ECE 448
Lecture 4

Sequential-Circuit Building Blocks

Mixing Description Styles

Reading

Required

- P. Chu, *FPGA Prototyping by VHDL Examples*

  Chapter 4, Regular Sequential Circuit

Recommended

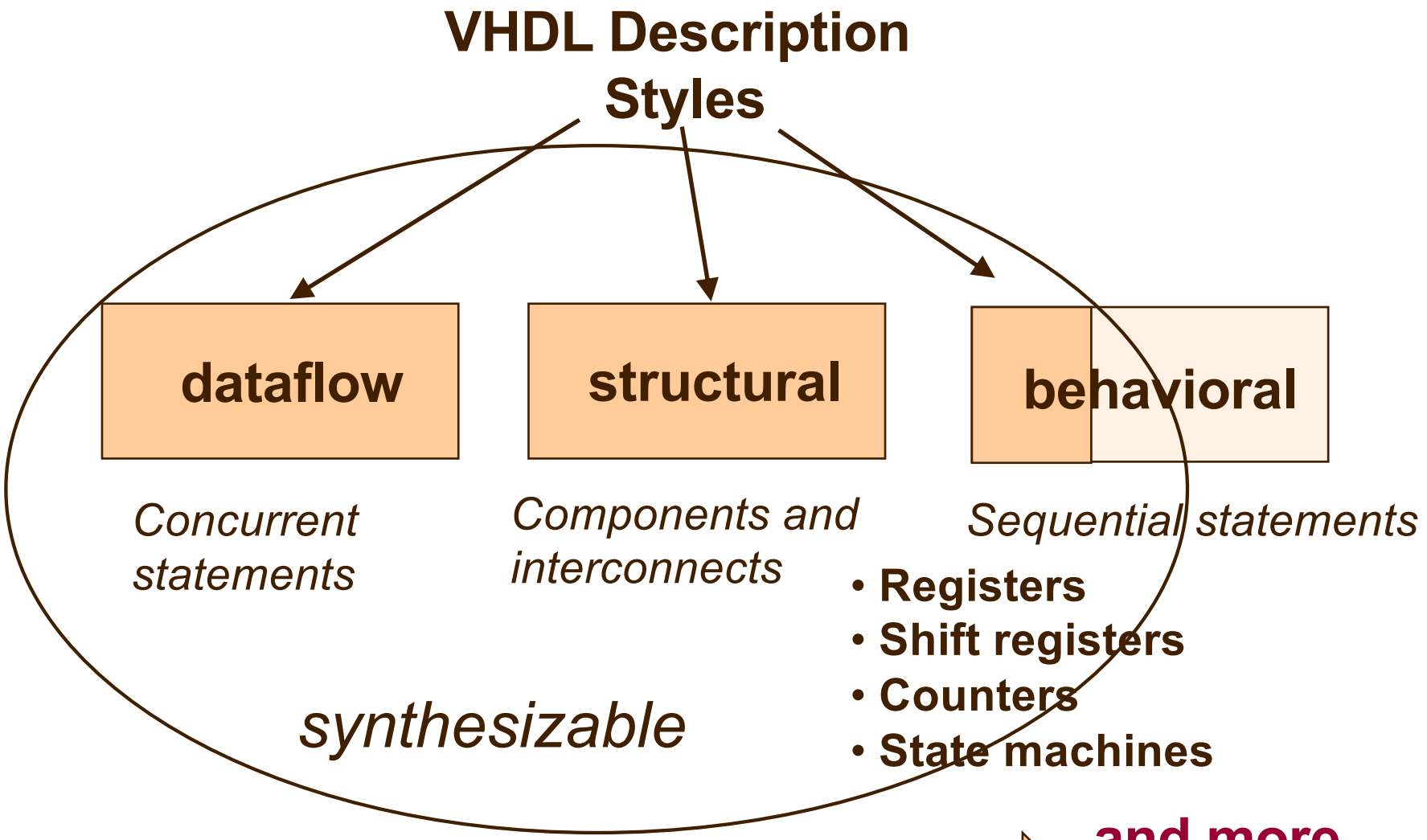
- S. Brown and Z. Vranesic, *Fundamentals of Digital Logic with VHDL Design*

  Chapter 7, Flip-Flops, Registers, Counters, and a Simple Processor



Behavioral Design Style: Registers & Counters

VHDL Description Styles



Processes in VHDL

- Processes Describe Sequential Behavior
- Processes in VHDL Are Very Powerful Statements
  - Allow to define an arbitrary behavior that may be difficult to represent by a real circuit
  - Not every process can be synthesized
- Use Processes with Caution in the Code to Be Synthesized
- Use Processes Freely in Testbenches

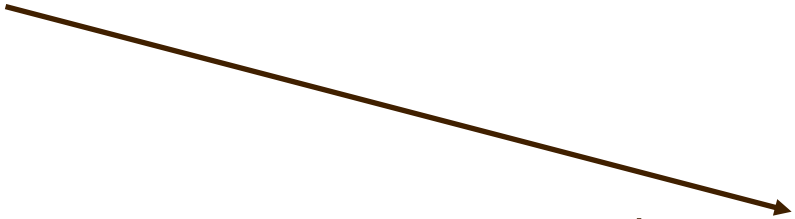
Anatomy of a Process



[label:] PROCESS [(*sensitivity list*)]
    [d*eclaration part*]
BEGIN
    statement part
END PROCESS [label];

PROCESS with a SENSITIVITY LIST

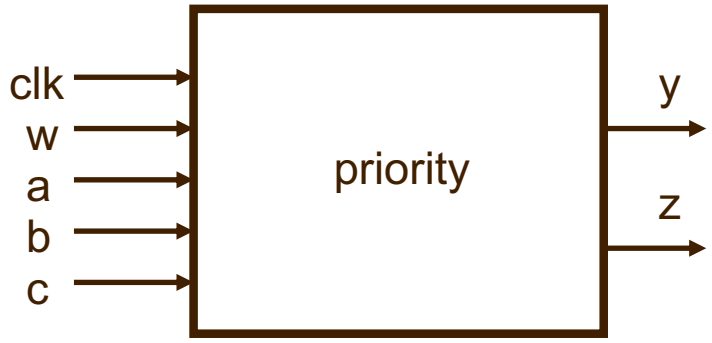
- List of signals to which the process is sensitive.
- Whenever there is an event on any of the signals in the sensitivity list, the process fires.
- Every time the process fires, it will run in its entirety.
- **WAIT statements are NOT ALLOWED in a processes with SENSITIVITY LIST.**



```
label: process (sensitivity list)
    declaration part
begin
    statement part
end process;
```

Component Equivalent of a Process

```
priority: PROCESS (clk)
BEGIN
        IF w(3) = '1' THEN
                y <= "11" ;
        ELSIF w(2) = '1' THEN
                y <= "10" ;
        ELSIF w(1) = c THEN
                y <= a and b;
        ELSE
                z <= "00" ;
        END IF ;
END PROCESS ;
```



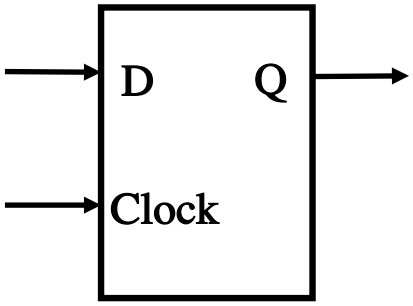
- All signals which appear on the left of signal assignment statement (<=) are outputs e.g. *y, z*
- All signals which appear in the sensitivity list are inputs e.g. *clk*
- All signals which appear on the right of signal assignment statement (<=) or in logic expressions are inputs e.g. *w, a, b, c*
- Note that not all inputs need to be included in the sensitivity list


