



TTÜ1918



Digital Systems Modeling and Synthesis

Digitaalsüsteemide modelleerimine ja süntees

IAS0340 – 6.0 EAP 4 2-2-0 E Sp

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Course plan

- **Introduction and simulation principles [1 h]**
- **High-level synthesis [5 h]**
- **Hardware description language SystemC [2 h]**
- **Co-modeling and co-simulation of digital systems, testbenches [4 h]**
- **Hardware description language SystemVerilog [4 h]**
- **VHDL and RTL synthesis [2 h]**
- **Synthesis at various abstraction levels [2 h]**
- **Simulation of analog and digital systems – Spice, VHDL-AMS, etc. [2 h]**
- **Code transformations and system level description languages [2 h]**
- **Hands-on exercises [14*2 h] + selftest in the first or second week [<2 h]**
 - **FIR filter design – HLS, synthesis, SystemC [6+2 h]**
 - **PicoCPU & co-modeling at various level [6+6+6 h]**
 - **Analog simulation (optional) [2 h]**



Textbooks

- **Dirk Jansen et al. (editors), “The electronic design automation handbook.”**
- **Peter J. Ashenden, “The Designer's Guide to VHDL.”**
- **Volnei A. Pedroni, “Circuit Design with VHDL.”**
- **Stuart Sutherland, Simon Davidman, Peter Flake, “System Verilog for Design.”**
- **Michael John Sebastian Smith, “Application-Specific Integrated Circuits.”**
 - <http://www10.edacafe.com/book/ASIC/ASICs.php>
- **David C. Black, Jack Donovan, “SystemC: From the Ground Up.”**

- **Plus some good older ones**
 - **Kalle Tammemäe, “Riistvara kirjeldamiskeel VHDL.”**
 - **K.C. Chang, “Digital systems design with VHDL and synthesis: an integrated approach.”**
 - **Ken Coffman, “Real world FPGA design with Verilog.”**

- **Plus web-based source, incl. Wikipedia**
 - **Bryan Mealy, Fabrizio Tappero, “Free Range VHDL.” – <http://freerangefactory.org>**



Motivation

- **Multi and many core systems on chip (SoC, NoC, etc.) require new design methodologies**
 - to increase designers productivity
 - to get products faster into market
- **There exists a demand for efficient design methodologies at higher abstraction levels**
- **A different thinking needed from the designers**
- **At higher abstraction levels**
 - a designer has much wider selection of possible decisions
 - each of these decisions has also a stronger impact onto the quality of the final design



Optimizations

- **Optimizations at logic level**
 - thousands of nodes (gates) can exist
 - only few possible ways exist how to map an abstract gate onto physical gate from target library
 - optimization algorithms can take into account only few of the neighbors
- **Optimizations at register transfer level (RTL)**
 - hundreds of nodes exist (adders, registers, etc.)
 - there are tens of possibilities how to implement a single module
- **At higher levels, e.g. at system level**
 - there are only tens of nodes to handle (to optimize)
 - there may exist hundreds of ways how to implement a single node
 - every possible decision affects much stronger the constraints put onto neighboring nodes thus significantly affecting the quality of the whole design



Decisions at higher abstraction levels

- **Two major groups of decisions**
 - **selection of the right algorithm to solve a subtask**
 - making transformations inside the algorithm, e.g. parallel versus sequential execution
 - affect primarily the final architecture of the chip
 - **decisions about the data representation**
 - e.g. floating point versus fixed point arithmetic, bit-width, precision.
- **Selection of a certain algorithm puts additional constraints also onto the data representation**
- **Selecting a data representation narrows also the number of algorithms available**



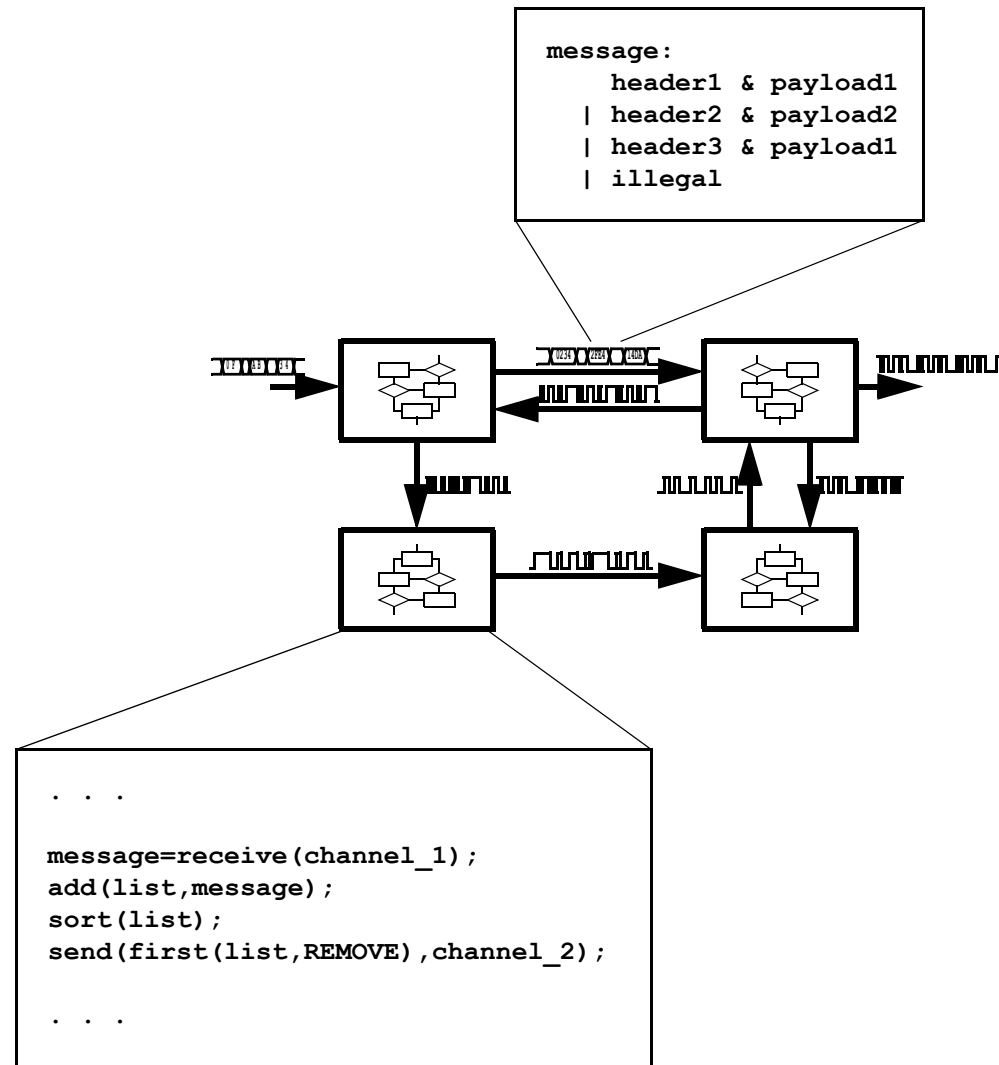
Design steps

- **System design**
 - a.k.a.* Architectural-level synthesis
 - a.k.a.* High-level synthesis
 - a.k.a.* Structural synthesis
 - description / specification → block diagram
 - determining the macroscopic structure, *i.e.*, interconnection of the main modules (blocks) and their functionality
- **Logic design**
 - block diagram → logic gates
 - determining the microscopic structure, *i.e.*, interconnection of logic gates
- **Physical design**
 - a.k.a.* Geometrical-level synthesis
 - logic gates → transistors, wires

Abstraction levels

- **System level**
 - modules / methods
 - channels / protocols

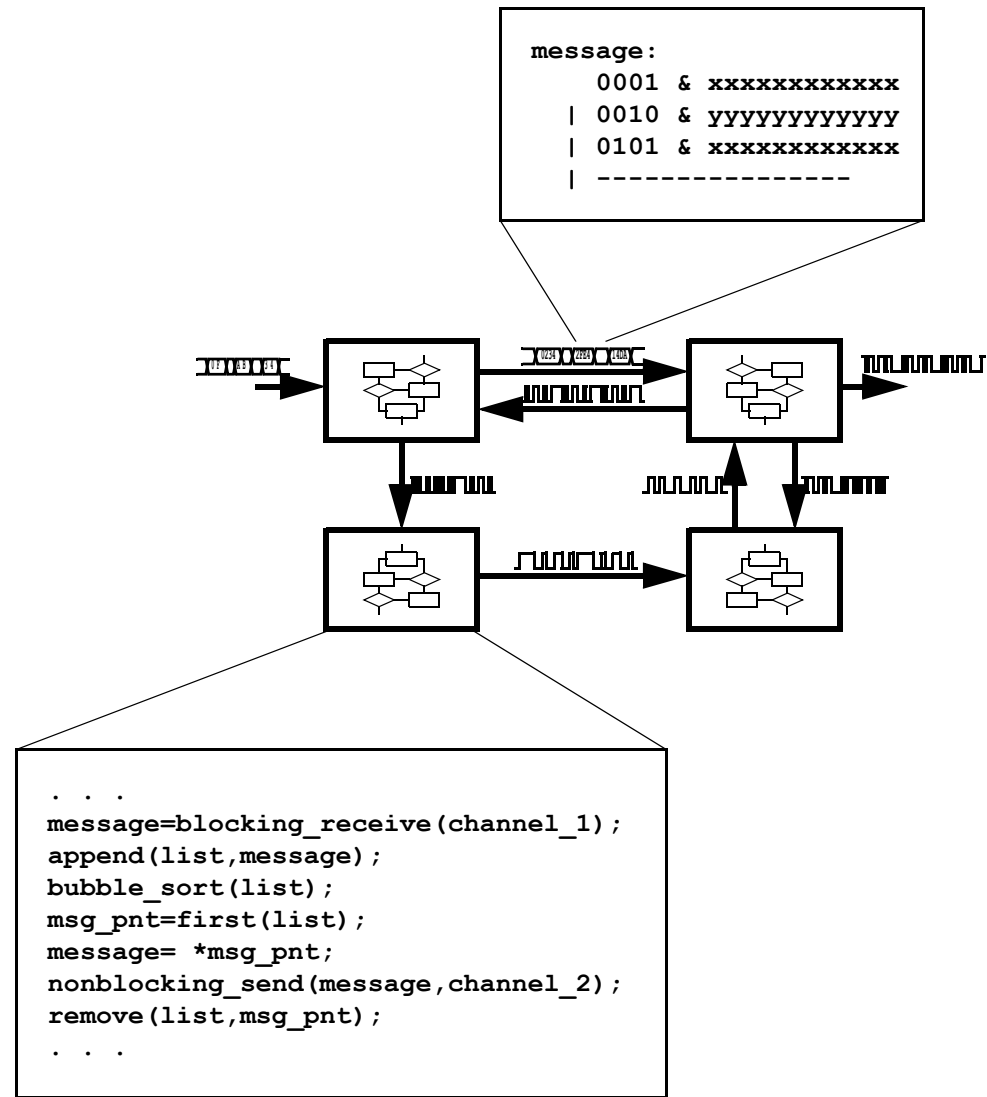
- **System Level Synthesis**
 - Clustering.
 - Communication synthesis.



