

FPGA

Field-Programmable

Gate Arrays

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Outline

- › Introduction to FPGAs
- › How to use them
- › Heterogeneous programming
- › FPGA-based heterogeneous programming
- › How to program it
- › Xilinx: now and soon...

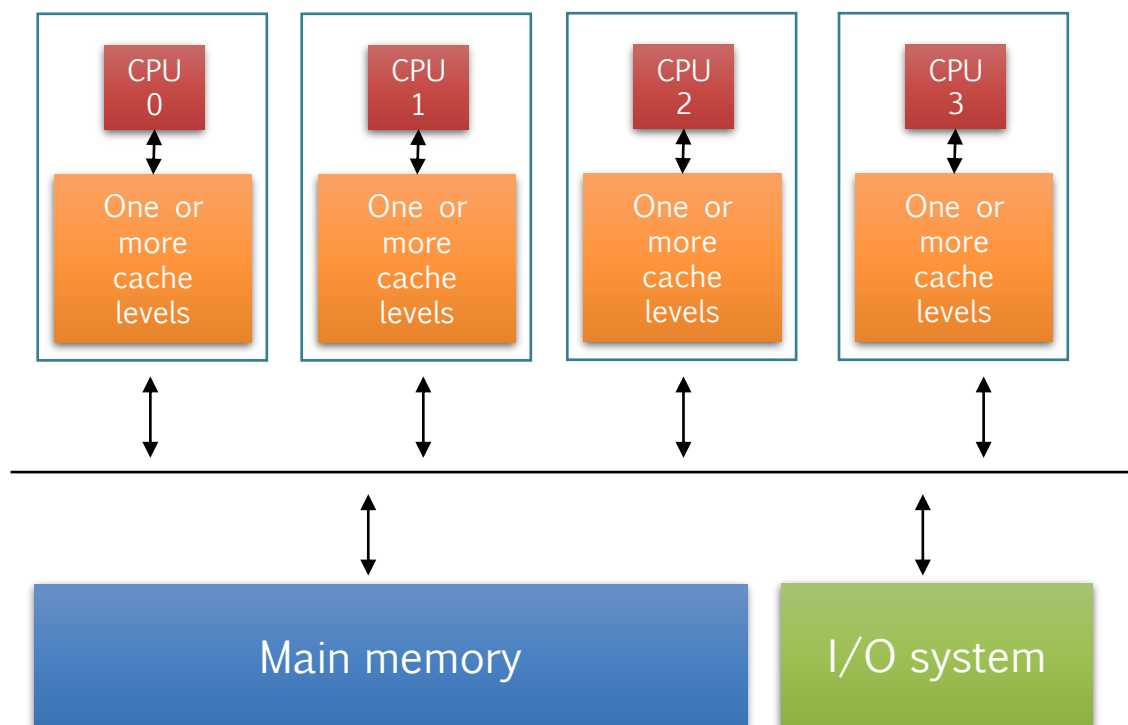


The world, till now

› (A) Symmetric multi-processing

- Single or multi-core

Can be 1 bus, N
busses, or any
network

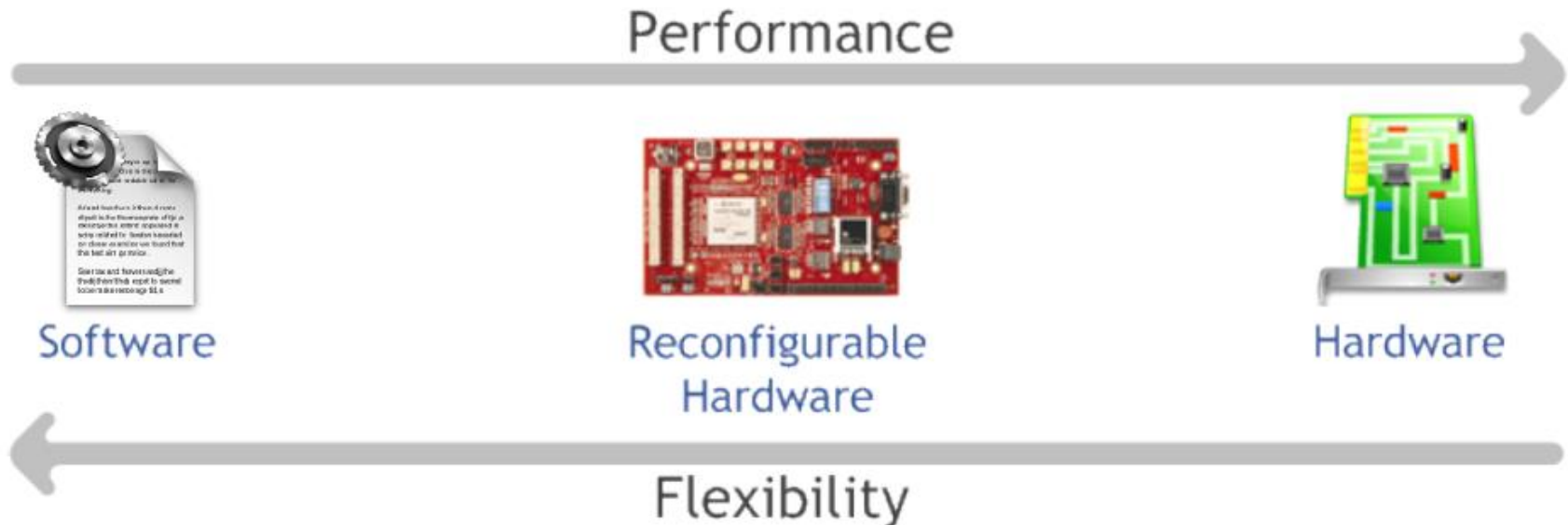




Reconfigurable Hardware

"Reconfigurable computing is intended to fill the gap between hardware and software, achieving potentially much higher performance than software, while maintaining a higher level of flexibility than hardware"

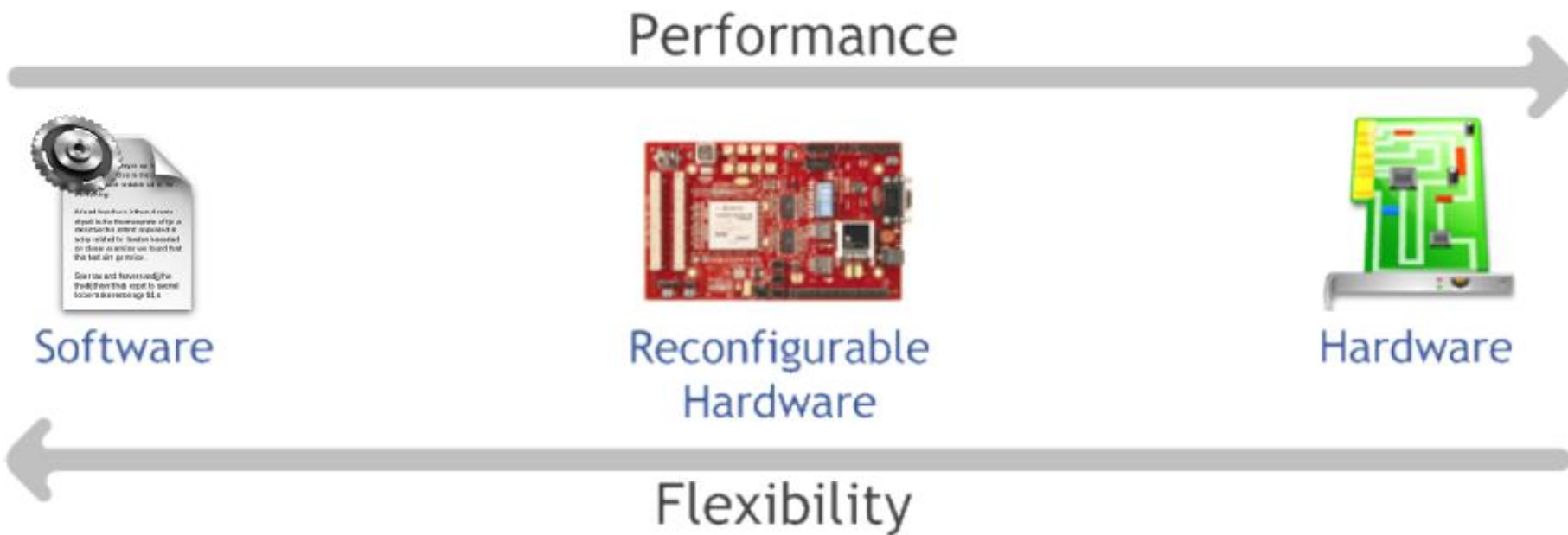
(K. Compton and S. Hauck, *Reconfigurable Computing: a Survey of Systems and Software*, 2002)



...eh?

We are used to have

- › On one (left) side, full programmable artifacts (software)
 - Run on single or multi-cores, designed for General Purpose computing
- › On one (right) side, hardware blocks to perform specific (subset of) operations





What if?

...we had a "sea" of hardware blocks that we can program as we want

- › We can build cores
- › We can build co-processors
- › We can build what we want

What would you use them?

- › For prototyping!

Hardware development process is long and cumbersome

- › Imagine a full-fledged cores
- › Typically, years of development
- › You can "try, and see whether it works"



History of reconfigurable technologies

- › Logic gates (1950s-60s)
 - › Regular structures for two-level logic (1960s-70s)
 - Muxes and decoders, PLAs
 - › Programmable sum-of-products arrays (1970s-80s)
 - PLDs, complex PLDs
 - › Programmable gate arrays (1980s-90s)
 - densities high enough to permit entirely new class of application, e.g., prototyping, emulation, acceleration
- trend toward
higher levels
of integration



Field-programmable gate arrays

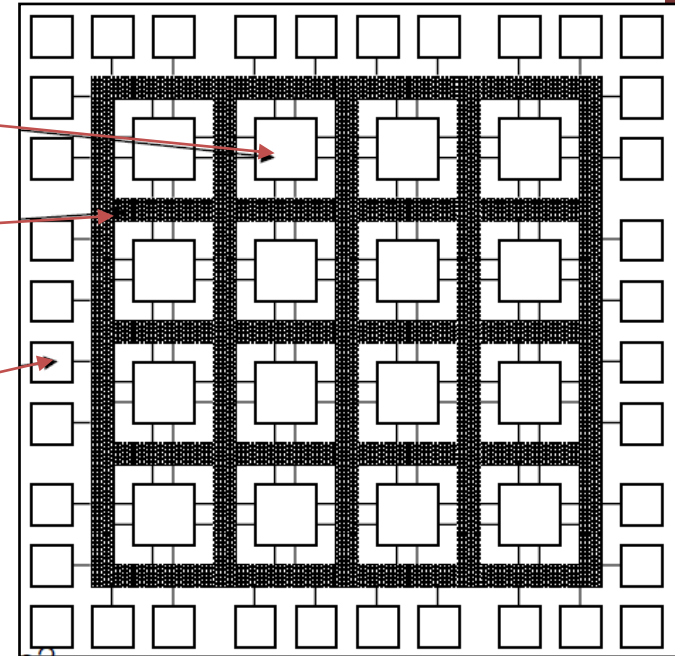
- › *"A field-programmable gate array (FPGA) is an integrated circuit designed to be **configured** by a customer or a designer **after manufacturing**."*
- › Traditionally used for **prototyping**
 - Takes minutes vs years for "real" hardware
- › Tech has evolved so they are actively used in production settings
 - Less powerful, yet more energy-efficient than a GPU
 - **Way** more flexible

Integrated into System-on-chips

- › As reconfigurable accelerator
- › We'll see later...

FPGAs

- › Logic blocks
 - to implement combinational and sequential logic
- › Interconnect
 - wires to connect inputs and outputs to logic blocks
- › I/O blocks
 - special logic blocks at periphery of device for external connections

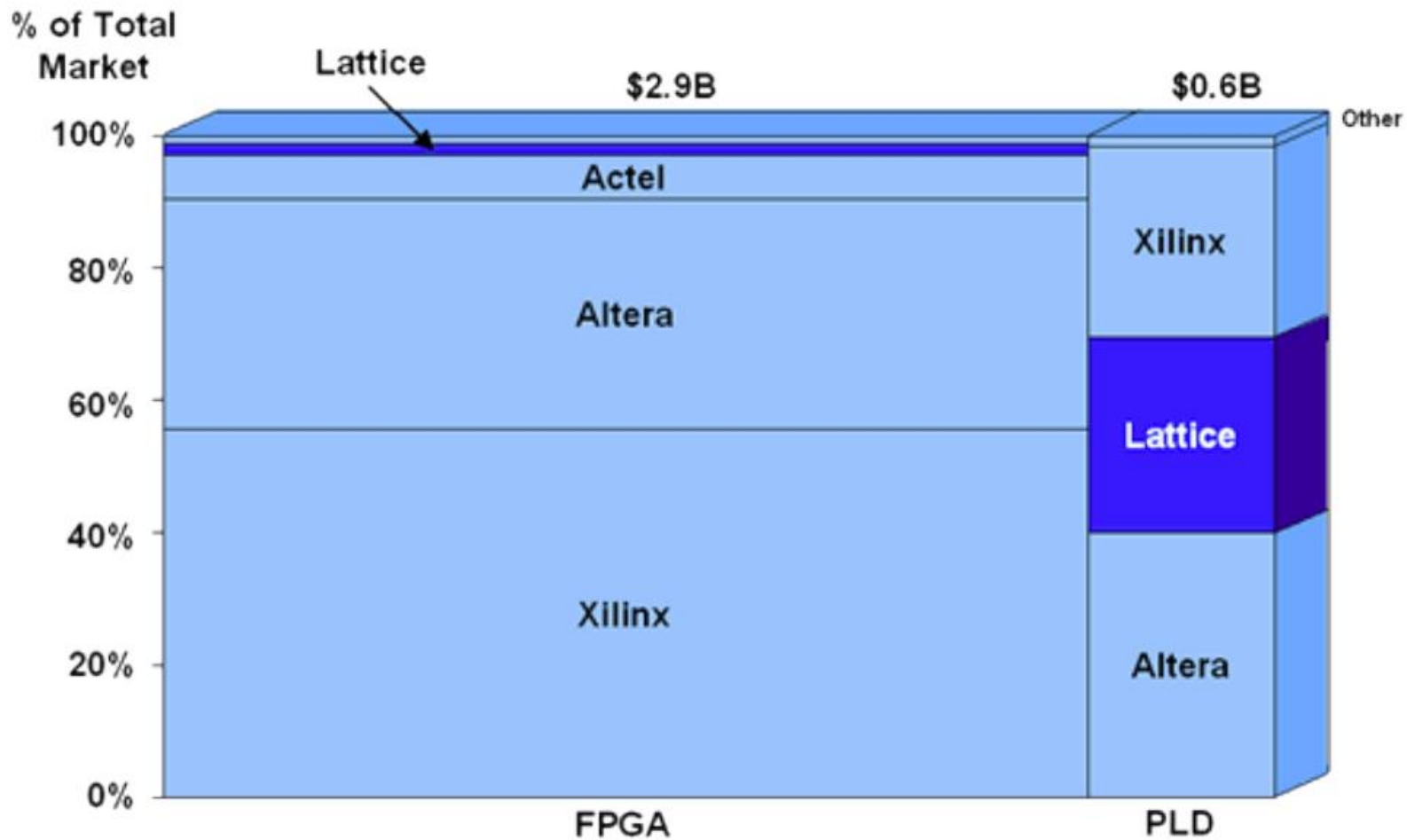


Key questions:

- › how to make logic blocks programmable?
- › how to connect the wires?
- › after the chip has been fabbed



Commercial FPGA companies

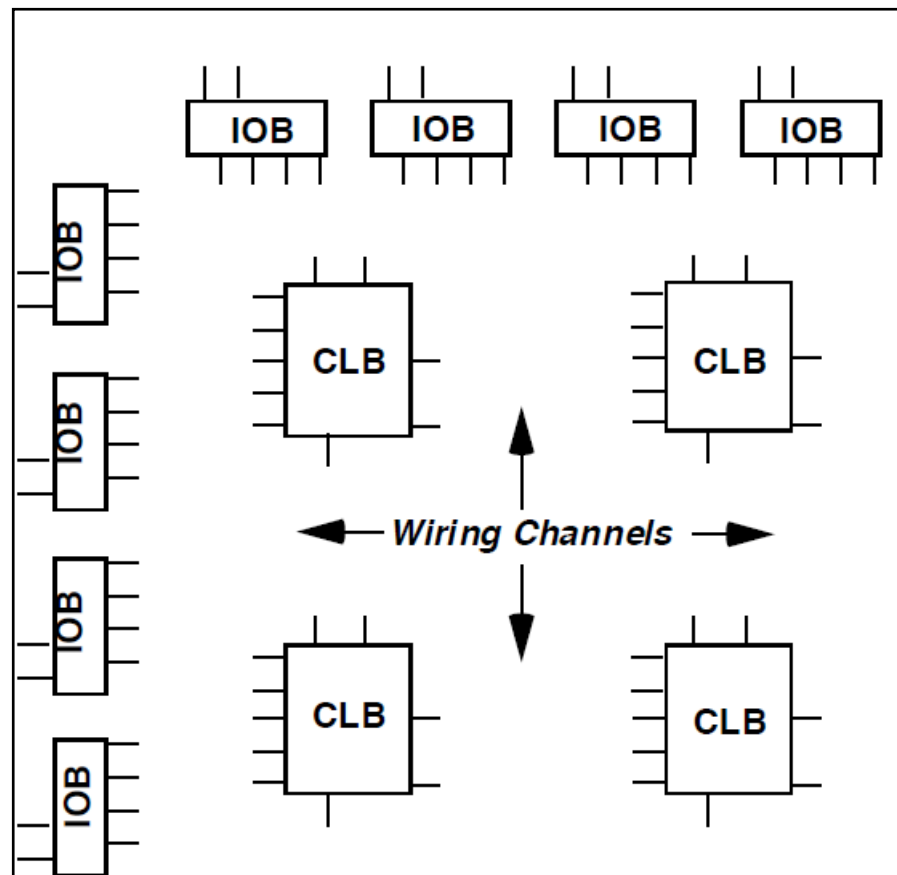




(Xilinx) Programmable Gate Arrays

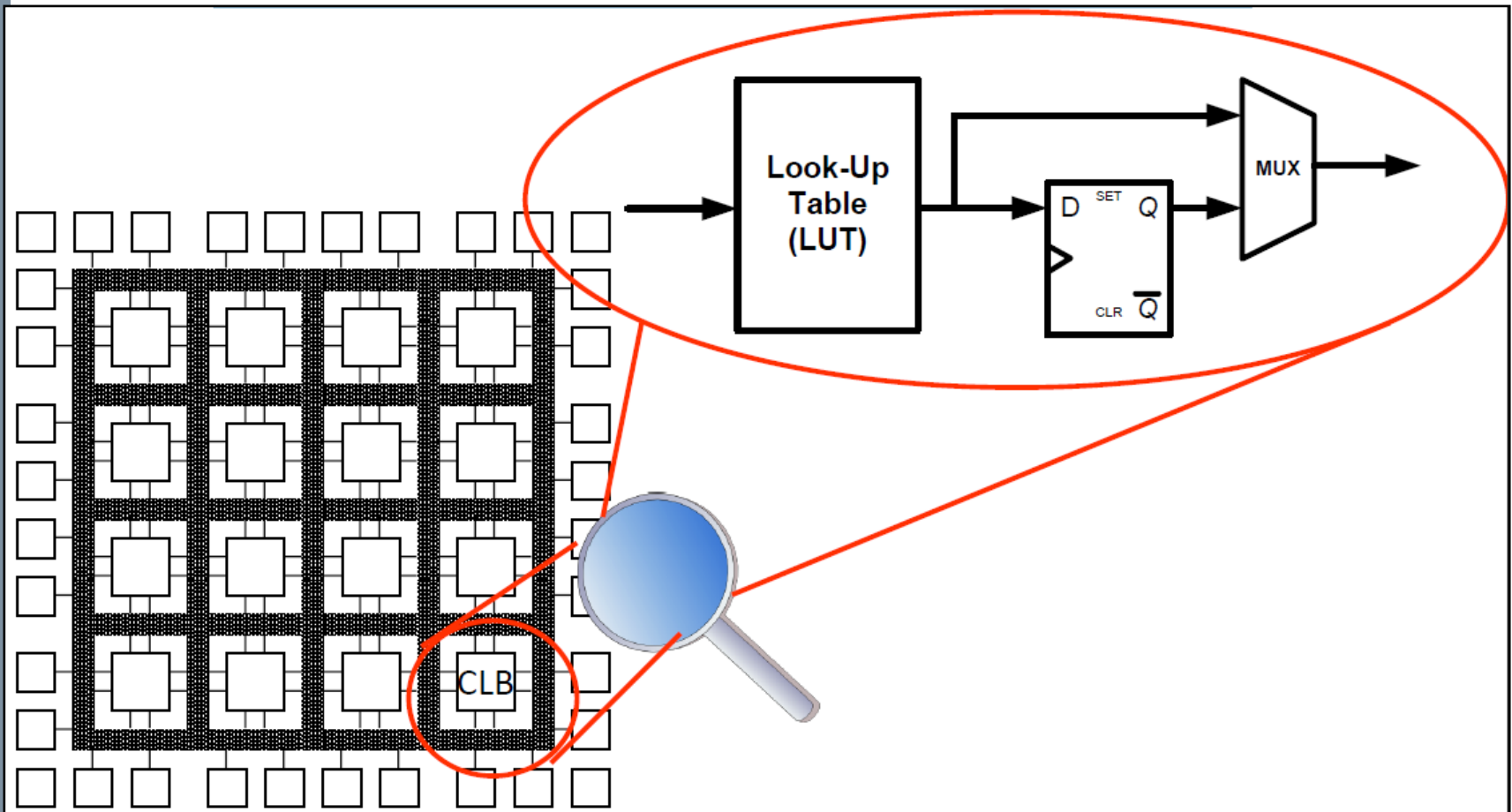
CLB - Configurable Logic Block

- › Built-in fast carry logic
- › Can be used as memory
- › Three types of routing
 - direct
 - general-purpose
 - long lines of various lengths
- › RAM-programmable
 - can be reconfigured