High Performance
Low Power
Cool Clock
XILINX
CoolRunner-II

Registers

D latch

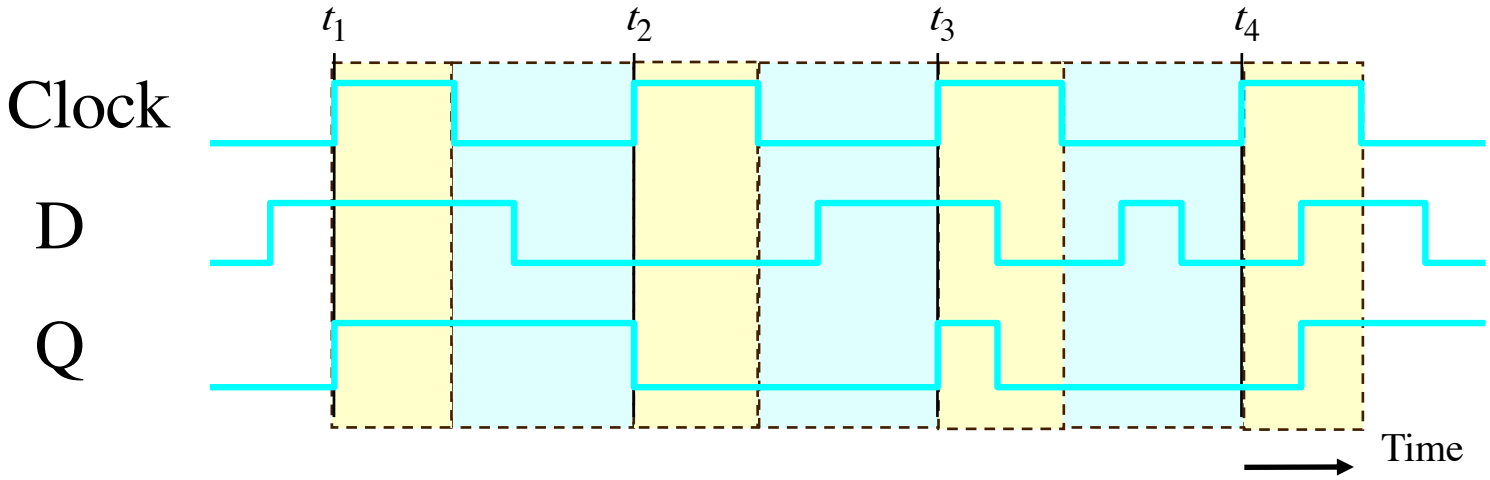
Graphical symbol



Truth table

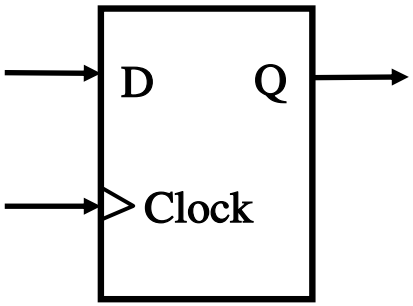
Clock	D	Q(*t*+1)
0	–	Q(*t*)
1	0	0
1	1	1

Timing diagram



D flip-flop

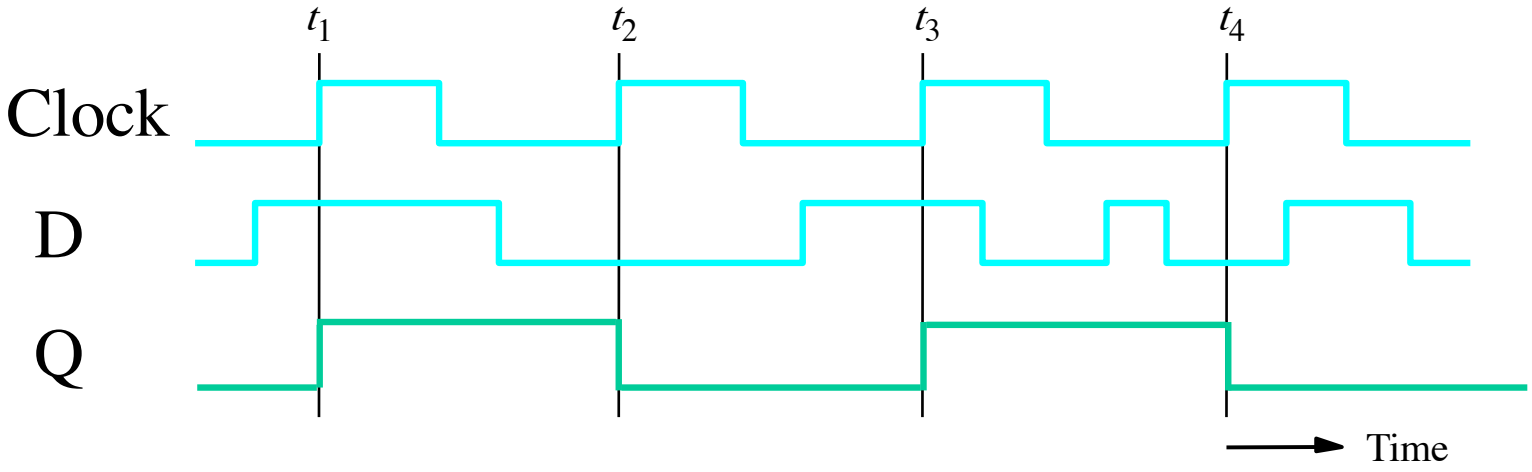
Graphical symbol



Truth table

Clk	D	Q(t+1)
↑	0	0
↑	1	1
0	–	Q(t)
1	–	Q(t)

Timing diagram

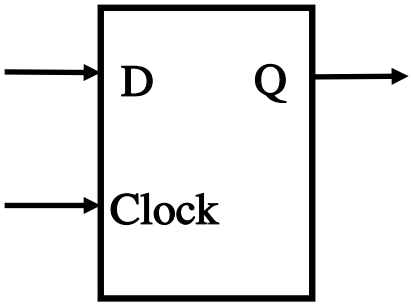


D latch

```
LIBRARY ieee ;
USE ieee.std_logic_1164.all ;

ENTITY latch IS
      PORT (   D, Clock  : IN       STD_LOGIC ;
               Q         : OUT      STD_LOGIC) ;
END latch ;

ARCHITECTURE behavioral OF latch IS
BEGIN
      PROCESS ( D, Clock )
      BEGIN
            IF Clock = '1' THEN
                  Q <= D ;
            END IF ;
      END PROCESS ;
END behavioral;
```

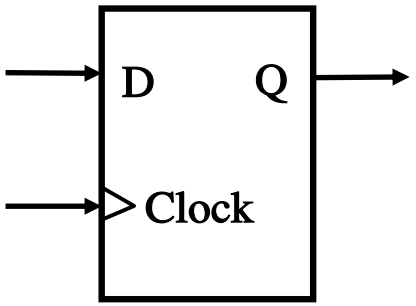


D flip-flop

```
LIBRARY ieee ;
USE ieee.std_logic_1164.all ;

ENTITY flipflop IS
      PORT (   D, Clock  : IN      STD_LOGIC ;
               Q         : OUT   STD_LOGIC) ;
END flipflop ;

ARCHITECTURE behavioral OF flipflop IS
BEGIN
      PROCESS ( Clock )
      BEGIN
           IF rising_edge(Clock) THEN
                Q <= D ;
           END IF ;
      END PROCESS ;
END behavioral;
```

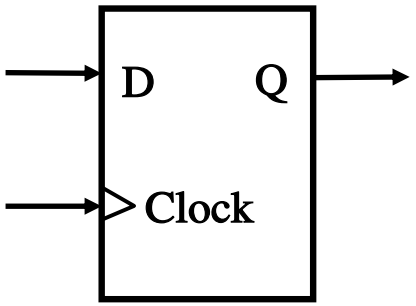


D flip-flop

```
LIBRARY ieee ;
USE ieee.std_logic_1164.all ;

ENTITY flipflop IS
      PORT (   D, Clock  : IN      STD_LOGIC ;
               Q         : OUT   STD_LOGIC) ;
END flipflop ;

ARCHITECTURE behavioral2 OF flipflop IS
BEGIN
      PROCESS ( Clock )
      BEGIN
          IF Clock'EVENT AND Clock = '1' THEN
               Q <= D ;
          END IF ;
      END PROCESS ;
END behavioral2 ;
```

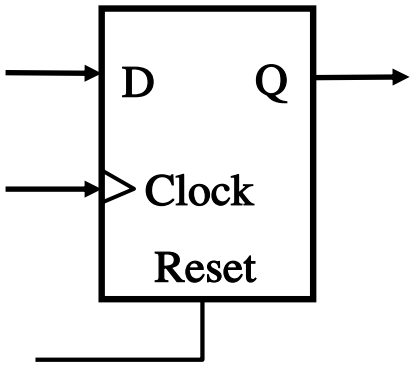


D flip-flop with asynchronous reset

```
LIBRARY ieee ;
USE ieee.std_logic_1164.all ;

ENTITY flipflop_ar IS
      PORT (   D, Reset, Clock     : IN      STD_LOGIC ;
               Q                   : OUT     STD_LOGIC) ;
END flipflop_ar ;

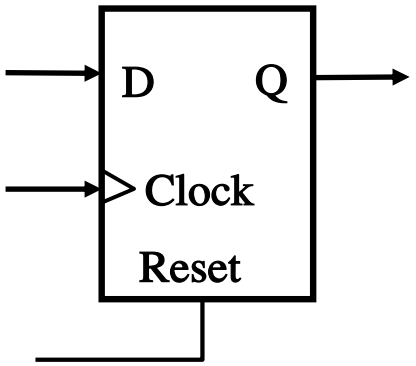
ARCHITECTURE behavioral OF flipflop_ar IS
BEGIN
      PROCESS ( Reset, Clock )
      BEGIN
            IF Reset = '1' THEN
                  Q <= '0' ;
            ELSIF rising_edge(Clock) THEN
                  Q <= D ;
            END IF ;
      END PROCESS ;
END behavioral ;
```



D flip-flop with synchronous reset

```
LIBRARY ieee ;
USE ieee.std_logic_1164.all ;
ENTITY flipflop_sr IS
        PORT (      D, Reset, Clock : IN   STD_LOGIC ;
                    Q               : OUT  STD_LOGIC) ;
END flipflop_sr ;

ARCHITECTURE behavioral OF flipflop_sr IS
BEGIN
        PROCESS(Clock)
        BEGIN
                IF rising_edge(Clock) THEN
                        IF Reset = '1' THEN
                                Q <= '0' ;
                        ELSE
                                Q <= D ;
                        END IF ;
                END IF;
        END PROCESS ;
END behavioral ;
```



Asychronous vs. Synchronous

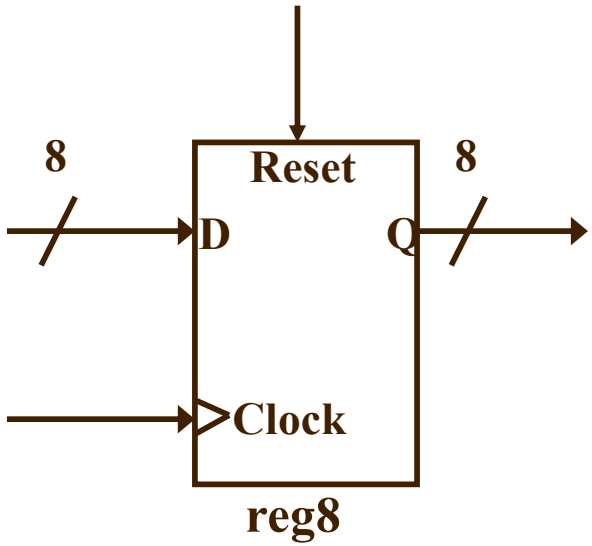
- In the IF loop, asynchronous items are
  - **Before** the rising_edge(Clock) statement
- In the IF loop, synchronous items are
  - **After** the rising_edge(Clock) statement