Abstraction levels

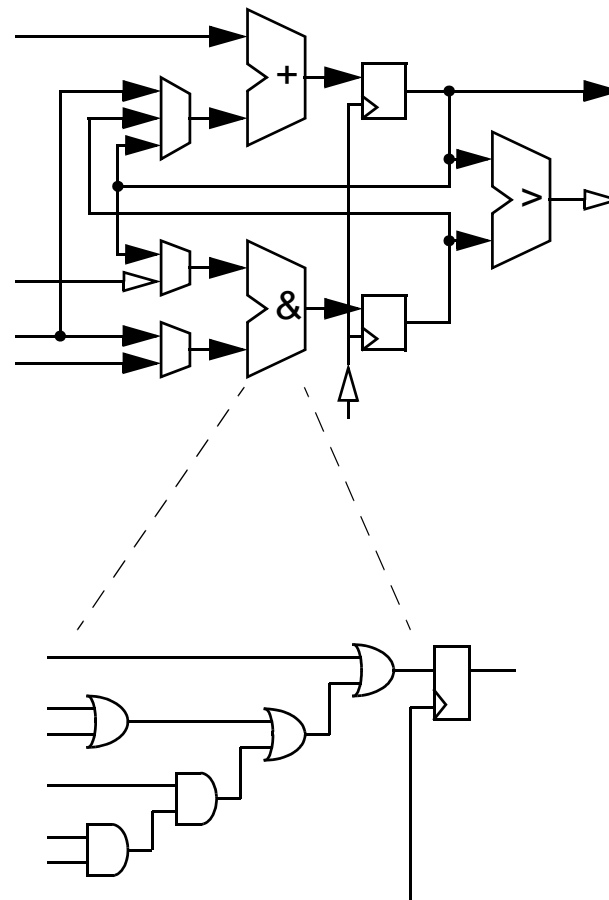
- **Algorithmic level**
 - (sub)modules / algorithms
 - buses / protocols

- **High-Level Synthesis**
 - Resource or time constrained scheduling.
 - Resource allocation. **Binding.**



Abstraction levels

- **Register transfer (RT) level**
 - blocks / logic expressions
 - buses / words
- **Level Synthesis**
 - Data-path synthesis.
Controller synthesis.
- **Logic level**
 - logic gates / logic expressions
 - nets / bits
- **Logic Level Synthesis**
 - Logic minimization.
Optimization, overhead removal.

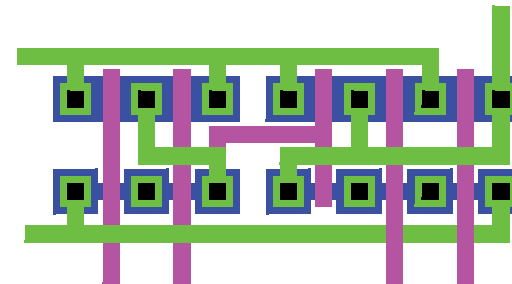
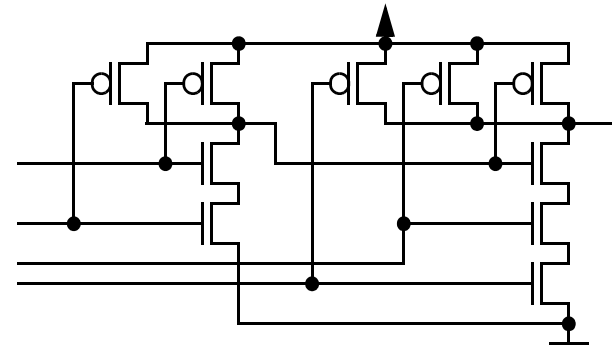




Abstraction levels

- **Physical level**
 - transistors / wires
 - polygons

- **Physical Level Synthesis**
 - Library mapping.
Placement. Routing.

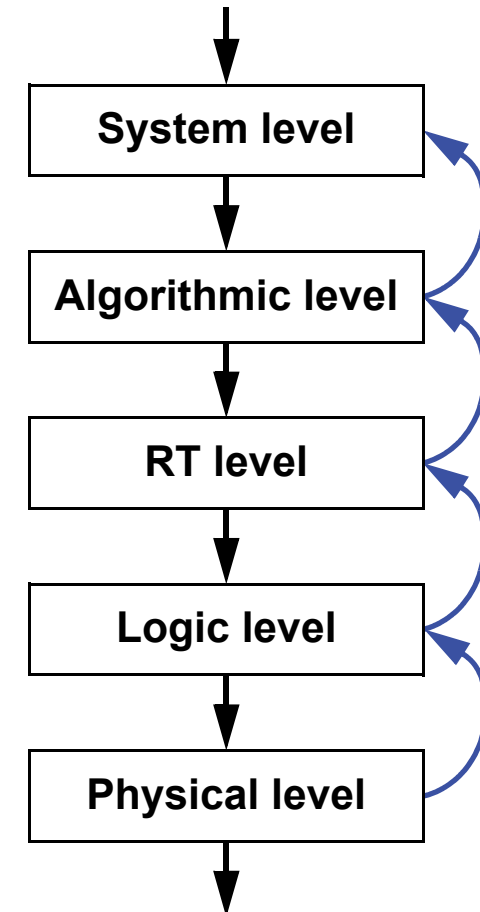




Design flow

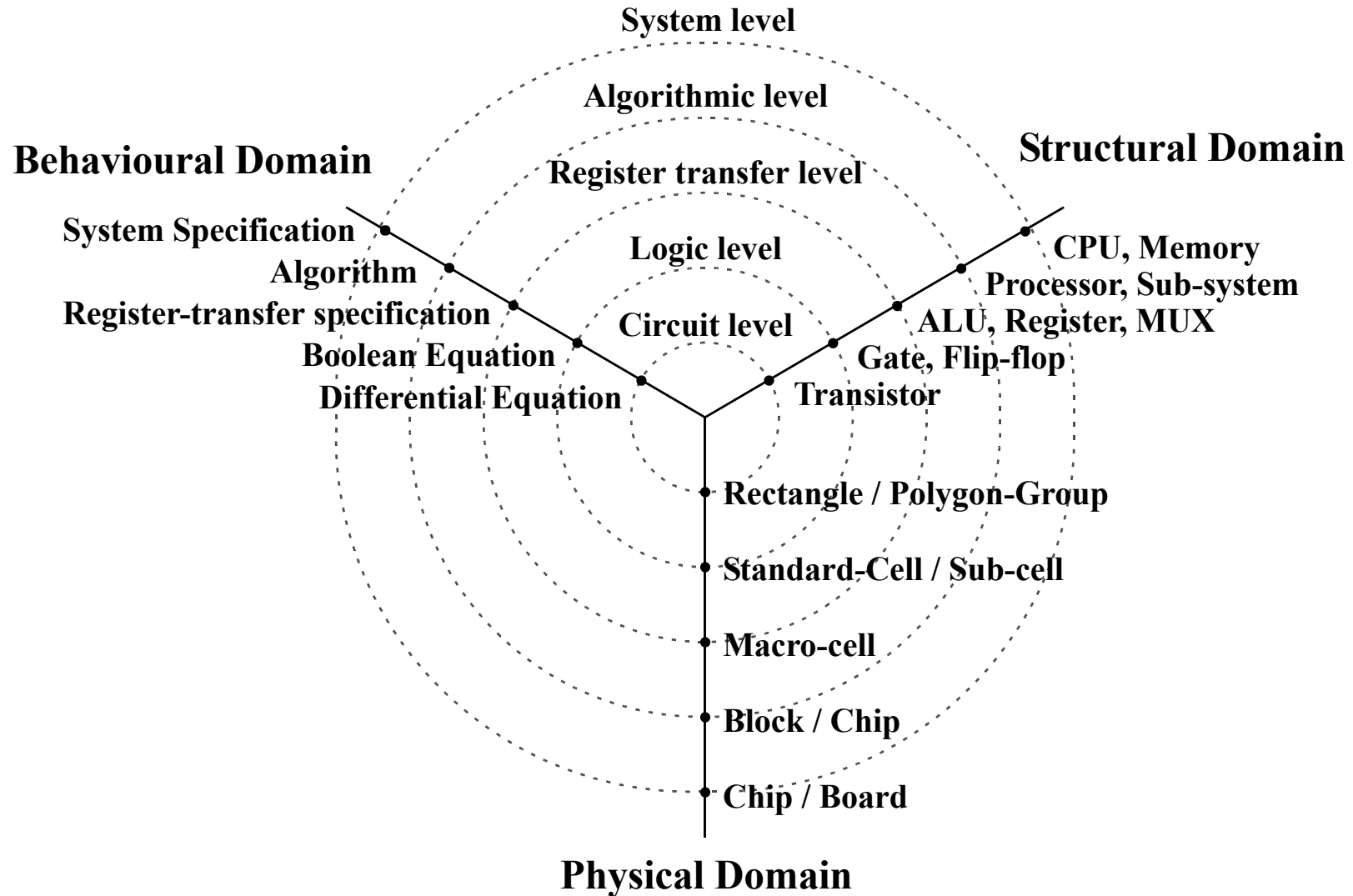
- **Specification refinement**
 - from higher to lower abstraction levels
 - refinement = transformations
- **Algorithm selection**
 - universal vs. specific
 - speed vs. memory consumption
- **Partitioning**
 - introducing structure
 - implementation environment – HW vs. SW
- **Technology mapping**
 - converting algorithm into Boolean equations
 - replacing Boolean equations with gates

