Introduction to Field Programmable Gate Arrays

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What is a **F**ield **P**rogrammable **G**ate **A**rray ?
.. a quick answer for the impatient

- An FPGA is an integrated circuit
  - Mostly digital electronics
- An FPGA is programmable in the in the field (=outside the factory), hence the name “field programmable”
  - Design is specified by schematics or with a hardware description language
  - Tools compute a programming file for the FPGA
  - The FPGA is configured with the design (gateware / firmware)
  - Your electronic circuit is ready to use

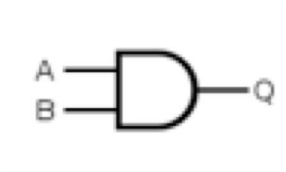
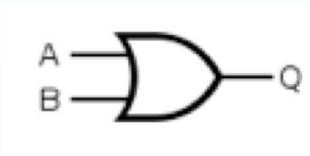
With an FPGA you can build electronic circuits …
… without using a bread board or soldering iron
… without plugging together NIM modules
… without having a chip produced at a factory

Outline

- Quick look at digital electronics
- Short history of programmable logic devices
- FPGAs and their features
- Programming techniques
- Design flow
- Example Applications in the Trigger and DAQ domain

Digital electronics

The building blocks: logic gates

		Truth table	C equivalent
AND gate			q = a && b;
OR gate			q = a || b;
Exclusive OR gate XOR gate			q = a != b;

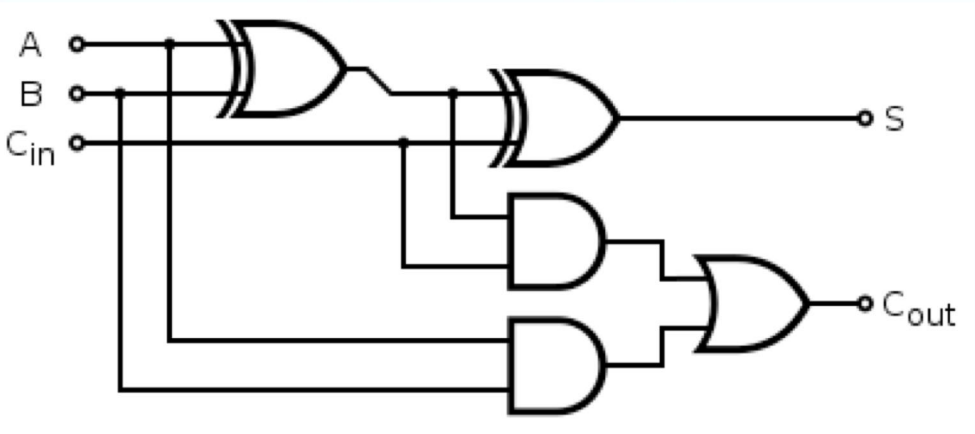
INPUT		OUTPUT
A	B	A AND B
0	0	0
0	1	0
1	0	0
1	1	1

INPUT		OUTPUT
A	B	A + B
0	0	0
0	1	1
1	0	1
1	1	1

INPUT		OUTPUT
A	B	A XOR B
0	0	0
0	1	1
1	0	1
1	1	0

⋮

Combinatorial logic (asynchronous)



Example: Full adder with carry-in, carry-out

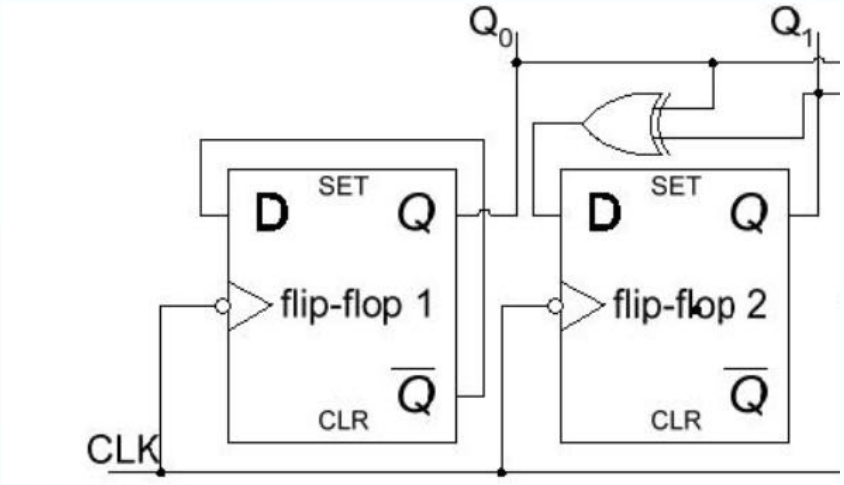
Outputs are determined by Inputs, only

A	B	C_{in}	S	C_{out}
0	0	0	0	0
1	0	0	1	0
0	1	0	1	0
1	1	0	0	1
0	0	1	1	0
1	0	1	0	1
0	1	1	0	1
1	1	1	1	1

Combinatorial logic may be implemented using Look-Up Tables (LUTs)

LUT = small memory

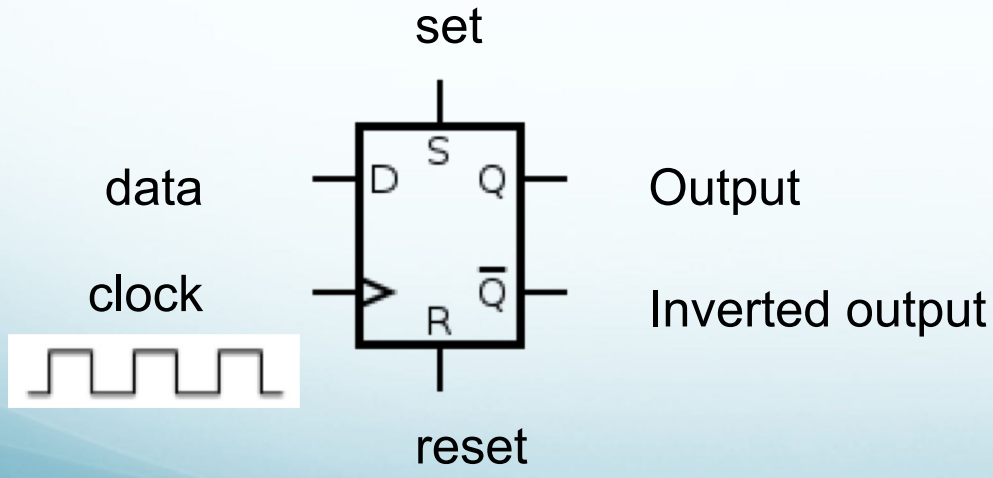
(Synchronous) sequential logic



Outputs are determined
by Inputs and their History
(Sequence)
The logic has an internal state

2-bit binary counter

https://www.zeepedia.com/read.php?b=9&c=32&d_flip-flop_based_implementation_digital_logic_design



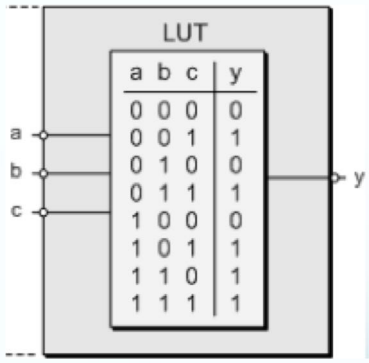
D Flip-flop:

samples the data at the rising (or falling) edge of the clock

The output will be equal to the last sampled input until the next rising (or falling) clock edge

D Flip-flop (D=data, delay)

Synchronous sequential logic



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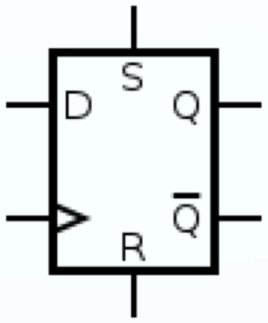

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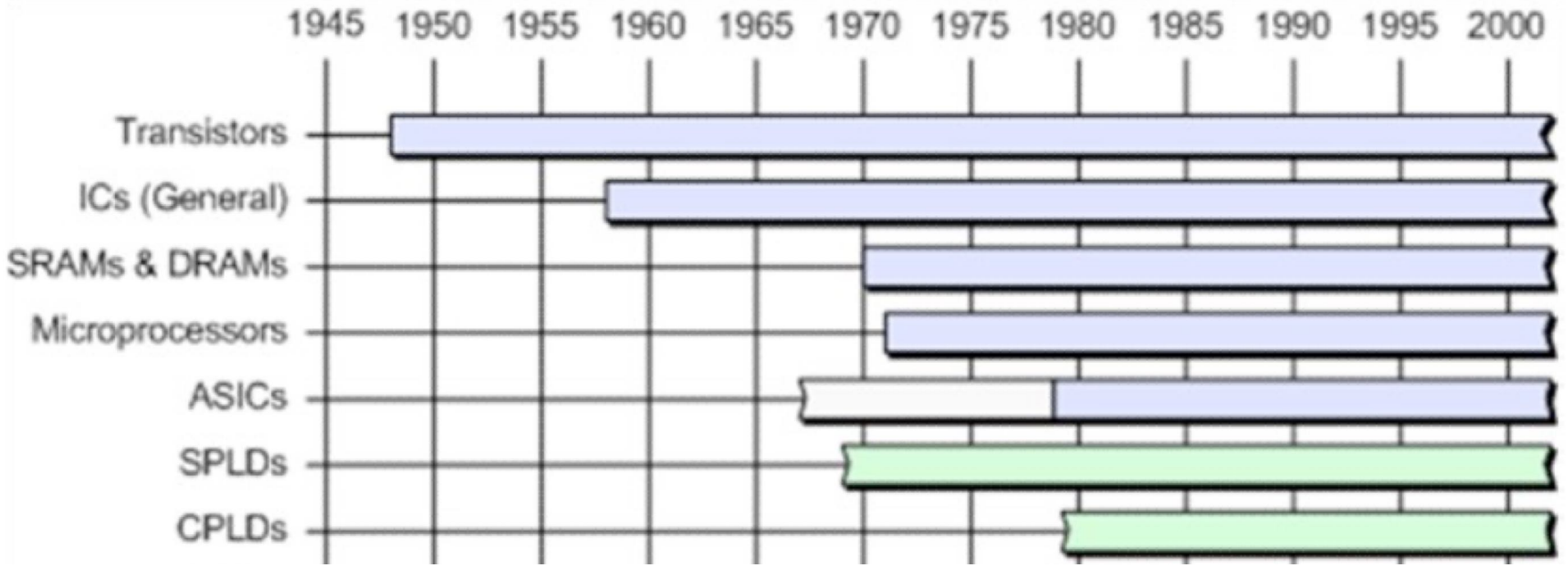
Using Look-Up-Tables and Flip-Flops
any kind of digital electronics may be implemented

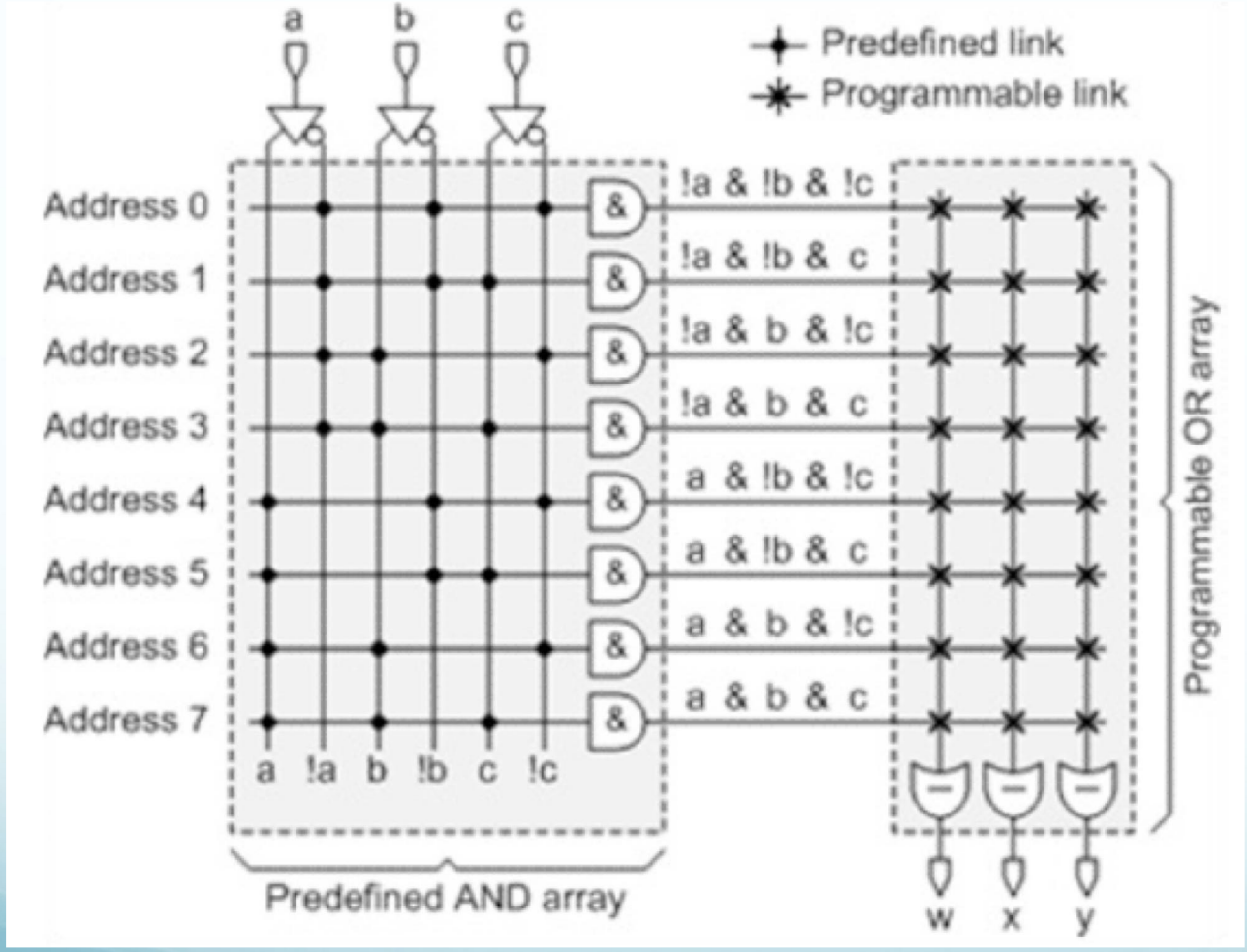
Of course there are some details
to be learnt about electronics design …

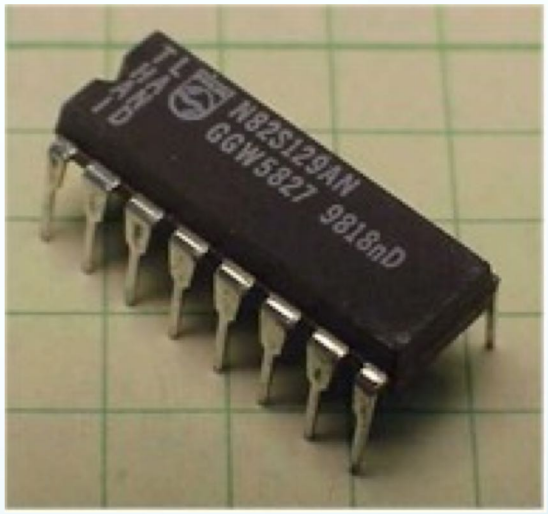
Quick history of programmable digital electronics

Long long time ago ...



Simple Programmable Logic Devices (sPLDs)
a) Programmable Read Only Memory (PROMs)

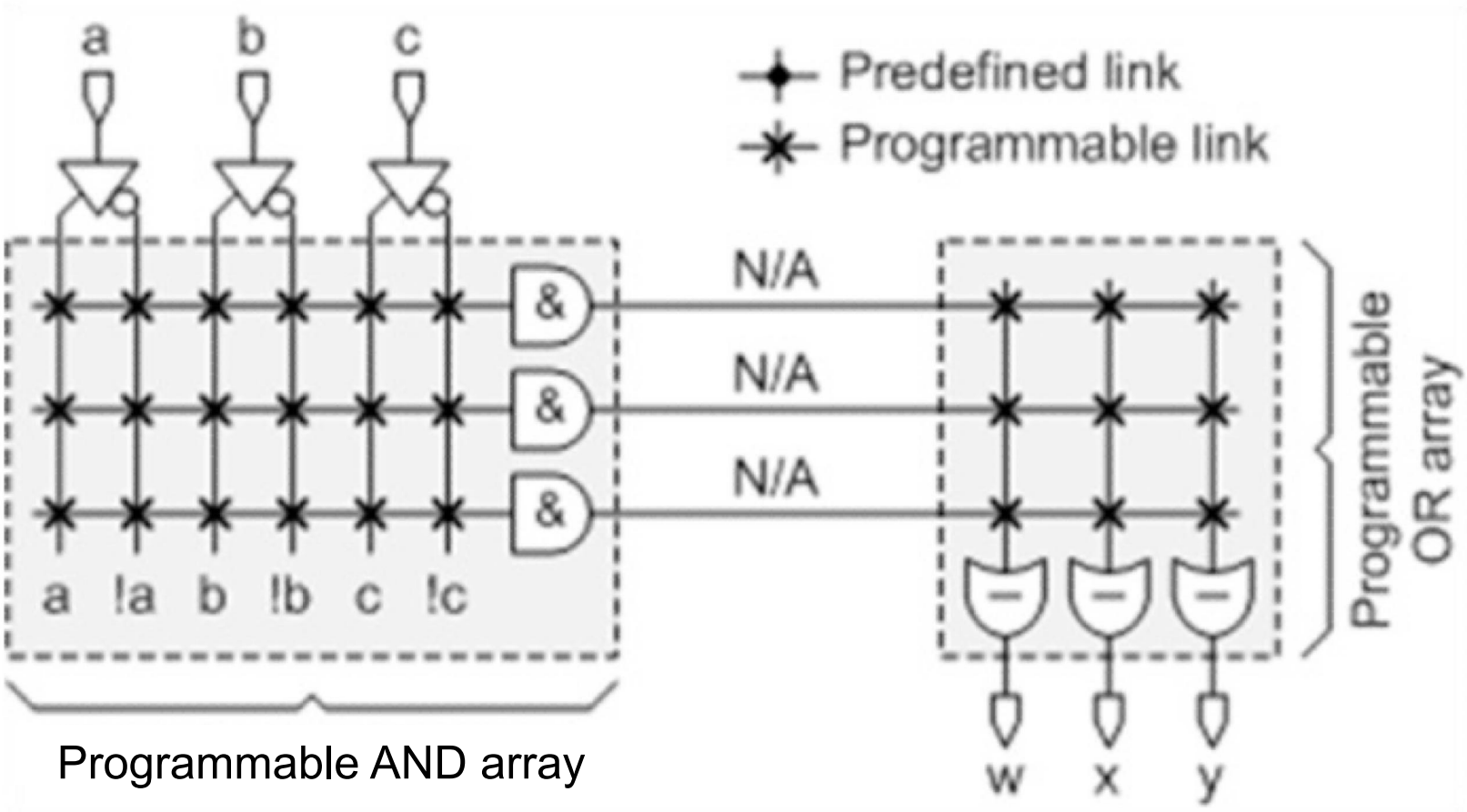




Late 60's

Unprogrammed PROM (Fixed AND Array, Programmable OR Array)

Simple Programmable Logic Devices (sPLDs)
b) Programmable Logic Arrays (PLAs)

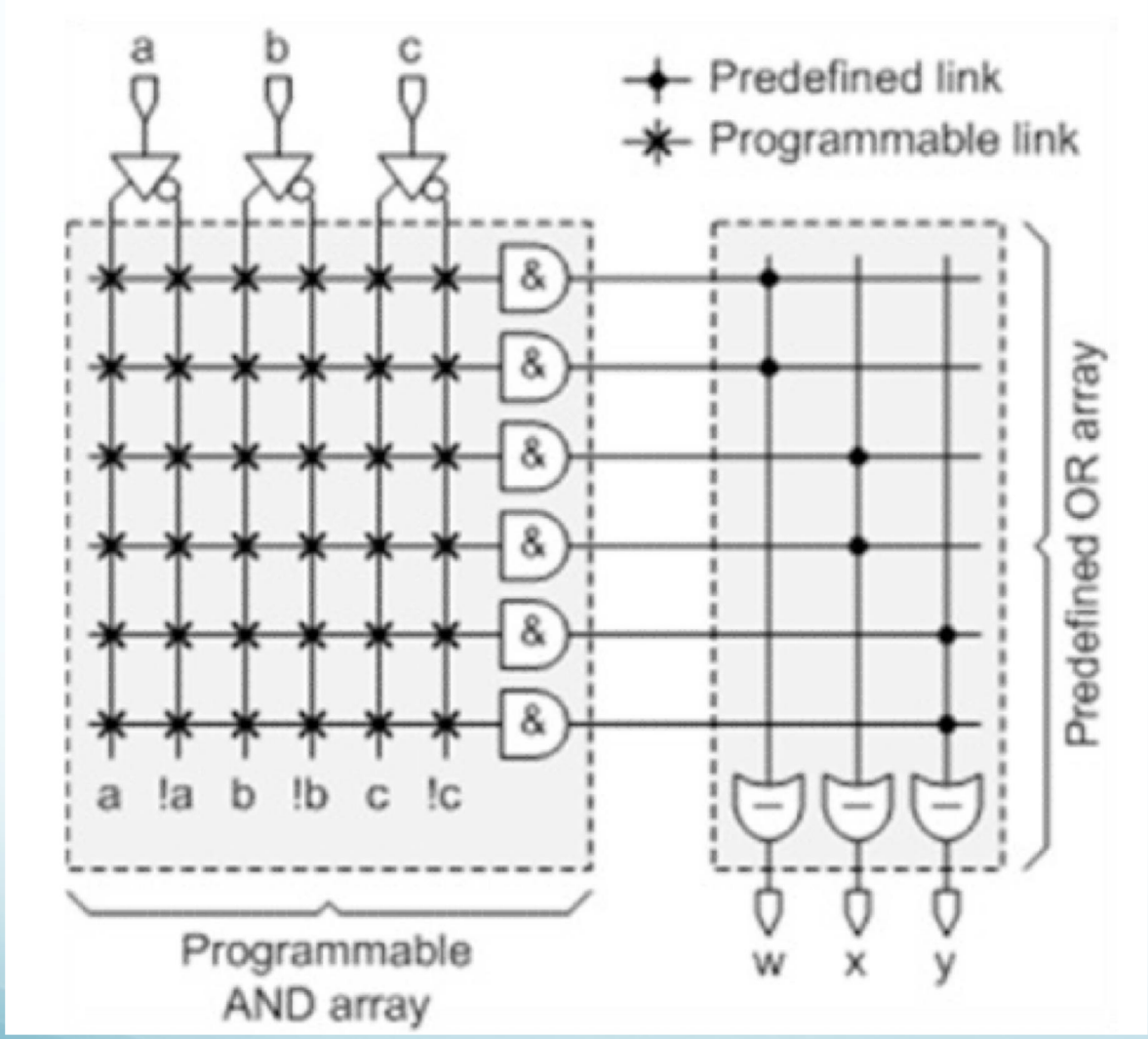


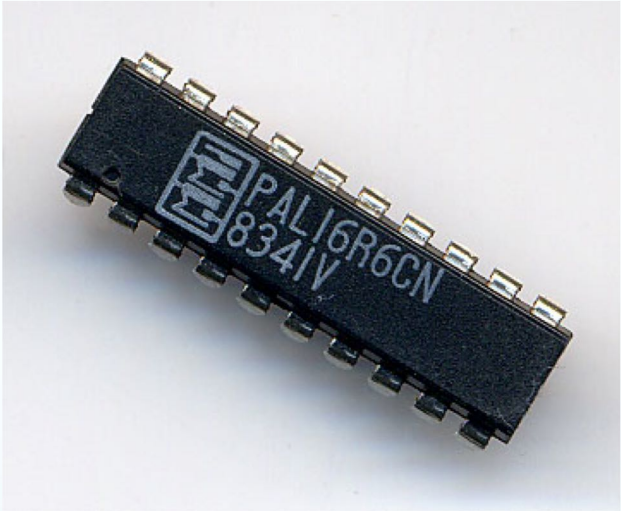
Unprogrammed PLA (Programmable AND and OR Arrays)

Most flexible
but slower

1975

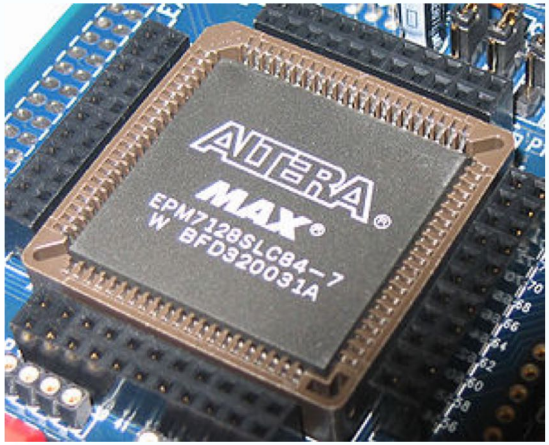
Simple Programmable Logic Devices (sPLDs)
c) Programmable Array Logic (PAL)