8-bit register with asynchronous reset

```
LIBRARY ieee ;
USE ieee.std_logic_1164.all ;

ENTITY reg8 IS
      PORT (   D                 : IN     STD_LOGIC_VECTOR(7 DOWNTO 0) ;
               Reset, Clock      : IN     STD_LOGIC ;
               Q                 : OUT    STD_LOGIC_VECTOR(7 DOWNTO 0) ) ;
END reg8 ;

ARCHITECTURE behavioral OF reg8 IS
BEGIN
      PROCESS ( Reset, Clock )
      BEGIN
            IF Reset = '1' THEN
                  Q <= "00000000" ;
            ELSIF rising_edge(Clock) THEN
                  Q <= D ;
            END IF ;
      END PROCESS ;
END behavioral ;`
```

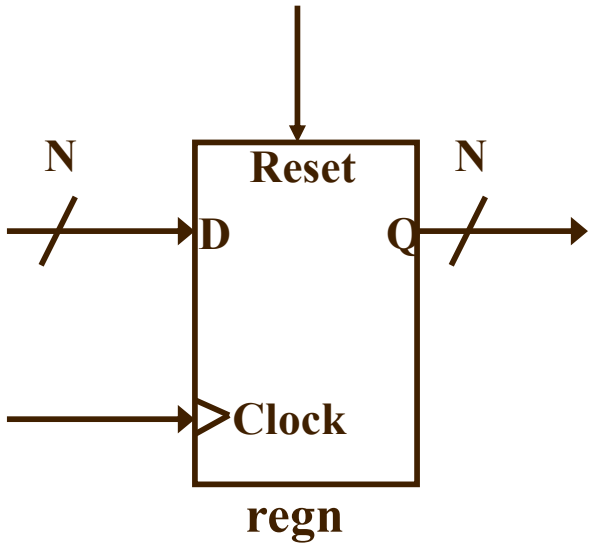


N-bit register with asynchronous reset

```
LIBRARY ieee ;
USE ieee.std_logic_1164.all ;

ENTITY regn IS
        GENERIC ( N : INTEGER := 16 ) ;
        PORT (    D              : IN     STD_LOGIC_VECTOR(N-1 DOWNTO 0) ;
                  Reset, Clock   : IN     STD_LOGIC ;
                  Q              : OUT    STD_LOGIC_VECTOR(N-1 DOWNTO 0) ) ;
END regn ;

ARCHITECTURE behavioral OF regn IS
BEGIN
        PROCESS ( Reset, Clock )
        BEGIN
                IF Reset = '1' THEN
                        Q <= (OTHERS => '0') ;
                ELSIF rising_edge(Clock) THEN
                        Q <= D ;
                END IF ;
        END PROCESS ;
END behavioral ;
```



A word on generics

- Generics are typically **integer** values
  - In this class, the entity inputs and outputs should be std_logic or std_logic_vector
  - But the generics can be **integer**
- Generics are given a default value
  - **GENERIC (N : INTEGER := 16)** ;
  - This value can be overwritten when entity is instantiated as a component
- Generics are very useful when instantiating an often-used component
  - Need an 8-bit register in one place, and 16-bit register in another
  - Can use the same generic code, just configure them differently

Use of OTHERS

OTHERS stand for any index value that has not been previously mentioned.

Q <= “00000001” can be written as Q <= (0 => ‘1’, OTHERS => ‘0’)

Q <= “10000001” can be written as Q <= (7 => ‘1’, 0 => ‘1’, OTHERS => ‘0’)
or Q <= (7 | 0 => ‘1’, OTHERS => ‘0’)

Q <= “00011110” can be written as Q <= (4 downto 1=> ‘1’, OTHERS => ‘0’)

Component Instantiation in VHDL-93

```
U1:  ENTITY work.regn(behavioral)
                GENERIC MAP (N => 4)
                PORT MAP (D => z ,
                                Reset => reset ,
                                Clock => clk,
                                Q => t );
```

Component Instantiation in VHDL-87

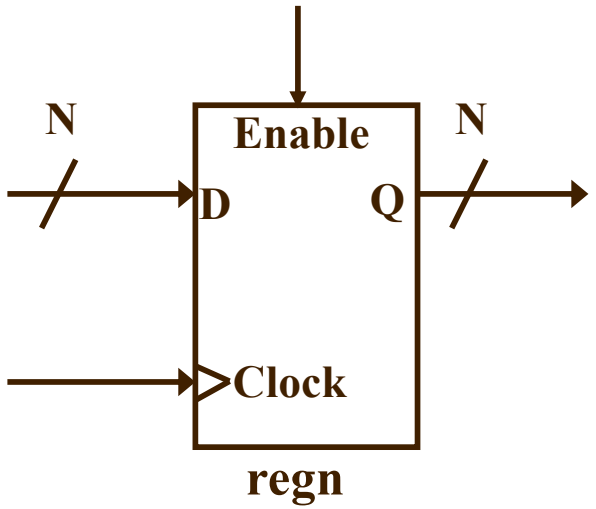
```
U1: regn      GENERIC MAP (N => 4)
              PORT MAP (D => z ,
                        Reset => reset ,
                        Clock => clk,
                        Q => t );
```

N-bit register with enable

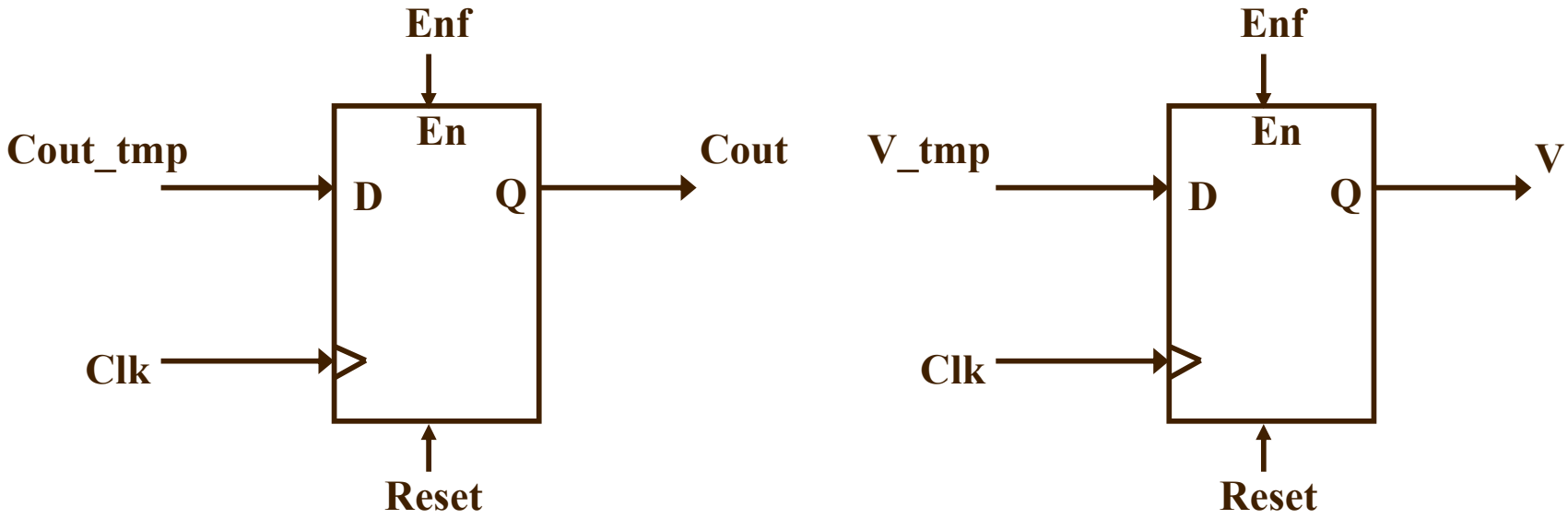
```
LIBRARY ieee ;
USE ieee.std_logic_1164.all ;

ENTITY regne IS
        GENERIC ( N : INTEGER := 8 ) ;
        PORT (      D                   : IN      STD_LOGIC_VECTOR(N-1 DOWNTO 0) ;
                    Enable, Clock       : IN      STD_LOGIC ;
                    Q                   : OUT     STD_LOGIC_VECTOR(N-1 DOWNTO 0) ) ;
END regne ;

ARCHITECTURE behavioral OF regne IS
BEGIN
        PROCESS (Clock)
        BEGIN
                IF rising_edge(Clock) THEN
                        IF Enable = '1' THEN
                                Q <= D ;
                        END IF ;
                END IF;
        END PROCESS ;
END behavioral ;
```



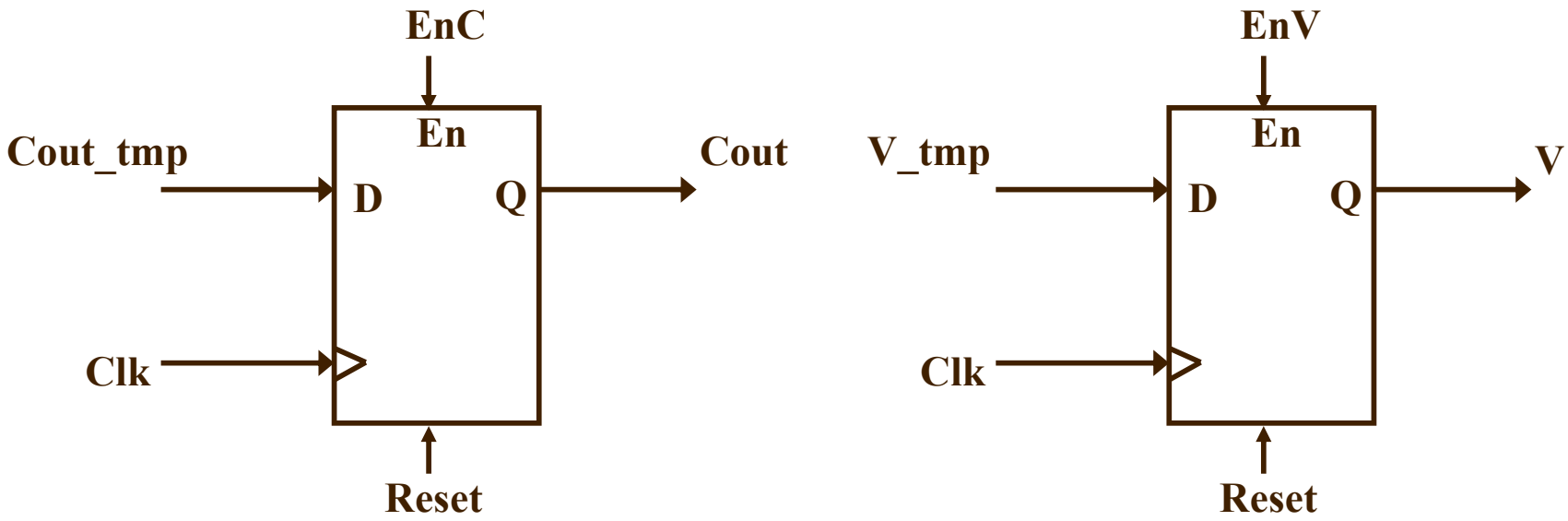
Implementing two registers in a single process



