



UNIMORE
UNIVERSITÀ DEGLI STUDI DI
MODENA E REGGIO EMILIA



Field-Programmable Gate Arrays

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Outline

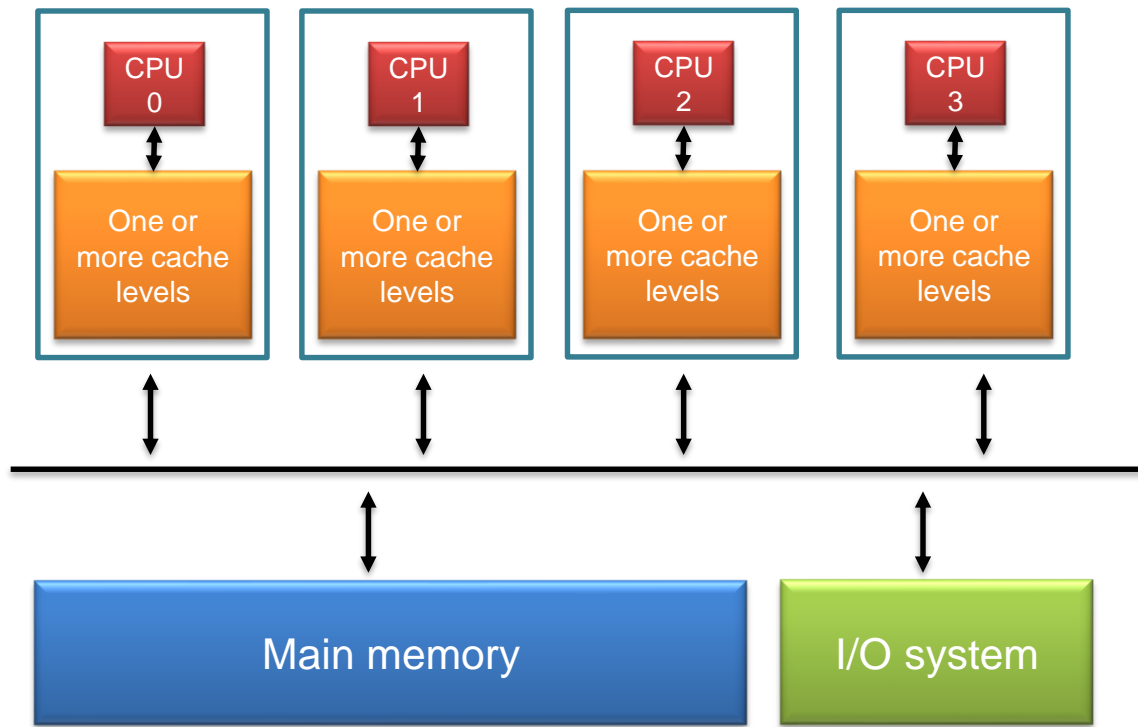
- ✓ Introduction to FPGAs
- ✓ How to use them
- ✓ Heterogeneous programming
- ✓ FPGA-based heterogeneous programming
- ✓ How to program it
- ✓ Xilinx: now and soon...



The world, till now

- ✓ (A) Symmetric multi-processing
 - Single or multi-core

Can be 1 bus, N busses, or any network

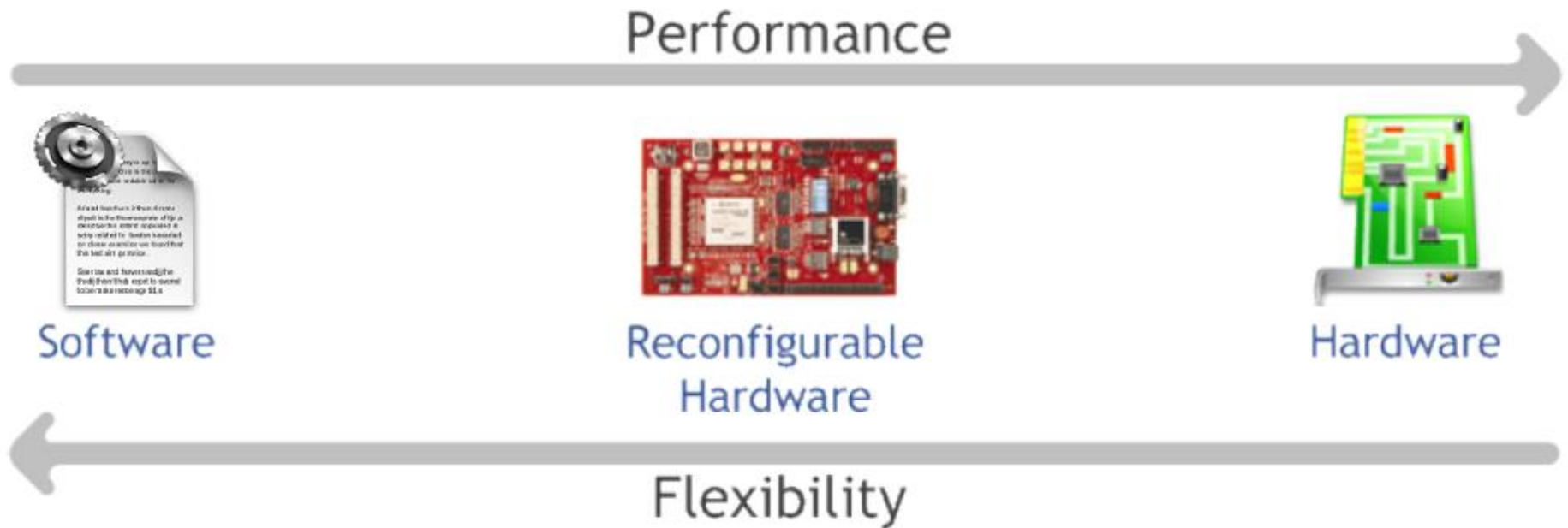




Reconfigurable Hardware

“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)

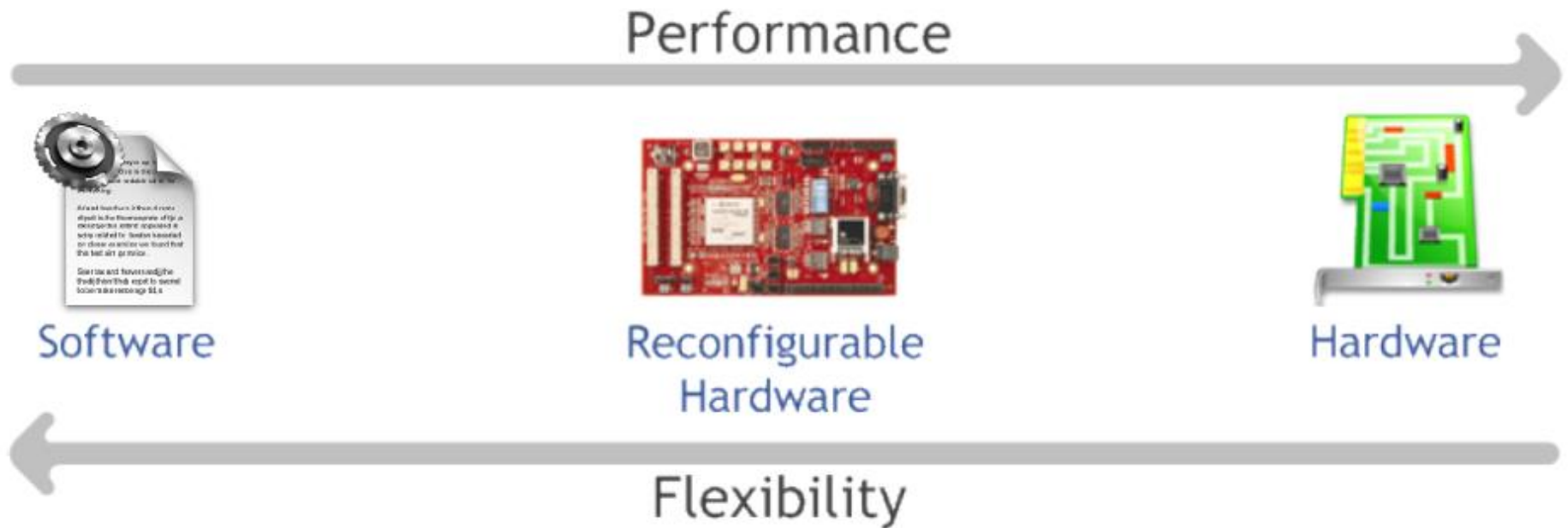




...eh?

