

Hardware Modeling [VU] (191.011)

– WS25 –

Logic Synthesis, Place and Route

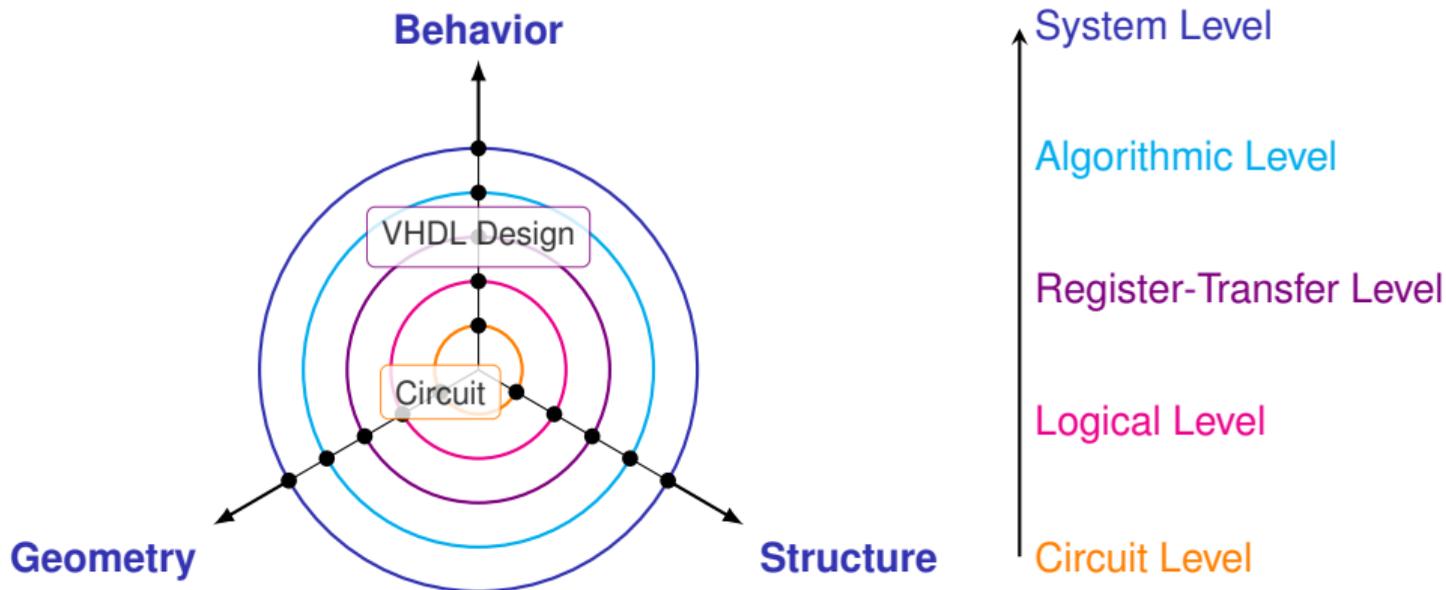
Florian Huemer & Sebastian Wiedemann & Dylan Baumann

WS 2025/26

Recall: Y-Diagram

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- Tools translate between different views

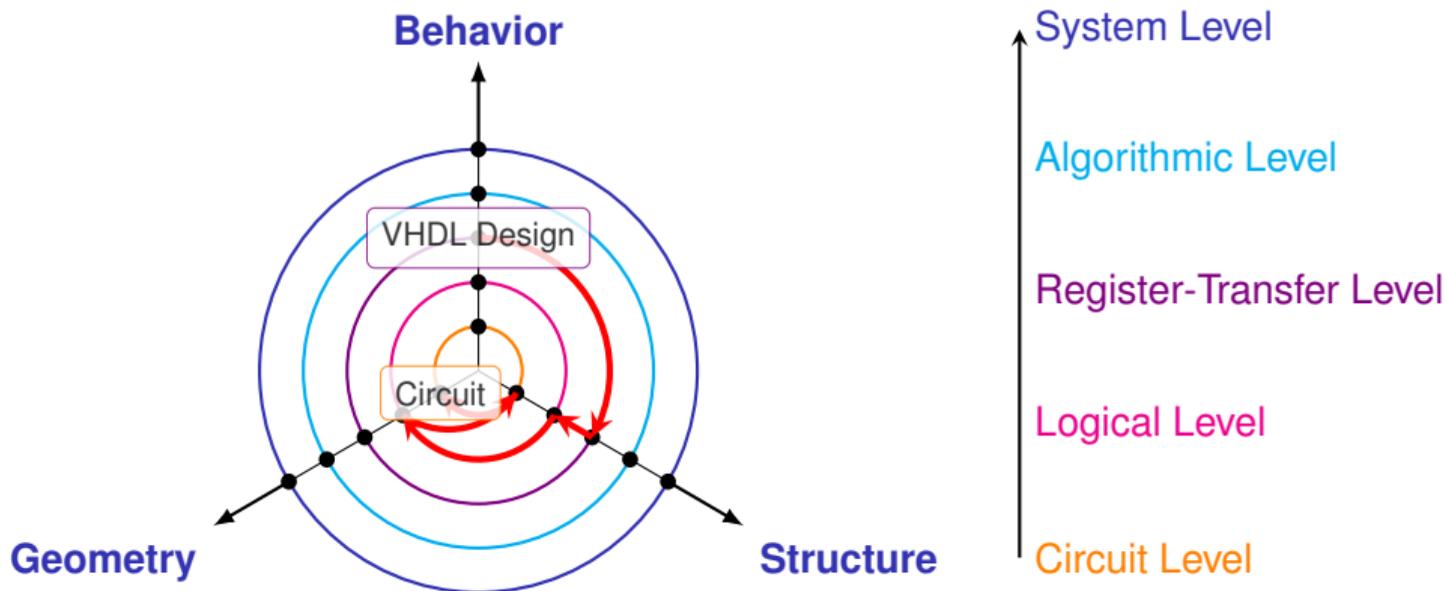


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Recall: Y-Diagram

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- Tools translate between different views
 - VHDL design to circuit implementation



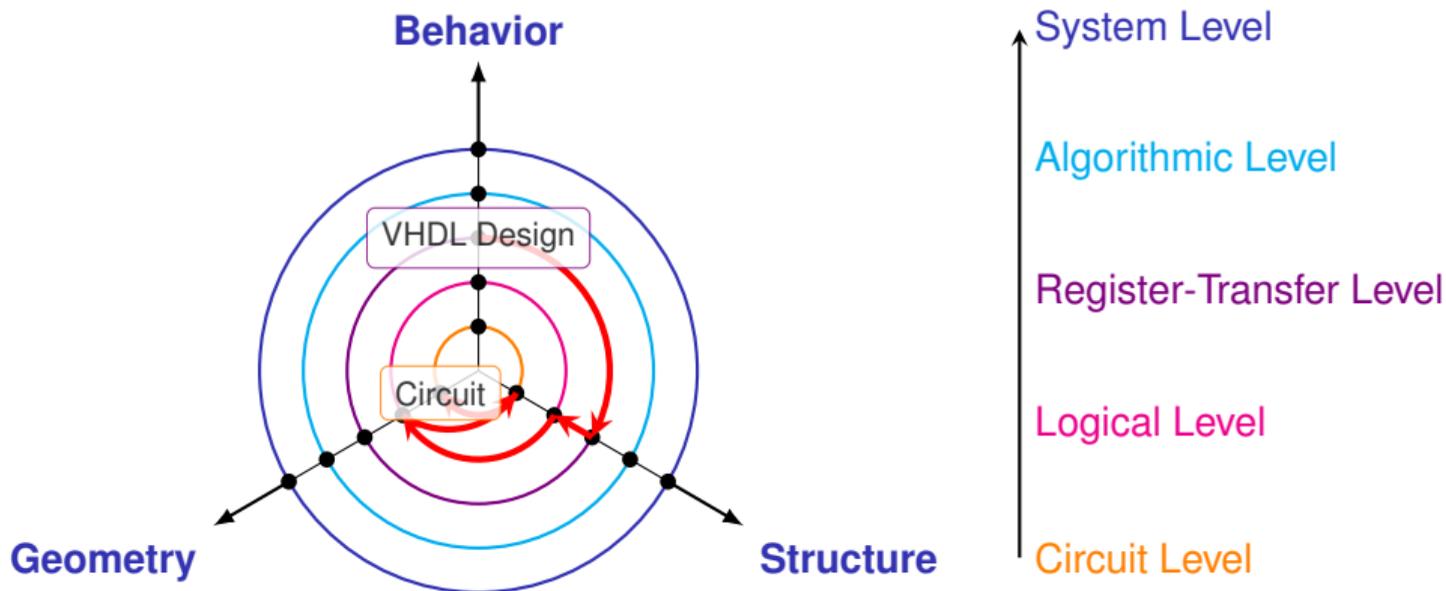
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Recall: Y-Diagram

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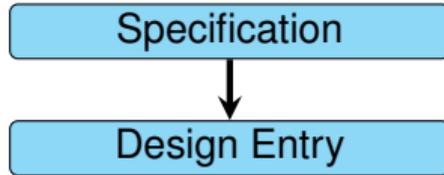
- Tools translate between different views
 - VHDL design to circuit implementation
- What do the tools do? How do translations work?