HW design flow



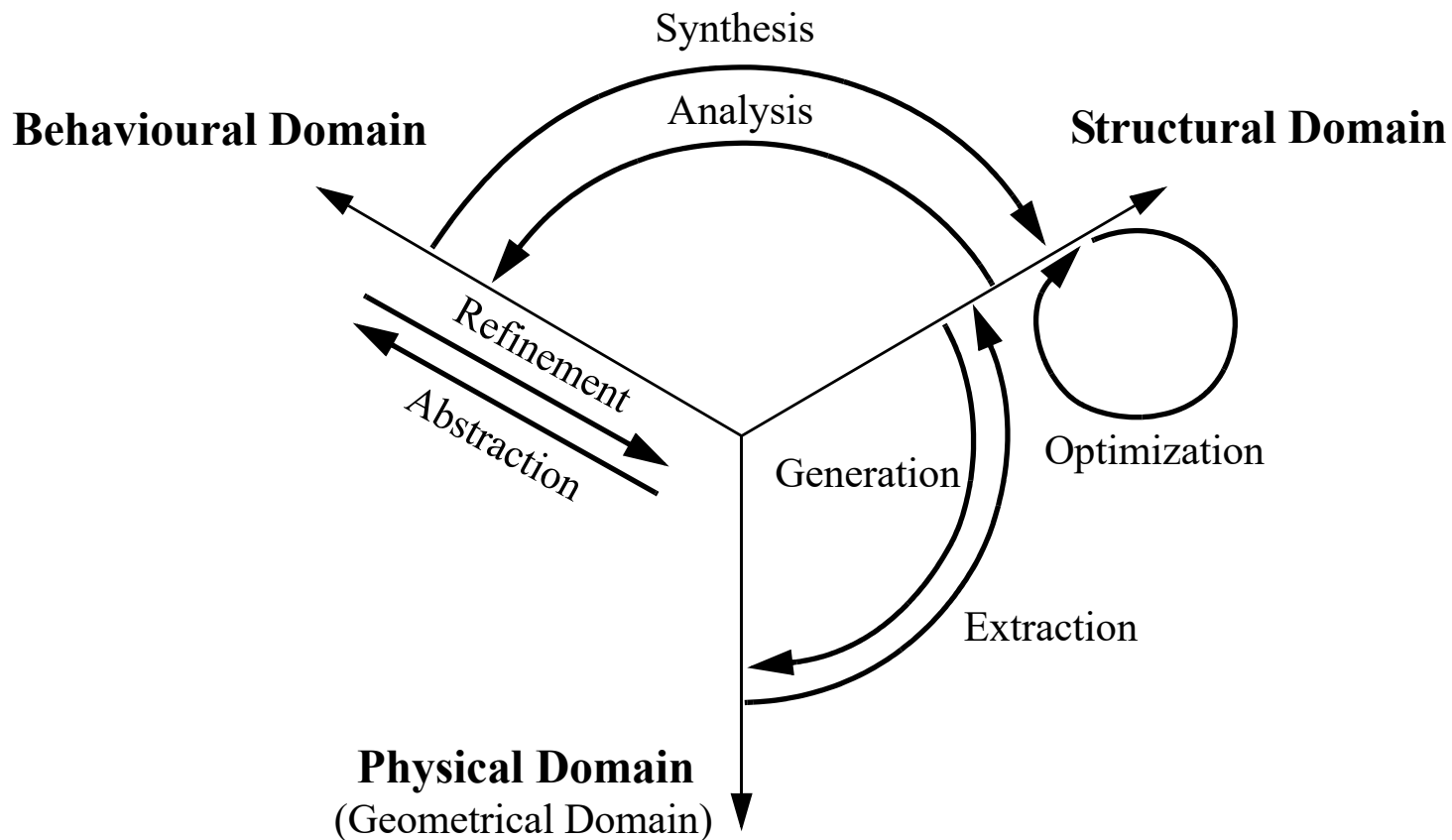


Y-chart



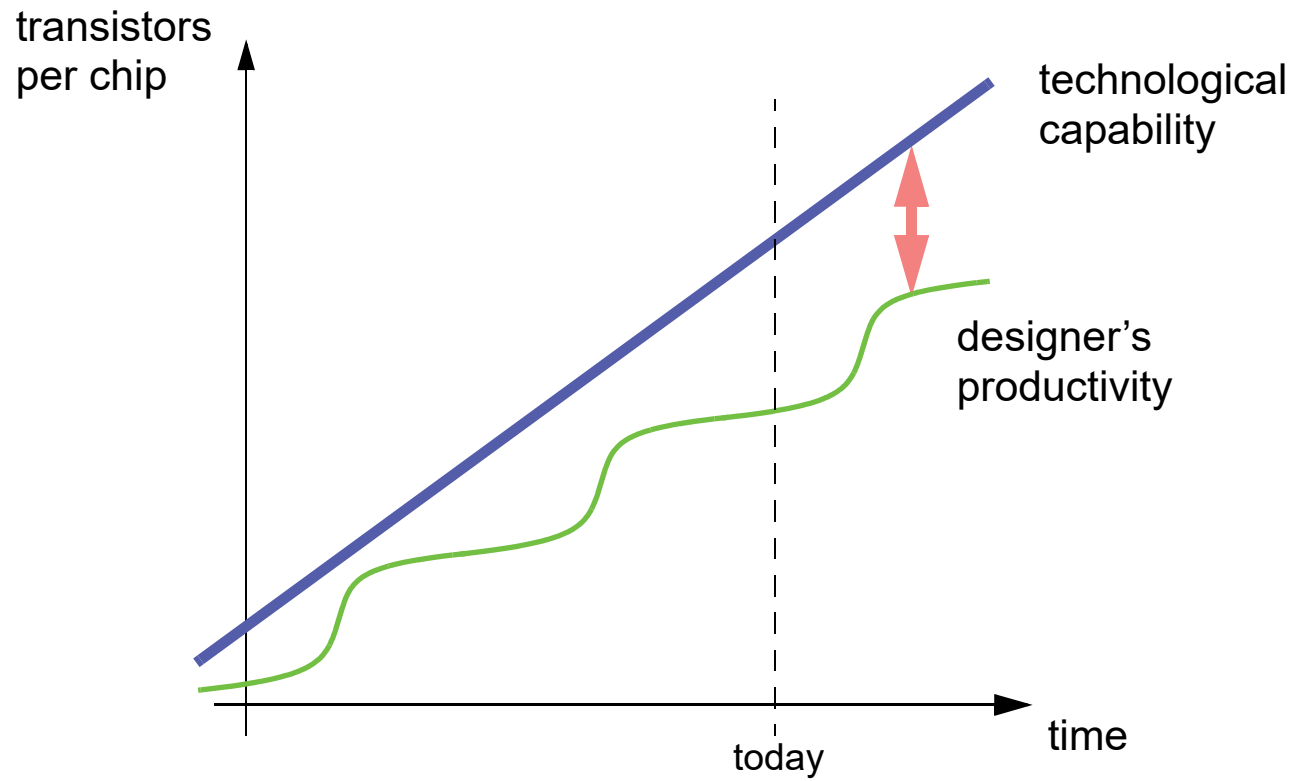


Y-transformations





Synthesis – design automation





Design automation – a bit optimistic & idealistic view

- 1990 – 4 K gates / year / designer
- 1993 – inhouse place and route – 5.6K
- 1995 – engineer (RTL→GDSII) – 9.1K
- 1997 – small blocks reuse (2.5K-75K) – 40K
- 1999 – large blocks reuse (75K-1M) – 56K
- 2001 – synthesis (RTL→GDSII) – 91K
- 2003 – intelligent testbench – 125K
- 2005 – behavioral and architectural levels, HW/SW (co)design – 200K
- 2007 – very large blocks reuse (>1M, IP cores) – 600K
- 2009 – homogeneous parallel processing (multi-core) – 1200K
- *Future – hw/sw co-verification, executable specification, etc.*