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
 - DSPs, co-processors





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 echnologies

- ✓ 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 energy-efficient than a GPU
 - **Way** more flexible

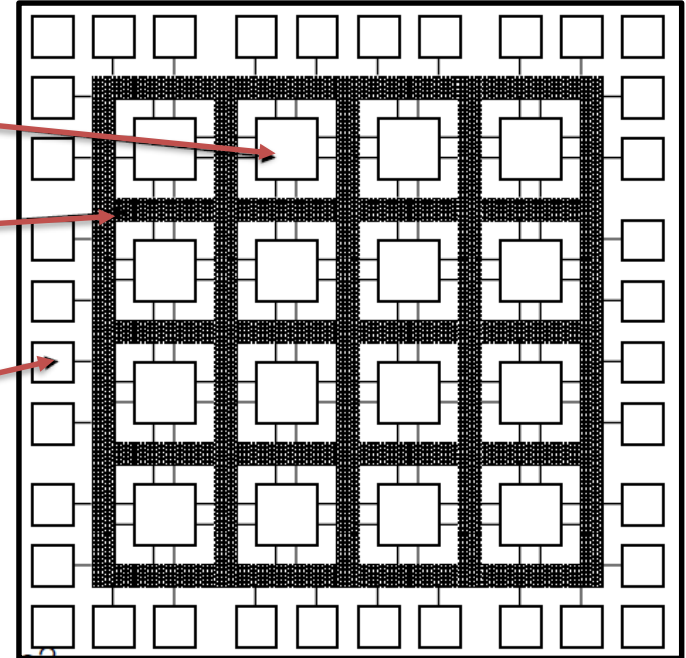
Integrated into System-on-chips

- ✓ 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

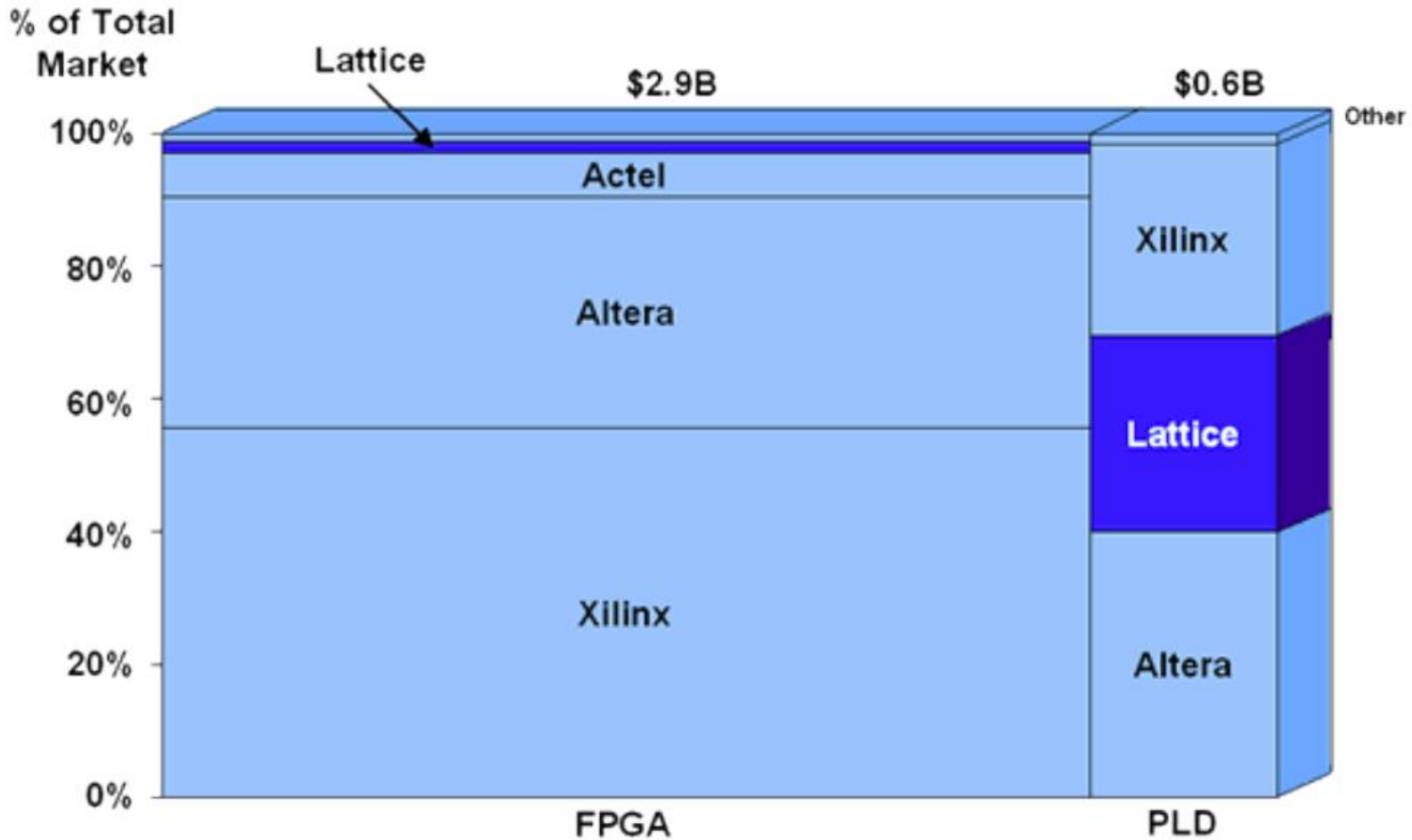


Key questions:

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



Commercial FPGA companies

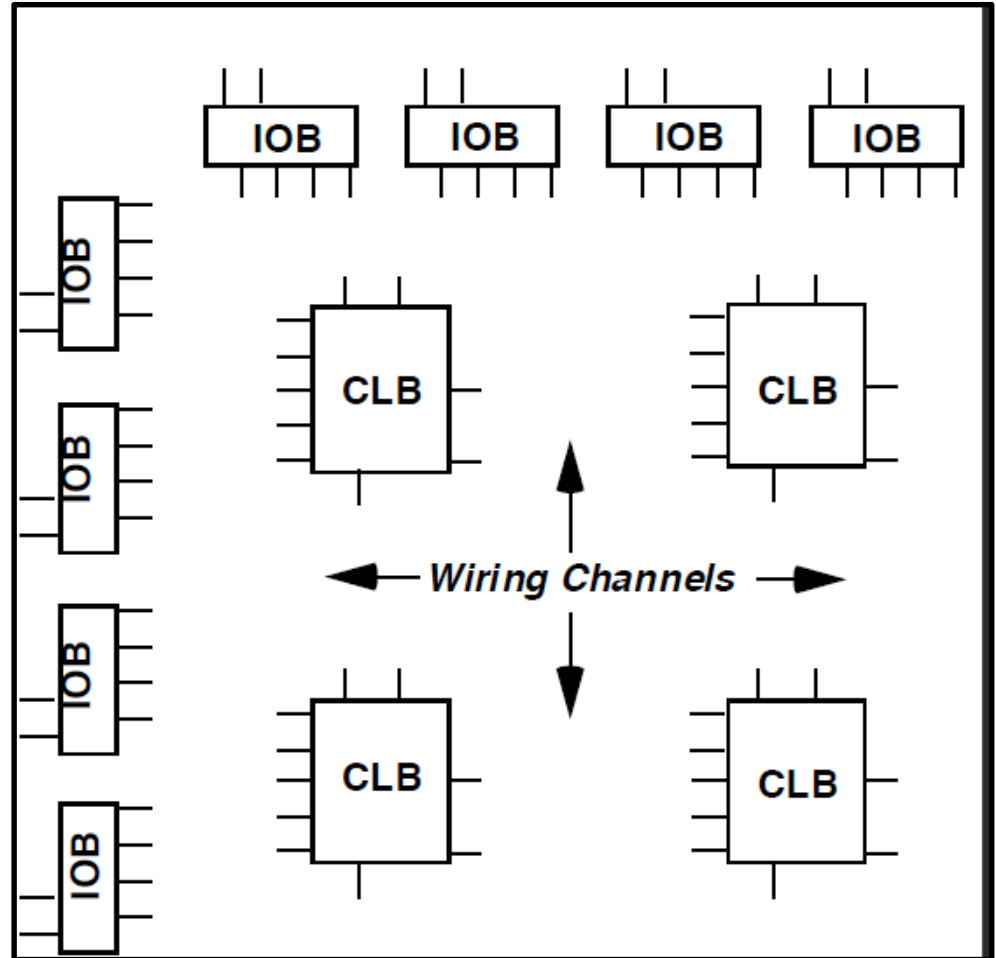




(Xilinx) Programmable Gate Arrays

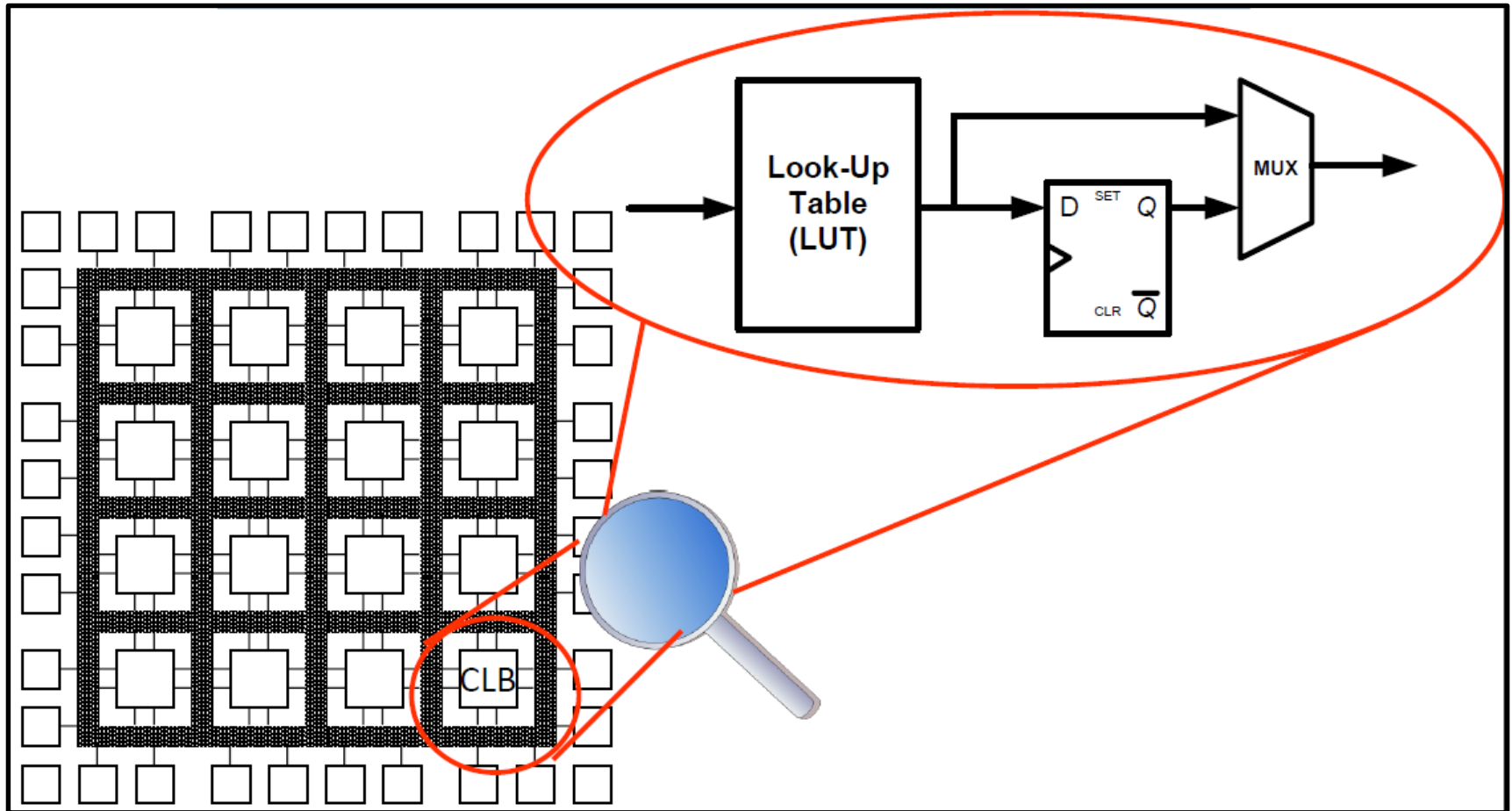
CLB - Configurable Logic Block