Implementing two registers in a single process

```
PROCESS (Clk, Reset)
BEGIN
        IF Reset= '1' THEN
                Cout <= '0';
                V <= '0';
        ELSIF rising_edge(Clk) THEN
                IF Enf = '1' THEN
                        Cout <= Cout_tmp ;
                        V <= V_tmp;
                END IF ;
        END IF;
END PROCESS ;
```

Implementing two registers in a single process



Implementing two registers in a single process

```
PROCESS (Clk, Reset)
BEGIN
        IF Reset = '1' THEN
                Cout <= ‘0’;
                V <= '0';
        ELSIF rising_edge(Clk) THEN
                IF EnC = '1' THEN
                        Cout <= Cout_tmp ;
                END IF ;
                IF EnV = '1' THEN
                        V <= V_tmp;
                END IF ;
        END IF;
END PROCESS ;
```

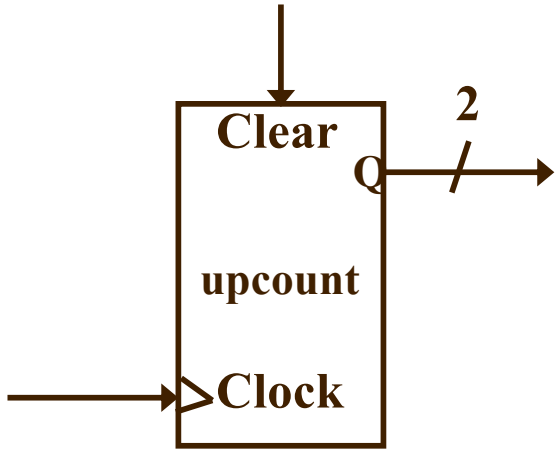


Counters

2-bit up-counter with synchronous reset

```
LIBRARY ieee ;
USE ieee.std_logic_1164.all ;
USE ieee.numeric_std.all ;
ENTITY upcount IS
        PORT (      Clear, Clock      : IN          STD_LOGIC ;
                    Q                 : OUT     STD_LOGIC_VECTOR(1 DOWNTO 0) ) ;
END upcount ;

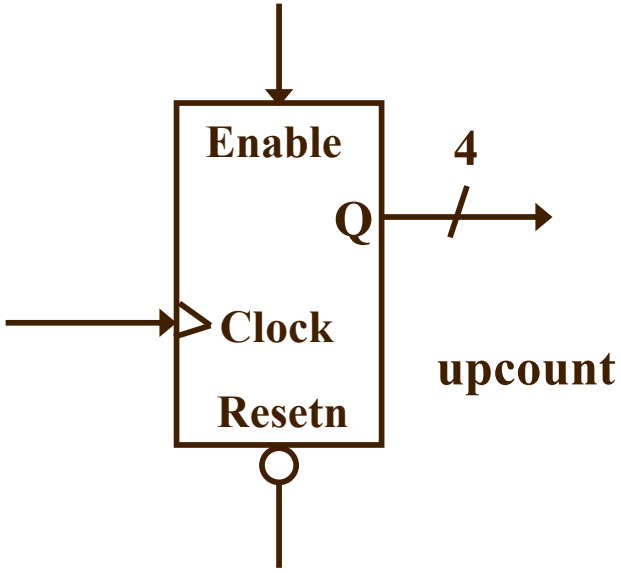
ARCHITECTURE behavioral OF upcount IS
   SIGNAL Count : unsigned(1 DOWNTO 0);
BEGIN
        upcount: PROCESS ( Clock )
        BEGIN
                IF rising_edge(Clock) THEN
                        IF Clear = '1' THEN
                                Count <= "00" ;
                        ELSE
                                Count <= Count + 1 ;
                        END IF ;
                END IF;
        END PROCESS;
       Q <= std_logic_vector(Count);
END behavioral;
```



4-bit up-counter with asynchronous reset (1)

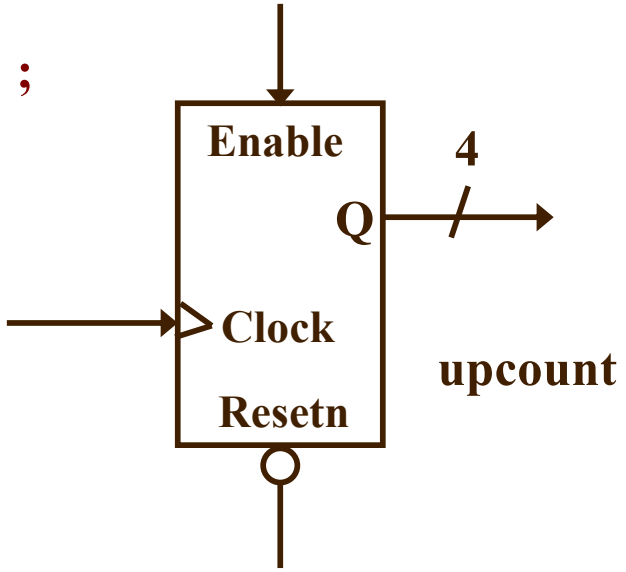
```
LIBRARY ieee ;
USE ieee.std_logic_1164.all ;
USE ieee.numeric_std.all ;

ENTITY upcount_ar IS
      PORT (   Clock, Resetn, Enable   : IN       STD_LOGIC ;
               Q                       : OUT  STD_LOGIC_VECTOR (3 DOWNTO 0)) ;
END upcount_ar ;
```



4-bit up-counter with asynchronous reset (2)

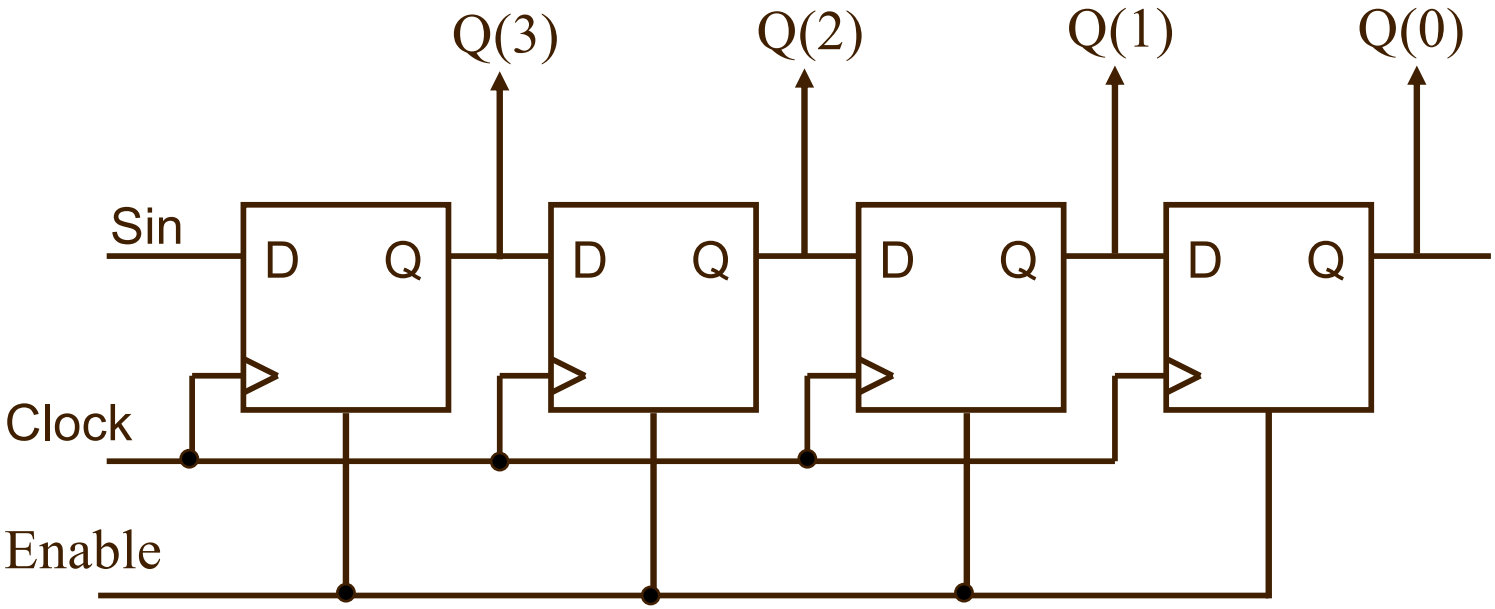
```
ARCHITECTURE behavioral OF upcount _ar IS
        SIGNAL Count : UNSIGNED (3 DOWNTO 0) ;
BEGIN
        PROCESS ( Clock, Resetn )
        BEGIN
                IF Resetn = '0' THEN
                        Count <= "0000" ;
                ELSIF rising_edge(Clock) THEN
                        IF Enable = '1' THEN
                                Count <= Count + 1 ;
                        END IF ;
                END IF ;
        END PROCESS ;
        Q <= std_logic_vector(Count) ;
END behavioral ;
```