Hardware Design Flow

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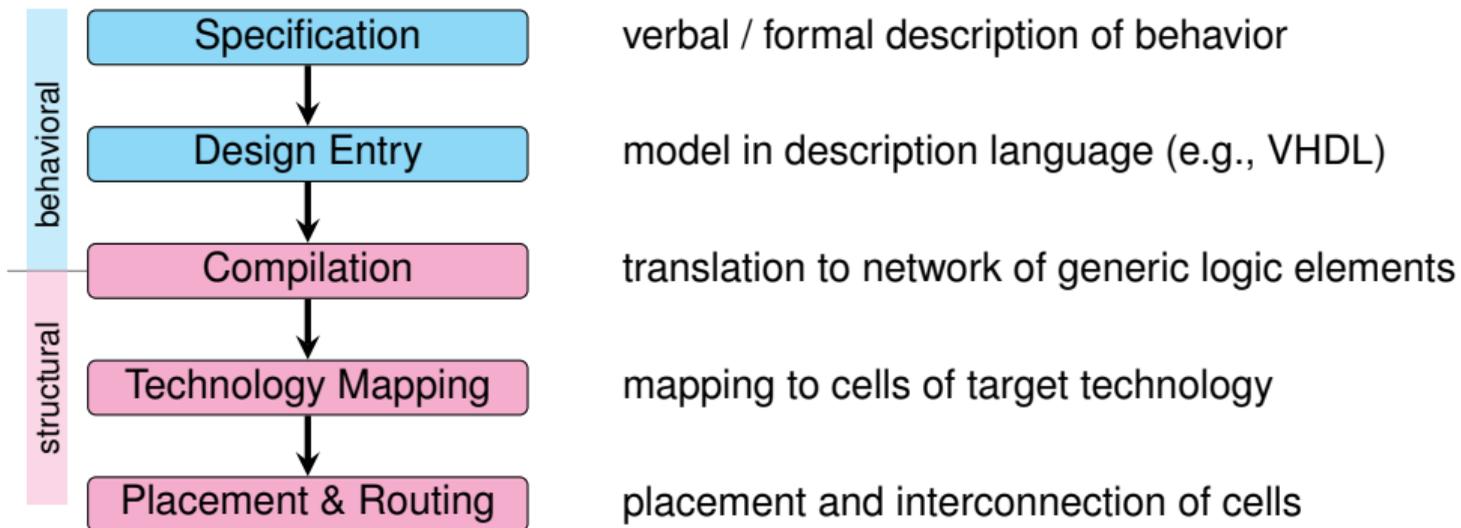
verbal / formal description of behavior

model in description language (e.g., VHDL)

Hardware Design Flow

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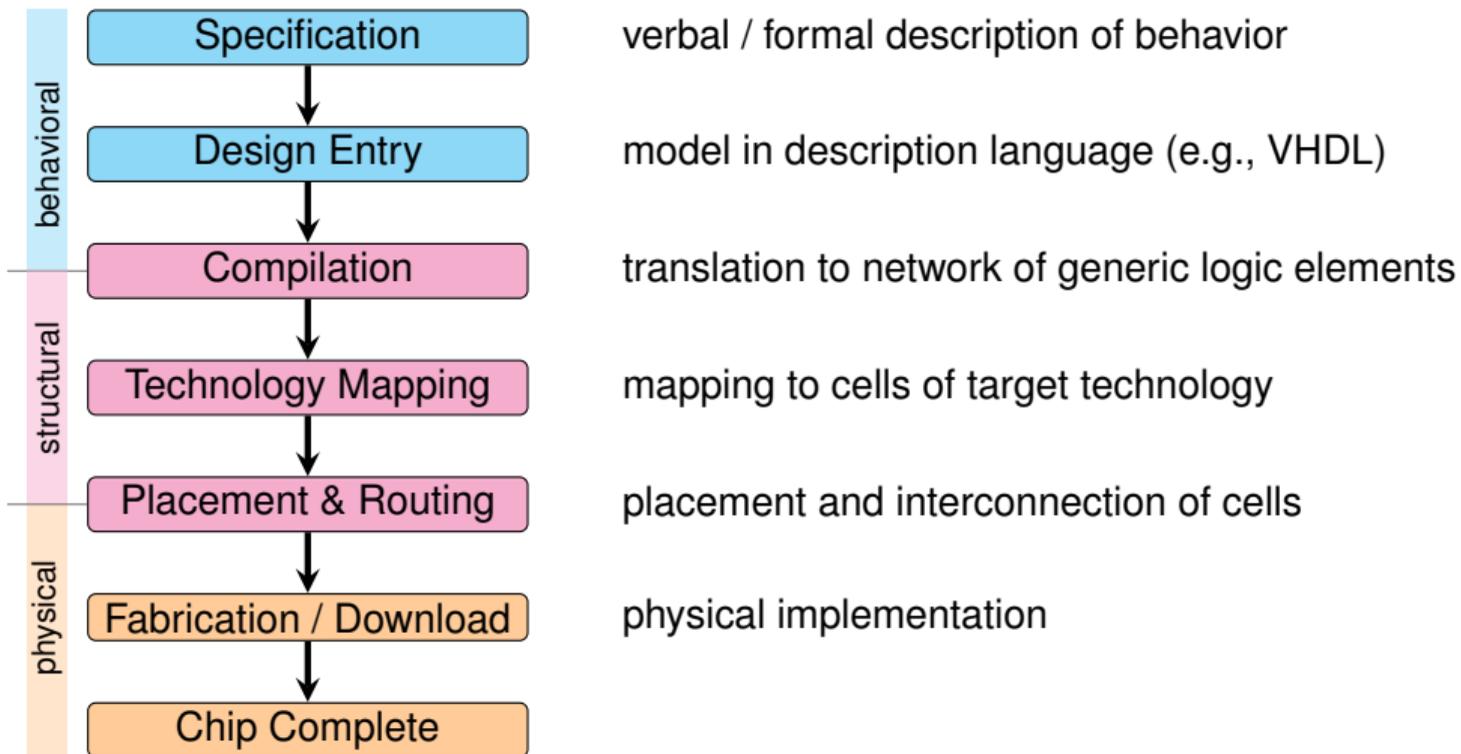
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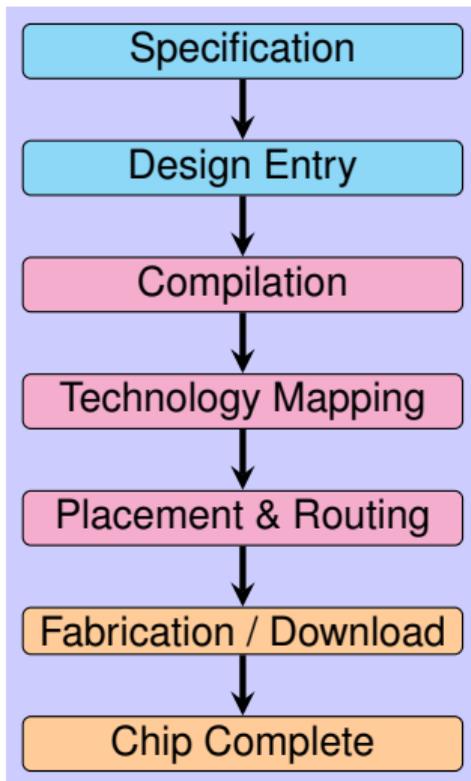
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Hardware Design Flow (cont'd)

