

Introduction to FPGA Programming



XV Seminar on Software for Nuclear,
Subnuclear and Applied Physics - Alghero (Italy)



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Computing Devices

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- Microprocessors (CPUs).
- Microcontrollers (Arduino, PICs, Etc).
- GPU.
- SoCs (RaspberryPI, Etc).
- ASICs.



- All are electronic components.



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- All are digital.



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Does the component behavior changes ?

There is another class of electronic components: the programmable logic ones.



A Field Programmable Gate Array (FPGA) is the most important example of programmable logic device.

There is difference among:

- Programmable CHIP.
- Programmable Logic CHIP.



Why FPGA is becoming so interesting in computing ?



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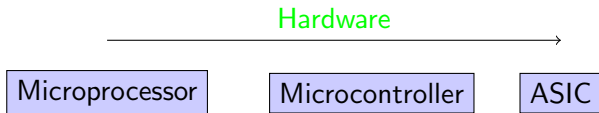
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 - Hard to program.
 - Hard to schedule.

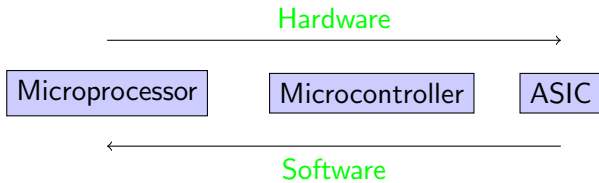


Microprocessor

Microcontroller

ASIC







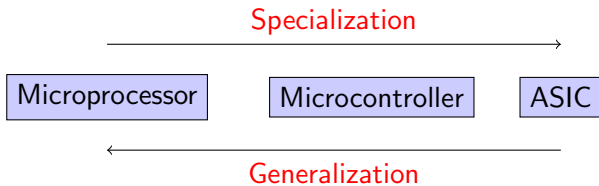
Specialization



Microprocessor

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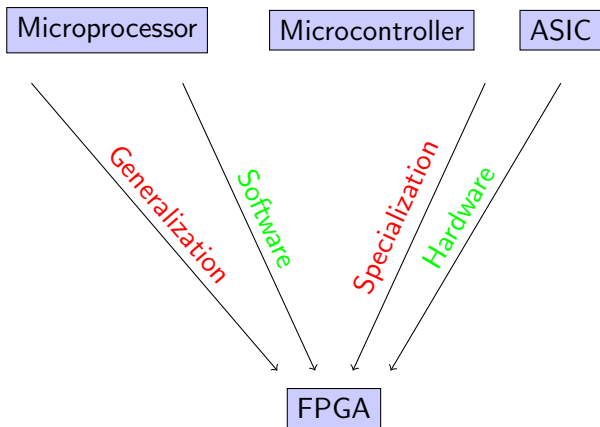


Microprocessor

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FPGA





- We can work with a minor gap among HW/SW.



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- We can work with a minor gap among HW/SW.
- We can benefit from the intrinsic concurrency of FPGA.
- We can easily build heterogeneous systems.

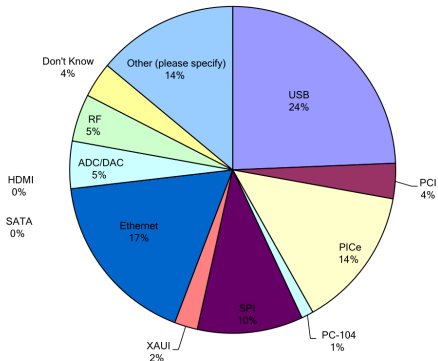


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FPGA

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FPGA exists since several years, their main purpose was for prototyping.





Later (about 2008), we had many advances in this kind of technology:

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- The operating frequencies also increased.