Market = \$\$\$

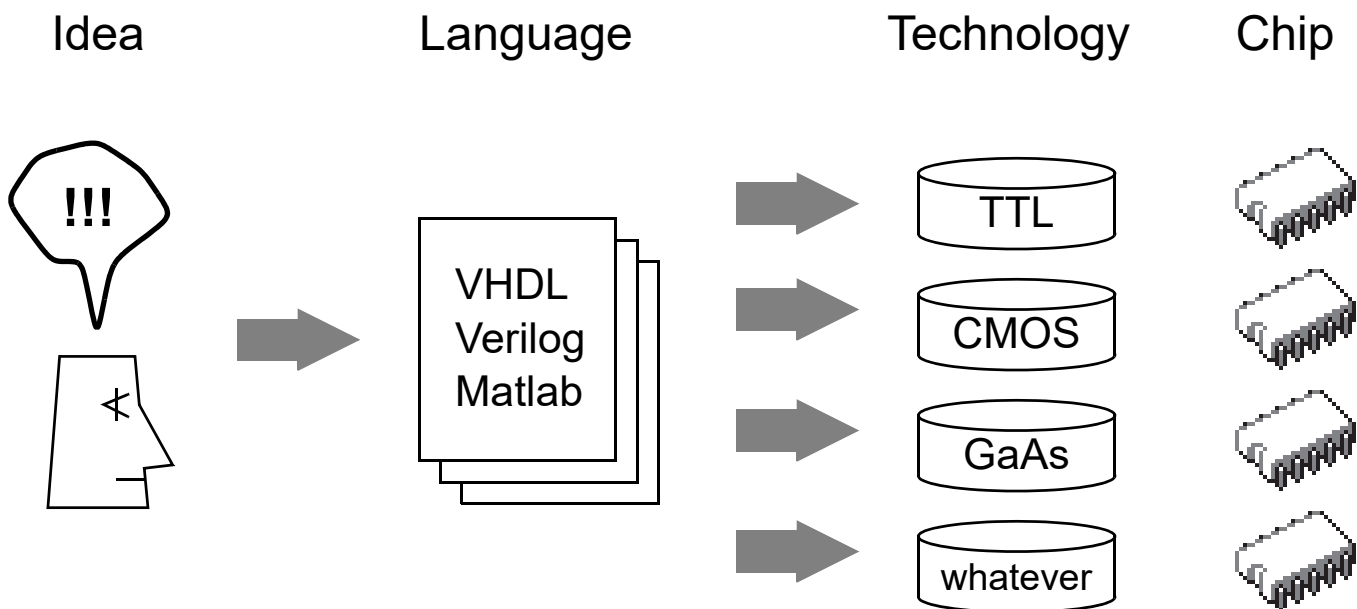
- **Design cost**
 - *design time & chips production cost*
 - *huge investments (G\$)*
 - *almost impossible to correct*
- **High cost of modifications**
 - *large production volumes are more cost effective*
 - *zero-defect is very important*
 - *following market trends is important*
- **Price is inversely proportional to production volume**
 - *common purpose processors - cheap but not always usable*
 - *ASIC - application specific tuning (e.g. telecommunication)*
 - *prototypes - flexibility is extremely important in the development phase*
 - *special purpose chips (e.g. satellites)*
- **Reconfigurability**
 - *flexible products, possibility to modify working circuits*



Design criteria

- **Three dimensions - area, delay, power**
 - size, speed, energy consumption
 - four dimensions - plus testability (reliability)
- **Area**
 - gates, wires, buses, etc.
- **Delay**
 - inside a module, between modules, etc.
- **Power consumption**
 - average, peak and total
- **Optimizations**
 - transferring from one dimension to another
 - design quality is measured by combined parameters, e.g., energy consumption per input sample

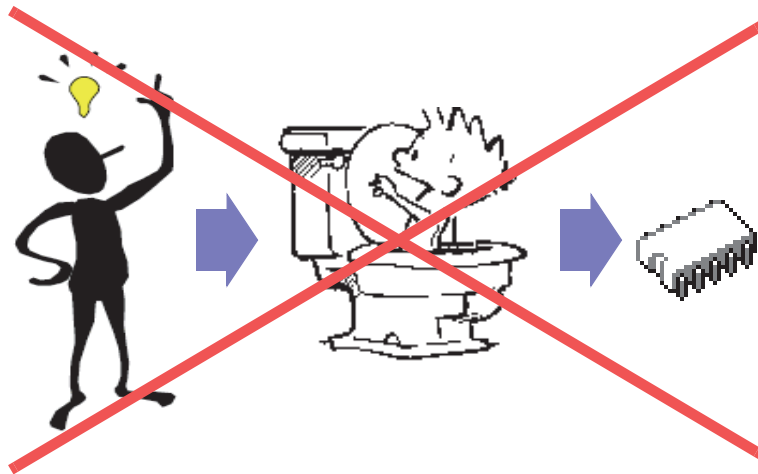
HDL – designing Systems-on-Chip (SoC) & Networks-on-Chip (NoC)



- **Fully automated flow from specification to implementation?**
 - analysis, modeling, iterations etc. needed...

MYTH #1

- High level design is a single pass

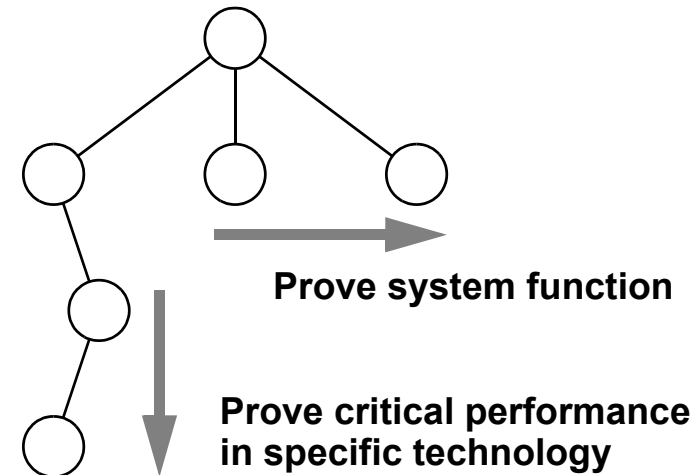
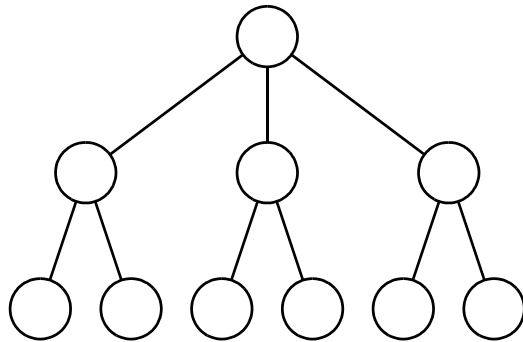


- Iterations needed
 - Functionality
 - Design goals



MYTH #2

- **Top down design, in its purest form, works**



- **The pure breadth-first approach never actually works in practice**
 - **Bottom-up technology information must be considered early and often**
 - **Go depth-first for critical parts**
 - **Mix breadth-first with depth-first**



MYTH #3

- **You don't need to understand digital design anymore**
- **One must know hardware to get a good hardware**
- **Hope**
 - **Intimate knowledge of hardware is not necessary to design digital systems**
- **Fear**
 - **Using HDL based design methodology will turn them into software hackers**
- **Reality**
 - **High performance designs require a good deal of understanding about hardware**
 - **Designers must seed the synthesis tools with good starting points**
 - **Understanding the synthesis process is necessary to get good quality designs**



MYTH #4

- **Designer's job is just the functional specification now**

- **Specification = Functionality +
Design goals +
Operating conditions**

- **Schematic capture**
 - **Design goals and operating conditions were implicit (in designer's mind)**
 - **Implementation was chosen (modified) to meet goals and conditions**

- **HDL**
 - **Design goals (area, speed, power, etc.) are explicitly specified**
 - **Operating conditions (variations, loads, drives) are also explicitly specified**