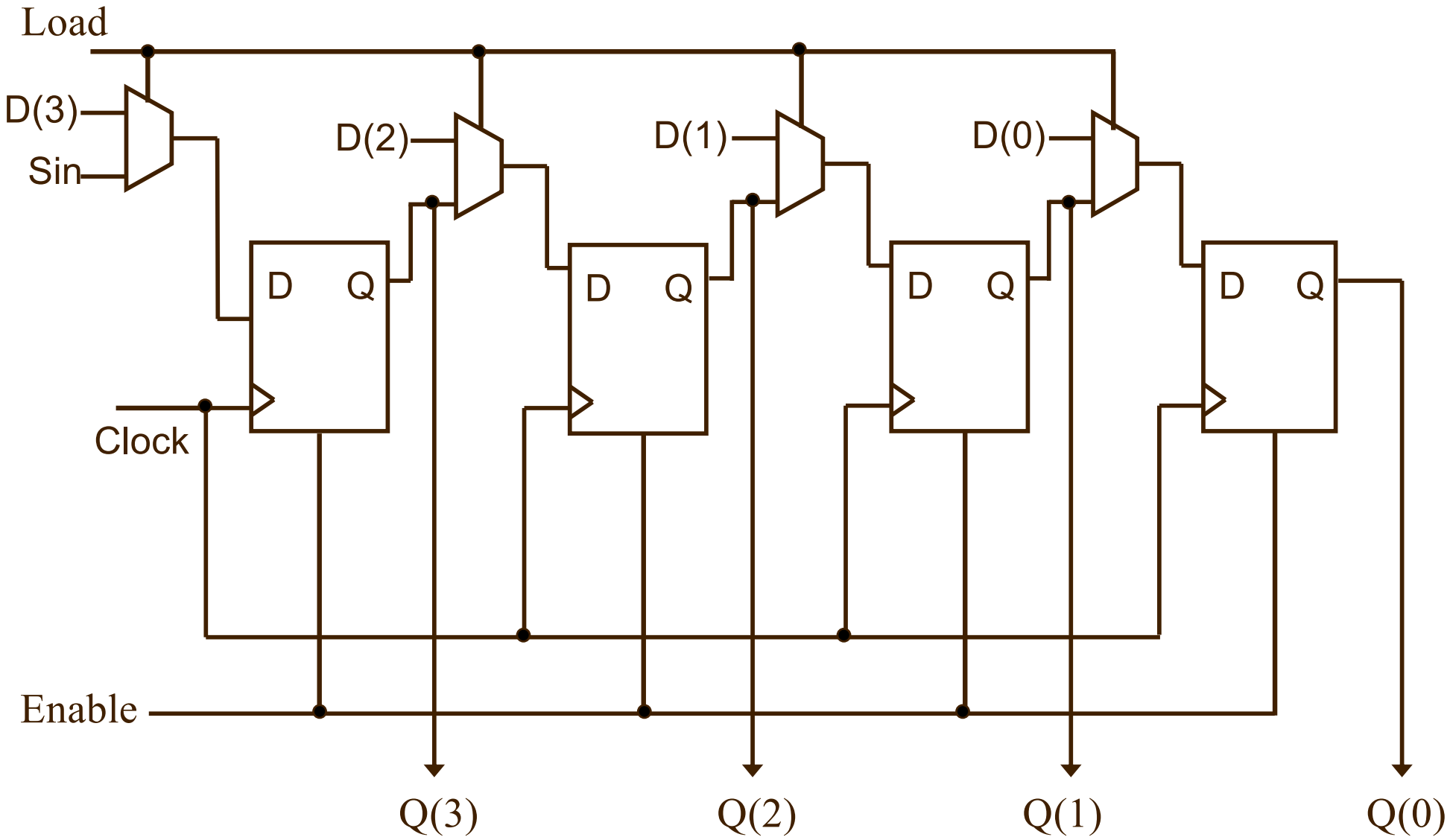


Shift Registers

Shift register – internal structure



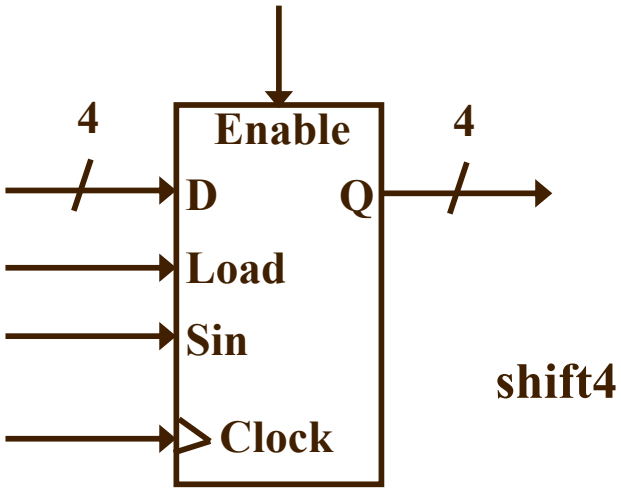
Shift Register With Parallel Load



4-bit shift register with parallel load (1)

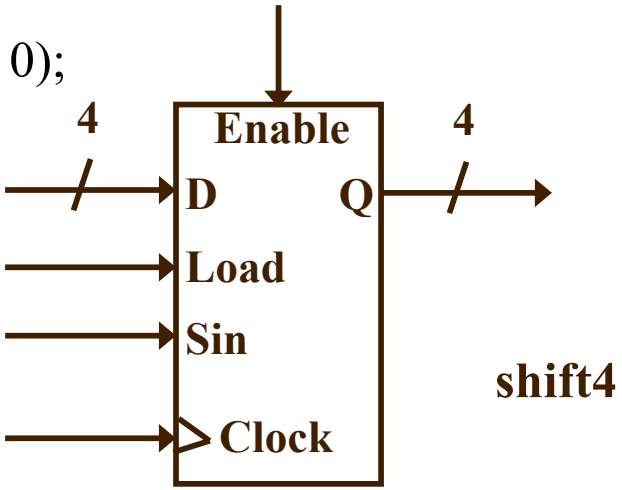
```
LIBRARY ieee ;
USE ieee.std_logic_1164.all ;

ENTITY shift4 IS
      PORT (   D        : IN     STD_LOGIC_VECTOR(3 DOWNTO 0) ;
               Enable   : IN     STD_LOGIC ;
               Load     : IN     STD_LOGIC ;
               Sin      : IN     STD_LOGIC ;
               Clock    : IN     STD_LOGIC ;
               Q        : OUT    STD_LOGIC_VECTOR(3 DOWNTO 0) ) ;
END shift4 ;
```



4-bit shift register with parallel load (2)

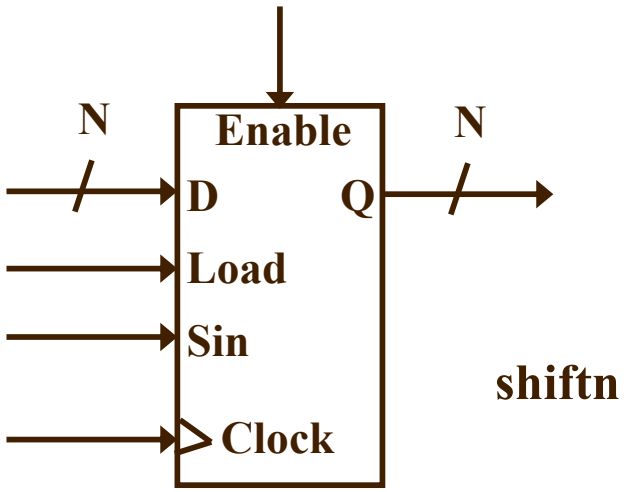
```
ARCHITECTURE behavioral OF shift4 IS
        SIGNAL Qt : STD_LOGIC_VECTOR(3 DOWNTO 0);
BEGIN
        PROCESS (Clock)
        BEGIN
                IF rising_edge(Clock) THEN
                        IF Enable = '1' THEN
                                IF Load = '1' THEN
                                        Qt <= D ;
                                ELSE
                                        Qt <= Sin & Qt(3 downto 1);
                                END IF ;
                        END IF;
                END IF ;
        END PROCESS ;
        Q <= Qt;
END behavioral ;
```



N-bit shift register with parallel load (1)

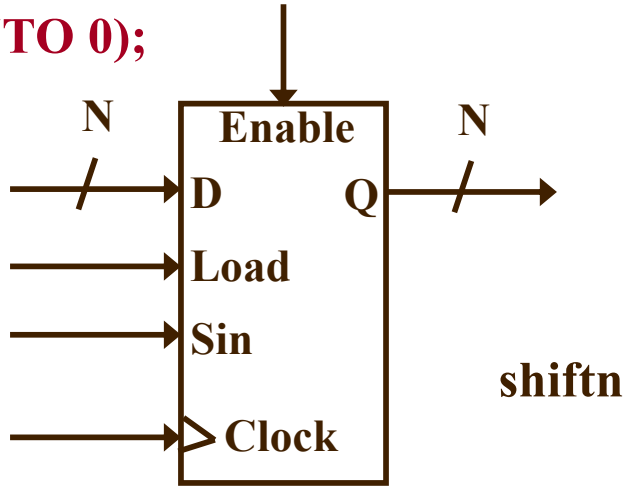
```
LIBRARY ieee ;
USE ieee.std_logic_1164.all ;

ENTITY shiftn IS
        GENERIC ( N : INTEGER := 8 ) ;
        PORT (  D : IN STD_LOGIC_VECTOR(N-1 DOWNTO 0) ;
                Enable  : IN    STD_LOGIC ;
                Load    : IN    STD_LOGIC ;
                Sin     : IN    STD_LOGIC ;
                Clock   : IN    STD_LOGIC ;
                Q       : OUT   STD_LOGIC_VECTOR(N-1 DOWNTO 0) ) ;
END shiftn ;
```