- ✓ 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

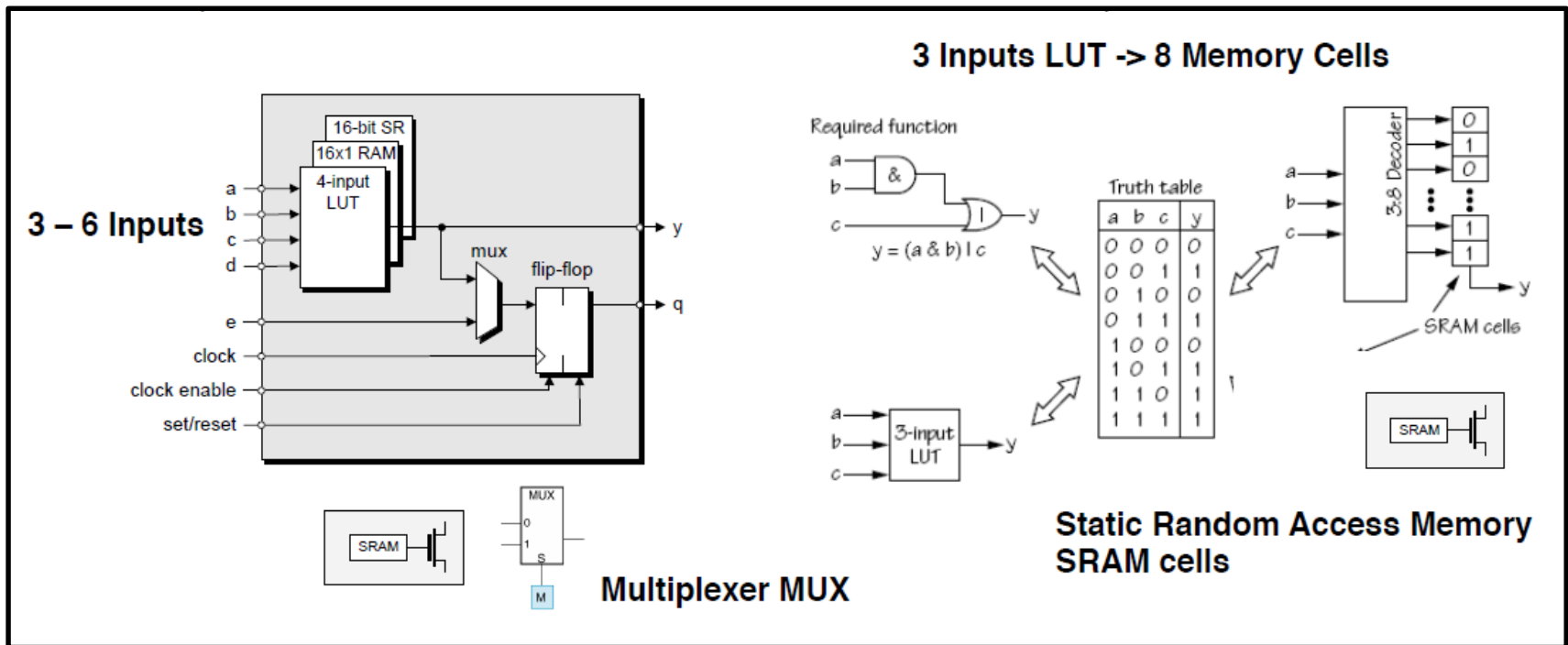




LookUp Tables

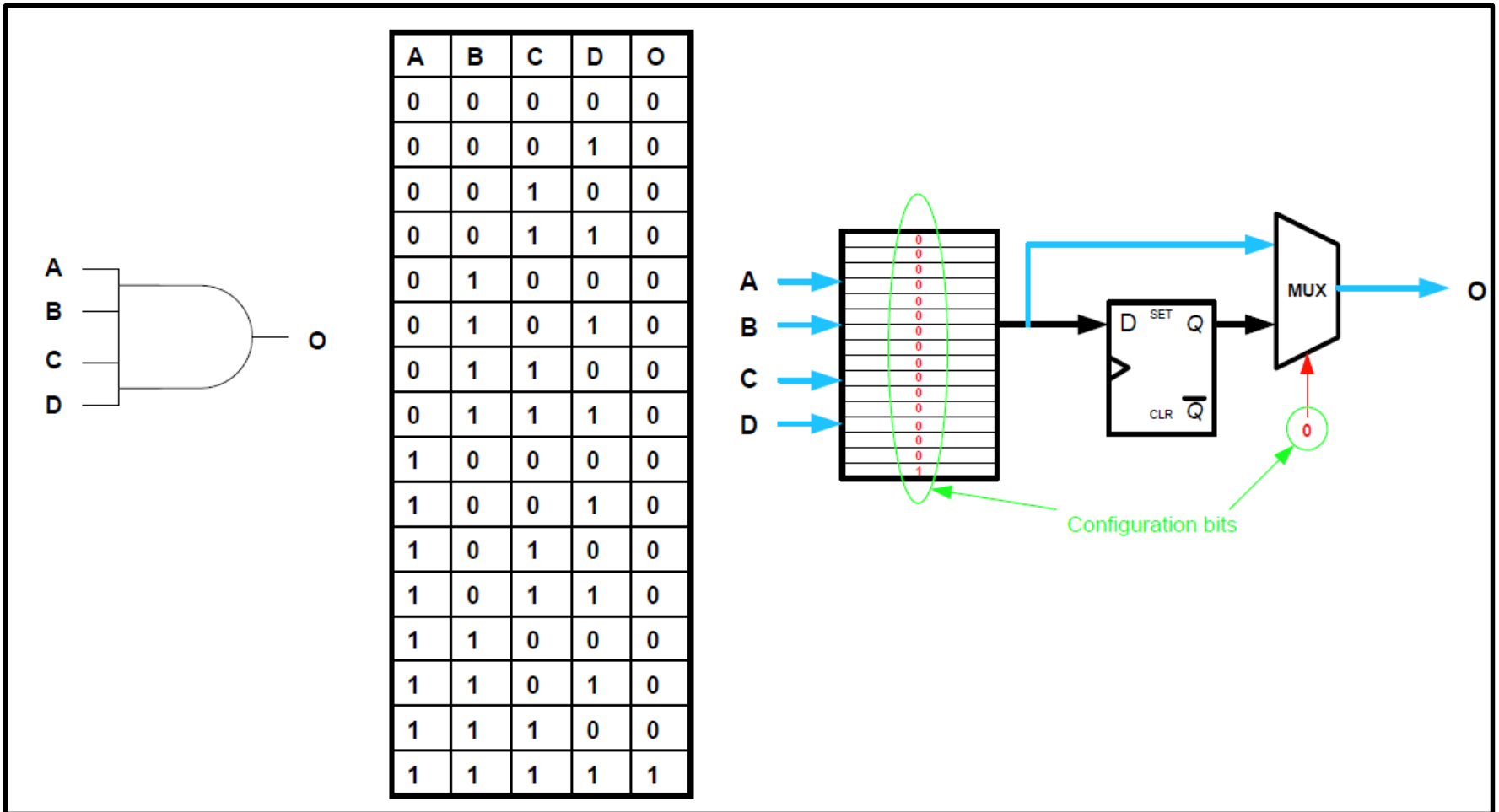
LUT contains Memory Cells to implement small logic functions