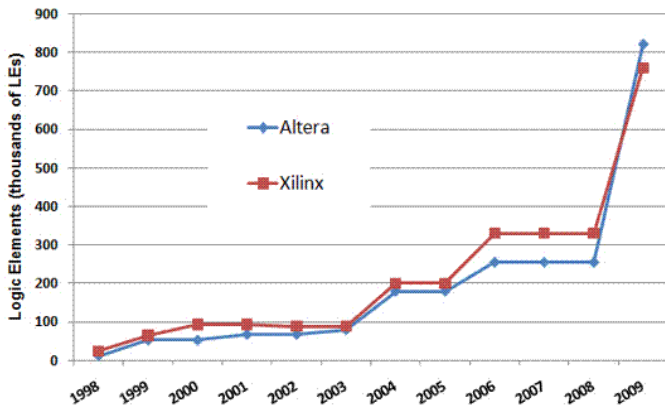
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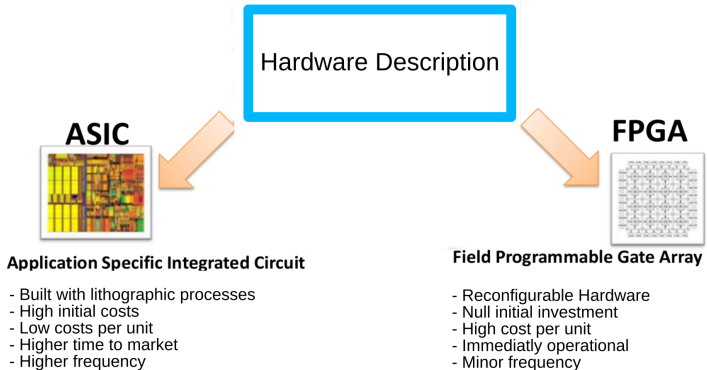
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- The operating frequencies also increased.
- Device become cheaper.

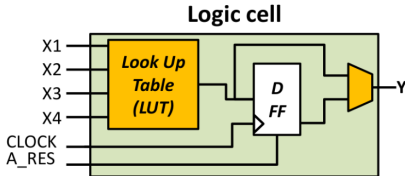
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- Device become cheaper.

FPGA made their appearance directly, within products.







General reference Cell model

Cells details can change for different vendors or FPGA models.

Look-Up Table

X1	X2	X3	X4	Y
0	0	0	1	?
0	0	1	0	?
...	?
1	1	1	1	?



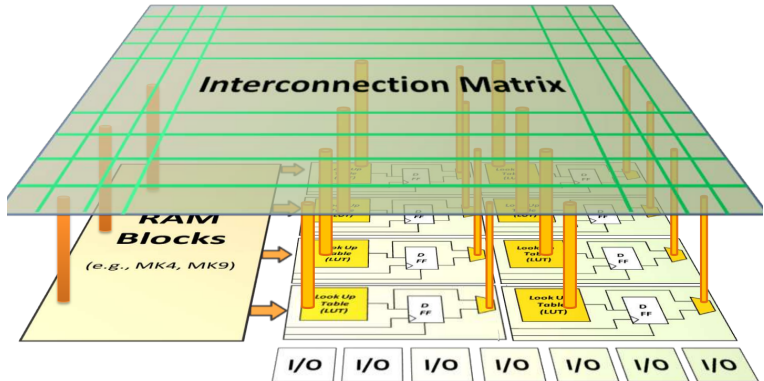
Programmable element

A Cell usually contains:

- A **look-up table**: allow to map any combinational function of 4 inputs and 1 output.
- a **FF of type D**: to store persistent data.
- A **mux 2 -> 1**: to eventually bypass the FF for purely combinational cells.

FPGA Architecture

Interconnection





- Xilinx: Vivado
- Altera (Intel): Quartus Prime
- Lattice: Icecube2

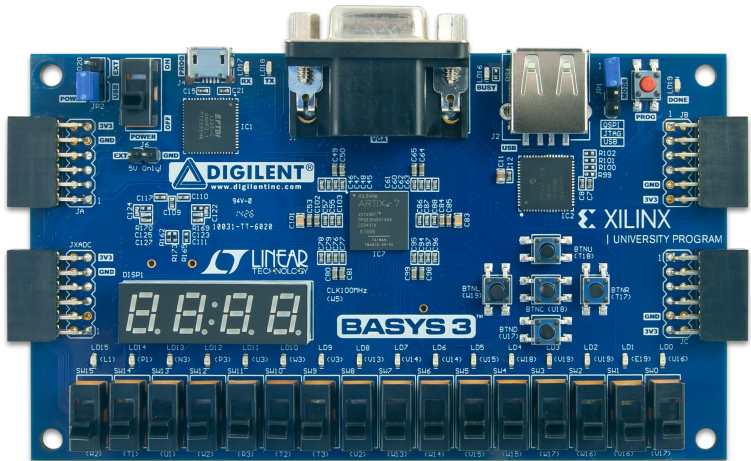


Not open source:

- Modelsim

Open source:

- Iverilog
- GHDL
- Gtkwave



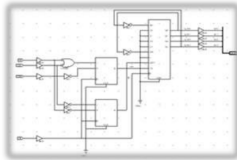


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Programming

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Blocks



PROS:

- Easy and fast development
- Legacy components

CONS:

- Non standard files
- Difficult to maintain
- Difficult for complex designs

Hardware Description Languages

VHDL, Verilog, SystemC

```
begin
  if (RESET_N = '0') then
    for col in 0 to BOARD_COLUMNS-1 loop
      ...
      elsif (rising_edge(CLOCK)) then
```

PROS:

- Standard languages
- Flexibility and easy maintenance
- Complex designs

CONS:

- Computational model



The programming of FPGA devices usually is done through HDL (Hardware Description Language) languages.

The most used are:

- Verilog
- VHDL



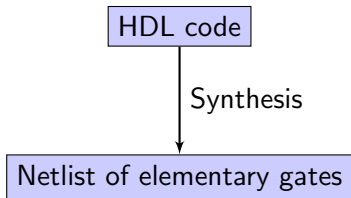
HDL languages offer a computational model to build hardware. Although they may appear standard programming languages like C, C++ or Java, they are not.

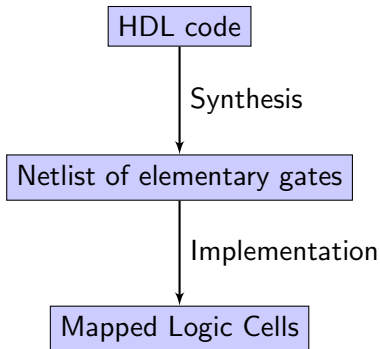
In standard programming languages, statements define instructions that are sequentially executed by the infrastructure (the CPU or a VM). On the other hand, in HDL languages statements define hardware blocks, circuits.

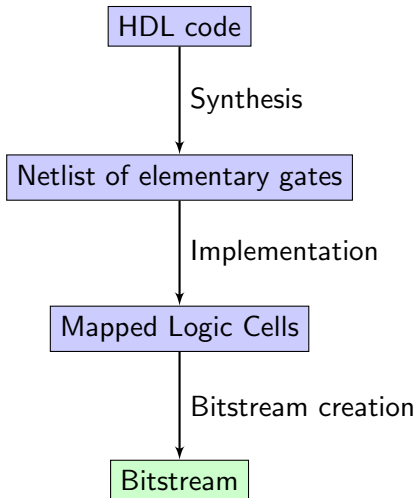
There is no sequential execution, no infrastructure, no run-time.



HDL code









The synthesis phase takes an HDL description and transforms it into a netlist of elementary gates

The synthesis usually acts on a subset of the HDL language

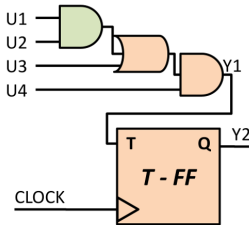
The synthesis occurs by applying templates that match language structures and map them to logic components.

The synthesis result depends upon the mapping libraries in use and upon the used synthesizer.

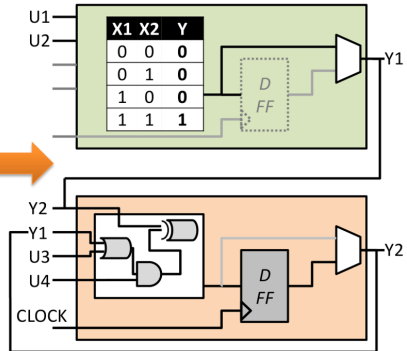


The synthesis essentially transform the HDL code into a block diagram

This block diagram representation has not (yet) a direct correspondence with the hardware, it is only a functional purpose



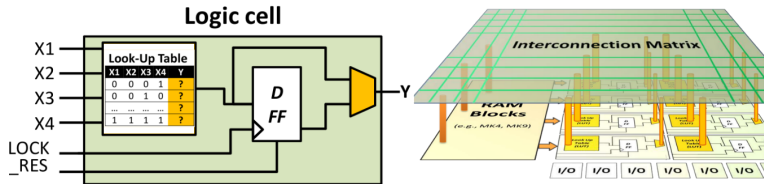
The components inferred during the synthesis phase are mapped on the hardware using the actual FPGA resources.