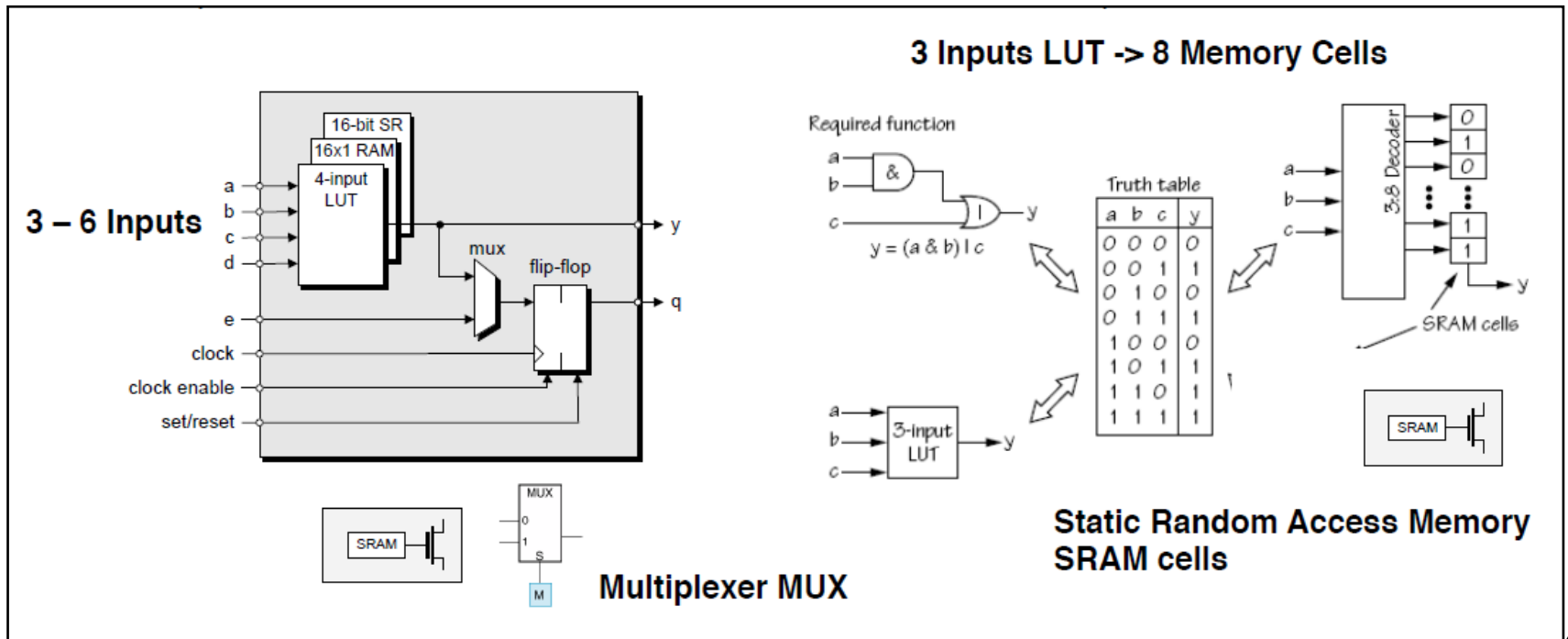
Simplified CLB Structure



LookUp Tables

LUT contains Memory Cells to implement small logic functions

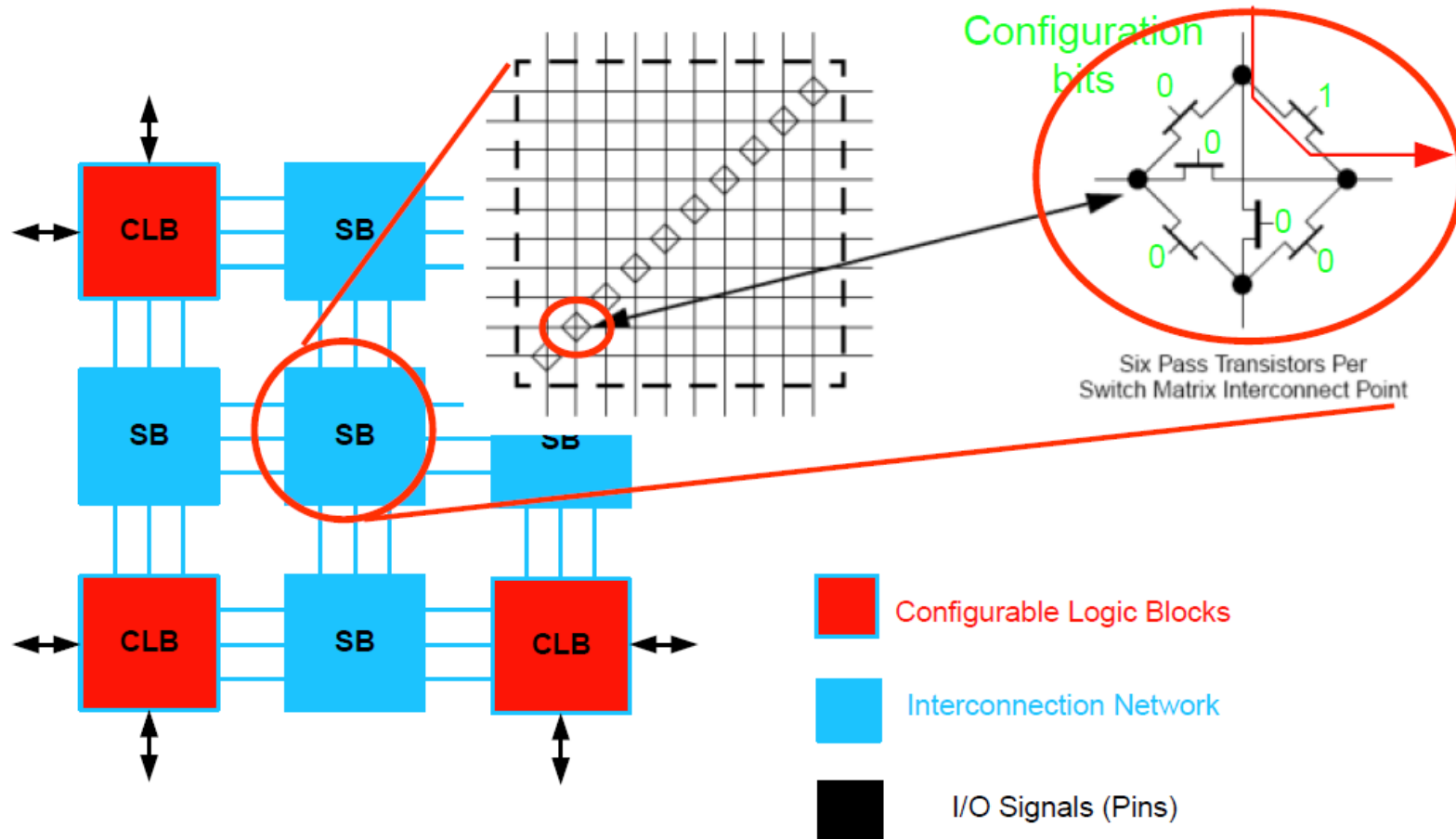
- › Each cell holds '0' or '1'
- › Programmed with outputs of Truth Table
- › Inputs select content of one of the cells as output





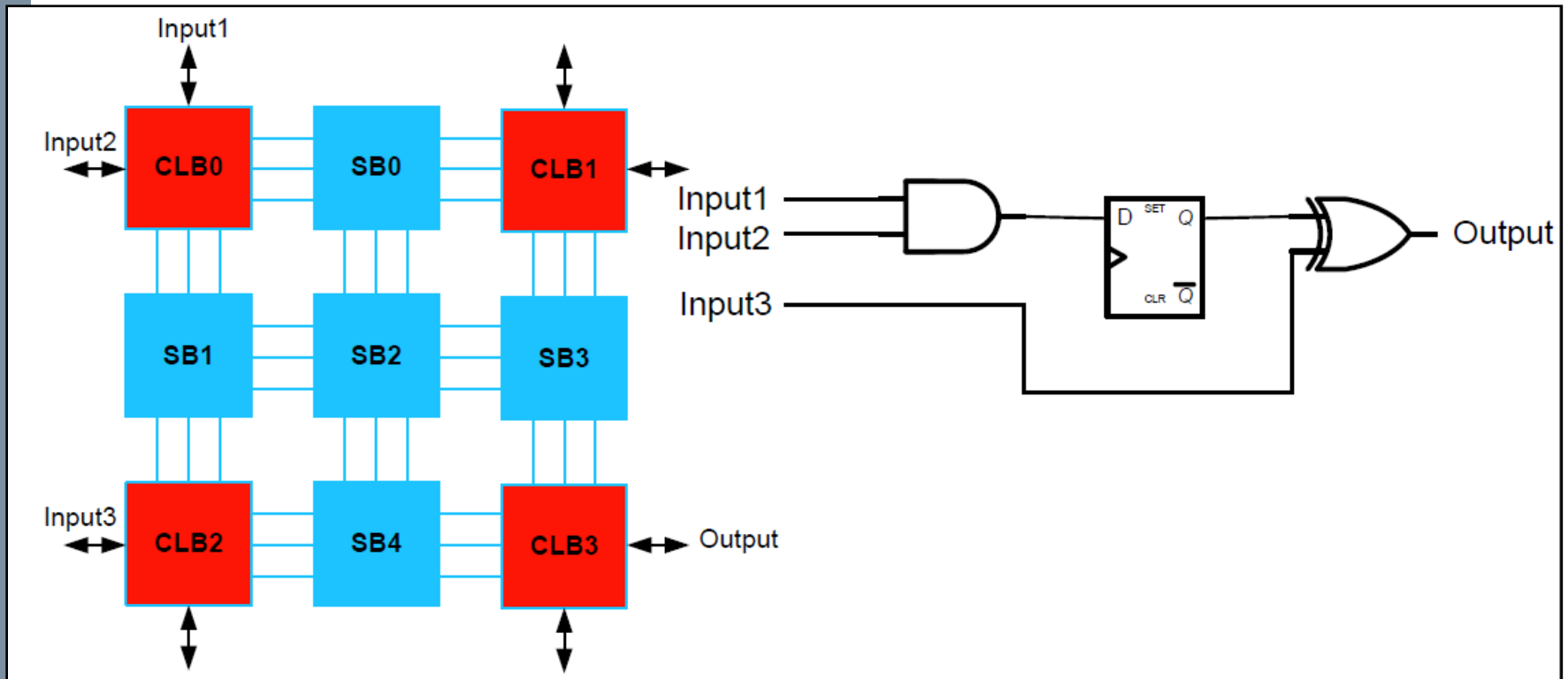


Interconnection Network



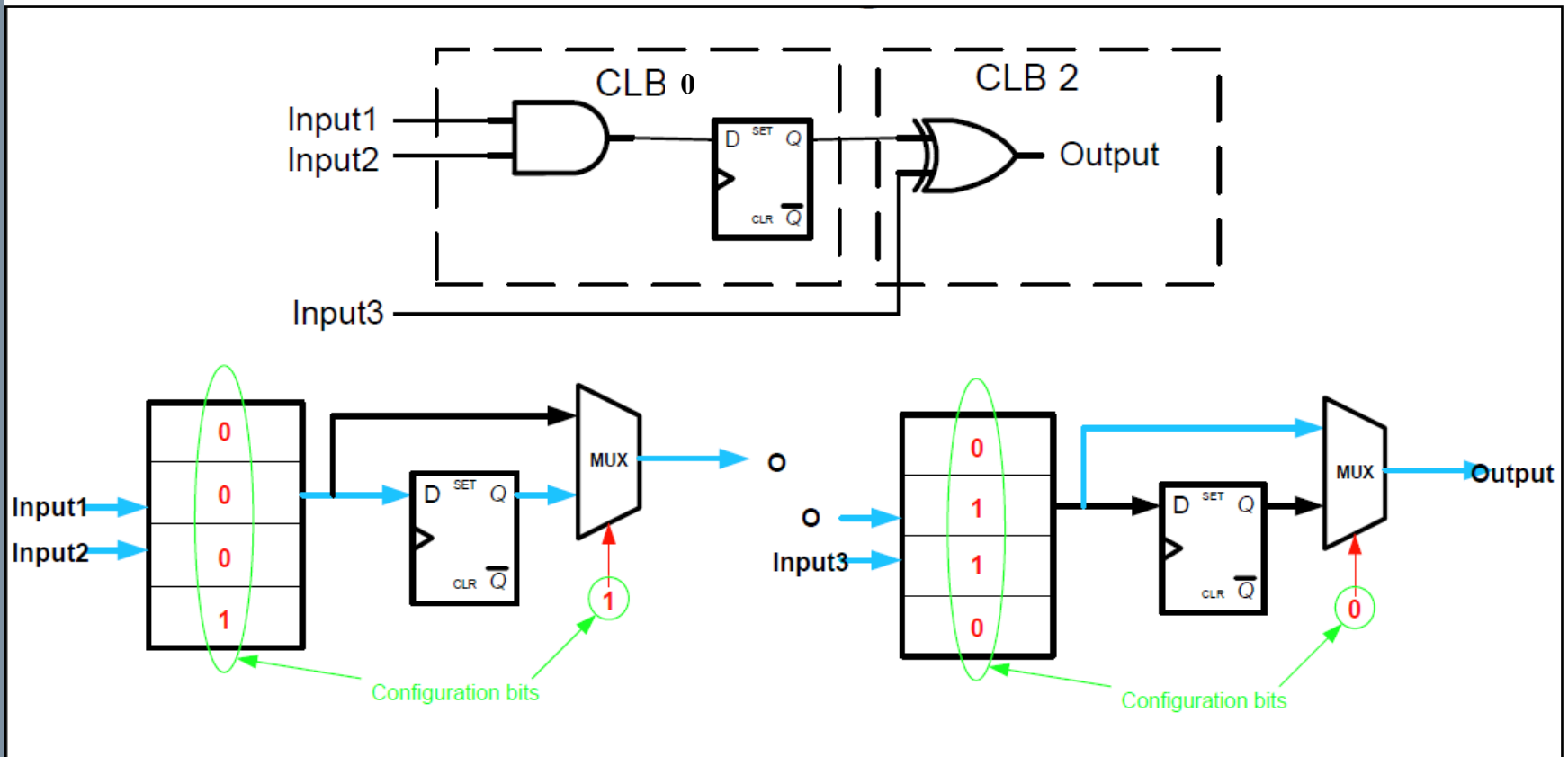
Example

- › Determine the configuration bits for the following circuit implementation in a 2x2 FPGA, with I/O constraints as shown in the following figure. Assume 2-input LUTs in each CLB