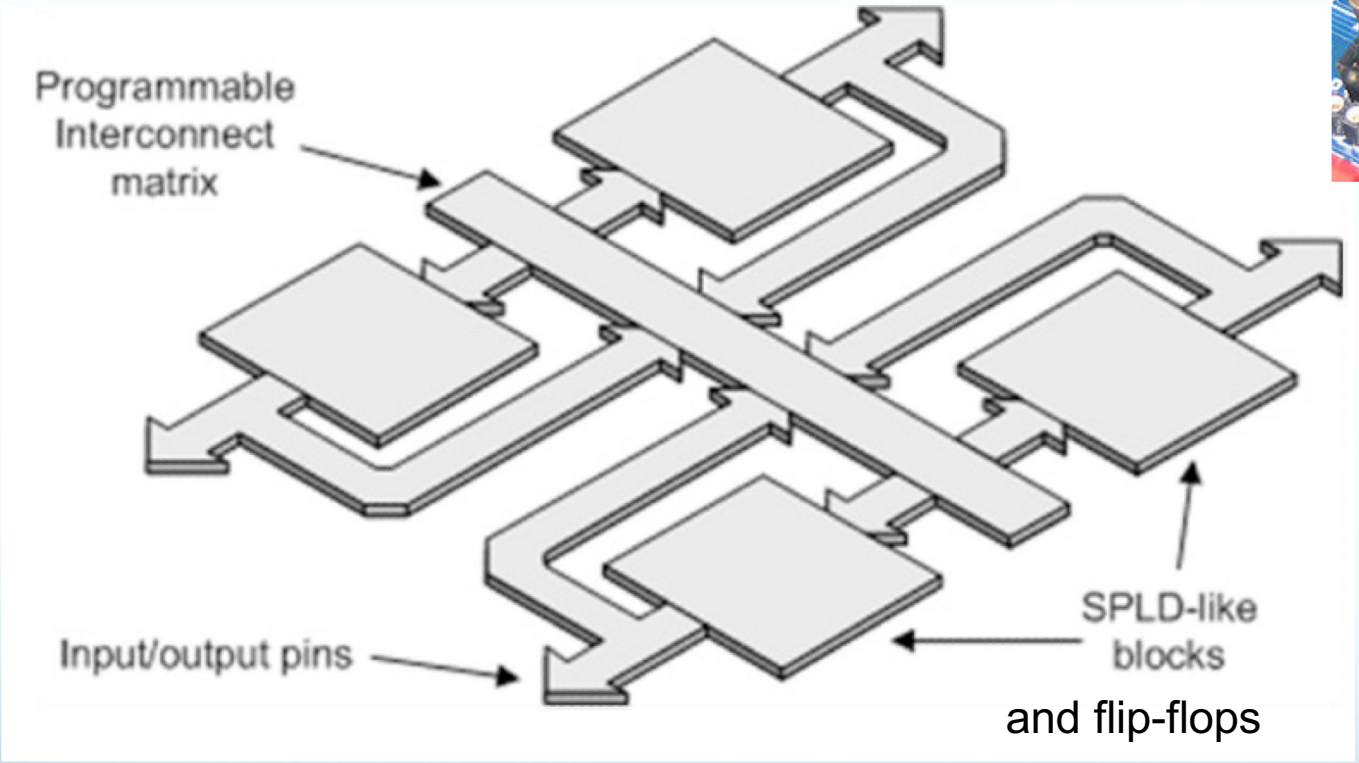




Unprogrammed PAL (Programmable AND Array, Fixed OR Array)

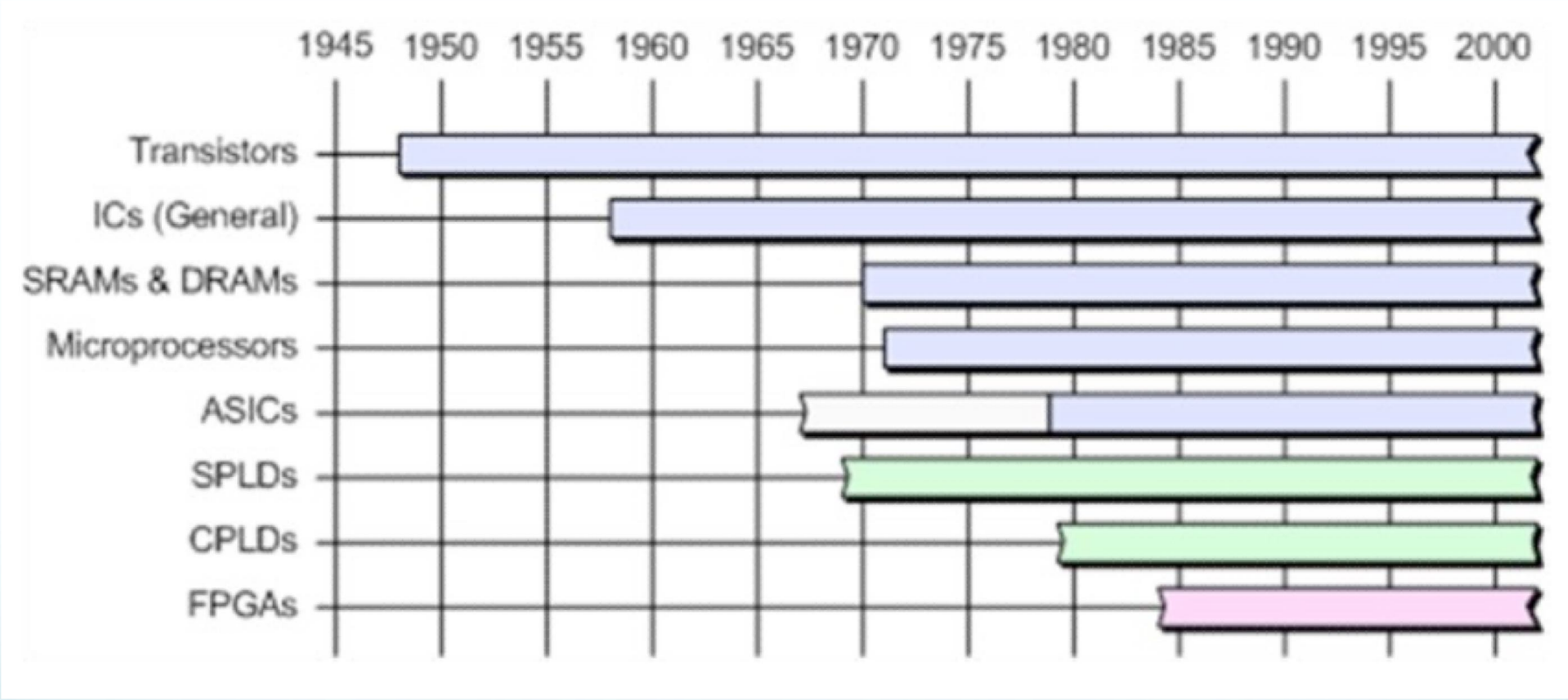
Complex PLDs (CPLDs)



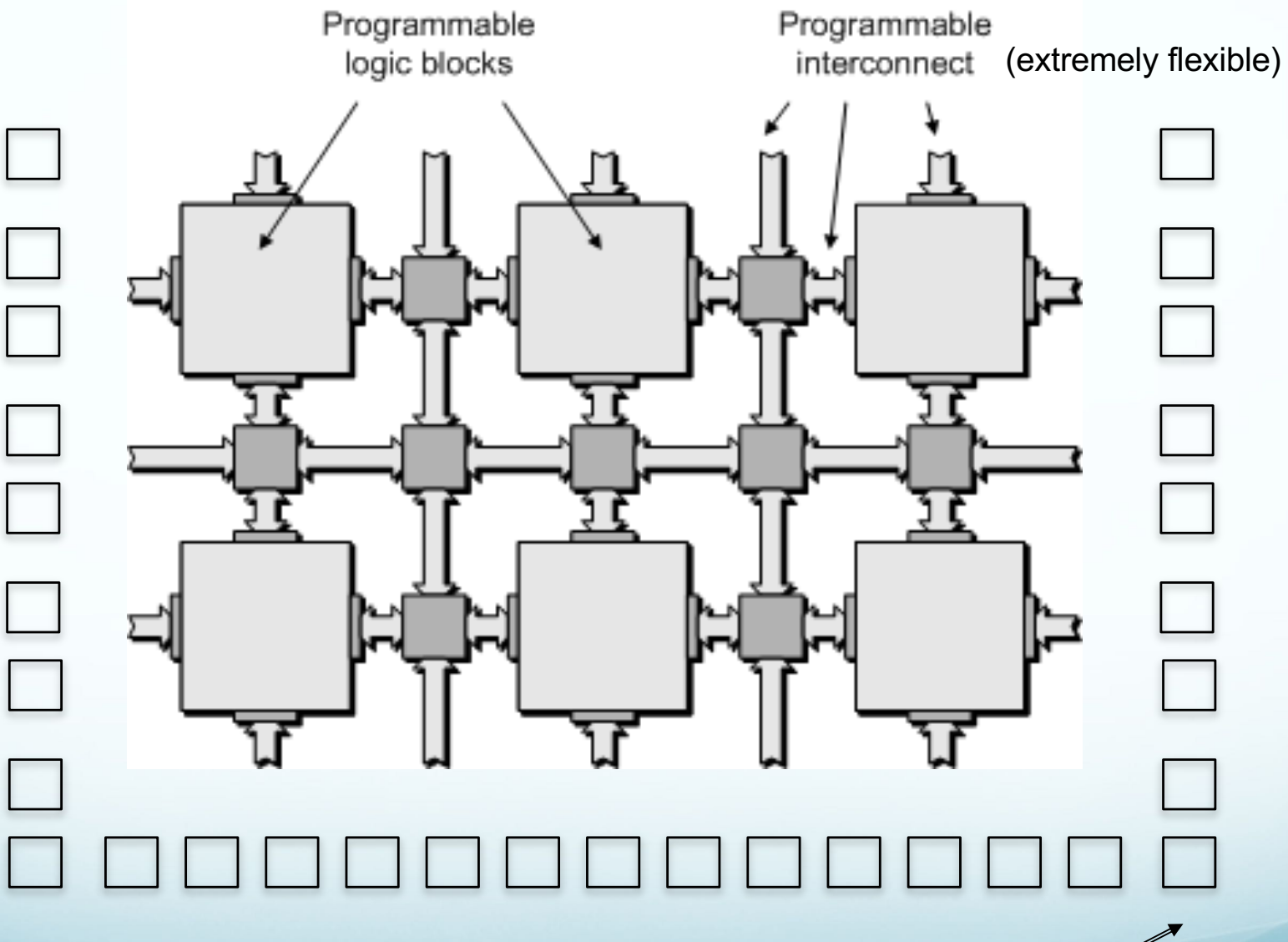


Coarse grained
100's of blocks, restrictive structure
(EE)PROM based

FPGAs ...

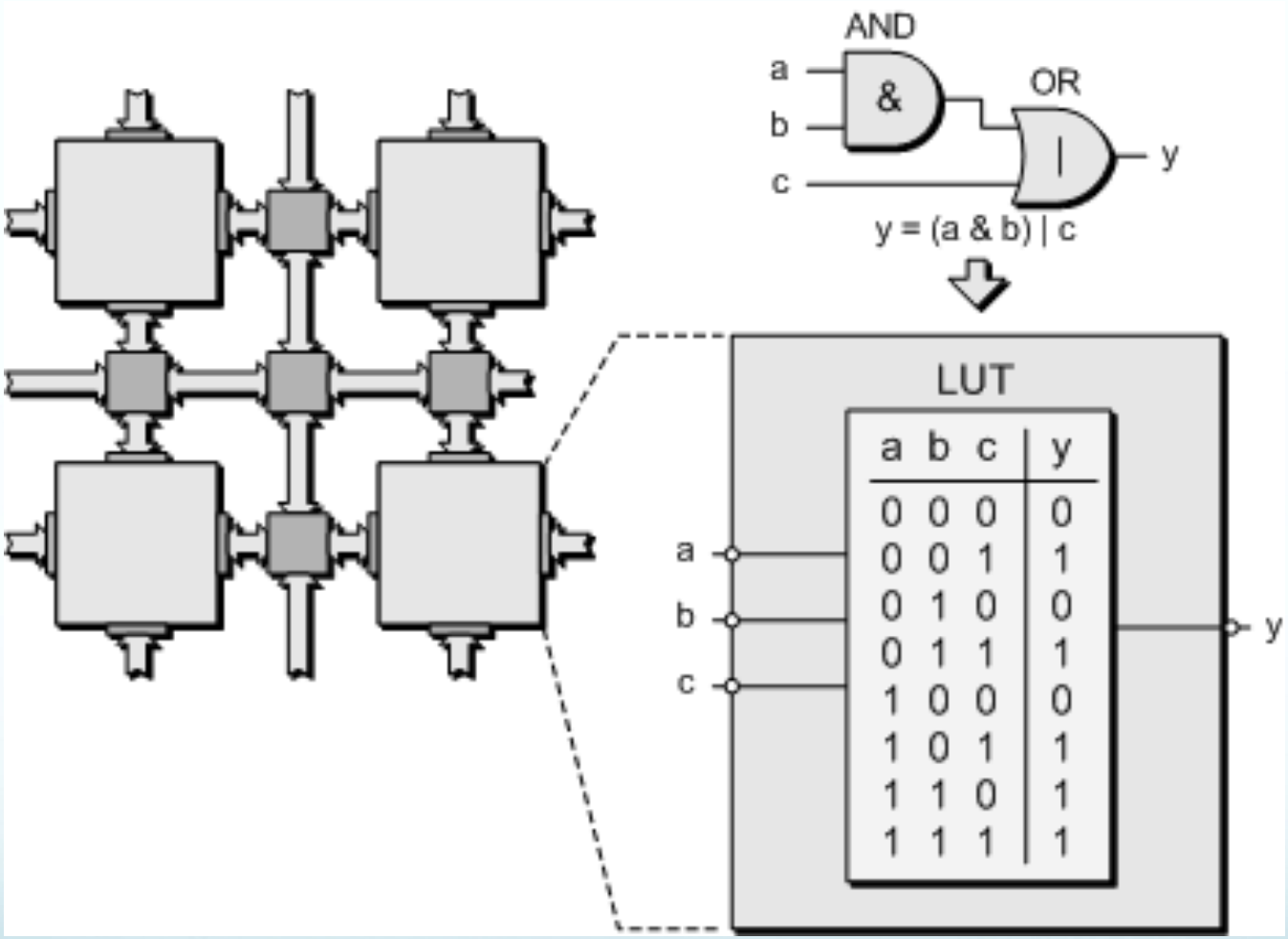

1945
1950
1955
1960
1965
1970
1975
1980
1985
1990
1995
2000
Transistors
ICs (General)
SRAMs & DRAMs
Microprocessors
ASICs
SPLDs
CPLDs
FPGAs

FPGAs

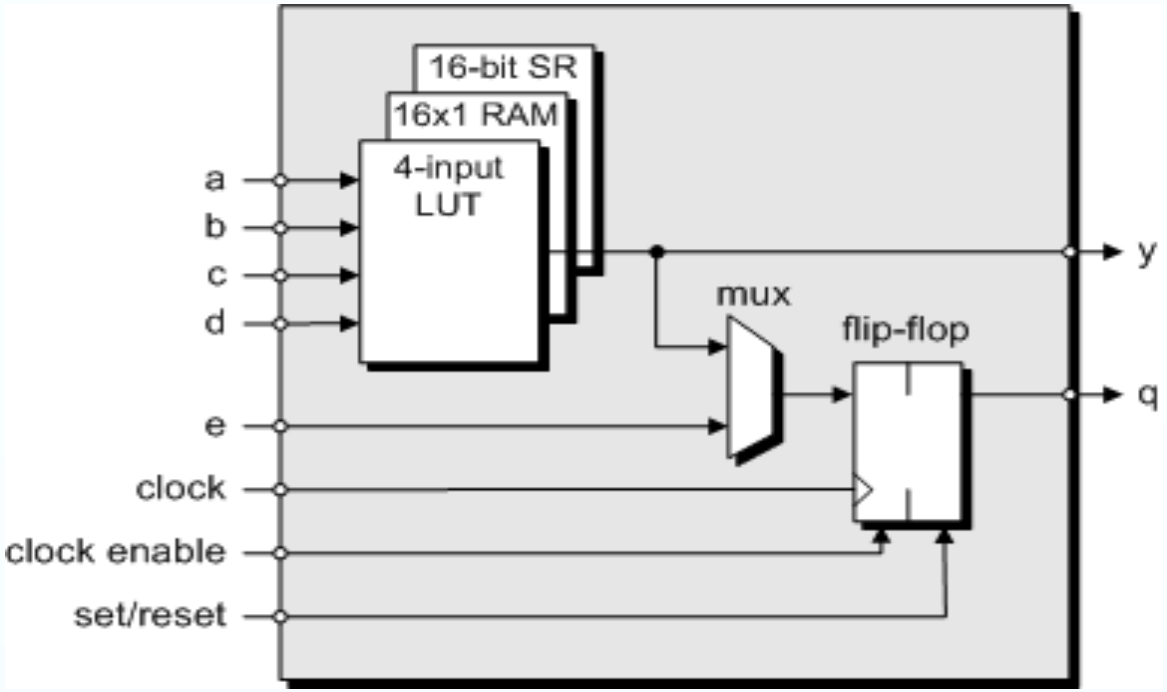


Fine-grained: 100.000's of blocks
today: up to 5 million logic blocks

LUT-based Fabrics



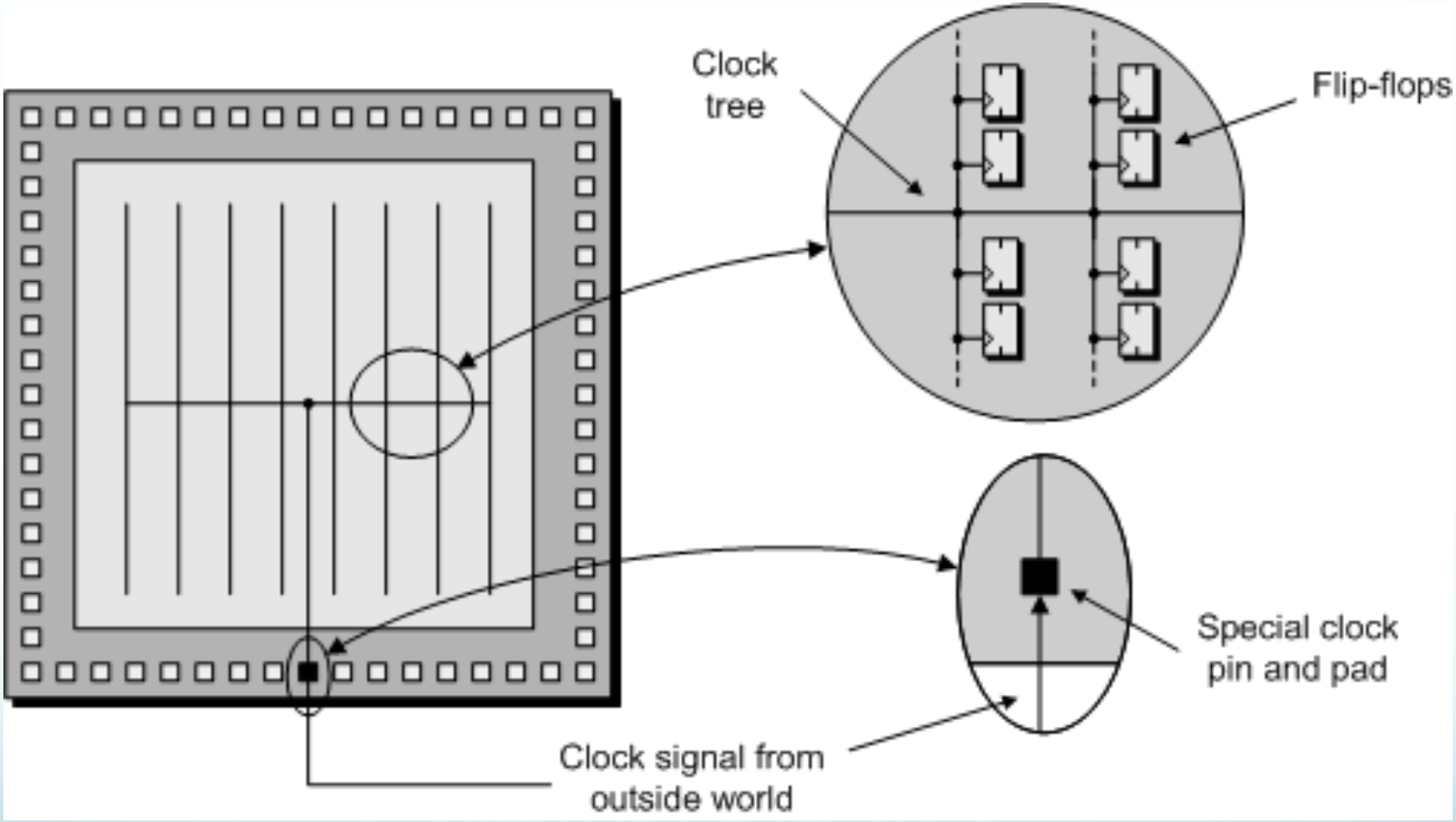
Typical LUT-based Logic Cell



Xilinx: logic cell,
Altera: logic element

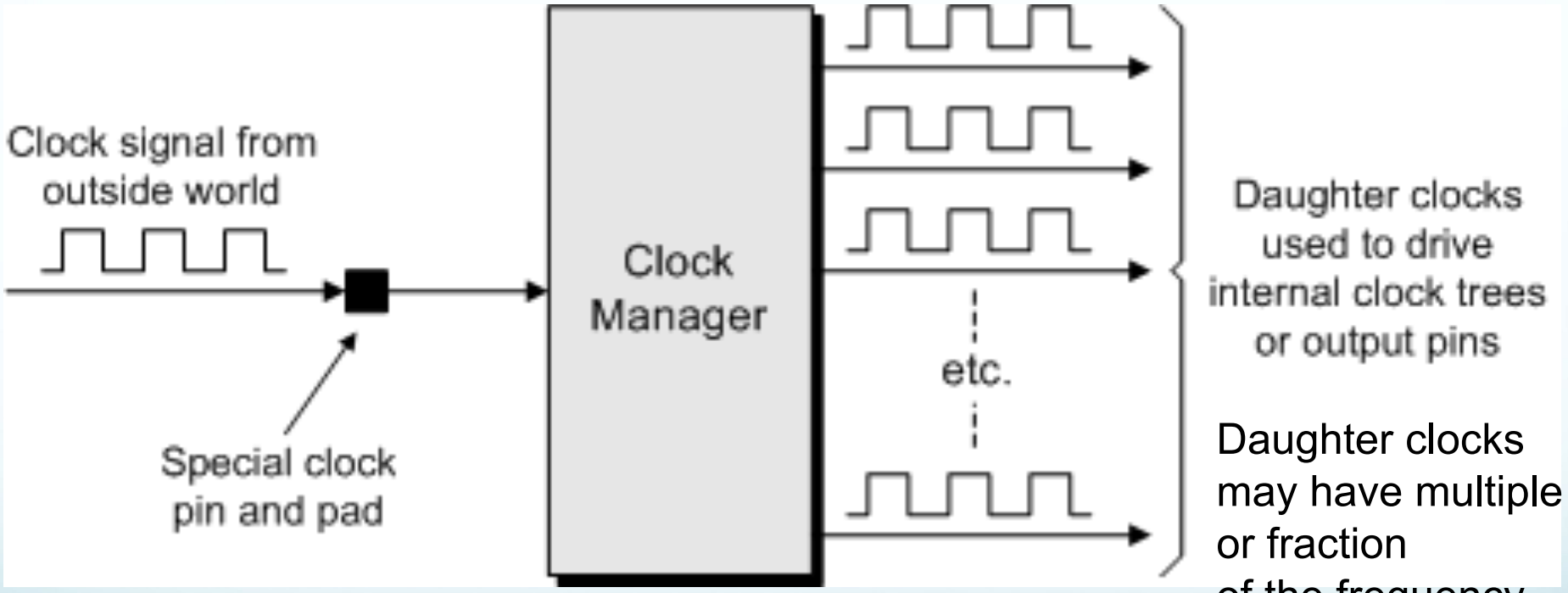
- LUT may implement any function of the inputs
- Flip-Flop registers the LUT output
- May use only the LUT or only the Flip-flop
- LUT may alternatively be configured a shift register
- Additional elements (not shown): fast carry logic