During the implementation phase several steps are carried on:

- The memory elements are identified (registers, counters, shift-registers) and mapped to elementary Flip-Flop
- The transfer functions (boolean equations) are also identified. Paths could be among (i) registers, (ii) inputs and registers, (iii) registers and outputs, (iv) inputs and outputs.
- The equations are reduced (optimization)
- The resulting equations are mapped to the look-up table of the logic cells

The values of the look-up tables, muxes and interconnection can be packed in a file called bitstream that can be used to program a specific FPGA (filling the yellow elements)





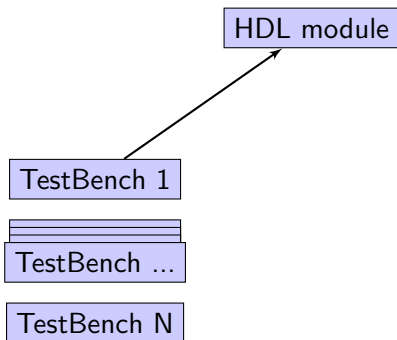
There is another very important work-flow to consider



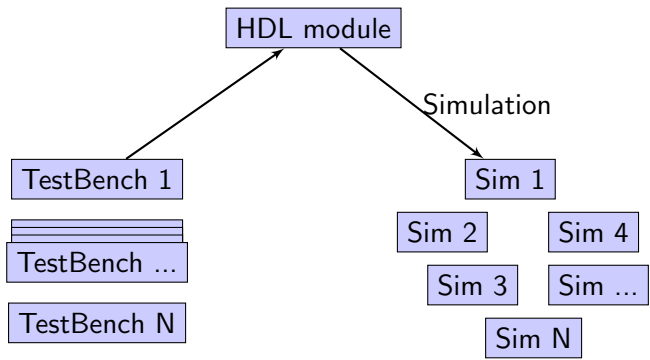
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HDL module

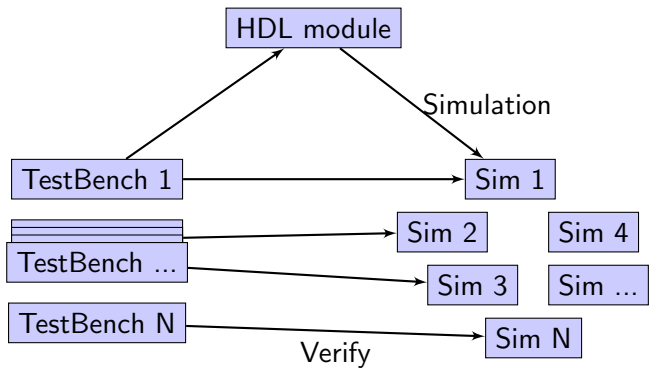
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An important part of FPGA programming is to simulate the components behavior

A Testbench is a verilog module created to test the functionalities of other components



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Verilog

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- Verilog modules are blocks of code (circuit) that can be reused within other blocks (similar to functions in computer programming languages)



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- The keyword “module” starts a block that ends with “endmodule” .
- They could have input and output parameters.

```
module MyModule ([parameters]);  
  inputs ...  
  outputs ...  
  internal variables ...  
  ...  
  Module Code ...  
endmodule
```



- A specific module is tagged as the main module. (similar to the main on a programming language)



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- It is the “program” entry point.
- Usually it has inputs and outputs connected to FPGA physical IO.

Operator Type	Operator Symbol	Operation Performed
Arithmetic	*	Multiply
	/	Division
	+	Add
	-	Subtract
	%	Modulus
	+	Unary plus
Logical	-	Unary minus
	!	Logical negation
Relational	&&	Logical and
		Logical or
	>	Greater than
Equality	<	Less than
	>=	Greater than or equal
	<=	Less than or equal
	==	Equality
Reduction	!=	inequality
	~	Bitwise negation
	~&	nand
		or
	~	nor
	^	xor
	^~	xnor
	~^	xnor
Shift	>>	Right shift
	<<	Left shift
Concatenation	{ }	Concatenation
Conditional	?	conditional

**Wire:**

They are used to connect different elements. They can be thought as physical wires. They can be read or assigned but they does not store information. Indeed they need to be continuously driven from an assignment or a module port.