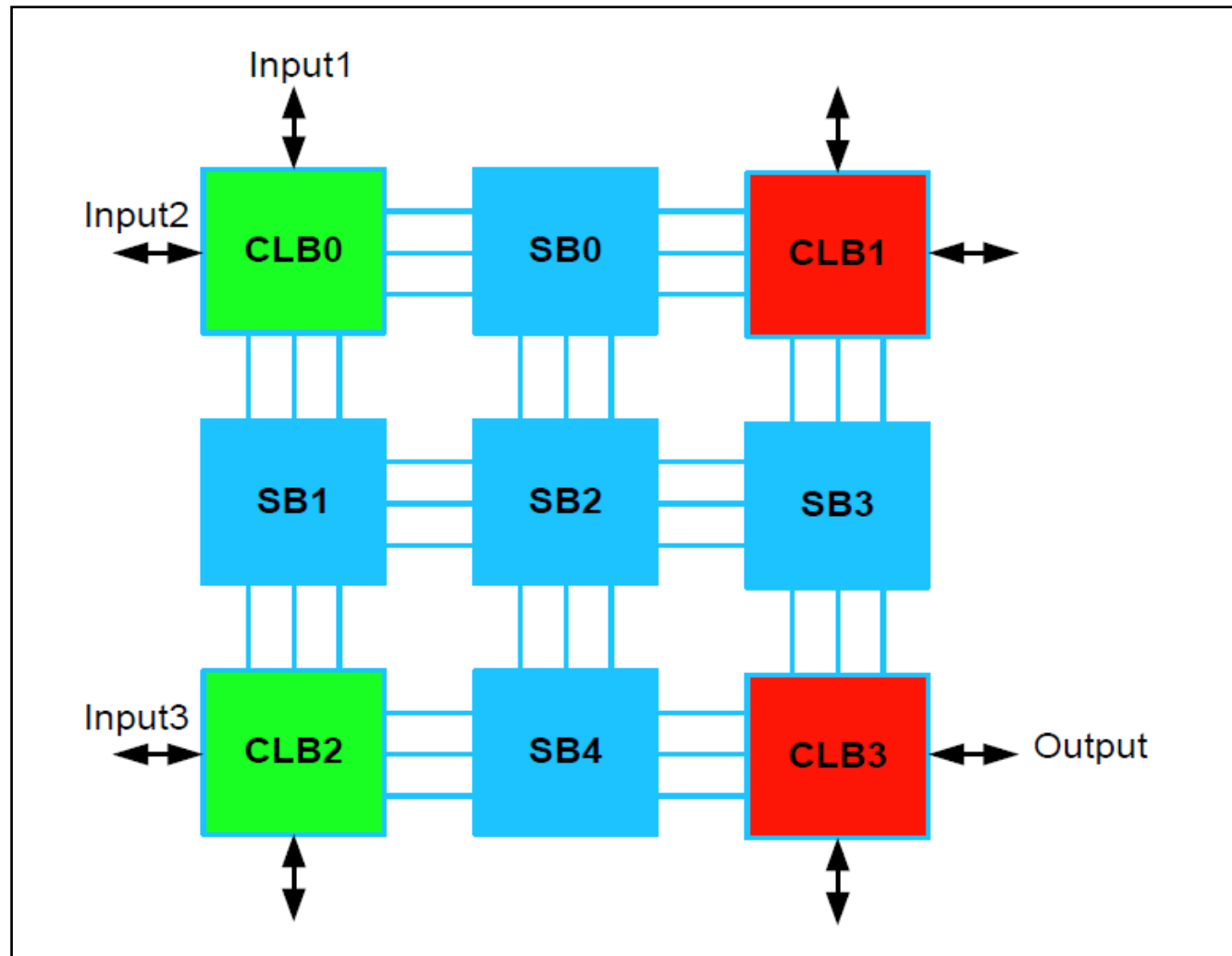


Configure CLBs

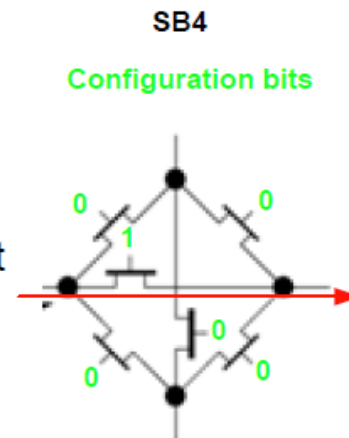
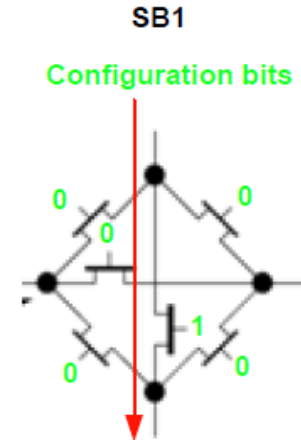
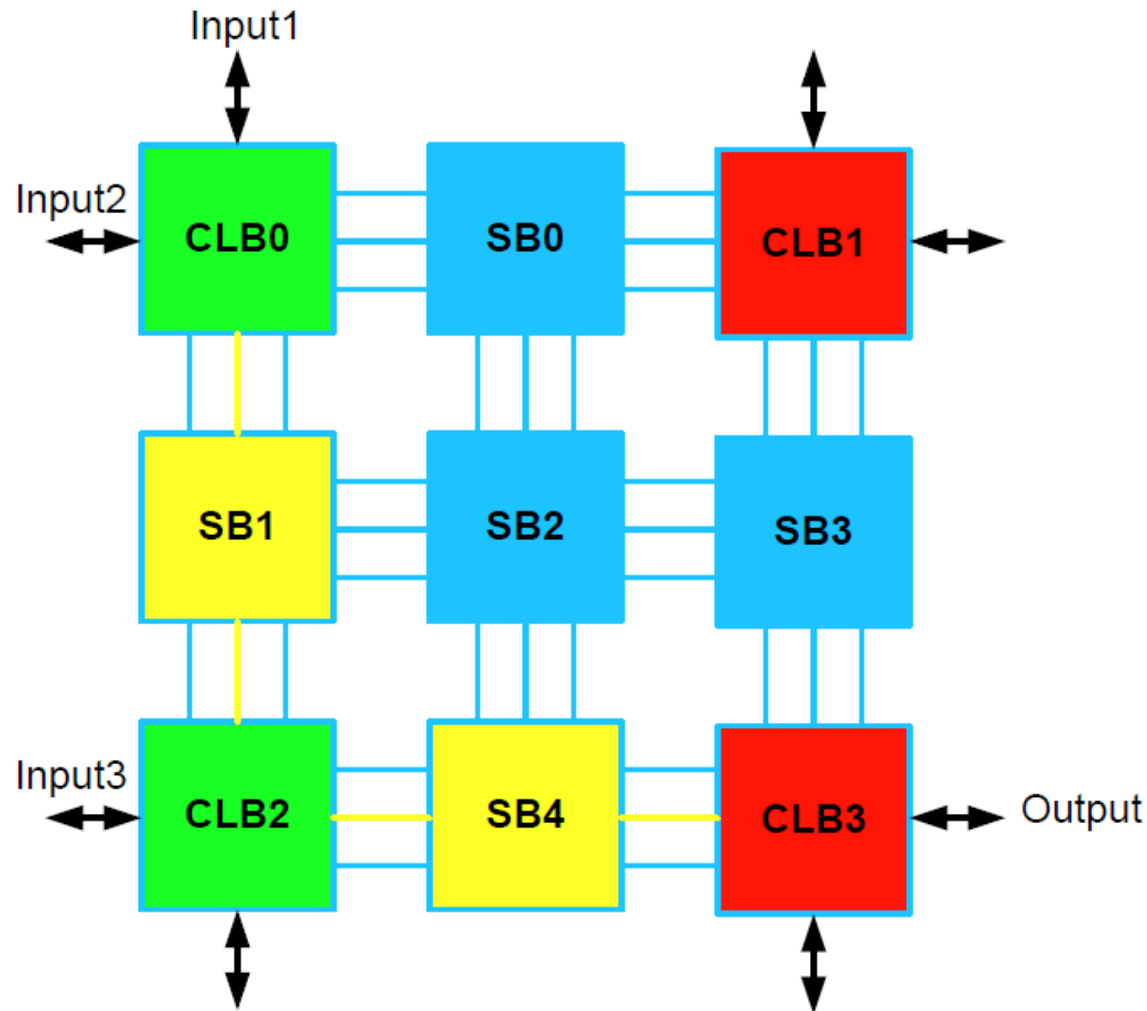




Placement: select CLBs



Routing: Select path





Configuration Bitstream

- › The configuration bitstream must include ALL CLBs and SBs, even unused ones
- › CLB0: 00011
- › CLB1: ?????
- › CLB2: 01100
- › CLB3: XXXXX
- › SB0: 000000
- › SB1: 000010
- › SB2: 000000
- › SB3: 000000
- › SB4: 000001



Some Definitions

- › **Object Code (aka "Bitstream")**: the executable active physical (either HW or SW) implementation of a given functionality
- › **Core**: a specific representation of a functionality. It is possible, for example, to have a core described in VHDL, in C or in an intermediate representation (e.g. a DFG)
- › **IP-Core**: a core described using a HD Language combined with its communication infrastructure (i.e. the bus interface)
- › **Reconfigurable Functional Unit**: an IP-Core that can be plugged and/or unplugged at runtime in an already working architecture
- › **Reconfigurable Region**: a portion of the device area used to implement a reconfigurable core



Computer-Aided Design

Can't design FPGAs by hand!

- › way too much logic to manage, hard to make changes
- › Hardware description languages (HDL), es: Verilog, VHDL
 - specify functionality of logic at a high level
- › Logic synthesis
 - process of compiling HDL program into logic gates and flip-flops
- › Validation - high-level simulation to catch specification errors
 - verify pin-outs and connections to other system components
 - low-level to verify and check performance



CAD Tool Path (cont'd)

› Technology mapping

- map the logic onto elements available in the implementation technology (LUTs for Xilinx FPGAs)

› Placement and routing

- assign logic blocks to functions
- make wiring connections

› Partitioning and constraining

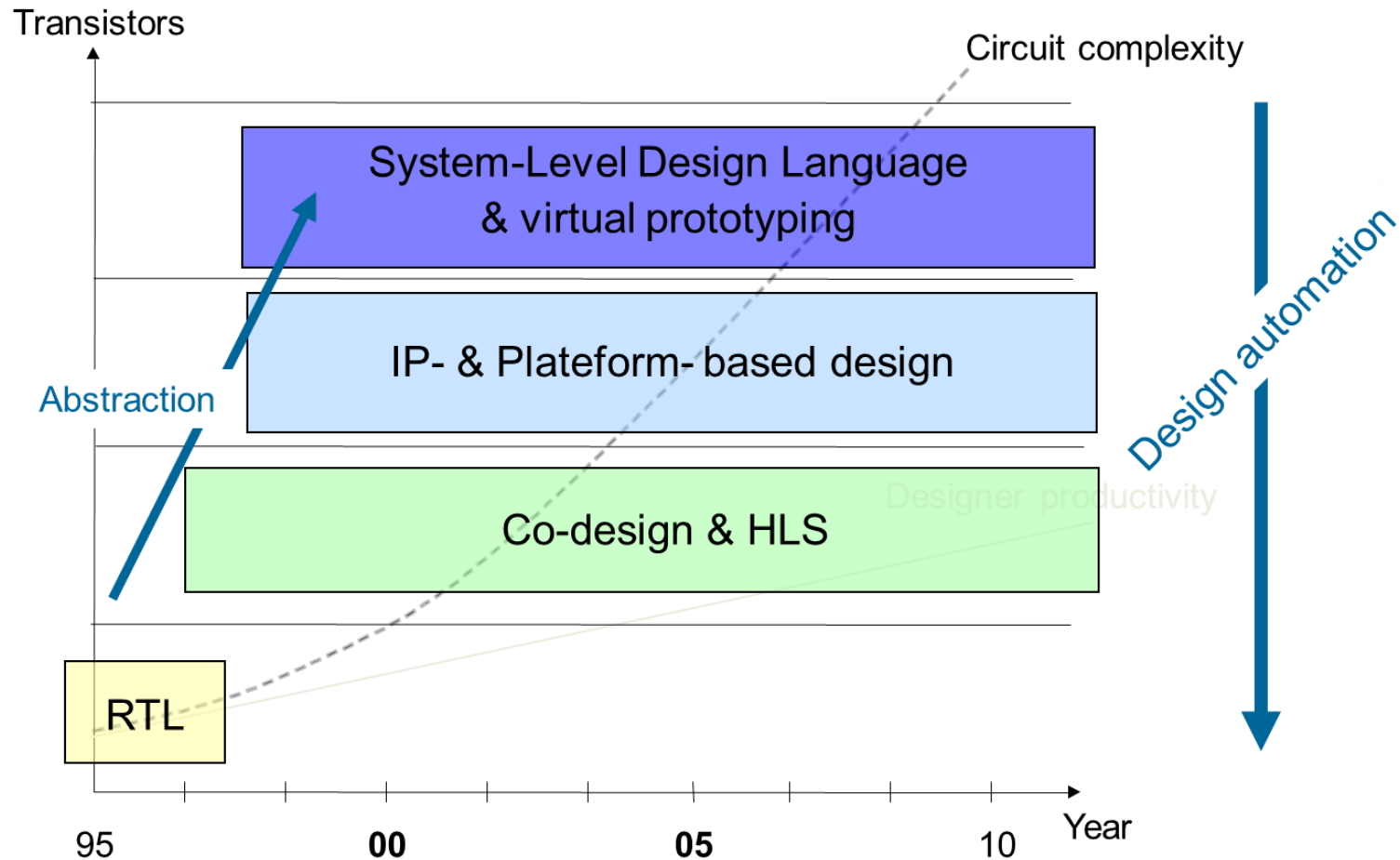
- if design does not fit or is unroutable as placed split into multiple chips
- if design is too slow prioritize critical paths, fix placement of cells, etc.
- few tools to help with these tasks exist today

› Generate programming files - bits to be loaded into chip for configuration



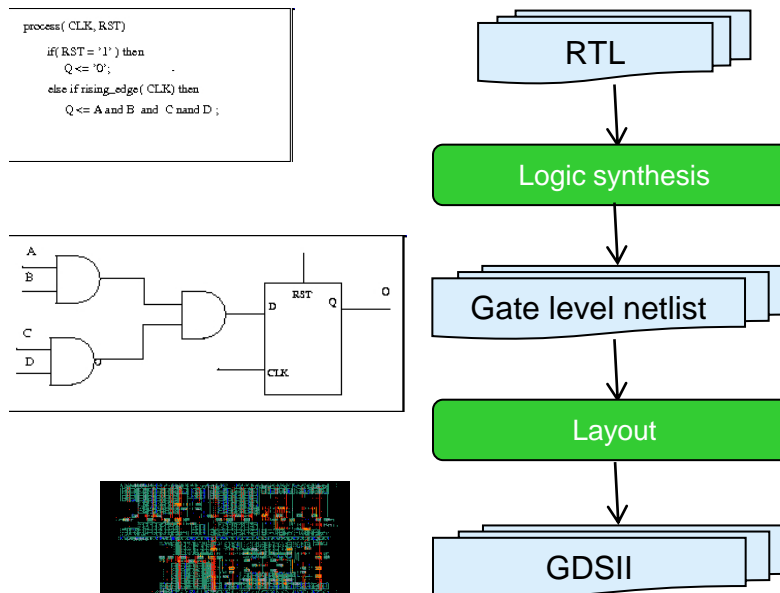
High-level synthesis

Electronic System Level Design (ESLD)



Typical HW design flow

- › Starting from a Register Transfer Level description, generate an IC layout



Typical HW design flow

- › Starting from a Register Transfer Level description, generate an IC layout

```
#define N 2

typedef int matrix[N][N];

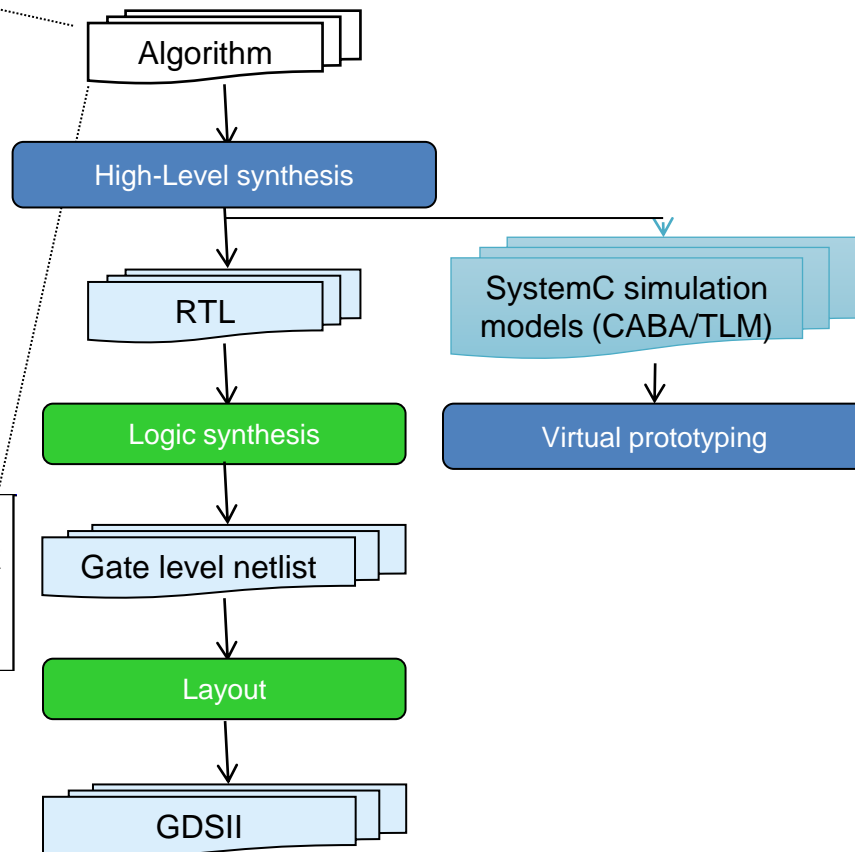
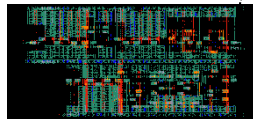
int main(const matrix A, matrix C)
{
    const matrice B = {{1, 2},{ 3, 4}};
    int tmp;
    int i,j,k;

    for (i=0;i<N;i++)
        for (j=0;j<N;j++){
            tmp = A[i][0]*B[0][j];

            for (k=1;k<N - 1;k++)
                tmp = tmp + A[i][k] * B[k][j];

            C[i][j] = tmp + A[i][N-1] * B[N-1][j];
        }

    return 0;
}
```

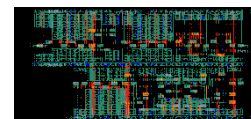
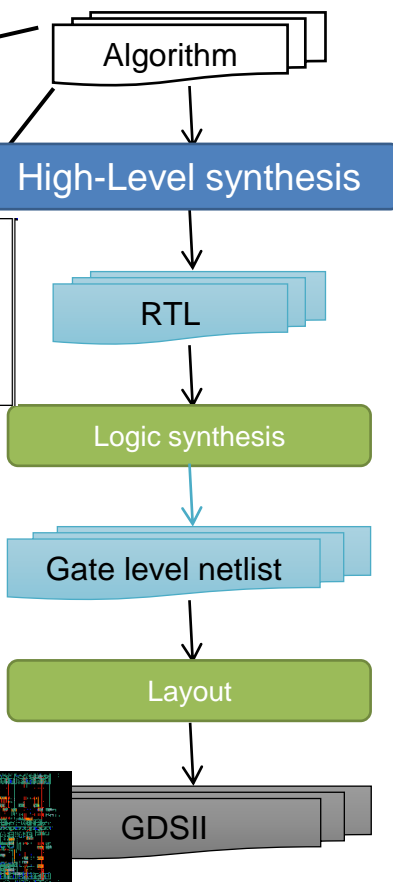
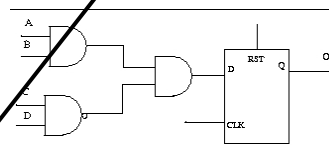


- › Starting from C code, generate RTL, and then, layout
 - Typically, HW accelerators (FFT?) Ips
 - Can also synthesize a fully fledged processor!!
 - Soft-cores

```
#define N 2
typedef int matrix[N][N];

int main(const matrix A, matrix C)
{
    const matrix B = {{1, 2},{ 3, 4}};
    int tmp;
    int i,j,k;
    for (i=0;i<N;i++)
        for (j=0;j<N;j++) {
            tmp = A[i][0]*B[0][j];
            for (k=1;k<N - 1;k++)
                tmp = tmp + A[i][k] * B[k][j];
            C[i][j] = tmp + A[i][N-1] *
                B[N-1][j];
        }
    return 0;
}
```

```
process( CLK, RST)
if( RST = '1' ) then
    Q <= '0';
else if rising_edge( CLK) then
    Q <= A and B and C and D;
```



It is basically, a compiler!

- › From C code
 - Generates the "physical" representation of Hardware modules
 - Registry Transfer Level, RTL
 - That will be deployed on the board

- › Automatically

Synthesizable C subset

- › No pointers
 - Statically unresolved
 - Arrays are allowed!
- › No standard function call
 - printf, scanf, fopen, malloc...
- › Function calls are allowed
 - Can be in-lined or not
- › Nearly all datatypes are allowed
 - Specific datatypes are encouraged
 - Bit accurate integers, fixed point, signed, unsigned...



Example #1: a simple C code

```
#define N 16

int main(int data_in, int *data_out) {
    static const int Coeffs [N] = { 98, -39, -327, 439, 950, -2097, -1674, 9883,
                                     9883, -1674, -2097, 950, 439, -327, -39, 98 };

    int Values[N];
    int temp;
    int sample,i,j;

    sample = data_in;
    temp = sample * Coeffs[N-1];

    for(i = 1; i<=(N-1); i++) {
        temp += Values[i] * Coeffs[N-i-1];
    }

    for(j=(N-1); j>=2; j-=1 ) {
        Values[j] = Values[j-1];
    }

    Values[1] = sample;
    *data_out=temp;

    return 0;
}
```




Example #2: bit accurate C++ code

```
#include "ac_fixed.h" // From Mentor Graphics
#define PORT_SIZE ac_fixed<16, 12, true, AC_RND, AC_SAT> // 16 bits, 12 bits after the \
    point, quantization = rounding, overflow = saturation
#define N 16

int main(PORT_SIZE data_in, PORT_SIZE &data_out) {
    static const PORT_SIZE Coeffs [N]= { 1.1, 1.5, 1.0, 1.0, 1.7, 1.8, 1.2, 1.0,
                                           1.6, 1.0, 1.5, 1.1, 1.9, 1.3, 1.4, 1.7 };

    PORT_SIZE Values[N];
    PORT_SIZE temp;
    PORT_SIZE sample;

    sample= data_in;
    temp = sample * Coeffs[N-1];

    for(int i = 1; i<=(N-1); i++) {
        temp = Values [i] * Coeffs[N-i-1] + temp;
    }

    for(int j=(N-1); j>=2; j-=1 ) {
        Values[j] = Values [j-1];
    }

    Values[1] = sample;
    data_out=temp;

    return 0;
}
```

› Loops

- Loop pipelining,
- Loop unrolling
- Loop merging
- Loop tiling
- ...