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Implementation



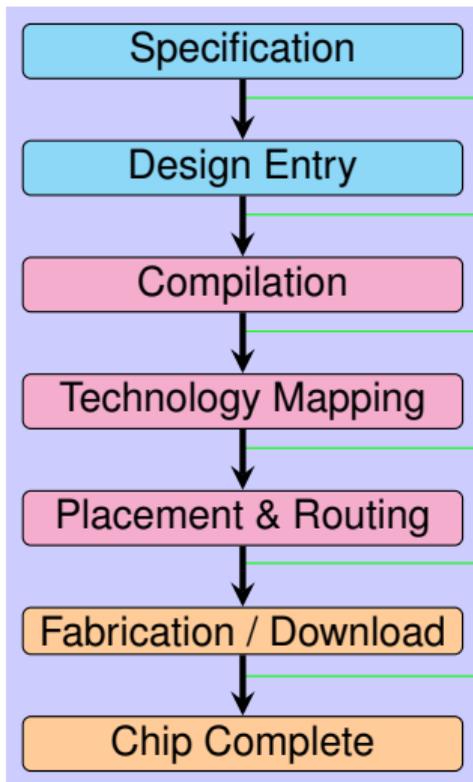
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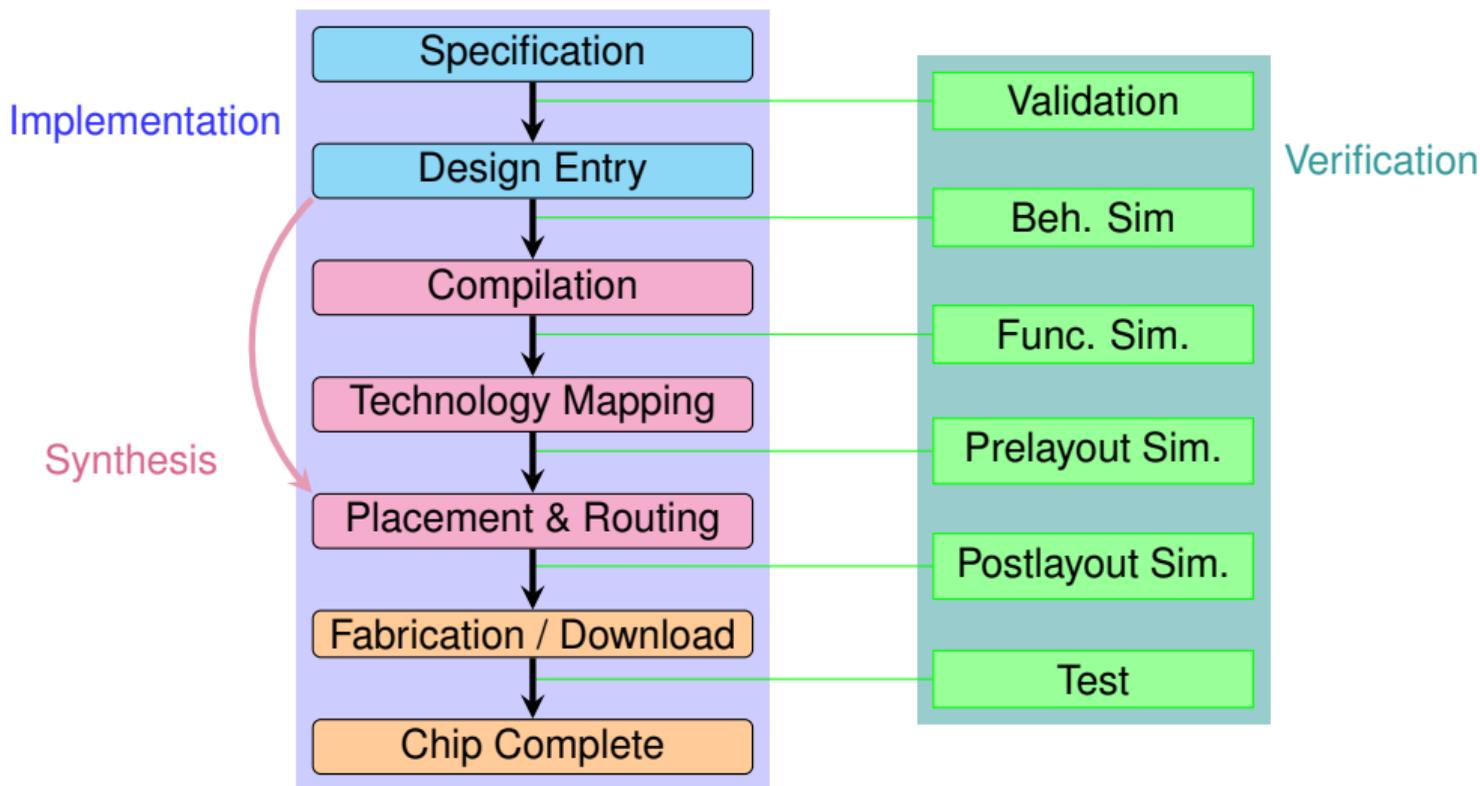
Verification



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Design Entry

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- Description of target circuit (behavioral RTL in VHDL)

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- Description of target circuit (behavioral RTL in VHDL)
 - Readable by tools, basis for simulation and documentation

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Place & Route

- Description of target circuit (behavioral RTL in VHDL)
 - Readable by tools, basis for simulation and documentation
- Example: Synchronous counter

```
1 entity counter is
2   port (
3     clk, res_n : in std_ulogic;
4     number      : out unsigned(7 downto 0)
5   );
6 end entity;
7
8 architecture beh of counter is begin
9   sync : process (clk, res_n) begin
10     if res_n = '0' then
11       number <= (others => '0');
12     elsif rising_edge(clk) then
13       number <= number + 1;
14     end if;
15   end process;
16 end architecture;
```

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Place & Route

- Design entry converted to **technology-agnostic** *netlist*

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Place & Route

- Design entry converted to **technology-agnostic** *netlist*
- Netlist: circuit as graph \Leftrightarrow RTL schematic

Compilation

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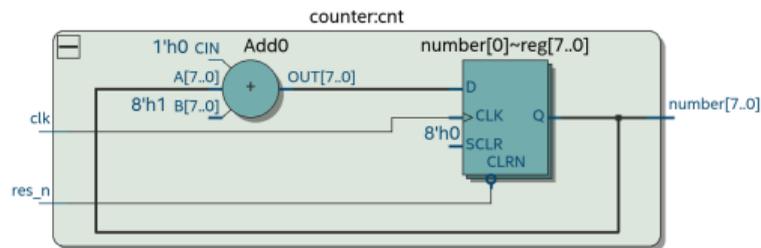
Compilation

Tech. Map

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Place & Route

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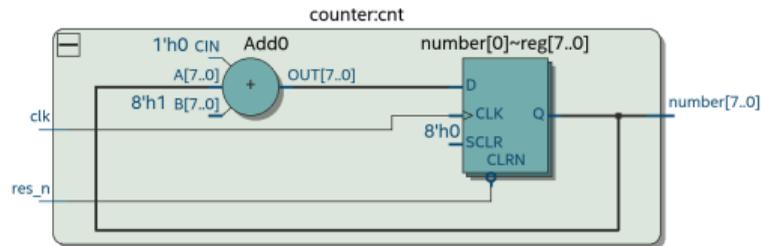
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Tech. Map

FPGAs

Place & Route

- Design entry converted to **technology-agnostic netlist**
- Netlist: circuit as graph \Leftrightarrow RTL schematic
- Generic components (MUX, adder, basic gates)



