Modeling Digital Systems with VHDL

Reference: Roth & John text – Chapter 2
Michael Smith text – Chapters 8 & 10
**Hardware Description Languages**

- **VHDL** = VHSIC Hardware Description Language  
  (VHSIC = Very High Speed Integrated Circuits)
  - Developed by DOD from 1983 – based on ADA language
  - Gate level through system level design and verification

- **Verilog** – created in 1984 by Philip Moorby of Gateway Design Automation (merged with Cadence)
  - Based on the C language
  - IEEE P1800 “System Verilog” in voting stage & will be merged with 1364
  - Primarily targeted for design ofASICs (Application-Specific ICs)
Related VHDL Standards

- **1076.1**–1999: VHDL-AMS (Analog & Mixed-Signal Extensions)
- **1076.2**–1996: Std. VHDL Mathematics Packages
- **1076.3**-1997: Std. VHDL Synthesis Packages
- **1076.4**-1995: Std. VITAL Modeling Specification (VHDL Initiative Towards ASIC Libraries)
- **1076.6**-1999: Std. for VHDL Register Transfer Level (RTL) Synthesis
- **1164**-1993: Std. Multi-value Logic System for VHDL Model Interoperability
HDLs in Digital System Design

- **Model and document digital systems**
  - **Behavioral** model: describes I/O responses & behavior of design
  - **Register Transfer Level (RTL)** model: data flow description at the register level
  - **Structural** model: components and their interconnections (netlist), hierarchical designs

- **Simulation** to verify circuit/system design

- **Synthesis** of circuits from HDL models
  - using components from a technology library
  - output is primitive cell-level netlist (gates, flip flops, etc.)
Typical Product Development & Design Verification Cycle Using HDLs

1. Specifications
   - Behavioral Simulation
2. Architectural design
   - RTL Simulation
3. Register-level design
   - Logic and Timing
4. Gate-level design
   - Timing
5. Physical design
6. Implementation - ASIC, FPGA, etc.
Benefits of HDLs

- Early design verification via high level design verification
- Evaluation of alternative architectures
- Top-down design \((w/synthesis)\)
- Reduced risk to project due to design errors
- Design capture \((w/synthesis; independent of implementation)\)
- Reduced design/development time & cost \((w/synthesis)\)
- Base line testing of lower level design representations
  - Example: gate level or register level design
- Ability to manage/develop complex designs
- Hardware/software co-design
- Documentation of design \((depends on quality of designer comments)\)
Designer concerns about HDLs

- Loss of control of detailed design
- **Synthesis may be inefficient**
- Quality of synthesis varies between synthesis tools
- Synthesized logic might not perform the same as the HDL
- Learning curve associated with HDLs & synthesis tools
- Meeting tight design constraints (time delays, area, etc.)
Design Space Issues

- Area (chip area, how many chips, how much board space)
- Speed/performance
- Cost of product
- Production volume
- Design time (to meet market window & development cost)
- Risk to project (working, cost-effective product on schedule)
- Reusable resources (same circuit - different modes of operation)
- Implementation technology (ASIC, FPGA, PLD, etc.)
- Technology limits
- Designer experience
- CAD tool availability and capabilities
DoD requirements on VHDL in mid 80s:

- Design & description of hardware
- Simulation & documentation (with designer comments)
- Design verification & testing
- Concurrency to accurately reflect behavior & operation of hardware (all hardware operates concurrently)
  - as a result, all VHDL simulation is event-driven
- Hierarchical design – essential for efficient, low-risk design
- Library support – for reuse of previously verified components
- Generic design - independent of implementation media
- Optimize - for area and/or performance
- Timing control – to assign delays for more accurate simulation
- Portability between simulators & synthesis tools (not always true)
Anatomy of a VHDL model

- “Entity” describes the external view of a component
- “Architecture” describes the internal behavior and/or structure of the component
- Example: 1-bit full adder

This view is captured by the VHDL “entity” (next slide)
Example: 1-Bit Full Adder

entity full_add1 is
  port ( -- I/O ports
    a: in bit; -- addend input
    b: in bit; -- augend input
    cin: in bit; -- carry input
    sum: out bit; -- sum output
    cout: out bit); -- carry output
end full_add1 ;

Comments follow double-dash

Signal type
Signal direction (mode)
I/O Port Declarations
Signal name
Port Format - Name: Direction Signal_type;