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



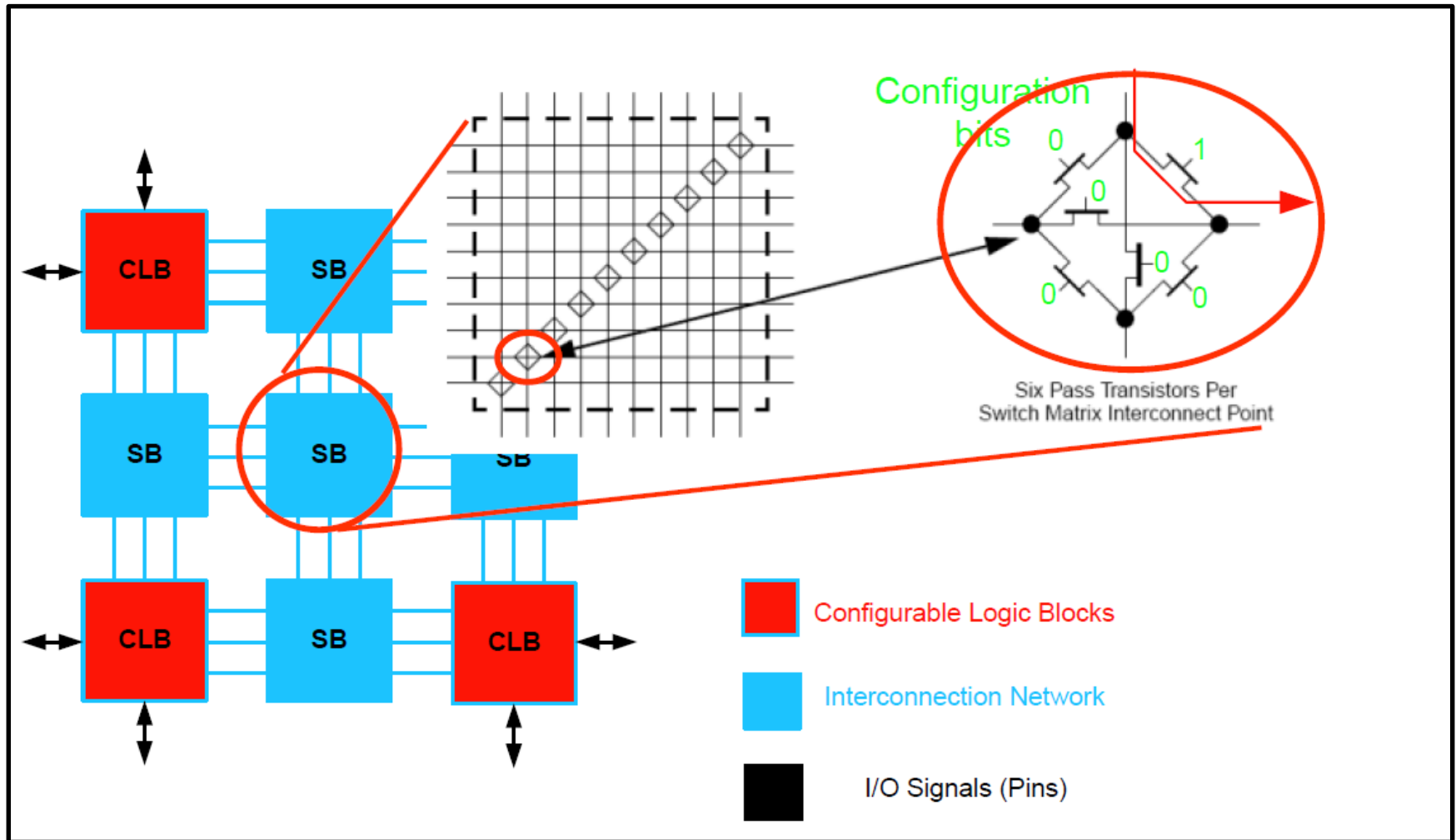


Example: 4-input AND gate





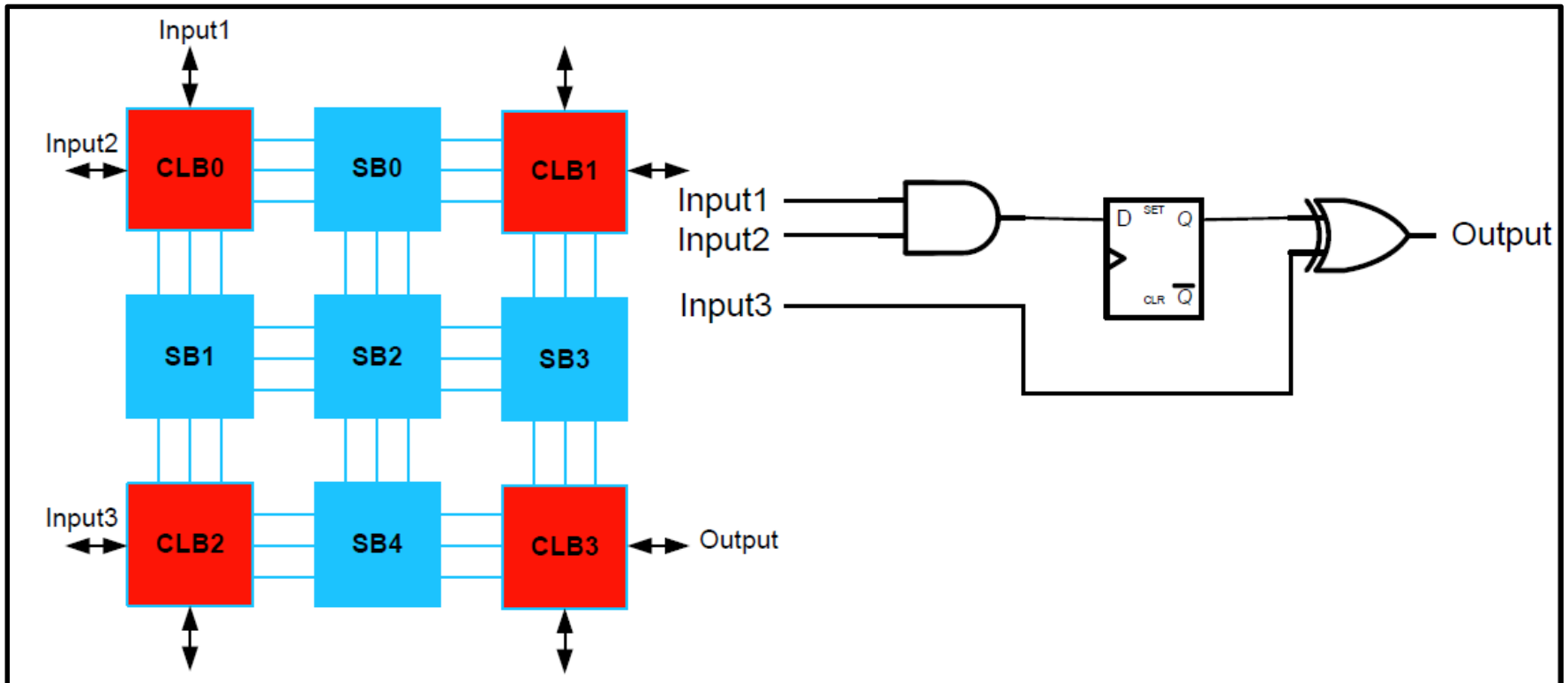
Interconnection Network





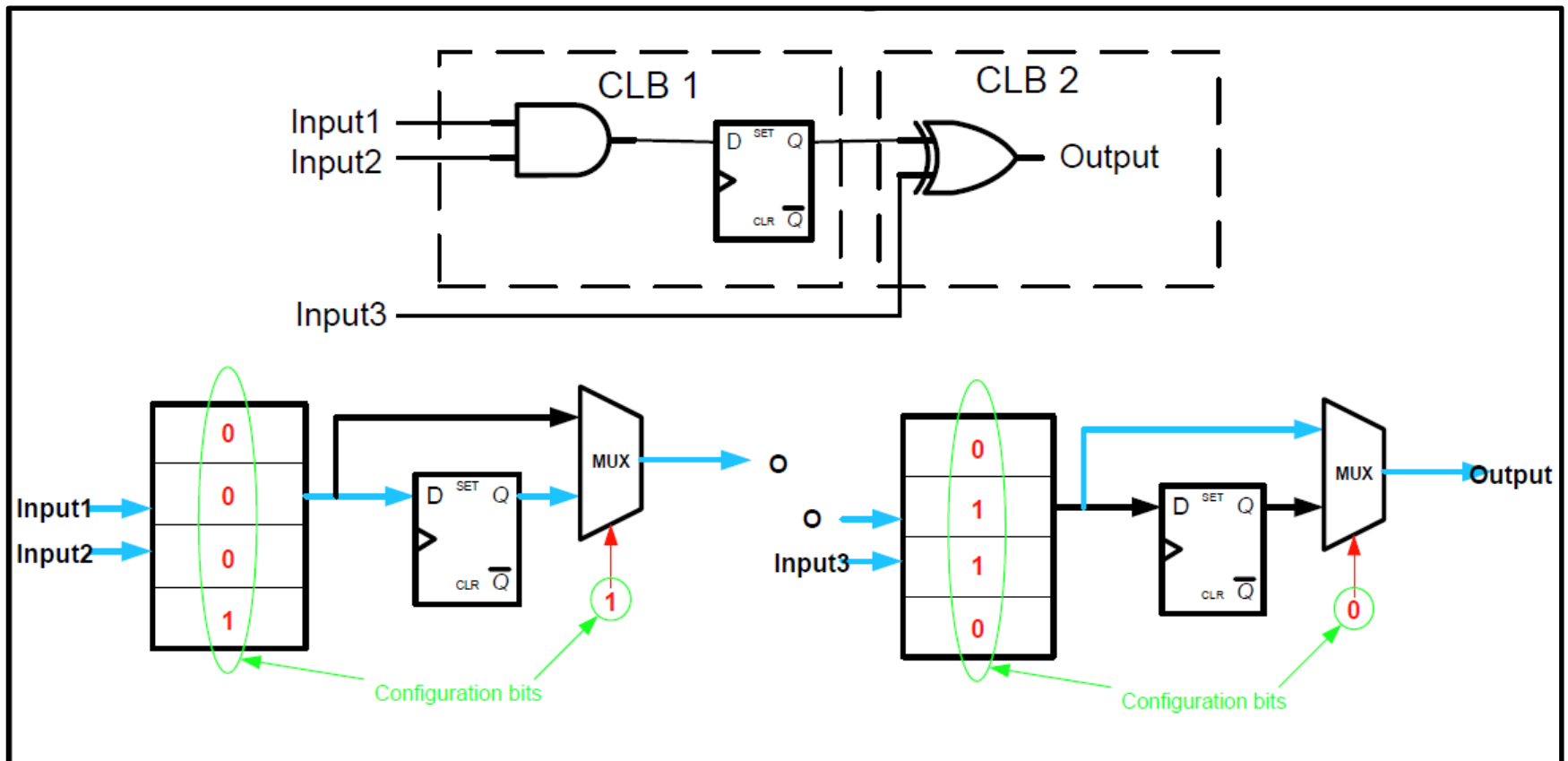
Example