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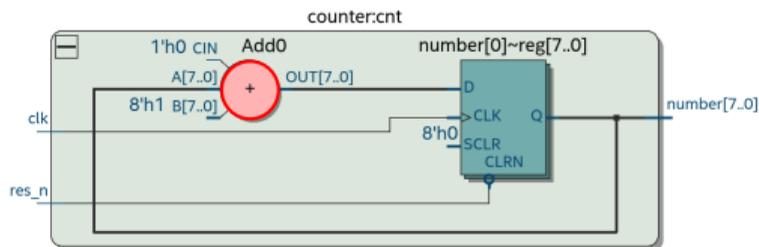
Compilation

Tech. Map

FPGAs

Place & Route

- Design entry converted to **technology-agnostic netlist**
- Netlist: circuit as graph \Leftrightarrow RTL schematic
- Generic components (MUX, adder, basic gates)
 - Tools determine interfaces and check connections



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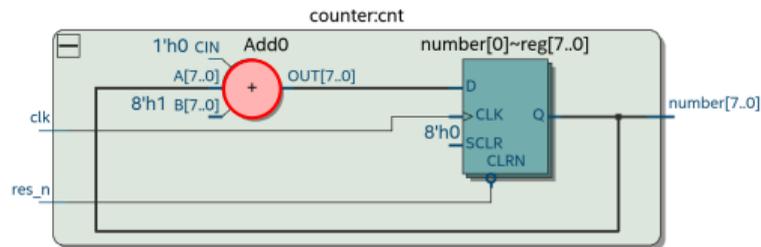
Compilation

Tech. Map

FPGAs

Place & Route

- Design entry converted to **technology-agnostic netlist**
- Netlist: circuit as graph \Leftrightarrow RTL schematic
- Generic components (MUX, adder, basic gates)
 - Tools determine interfaces and check connections
 - Might not exist in target technology



Technology Mapping

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Place & Route

- Map generic elements to target technology

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Place & Route

- Map generic elements to target technology
 - E.g.: ASIC, PAL, Gate-Array, **FPGA**

Technology Mapping

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Place & Route

- Map generic elements to target technology
 - E.g.: ASIC, PAL, Gate-Array, **FPGA**
- Requires *target library* of available cells
 - Gates, sequential elements, etc.
- Target technology is now fixed

Introduction to FPGAs

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■ **Field Programmable Gate Array**

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- **Field Programmable Gate Array ?!**

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- **Field Programmable Gate Array ?!**
- Generic circuit, configurable for target circuit

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- **Field Programmable Gate Array ?!**
- Generic circuit, configurable for target circuit
- Programmable logic cells and interconnect

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Place & Route

- **Field Programmable Gate Array ?!**
- Generic circuit, configurable for target circuit
- Programmable logic cells and interconnect
 - + Large volumes \Rightarrow comparably cheap

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- **Field Programmable Gate Array ?!**
- Generic circuit, configurable for target circuit
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 - + Already fabricated \Rightarrow simpler, faster design

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- **Field Programmable Gate Array ?!**
- Generic circuit, configurable for target circuit
- Programmable logic cells and interconnect
 - + Large volumes \Rightarrow comparably cheap
 - + Already fabricated \Rightarrow simpler, faster design
 - Already fabricated \Rightarrow less optimizations

- **Field Programmable Gate Array ?!**
- Generic circuit, configurable for target circuit
- Programmable logic cells and interconnect
 - + Large volumes \Rightarrow comparably cheap
 - + Already fabricated \Rightarrow simpler, faster design
 - Already fabricated \Rightarrow less optimizations
 - Generic design \Rightarrow inevitable overhead

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- **Field Programmable Gate Array ?!**
- Generic circuit, configurable for target circuit
- Programmable logic cells and interconnect
 - + Large volumes \Rightarrow comparably cheap
 - + Already fabricated \Rightarrow simpler, faster design
 - Already fabricated \Rightarrow less optimizations
 - Generic design \Rightarrow inevitable overhead
- How can such circuits be built?

Look-Up Tables (LUTs)

HWMod
WS25

- How to implement arbitrary logic functions?
 - Map inputs to outputs \Rightarrow truth table

| a | b | y |
|-----|-----|-----|
| 0 | 0 | 1 |
| 0 | 1 | 1 |
| 1 | 0 | 0 |
| 1 | 1 | 0 |

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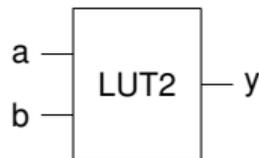
Place & Route

Look-Up Tables (LUTs)

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- How to implement arbitrary logic functions?
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 - \Rightarrow Same in FPGAs: *Look-up Tables* (LUTs)

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Look-Up Tables (LUTs)

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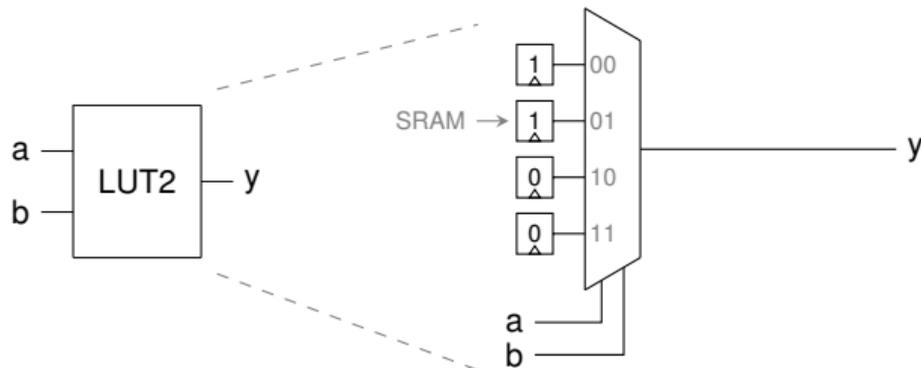
Tech. Map.

FPGAs

Place & Route

- How to implement arbitrary logic functions?
 - Map inputs to outputs \Rightarrow truth table
 - \Rightarrow Same in FPGAs: *Look-up Tables (LUTs)*
 - Store in SRAM cells, use inputs to select

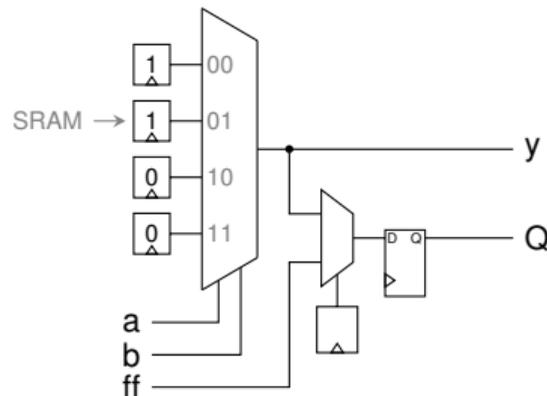
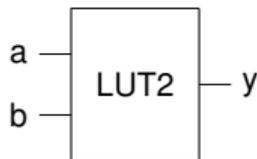
| a | b | y |
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Look-Up Tables (LUTs)

- How to implement arbitrary logic functions?
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 - Store in SRAM cells, use inputs to select
- For sequential logic, add flip-flops

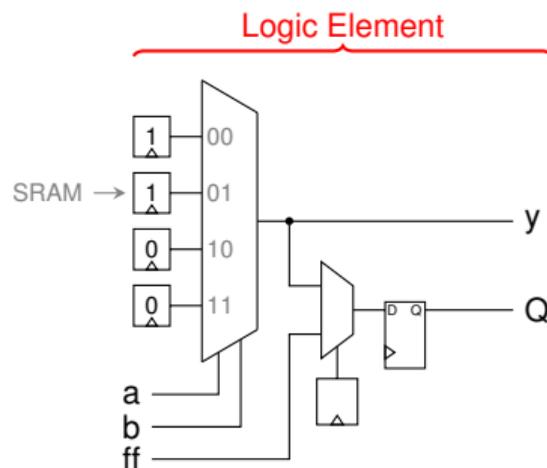
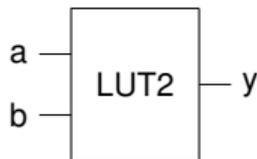
| a | b | y |
|-----|-----|-----|
| 0 | 0 | 1 |
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| 1 | 0 | 0 |
| 1 | 1 | 0 |