Clock Trees

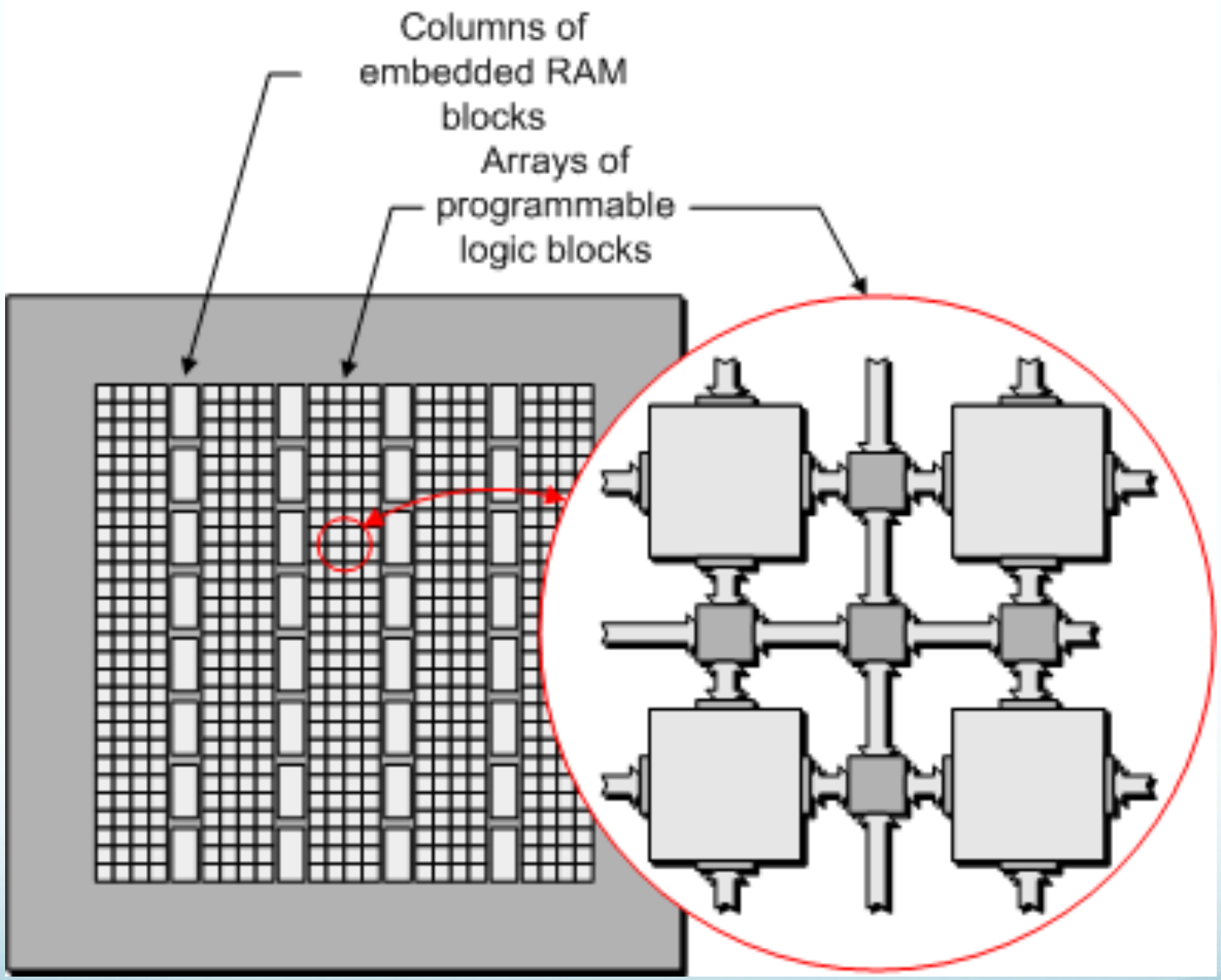


Clock trees guarantee that the clock arrives at the same time at all flip-flops

Clock Managers

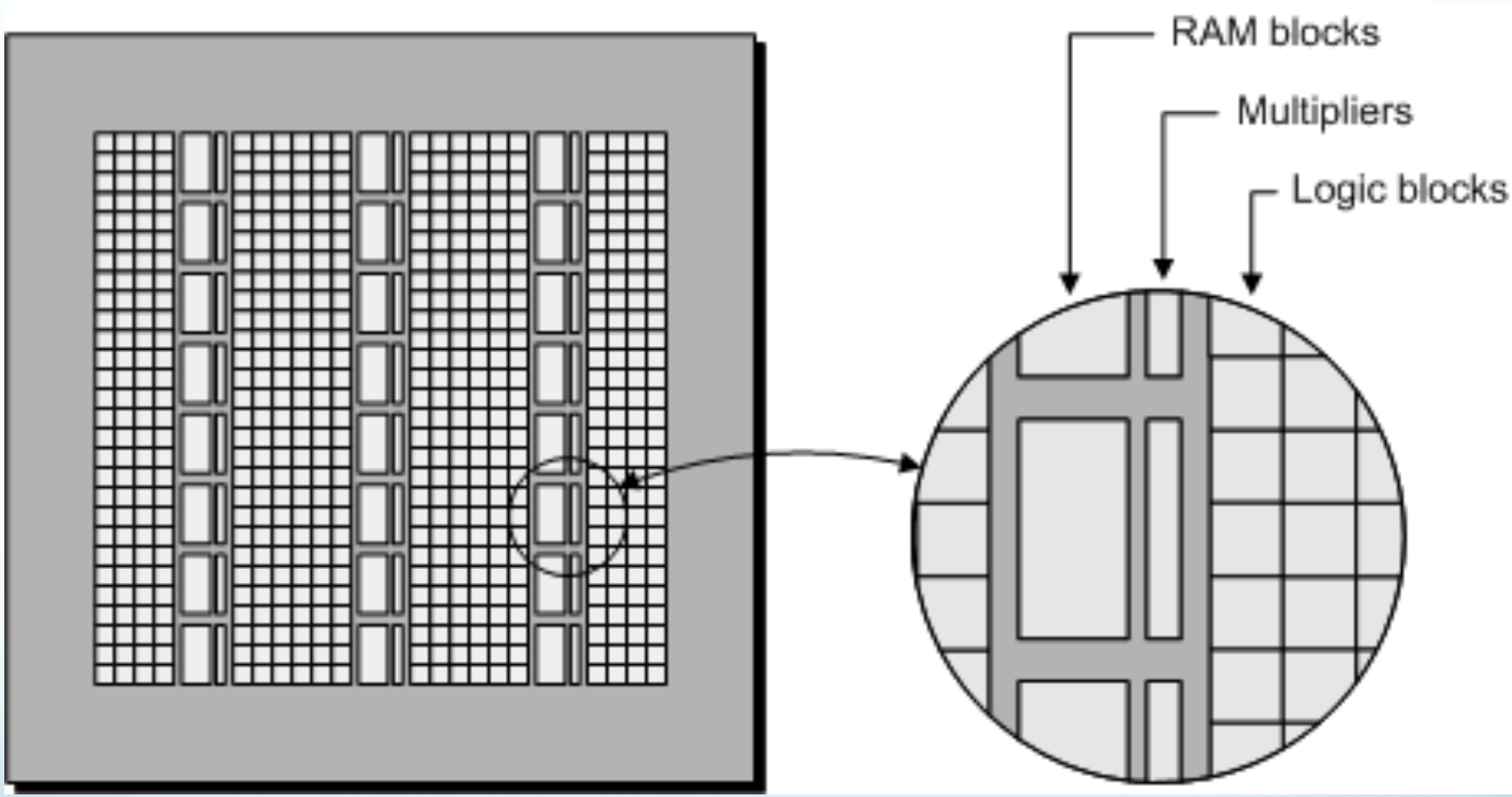


Embedded RAM blocks

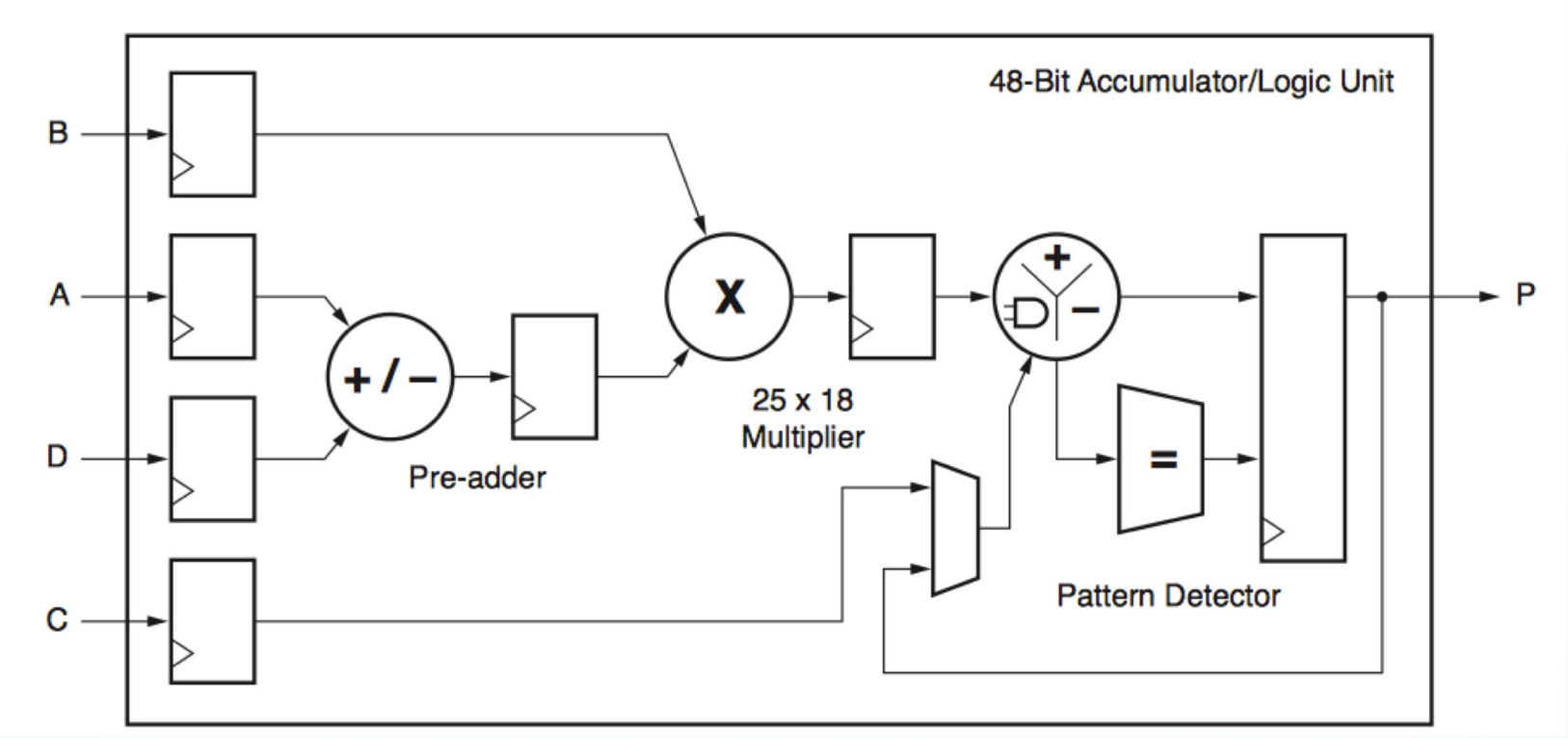


Today: Up to ~500 Mbit of RAM

Embedded Multipliers & DSPs



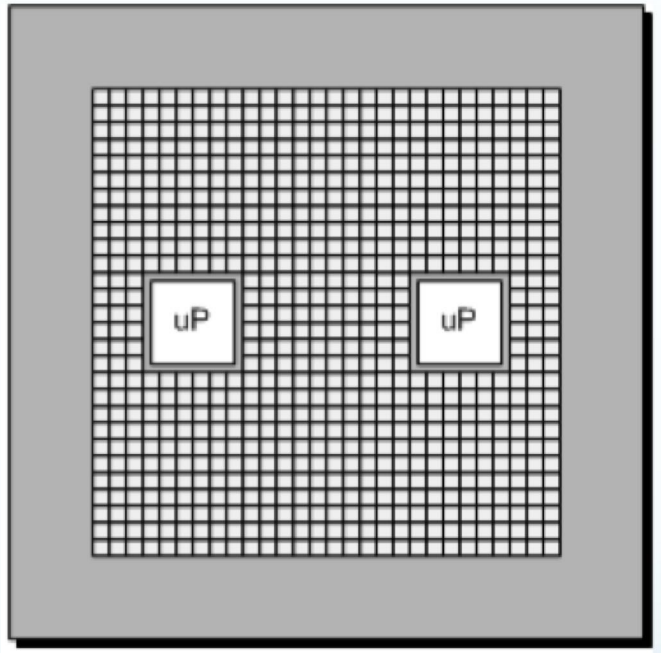
Digital Signal Processor (DSP)



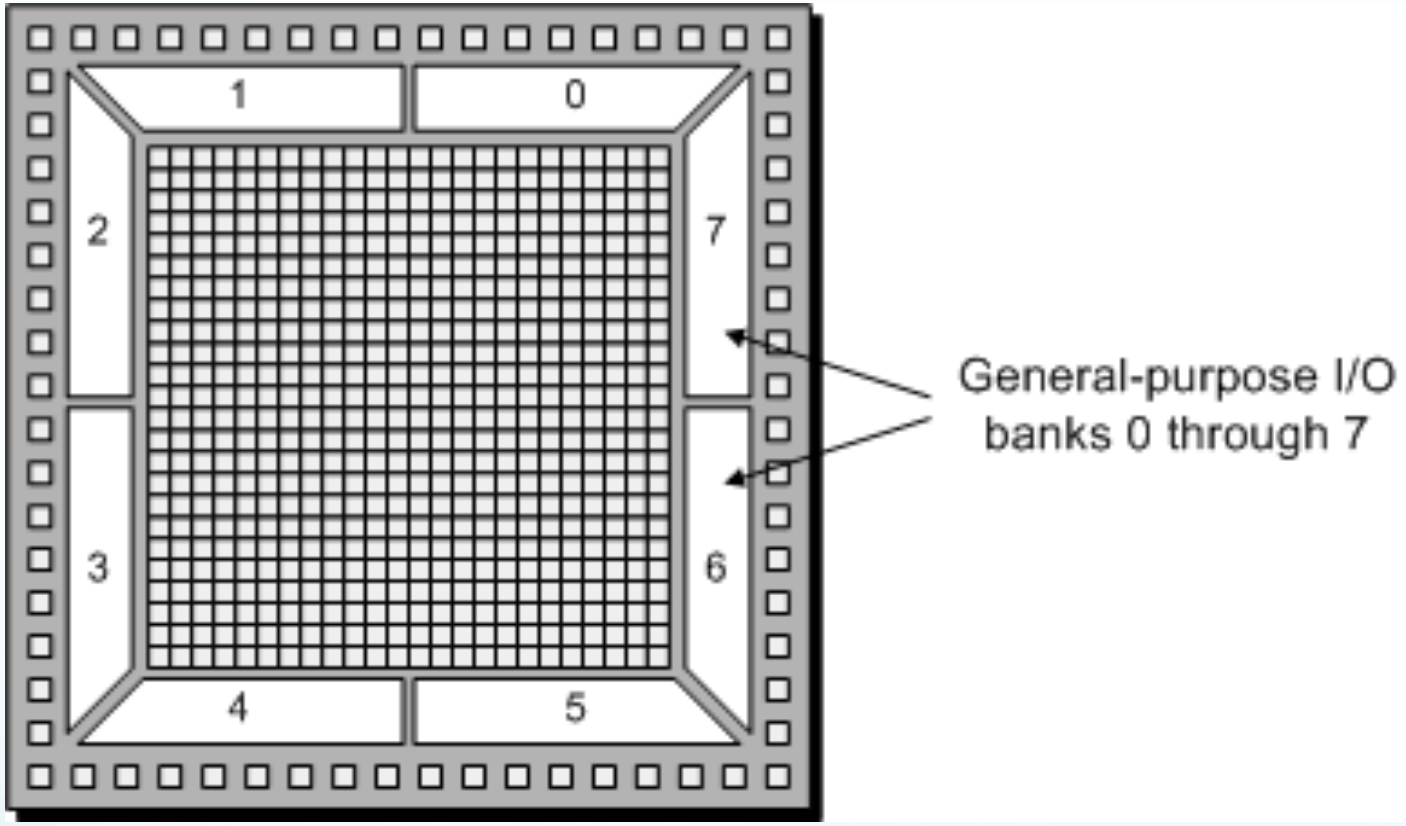
DSP block (Xilinx 7-series)
Up to several 1000 per chip

Soft and Hard Processor Cores

- Soft core
  - Design implemented with the programmable resources (logic cells) in the chip
- Hard core
  - Processor core that is available in addition to the programmable resources
  - E.g.: Power PC, ARM



General-Purpose Input/Output (GPIO)

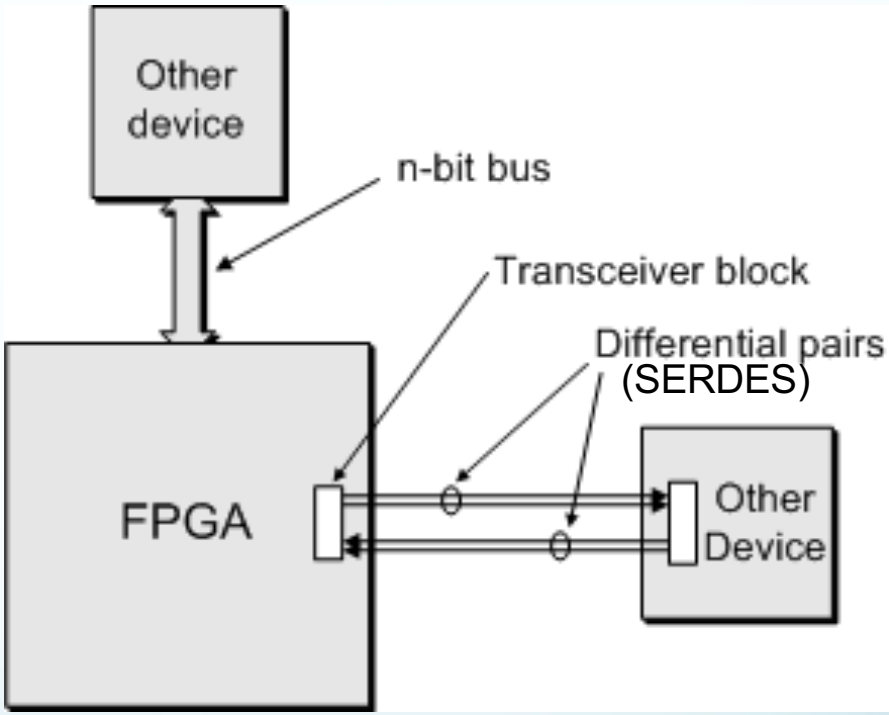


Today: Up to 1200 user I/O pins

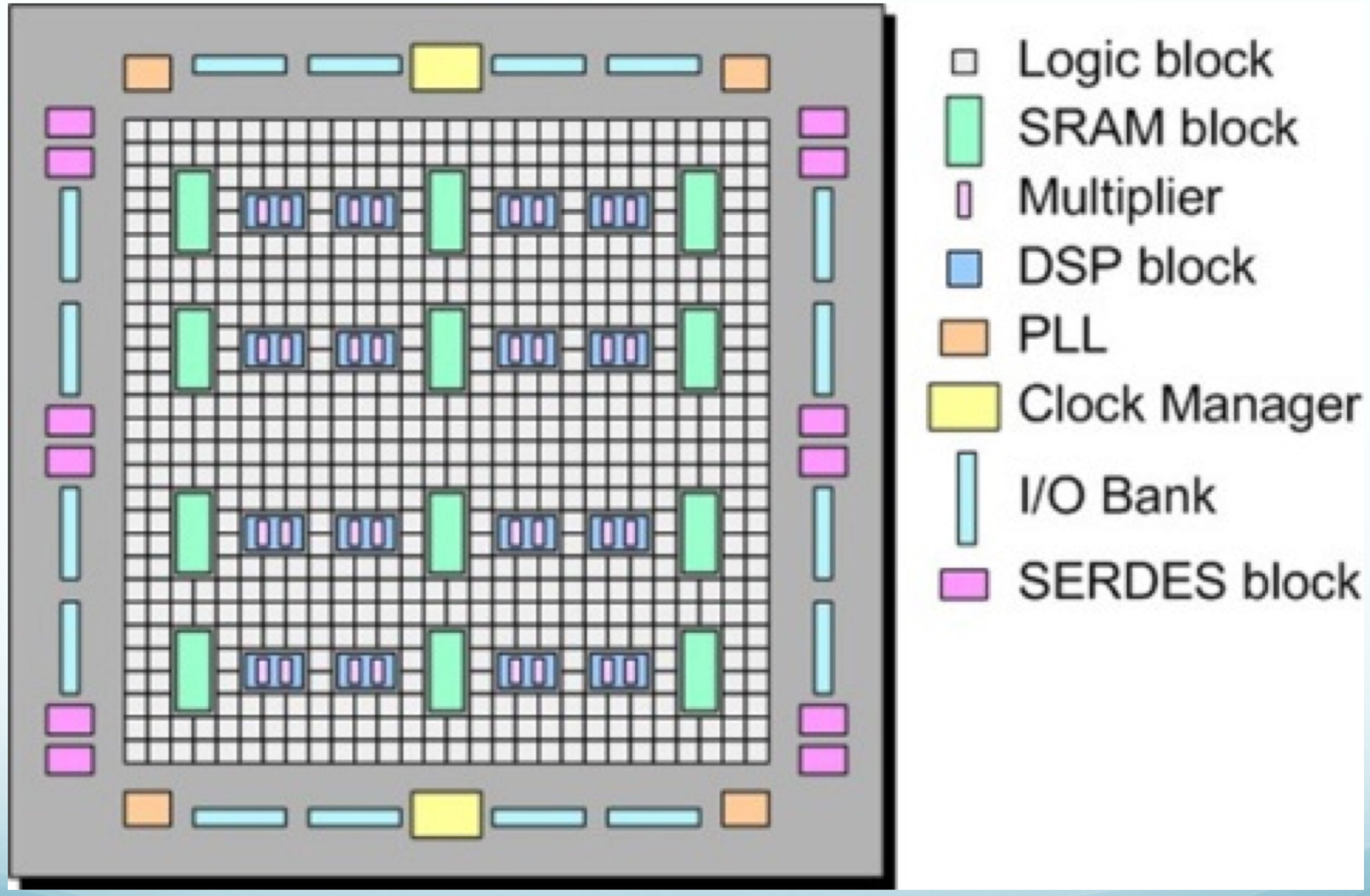
- Input and / or output
- Voltages from (1.0), 1.2 .. 3.3 V
- Many IO standards
- Single-ended: LVTTL, LVCMOS, …
- Differential pairs: LVDS, …

High-Speed Serial Interconnect

- Using differential pairs
- Standard I/O pins limited to about 1 Gbit/s
- Latest serial transceivers: typically 10 Gb/s, 25 Gb/s,
  - up to 32.75 Gb/s
  - up to 112 Gb/s with Pulse Amplitude Modulation (PAM)
- FPGAs with multi-Tbit/s IO bandwidth

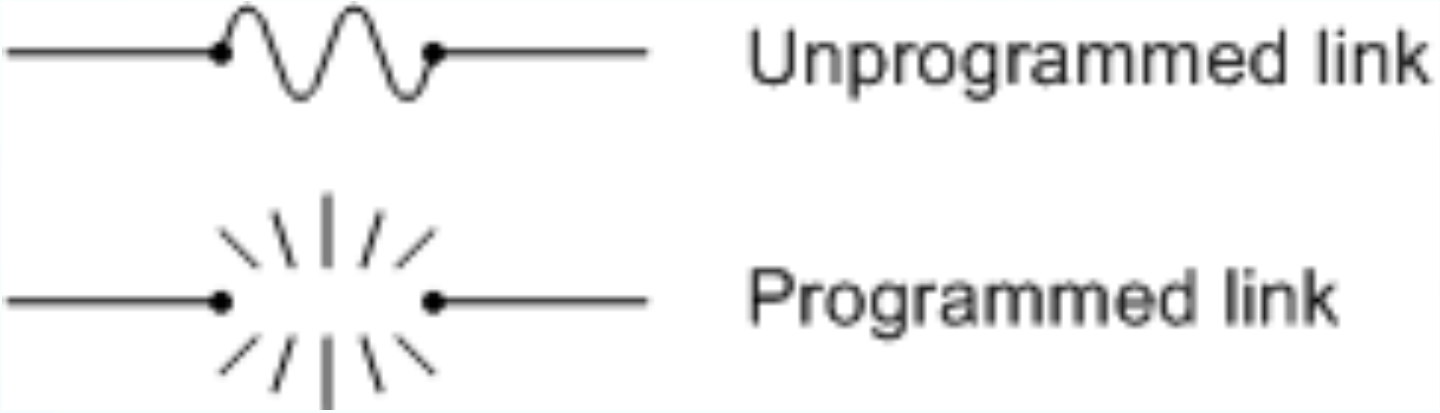


Components in a modern FPGA

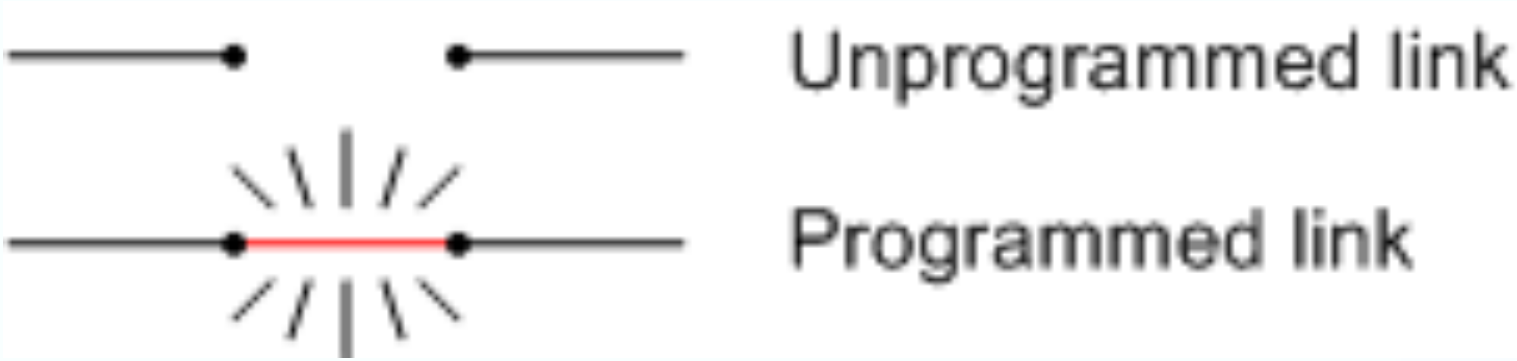


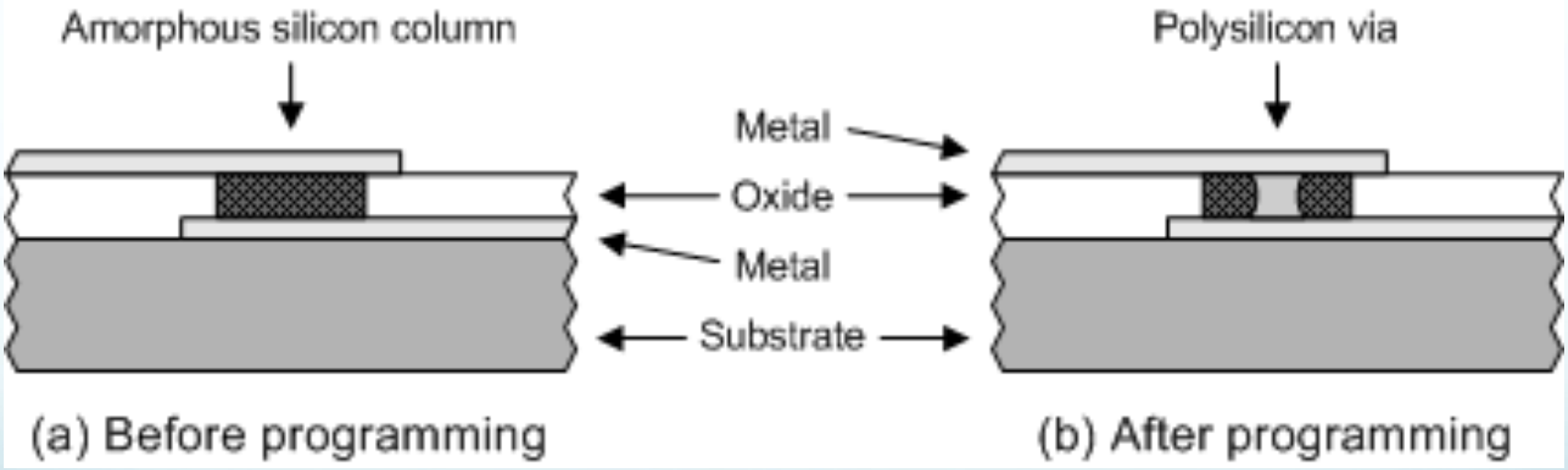
Programming techniques

Fusible Links (not used in FPGAs)