Reg:

Store a value in Verilog. The value is kept until assigned again (similar to a variable)



The generic number value in Verilog is:

```
<size>'<base><value>
```

Esempi:

```
12 // decimal (base 10)
```

```
8 'h5F // hexadecimal, 8 bit
```

```
6 'b11_0010 // binary, 6 bit
```

```
'o576 // octal with no dimension
```

```
32 'bz // binary a 32 bit Hi-Z
```

The char `_` is ignored and can be used as separator.



Variable can be scalar or vectors.

Examples:

```
reg out; // scalar
```

```
reg [7:0] databus; // 8 bit bus
```

```
wire [1:0] select; // 2 bit bus
```

```
wire enabled; // scalar
```

The verilog block are defined with begin - end.

There are two types of blocks:

Initial block

Is executed when the simulation start or as initial value.

Always block

It is always executed and is associated to a list that specify when execute the block

```
always @ (a or b or sel)
begin
    ...
end
```



Blocking assignment

`A = 3;`

The expression is evaluated in the execution flux and the variable assigned immediately.

NON blocking assignment

`A <= A + 1;`

The expression is evaluated in the execution flux and the result stored in a temporary variable and assigned on the next step

Continuous assignment:

`assign A = in1 & in2; // A is a wire type`

used to model combinatorial logic and rename signals.



Flow control If-else e case

```
if( A == B )  
begin  
    C = 0;  
end  
else  
begin  
    C = 1;  
end
```

```
case (sel)  
    2'b00: out = 0;  
    2'b01: out = 1;  
    default: out = x;  
endcase
```



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Exercises

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`https:
//www.fisgeo.unipg.it/mirko.mariotti/Exercises.tgz`



Specs:

- Vendor: Digilent
- Chip: Xilinx Artix 7 - XC7A35T-1CPG236C
- Cells: 33280
- Frequency: 450 MHz
- 16 user switches
- 16 user LEDs
- Part number: **xc7a35ticpg236-1L**
- ...

Exercise:

- Creation of a Vivado project.
- Creation of a verilog module for the not gate.

```
module notm (  
    input wire A,  
    output wire B  
);  
  
    assign B = ~ A;  
  
endmodule
```

- Synthesis.
- Check of the resulting block diagram.
- Check of the truth values.



Exercise:

- Try the same with the OR gate and with the AND gate.



Logic ports a more complex example 1

Check what is the result with a more complex example

```
module complex(  
    input wire A,  
    input wire B,  
    input wire C,  
    output wire D,  
    output wire E  
);  
  
    assign D = A & (B | C);  
    assign E = B | C;  
endmodule
```



Logic ports

a more complex example 2

Check what is the result with a more complex example

```
module complex(  
    input wire A,  
    input wire B,  
    input wire C,  
    input wire D,  
    input wire E,  
    input wire F,  
    input wire G,  
    output wire H  
);  
  
    assign H = A & ((B | C) & (~D & (F | ~G)) | E);  
endmodule
```



- The constraints file maps the evaluation board peripherals to FPGA I/O pins
- Usually its template is made by the board vendor.
- Has to be included in the project.
- Basys3_master.xdc



Exercise:

- Set the clock as an input.
- Set a led as an output.
- Make the led blink.

```
module blink(  
    input  clk,  
    output reg [7:0] led  
);  
    reg counter;  
    initial  
        counter = 0;  
    always @ (posedge clk) begin  
        led[0] <= counter;  
        counter <= counter + 1;  
    end  
endmodule
```



Make a led blink with about 2Hz freq.

```
module counter(  
    input  clk,  
    output reg [7:0] led  
);  
  
    reg [32:0] counter;  
  
    initial  
        counter = 0;  
  
    always @ (posedge clk) begin  
        led[0] <= counter[23];  
        counter <= counter + 1;  
    end  
  
endmodule
```




Make a led blink with about 2Hz freq, but only if the first switch is on.



Make a led blink with about 2Hz freq when the first switch is off. If the switch goes on double the frequency.



Create a binary counter with the 16 leds



Starting from all the leds off, set the first led on when the central button of the joystick is pressed. If it is pressed again switch the led to off (and so forth).



Starting from all the leds off except the first create a firmware that:

- Move the light right if the right joystick button is pressed (and the external right position is not reached)
- Move the light left if the left joystick button is pressed (and the external left position is not reached)