Look-Up Tables (LUTs)

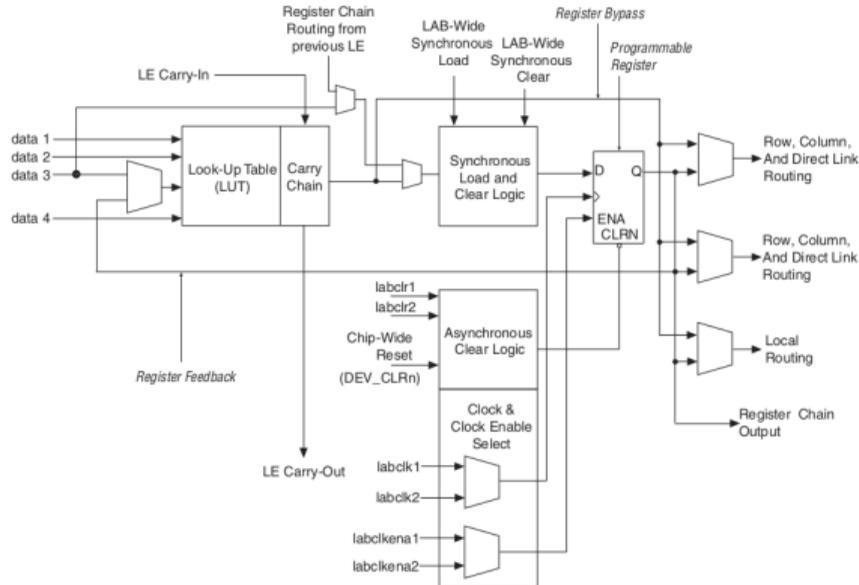
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 - Map inputs to outputs \Rightarrow truth table
 - \Rightarrow Same in FPGAs: *Look-up Tables* (LUTs)
 - Store in SRAM cells, use inputs to select
- For sequential logic, add flip-flops
- *Logic Element* (LE)

| a | b | y |
|-----|-----|-----|
| 0 | 0 | 1 |
| 0 | 1 | 1 |
| 1 | 0 | 0 |
| 1 | 1 | 0 |



LEs in Real FPGAs

- Real LEs are more complex and powerful



LEs in Real FPGAs

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- Real LEs are more complex and powerful
- Bigger LUTs (3-6 inputs)

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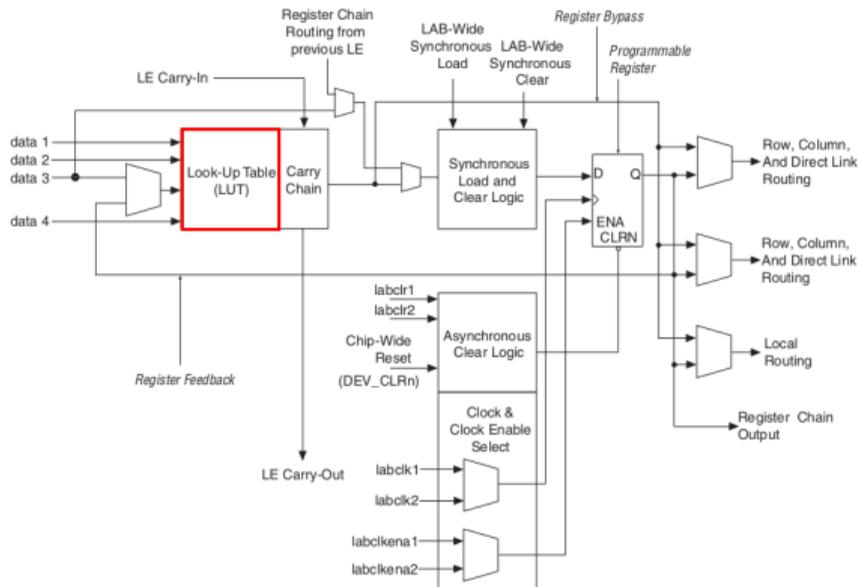
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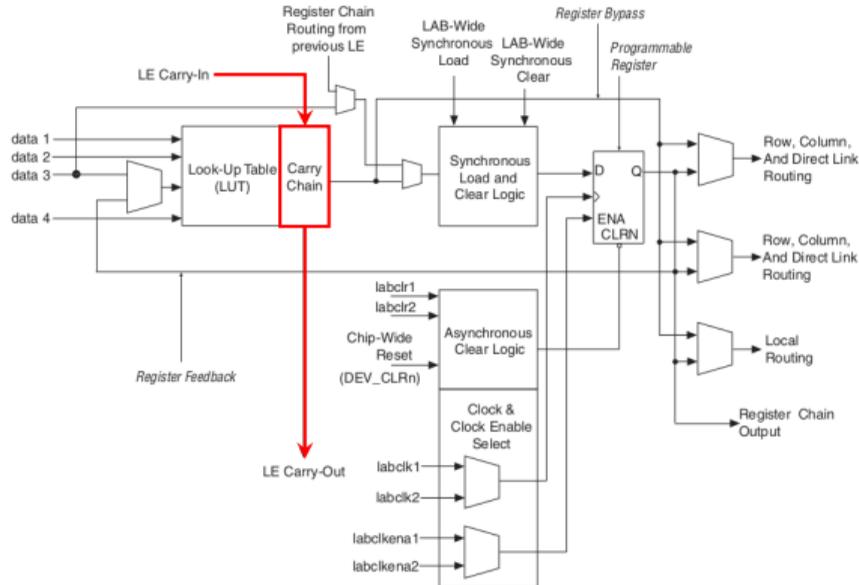
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LEs in Real FPGAs

- Real LEs are more complex and powerful
- Bigger LUTs (3-6 inputs), dedicated carry chains



LEs in Real FPGAs

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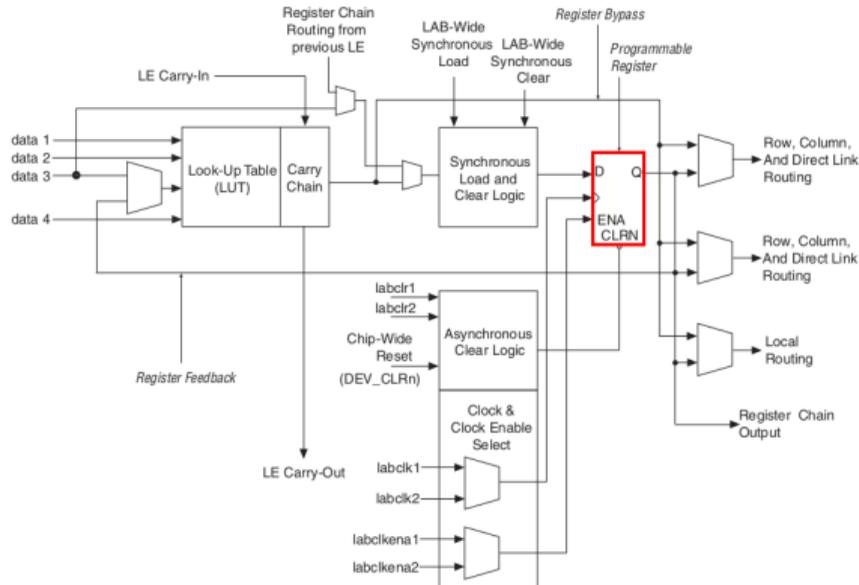
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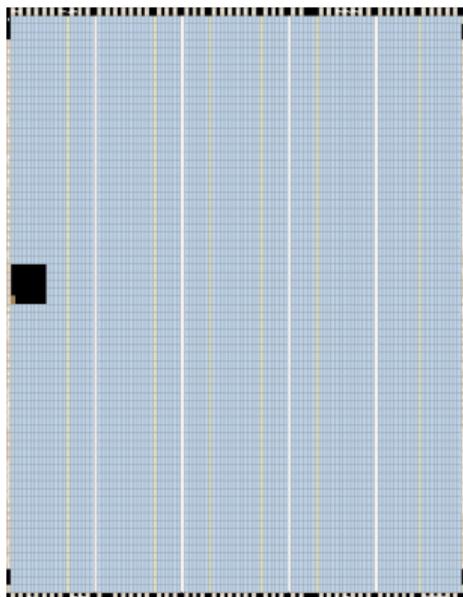
- Real LEs are more complex and powerful
- Bigger LUTs (3-6 inputs), dedicated carry chains
- Clear/set logic, sometimes multiple FFs