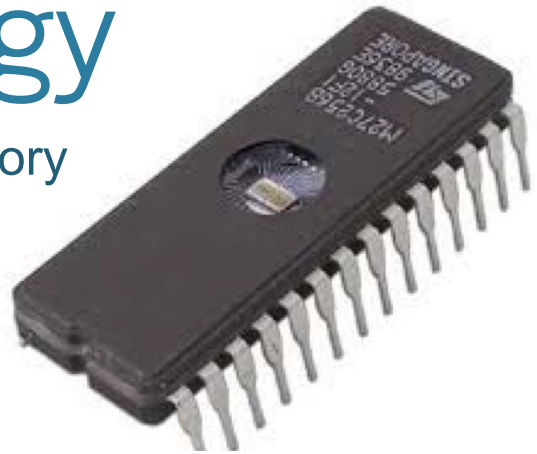
Antifuse Technology

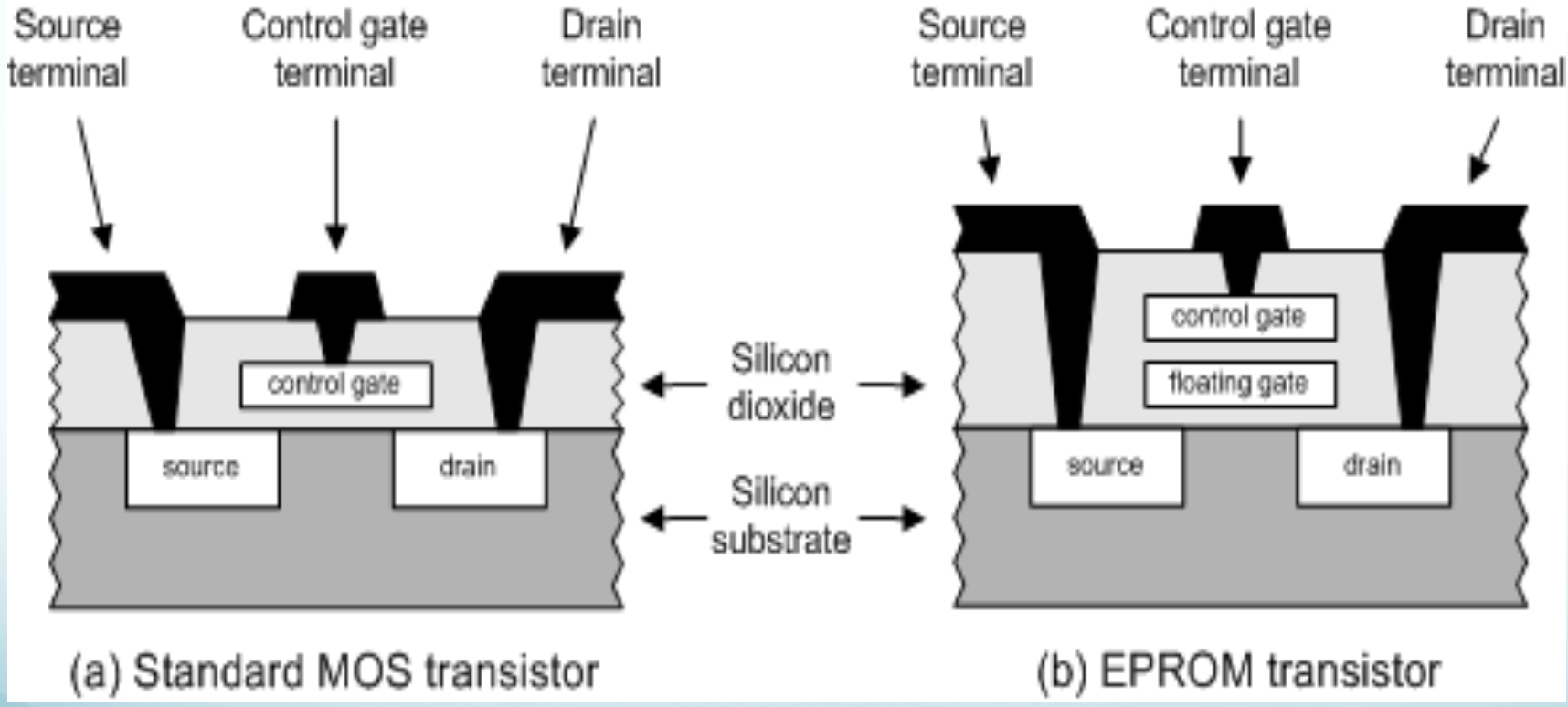




EPROM Technology

Erasable Programmable Read Only Memory

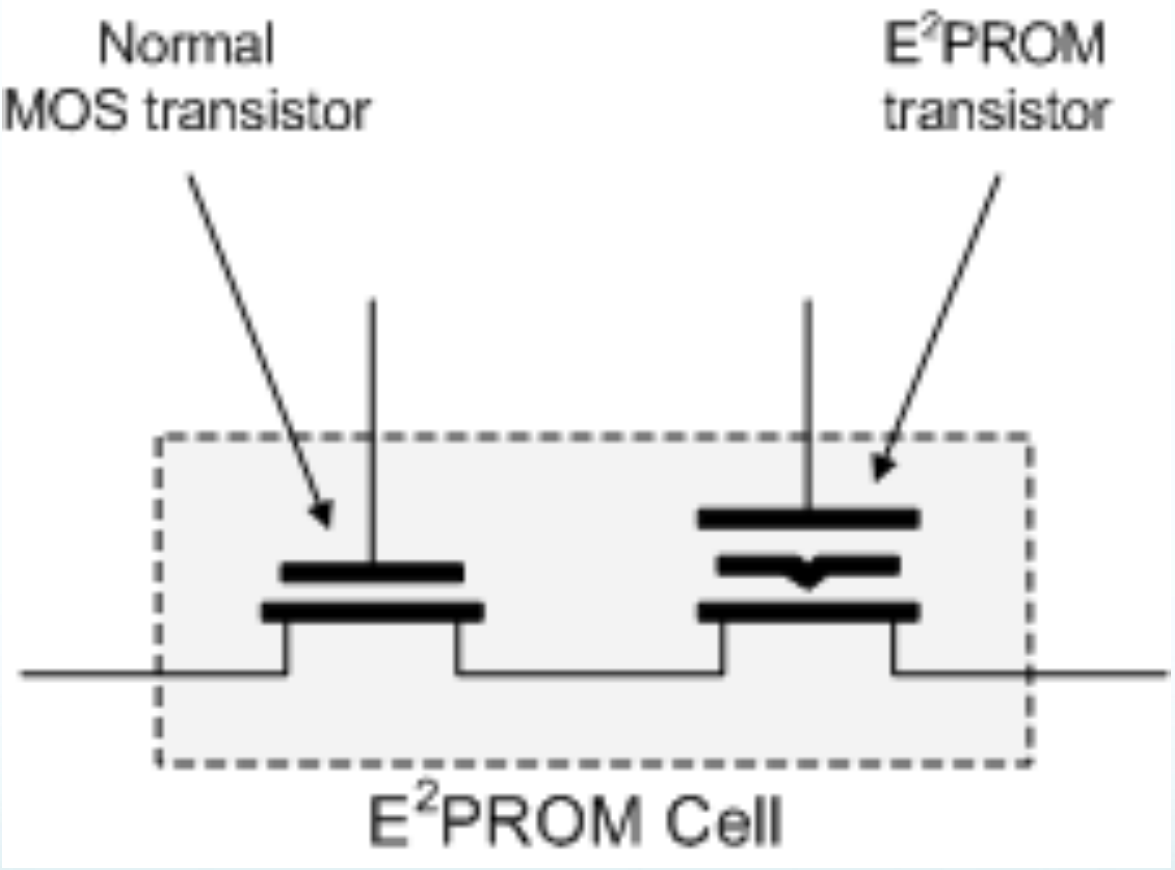




Intel, 1971

EEPROM and FLASH Technology

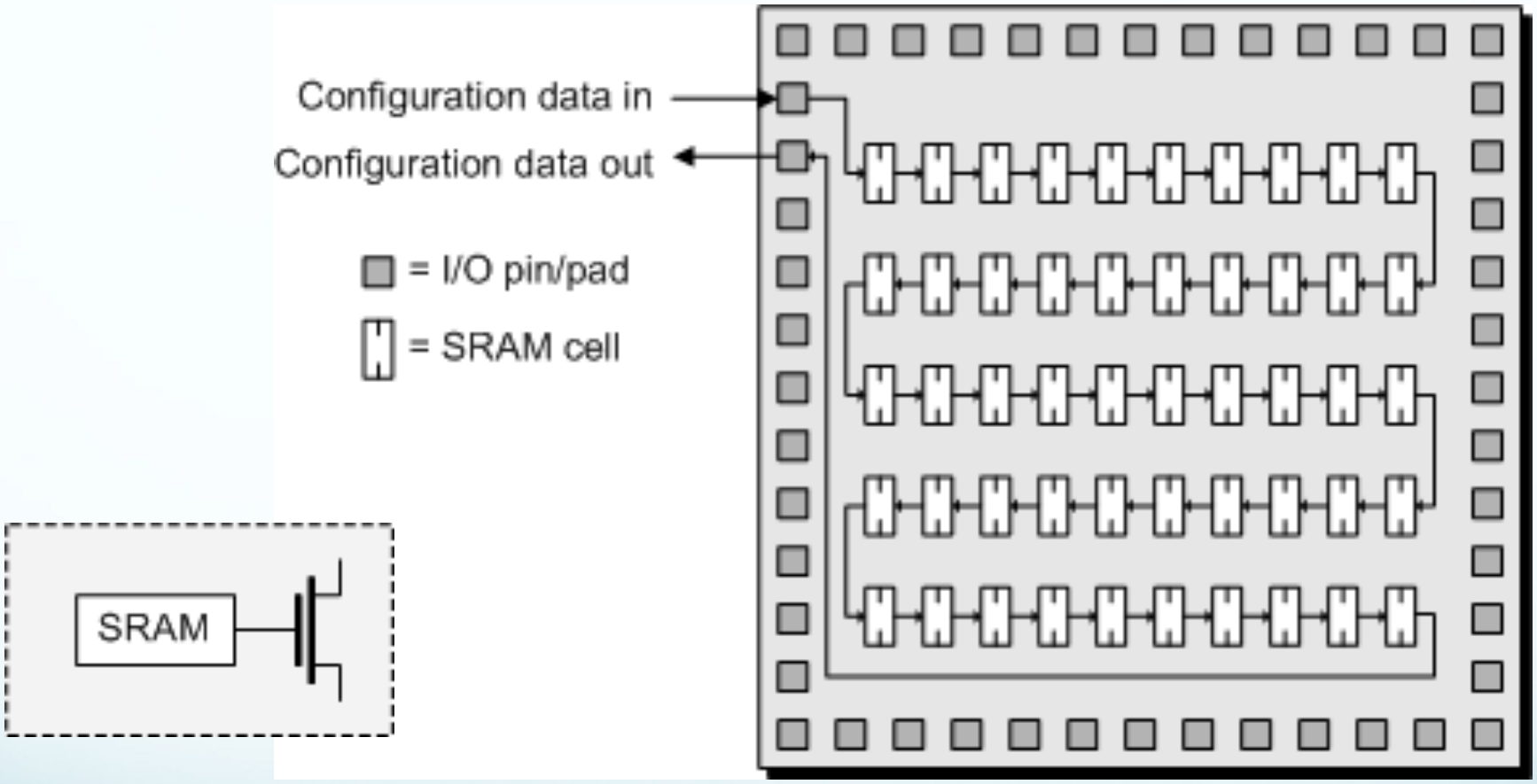
Electrically Erasable Programmable Read Only Memory



EEPROM: erasable word by word
FLASH: erasable by block or by device

Erasure by “Fowler-Nordheim” Tunneling

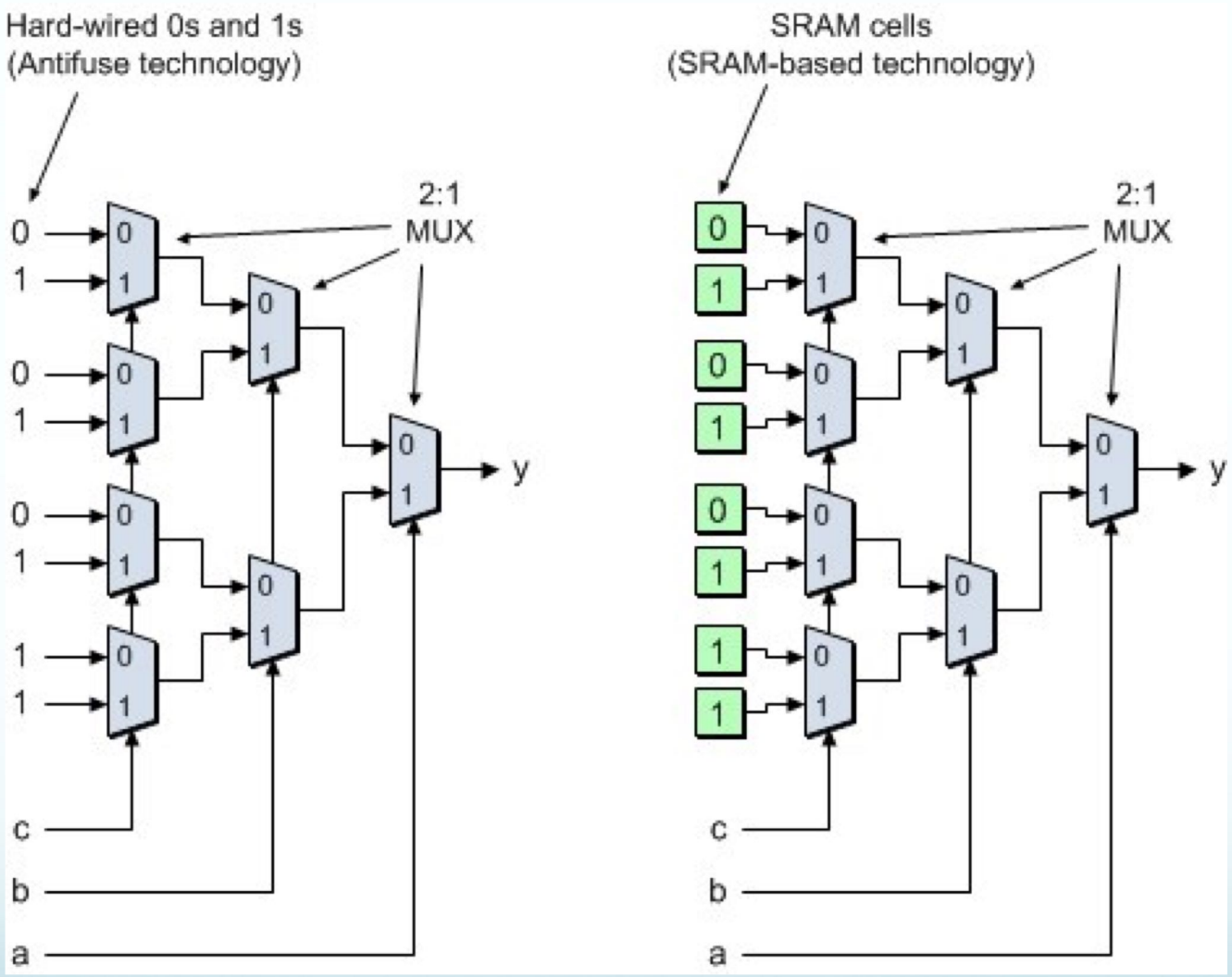
SRAM-Based Devices



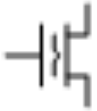
Multi-transistor SRAM cell

Keeps configuration only while powered

Programming a 3-bit wide LUT



Summary of Technologies

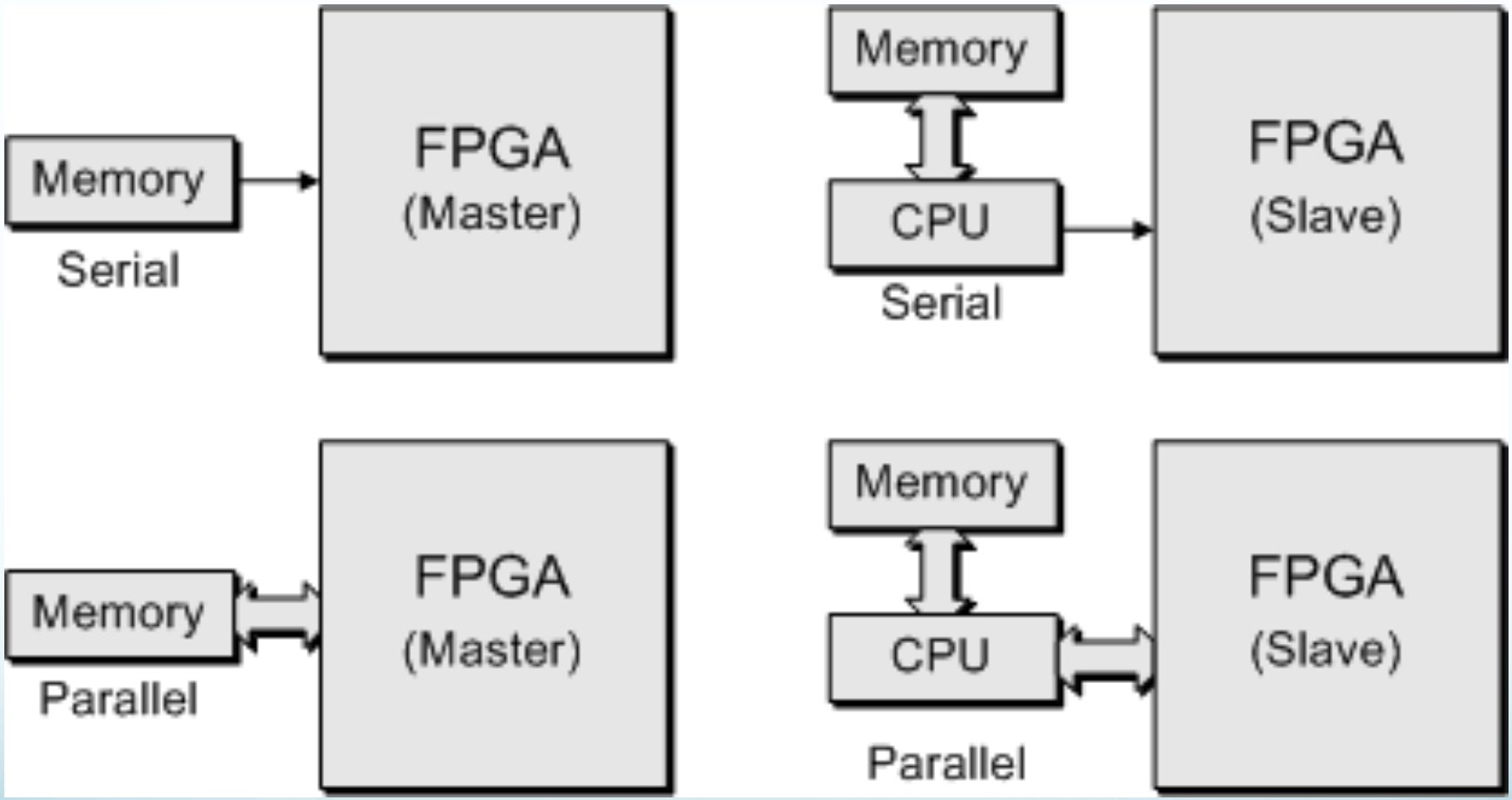
Technology	Symbol	Predominantly associated with ...
Fusible-link		SPLDs
Antifuse		FPGAs
EPROM		SPLDs and CPLDs
E^2PROM/ FLASH		SPLDs, CPLDs, and FPGAs
SRAM		FPGAs (some CPLDs)

Rad-tolerant secure

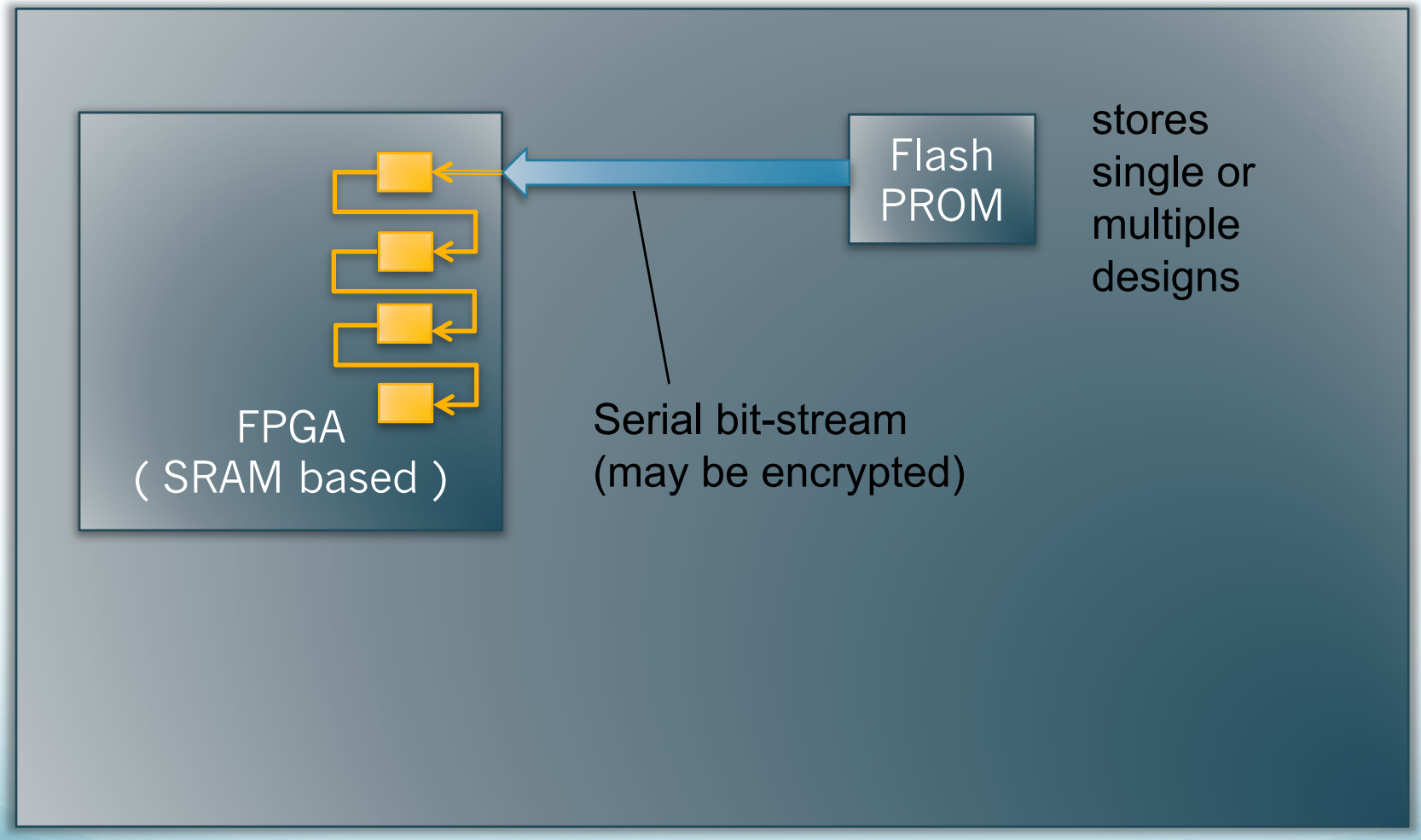
Rad-tolerant (e.g. Alice)

Used in most FPGAs

Design Considerations (SRAM Config.)



