else "000";
dout <= "001"   when (y1 = '1') else "000";
dout <= "000" ;

end process;
end bad;
```

Comments on "bad" Priority Circuit

- 2. The writer seems to think that the order of the concurrent statements makes a difference (ie, the last concurrent statement just assigns a '000').
  - **The order in which you arrange concurrent statements MAKES NO DIFFERENCE.** The synthesized logic will be the same.
  - Ordering of statements only **makes a difference within a process**. This is why statements within a process are called '**sequential**' statements; the logic synthesized reflects the statement ordering
  - Of course, makes a difference only for assignments to the same output: A <=2, A<=3, last wins.

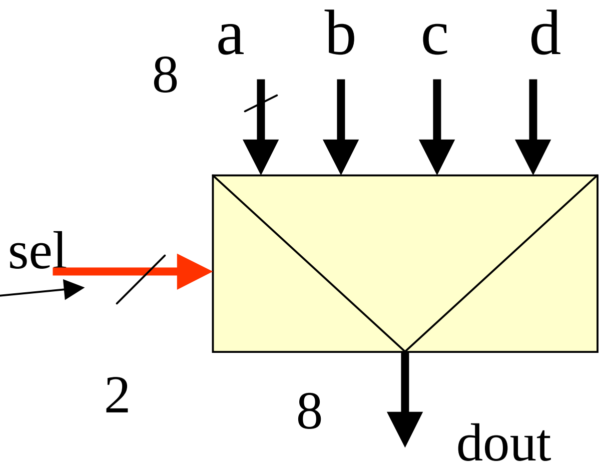
```
architecture bad of priority  is
begin
-- priority circuit, Y7 highest priority input
-- Y1 is lowest priority input
-- uses just one when-else concurrent statement.
dout <= "111"   when (y7 = '1') else "000";
dout <= "110"   when (y6 = '1') else "000";
dout <= "101"   when (y5 = '1') else "000";
dout <= "100"   when (y4 = '1') else "000";
dout <= "011"   when (y3 = '1') else "000";
dout <= "010"   when (y2 = '1') else "000";
dout <= "001"   when (y1 = '1') else "000";
dout <= "000" ;

end process;
end bad;
```

NEW EXAMPLE: 4-to-1 mux with 8 bit Datapaths

```
library ieee;
use ieee.std_logic_1164.all;
entity mux4to1_8 is
   port ( a,b,c,d : in std_logic_vector(7 downto 0);
             sel: in std_logic_vector (1 downto 0);
            dout: out std_logic_vector(7 downto 0)
  );
end mux4to1_8;
architecture whenelse of mux4to1_8  is
begin
dout <=  b when (sel = "01") else
              c  when (sel  = "10") else
             d when (sel = "11") else
              a;       -- default

end process;
end whenelse;
```



We do not use ***with***

Comments on Mux example

- This is one way to write a mux, but is **not the best** way.
- The **when-else** structure here is actually a *priority structure*.
  - A mux has no priority between inputs, just a simple selection.
  - The synthesis tool has to work harder than necessary to understand that all possible choices for **sel** are specified and that no priority is necessary.
- Just want a simple selection mechanism.

```
library ieee;
use ieee.std_logic_1164.all;
entity mux4to1_8 is
   port ( a,b,c,d : in std_logic_vector(7 downto 0);
             sel: in std_logic_vector (1 downto 0);
            dout: out std_logic_vector(7 downto 0)
  );
end mux4to1_8;
architecture whenelse of mux4to1_8  is
begin
dout <=  b when (sel = "01") else
               c  when (sel  = "10") else
              d when (sel = "11") else
               a;      -- default

end process;
end whenelse;
```

repeated

A better way uses "with"

4-to-1 Mux using Select Concurrent Statement

```
architecture select_statement of mux4to1_8  is
begin
with sel  select
   dout <= b when  "01",
                     c when  "10",
                     d when "11",
                     a when others;
end select_statement;
```

• Some synthesis tools will automatically recognize this structure (*using with*) as a **mux**

•They will find a more efficient implementation than using a *when-else* or *if* statement structure

• Remember in general that *when-else* and *if* structures define **priority structures for compilation**.

4-to-1 Mux using Select Concurrent Statement

```
architecture select_statement of mux4to1_8  is
begin
with sel  select
    dout <= b when  "01",
                  c when  "10",
                  d when "11",
                  a when others;
end select_statement;
```

continued

- The ***others*** case must be specified.
- This is a concurrent statement, *no process*.
- The sequential version of the select statement is the *case* statement.

4-to-1 Mux using Case Sequential Statement

