Digital Design: An Embedded Systems Approach Using VHDL

Chapter 1
Introduction and Methodology

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Digital Design

- **Digital**: circuits that use two voltage levels to represent information
  - **Logic**: use truth values and logic to analyze circuits
- **Design**: meeting functional requirements while satisfying constraints
  - Constraints: performance, size, power, cost, etc.
Design using Abstraction

- Circuits contain millions of transistors
  - How can we manage this complexity?
- Abstraction
  - Focus on aspects relevant aspects, ignoring other aspects
  - Don’t break assumptions that allow aspect to be ignored!
- Examples:
  - Transistors are on or off
  - Voltages are low or high

Digital Systems

- Electronic circuits that use discrete representations of information
  - Discrete in space and time
Embedded Systems

- Most real-world digital systems include embedded computers
  - Processor cores, memory, I/O
- Different functional requirements can be implemented
  - by the embedded software
  - by special-purpose attached circuits
- Trade-off among cost, performance, power, etc.

Binary Representation

- Basic representation for simplest form of information, with only two states
  - a switch: open or closed
  - a light: on or off
  - a microphone: active or muted
  - a logical proposition: false or true
  - a binary (base 2) digit, or bit: 0 or 1
- Signal represents the state of the switch
  - high-voltage => pressed,
    low-voltage => not pressed
- Equally, it represents state of the lamp
  - lamp_lit = switch_pressed

- dark: it’s night time
- lamp_enabled: turn on lamp at night
- lamp_lit: lamp_enabled AND dark
- Logically: day time => NOT lamp_lit
Basic Gate Components

- Primitive components for logic design

AND gate

OR gate

Inverter

Multiplexer

Combinational Circuits

Circuit whose output values depend purely on current input values
Sequential Circuits

- Circuit whose output values depend on current *and previous* input values
  - Include some form of storage of values
- Nearly all digital systems are sequential
  - Mixture of gates and storage components
  - Combinational parts transform inputs and stored values

Flipflops and Clocks

- Edge-triggered D-flipflop
  - Stores one bit of information at a time
- Timing diagram
  - Graph of signal values versus time
Real-World Circuits

- Assumptions behind digital abstraction
  - ideal circuits, only two voltages, instantaneous transitions, no delay
- Greatly simplify functional design
- Constraints arise from real components and real-world physics
- Meeting constraints ensures circuits are “ideal enough” to support abstractions

Integrated Circuits (ICs)

- Circuits formed on surface of silicon wafer
  - Minimum feature size reduced in each technology generation
  - Currently 90nm, 65nm
  - Moore’s Law: increasing transistor count
  - CMOS: complementary MOSFET circuits
Logic Levels

- Actual voltages for “low” and “high”
  - Example: 1.4V threshold for inputs

VHDL Logic Levels

TTL logic levels with noise margins

- VOL: output low voltage
- VOH: output high voltage
- VIL: input low voltage
- VIH: input high voltage

signal with added noise

V_{OL}, V_{IL} \quad \text{noise margin}

V_{OH}, V_{IH} \quad \text{noise margin}
Static Load and Fanout

- Current flowing into or out of an output
  - High: SW1 closed, SW0 open
    - Voltage drop across R1
    - Too much current: $V_O < V_{OH}$
  - Low: SW0 closed, SW1 open
    - Voltage drop across R0
    - Too much current: $V_O > V_{OL}$
  - Fanout: number of inputs connected to an output
determines static load

Capacitive Load and Prop Delay

- Inputs and wires act as capacitors

- $t_r$: rise time
- $t_f$: fall time
- $t_{pd}$: propagation delay
delay from input transition to output transition
Other Constraints

- Wire delay: delay for transition to traverse interconnecting wire
- Flipflop timing
  - delay from clk edge to Q output
  - D stable before and after clk edge
- Power
  - current through resistance => heat
  - must be dissipated, or circuit cooks!