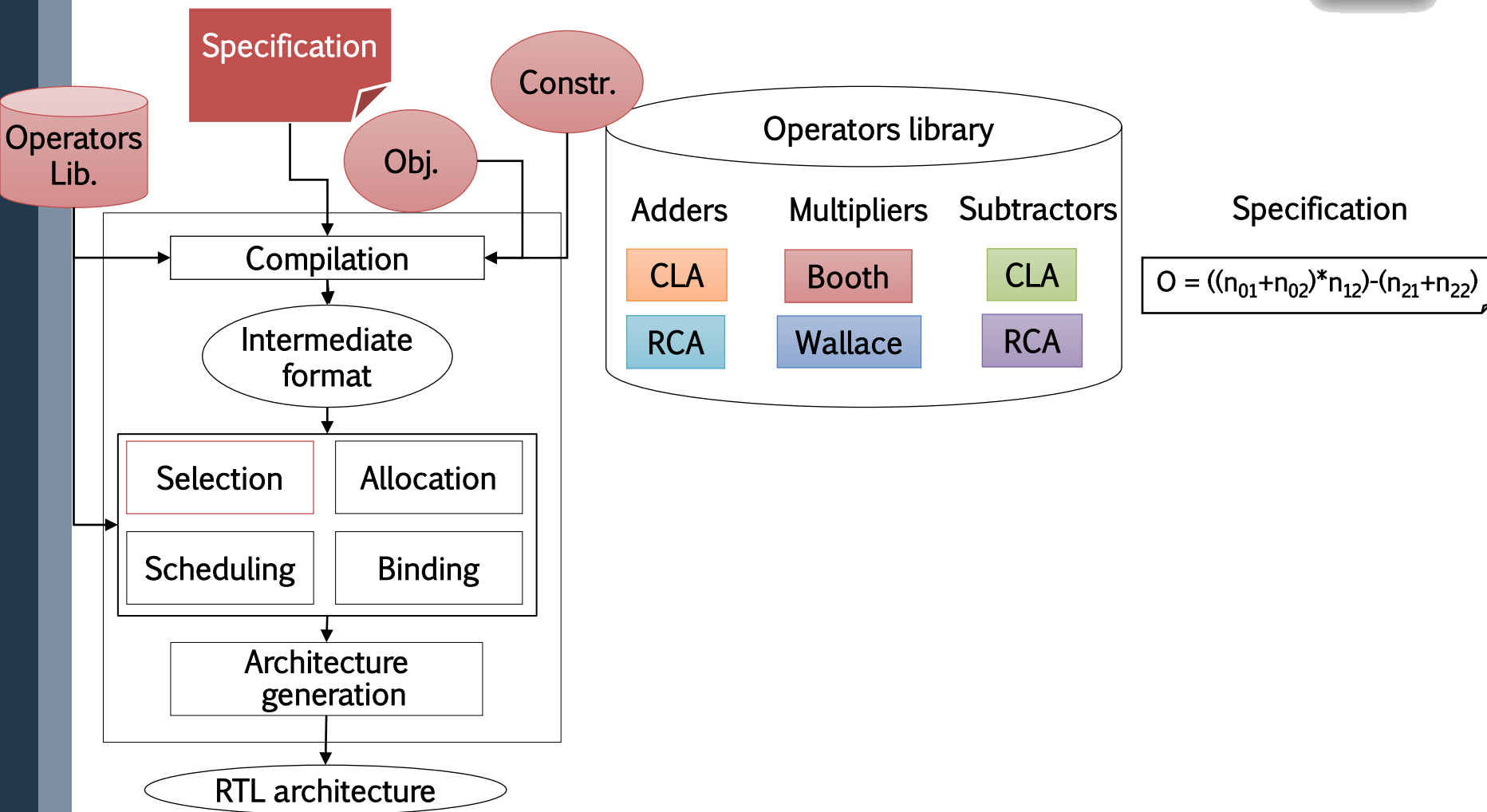
› Arrays mapping

- Arrays can be mapped on memory banks
- Arrays can be synthesized as registers
- Constant arrays can be synthesized as logic
- ...

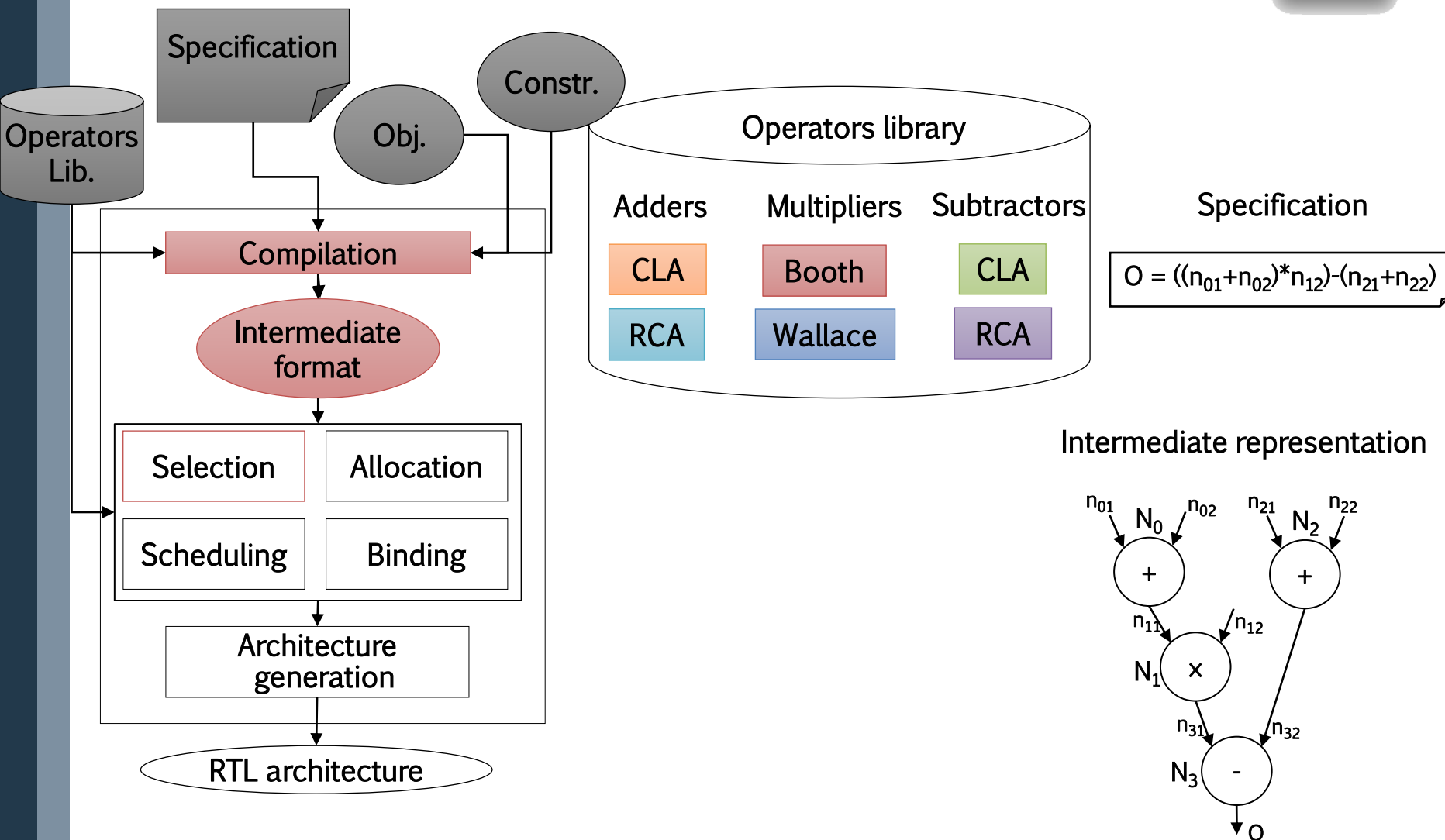
› Functions

- Function calls can be in-lined
- Function is synthesized as an operator
 - › Sequential, pipelined, functional unit...
- Single function instantiation
- ...