N-bit shift register with parallel load (2)

```
ARCHITECTURE behavioral OF shiftn IS
        SIGNAL Qt: STD_LOGIC_VECTOR(N-1 DOWNTO 0);
BEGIN
        PROCESS (Clock)
        BEGIN
                IF rising_edge(Clock) THEN
                        IF Enable = '1' THEN
                                IF Load = '1' THEN
                                        Qt <= D ;
                                ELSE
                                        Qt <= Sin & Qt(N-1 downto 1);
                                END IF ;
                        END IF;
                END IF ;
        END PROCESS ;
        Q <= Qt;
END behavior al;
```





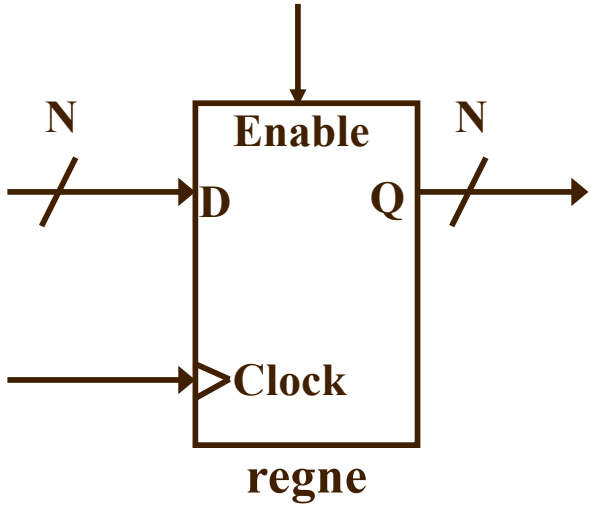
Generic Component Instantiation

N-bit register with enable

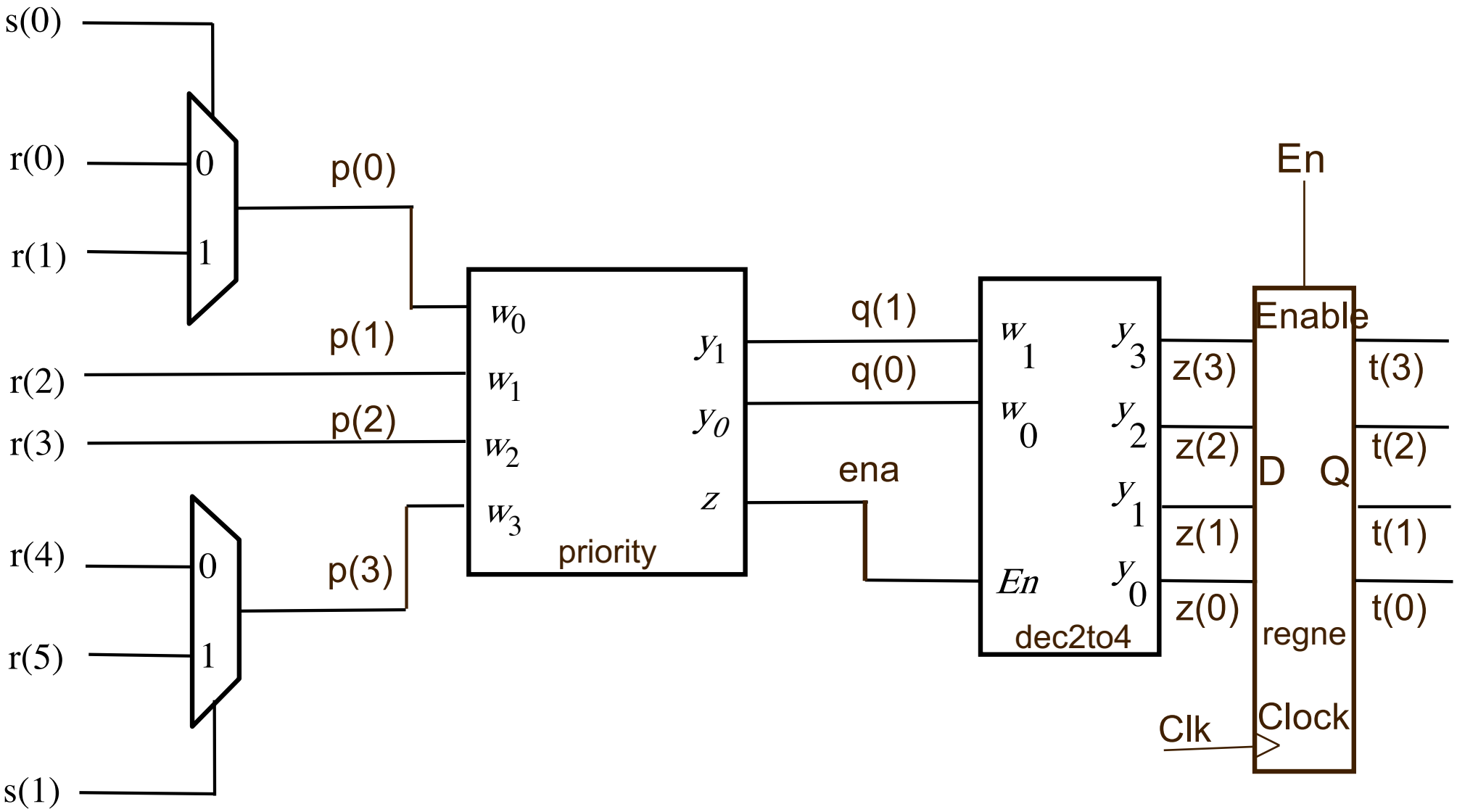
```
LIBRARY ieee ;
USE ieee.std_logic_1164.all ;

ENTITY regne IS
        GENERIC ( N : INTEGER := 8 ) ;
        PORT (      D                   : IN        STD_LOGIC_VECTOR(N-1 DOWNTO 0) ;
                    Enable, Clock       : IN        STD_LOGIC ;
                    Q                   : OUT       STD_LOGIC_VECTOR(N-1 DOWNTO 0) ) ;
END regne ;

ARCHITECTURE Behavior OF regne IS
BEGIN
        PROCESS (Clock)
        BEGIN
                IF (Clock'EVENT AND Clock = '1' ) THEN
                        IF Enable = '1' THEN
                                Q <= D ;
                        END IF ;
                END IF;
        END PROCESS ;
END Behavior ;
```



Circuit built of medium scale components



Structural description – example (1) VHDL-93

```
LIBRARY ieee ;
USE ieee.std_logic_1164.all ;

ENTITY priority_resolver IS
    PORT (r       : IN     STD_LOGIC_VECTOR(5 DOWNTO 0) ;
          s       : IN     STD_LOGIC_VECTOR(1 DOWNTO 0) ;
          clk     : IN     STD_LOGIC;
          en      : IN     STD_LOGIC;
          t       : OUT    STD_LOGIC_VECTOR(3 DOWNTO 0) ) ;
END priority_resolver;

ARCHITECTURE structural OF priority_resolver IS

SIGNAL  p : STD_LOGIC_VECTOR (3 DOWNTO 0) ;
SIGNAL  q : STD_LOGIC_VECTOR (1  DOWNTO 0) ;
SIGNAL  z : STD_LOGIC_VECTOR (3 DOWNTO 0) ;
SIGNAL  ena : STD_LOGIC ;
```

Structural description – example (2) VHDL-93

```
BEGIN

    u1:  ENTITY work.mux2to1(dataflow)
                    PORT MAP (w0 => r(0) ,
                                    w1 => r(1),
                                     s => s(0),
                                     f => p(0));
    p(1) <= r(2);
    p(2) <= r(3);

    u2:  ENTITY work.mux2to1(dataflow)
                    PORT MAP (w0 => r(4) ,
                                    w1 => r(5),
                                    s => s(1),
                                    f => p(3));

    u3: ENTITY work.priority(dataflow)
                   PORT MAP (w => p,
                                   y => q,
                                   z => ena);
```

Structural description – example (3) VHDL-93

```
u4: ENTITY work.dec2to4 (dataflow)
            PORT MAP (w => q,
                      En => ena,
                       y => z);

u5: ENTITY work.regne(behavioral)
            GENERIC MAP (N => 4)
             PORT MAP (D => z ,
                       Enable => En ,
                       Clock => Clk,
                       Q => t );
END structural;
```

Structural description – example (1) VHDL-87

```
LIBRARY ieee ;
USE ieee.std_logic_1164.all ;

ENTITY priority_resolver IS
    PORT (r      : IN     STD_LOGIC_VECTOR(5 DOWNTO 0) ;
          s      : IN     STD_LOGIC_VECTOR(1 DOWNTO 0) ;
          clk    : IN     STD_LOGIC;
          en     : IN     STD_LOGIC;
          t      : OUT    STD_LOGIC_VECTOR(3 DOWNTO 0) ) ;
END priority_resolver;

ARCHITECTURE structural OF priority_resolver IS

SIGNAL  p : STD_LOGIC_VECTOR (3 DOWNTO 0) ;
SIGNAL  q : STD_LOGIC_VECTOR (1  DOWNTO 0) ;
SIGNAL  z : STD_LOGIC_VECTOR (3 DOWNTO 0) ;
SIGNAL  ena : STD_LOGIC ;
```

Structural description – example (2)
VHDL-87

```
COMPONENT mux2to1
  PORT (w0, w1, s      : IN     STD_LOGIC ;
        f              : OUT    STD_LOGIC ) ;
END COMPONENT ;

COMPONENT priority
  PORT (w      : IN     STD_LOGIC_VECTOR(3 DOWNTO 0) ;
        y      : OUT    STD_LOGIC_VECTOR(1 DOWNTO 0) ;
        z      : OUT    STD_LOGIC ) ;
END COMPONENT ;

COMPONENT dec2to4
  PORT (w      : IN     STD_LOGIC_VECTOR(1 DOWNTO 0) ;
        En     : IN     STD_LOGIC ;
        y      : OUT    STD_LOGIC_VECTOR(3 DOWNTO 0) ) ;
END COMPONENT ;
```