- ✓ 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



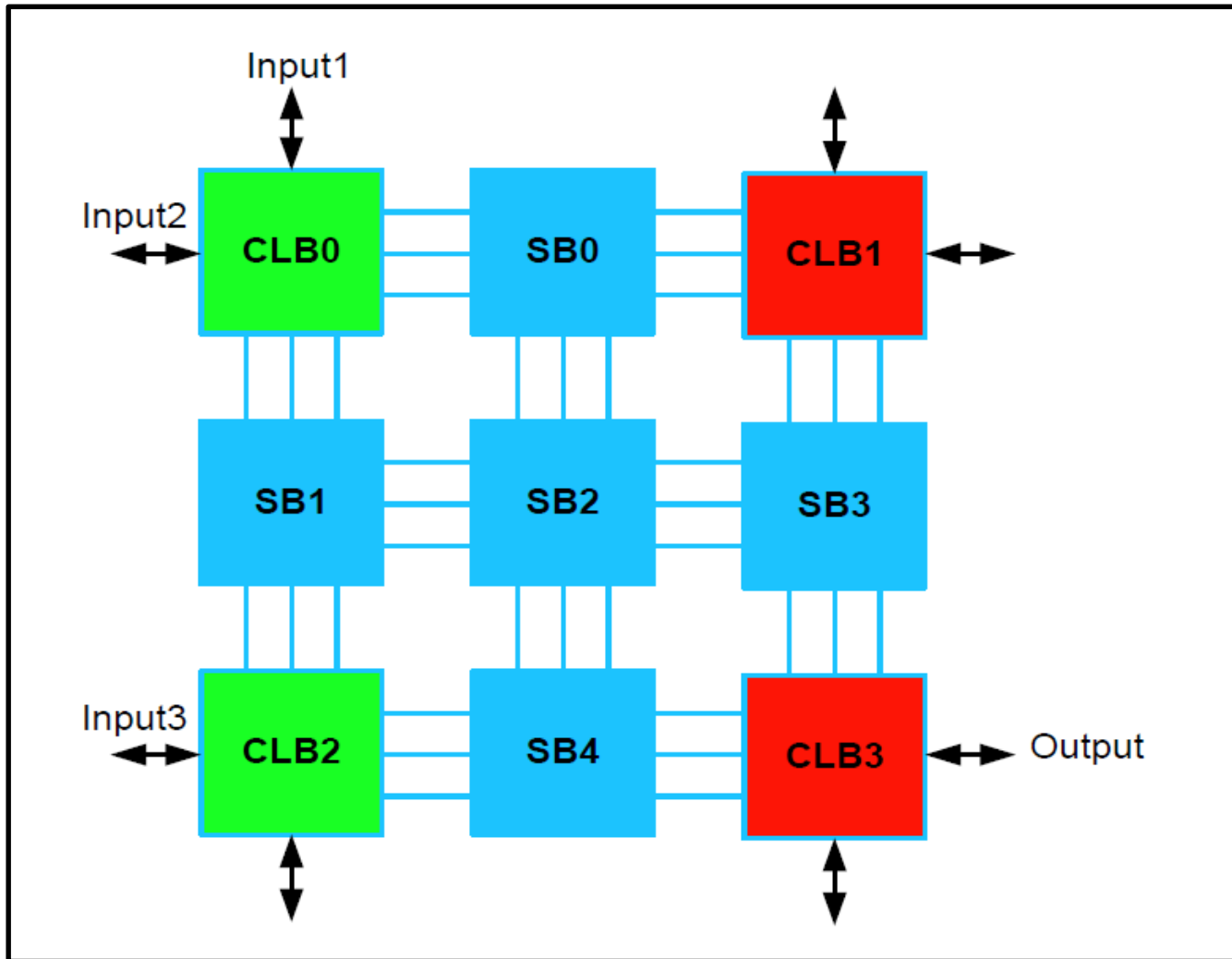


Configure CLBs



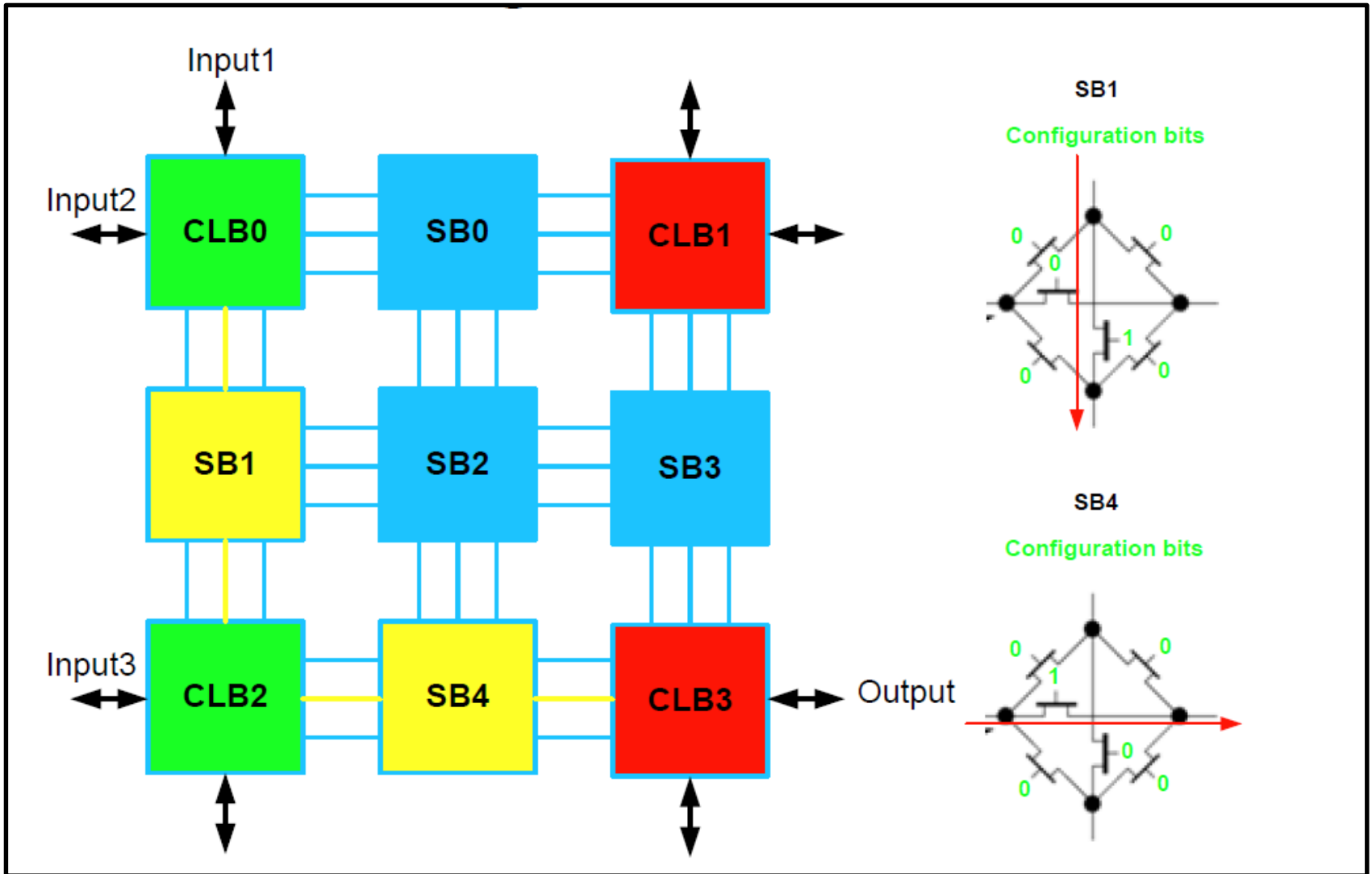


Placement: select CLBs





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

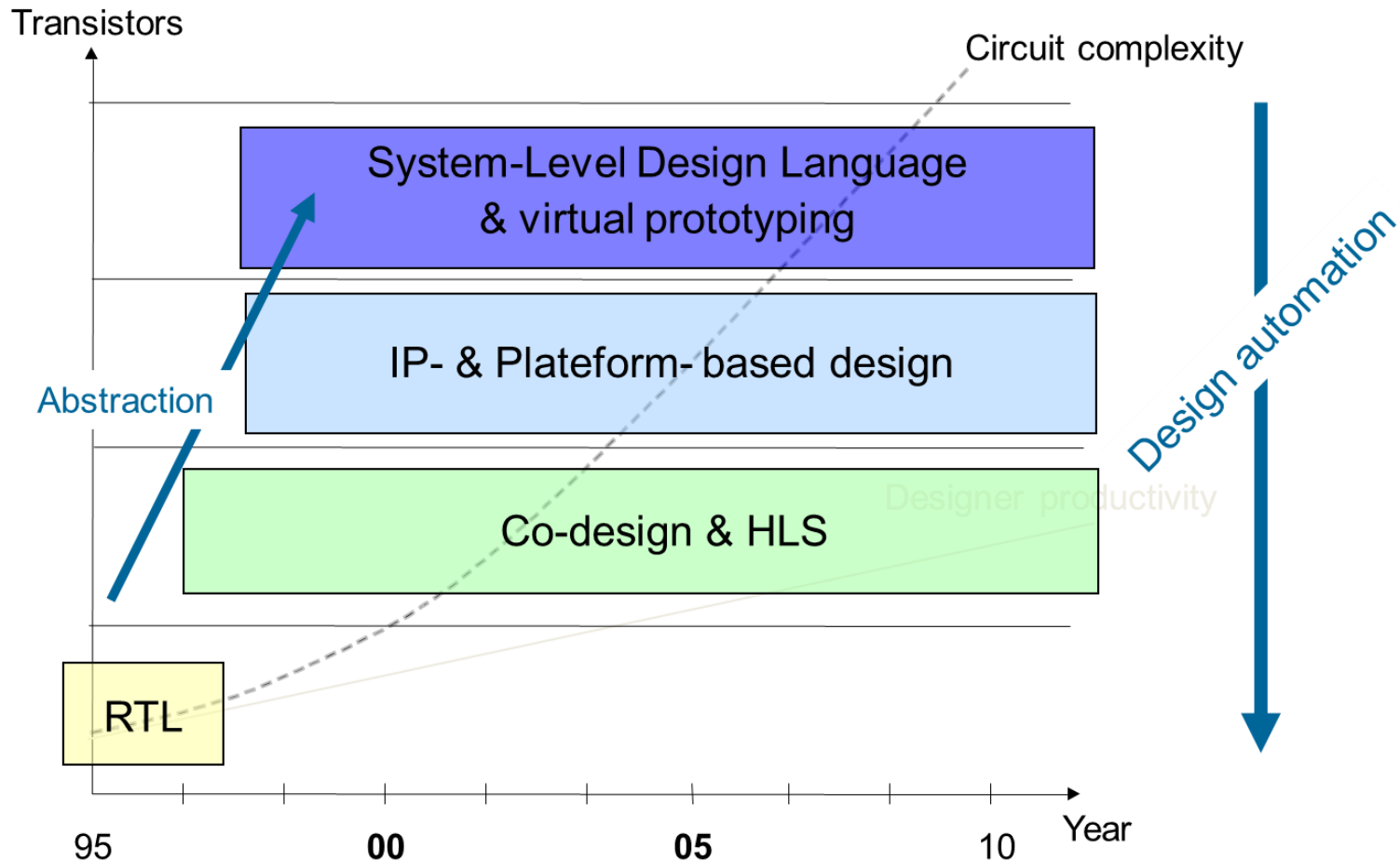