- **Direction**
  - **in** - driven into the entity by an external source  
    \(\text{can read, but not drive, within the architecture}\)
  - **out** - driven from within the entity  
    \(\text{can drive, but not read, within the architecture}\)
  - **buffer** – like “out” but can read and drive
  - **inout** – bidirectional; signal driven both by external source and within the architecture  
    \(\text{can read or drive within the architecture}\)

- **Signal_type**: any scalar or aggregate signal data type
Built-in Data Types

- Scalar (single-value) signal types:
  - bit – values are ‘0’ or ‘1’
  - boolean – values are TRUE and FALSE
  - integer - values \([-2^{31} \ldots +2^{31}-1]\) on 32-bit host

- Aggregate of multiple scalar signal types:
  - bit_vector – array of bits;
    - must specify “range” of elements

Examples:

```vhdl
signal b: bit_vector(7 downto 0);
signal c: bit_vector(0 to 7);
b <= c after 1 ns;   --drive b with value of c
c <= "01010011";   --drive c with constant value
```
8-bit adder - entity

-- Internally - cascade 8 1-bit adders for 8-bit adder

entity Adder8 is

port (A, B: in BIT_VECTOR(7 downto 0);
    Cin: in BIT;
    Cout: out BIT;
    Sum: out BIT_VECTOR(7 downto 0));

end Adder8;
-- VHDL “package” is similar to a C “include” file
-- IEEE std_logic_1164 package defines nine logic states for signal values

package Part_STD_LOGIC_1164 is
  type STD_ULOGIC is ( 'U', -- Uninitialized/undefined value
                       'X', -- Forcing Unknown
                       '0', -- Forcing 0 (drive to GND)
                       '1', -- Forcing 1 (drive to VDD)
                       'Z', -- High Impedance (floating, undriven, tri-state)
                       'W', -- Weak Unknown
                       'L', -- Weak 0 (resistive pull-down)
                       'H', -- Weak 1 (resistive pull-up)
                       '-' -- Don't Care (for synthesis minimization)
                     );

  subtype STD_LOGIC is resolved STD_ULOGIC; --see next slide
  type STD_LOGIC_VECTOR is array (NATURAL range <>) of STD_LOGIC;

  STD_LOGIC/STD_LOGIC_VECTOR generally used instead of BIT/BIT_VECTOR
**Bus resolution function**

`std_logic` includes a “bus resolution function” to determine the signal state where there are multiple drivers.

```cpp
function resolved (s : STD_ULOGIC_VECTOR) return STD_ULOGIC;
```

<table>
<thead>
<tr>
<th>Driver A value</th>
<th>Driver B value</th>
<th>Resolved Bus Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>'0'</td>
<td>'0'</td>
<td>'0'</td>
</tr>
<tr>
<td>'0'</td>
<td>'0'</td>
<td>'X'</td>
</tr>
<tr>
<td>'1'</td>
<td>'X'</td>
<td>'1'</td>
</tr>
<tr>
<td>'1'</td>
<td>'1'</td>
<td>'1'</td>
</tr>
<tr>
<td>'Z'</td>
<td>'0'</td>
<td>'Z'</td>
</tr>
<tr>
<td>'Z'</td>
<td>'1'</td>
<td>'Z'</td>
</tr>
<tr>
<td>'X'</td>
<td>'X'</td>
<td>'X'</td>
</tr>
<tr>
<td>'X'</td>
<td>'X'</td>
<td>'X'</td>
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<td>'X'</td>
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<td>'X'</td>
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<td>'X'</td>
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<tr>
<td>'X'</td>
<td>'X'</td>
<td>'X'</td>
</tr>
<tr>
<td>'X'</td>
<td>'X'</td>
<td>'X'</td>
</tr>
</tbody>
</table>
Example: 1-Bit Full Adder

library ieee;                        --supplied library
use ieee.std_logic_1164.all;        --package of definitions
entity full_add1 is
port ( -- I/O ports
    a: in   std_logic;    -- addend input
    b: in   std_logic;       -- augend input
    cin: in   std_logic;       -- carry input
    sum: out std_logic;       -- sum output
    cout: out std_logic;       -- carry output
)
end full_add1 ;
Example: 8-bit full adder

library ieee; -- supplied library
use ieee.std_logic_1164.all; -- package of definitions

entity full_add8 is -- 8-bit inputs/outputs
  port ( a: in std_logic_vector(7 downto 0);
         b: in std_logic_vector(7 downto 0);
         cin: in std_logic;
         sum: out std_logic_vector(7 downto 0);
         cout: out std_logic);

end full_add8 ;
Architecture defines function/structure

ARCHITECTURE architecture_name OF entity_name IS
  -- data type definitions (ie, states, arrays, etc.)
  -- internal signal declarations
  -- component declarations
  -- function and procedure declarations
BEGIN
  -- behavior of the model is described here using:
    -- component instantiations
    -- concurrent statements
    -- processes
END;  --optionally: END ARCHITECTURE architecture_name;
Architecture defines function/structure

entity Half_Adder is
  port (X, Y : in STD_LOGIC := '0';
       Sum, Cout : out STD_LOGIC); -- formals
end;