MYTH #5

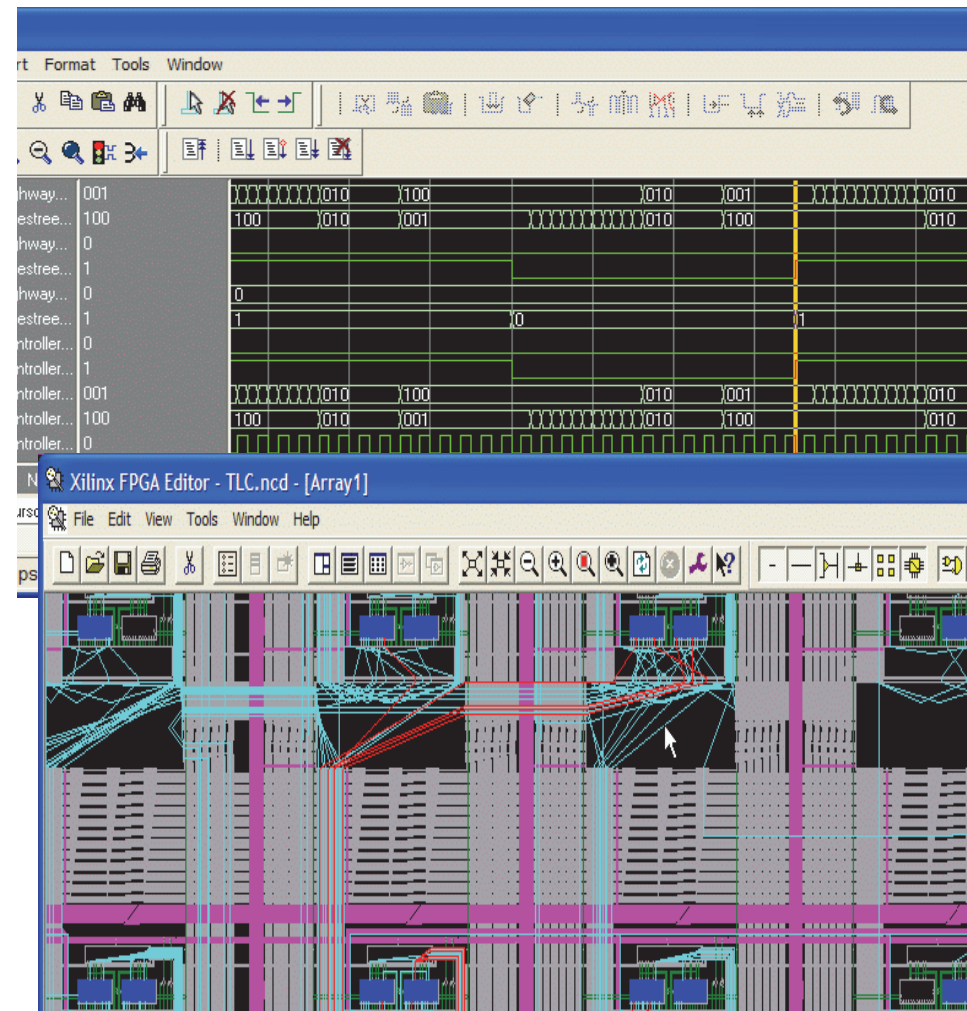
- **Behavioral level is better than RTL**
- **Behavioral (a.k.a. algorithmic, high) level synthesis is not as mature as RTL (register-transfer level)**
- **If your specification includes enough timing information use RTL synthesis**
- **Behavioral constructs like *while*, *if-then-else* does not necessarily mean behavioral specification**
 - **... and/or can be misinterpreted**

Design process today

- **Hardware Description Language**

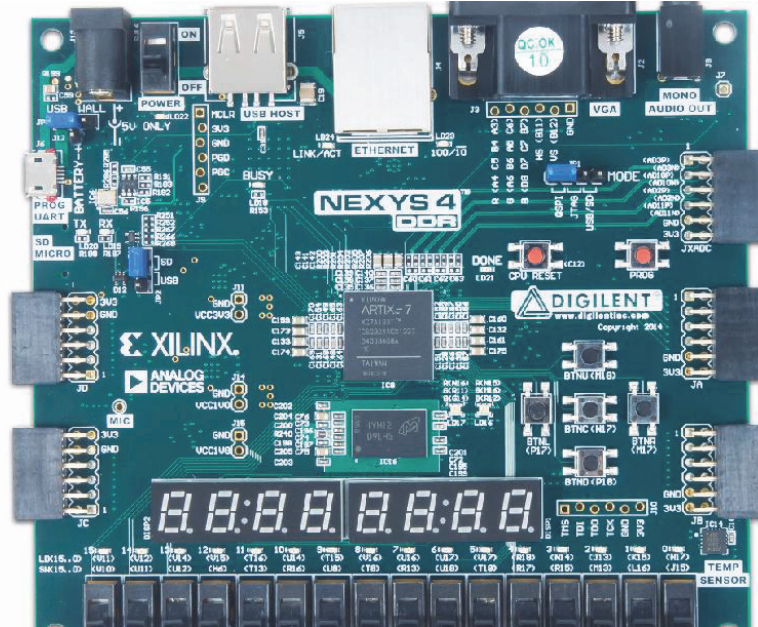
```

--
-- Highway is green, sidestreet is red.
--
if sidestreet_car = NoCar then
  wait until sidestreet_car = Car;
end if;
-- Waiting for no more than 25 seconds ...
if highway_car = Car then
  wait until highway_car = NoCar for 25 sec;
end if;
-- ... and changing lights
highway_light <= GreenBlink;
wait for 3 sec;
highway_light <= Yellow;
sidestreet_light <= Yellow;
wait for 2 sec;
highway_light <= Red;
sidestreet_light <= Green;
  
```

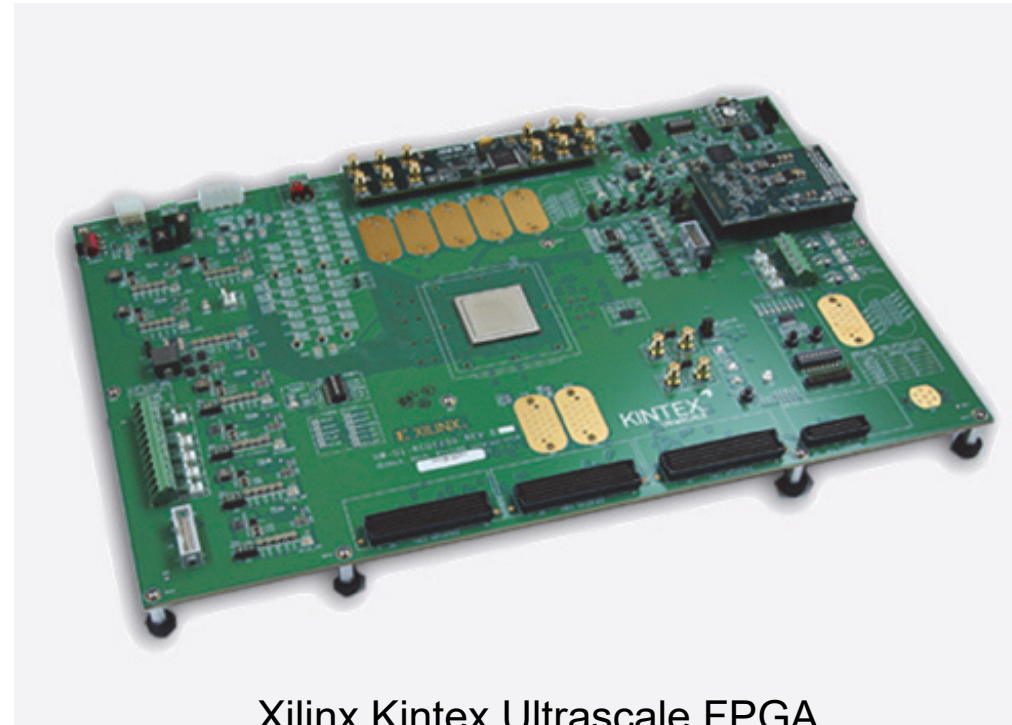


Prototyping

- Possibility to check how a system works at conditions very close to the operating environment without the need to create expensive chips



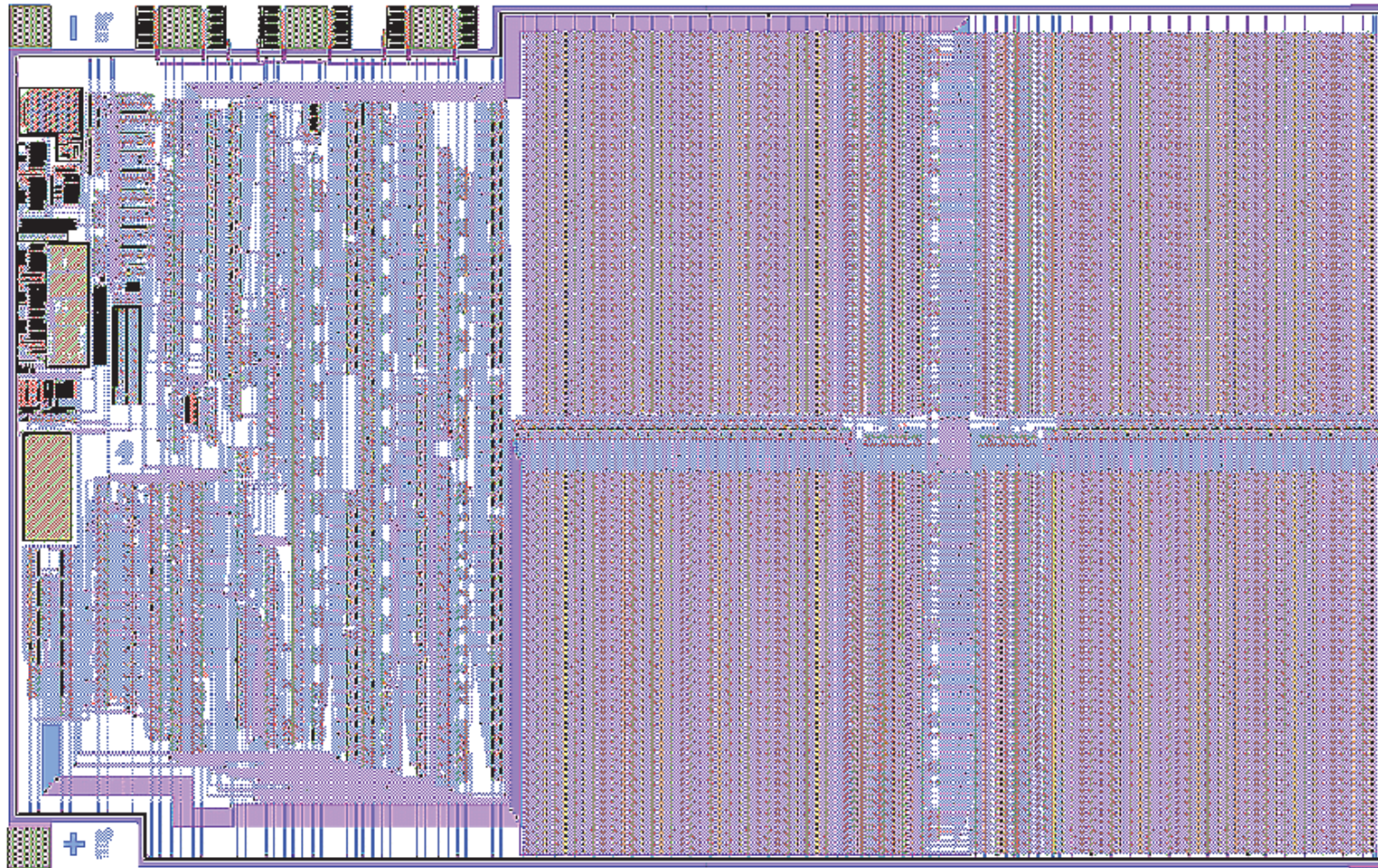
Digilent Nexys 4 DDR Artix-7 FPGA
[XC7A100T-1CSG324C; \$320]