FPGA Structure

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- FPGA: grid of LE clusters and other elements



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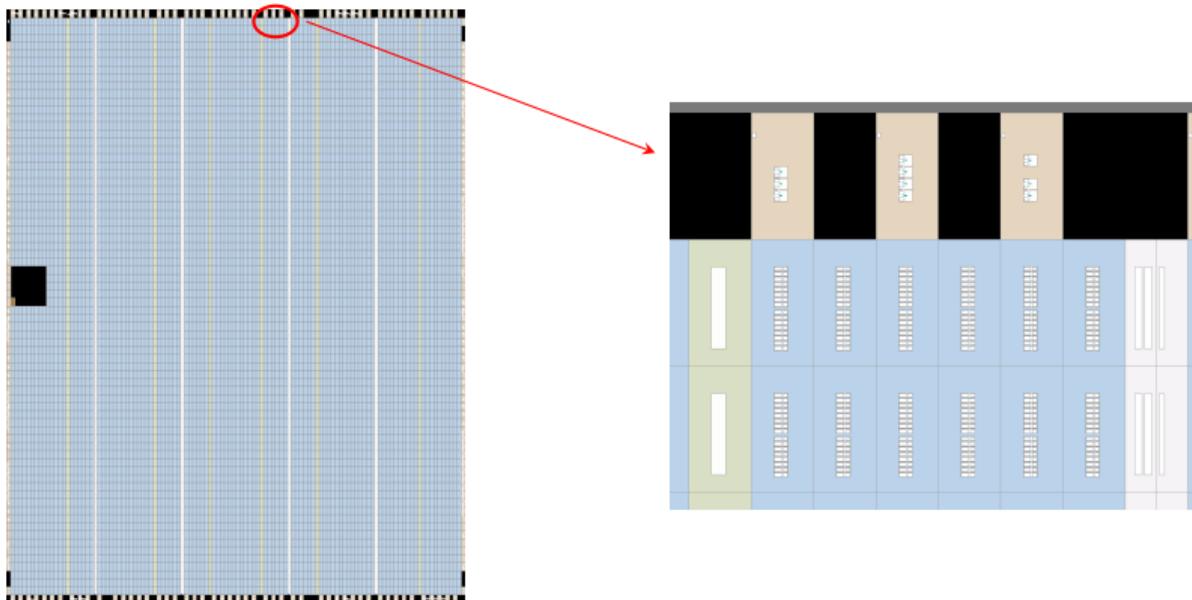
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FPGA Structure

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- FPGA: grid of LE clusters and other elements

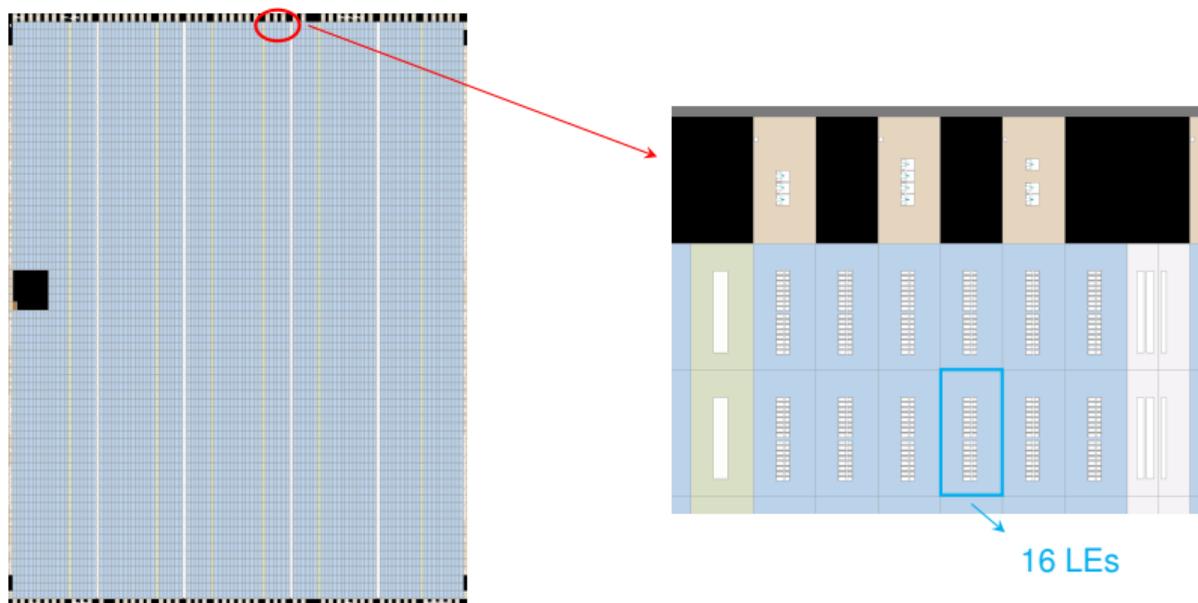


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FPGA Structure

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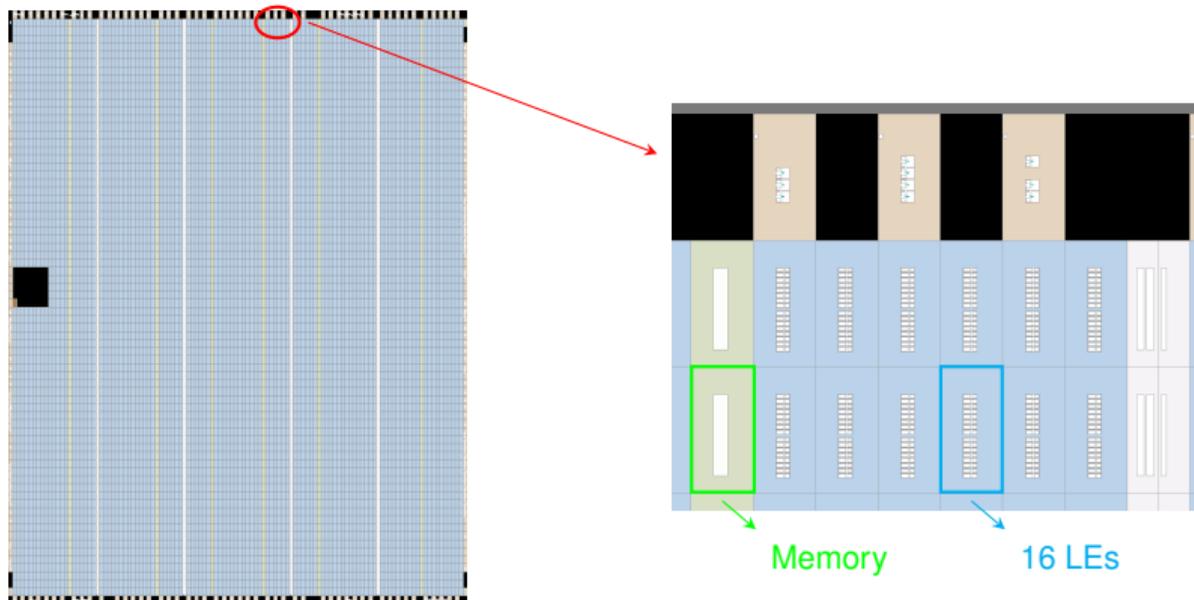