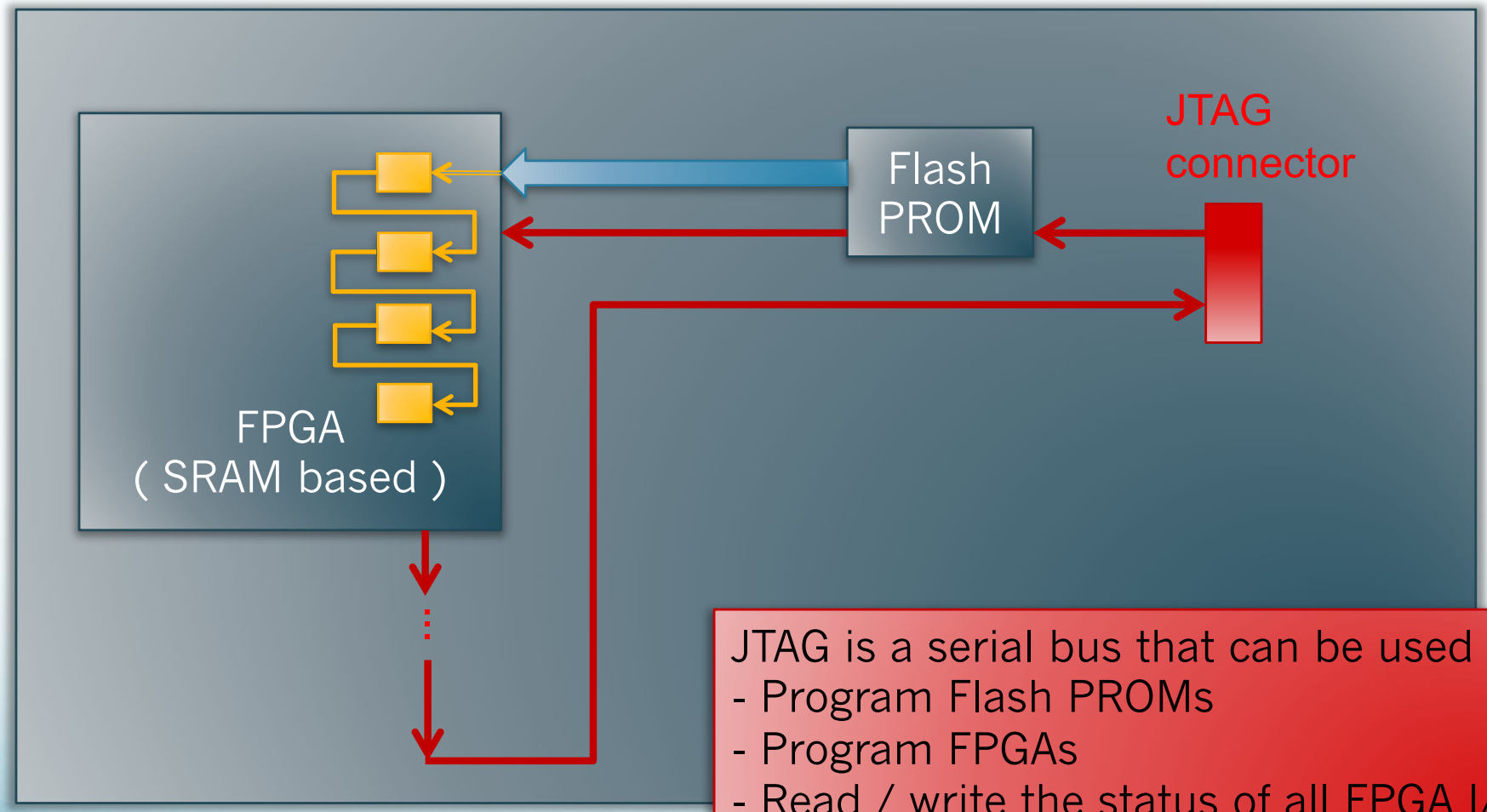
Configuration at power-up



Typical FPGA configuration time: milliseconds

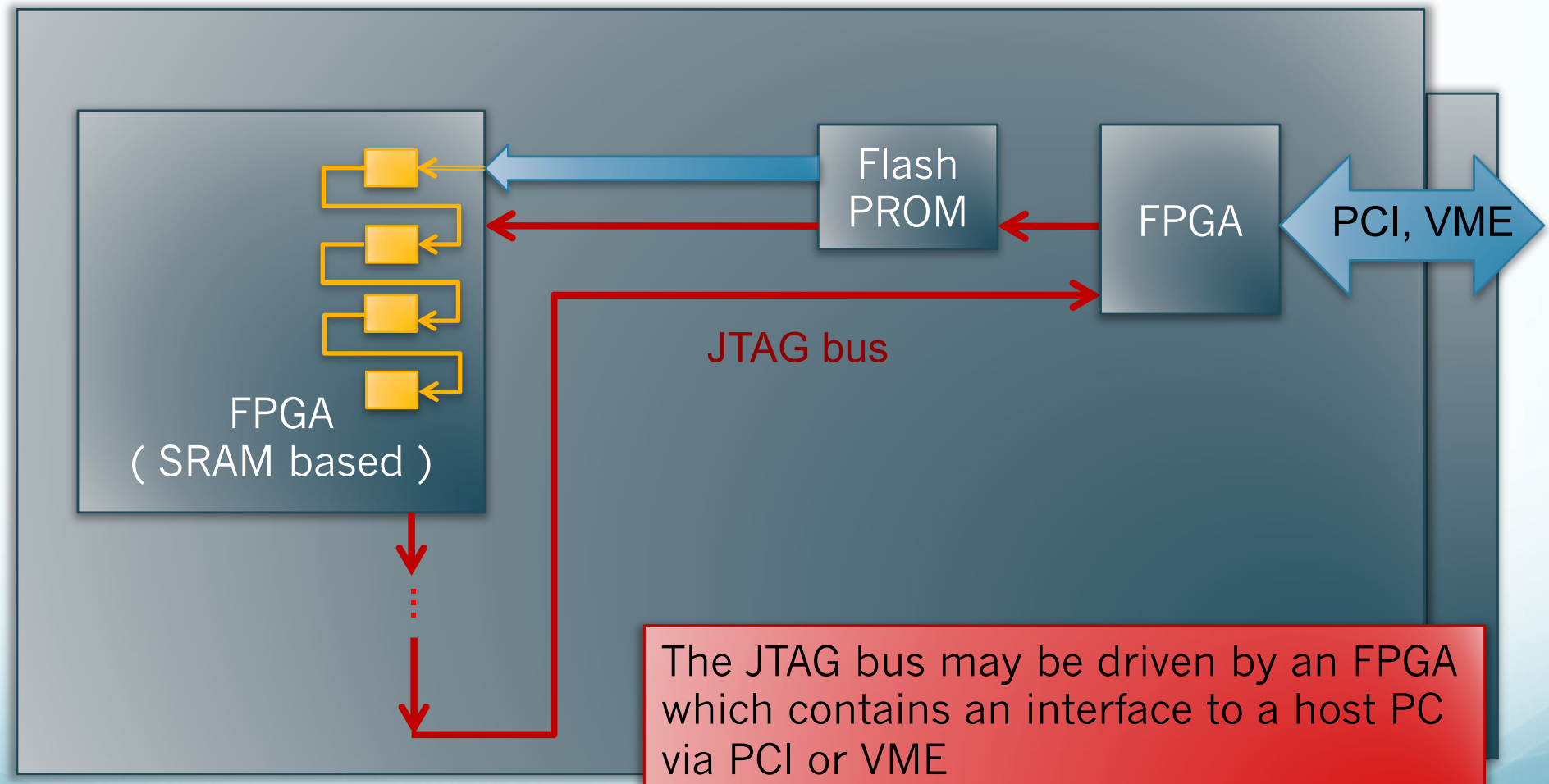
Programming via JTAG

Joint Test Action Group



JTAG is a serial bus that can be used to
- Program Flash PROMs
- Program FPGAs
- Read / write the status of all FPGA I/Os
  (= Boundary scan)

Remote programming



The JTAG bus may be driven by an FPGA which contains an interface to a host PC via PCI or VME

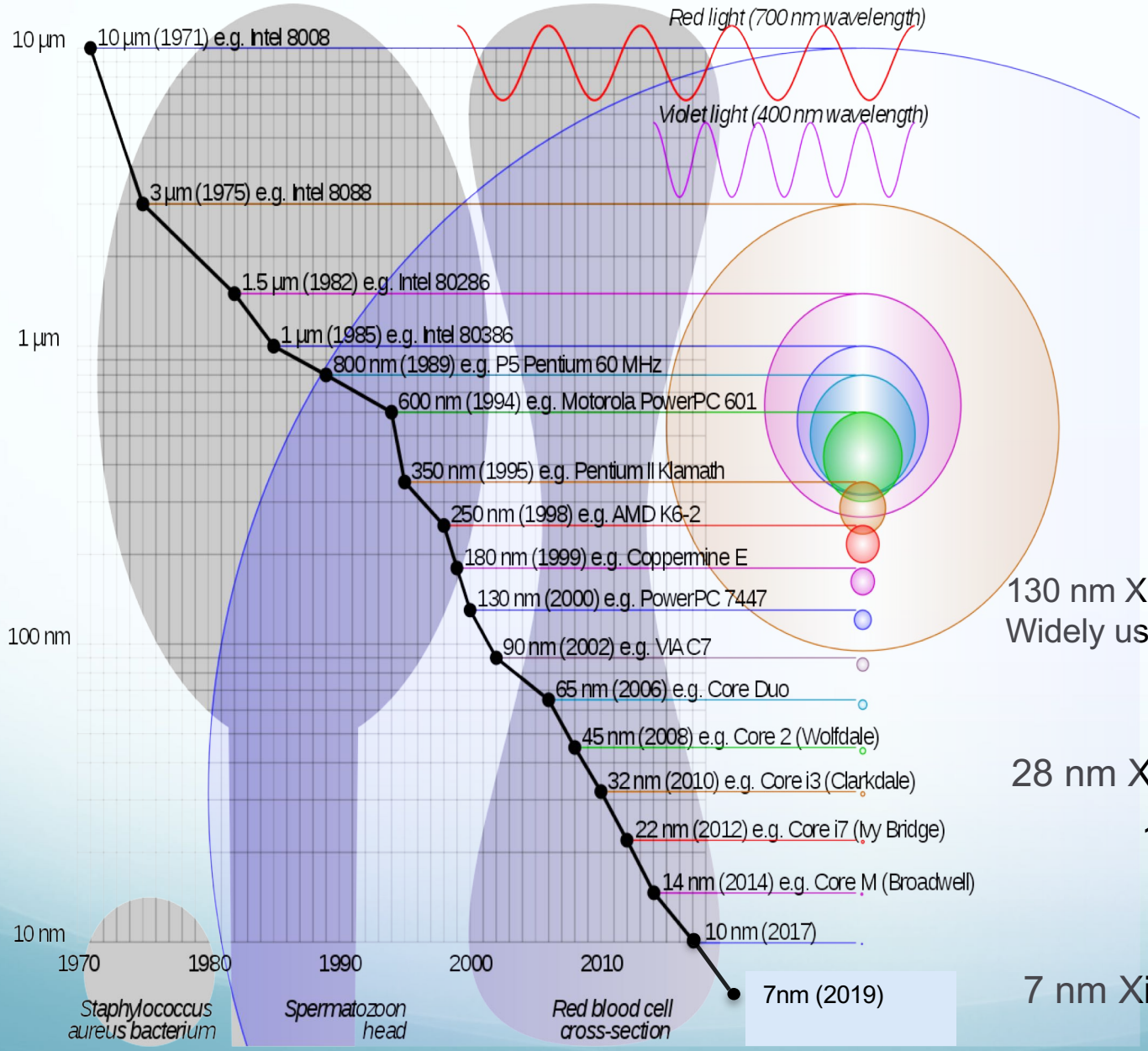
gateware can then be updated remotely

Major Manufacturers

- AMD Xilinx
  - First company to produce FPGAs in 1985
  - About 55% market share, today
  - SRAM based CMOS devices
  - Bought by AMD in 2022
- Intel FPGA (formerly Altera)
  - About 35% market share
  - SRAM based CMOS devices
- Microchip (Microsemi, Actel)
  - Anti-fuse FPGAs
  - Flash based FPGAs
  - Mixed Signal
- Lattice Semiconductor
  - SRAM based with integrated Flash PROM
  - low power

Trends

Ever-decreasing feature size



- Higher capacity
- Higher speed
- Lower power consumption

130 nm Xilinx Virtex-2
Widely used at LHC startup

28 nm Xilinx Virtex-7 / Altera Stratix V

16 nm Xilinx UltraScale +

14 nm Intel Stratix 10

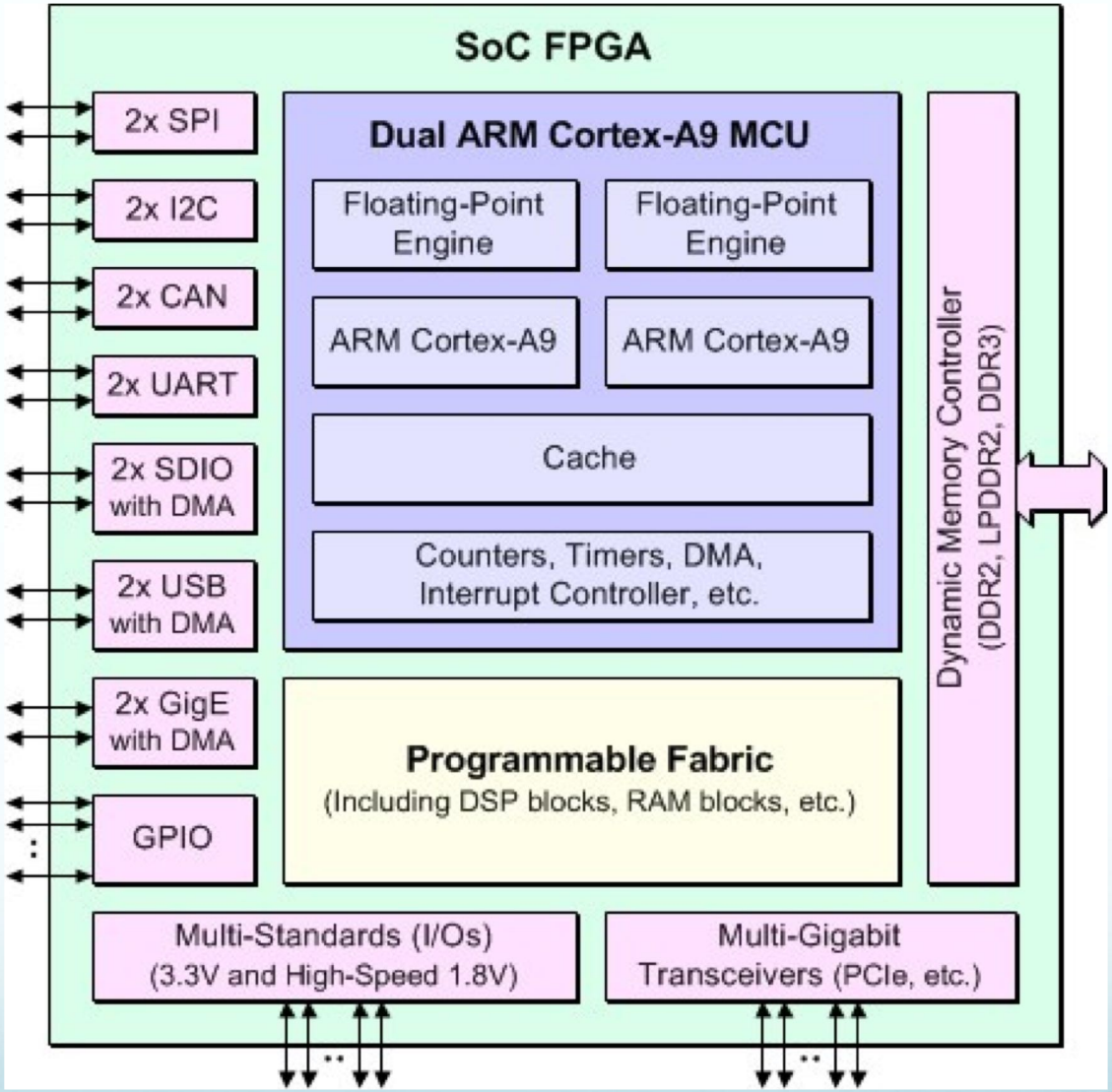
7 nm Xilinx Versal ACAP(*)

(*) Adaptive Compute Acceleration Platform

Trends

- Speed of logic increasing
- Look-up-tables with more inputs (5 or 6)
- Speed of serial links increasing (multiple Gb/s)
- More integrated memory
  - Integrated High Bandwidth Memory (HBM) in-package
    - 10x faster than DDR4 (Xilinx: up to 8 GB, Intel: up to 16GB)
- Additional Flip Flops in routing resources (Intel hyperflex)
- More and more hard macro cores on the FPGA
  - PCI Express
    - Gen2: 5 Gb/s per lane
    - Gen3: 8 Gb/s per lane (typically up to 16 lanes)
    - Gen4: 16 Gb/s per lane
  - 10 Gb/s, 40 Gb/s, 100 Gb/s Ethernet, 150 Gb/s Interlaken
- Sophisticated soft macros
  - CPUs
  - Gb/s MACs
  - Memory interfaces (DDR2/3/4)
- Processor-centric architectures – see next slide

System-On-a-Chip (SoC) FPGAs



Xlinix Zynq

Intel Stratix 10 SoC

CPU(s) + Peripherals + FPGA in one package

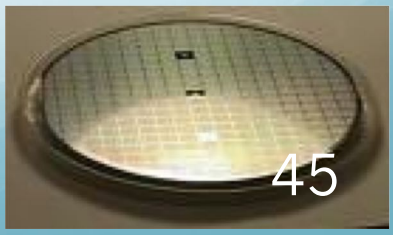
FPGA – ASIC comparison

FPGA

- Rapid development cycle (minutes / hours)
- May be reprogrammed in the field (gateware upgrade)
  - New features
  - Bug fixes
- Low development cost
  - You can get started with a development board (< $100) and free software
- High-end FPGAs rather expensive

ASIC

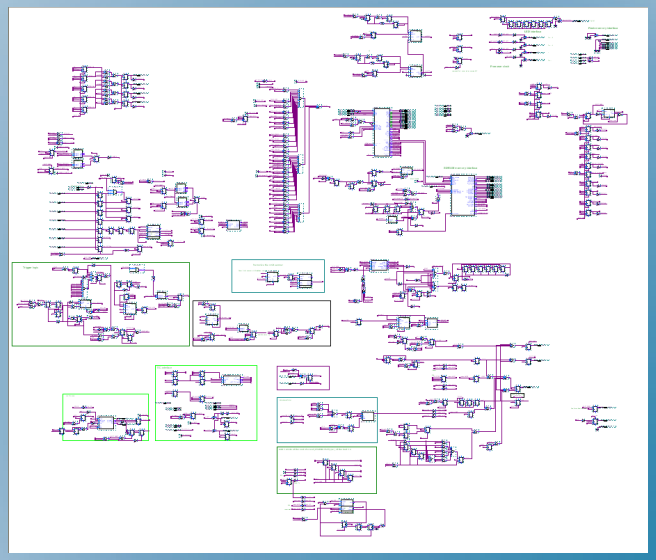
- Higher performance
  - Speed, Area, Power
- Analog designs possible
- Better radiation hardness
- Long development cycle (weeks / months)
- Design cannot be changed once it is produced
- Extremely high development cost
  - ASICs are produced at a semiconductor fabrication facility ("fab") according to your design
- Lower cost per device compared to FPGA, when large quantities are needed



FPGA development

Design entry

Schematics



- Graphical overview
- Can draw entire design
- Use pre-defined blocks

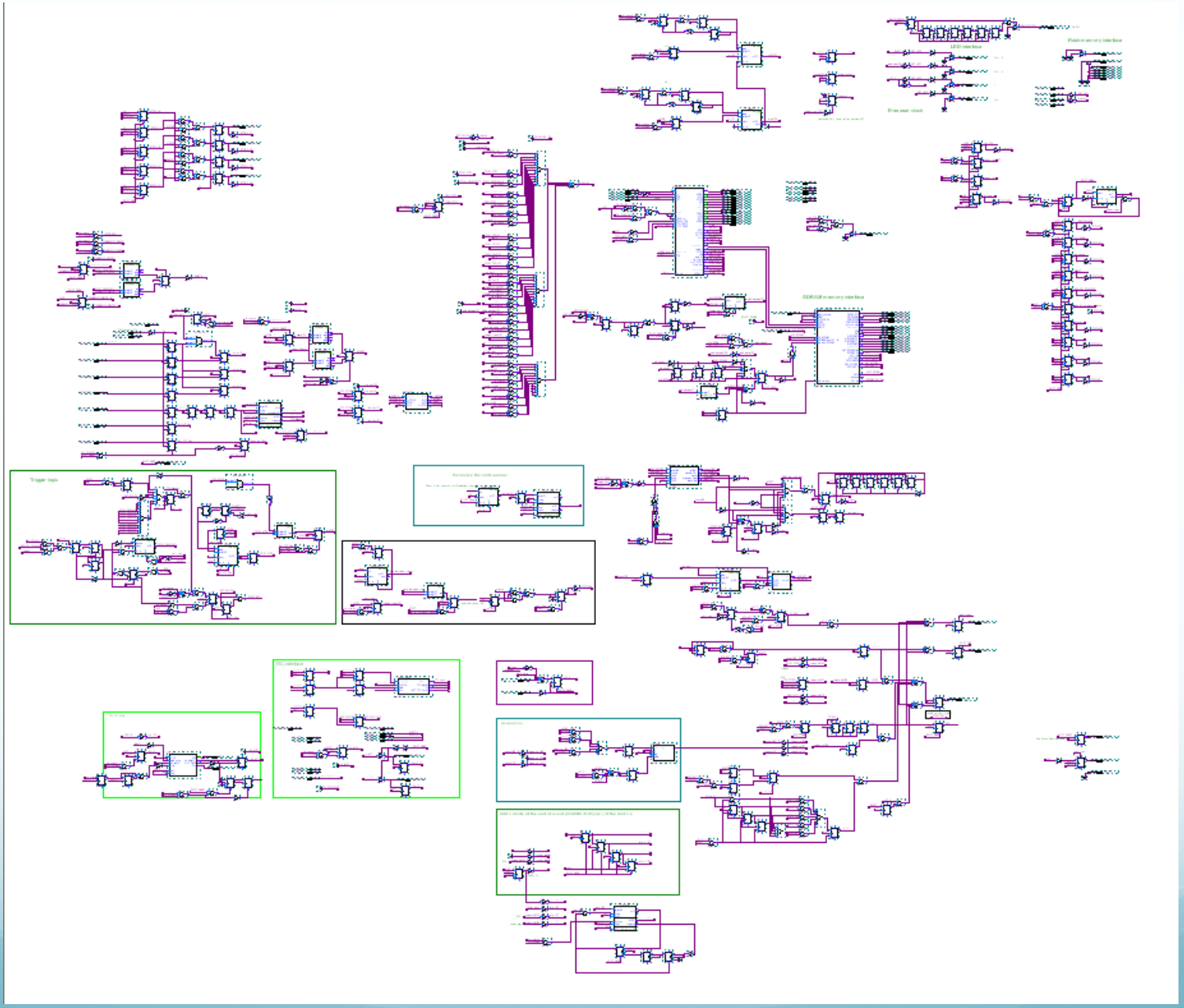
Hardware description language
VHDL, Verilog

```
entity DelayLine is

  generic (
    n_halfcycles : integer := 2);

  port (
    x         : in std_logic_vector;
    x_delayed : out std_logic_vector;
    clk       : in std_logic);

end entity DelayLine;
```

- Can generate blocks using loops
- Can synthesize algorithms
- Independent of design tool
- May use tools used in SW development (git, CI ...)

Mostly a personal choice depending on previous experience

Schematics



Hardware Description Language

- Looks similar to a programming language
  - BUT be aware of the difference
    - Programming Language => translated into machine instructions that are executed by a CPU
    - HDL => translated into gateware (logic gates & flip-flops)
- Common HDLs
  - VHDL
  - Verilog
- Newer trends
  - High Level Synthesis (HLS) from C/C++
  - Other C-like languages (handle-C, System C)
  - Labview

Example: VHDL

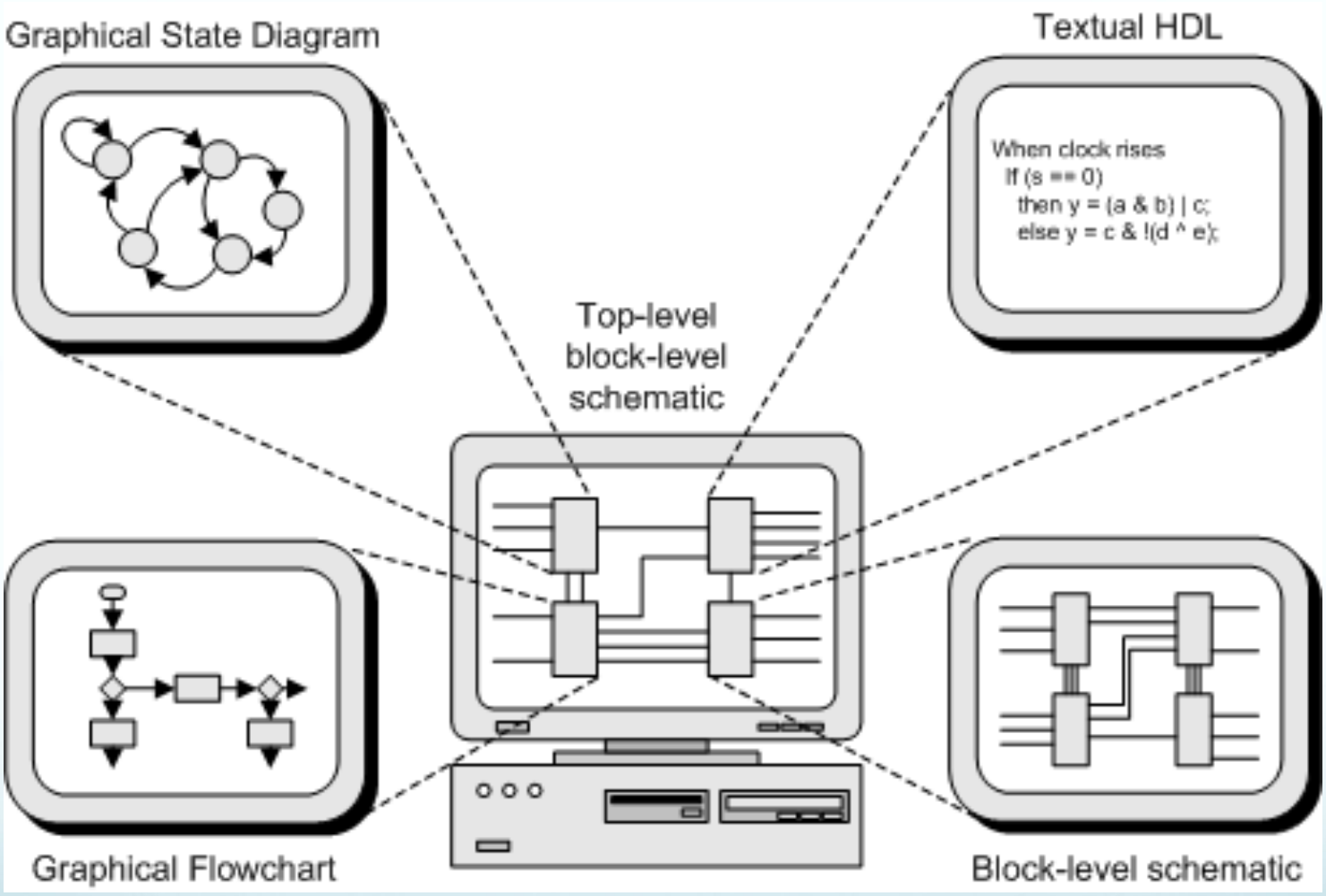
```
architecture behavioral of VMEReg is

  signal vme_en_i   : std_logic;
  signal Q : std_logic_vector(15 downto 0);

begin  -- behavioral

  vme_addr_decode : process (vme_addr, vme_en) is
    variable my_addr_vec : std_logic_vector(vme_addr'high downto 0);
    variable selected    : boolean;
  begin  -- process vme_addr_decode
    my_addr_vec := std_logic_vector( TO_UNSIGNED ( my_vme_base_address, vme_addr'high+1 ) );
    selected    := my_addr_vec(vme_addr'high downto 1) = vme_addr(vme_addr'high downto 1);
    vme_en_i <= '0' ;
    if selected then
      vme_en_i <= vme_en;
    end if;
  end process vme_addr_decode;

  reg: process (vme_clk, reset) is
  begin  -- process reg
    if reset = '1' then                 -- asynchronous reset
        Q <= init_val;
        vme_en_out <= '0';
    elsif vme_clk'event and vme_clk = '1' then  -- rising clock edge
      vme_en_out <= vme_en_i;
      if vme_en_i = '1' and vme_wr = '1' then
        Q <= vme_data;
      end if;
    end if;
  end process reg;

  data <= Q;
  vme_data_out <= Q;

end behavioral;
```