Area and Packaging

- Circuits implemented on silicon chips
  - Larger circuit area => greater cost
- Chips in packages with connecting wires
  - More wires => greater cost
  - Package dissipates heat
- Packages interconnected on a printed circuit board (PCB)
  - Size, shape, cooling, etc, constrained by final product
Models

- Abstract representations of aspects of a system being designed
  - Allow us to analyze the system before building it
- Example: Ohm’s Law
  - $V = I \times R$
  - Represents electrical aspects of a resistor
  - Expressed as a mathematical equation
  - Ignores thermal, mechanical, materials aspects

VHDL

- VHSIC Hardware Description Language
  - A computer language for modeling behavior and structure of digital systems
- Electronic Design Automation (EDA) using VHDL
  - Design entry: alternative to schematics
  - Verification: simulation, proof of properties
  - Synthesis: automatic generation of circuits
**Entity Declarations**

- Describes input and outputs of a circuit

```vhdl
library ieee; use ieee.std_logic_1164.all;
entity vat_buzzer is
  port ( above_25_0, above_30_0, low_level_0 : in std_logic;
         above_25_1, above_30_1, low_level_1 : in std_logic;
         select_vat_1 : in std_logic;
         buzzer : out std_logic);
end entity vat_buzzer;
```
**Structural Architectures**

```vhdl
library dld; use dld.gates.all;
architecture struct of vat_buzzer is
  signal below_25_0, temp_bad_0, wake_up_0 : std_logic;
  signal below_25_1, temp_bad_1, wake_up_1 : std_logic;
begin
  -- components for vat 0
  inv_0 : inv (above_25_0, below_25_0);
  or_0a : or2 (above_30_0, below_25_0, temp_bad_0);
  or_0b : or2 (temp_bad_0, low_level_0, wake_up_0);
  -- components for vat 1
  inv_1 : inv (above_25_1, below_25_1);
  or_1a : or2 (above_30_1, below_25_1, temp_bad_1);
  or_1b : or2 (temp_bad_1, low_level_1, wake_up_1);
  select_mux : mux2 (wake_up_0, wake_up_1, select_vat_1, buzzer);
end architecture struct;
```

**Behavioral Architectures**

```vhdl
architecture behavior of vat_buzzer is
begin
  buzzer <=
    low_level_1 or
    (above_30_1 or not above_25_1)
  when select_vat_1 = '1' else
    low_level_0 or
    (above_30_0 or not above_25_0);
end architecture behavior;
```
Design Methodology

- Simple systems can be designed by one person using *ad hoc* methods
- Real-world systems are designed by teams
  - Require a systematic design methodology
- Specifies
  - Tasks to be undertaken
  - Information needed and produced
  - Relationships between tasks
    - dependencies, sequences
  - EDA tools used

A Simple Design Methodology

1. Requirements and Constraints
2. Design
   - Functional Verification
     - OK? Y N
3. Synthesize
   - Post-synthesis Verification
     - OK? Y N
4. Physical Implementation
   - Physical Verification
     - OK? Y N
5. Manufacture
   - Test
     - Y
Hierarchical Design

- Circuits are too complex for us to design all the detail at once
- Design subsystems for simple functions
- Compose subsystems to form the system
  - Treating subcircuits as “black box” components
  - Verify independently, then verify the composition
- Top-down/bottom-up design
Synthesis

- We usually design using register-transfer-level (RTL) VHDL
  - Higher level of abstraction than gates
- Synthesis tool translates to a circuit of gates that performs the same function
- Specify to the tool
  - the target implementation fabric
  - constraints on timing, area, etc.
- Post-synthesis verification
  - synthesized circuit meets constraints

Physical Implementation

- Implementation fabrics
  - Application-specific ICs (ASICs)
  - Field-programmable gate arrays (FPGAs)
- Floor-planning: arranging the subsystems
- Placement: arranging the gates within subsystems
- Routing: joining the gates with wires
- Physical verification
  - physical circuit still meets constraints
  - use better estimates of delays
Codesign Methodology

Digital systems use discrete (binary) representations of information
- Basic components: gates and flipflops
- Combinational and sequential circuits
- Real-world constraints
  - logic levels, loads, timing, area, etc
- VHDL models: structural, behavioral
- Design methodology