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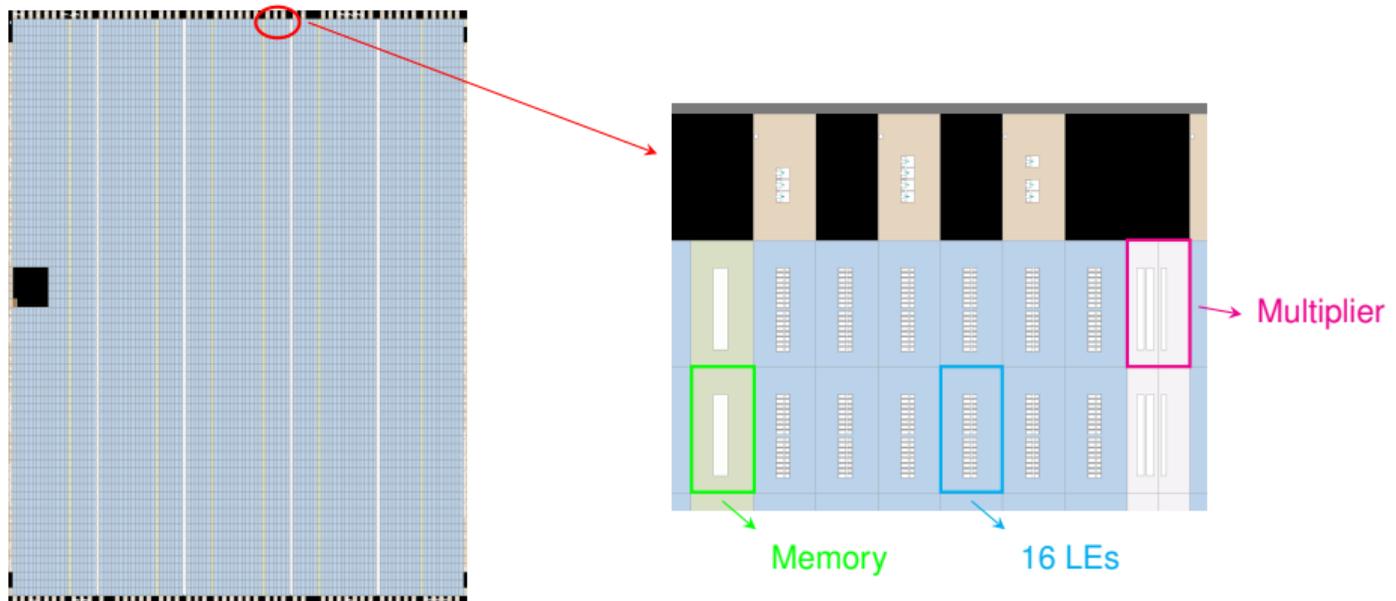


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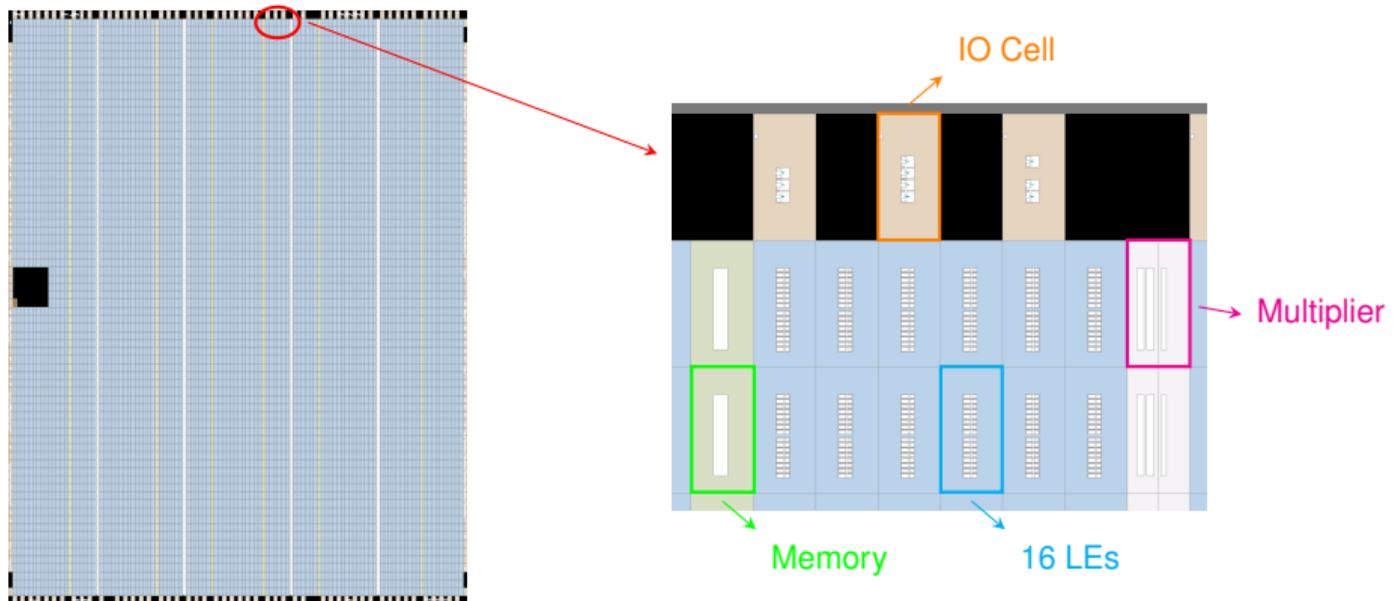


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FPGA Programmable Interconnect

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Place & Route

- How to connect LEs to form complex circuits?

FPGA Programmable Interconnect

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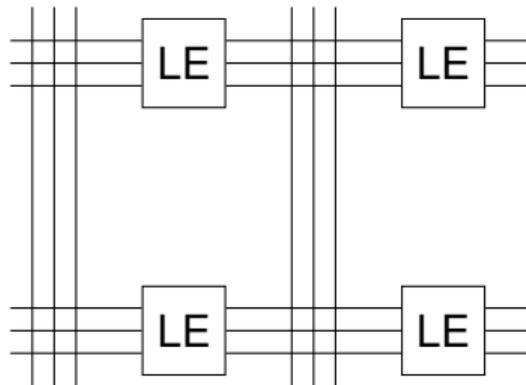
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- How to connect LEs to form complex circuits?
⇒ Programmable interconnect



FPGA Programmable Interconnect

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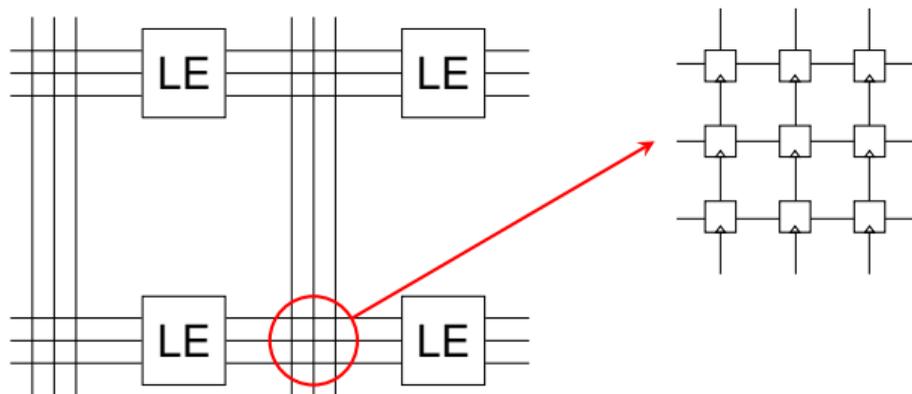
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Place & Route

- How to connect LEs to form complex circuits?
 - ⇒ Programmable interconnect
 - Programmable via SRAM (connected through MUXes)



Technology Mapping to an FPGA

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- Generic elements implemented using LEs