Asynchronous logic
All signals in sensitivity list

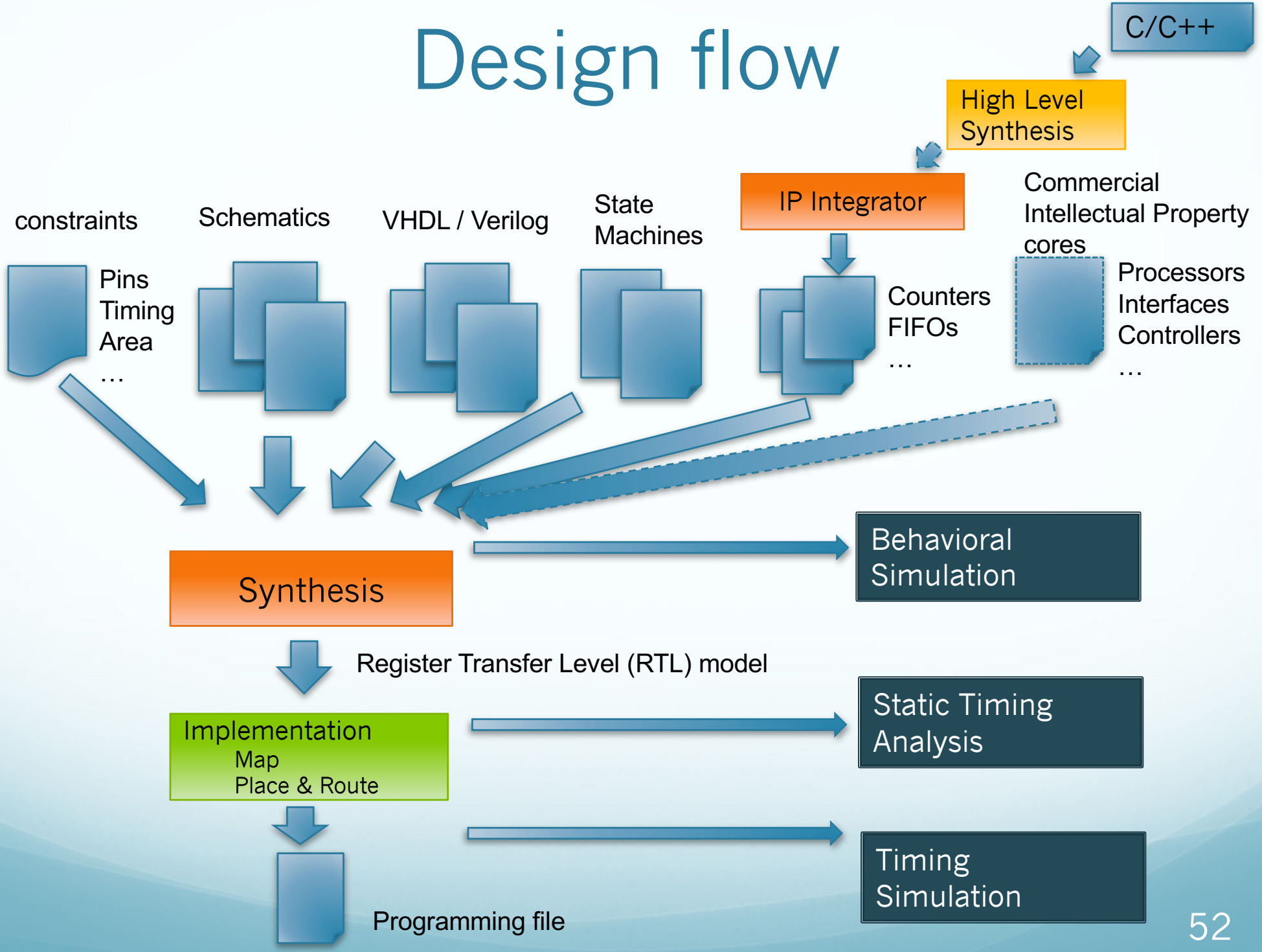
Synchronous logic
Only clock (and reset) in sensitivity list

- Looks like a programming language
- All statements executed in parallel, except inside processes

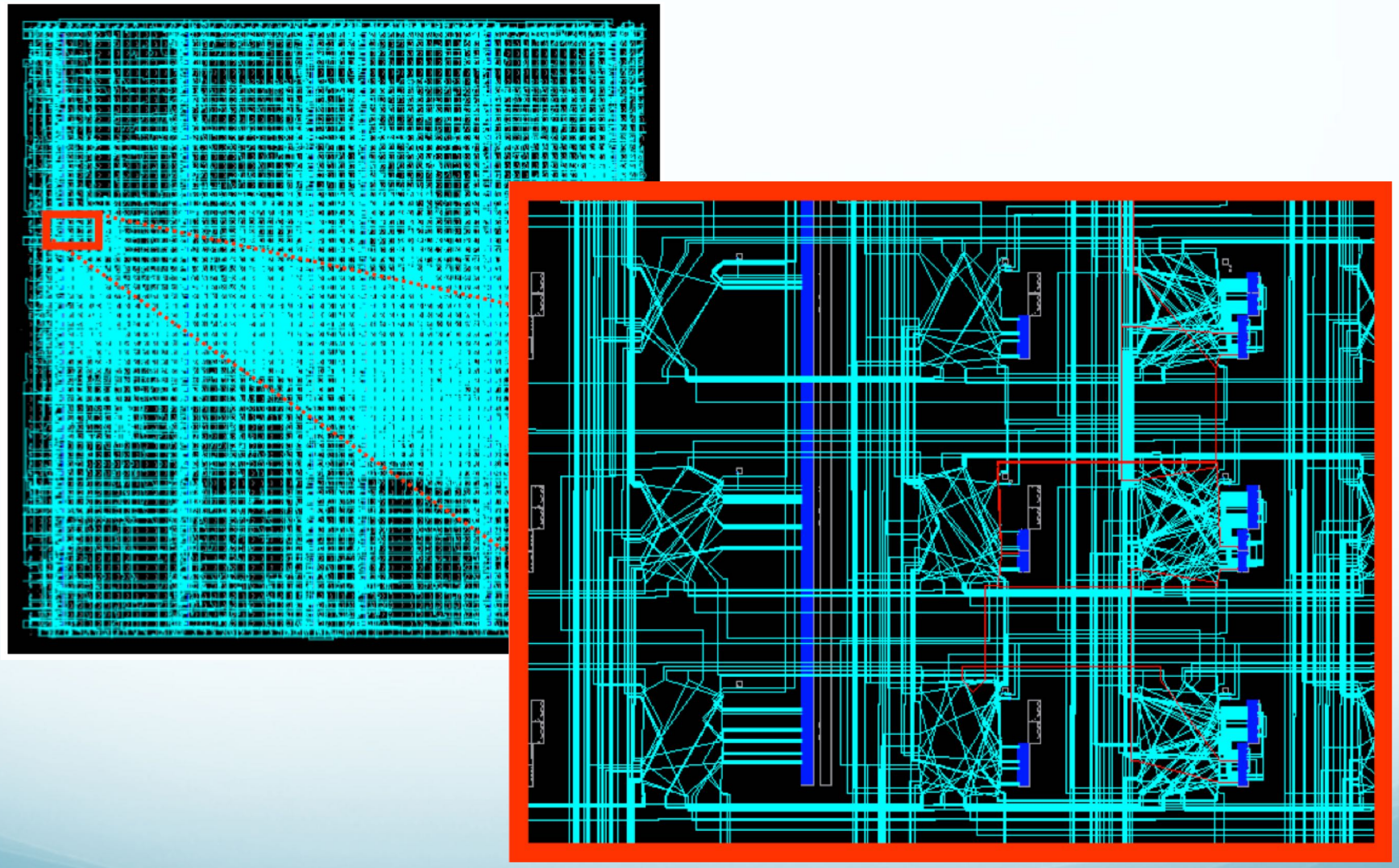
Schematics & HDL combined



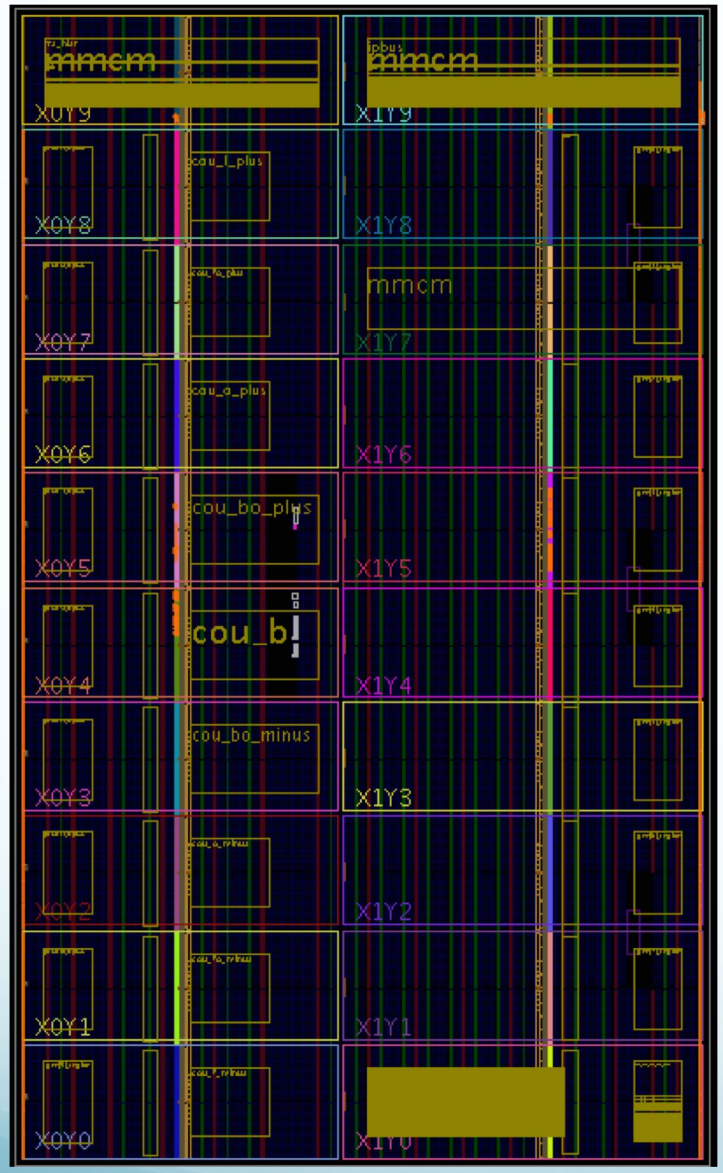
Design flow


C/C++
High Level Synthesis
IP Integrator
Commercial Intellectual Property cores
constraints
Schematics
VHDL / Verilog
State Machines
Pins
Timing
Area
…
Counters
FIFOs
…
Processors
Interfaces
Controllers
…
Synthesis
Behavioral Simulation
Register Transfer Level (RTL) model
Implementation
Map
Place & Route
Static Timing Analysis
Programming file
Timing Simulation

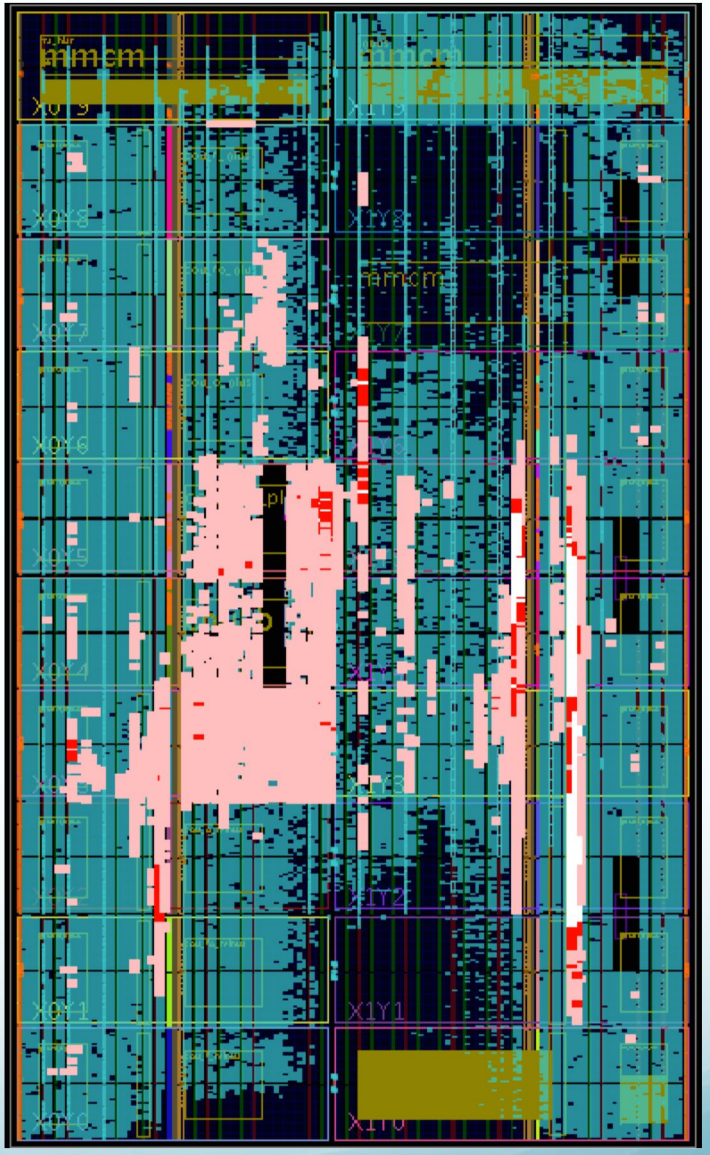
Floorplan (Xlinx Virtex 2)



Manual Floor planning

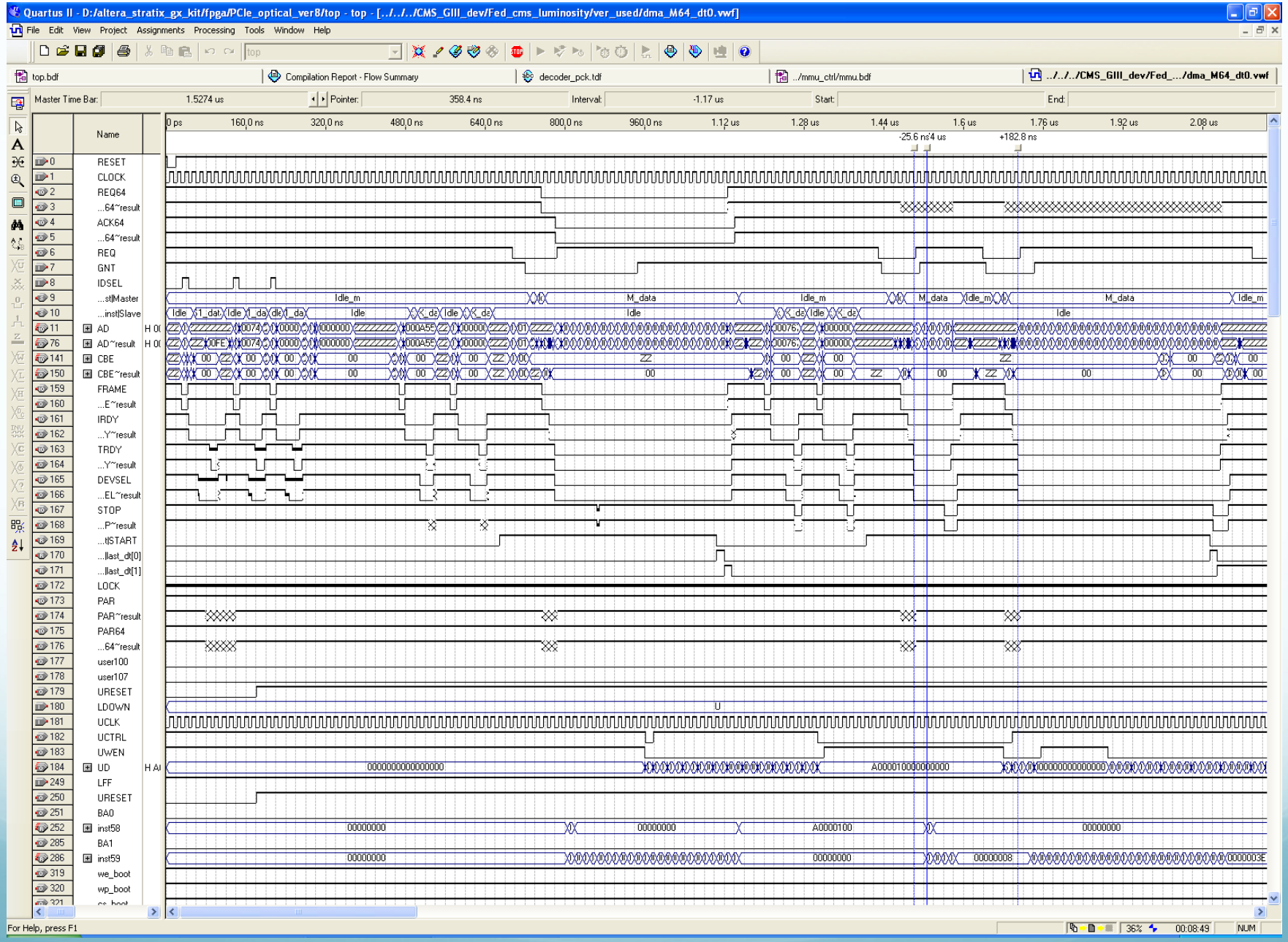


- For large designs, manual floor planning may be necessary

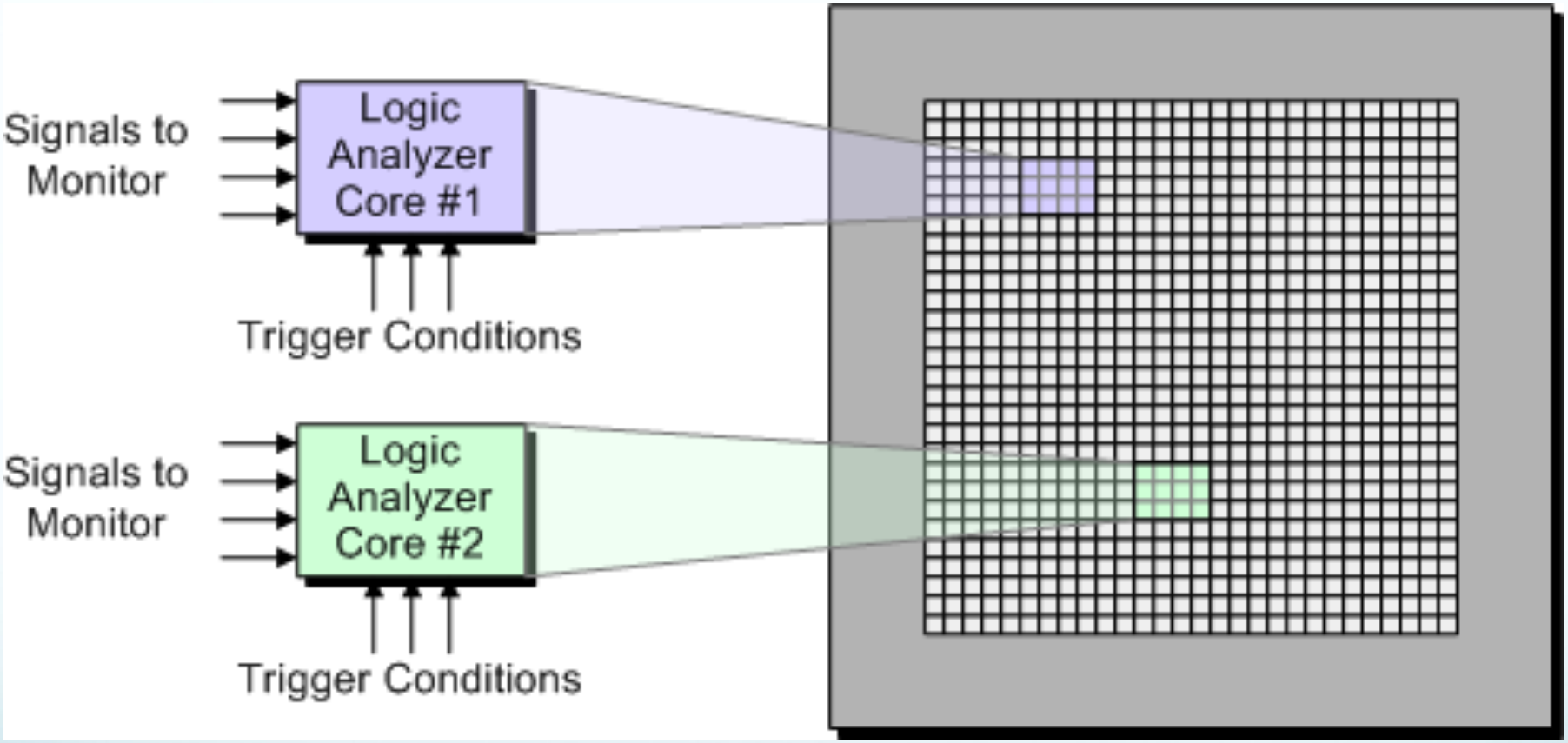


Routing congestion
Xilinx Virtex 7 (Vivado)

Simulation


Quartus II - D:/altera_stratix_gx_kit/fpga/PCIe_optical_ver8/top - top - [../../../CMS_GIII_dev/Fed_cms_luminosity/ver_used/dma_M64_dt0.vwf]
File Edit View Project Assignments Processing Tools Window Help
top.bdf
Compilation Report - Flow Summary
decoder_pck.tdf
../mmu_ctrl/mmu.bdf
../../../CMS_GIII_dev/Fed_.../dma_M64_dt0.vwf
Master Time Bar: 1.5274 us
Pointer: 358.4 ns
Interval: -1.17 us
Start:
End:
Name
RESET
CLOCK
REQ64
ACK64
REQ
GNT
IDSEL
AD
AD~result
CBE
CBE~result
FRAME
IRDY
TRDY
DEVSEL
STOP
LOCK
PAR
PAR~result
PAR64
user100
user107
URESET
LDOWN
UCLK
UCTRL
UWEN
UD
LFF
URESET
BA0
inst58
BA1
inst59
we_boot
wp_boot
Idle_m
M_data
Idle
For Help, press F1
NUM

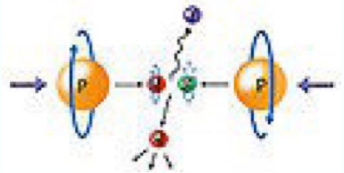
Embedded Logic Analyzers



A great tool for debugging your design

FPGA applications in the Trigger & DAQ domain

First-Level Trigger at Collider



Timing: beam crossings

LHC: 25 ns

detector

Coarse grain data

Full data
(fine grain)

Delay
FIFO

First Level Trigger

Pipelined
Logic

Fixed Latency
(= processing time
of the first
level trigger)

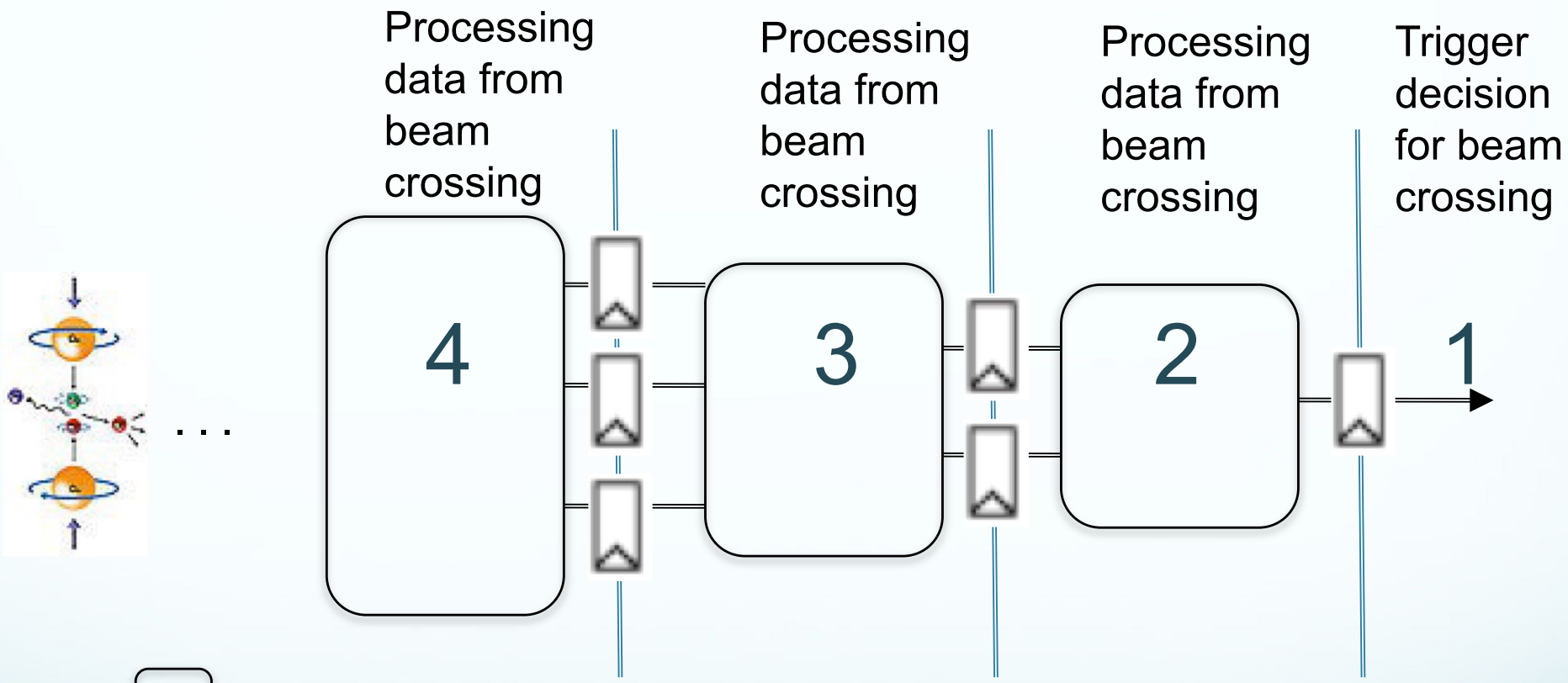
N beam crossings

Trigger decision YES / NO
(for every beam crossing)