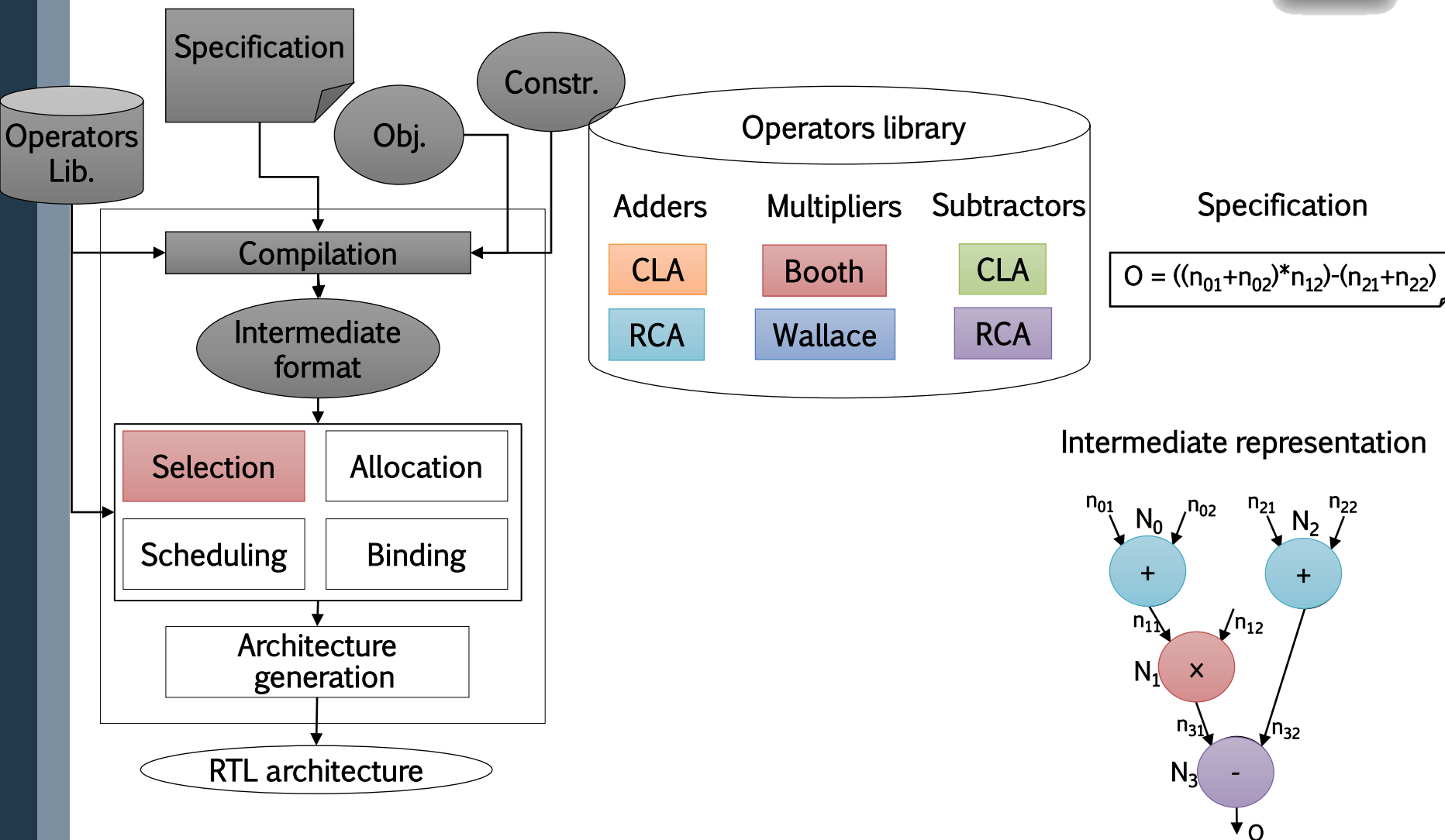
HLS steps: Inputs



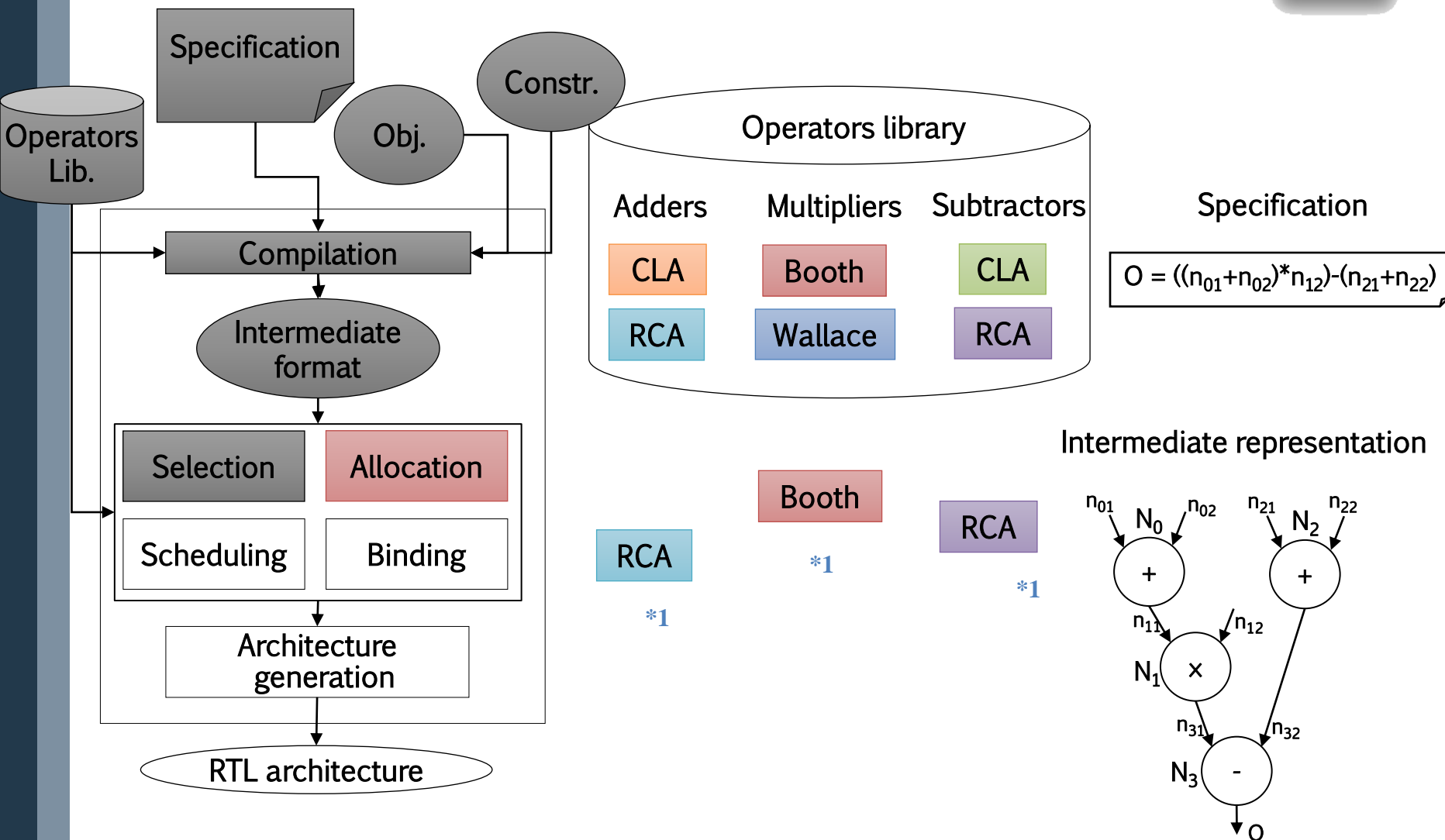
HLS steps: Compilation



HLS steps: Selection

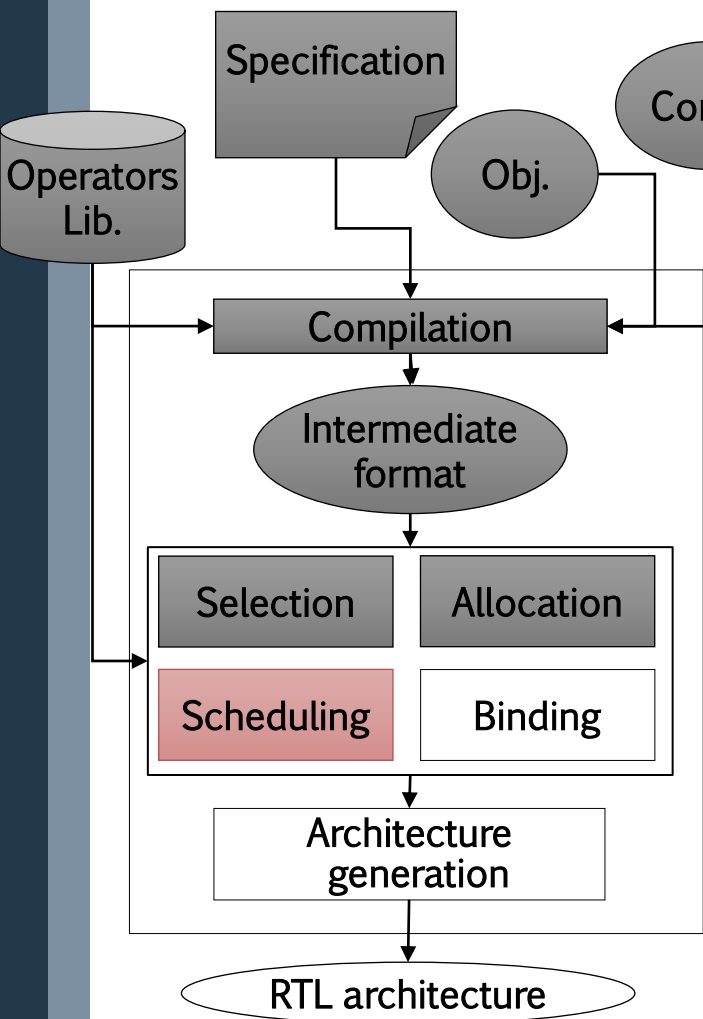


HLS steps: Allocation





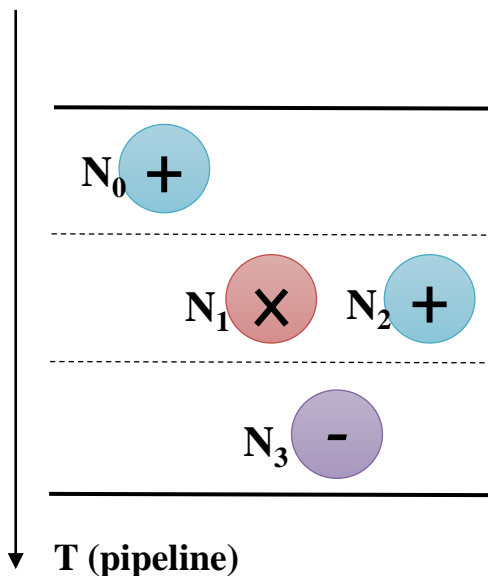
HLS steps: Scheduling



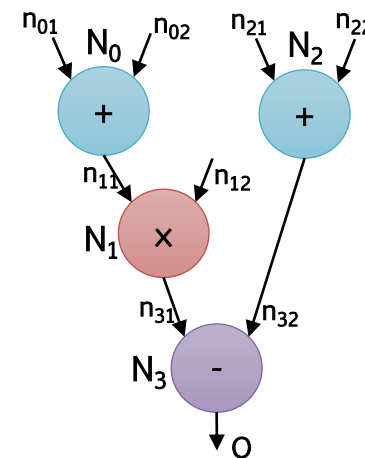
RCA
*1

Booth
*1

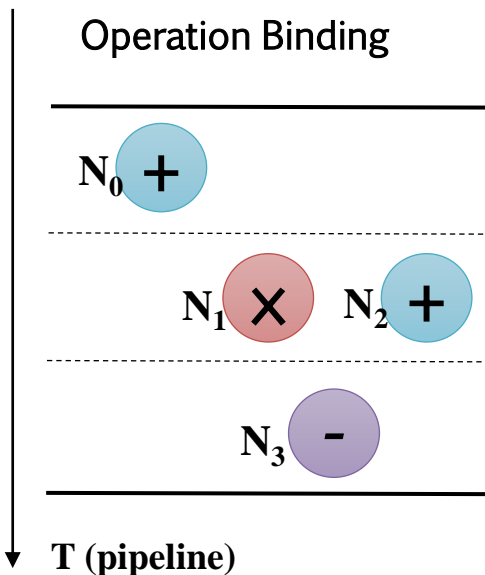
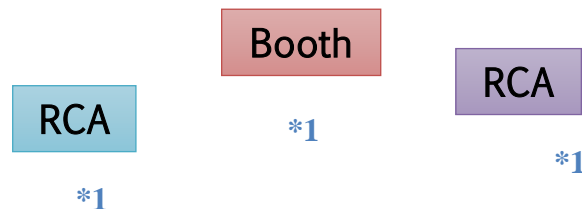
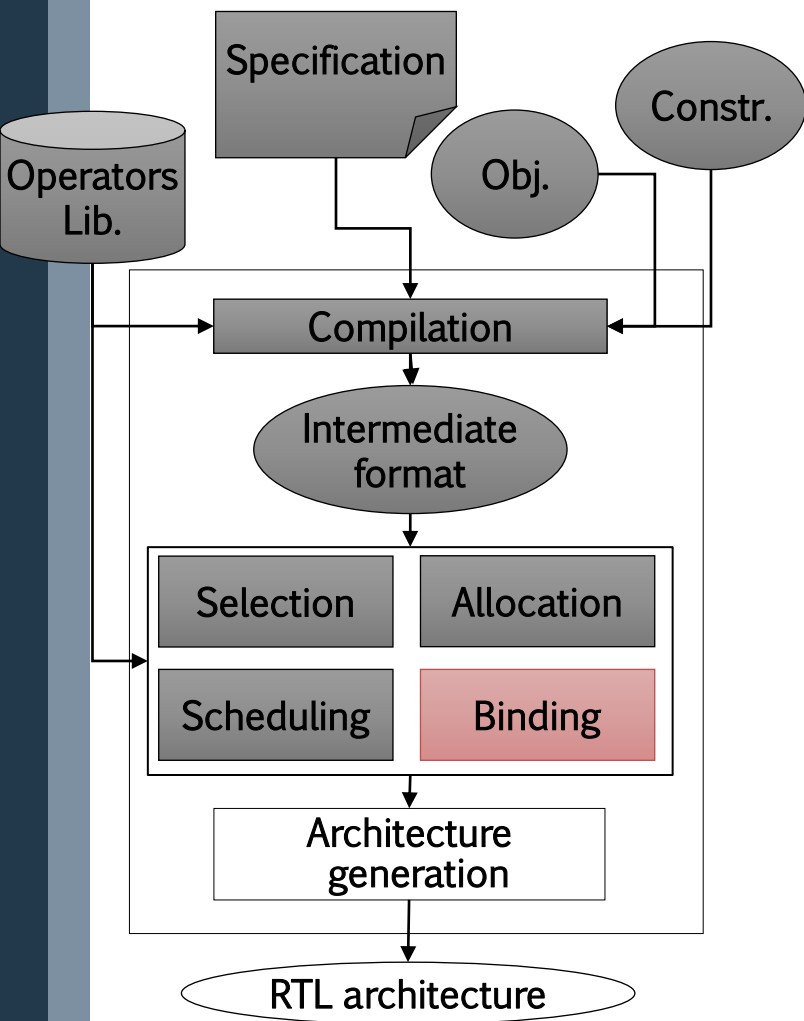
RCA
*1



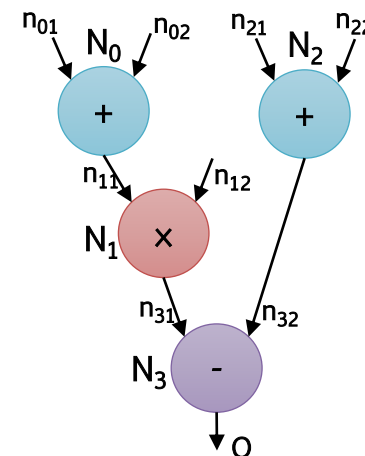
Intermediate representation



HLS steps: Binding



Intermediate representation

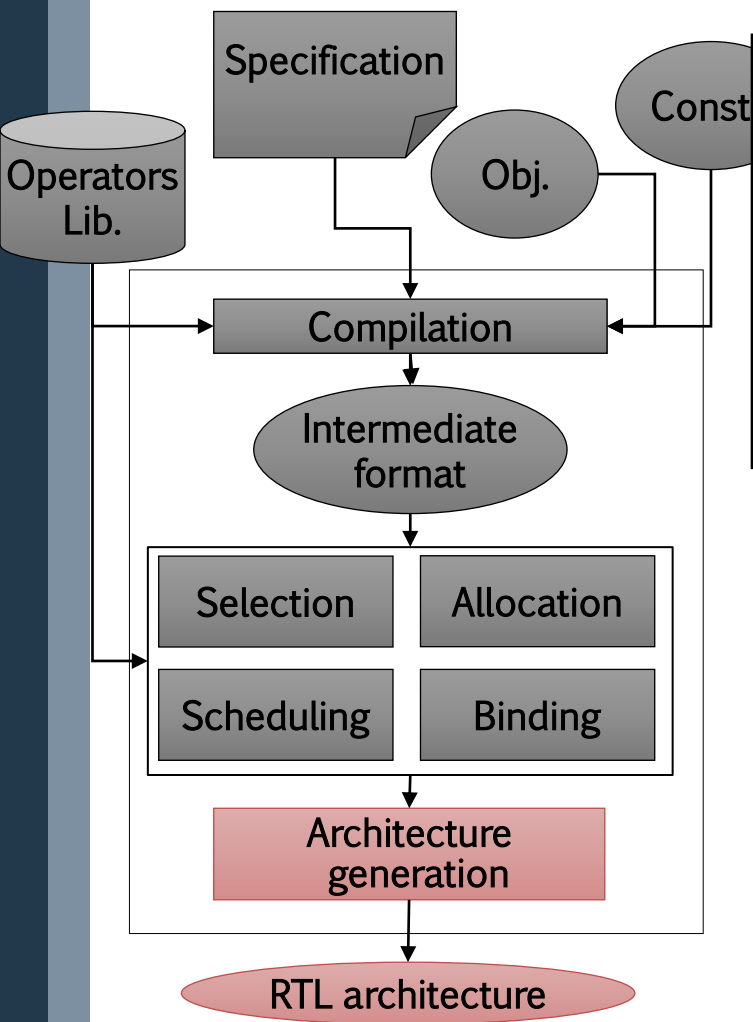


Data Binding

n_{01}	\rightarrow	R_1
n_{02}	\rightarrow	R_2
n_{21}, n_{11}	\rightarrow	R_3
n_{22}, n_{12}	\rightarrow	R_4
n_{31}	\rightarrow	R_5
n_{32}	\rightarrow	R_6

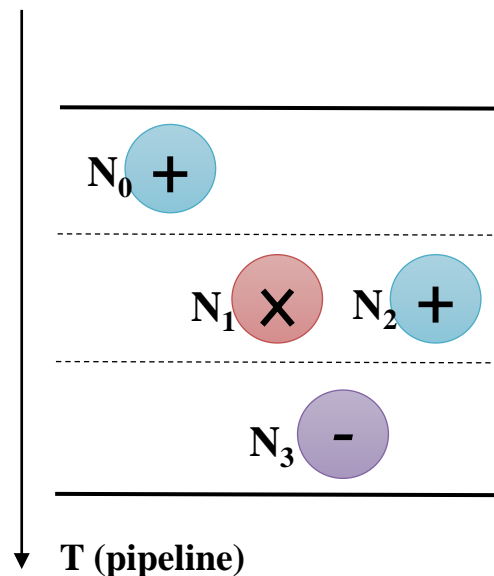
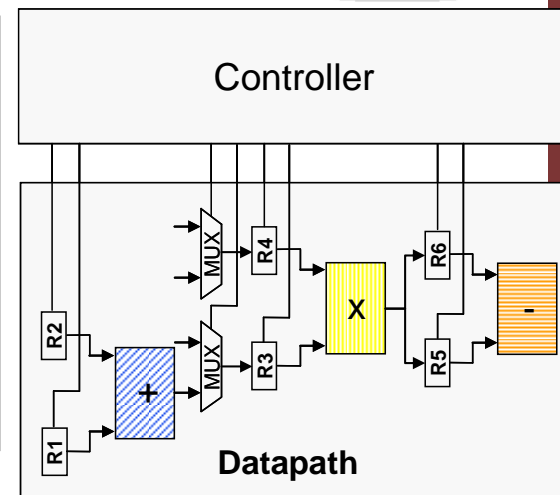


HLS steps: Binding



- Controller**
- FSM controller
 - Programmable controller

- Datapath components**
- Storage components
 - Functional units
 - Connection components



Data Binding

$n_{01} \rightarrow R_1$
 $n_{02} \rightarrow R_2$
 $n_{21}, n_{11} \rightarrow R_3$
 $n_{22}, n_{12} \rightarrow R_4$
 $n_{31} \rightarrow R_5$
 $n_{32} \rightarrow R_6$



Xilinx's Vivado SDK

The FPGA development tool

- › Starting from C or RTL...
- › ...generates and deploys the IP on the FPGA
- › ..as well as SW artifacts to interact with them (drivers)

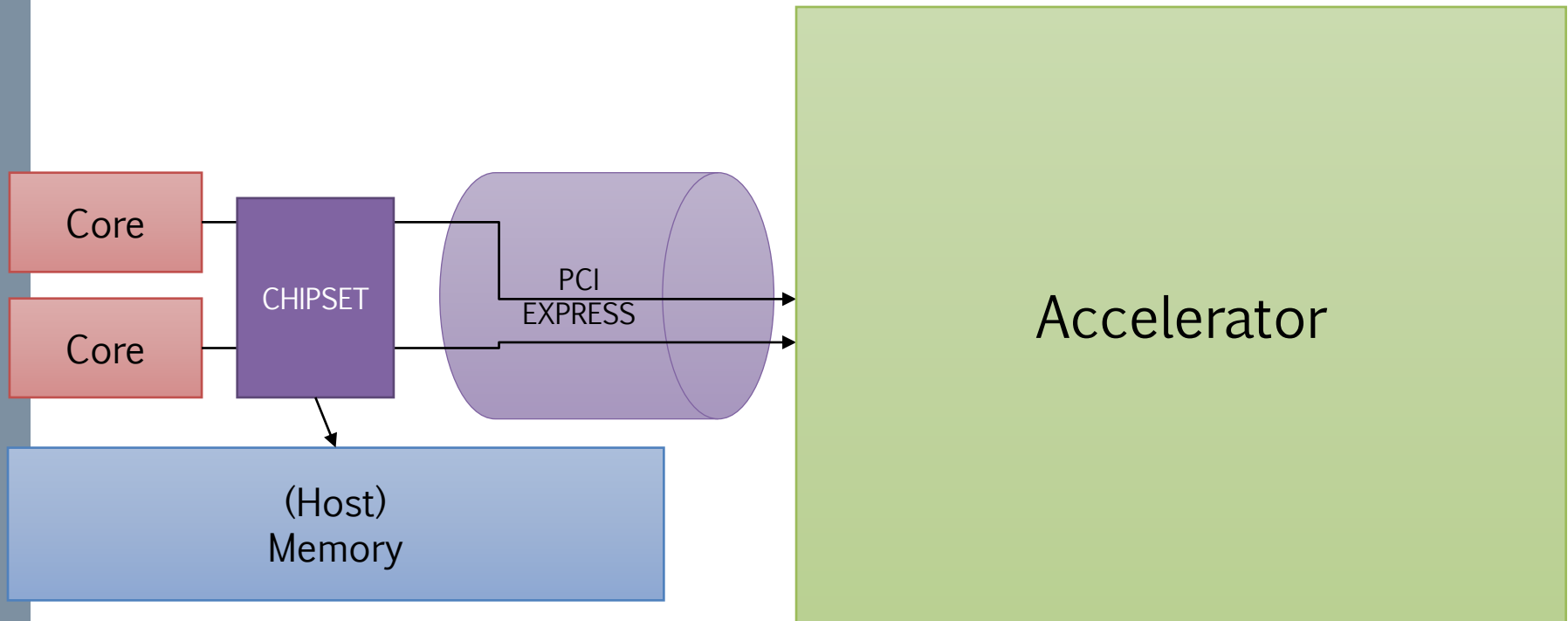


Heterogeneous systems



Host-accelerator model

- › Multi-core General purpose host
 - The "traditional" core
- › Coupled with a co-processor/accelerator

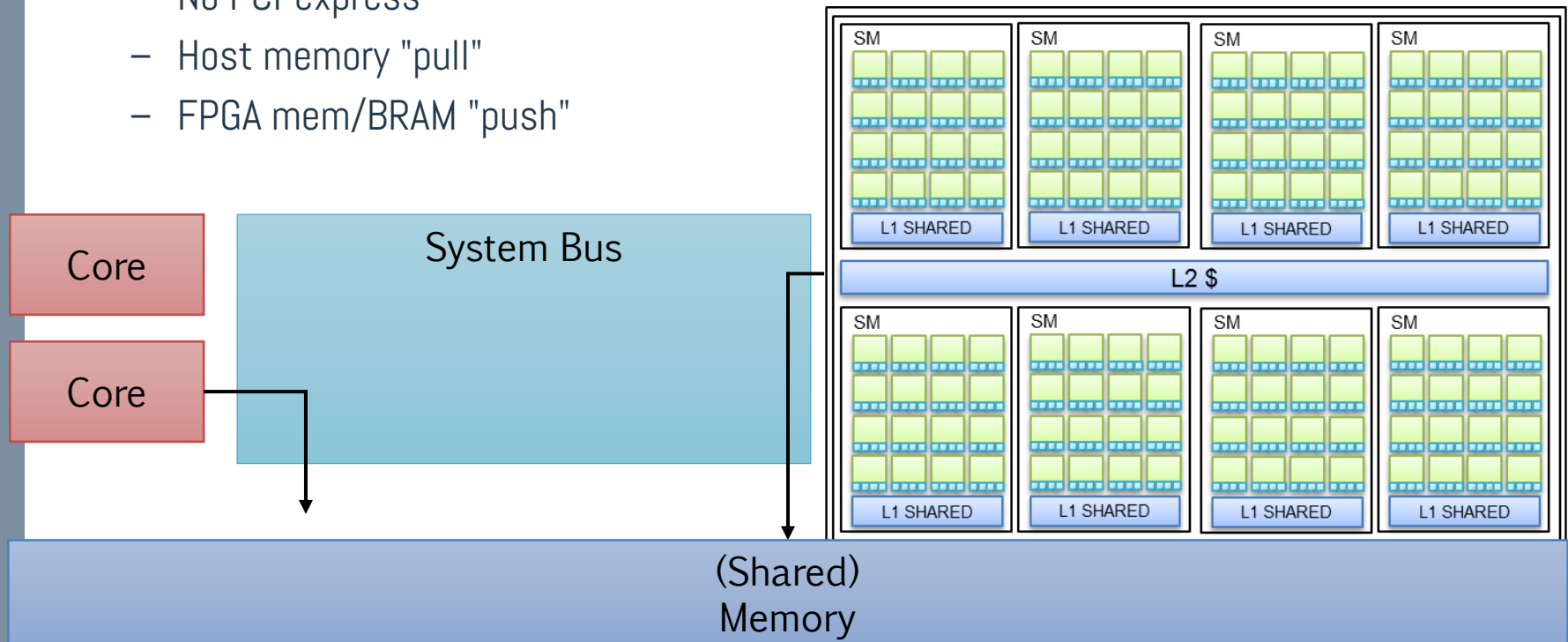




Do you remember (i)GPGPUs?

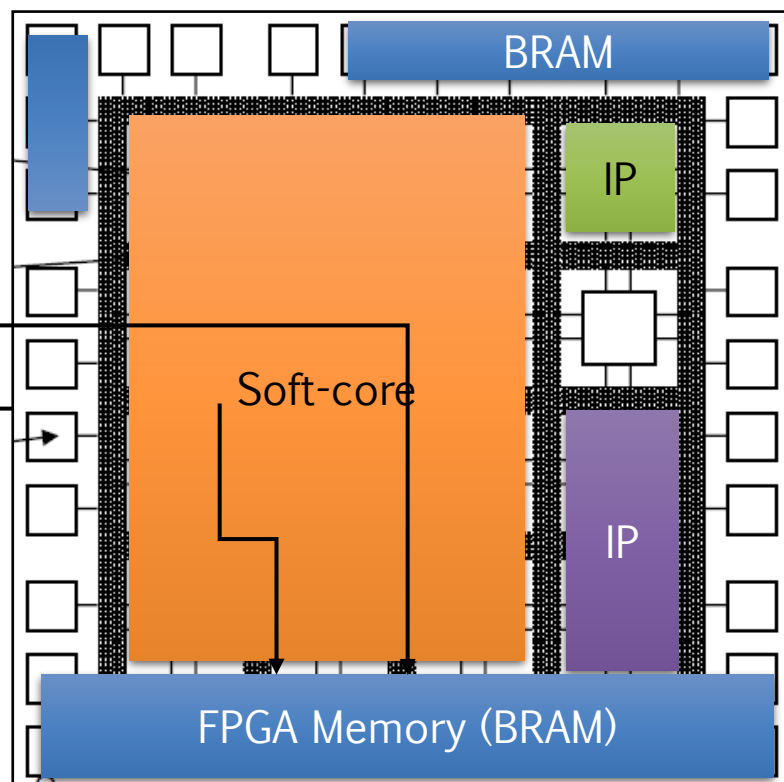
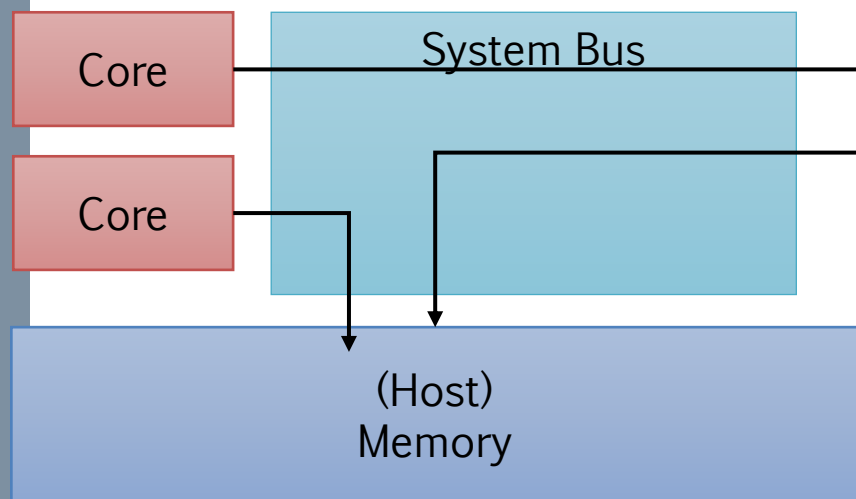
Integrated GP-GPUs for embedded platforms

- › Host + accelerator model
- › Communicate via shared memory
 - No PCI-express
 - Host memory "pull"
 - FPGA mem/BRAM "push"



FPGA-based accelerators

- › Can create hundreds of small HW accelerators (de/encrypt, de/coders)
- › Can even create a single core (as co-processor)
 - Soft-cores
- › Communicate via shared memory
 - No PCI-express
 - Host memory "pull"
 - FPGA mem/BRAM "push"