```
architecture select_statement of mux4to1_8  is
begin

   process (a, b, c, d, sel)
   begin
      case sel is
           when "01"   =>    dout <= b ;
           when "10"   =>    dout <= c;
           when "11"   =>    dout <= d;
           when others  =>   dout <= a;
       end case;
    end process;
end select_statement;
```

•There can be multiple statements for each case;
• only one statement is needed for each case in this example.

Uses process, it is sequential

Concurrent => use select

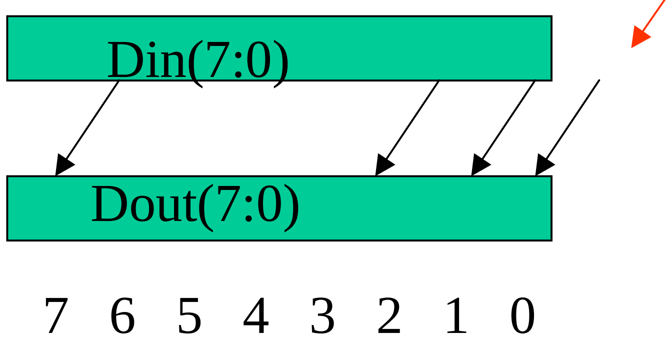
Sequential => use case

Pay attention to this arrow, how it is directed

Logical Shift Left by 1

```
library ieee;
use ieee.std_logic_1164.all;
entity lshift is
   port ( din : in std_logic_vector(7 downto 0);
             shift_en: in std_logic;
            dout: out std_logic_vector(7 downto 0)
  );
end lshift;
architecture brute_force of lshift  is
begin
```

```
process (din, shift_en)
begin
      dout <= din;     -- default case
      if (shift_en = '1') then
           dout(0) <= '0';     -- shift a zero into LSB
           dout (1) <= din(0);
           dout (2) <= din(1);
           dout (3) <= din(2);
           dout (4) <= din(3);
           dout (5) <= din(4);
           dout (6) <= din(5);
           dout (7) <= din(6);
       end if;
end process;
end brute_force;
end lshift;
```



This is one way to do it; surely there is a better way?

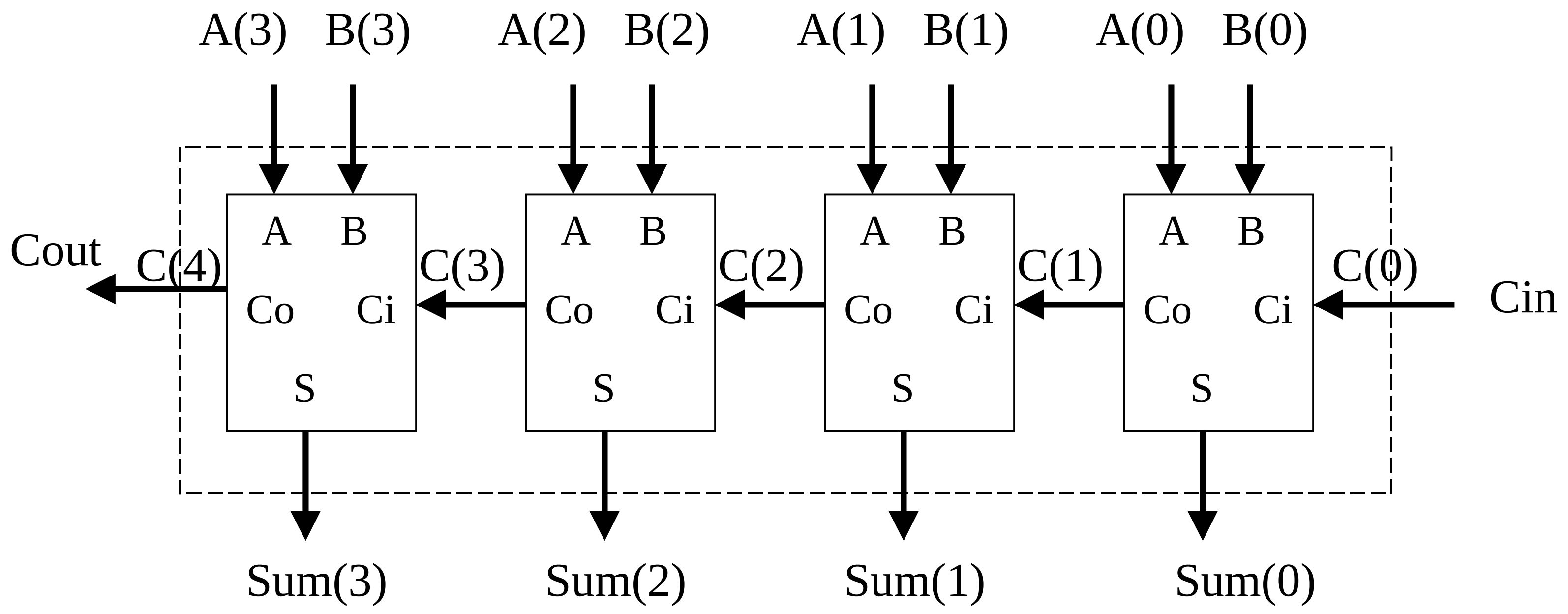
Logical Shift Left by 1 (better way)