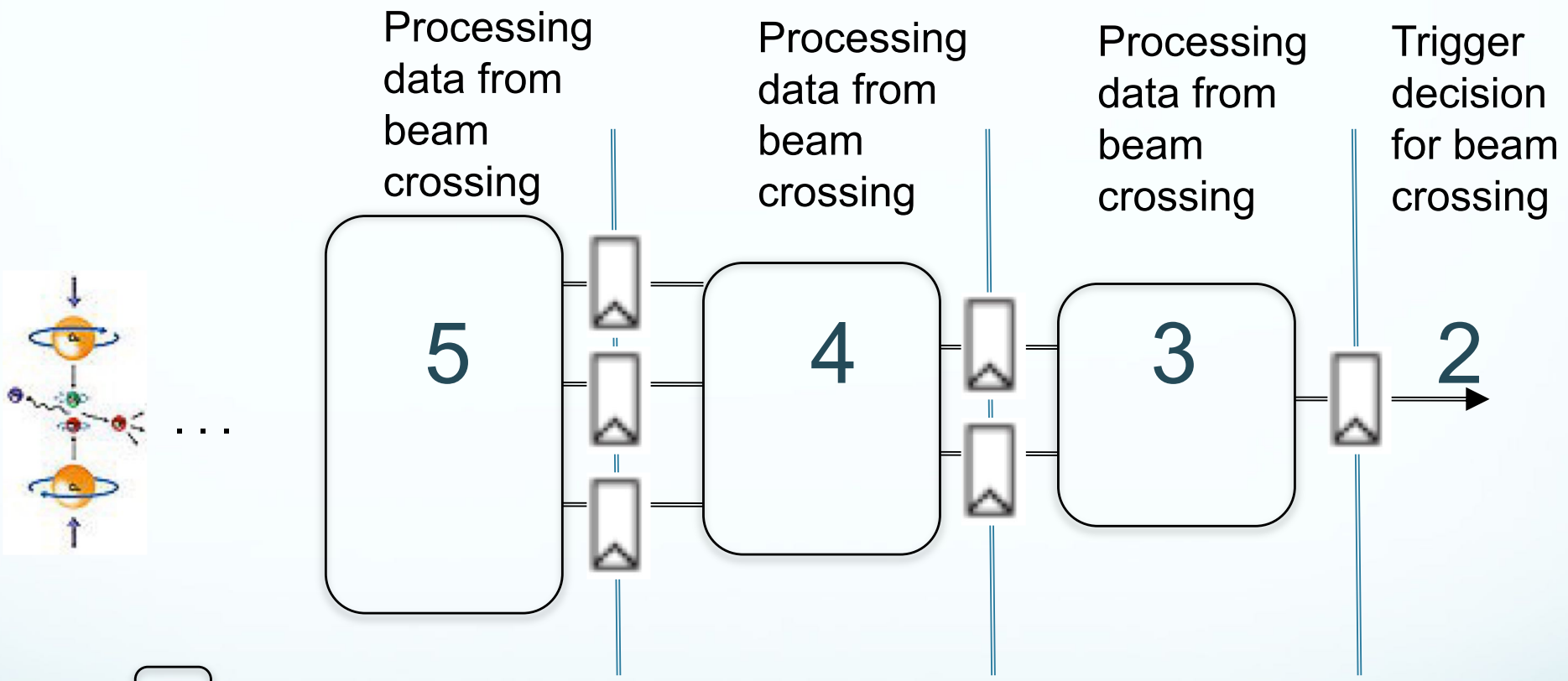
De-
randomizer
FIFO

Latency should be short
In order to limit the length
of the delay FIFOS

Pipelined Logic



Pipelined Logic – a clock cycle later



Why are FPGAs ideal for First-Level Triggers ?

- They are fast
  - Much faster than discrete electronics (shorter connections)
- Many inputs
  - Data from many parts of the detector has to be combined

Low latency

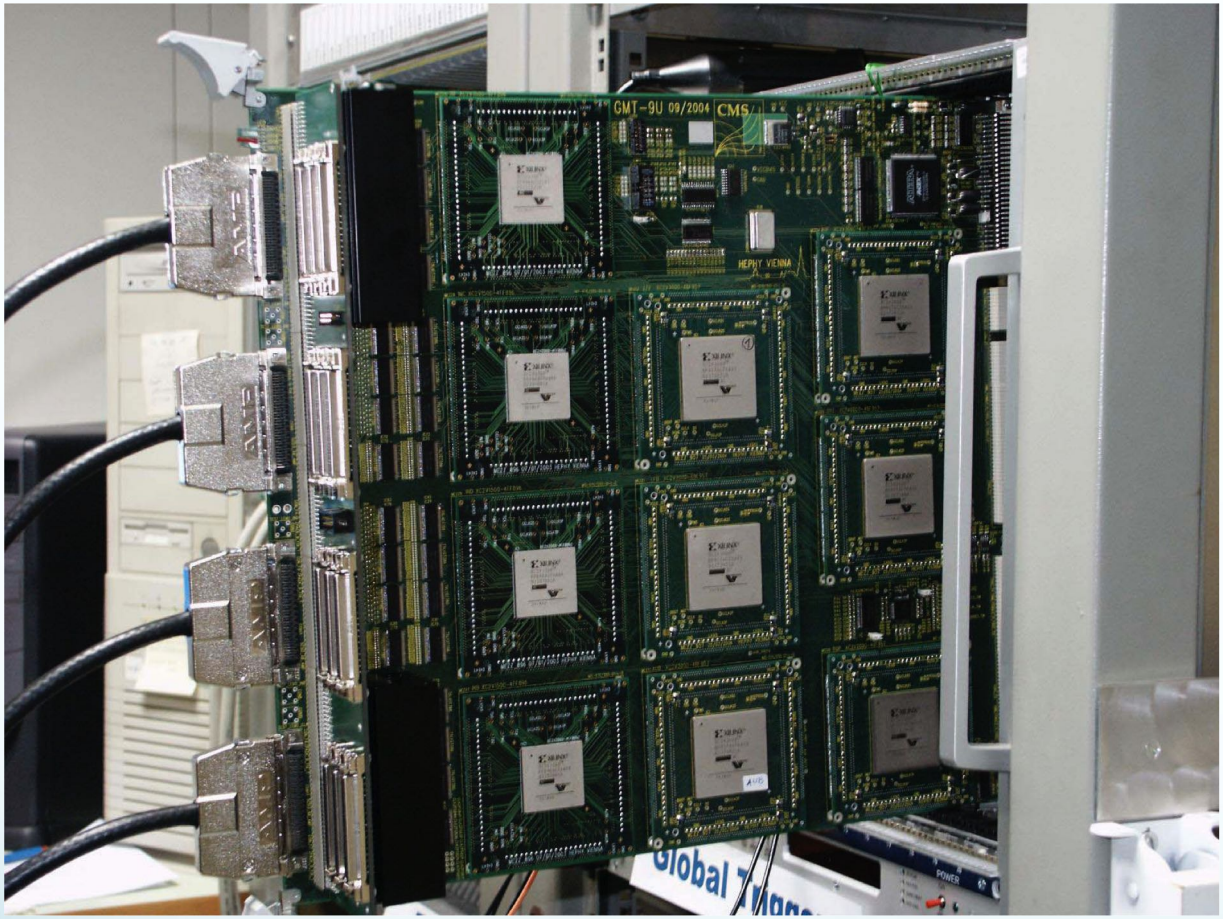
- All operations are performed in parallel
  - Can build pipelined logic
- They can be re-programmed
  - Trigger algorithms can be optimized

High performance

Trigger algorithms implemented in FPGAs

- Trigger
  - Peak finding
  - Pattern Recognition
  - Track Finding
  - Clustering / Energy summing
  - Topological Algorithms (invariant mass)
  - Vertex Finding
  - Particle flow (reconstruction jets, etc. from individual particle tracks)
  - Inference with Neural Networks
  - Many more …
- Trigger Control system
  - Fast (busy) signal merging & monitoring
  - Generation of random triggers
  - Generation of calibration sequences
  - Automatic recovery sequences
  - Monitoring (dead times, rates, …)

CMS Run-1 Global Muon Trigger

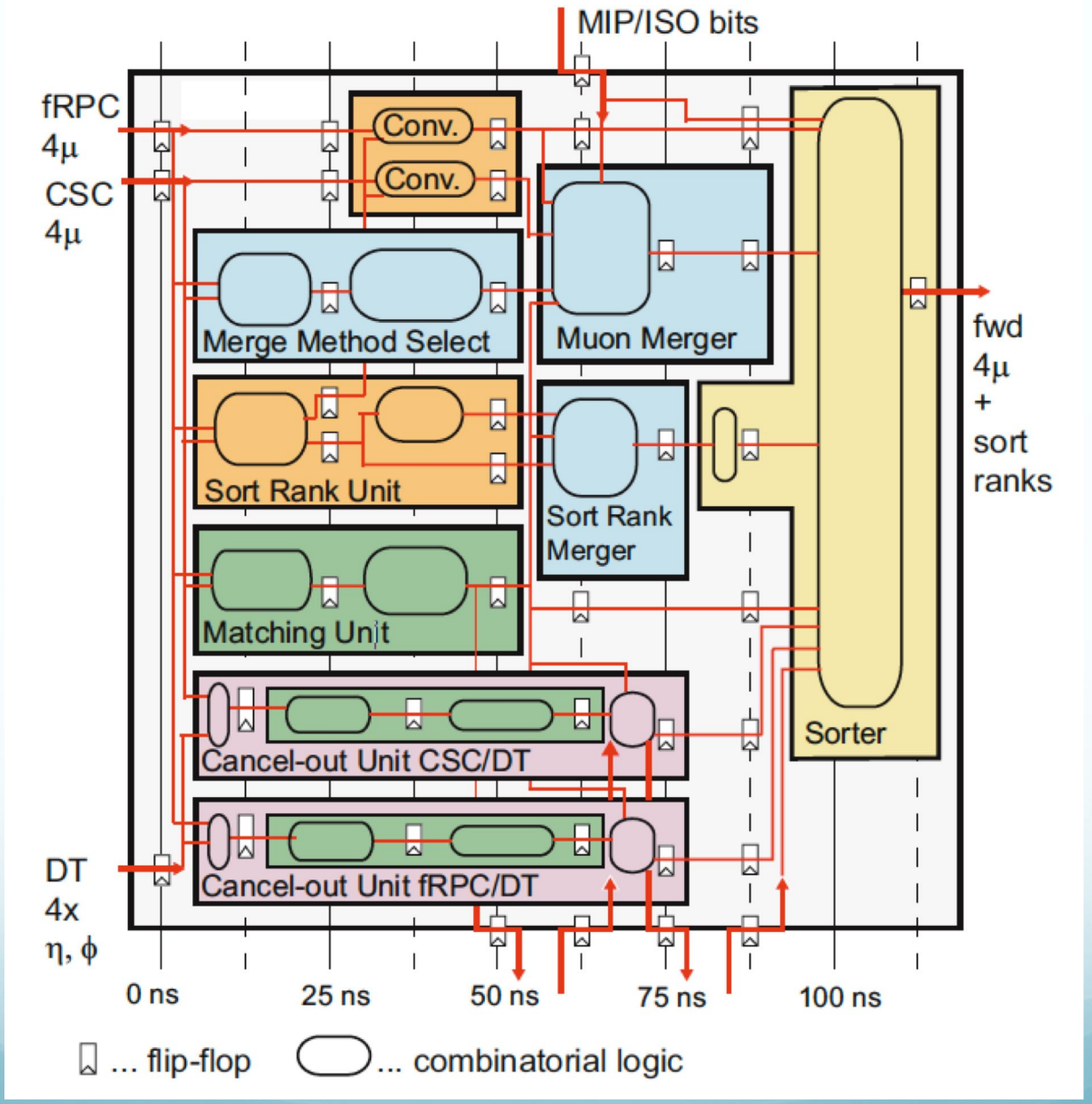


- Input: ~1000 bits
  @ 40 and 80 MHz
- Output: ~50 bits @ 80MHz
- Processing time: 250 ns
- Pipelined logic
  one new result every 25 ns

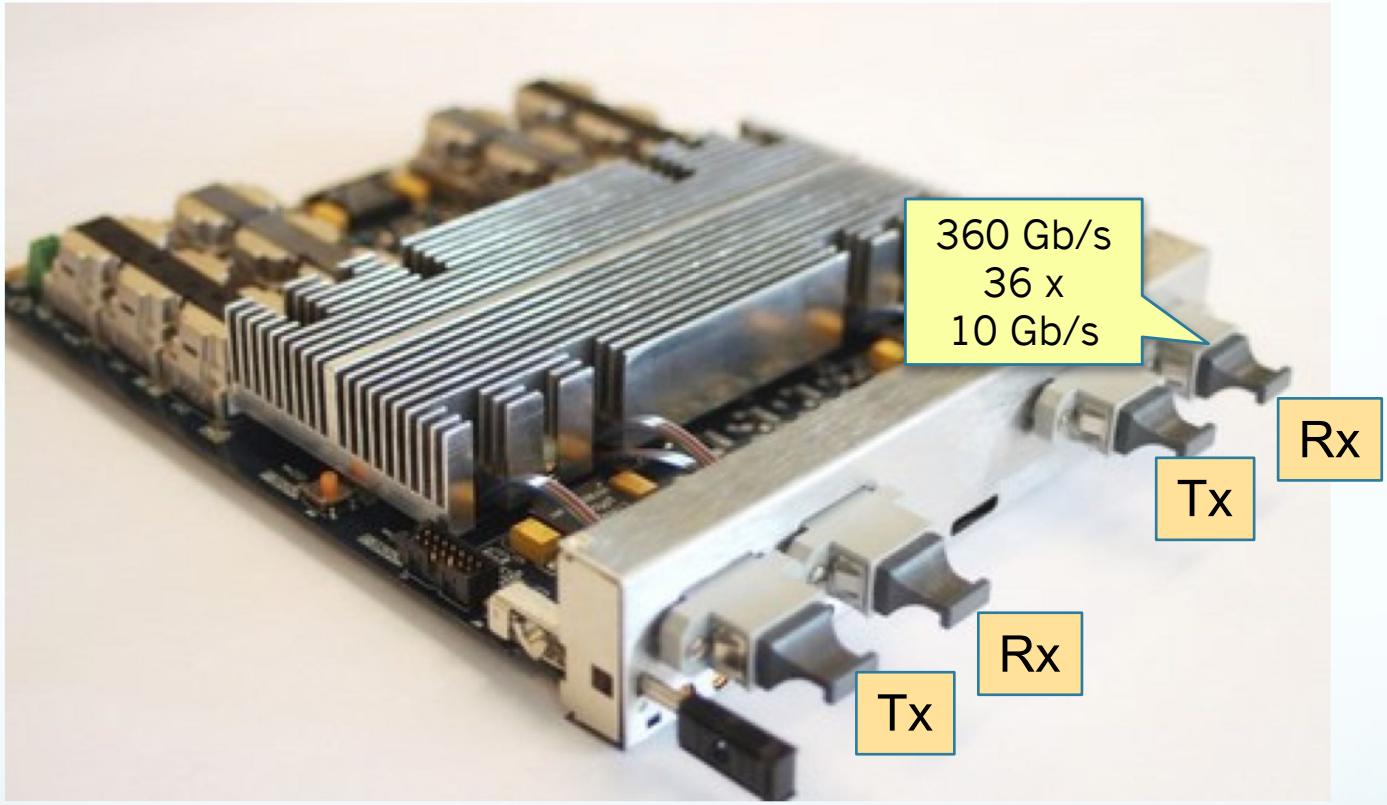
- 10 Xilinx Virtex-II FPGAs
- up to 500 user I/Os per chip
- Up to 25000 LUTs per chip used
- Up to 96 x 18kbit RAM used
- In use in the CMS trigger 2008-2015

- The CMS Global Muon trigger received 16 muon candidates from the three muon systems of CMS
- It merged different measurements for the same muon and found the best 4 over-all muon candidates

CMS Run-1 Global Muon Trigger main FPGA



Micro-TCA board for Run 2&3
CMS trigger based on Virtex 7



MP7, Imperial College

Virtex 7 with 690k logic cells
- 80 x 10 Gb/s transceivers bi-directional
- 72 of them as optical links on front panel
  - 0.75 + 0.75 Tb/s

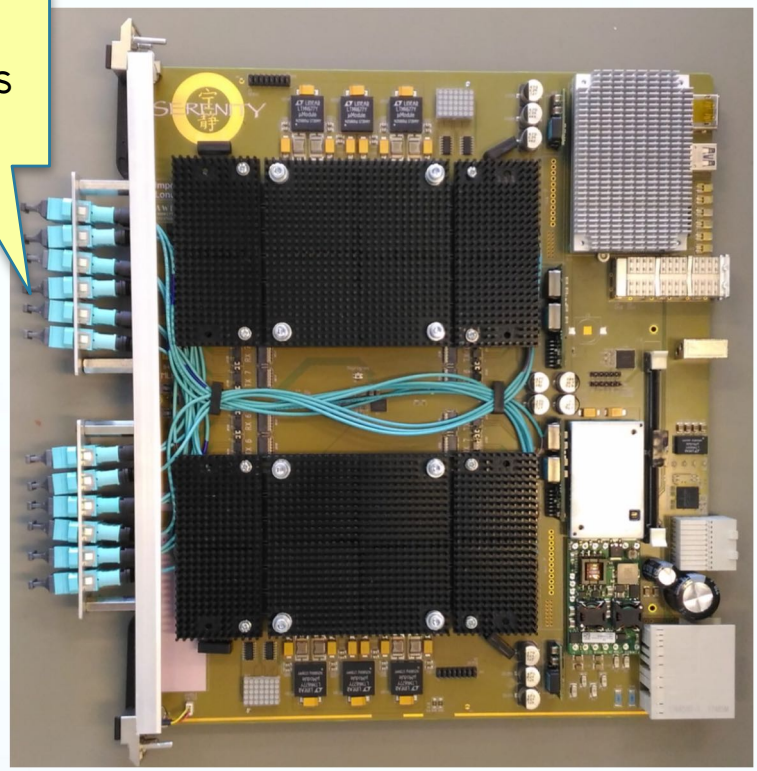
Being used in the CMS trigger since 2015

Input/output:
up to 14k bits per 40 MHz clock

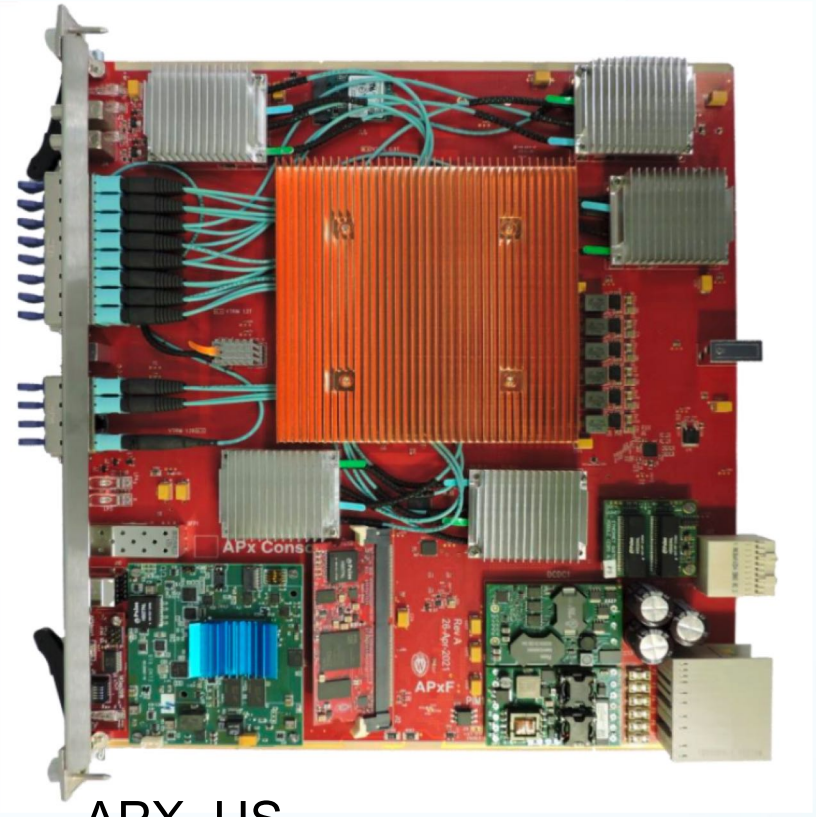
Same board used for different functions (different gateware)
Separation of framework + algorithm fw

CMS ATCA Trigger boards for HL-LHC

120 x
25 Gb/s



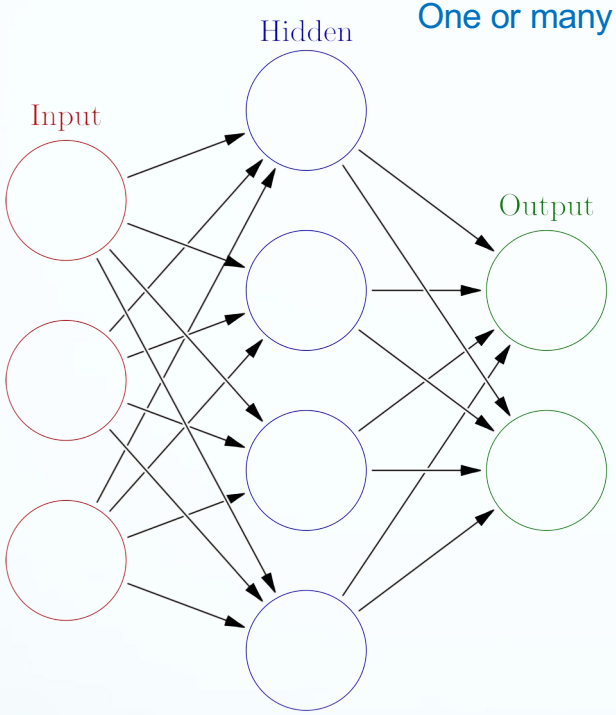
Serenity, UK



APX, US

- Few types of generic boards, ATCA standard
- Xilinx Virtex/Kintex Ultrascale+ FPGAs
- 25-28 Gb/s optical links
- SoC FPGAs used for board control (on some boards)
- Advanced firmware algorithms
  - Vertex finding
  - Particle flow
  - Neural network classifiers

Neural Networks in Trigger



One or many hidden layers

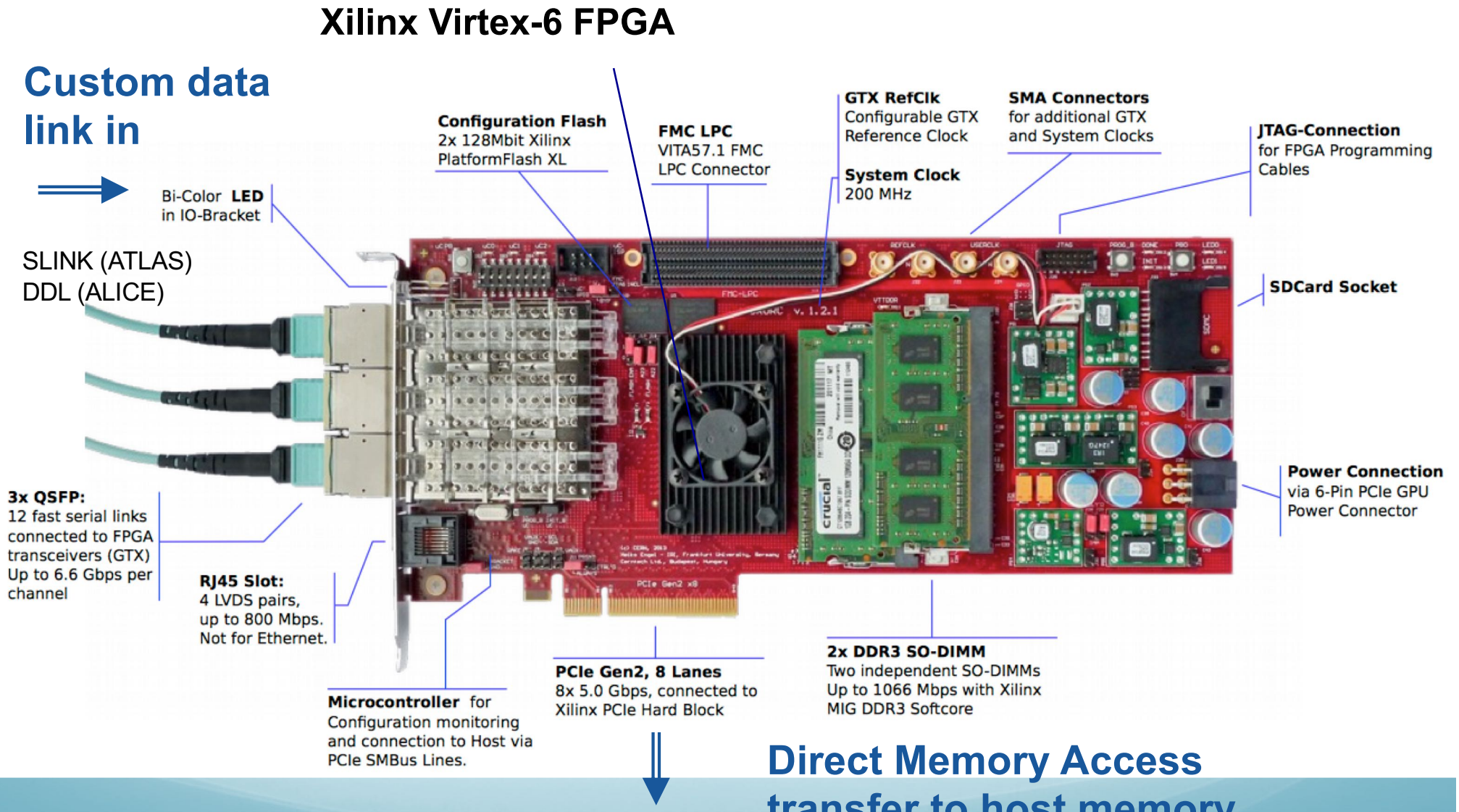
By Glosser.ca - Own work, Derivative of File:Artificial neural network.svg, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=24913461

- Principle
  - Node is assigned a value based on the weighted sum of nodes in the previous layer
  - Maps well to DSP resources in FPGA (multiplier + adder)
- Applications:
  - Jet classification
  - Assignment of transverse momentum based on many measurements
  - …
- Tools
  - Many commercial tools
  - hls4ml (optimized for latency)
    - Firmware generation from high-level model using Vivado HLS

FPGAs in Data Acquisition

- Frontend & Backend Electronics
  - Pedestal subtraction
  - Zero suppression
  - Compression
  - ...
- Custom data links
  - E.g. SLINK-64 over copper
    - Several serial LVDS links in parallel
    - Up to 400 MB/s
  - SLINK-express over optical fibre
  - Lp-GBT
- Interface from custom hardware to commercial electronics
  - PCI/PCIe, VME bus, Myrinet, 10/40/100 Gb/s Ethernet etc.