Xilinx Kintex Ultrascale FPGA
KCU1250 Characterization Kit
[XCKU040-2FFVA1156E; \$7,495]



Chip - the final result





Reality

- **Found On First Spin ICs/ASICs**
 - **Functional Logic Error - 43%**
 - **Analog Tuning Issue - 20%**
 - **Signal Integrity Issue - 17%**
 - **Clock Scheme Error - 14%**
 - **Reliability Issue - 12%**
 - **Mixed Signal Problem - 11%**
 - **Uses Too Much Power - 11%**
 - **Has Path(s) Too Slow - 10%**
 - **Has Path(s) Too Fast - 10%**
 - **IR Drop Issues - 7%**
 - **Firmware Error - 4%**
 - **Other Problem - 3%**
- **Overall 61% of New ICs/ASICs Require At Least One Re-Spin.**
 - **Aart de Geus, Chairman & CEO of Synopsys, Boston SNUG keynote address, 9.09.2003**



Trends

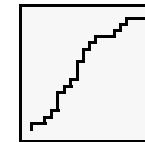
	2000	2010	2020
memory size	2 Gbit	256 Gbit	1024 Gbit
transistors per cm ²	$8 \cdot 10^6$	$160 \cdot 10^6$	$480 \cdot 10^6$
internal clock frequency	1.5 GHz	10 GHz	40 GHz
external / bus clock frequency	0.5 GHz	1.5 GHz	2.5 GHz
pin count	2000	6000	10000
chip area	800 mm ²	1300 mm ²	1800 mm ²
wire width	140 nm	40 nm	10 nm
supply voltage	1.5 V	0.8 V	0.5 V
power consumption	100 W	170 W	300 W
power consumption (batteries)	0.5 W	1.5 W	2.5 W

NB! These are rough estimates only!



Problems

physical level	quantum effects
	noise
logic level	crosstalk
	speed of light
system level	# of transistors



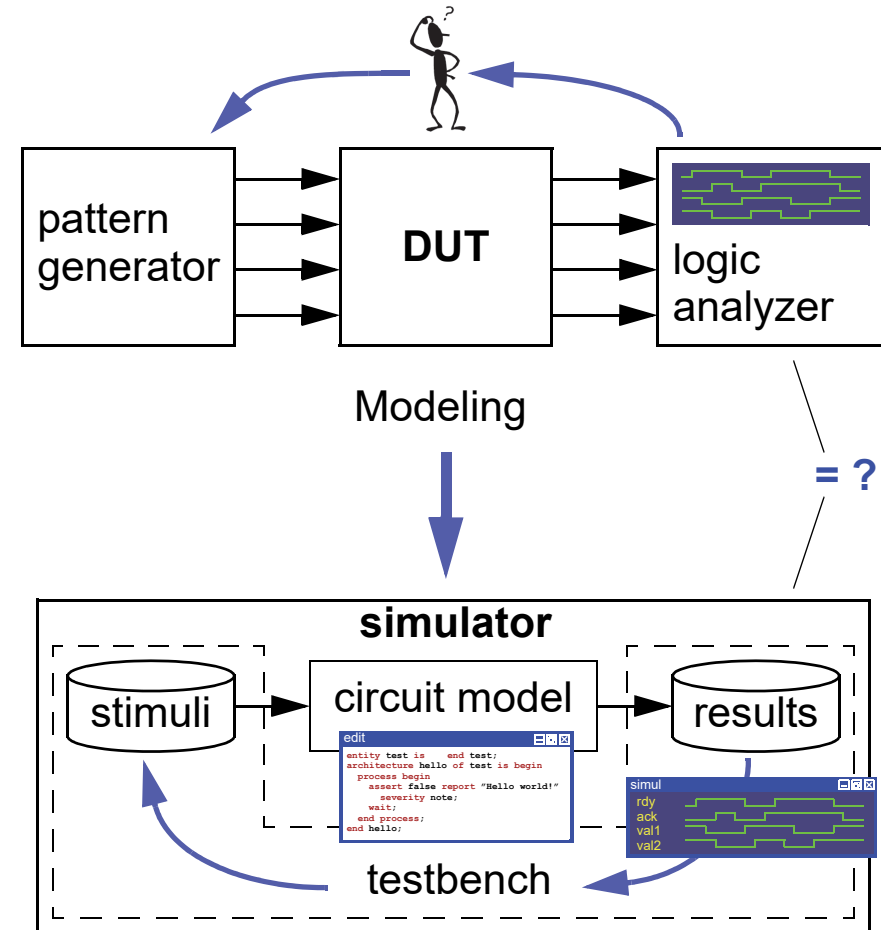
10 mm \rightarrow (10^8 m/s) \rightarrow
 10^{-10} s \rightarrow (10%) \rightarrow
1 GHz !?

- **GALS – globally asynchronous locally synchronous**
- **mixed signal – digital and analog circuits on the same chip**
- **Modeling is getting more and more important...**



Simulation

- **Simulation = modeling + analysis**
- **Logic level simulation**
- **RT-level simulation**
- **Functional level simulation**
- **Behavioral level simulation**
- **System level simulation**
- **Test environment == stimuli generator + DUT + results analyzer**
- **NB! Detailed simulation is slow!**



Use of HDL → Simulation

- **Simulation = modeling + analysis**
 - **Logic / register-transfer / functional (behavioral) / system level simulation**

concurrent / parallel modules

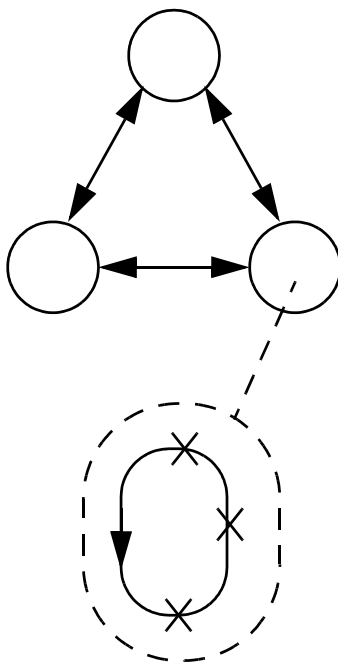
connected via signal / channels

sequential vs. concurrent execution?

execution order?!

**current / new values to avoid
non-determinism**

event queue history+future



module / unit / process

continuous execution is slow

only when needed?

