Synthesis Of VHDL Code
Outline

1. Fundamental limitation of EDA software
2. Realization of VHDL operator
3. Realization of VHDL data type
4. VHDL synthesis flow
5. Timing consideration
1. Fundamental limitation of EDA software

- Can “C-to-hardware” be done?

- EDA tools:
  - Core: optimization algorithms
  - Shell: wrapping

- What does theoretical computer science say?
  - Computability
  - Computation complexity
Computability

• A problem is computable if an algorithm exists.
• E.g., “halting problem”:  
  – can we develop a program that takes any program and its input, and determines whether the computation of that program will eventually halt?
• any attempt to examine the “meaning” of a program is uncomputable
Computation complexity

• How fast an algorithm can run (or how good an algorithm is)?
• “Interferences” in measuring execution time:
  – types of CPU, speed of CPU, compiler etc.
Big-O notation

• $f(n)$ is $O(g(n))$: 
  if $n_0$ and $c$ can be found to satisfy: 
  $f(n) < cg(n)$ for any $n$, $n > n_0$

• $g(n)$ is simple function: $1$, $n$, $\log_2 n$, $n^2$, $n^3$, $2^n$

• Following are $O(n^2)$:
  
  • $0.1n^2$
  • $n^2 + 5n + 9$
  • $500n^2 + 1000000$
Interpretation of Big-O

• Filter out the “interference”: constants and less important terms
• \( n \) is the input size of an algorithm
• The “scaling factor” of an algorithm:
  What happens if the input size increases
E.g.,

<table>
<thead>
<tr>
<th>input size</th>
<th>$n$</th>
<th>$\log_2 n$</th>
<th>$n \log_2 n$</th>
<th>$n^2$</th>
<th>$n^3$</th>
<th>$2^n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>$2 \mu s$</td>
<td>$1 \mu s$</td>
<td>$2 \mu s$</td>
<td>$4 \mu s$</td>
<td>$8 \mu s$</td>
<td>$4 \mu s$</td>
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<tr>
<td>4</td>
<td>$4 \mu s$</td>
<td>$2 \mu s$</td>
<td>$8 \mu s$</td>
<td>$16 \mu s$</td>
<td>$64 \mu s$</td>
<td>$16 \mu s$</td>
</tr>
<tr>
<td>8</td>
<td>$8 \mu s$</td>
<td>$3 \mu s$</td>
<td>$24 \mu s$</td>
<td>$64 \mu s$</td>
<td>$512 \mu s$</td>
<td>$256 \mu s$</td>
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<tr>
<td>16</td>
<td>$16 \mu s$</td>
<td>$4 \mu s$</td>
<td>$64 \mu s$</td>
<td>$256 \mu s$</td>
<td>$4 \text{ms}$</td>
<td>$66 \text{ms}$</td>
</tr>
<tr>
<td>32</td>
<td>$32 \mu s$</td>
<td>$5 \mu s$</td>
<td>$160 \mu s$</td>
<td>$1 \text{ms}$</td>
<td>$33 \text{ms}$</td>
<td>$71 \text{min}$</td>
</tr>
<tr>
<td>48</td>
<td>$48 \mu s$</td>
<td>$5.5 \mu s$</td>
<td>$268 \mu s$</td>
<td>$2 \text{ms}$</td>
<td>$111 \text{ms}$</td>
<td>$9 \text{year}$</td>
</tr>
<tr>
<td>64</td>
<td>$64 \mu s$</td>
<td>$6 \mu s$</td>
<td>$384 \mu s$</td>
<td>$4 \text{ms}$</td>
<td>$262 \text{ms}$</td>
<td>$600,000 \text{year}$</td>
</tr>
</tbody>
</table>
• Intractable problems:
  – algorithms with $O(2^n)$
  – Not realistic for a larger $n$
  – Frequently tractable algorithms for sub-optimal solution exist

• Many problems encountered in synthesis are intractable
Theoretical limitation

- Synthesis software does not know your intention
- Synthesis software cannot obtain the optimal solution
- Synthesis should be treated as transformation and a "local search" in the "design space"
- Good VHDL code provides a good starting point for the local search
• What is the fuss about:
  – “hardware-software” co-design?
  – SystemC, HardwareC, SpecC etc.?
2. Realization of VHDL operator