- ✓ Generate programming files - bits to be loaded into chip for configuration



High-level synthesis



Electronic System Level Design (ESLD)

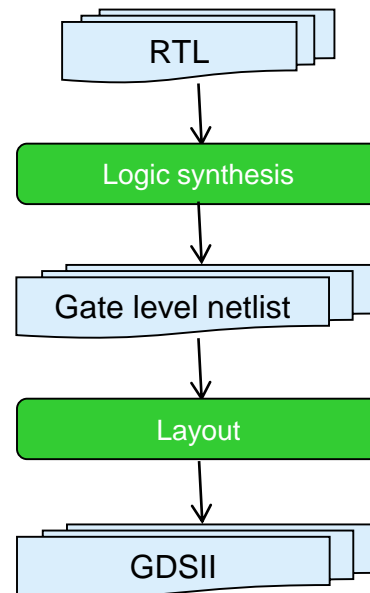
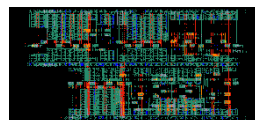
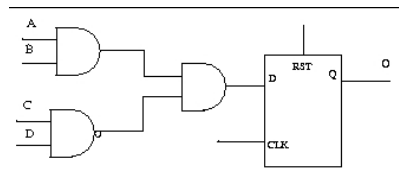