```
architecture better of lshift  is
begin
process (din, shift_en)
begin
      dout <= din;      -- default case
      if (shift_en = '1') then
           dout(0) <= '0';     -- shift a zero into LSB
           dout (7 downto 1) <= din(6 downto 0);
       end if;
end process;
end better;
end lshift;
```

• This illustrates the assignment of a segment of one bus to **another bus segment.**

• The bus ranges on each side of the assignment statement must be the name number of bits (each 6 bits in this case).

4 Bit Ripple Carry Adder



Want to write a VHDL model for a 4 bit ripple carry adder.

Logic equation for each full adder is:

```
sum <=   a xor b xor ci;
co    <=   (a and b) or (ci and (a or b));
```

4 Bit Ripple Carry Model

```
library ieee;
use ieee.std_logic_1164.all;
entity adder4bit is
   port ( a,b: in std_logic_vector(3 downto 0);
             cin : in std_logic;
             cout: out std_logic;
             sum: out std_logic_vector(3 downto 0)
  );
end adder4bit;
architecture bruteforce of adder4bit  is
 -- temporary signals for internal carries
   signal  c : std_logic_vector(4 downto 0); .
begin
    process (a, b, cin, c)
    begin
      c(0) <= cin;
      -- full adder 0
      sum(0) <= a(0) xor b(0) xor c(0);
      c(1)     <= (a(0) and b(0)) or (c(0) and (a(0) or b(0)));
      -- full adder 1
      sum(1) <= a(1) xor b(1) xor c(1);
      c(2)     <= (a(1) and b(1)) or (c(1) and (a(1) or b(1)));
```

```
      -- full adder 2
      sum(2) <= a(2) xor b(2) xor c(2);
      c(3)      <= (a(2) and b(2)) or (c(2) and
                   (a(2) or b(2)));
      -- full adder 3
      sum(3) <= a(3) xor b(3) xor c(3);
      c(4)      <= (a(3) and b(3)) or (c(3) and
                   (a(3) or b(3)));
      cout      <= c(4);
end process;
end bruteforce;
```

- **Straight forward implementation.**
- **Nothing wrong with this.**
- **However, is there an *easier* way?**

Not very elegant for long words, not scalable

4 Bit Ripple Carry Model using *For* Statement

```
architecture forloop of adder4bit  is

   signal  c : std_logic_vector(4 downto 0);  -- temporary signals for internal carries.
begin
    process (a, b, cin, c)
    begin
      c(0) <= cin;
      for i in 0 to 3 loop
          -- all four full adders
         sum(i) <= a(i) xor b(i) xor c(i);
         c(i+1)      <= (a(i) and b(i)) or (c(i) and (a(i) or b(i)));
      end loop;

      cout      <= c(4);
     end process;
end forloop;
```

Index "i" is not a signal , not a variable.

Comments on *for-loop* statement

- To visualize what logic is created, 'unroll' the loop by writing down each loop iteration with loop indices replaced hard numbers.

```
architecture forloop of adder4bit  is

  signal  c : std_logic_vector(4 downto 0);  -- temporary signals for internal carries.
begin
    process (a, b, cin, c)
    begin
      c(0) <= cin;
      for i in 0 to 3 loop
          -- all four full adders
         sum(i) <= a(i) xor b(i) xor c(i);
         c(i+1)      <= (a(i) and b(i)) or (c(i) and (a(i) or b(i)));
      end loop;

      cout      <= c(4);
     end process;
end forloop;
```

The *for-loop* can be used to repeat blocks of logic

The loop variable *i* is implicity declared for this loop; does not have to be declared anywhere else.

Summary

- There are many different ways to write VHDL ***synthesizable models for combinational logic.***
- There is no 'best' way to write a model; for now, just use the statements/style that you feel most comfortable with and can get to work (of course!)
- READ THE BOOK!!!!!!!!
  - **There is NO WAY that we can cover all possible examples in class. The book has many other VHDL examples.**
  - **I have intentionally left out MANY, MANY language details.**
  - **You can get by with what I have shown you, but feel free to experiment with other language features that you see discussed in the book or elsewhere.**

Summary (cont.)

- SEARCH THE WWW!!!!!
  - The WWW is full of VHDL examples, tutorials, etc.
- **TRY IT OUT!!!!**
  - If you have a question about a statement or example, try it out in the Altera Maxplus package and see what happens!
- This course is about Digital System *DESIGN,* not VHDL. As such, we will only have 3-4 lectures about VHDL, the rest will be on **design** topics.
  - VHDL is only a means for efficiently implementing your design - it is not interesting by itself.
  - You will probably learn multiple synthesis languages in your design career - it is the digital design techniques that you use that will be common to your designs, not the synthesis language.

Sources

- Bob Reese