Example: Xilinx Zynq

› Dual-core ARM host

› Programmable Logic

Shared memory

› Host caches

› Host SPM (On-chip Memory)

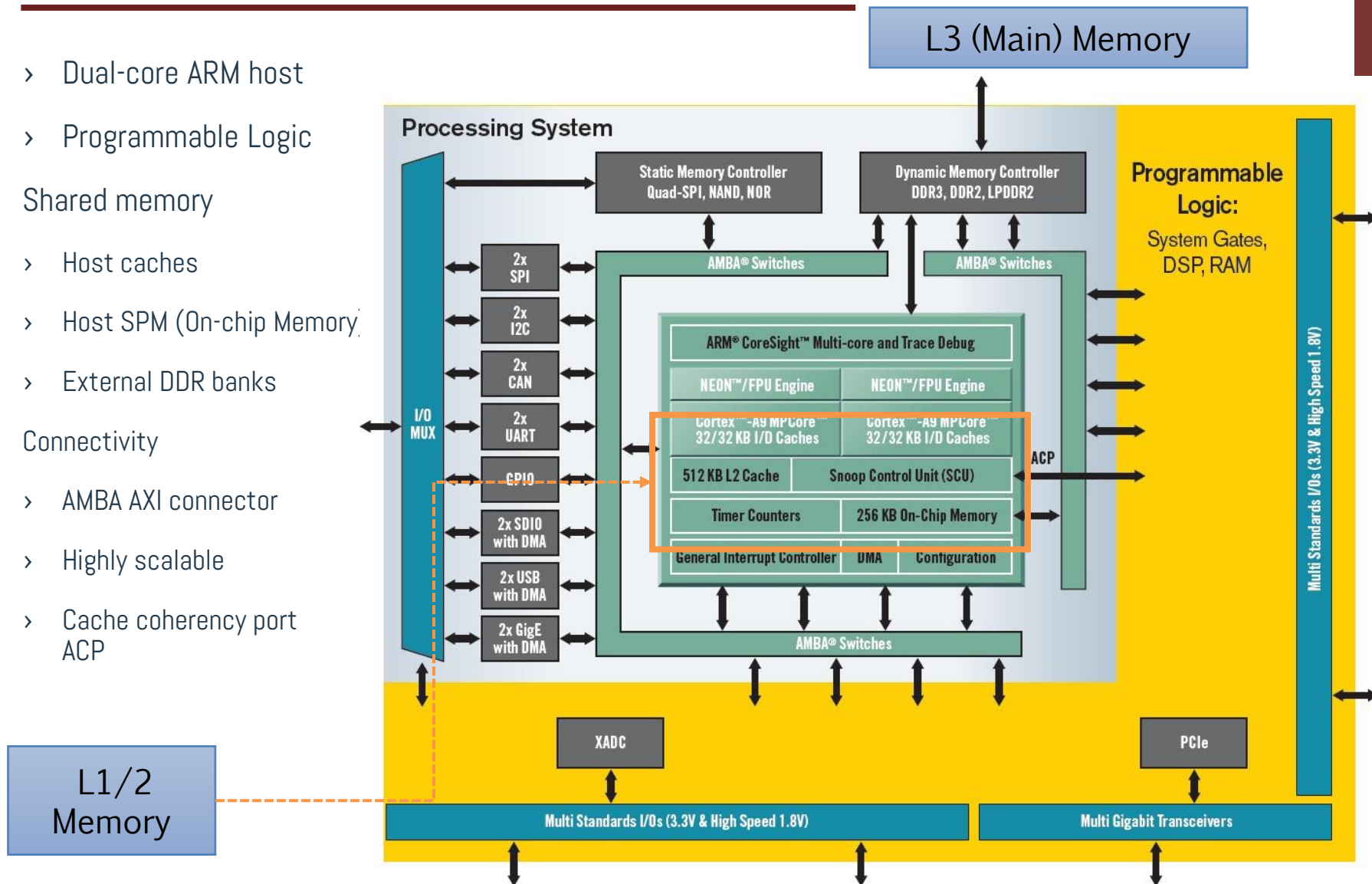
› External DDR banks

Connectivity

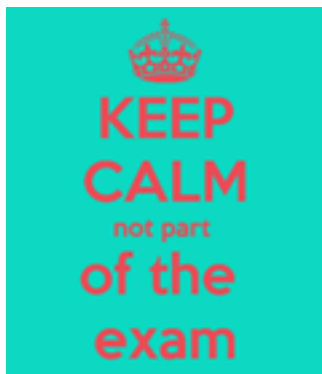
› AMBA AXI connector

› Highly scalable

› Cache coherency port
ACP



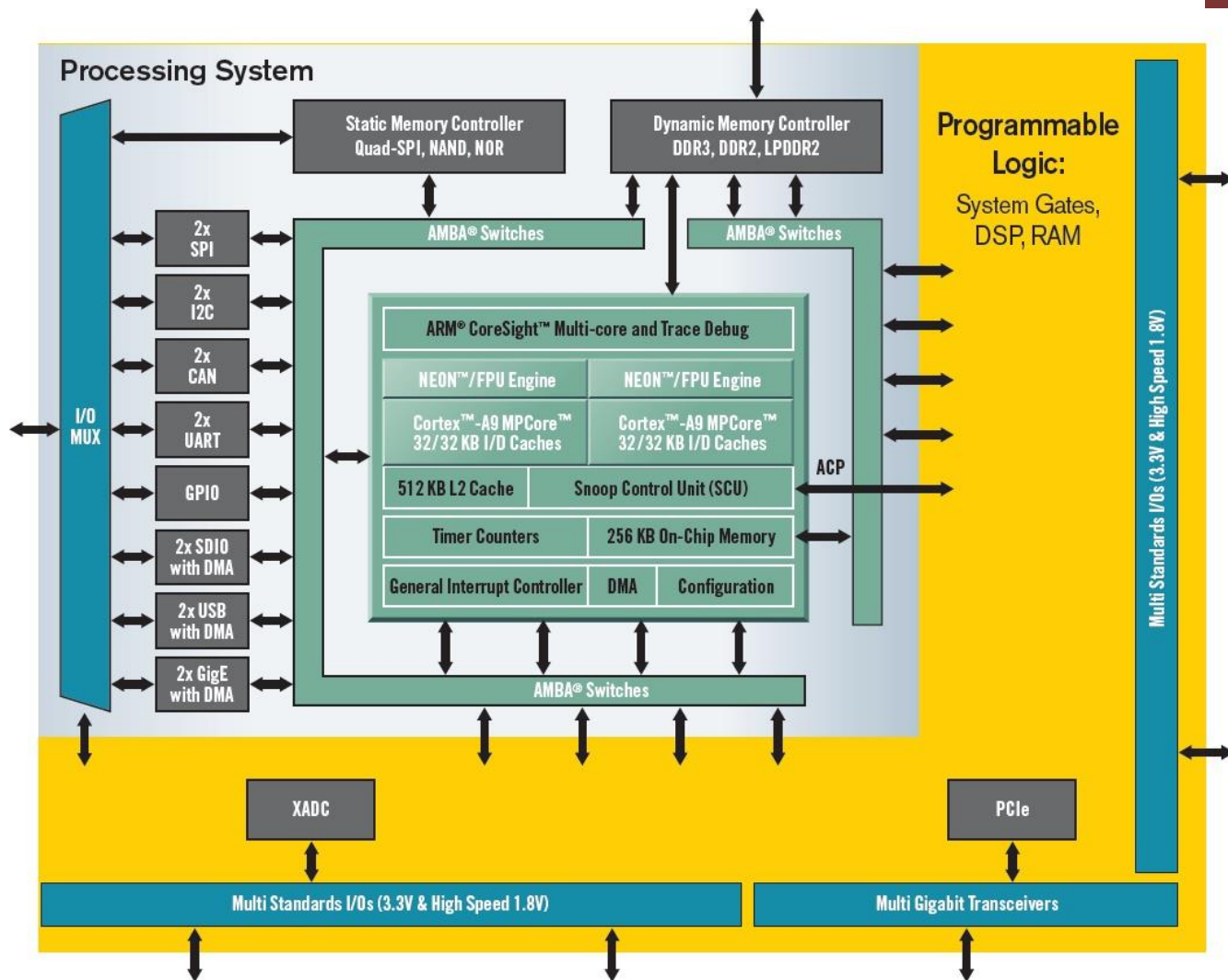
Xilinx FPGA SoCs





Xilinx Zynq-7000

- › Dual-core ARM host
- › Programmable Logic
- › Shared memory



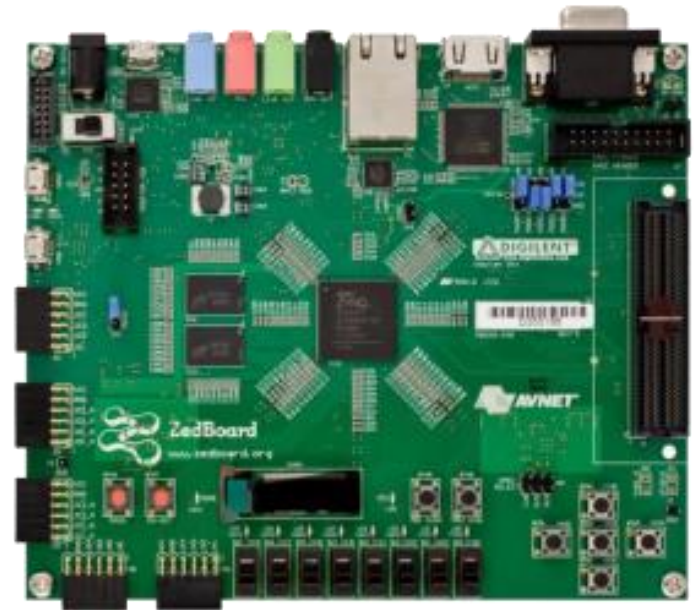


Xilinx Zynq-7000

FAMILY	PART	Logic Cells (K)	Block RAM (Mb)	DSP Slices	Maximum I/O Pins	Maximum Transceiver (Video Code Unit (VCU)
ZYNQ-7000							
	Z-7010	28	2,1	80	100	-	-
	Z-7015	74	3,3	160	150	4	-
	Z-7020	85	4,9	220	200	-	-
	Z-7030	125	9,3	400	250	4	-
	Z-7035	275	17,6	900	362	16	-
	Z-7045	350	19,1	900	362	16	-
	Z-7100	444	26,5	2020	400	16	-

Zedboard

- › Complete development kit with Xilinx Zynq-7000 SoC
- › Basic support for rapid prototyping and proof-of-concept development
- › Small 😊





UltraZed

- › System-On-Module (SOM)
 - › Based on the Ultrascale architecture: no host!
 - › Packages system memory, Ethernet, USB, and configuration memory needed for an embedded processing system
-
- › UltraZed EG
 - › UltraZed EV



Xilinx Pynq: Python for Zynq

- › Open-source project from Xilinx for design
- › Uses Python language and libraries
- › Maximizes productivity

Processor: Dual-Core ARM® Cortex®-A9

FPGA: 1.3 M reconfigurable gates

Memory: 512MB DDR3 / FLASH

Storage: Micro SD card slot

Video: HDMI In and HDMI Out

Audio: Mic in, Line Out

Network: 10/100/1000 Ethernet

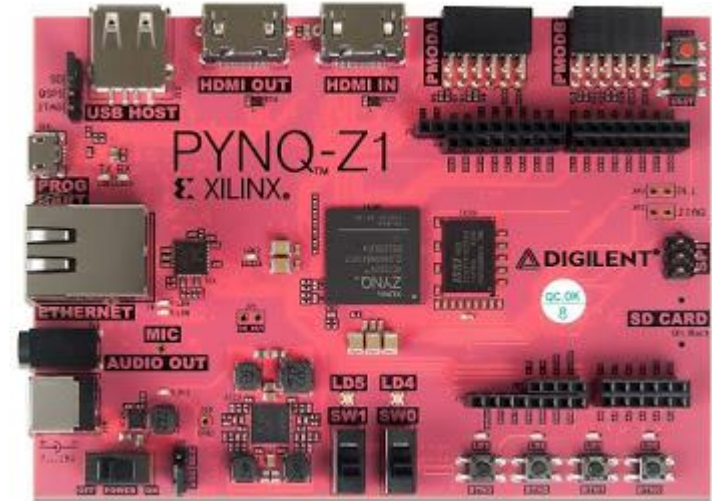
Expansion: USB Host connected to ARM PS

Interfaces: 1x Arduino Header, 2x Pmod (49 GPIO)

GPIO: 16 GPIO (65 in total with Arduino and Pmods)

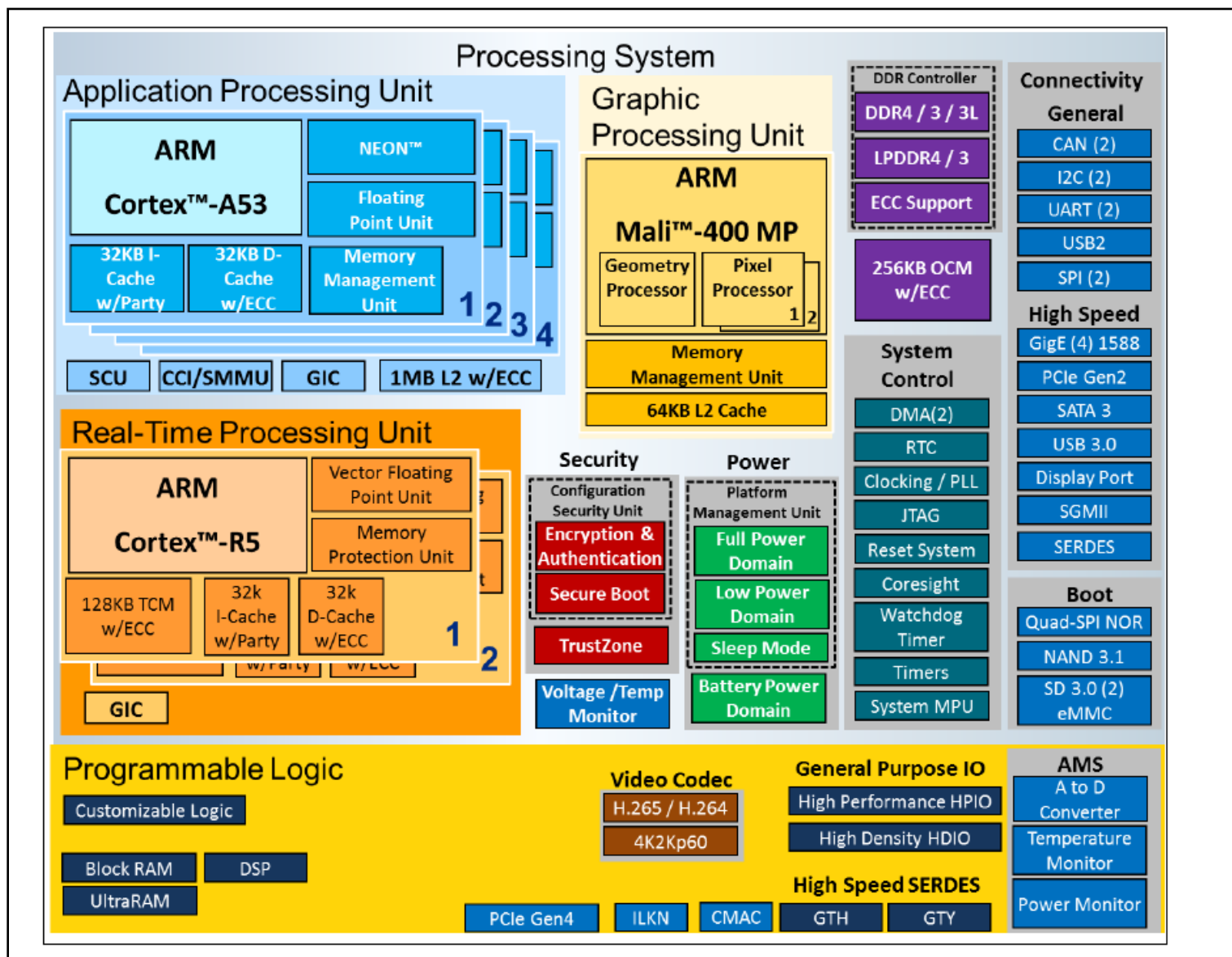
Other I/O: 6x User LEDs, 4x Pushbuttons, 2x Switches

Dimensions: 3.44" x 4.81" (87mm x 122mm)





Xilinx Zynq Ultrascale+





Xilinx Zynq Ultrascale portfolio

› Zynq UltraScale+ CG

- Dual-core Cortex-A53 and a dual-core Cortex-R5 real-time processor
- Programmable logic
- Optimized for industrial motor control, sensor fusion, and industrial IoT applications

› Zynq UltraScale+ EG

- Quad-core Cortex-A53 and dual-core Cortex-R5 real-time processors
- Mali-400 MP2 graphics processing unit + programmable logic
- Next-generation wired and 5G wireless infrastructure, cloud computing, and Aerospace and Defense applications

› Zynq UltraScale+ EV

- EG platform + integrated H.264 / H.265 video codec
- Multimedia, automotive ADAS, surveillance, and other embedded vision applications



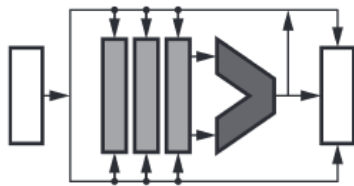
Xilinx Zynq Ultrascale+

FAMILY	PART	Logic Cells (K)	Block RAM (Mb)	DSP Slices	Maximum I/O Pins	Maximum Transceiver (Gbps)	Video Code Unit (VCU)
ZYNQ UltraScale+ CG							
	ZU2CG	103	5,3	240	252	-	-
	ZU3CG	154	7,6	360	252	-	-
	ZU4CG	192	18,5	728	252	-	-
	ZU5CG	256	23,1	1248	252	-	-
	ZU6CG	469	25,1	1973	328	-	-
	ZU7CG	504	38	1728	464	-	-
	ZU9CG	600	32,1	2520	328	-	-
ZYNQ UltraScale+ EG							
	ZU2EG	103	5,3	240	252	-	-
	ZU3EG	154	7,6	360	252	-	-
	ZU4EG	192	18,5	728	252	-	-
	ZU5EG	256	23,1	1248	252	-	-
	ZU6EG	469	25,1	1973	328	-	-
	ZU7EG	504	38	1728	464	-	-
	ZU9EG	600	32,1	2520	328	-	-
	ZU11EG	653	43,6	2928	512	-	-
	ZU15EG	747	57,7	3528	328	-	-
	ZU17EG	926	56,7	1590	668	-	-
	ZU19EG	1143	70,6	1968	668	-	-
ZYNQ UltraScale+ EV							
	ZU4EV	192	18,5	728	252	-	1
	ZU5EV	256	23,1	1248	252	-	1
	ZU7EV	504	38	1728	464	-	1

Next generation: Versal

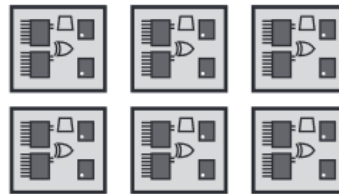
› Adaptive Compute Acceleration Platform (ACAP)

Scalar Processing



Complex Algorithms
and Decision Making

Adaptable Hardware

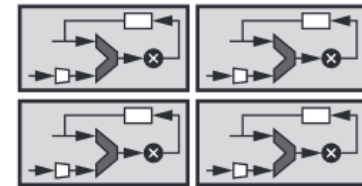


Processing of
Irregular Data Structures
Genomic Sequencing

Latency
Critical Workloads
Real-Time Control

Sensor Fusion
Pre-processing, Programmable I/O

Vector Processing (e.g., GPU, DSP)