Structural description – example (3)
VHDL-87

```
COMPONENT regne
   GENERIC ( N : INTEGER := 8 ) ;
   PORT (          D     : IN          STD_LOGIC_VECTOR(N-1 DOWNTO 0) ;
                   Enable, Clock     : IN                STD_LOGIC ;
                   Q     : OUT         STD_LOGIC_VECTOR(N-1 DOWNTO 0) ) ;
END COMPONENT ;
```

Structural description – example (4) VHDL-87

```
BEGIN

    u1: mux2to1 PORT MAP (w0 => r(0) ,
                          w1 => r(1),
                           s => s(0),
                           f => p(0));
    p(1) <= r(2);
    p(2) <= r(3);

    u2: mux2to1 PORT MAP (w0 => r(4) ,
                          w1 => r(5),
                          s => s(1),
                          f => p(3));

    u3: priority PORT MAP (w => p,
                           y => q,
                           z => ena);

    u4: dec2to4 PORT MAP (w => q,
                          En => ena,
                           y => z);
```

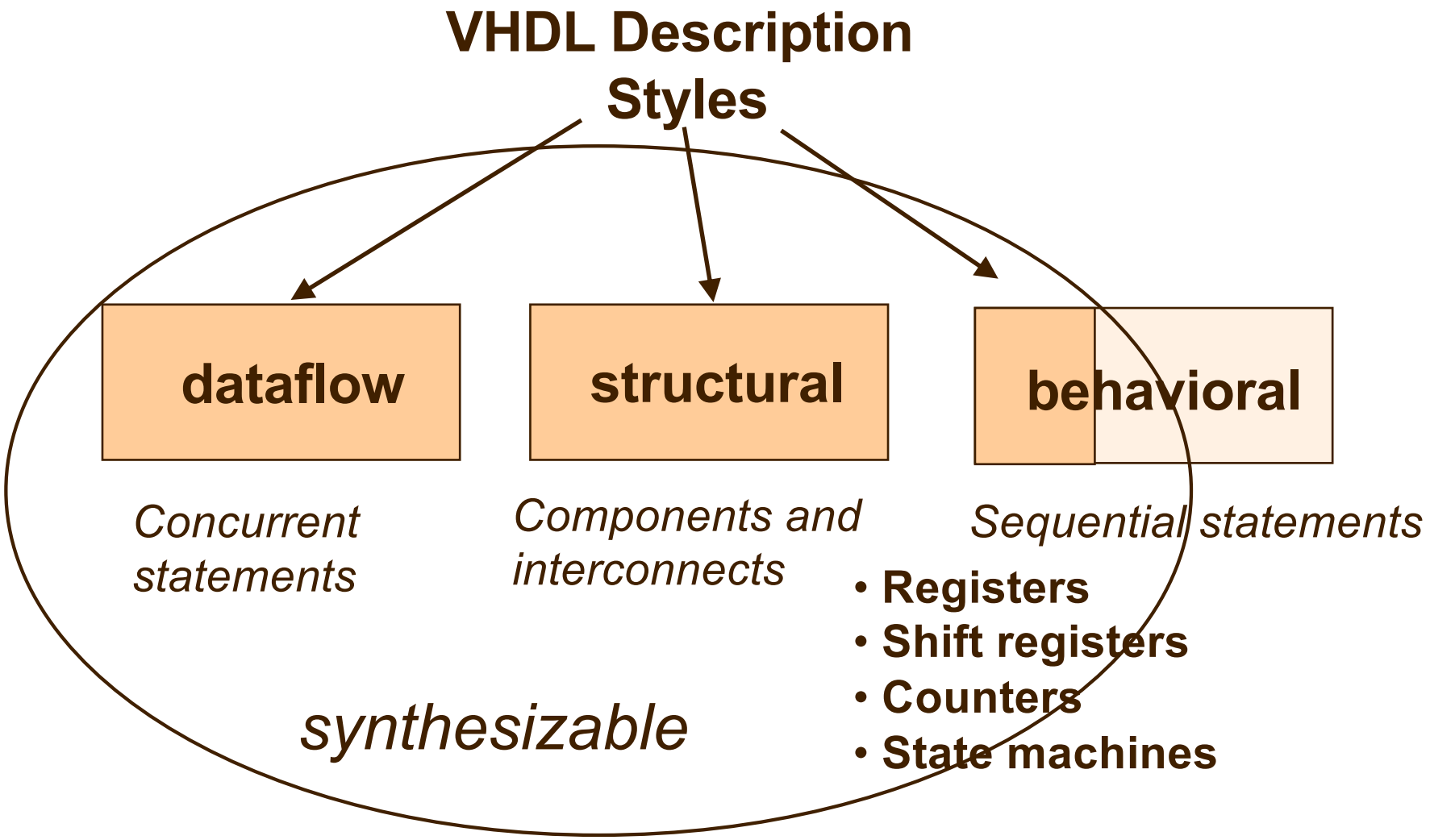
Structural description – example (5) VHDL-87

```
u5: regne       GENERIC MAP (N => 4)
                PORT MAP (D => z ,
                          Enable => En ,
                          Clock => Clk,
                          Q => t );
END structural;
```



Mixing Description Styles Inside of an Architecture

VHDL Description Styles



Mixed Style Modeling

architecture ARCHITECTURE_NAME **of** ENTITY_NAME **is**

- Here you can declare signals, constants, types, etc.

begin

Concurrent statements:

- Simple signal assignment
- Conditional signal assignment
- Selected signal assignment

Component instantiation statement

Process statement

- **inside process you can use only sequential statements**

end ARCHITECTURE_NAME;

PRNG Example (1)

```
library IEEE;
use IEEE.STD_LOGIC_1164.all;
use work.prng_pkg.all;

ENTITY PRNG IS
    PORT( Coeff          : in  std_logic_vector(4 downto 0);
          Load_Coeff     : in  std_logic;
          Seed           : in  std_logic_vector(4 downto 0);
          Init_Run       : in  std_logic;
          Clk            : in  std_logic;
          Current_State  : out std_logic_vector(4 downto 0));
END PRNG;

ARCHITECTURE mixed OF PRNG is
    signal Ands          : std_logic_vector(4 downto 0);
    signal Sin           : std_logic;
    signal Coeff_Q       : std_logic_vector(4 downto 0);
    signal Shift5_Q      : std_logic_vector(4 downto 0);
```

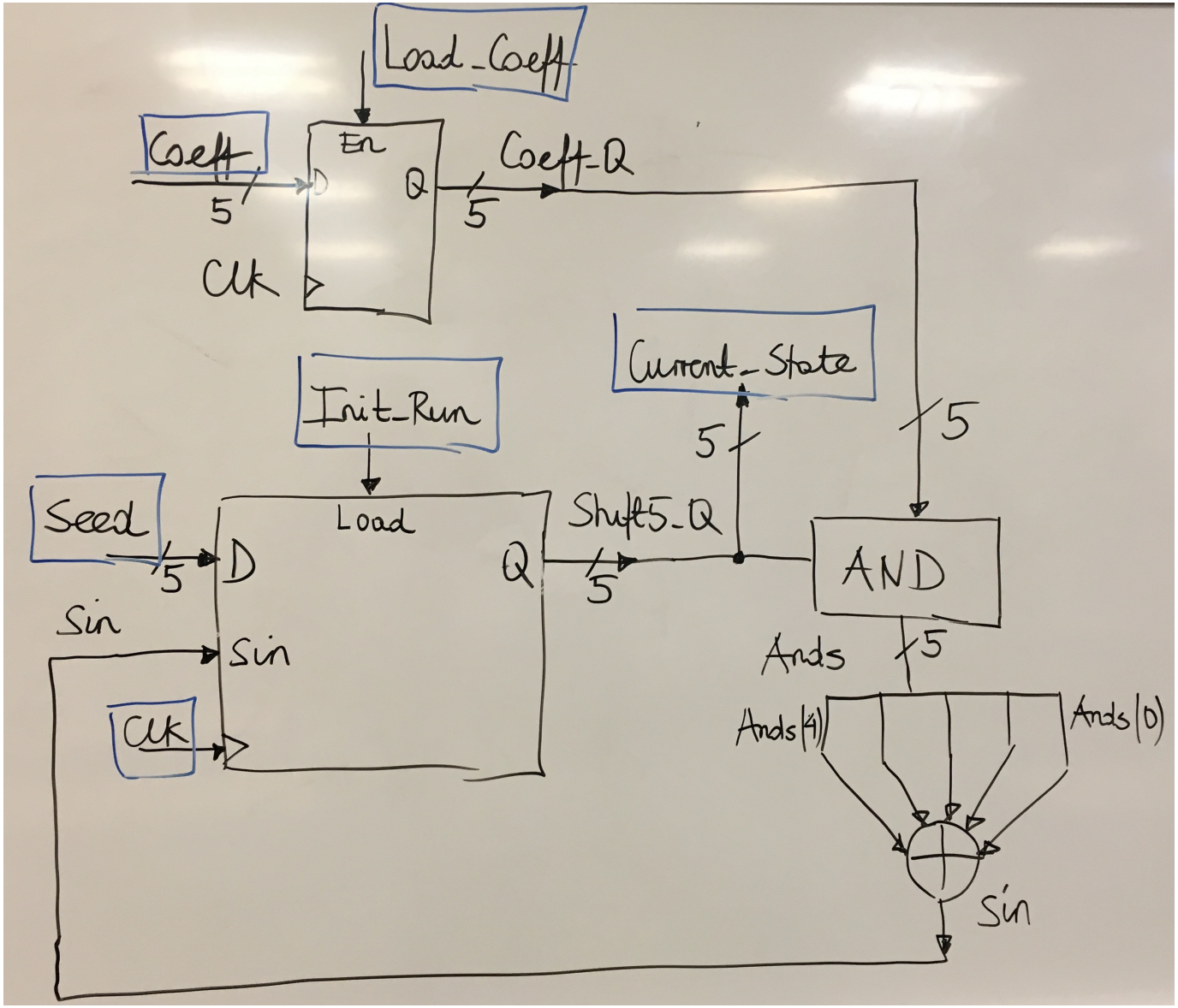
PRNG Example (2)