C-RORC (Alice) / Robin NP (ATLAS) for Run-2

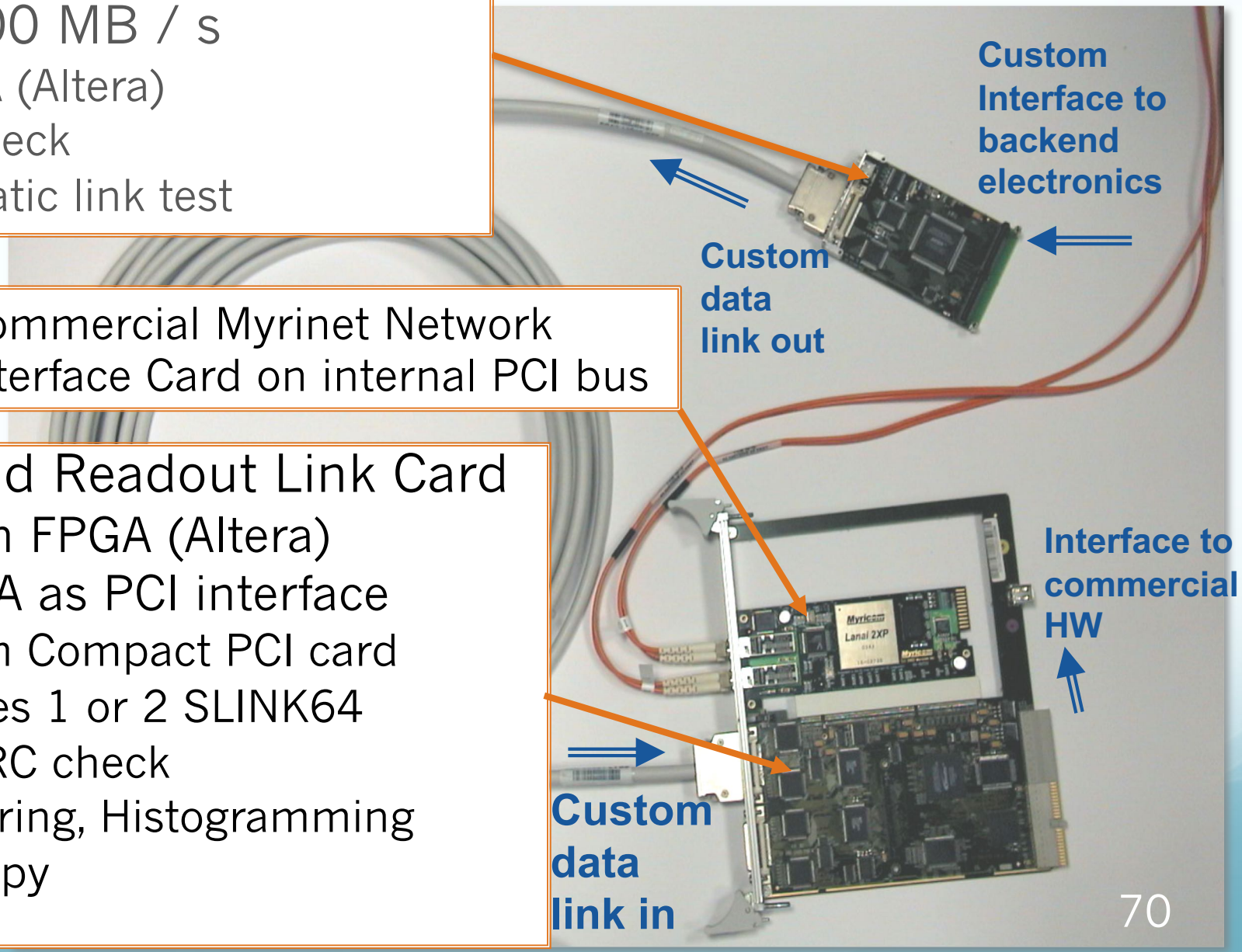


CMS Front-end Readout Link (Run-1)

- SLINK Sender Mezzanine Card: 400 MB / s
  - 1 FPGA (Altera)
  - CRC check
  - Automatic link test

Commercial Myrinet Network Interface Card on internal PCI bus

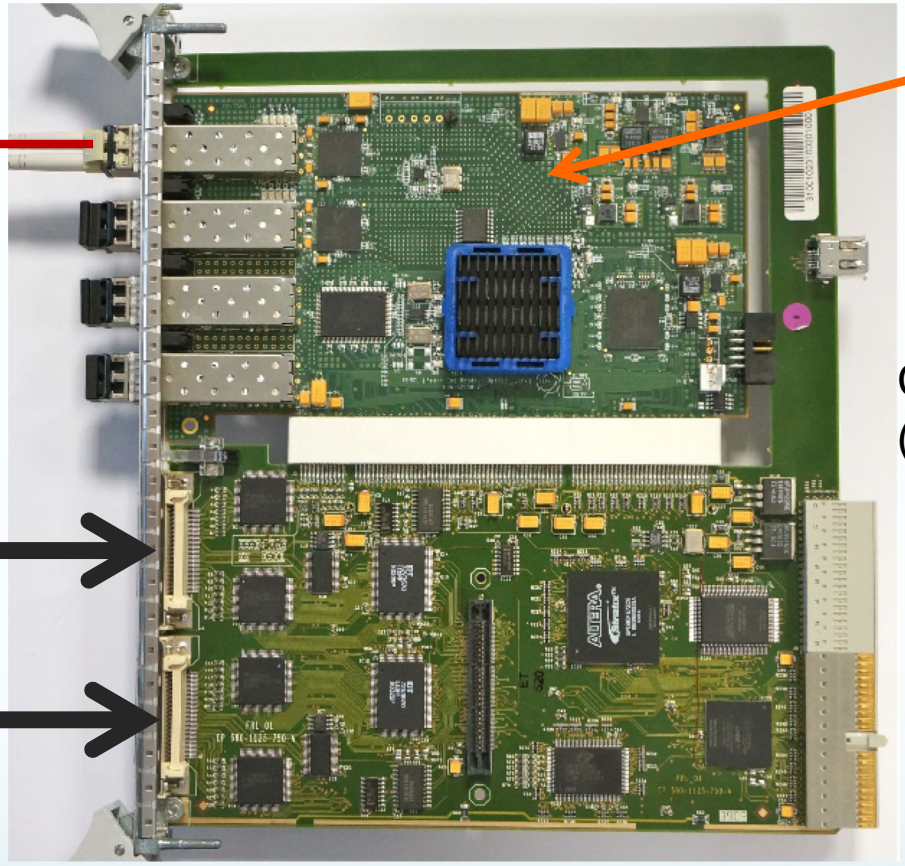
- Front-end Readout Link Card
  - 1 main FPGA (Altera)
  - 1 FPGA as PCI interface
  - Custom Compact PCI card
  - Receives 1 or 2 SLINK64
  - 2nd CRC check
  - Monitoring, Histogramming
  - Event spy



CMS Readout Link for Run-2&3 in use since 2015

Commercial data link out

10 Gb/s TCP/IP



Myrinet NIC replaced by custom-built card ("FEROL")

Cost effective solution (need many boards)
Rather inexpensive FPGA + commercial chip to combine 3 Gb/s links to 10 Gb/s

Custom data link in

SLINK-64 input
LVDS / copper

FEROL (Front End Readout Optical Link)

Input: 1x or 2x SLINK (copper)
1x or 2x 5Gb/s optical
1x 10Gb/s optical

Output: 10 Gb/s Ethernet optical
TCP/IP sender in FPGA

CMS Readout Link for Run-2&3 in use since 2015

Commercial data link out

10 Gb/s TCP/IP

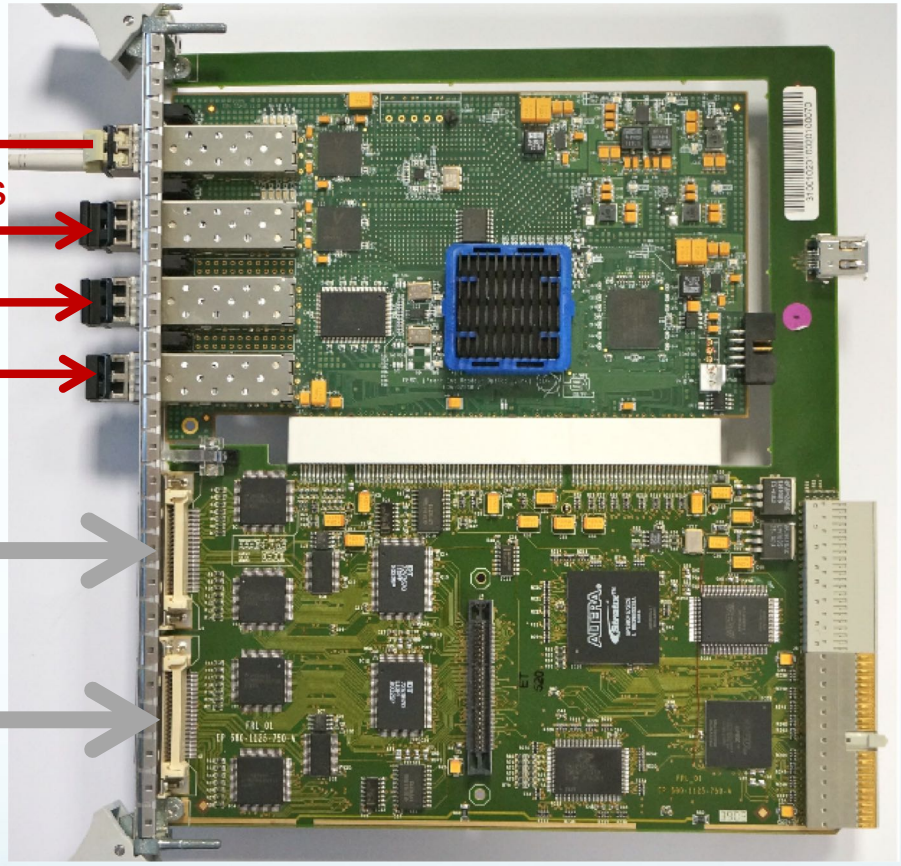
10 Gb/s SLINK Express

5 Gb/s SLINK Express

5 Gb/s SLINK Express

Custom data link in

SLINK-64 input
LVDS / copper



FEROL (Front End Readout Optical Link)

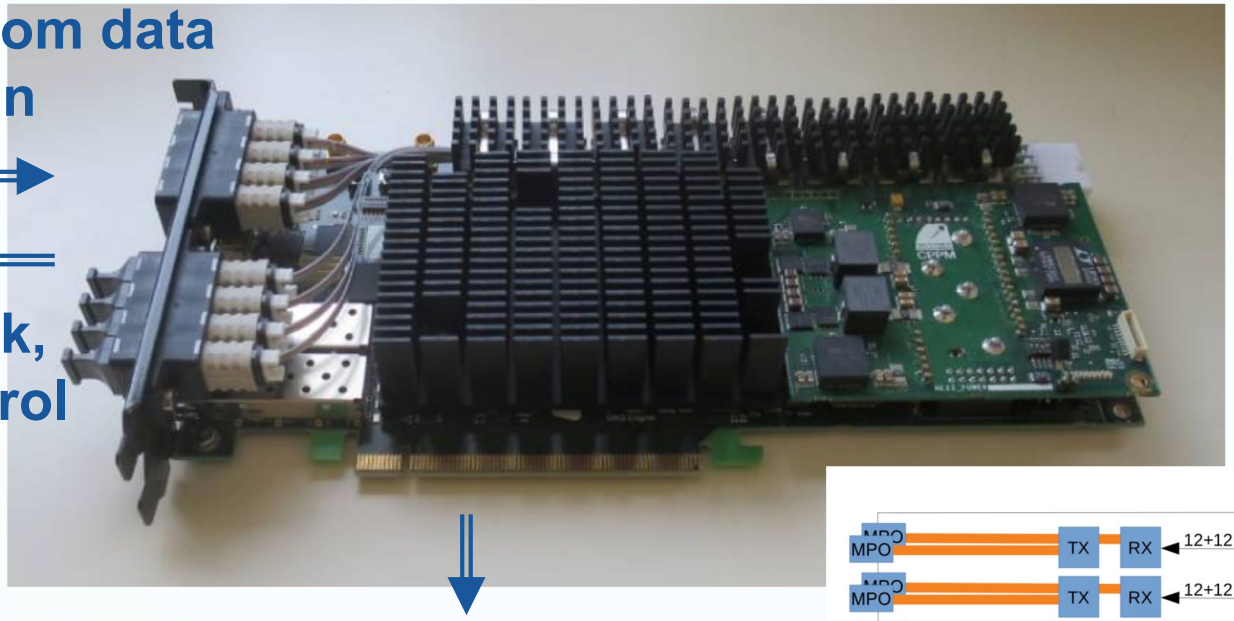
Input: 1x or 2x SLINK (copper)
1x or 2x 5Gb/s optical
1x 10Gb/s optical

Output: 10 Gb/s Ethernet optical
TCP/IP sender in FPGA

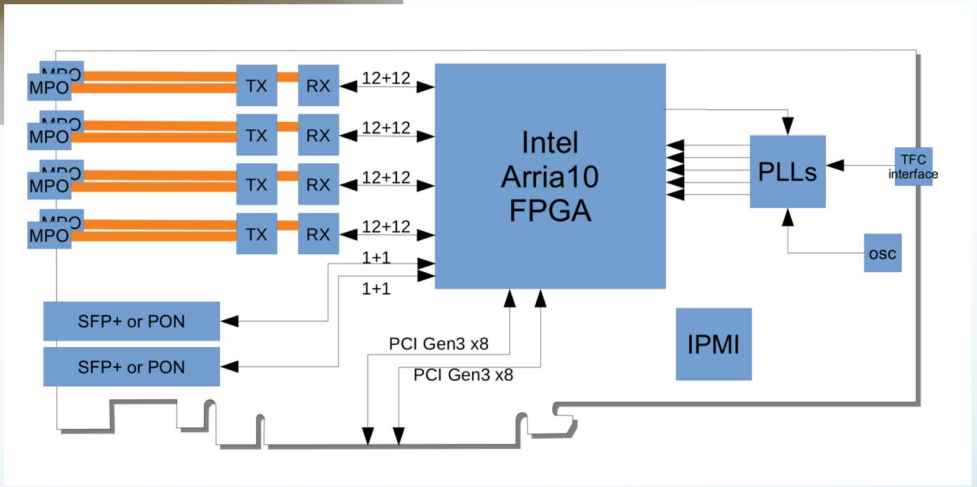
PCIe40 – LHCb and ALICE Run-3

Custom data link in

Clock, control



Direct Memory Access transfer to host memory



- 48 bidirectional links running at up to 10 Gbits/s each (minipods)
- 2 bidirectional links running at up to 10 Gbits/s devoted to time distribution (can use SFP+ or 10G PON devices)
- Sustained 112 Gbits/s interface with CPU through PCIe

CMS DTH (DAQ and Timing Hub) for HL-LHC

Custom data link in

Commercial data link (TCP/IP) out

Clock & control uplink

Main board

Rear transition module

DTH prototype 2

Clock & control distribution via backplane

- **ATCA** board using Xilinx Virtex Ultrascale + FPGAs
- One or two DAQ units per board
  - Up to 24 inputs at 25 Gb/s
  - **5x 100 Gb/s** Ethernet to commercial network
  - TCP/IP in FPGA
- Board contains switch for control network

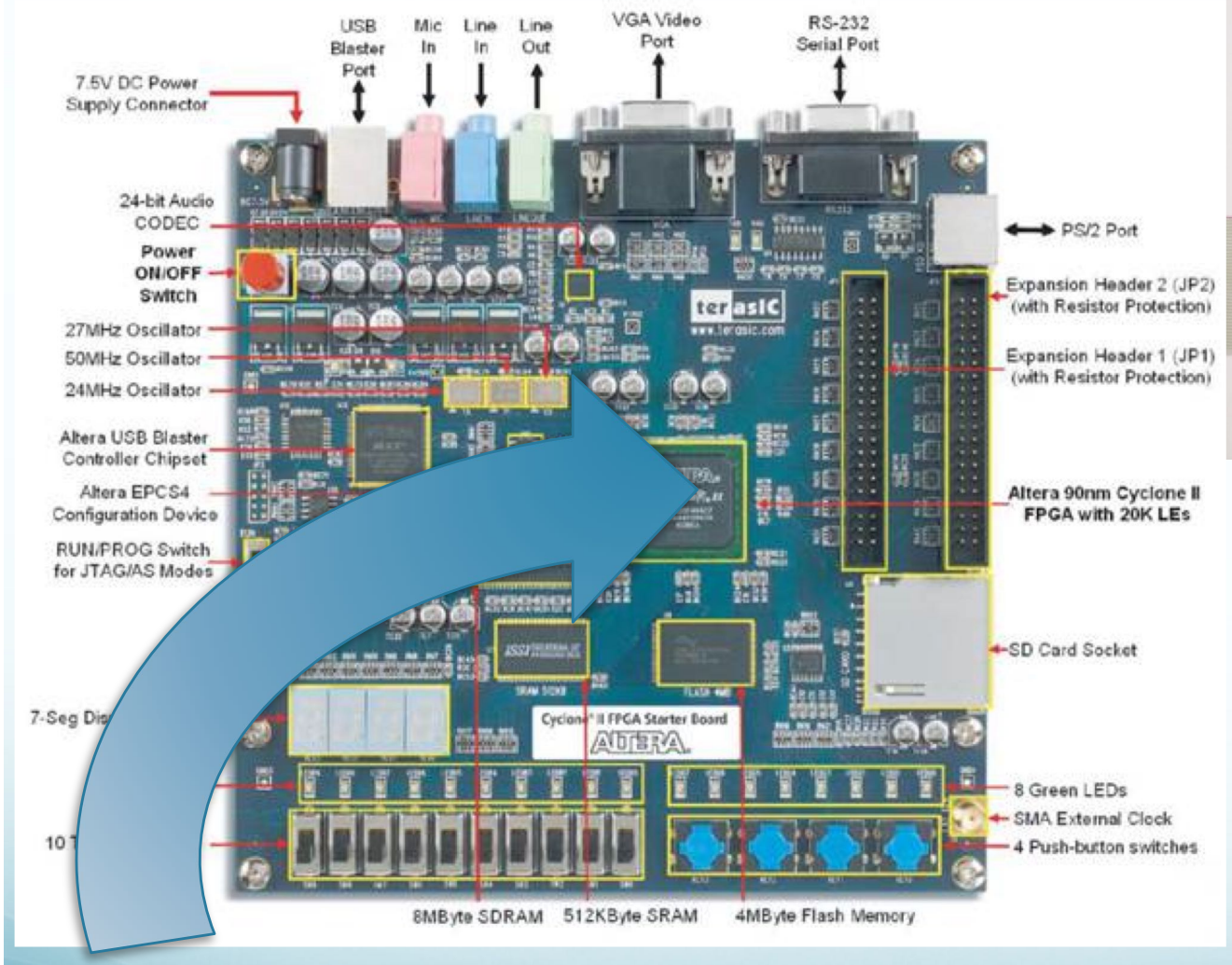
FPGAs in other domains

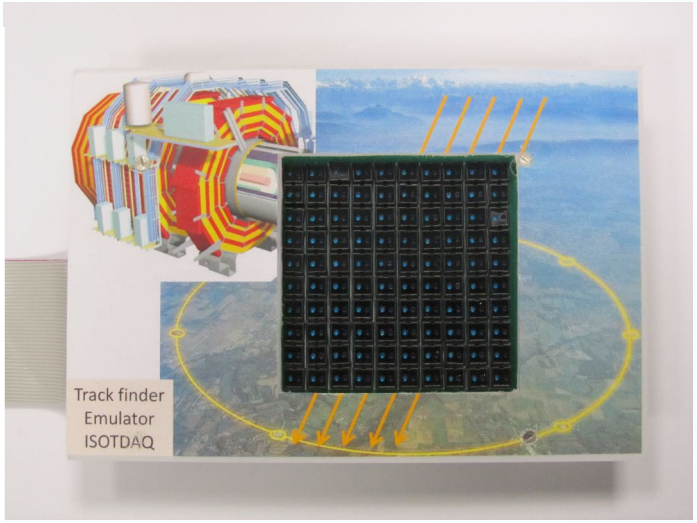
- Medical imaging
- Advanced Driver Assistance Systems (Image Processing)
- Speech recognition
- Cryptography
- Bioinformatics (Genome sequencing)
- Aerospace / Defense
- (Bitcoin mining)
- 5G Wireless

- ASIC Prototyping
- Compute accelerators
  - Accelerator cards

- Also available in the Cloud
- Financial
- Inferencing
- Video transcoding
- ...

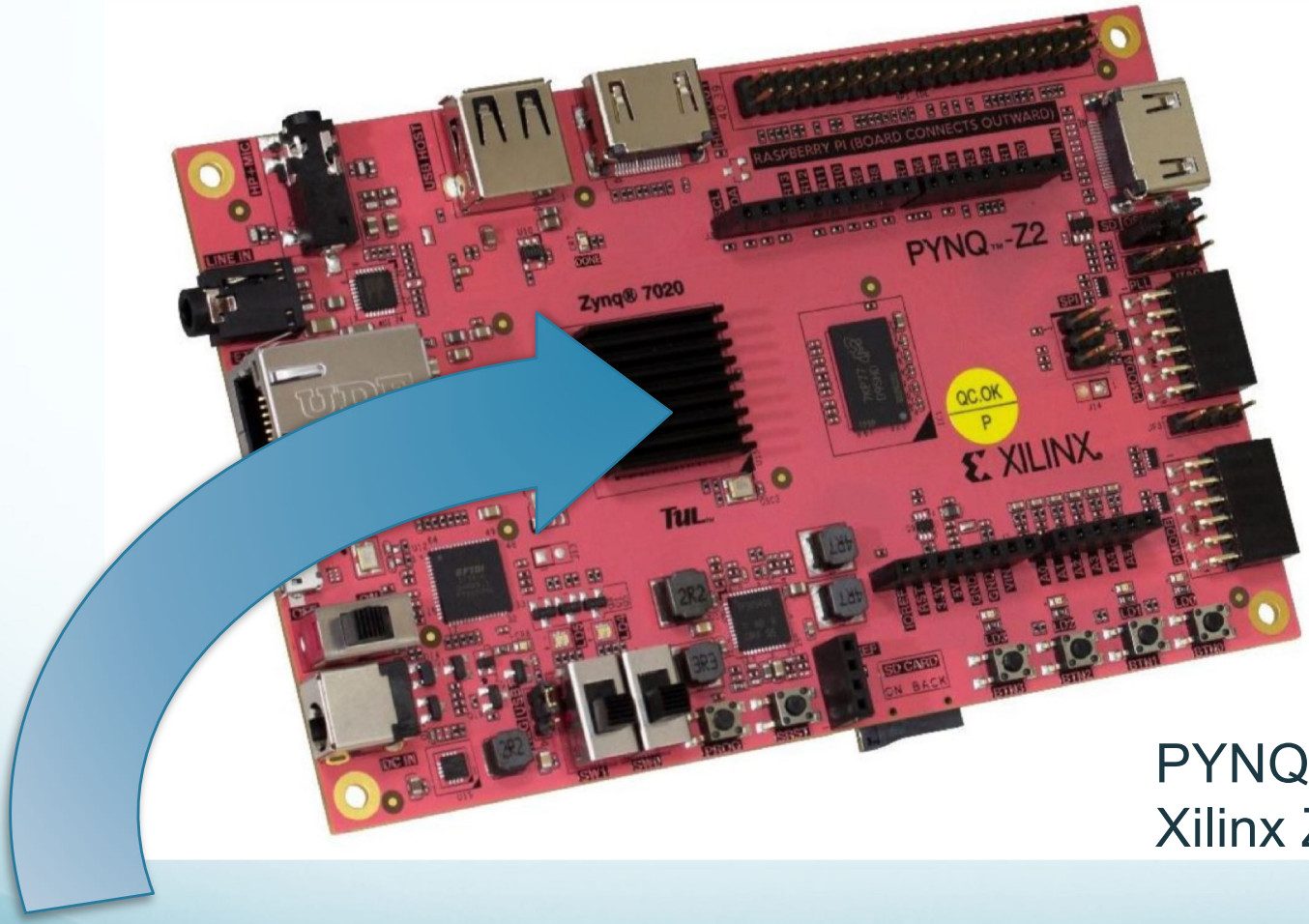
Lab Session 5: Programming an FPGA





You are going to design the digital electronics inside this FPGA !

Lab Session 13: System-on-a-chip FPGA



PYNQ-Z2 board
Xilinx Zynq w. dual-core ARM

Design the digital electronics and software in this SoC FPGA!

Thank you!

Acknowledgement

- Parts of this lecture are based on material by Clive Maxfield, author of several books on FPGAs. Many thanks for his kind permission to use his material!

Re-use