- Logic operator
  - Simple, direct mapping
- Relational operator
  - =, /= fast, simple implementation exists
  - >, < etc: more complex implementation, larger delay
- Addition operator
- Other arith operators: support varies
• Operator with two constant operands:
  – Simplified in preprocessing
  – No hardware inferred
  – Good for documentation
  – E.g.,

```vhdl
constant OFFSET: integer := 8;
signal boundary: unsigned(8 downto 0);
signal overflow: std_logic;

overflow <= '1' when boundary > (2**OFFSET-1) else '0';
```
• Operator with one constant operand:
  – Can significantly reduce the hardware complexity
  – E.g., adder vs. incrementor
  – E.g
    \[ y \leq \text{rotate\_right}(x, y); \quad \text{-- barrel shifter} \]
    \[ y \leq \text{rotate\_right}(x, 3); \quad \text{-- rewiring} \]
    \[ y \leq x(2 \text{ downto } 0) \& x(7 \text{ downto } 3); \]
  – E.g., 4-bit comparator: \( x=y \) vs. \( x=0 \)
    \[
    (x_3 \oplus y_3)' \cdot (x_2 \oplus y_2)' \cdot (x_1 \oplus y_1)' \cdot (x_0 \oplus y_0)'
    \]
    \[ x_3' \cdot x_2' \cdot x_1' \cdot x_0' \]
An example 0.55 um standard-cell CMOS implementation

<table>
<thead>
<tr>
<th>width</th>
<th>nand</th>
<th>xor</th>
<th>&gt;a</th>
<th>&gt;d</th>
<th>=</th>
<th>+1a</th>
<th>+1d</th>
<th>+a</th>
<th>+d</th>
<th>mux</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>8</td>
<td>22</td>
<td>25</td>
<td>68</td>
<td>26</td>
<td>27</td>
<td>33</td>
<td>51</td>
<td>118</td>
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<td>44</td>
<td>52</td>
<td>102</td>
<td>51</td>
<td>55</td>
<td>73</td>
<td>101</td>
<td>265</td>
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<td>32</td>
<td>32</td>
<td>85</td>
<td>105</td>
<td>211</td>
<td>102</td>
<td>113</td>
<td>153</td>
<td>203</td>
<td>437</td>
<td>85</td>
</tr>
<tr>
<td>64</td>
<td>64</td>
<td>171</td>
<td>212</td>
<td>398</td>
<td>204</td>
<td>227</td>
<td>313</td>
<td>405</td>
<td>755</td>
<td>171</td>
</tr>
</tbody>
</table>

area (gate count)

<table>
<thead>
<tr>
<th>delay (ns)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
</tr>
<tr>
<td>16</td>
</tr>
<tr>
<td>32</td>
</tr>
<tr>
<td>64</td>
</tr>
</tbody>
</table>
3. Realization of VHDL data type

- Use and synthesis of ‘Z’
- Use of ‘-’
Use and synthesis of ‘Z’

• Tri-state buffer:
  – Output with “high-impedance”
  – Not a value in Boolean algebra
  – Need special output circuitry (tri-state buffer)

\[
\begin{array}{ccc}
\text{oe} & & y \\
0 & & Z \\
1 & & \text{a_in} \\
\end{array}
\]
• Major application:
  – Bi-directional I/O pins
  – Tri-state bus
• VHDL description:
  \[ y <= 'Z' \text{ when } oe='1' \text{ else } \]
  \[ \text{a_in}; \]
• ‘Z’ cannot be used as input or manipulated
  \[ f <= 'Z' \text{ and } a; \]
  \[ y <= \text{data_a when in_bus='Z' else } \]
  \[ \text{data_b}; \]
• Separate tri-state buffer from regular code:
  – Less clear:
    ```vhdl
    with sel select
      y <= 'Z' when "00",
          '1' when "01"|"11",
          '0' when others;
    ```
  – better:
    ```vhdl
    with sel select
      tmp <= '1' when "01"|"11",
            '0' when others;
      y <= 'Z' when sel="00" else tmp;
    ```
Bi-directional i/o pins
entity bi_demo is
  port(bi: inout std_logic;
     . . .
begin
  sig_out <= output_expression;
  . . . <= expression_with_sig_in;
  . . .
  bi <= sig_out when dir='1' else 'Z';
sig_in <= bi;
  . . .
\texttt{\texttt{sig\_in} \ensuremath{\leftarrow} \texttt{bi} \textbf{when} \texttt{dir}='0' \textbf{else} 'Z';}
Tri-state bus
— binary decoder

```vhdl
with src_select select
  oe <= "0001" when "00",
       "0010" when "01",
       "0100" when "10",
       "1000" when others; — "11"
```