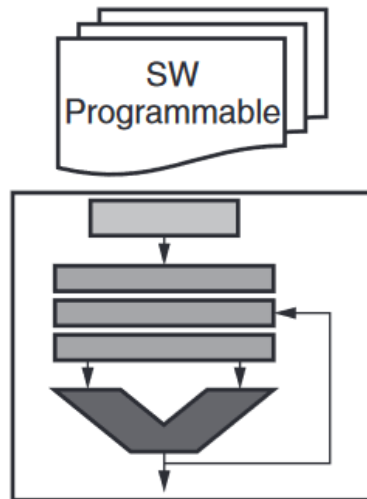
Domain-specific
Parallelism

Signal Processing
Complex Math, Convolutions

Video and
Image Processing

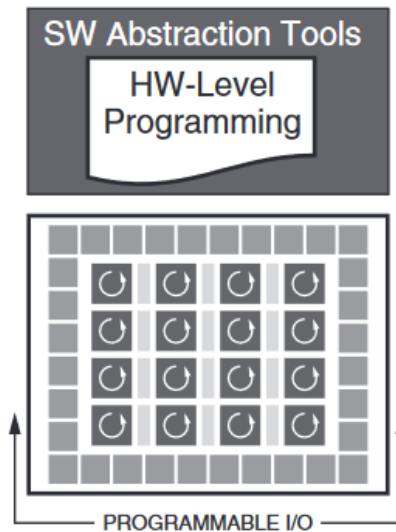
Programming Versal

CPU



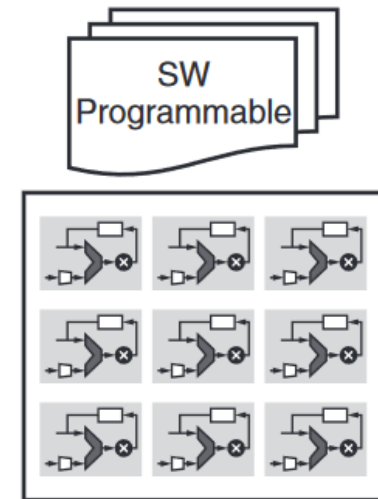
- Scalar, sequential processing
- Memory bandwidth limited
- Fixed pipeline, fixed I/O

FPGA



- Flexible parallel compute
- Fast local memory
- Custom I/O

Vector Processor




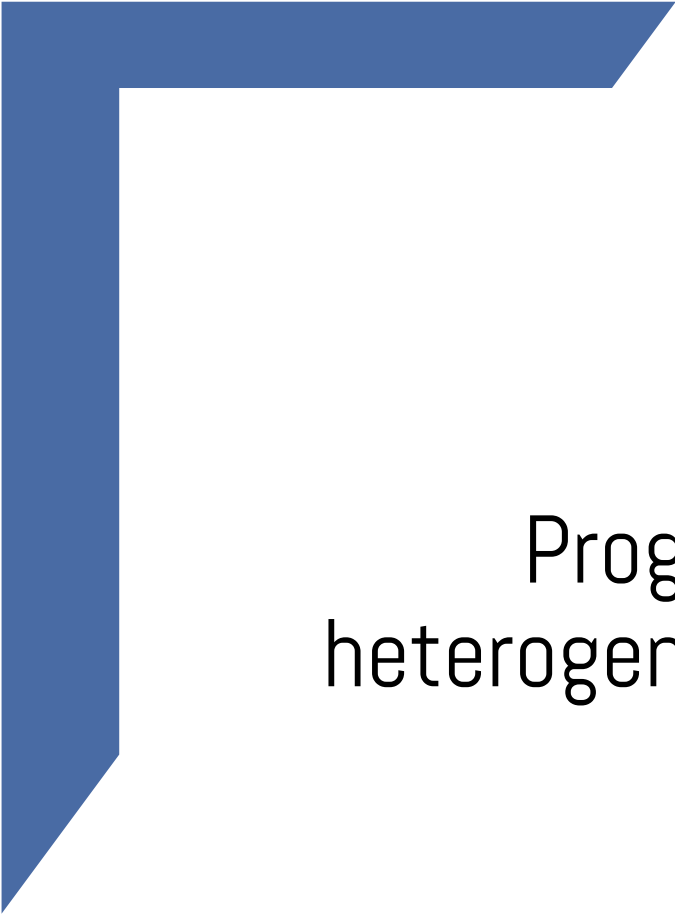
- Domain-specific parallelism
- High compute efficiency
- Fixed I/O and memory bandwidth

Scalar Engines

Adaptable Engines

Intelligent Engines

Integrated Software Programmable Interface

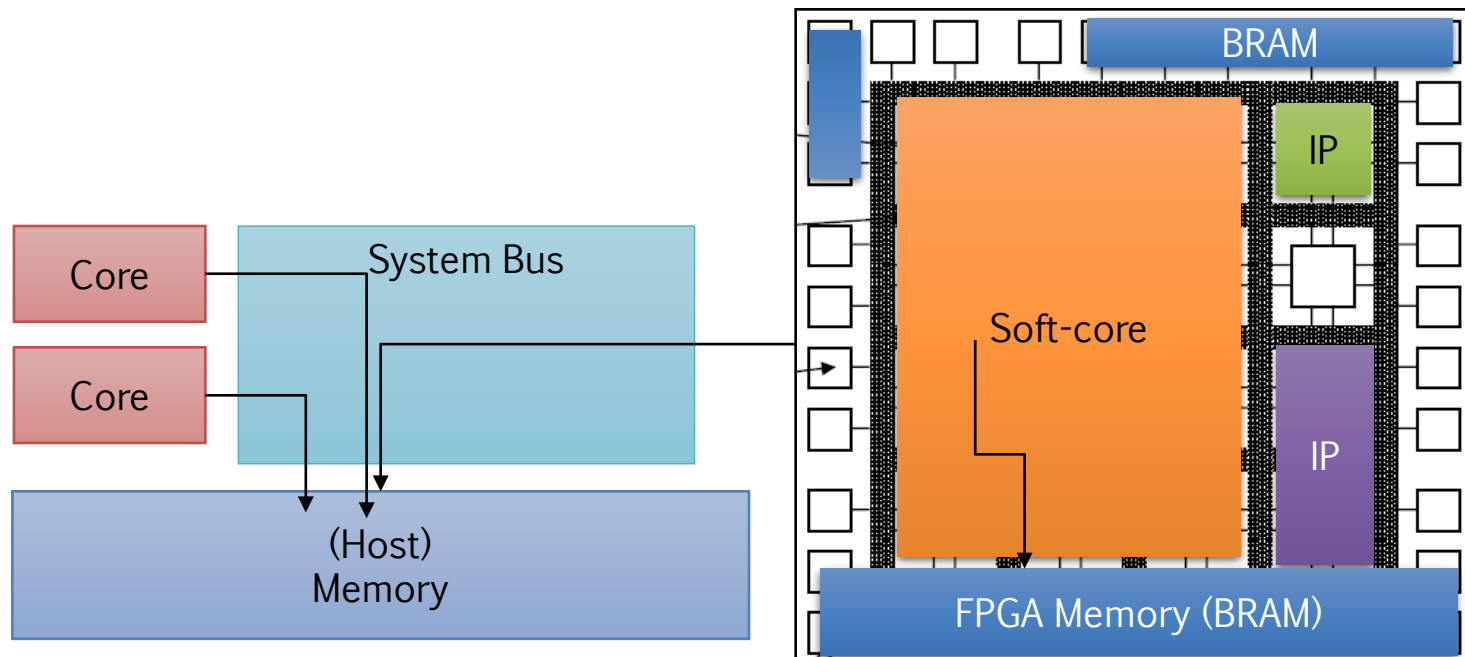


Programming heterogeneous systems

Heterogeneous programming

Besides a tool to generate the actual IPs, we need

- › A way to efficiently offload (pre-compiled) bitcode on the FPGA
 - On-the-fly Dynamic Partial Reconfiguration (DPR)
- › Simple offloading subroutines to the newly created HW blocks
 - To increase productivity
- › In case we have soft-cores, we need a toolchain to cross-compile for them





1) custom/"by hand"/CAD

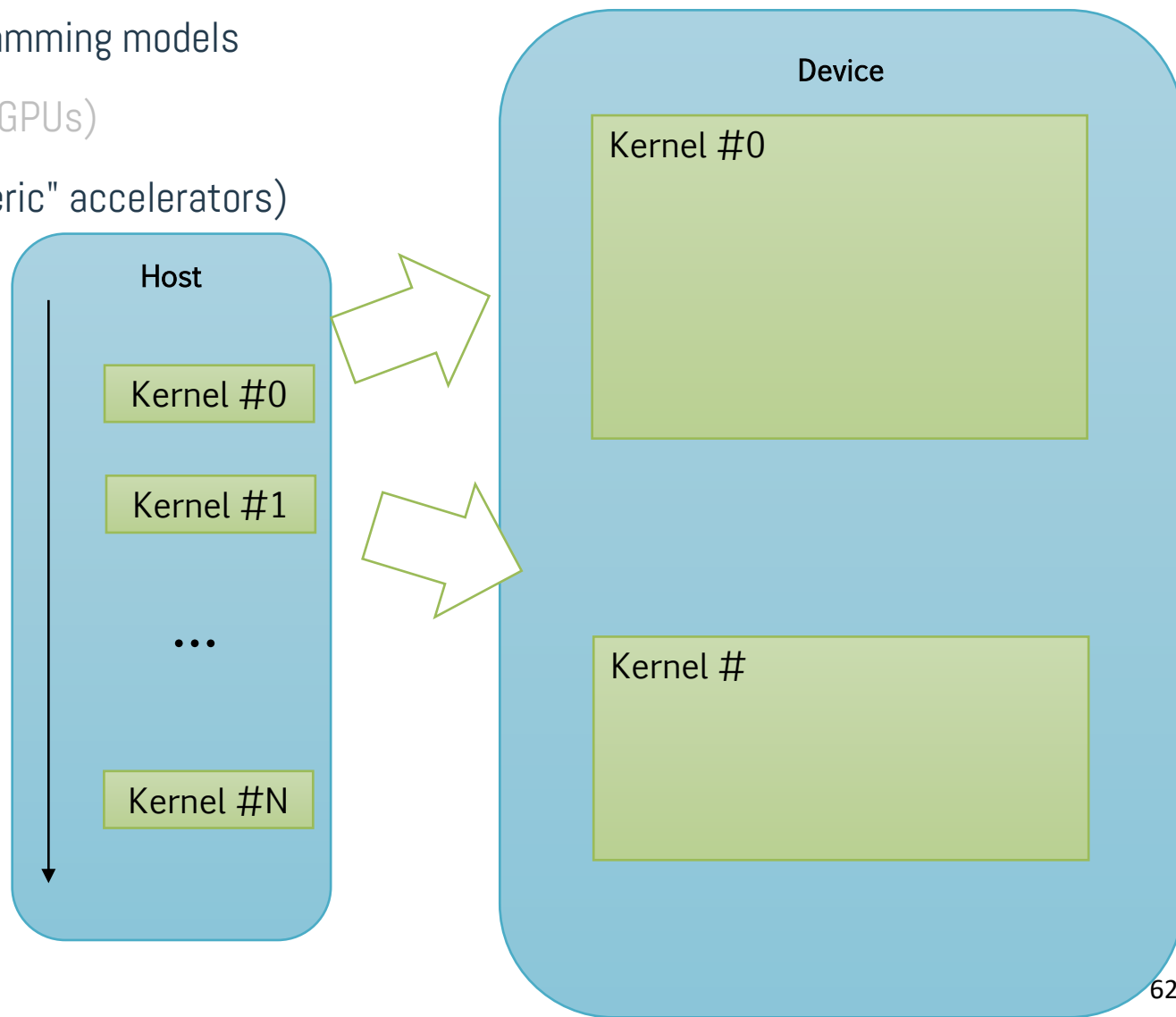
Code generated by logic synthesis tool

- › Step 1 – generate the bitcode of the accelerator
 - Vivado HLS
- › Step 2 – plug the accelerator in a design
 - Vivado
 - Include processing system (ARM host) + accelerator + IC + ...
- › Step 3 – generate the design
 - Bitcode ready to be installed of the IP
 - Architecture configuration files (memory maps...)
 - Software for host + drivers to communicate with the IP

2) offload-based programming

Offload-based programming models

- › CUDA (for NVIDIA GPUs)
- › OpenCL (for "generic" accelerators)
- › OpenMP 4.5





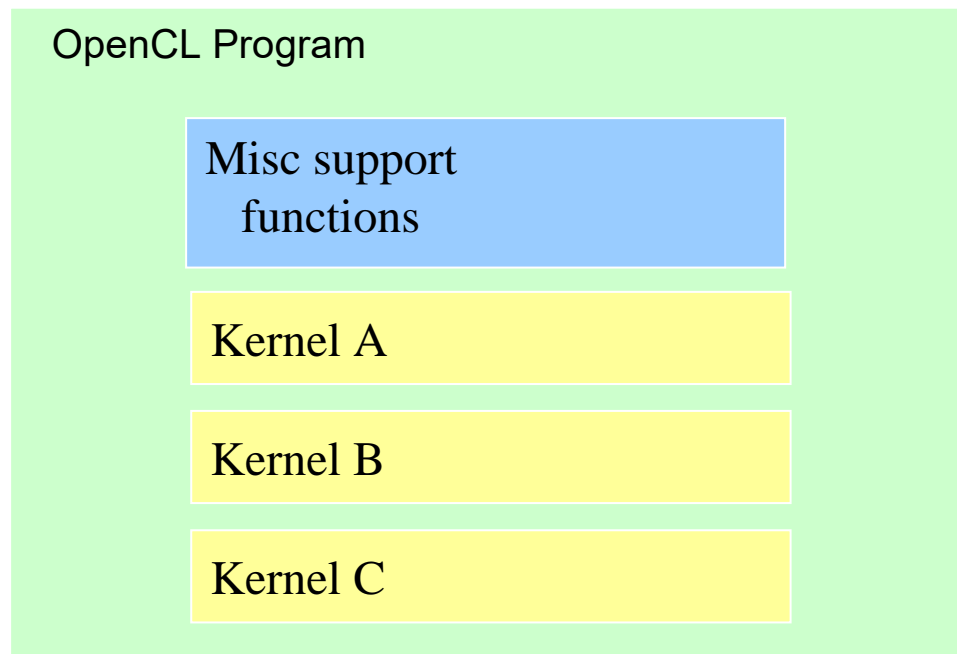
OpenCL

- › OpenCL was initiated by Apple and maintained by the Khronos Group (also home of OpenGL) as an industry standard API
 - For cross-platform parallel programming in CPUs, GPUs, DSPs, FPGAs,...
- › OpenCL host code is much more complex and tedious due to desire to maximize portability and to minimize burden on vendors



OpenCL program

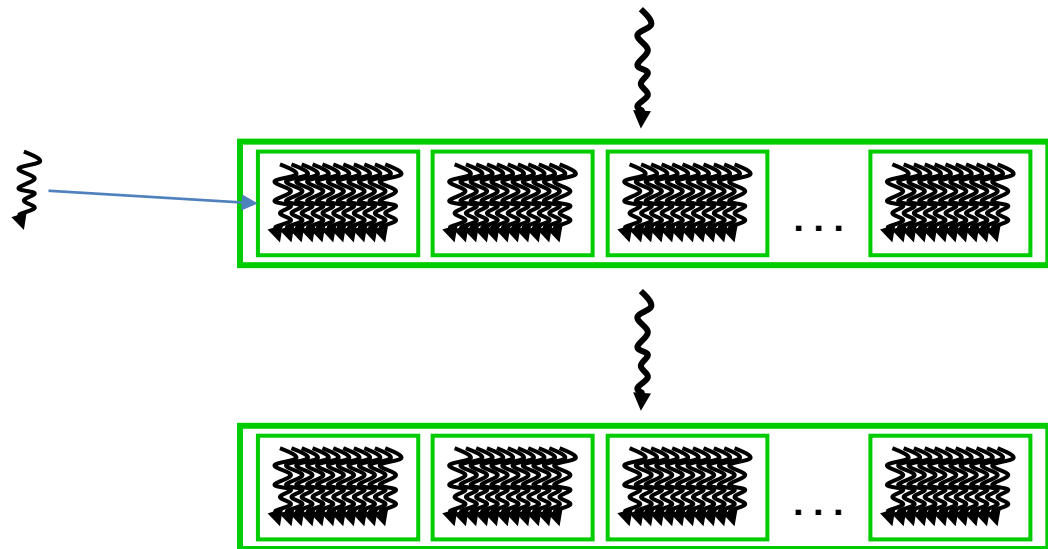
- › An OpenCL “program” is a C program that contains one or more “**kernels**” and any supporting routines that run on a target device
- › An OpenCL kernel is the basic unit of parallel code that can be executed on a target **device**
- › In our case, an FPGA





OpenCL execution model

- › Integrated host+device app C program
 - Serial or modestly parallel parts in host C code
 - Highly parallel parts in device SPMD kernel C code
- › Queues of command/data transfer to be executed on the device





OpenCL kernels – software version

- › Code that executes on target devices
- › Kernel body is instantiated N times (data parallel) – work items
- › Each OpenCL work item gets a unique index
- › In the FPGA case, we use IP drivers instead of this

```
__kernel void vadd(__global const float *a,  
                  __global const float *b,  
                  __global float *result)  
{  
    int id = get_global_id(0);  
    result[id] = a[id] + b[id];  
}
```



Host code – create exec ctx

```
cl_int clerr = CL_SUCCESS;
cl_context clctx = clCreateContextFromType(0, CL_DEVICE_TYPE_ALL, NULL, NULL,
&clerr);

size_t parmsz;
clerr = clGetContextInfo(clctx, CL_CONTEXT_DEVICES, 0, NULL, &parmsz);

cl_device_id* cldevs = (cl_device_id *) malloc(parmsz);
clerr = clGetContextInfo(clctx, CL_CONTEXT_DEVICES, parmsz, cldevs, NULL);

cl_command_queue clcmdq = clCreateCommandQueue(clctx, cldevs[0], 0, &clerr);
```



Host code – create data buffers

```
float *h_A = ..., *h_B = ...;
// allocate device (GPU) memory
cl_mem d_A, d_B, d_C;
d_A = clCreateBuffer(clctx, CL_MEM_READ_ONLY |
    CL_MEM_COPY_HOST_PTR, N *sizeof(float), h_A, NULL);
d_B = clCreateBuffer(clctx, CL_MEM_READ_ONLY |
    CL_MEM_COPY_HOST_PTR, N *sizeof(float), h_B, NULL);
d_C = clCreateBuffer(clctx, CL_MEM_WRITE_ONLY,
    N *sizeof(float), NULL, NULL);
```



Host code – device config setting

```
clkern=clCreateKernel(clpgm, "vadd", NULL);  
  
...  
clerr= clSetKernelArg(clkern, 0, sizeof(cl_mem), (void *)&d_A);  
clerr= clSetKernelArg(clkern, 1, sizeof(cl_mem), (void *)&d_B);  
clerr= clSetKernelArg(clkern, 2, sizeof(cl_mem), (void *)&d_C);  
clerr= clSetKernelArg(clkern, 3, sizeof(int), &N);
```



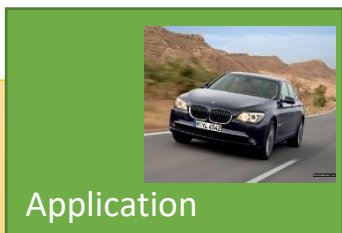
Host code – kernel launch

```
cl_event event=NULL;
clerr= clEnqueueNDRangeKernel(clcmdq, clkern, 2, NULL,
    Gsz, Bsz, 0, NULL, &event);
clerr= clWaitForEvents(1, &event);
clEnqueueReadBuffer(clcmdq, d_C, CL_TRUE, 0,
    N*sizeof(float), h_C, 0, NULL, NULL);
clReleaseMemObject(d_A);
clReleaseMemObject(d_B);
clReleaseMemObject(d_C);
}
```