-- behavior specified with logic equations
architecture Behave of Half_Adder is begin
  Sum <= X xor Y;       -- use formals from entity
  Cout <= X and Y;     -- “operators” are not “gates”
end Behave;

--operators and, or, xor, not applicable to bit/std_logic signals
Full adder behavioral architectures
(no circuit structures specified)

-- behavior expressed as logic equations
architecture dataflow of full_add1 is
begin
    sum <= a xor b xor cin;
    cout <= (a and b) or (a and cin) or (b and cin);
end;

-- equivalent behavior, using an internal signal
architecture dataflow of full_add1 is
    signal x1: std_logic; -- internal signal
begin
    x1 <= a xor b; -- drive x1
    sum <= x1 xor cin; -- reference x1
    cout <= (a and b) or (a and cin) or (b and cin);
end;
Signal assignment “events”

- Signal is driven to a value at a specified time \( (by \text{ “hardware”}) \)
  \[
  k \leq b \text{ and } c \text{ after } 1 \text{ ns};
  \]
- Creates a “driver” for signal \( k \), with scheduled events
  - “Event” = (value, time) pair
  - One driver per signal (unless a bus resolution function provided)
- Data types must match (strongly typed)
- Delay, from current time, can (optionally) be specified, as above
- If no delay specified, infinitesimally-small delay “delta” inserted
  \[
  k \leq b \text{ and } c;
  \]
  \( (To \ reflect \ that \ signals \ cannot \ change \ in \ zero \ time!) \)
- Delays are usually unknown in behavioral models and therefore omitted
Driving signal types must match driven signal type

VHDL: a strongly typed language
Concurrent Statements and Event-Driven Simulation

- Statements appear to be evaluated **concurrently**
  - To model behavior of actual hardware elements
- Each statement affected by a signal event at time $T$ is evaluated
  - Time $T$ is held constant while statements are evaluated
  - Any resulting events are “scheduled” in the affected signal driver, to occur at time $T + \text{delay}$
  - After all statements evaluated, $T$ is advanced to the time of the next scheduled event (among all the drivers)
  - New values do not take effect until simulation time advances to the scheduled event time, $T + \text{delay}$
Event-Driven Simulation Example

\[ a \leq b \text{ after 1ns}; \]
\[ c \leq a \text{ after 1ns}; \]

<table>
<thead>
<tr>
<th>Time</th>
<th>a</th>
<th>b</th>
<th>c</th>
</tr>
</thead>
<tbody>
<tr>
<td>T</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>T+1</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>T+2</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>T+3</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

- assume initial values all ‘0’ at time $T$
- external event changes $b$ at time $T+1$
- resulting event on $a$
- resulting event on $c$
Event-Driven Simulation Example

\[ a \leq b; \quad \text{-- delay } \partial \text{ inserted} \]
\[ c \leq a; \quad \text{-- delay } \partial \text{ inserted} \]

<table>
<thead>
<tr>
<th>Time</th>
<th>a</th>
<th>b</th>
<th>c</th>
</tr>
</thead>
<tbody>
<tr>
<td>T-1</td>
<td>‘0’</td>
<td>‘0’</td>
<td>‘0’</td>
</tr>
<tr>
<td>T</td>
<td>‘0’</td>
<td>‘1’</td>
<td>‘0’</td>
</tr>
<tr>
<td>T+\partial</td>
<td>‘1’</td>
<td>‘1’</td>
<td>‘0’</td>
</tr>
<tr>
<td>T+2\partial</td>
<td>‘1’</td>
<td>‘1’</td>
<td>‘1’</td>
</tr>
</tbody>
</table>

- assume initial values all ‘0’
- external event changes b at time T
- resulting event on a after \( \partial \) delay
- resulting event on c after 2\textsuperscript{nd} \( \partial \) delay

VHDL simulators generally show time and \( \partial \) delays