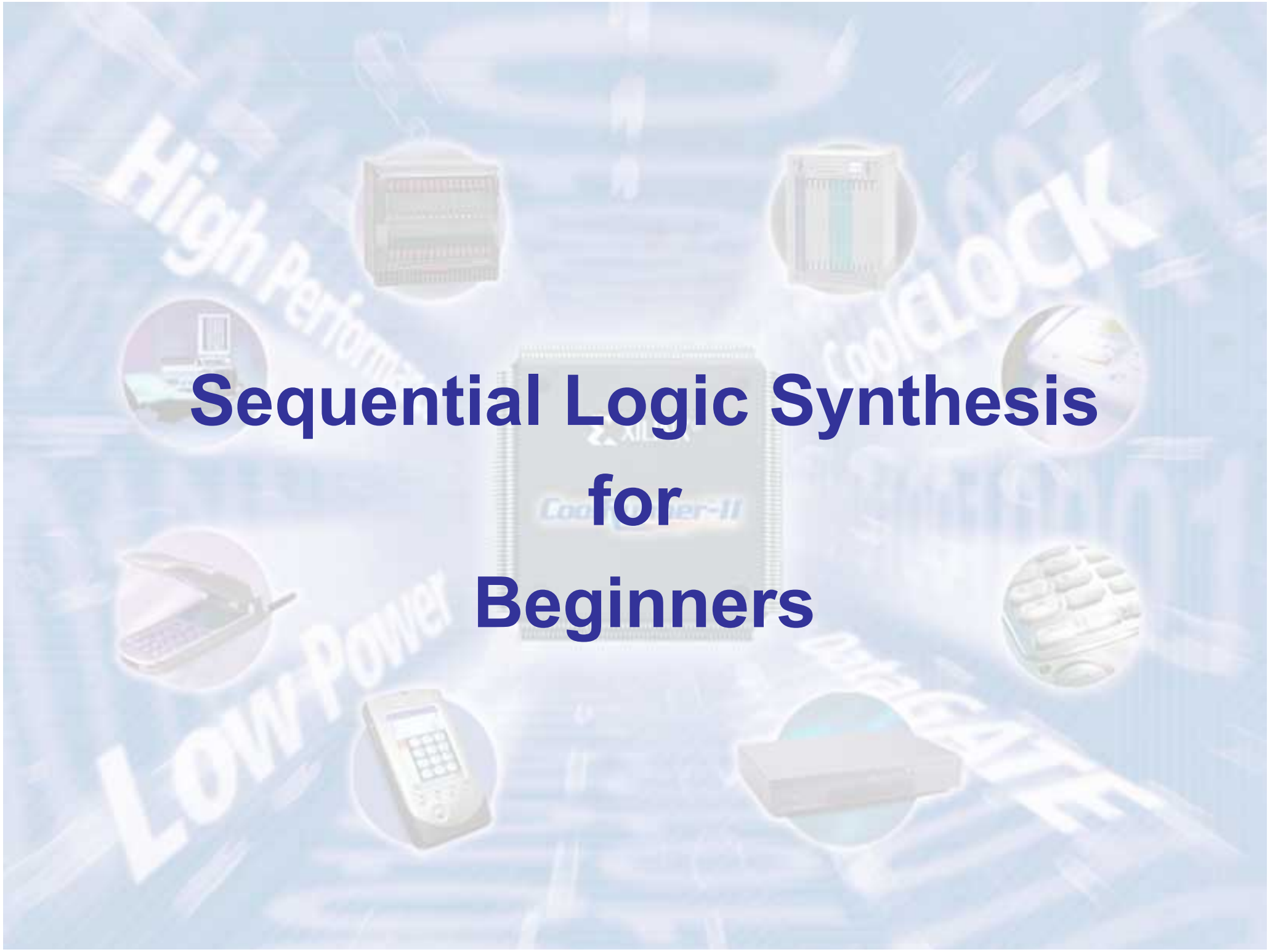
```
BEGIN
    -- Data Flow
    Sin <= Ands(0) XOR Ands(1) XOR Ands(2) XOR Ands(3) XOR Ands(4);
    Current_State <= Shift5_Q;
    Ands <= Coeff_Q AND Shift5_Q;

    -- Behavioral
    Coeff_Reg: PROCESS(Clk)
    BEGIN
        IF rising_edge(Clk)  THEN
            IF Load_Coeff = '1'   THEN
                Coeff_Q <= Coeff;
            END IF;
        END IF;
    END PROCESS;

    -- Structural
    Shift5_Reg : ENTITY work.Shift5(behavioral) PORT MAP ( D     => Seed,
                                                           Load  => Init_Run,
                                                           Sin   => Sin,
                                                           Clock => Clk,
                                                           Q     => Shift5_Q);
END mixed;
```

PRNG – Block Diagram





Sequential Logic Synthesis for Beginners

For Beginners

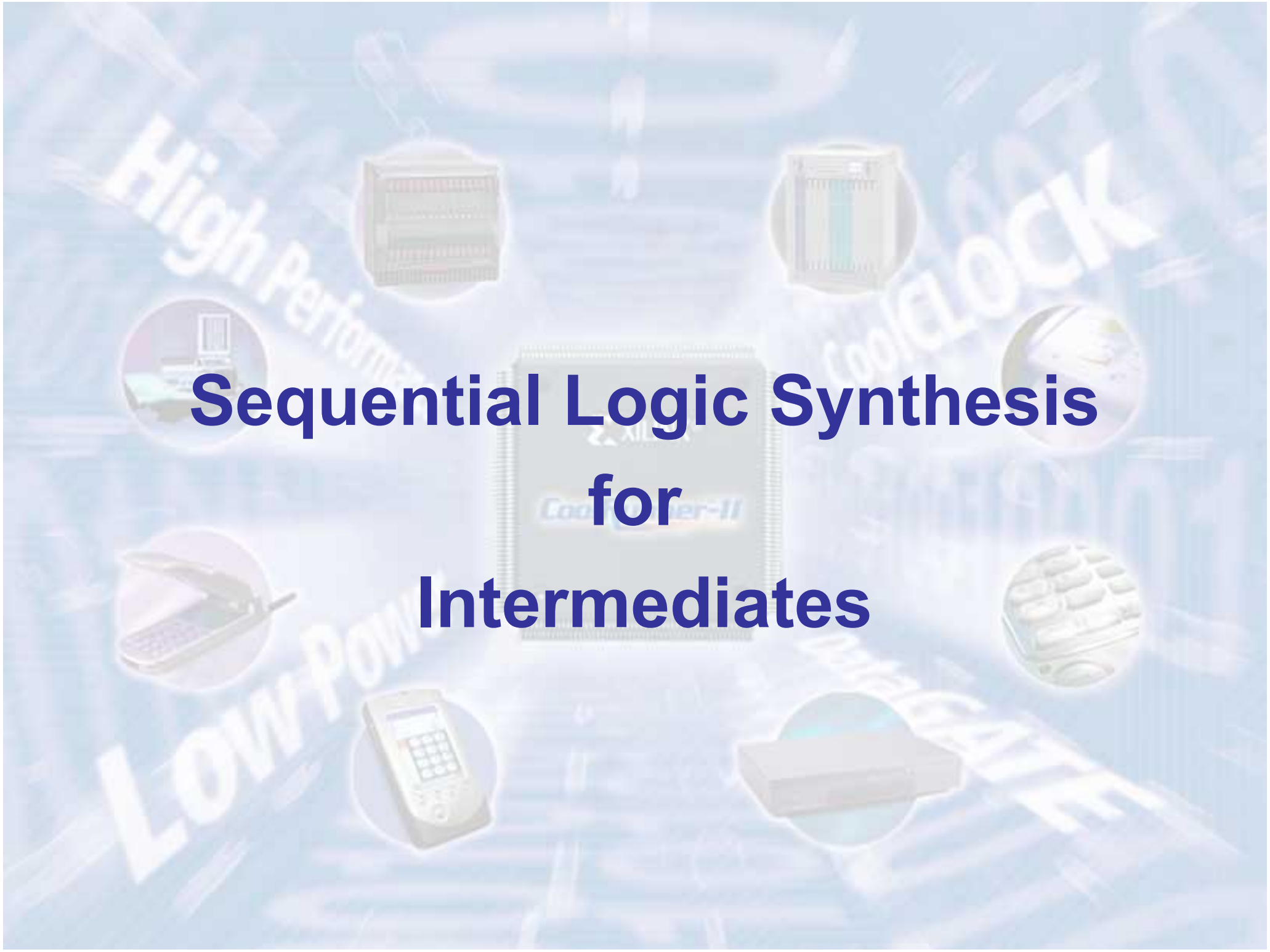
Use processes with very simple structure only to describe

- registers
- shift registers
- counters
- state machines.

Use examples discussed in class as a template.

Create **generic** entities for registers, shift registers, and counters, and instantiate the corresponding components in a higher level circuit using GENERIC MAP PORT MAP.

Supplement sequential components with combinational logic described using concurrent statements.



Sequential Logic Synthesis for Intermediates

For Intermmediates

1. Use Processes with IF and CASE statements only. Do not use LOOPS or VARIABLES.
2. Sensitivity list of the PROCESS should include **only** signals that can by themsleves change the outputs of the sequential circuit (typically, clock and asynchronous set or reset)
3. Do not use PROCESSes without sensitivity list

   (they can be synthesizable, but make simulation inefficient)

For Intermmediates (2)

Given a single signal, the assignments to this signal should only be made within a single process block in order to avoid possible conflicts in assigning values to this signal.

```
Process 1: PROCESS (a, b)
BEGIN
   y <= a AND b;
END PROCESS;

Process 2: PROCESS (a, b)
BEGIN
   y <= a OR b;
END PROCESS;
```