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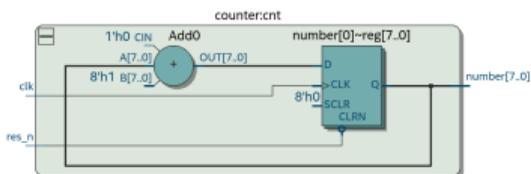
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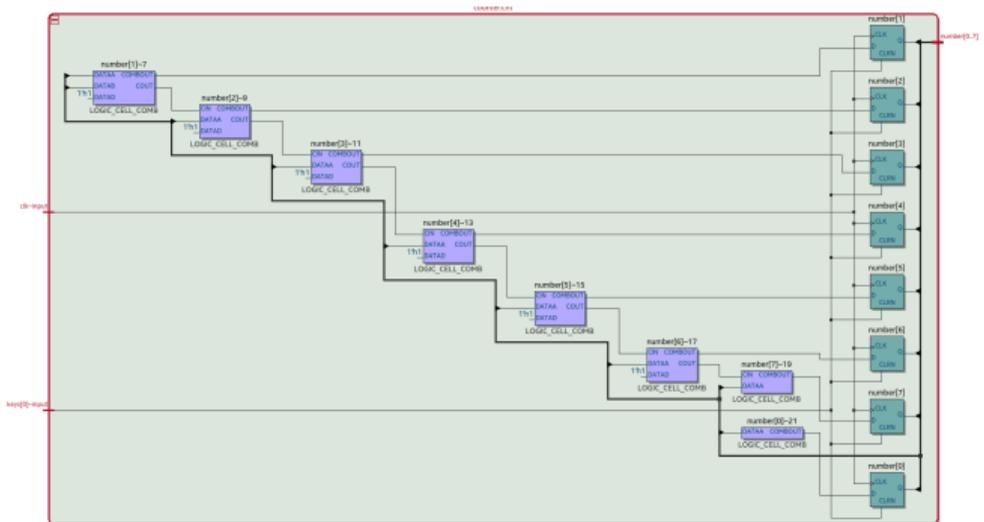
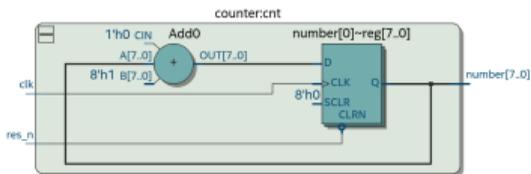
Technology Mapping to an FPGA

- Generic elements implemented using LEs
- Each LE implements part of the logic

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Technology Mapping to an FPGA

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- Generic elements implemented using LEs
- Each LE implements part of the logic
 - Here: carry chain for adders is used

Syn. & PR

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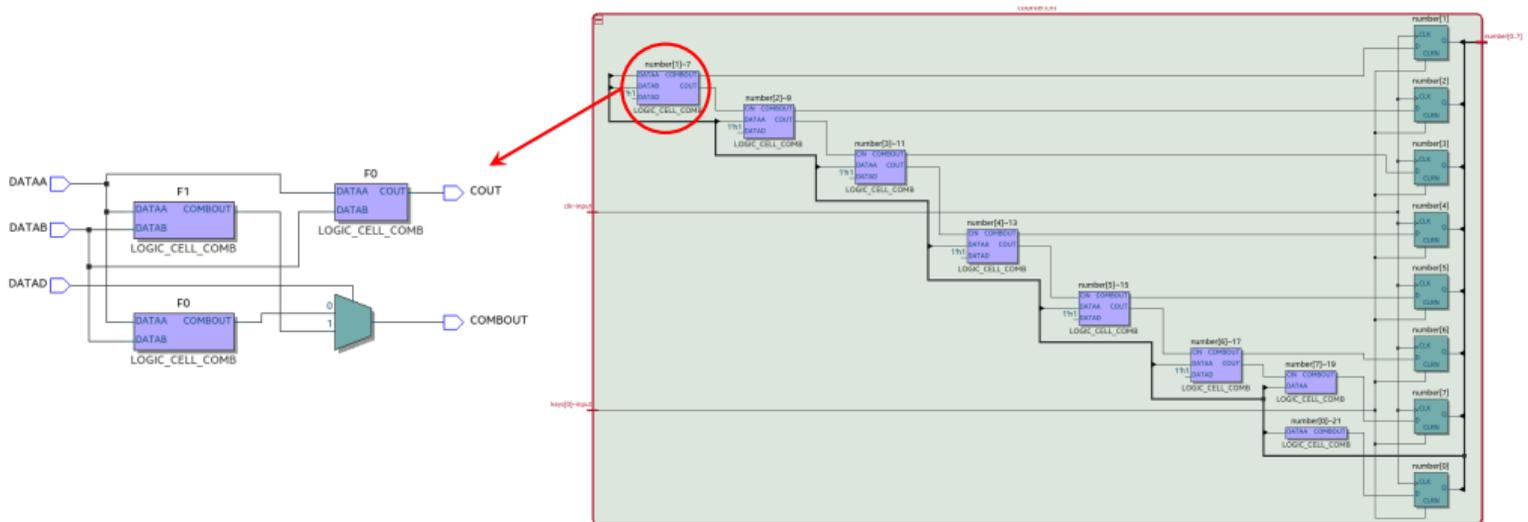
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Placement & Routing

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- Placement: Choose position of LEs

Placement & Routing

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- Placement: Choose position of LEs
 - Constrained by physical availability

Placement & Routing

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- Placement: Choose position of LEs
 - Constrained by physical availability
 - Minimize unknown interconnect

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- Placement: Choose position of LEs
 - Constrained by physical availability
 - Minimize unknown interconnect
- Routing: Connect placed cells
 - Constrained by available interconnect
 - Goal: Meet timing constraints

Placement & Routing

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Place & Route

- Placement: Choose position of LEs
 - Constrained by physical availability
 - Minimize unknown interconnect
- Routing: Connect placed cells
 - Constrained by available interconnect
 - Goal: Meet timing constraints
- Paramount for timing, non-trivial
 - Multiple iterations
 - Driven by heuristics

Placement & Routing

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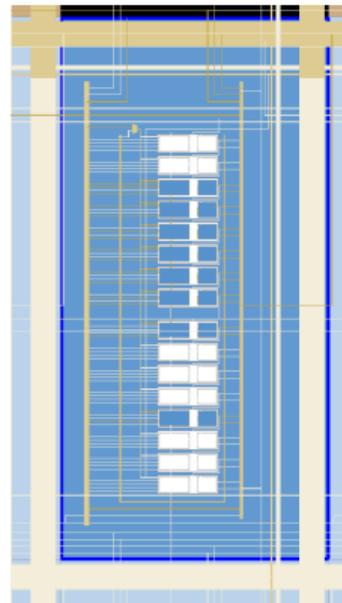
Compilation

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FPGAs

Place & Route

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 - Constrained by physical availability
 - Minimize unknown interconnect
- Routing: Connect placed cells
 - Constrained by available interconnect
 - Goal: Meet timing constraints
- Paramount for timing, non-trivial
 - Multiple iterations
 - Driven by heuristics



FPGA Bitstream

HWMod
WS25

Syn. & PR

Introduction

Design Entry

Compilation

Tech. Map.

FPGAs

Place & Route

- For FPGAs: result is a *bitstream*
 - Content of all SRAM cells
 - Configures LEs and interconnect

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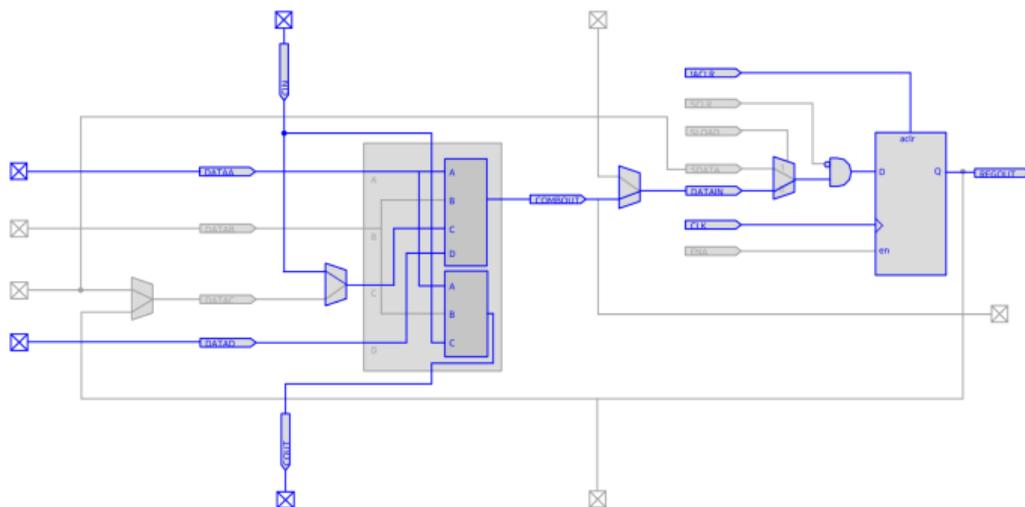
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Lecture Complete!