— tri-state buffers

```vhdl
y0 <= i0 when oe(0)='1' else 'Z';

y1 <= i1 when oe(1)='1' else 'Z';

y2 <= i2 when oe(2)='1' else 'Z';

y3 <= i3 when oe(3)='1' else 'Z';

data_bus <= y0;

data_bus <= y1;

data_bus <= y2;

data_bus <= y3;
```
• Problem with tri-state bus
  – Difficult to optimize, verify and test
  – Somewhat difficult to design: “parking”, “fighting”

• Alternative to tri-state bus: mux

```vhdl
with src_select select
  data_bus <= i0 when "00",
              i1 when "01",
              i2 when "10",
              i3 when others;    -- "11"
```
Use of ‘-’

- In conventional logic design
  - ‘-’ as input value: shorthand to make table compact
  - E.g.,

<table>
<thead>
<tr>
<th>input req</th>
<th>output code</th>
<th>input req</th>
<th>output code</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 0 0</td>
<td>10</td>
<td>1 0 1</td>
<td>10</td>
</tr>
<tr>
<td>1 1 0</td>
<td>10</td>
<td>1 1 1</td>
<td>10</td>
</tr>
<tr>
<td>0 1 0</td>
<td>01</td>
<td>0 1 1</td>
<td>01</td>
</tr>
<tr>
<td>0 0 1</td>
<td>00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0 0 0</td>
<td>00</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
- ‘-’ as output value: help simplification
- E.g.,
  ‘-’ assigned to 1: $a + b$
  ‘-’ assigned to 0: $a'b + ab$

<table>
<thead>
<tr>
<th>input</th>
<th>output</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a$</td>
<td>$b$</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

RTL Hardware Design Chapter 6 27
Use ‘-’ in VHDL

• As input value (against our intuition):

• Wrong:

```vhdl
y <= "10" when req="1--" else
    "01" when req="01-" else
    "00" when req="001" else
    "00";
```
• Fix #1:

```vhdl
y <= "10" when req(3)='1' else
    "01" when req(3 downto 2)="01" else
    "00" when req(3 downto 1)="001" else
    "00";
```

• Fix #2:

```vhdl
.
.
use ieee.numeric_std.all;
.
.
y <= "10" when std_match(req,"1--") else
    "01" when std_match(req,"01-") else
    "00" when std_match(req,"001") else
    "00";
```
• Wrong:

```
with req select
  y <= "10" when "1--",
       "01" when "01-",
       "00" when "001",
       "00" when others;
```

• Fix:

```
with req select
  y <= "10" when "100"|"101"|"110"|"111",
       "00" when "010"|"011",
       "00" when others;
```
• ‘-’ as an output value in VHDL
• May work with some software

```vhdl
sel <= a & b;
with sel select
  y <= '0' when "00",
      '1' when "01",
      '1' when "10",
      '-' when others;
```
4. VHDL Synthesis Flow

• Synthesis:
  – Realize VHDL code using logic cells from the device’s library
  – a refinement process
• Main steps:
  – RT level synthesis
  – Logic synthesis
  – Technology mapping
RT level synthesis

• Realize VHDL code using RT-level components
• Somewhat like the derivation of the conceptual diagram
• Limited optimization
• Generated netlist includes
  – “regular” logic: e.g., adder, comparator
  – “random” logic: e.g., truth table description
Module generator

- “regular” logic can be replaced by pre-designed module
  - Pre-designed module is more efficient
  - Module can be generated in different levels of detail
  - Reduce the processing time
Logic Synthesis

• Realize the circuit with the optimal number of “generic” gate level components
• Process the “random” logic
• Two categories:
  – Two-level synthesis: sum-of-product format
  – Multi-level synthesis
• E.g.,

(a) Two-level implementation

(b) multi-level implementation
Technology mapping

- Map “generic” gates to “device-dependent” logic cells
- The technology library is provided by the vendors who manufactured (in FPGA) or will manufacture (in ASIC) the device
E.g., mapping in standard-cell ASIC