time / event triggered

different simulation engines

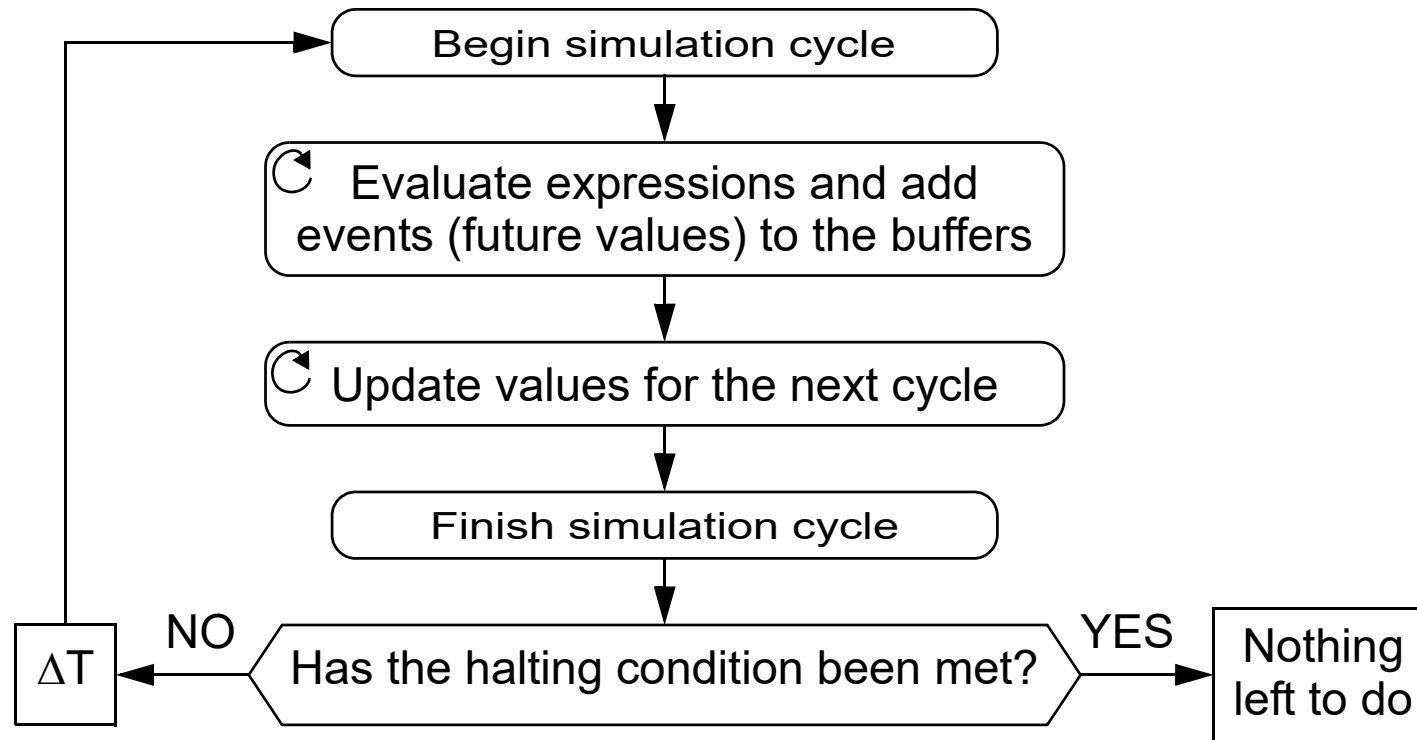


Simulators & timing/delay models

- **Time & events**
 - *Time-driven*:
all components of the digital logic system are evaluated at every time step
 - *Event-driven*:
system input events are kept in an time-ordered event queue
- **Delay models**
 - unit-delay (RTL simulator)
 - zero-delay (Verilog)
 - *delta*-delay (VHDL) – δ -delay, Δ -delay
- **Simulation engines**
 - all make use of the three following steps but details differ...
 - (1) calculate (and remember) new values for signals
 - (2) update signal values
 - (3) update time



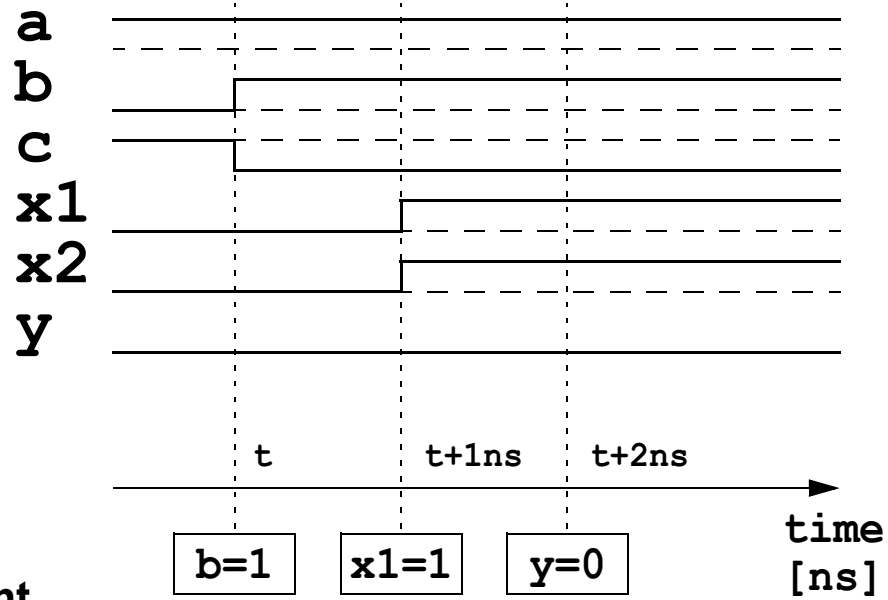
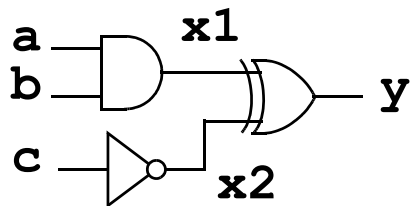
Unit-delay simulation model



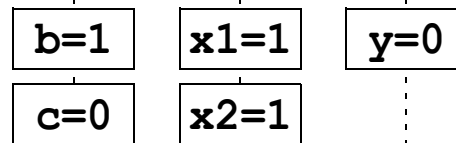


Unit-delay simulation model (example)

```
x1 <= a and b;  
x2 <= not c;  
y <= x1 xor x2;
```

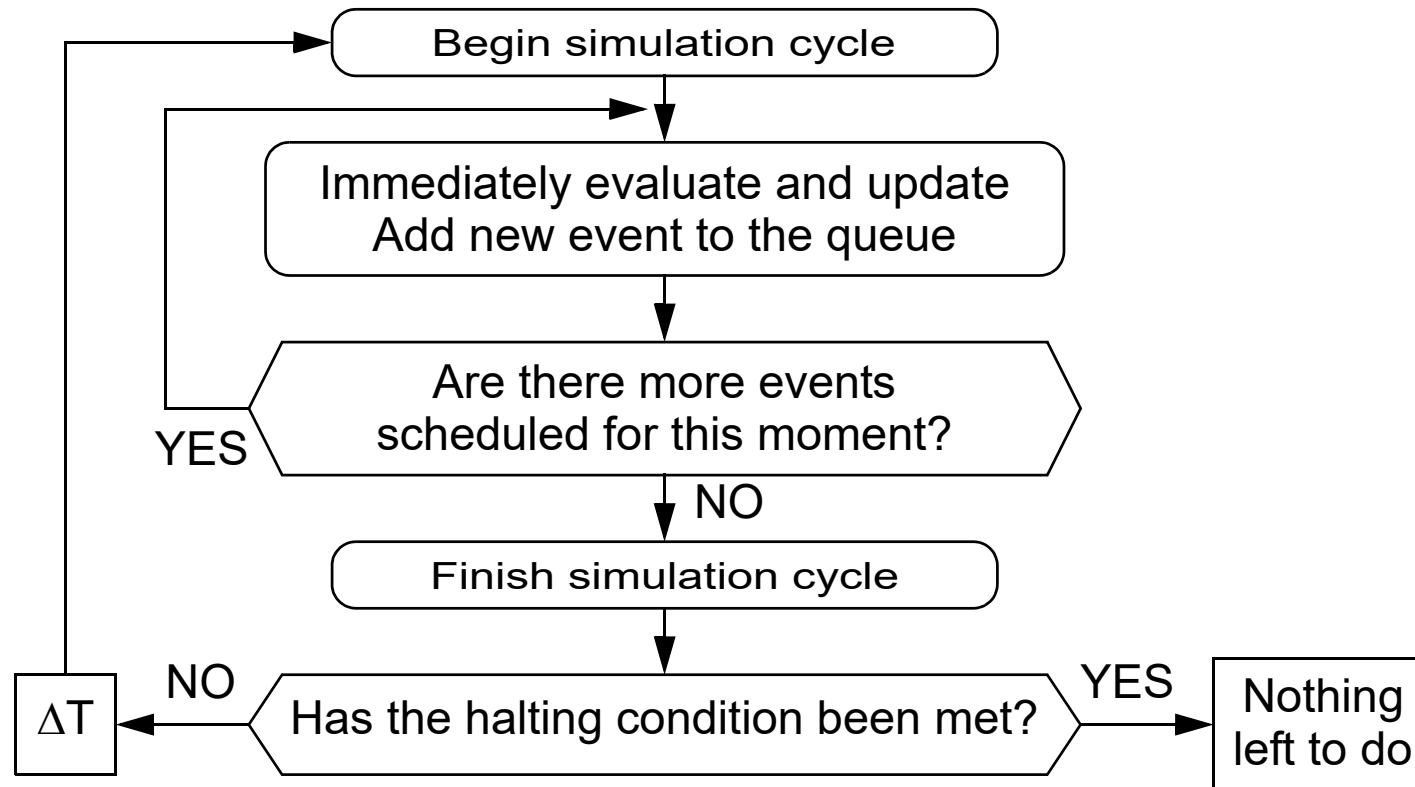


event queues





Zero-delay simulation model (Verilog)



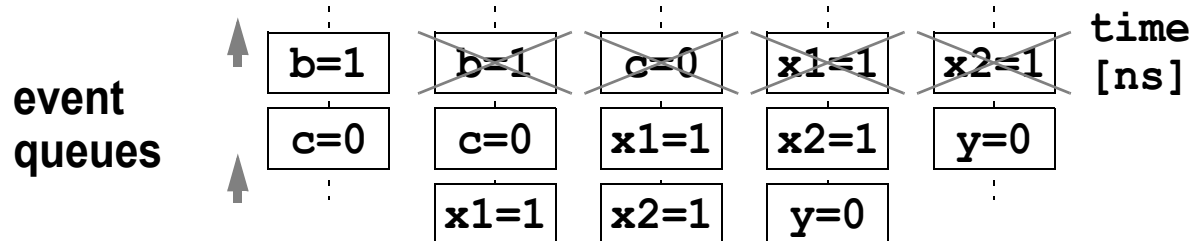
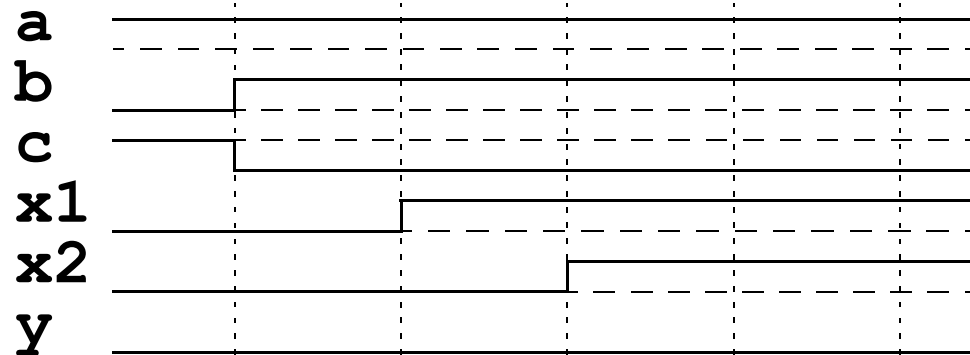
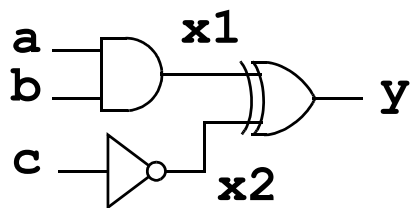