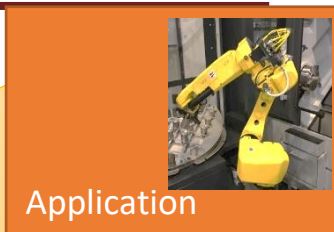


The Hercules framework

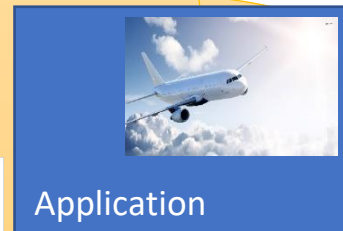
HERCULES



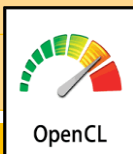
Application



Application



Application

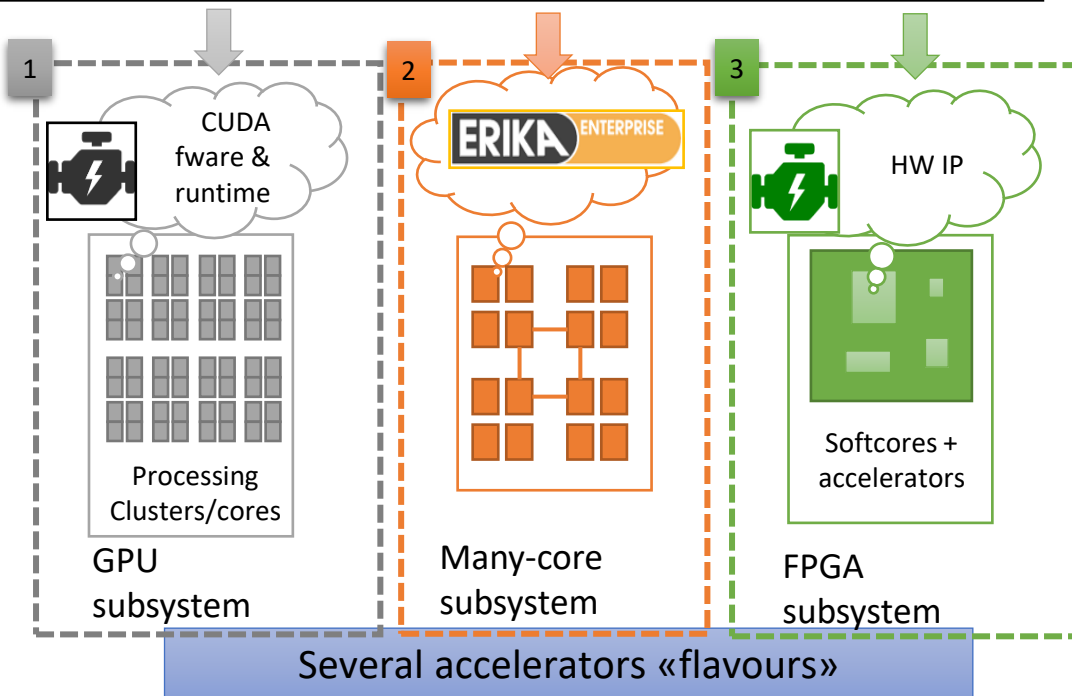
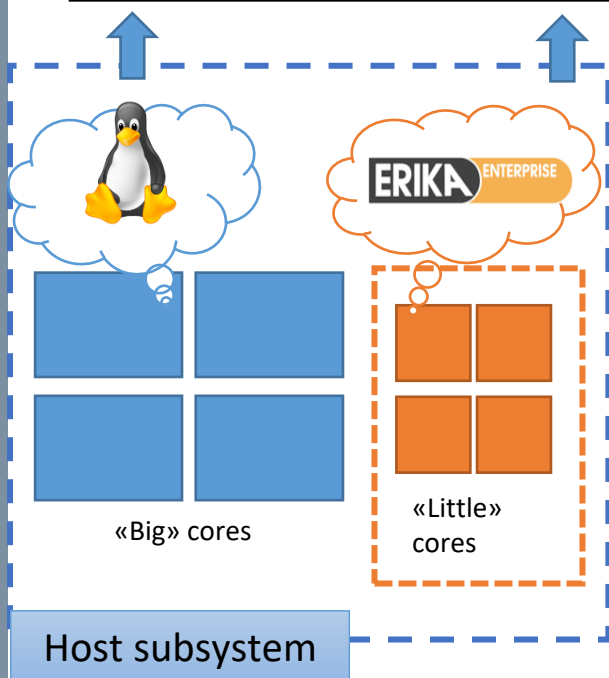


Programming model



Platform Abstraction

Offloading mechanism and communication API

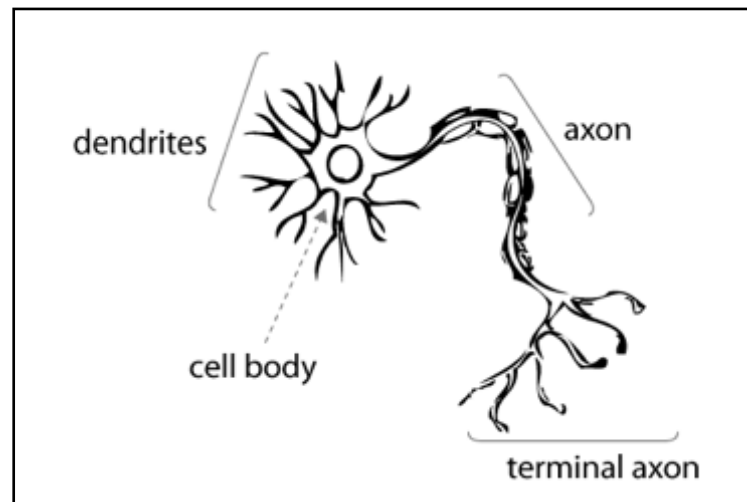
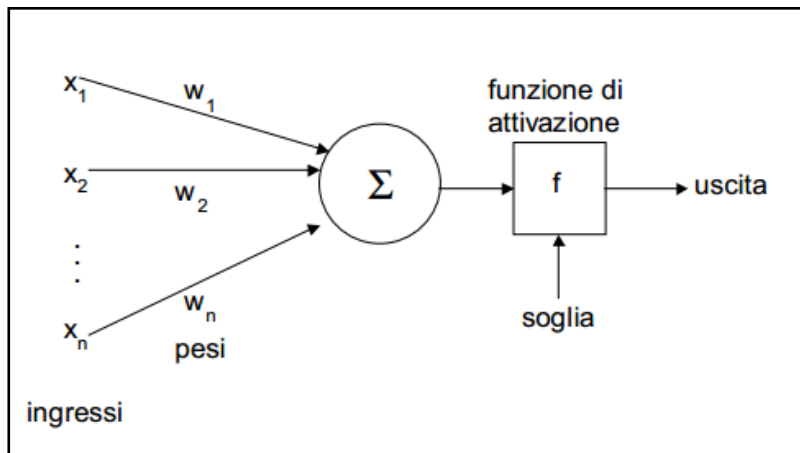




Neural Networks on FPGA accelerators

Neural networks

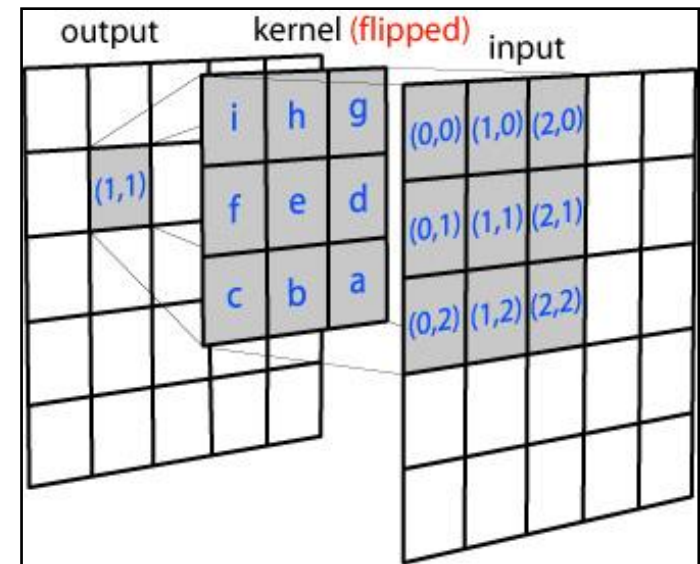
- › Bio-inspired
- › Based on neurons arranged in layers
 - And sub-layers
- › Convolutional neural network
 - Perform Convolutions



Convolution

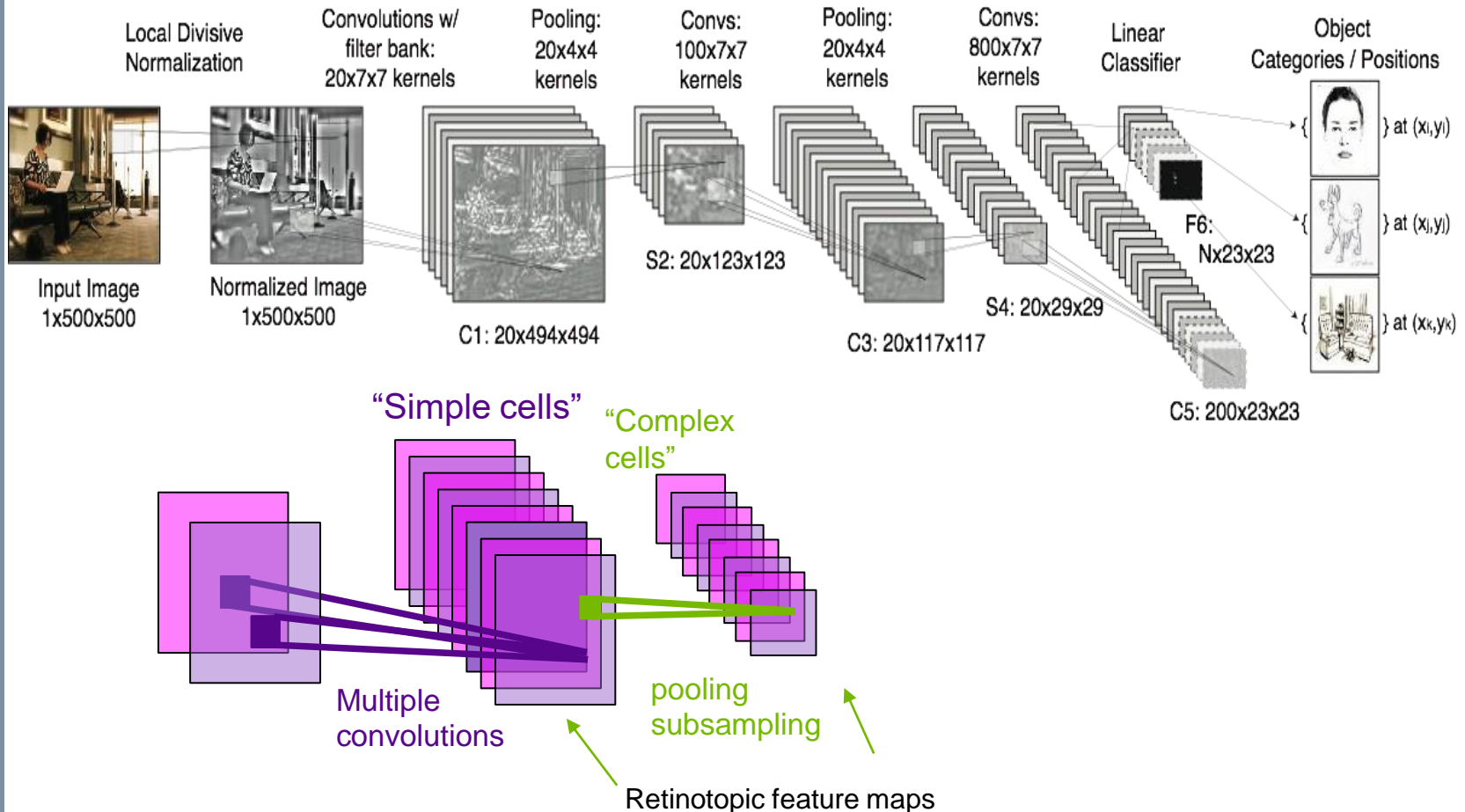
- › Computation-intensive
- › Suitable for implementation in hardware
- › In computer vision, blurring

$$\begin{aligned}
 (f * g)(t) &\stackrel{\text{def}}{=} \int_{-\infty}^{\infty} f(\tau)g(t - \tau) d\tau \\
 &= \int_{-\infty}^{\infty} f(t - \tau)g(\tau) d\tau.
 \end{aligned}$$



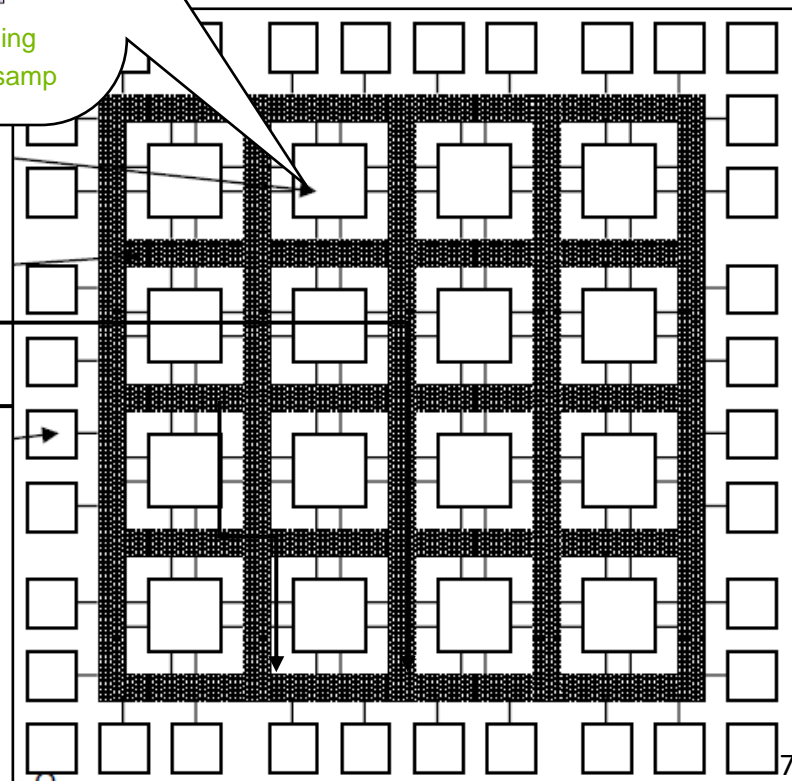
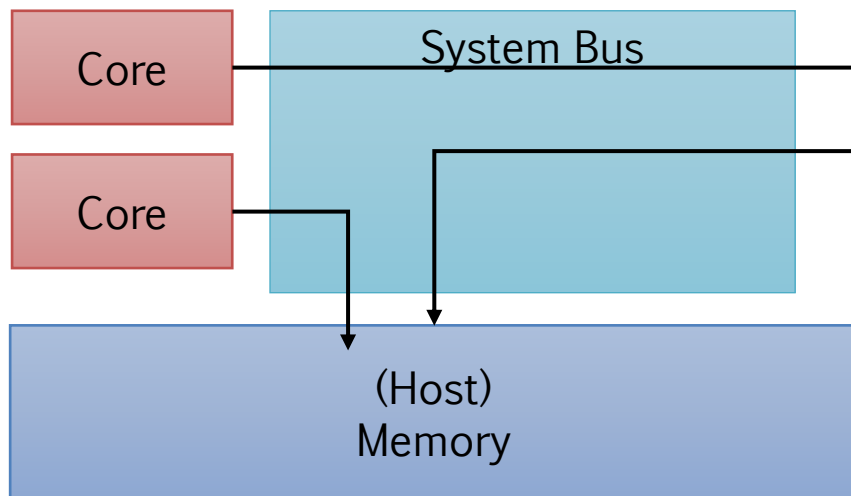
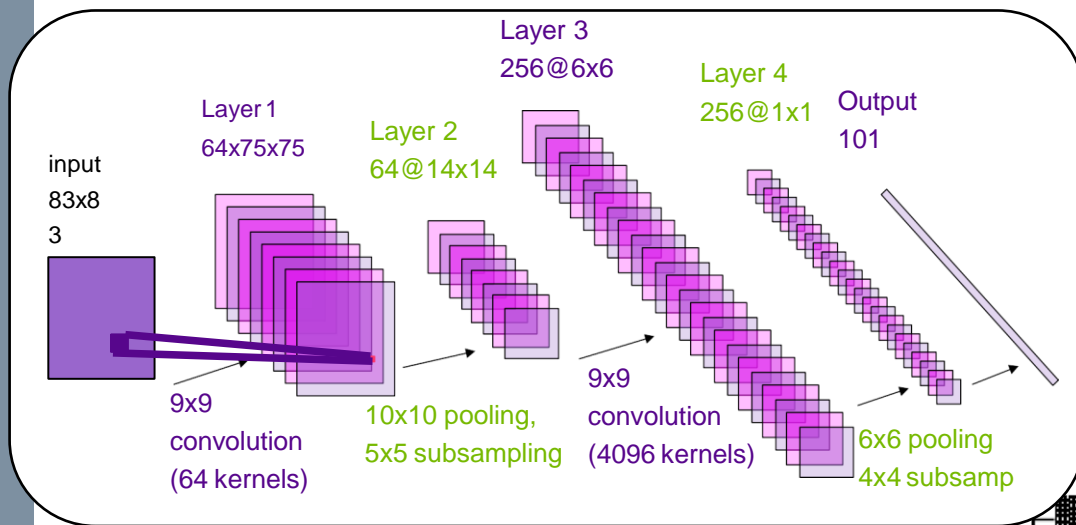
The convolutional net model

› (Multistage Hubel-Wiesel system)





The convolutional net model (cont'd)





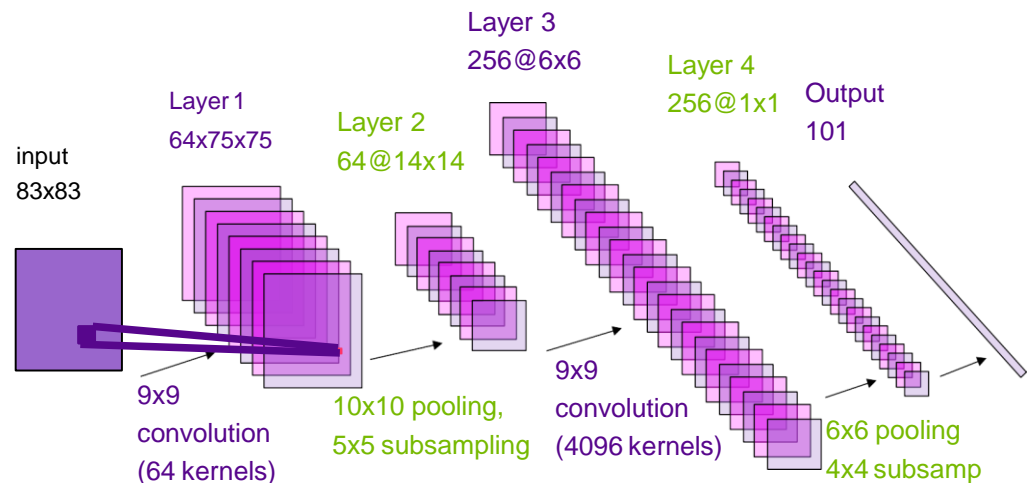
Network parameters

Network topology

- › How many layers and sublayers?
- › How big they are?
- › How are they connected?

Neuron type

- › CNN
- › int/float datatypes
- › How to perform pooling?





Course website

- › http://hipert.unimore.it/people/paolob/pub/Industrial_Informatics/index.html

My contacts

- › paolo.burgio@unimore.it
- › <http://hipert.mat.unimore.it/people/paolob/>

Resources

- › Xilinx Zynq-7000 All Programmable SoC => <https://www.xilinx.com/products/silicon-devices/soc/zynq-7000.html>
- › Pynq => <http://www.pynq.io/>
- › Xilinx Ultrascale => <https://www.xilinx.com/products/technology/ultrascale.html>
- › A "small blog" => <http://www.google.com>