- Device library

<table>
<thead>
<tr>
<th>cell name (cost)</th>
<th>symbol</th>
<th>nand-not representation</th>
</tr>
</thead>
<tbody>
<tr>
<td>not (2)</td>
<td>![Not symbol]</td>
<td>![Not nand-not representation]</td>
</tr>
<tr>
<td>nand2 (3)</td>
<td>![Nand2 symbol]</td>
<td>![Nand2 nand-not representation]</td>
</tr>
<tr>
<td>nand3 (4)</td>
<td>![Nand3 symbol]</td>
<td>![Nand3 nand-not representation]</td>
</tr>
<tr>
<td>nand4 (5)</td>
<td>![Nand4 symbol]</td>
<td>![Nand4 nand-not representation]</td>
</tr>
<tr>
<td>aoi (4)</td>
<td>![Aoi symbol]</td>
<td>![Aoi nand-not representation]</td>
</tr>
<tr>
<td>xor (4)</td>
<td>![Xor symbol]</td>
<td>![Xor nand-not representation]</td>
</tr>
</tbody>
</table>
- Cost: 31 vs. 17

(a) Initial mapping

(b) Better mapping
E.g., mapping in FPGA

- With 5-input LUT (Look-Up-Table) cells

(a) Initial mapping

(b) Better mapping
Effective use of synthesis software

• Logic operators: software can do a good job
• Relational/Arith operators: manual intervention needed
• “layout” and “routing structure”:
  – Silicon chip is 2-dimensional square
  – “rectangular” or “tree-shaped” circuit is easier to optimize
(a) Cascading-chain structure
5. Timing consideration

- Propagation delay
- Synthesis with timing constraint
- Hazards
- Delay-sensitive design
Propagation delay

- Delay: time required to propagate a signal from an input port to an output port
- Cell level delay: most accurate
- Simplified model:
  \[ \text{delay} = d_{\text{intrinsic}} + r \cdot C_{\text{load}} \]
- The impact of wire becomes more dominant
• E.g.
System delay

- The longest path (critical path) in the system
- The worst input to output delay
- E.g.
• “False path” may exists:

![Diagram showing false path in hardware design](image)
• RT level delay estimation:
  – Difficult if the design is mainly “random” logic
  – Critical path can be identified if many complex operators (such as adder) are used in the design.
Synthesis with timing constraint

- Multi-level synthesis is flexible
- It is possible to reduce by delay by adding extra logic
- Synthesis with timing constraint
  1. Obtain the minimal-area implementation
  2. Identify the critical path
  3. Reduce the delay by adding extra logic
  4. Repeat 2 & 3 until meeting the constraint
• E.g.,

(a) Optimized for area

(b) Optimized for delay
• **Area-delay trade-off curve**
• Improvement in “architectural” level design (better VHDL code to start with)
Timing Hazards

- Propagation delay: time to obtain a stable output

- Hazards: the fluctuation occurring during the transient period
  - Static hazard: glitch when the signal should be stable
  - Dynamic hazard: a glitch in transition

- Due to the multiple converging paths of an output port
- E.g., static-hazard \((sh=ab'+bc; \ a=c=1)\)
• E.g., dynamic hazard \((a=c=d=1)\)
Dealing with hazards

- Some hazards can be eliminated in theory
- E.g.,

(c) Revised Karnaugh map and schematic to eliminate hazards
• Eliminating glitches is very difficult in reality, and almost impossible for synthesis
• Multiple inputs can change simultaneously (e.g., 1111=>0000 in a counter)
• How to deal with it? Ignore glitches in the transient period and retrieve the data after the signal is stabilized
Delay sensitive design and its danger

- Boolean algebra
  - the theoretical model for digital design and most algorithms used in synthesis process
  - algebra deals with the stabilized signals

- Delay-sensitive design
  - Depend on the transient property (and delay) of the circuit
  - Difficult to design and analyze
• E.g., hazard elimination circuit: ac term is not needed
• E.g., edge detection circuit (pulse=a a’)

![Diagram of hazard elimination circuit](image1)

![Diagram of edge detection circuit](image2)
• What’s can go wrong:
  – E.g., pulse <= a \textbf{and} (not a);
  – During logic synthesis, the logic expressions will be rearranged and optimized.
  – During technology mapping, generic gates will be re-mapped
  – During placement & routing, wire delays may change
  – It is bad for testing verification
• If delay-sensitive design is really needed, it should be done manually, not by synthesis