Zero-delay simulation model (example #1)

```

x1 <= a and b;
x2 <= not c;
y <= x1 xor x2;

```



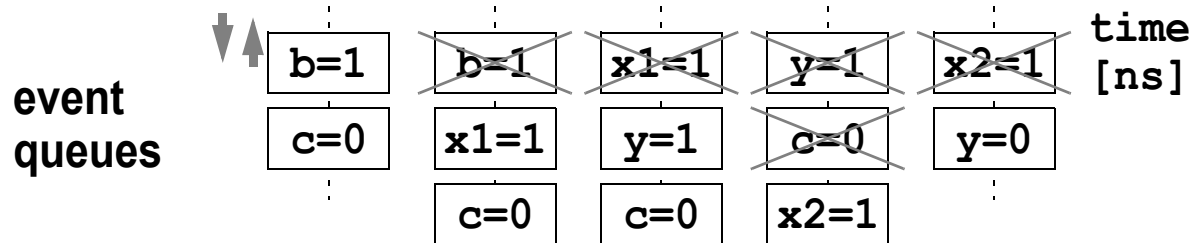
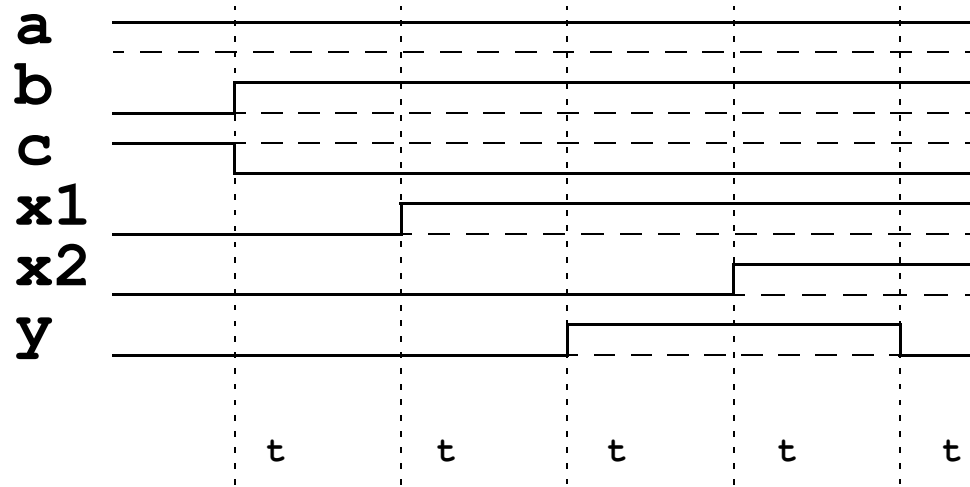
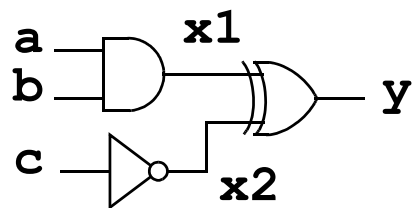


Zero-delay simulation model (example #2)

```

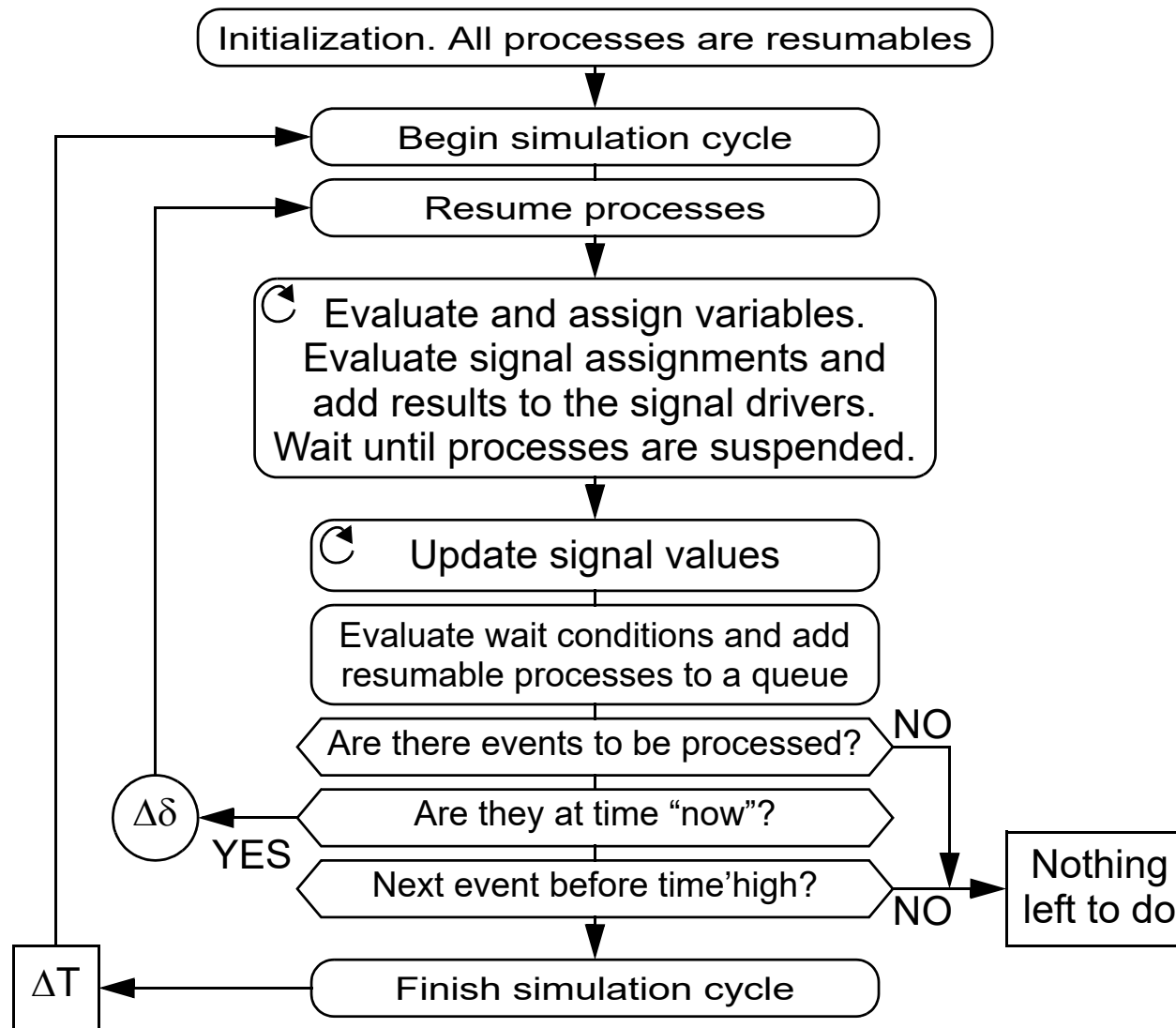
x1 <= a and b;
x2 <= not c;
y <= x1 xor x2;

```





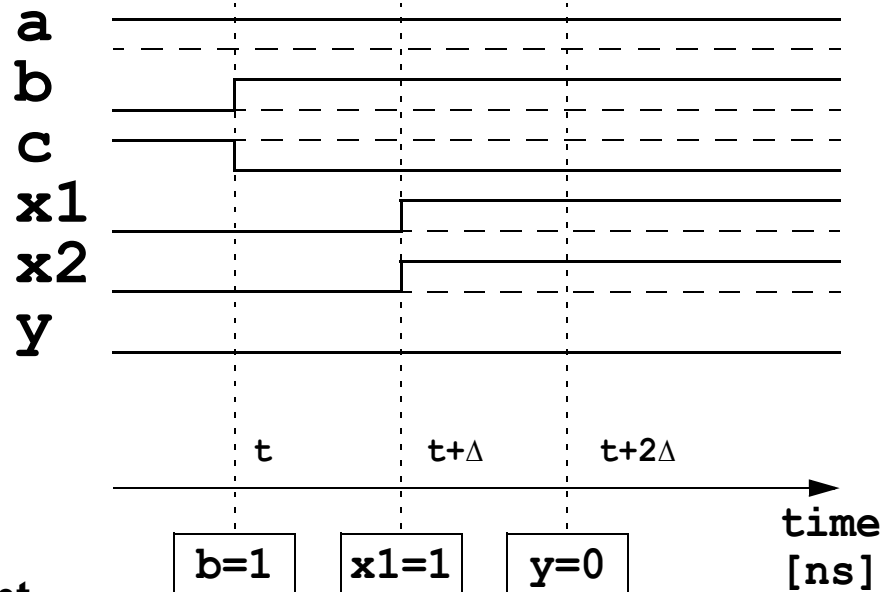
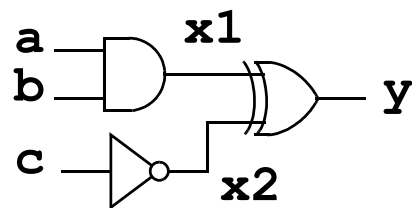
Delta-delay (VHDL) simulation model





Delta-delay (VHDL) simulation model (example)

```
x1 <= a and b;  
x2 <= not c;  
y <= x1 xor x2;
```



event
queues