Typical HW design flow

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

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





Typical HW design flow

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

```

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

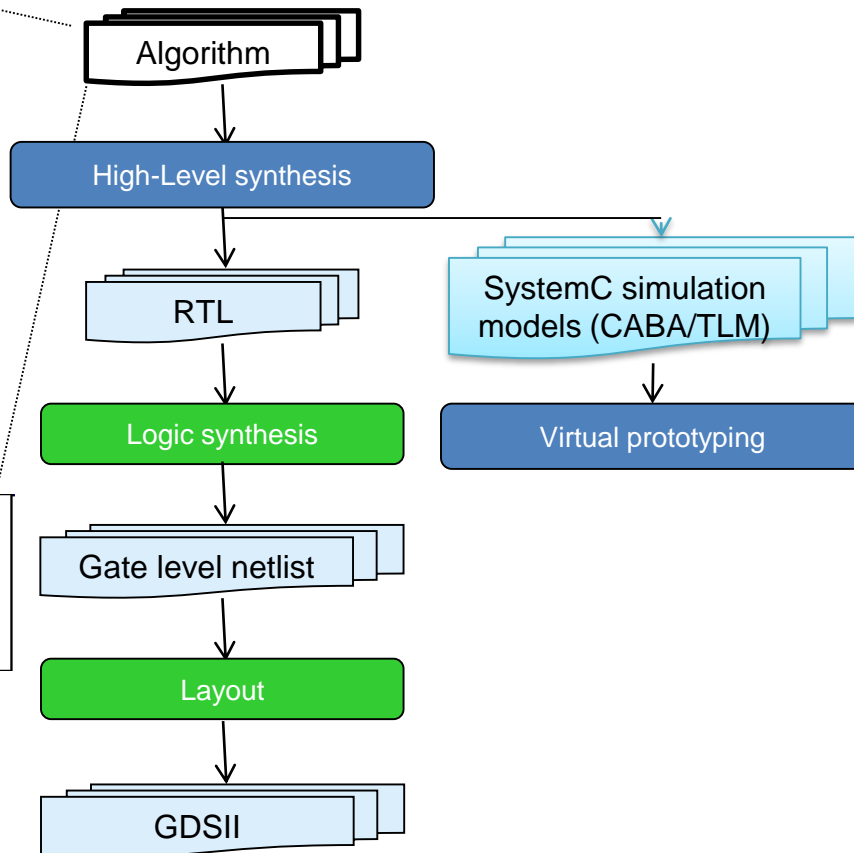
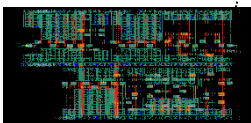
int main(const matrix A, matrix C)
{
    const matrice B = {{1, 2},{ 3, 4}};
    int tmp;
    int i,j,k;

    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;
}

```



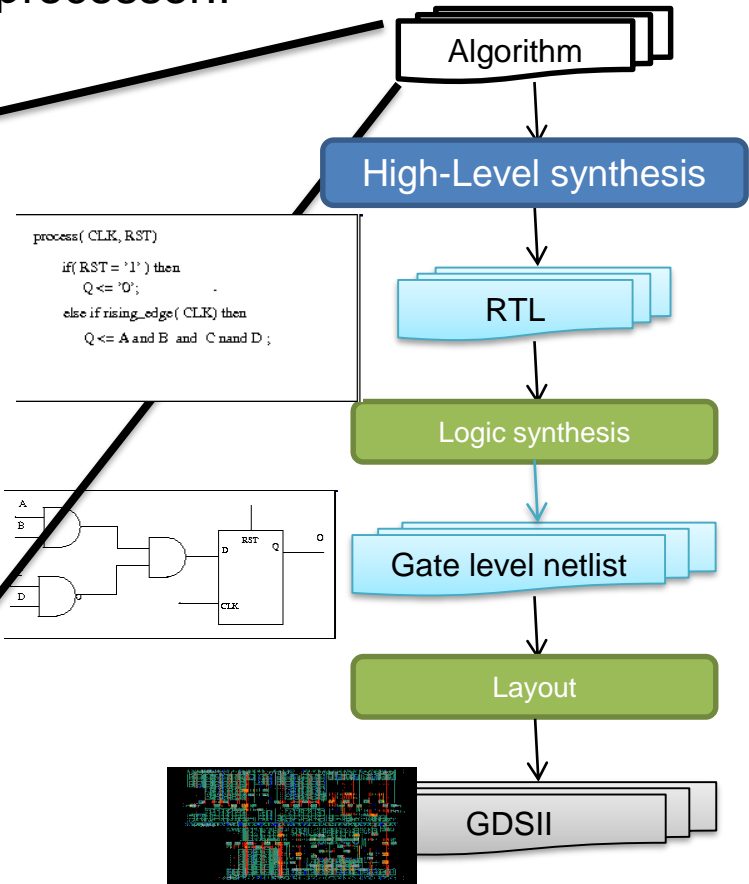


High-Level Synthesis

- ✓ 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 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;
}
```





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;
}
```




High-level transformations

✓ Loops

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

✓ Arrays mapping

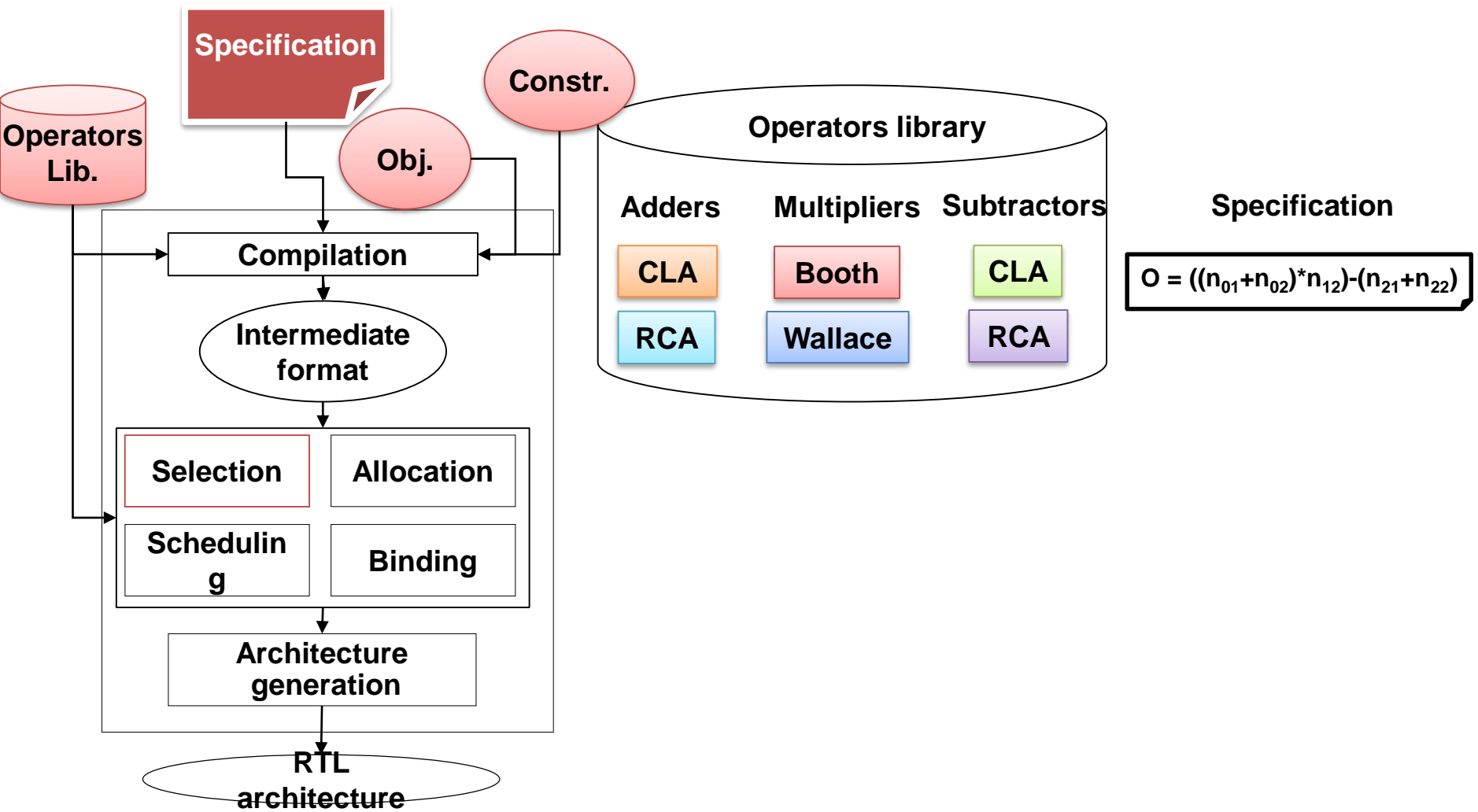
- Arrays can be mapped on memory banks
- Arrays can be synthesized as registers
- Constant arrays can be synthesized as logic
- ...

✓ Functions

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

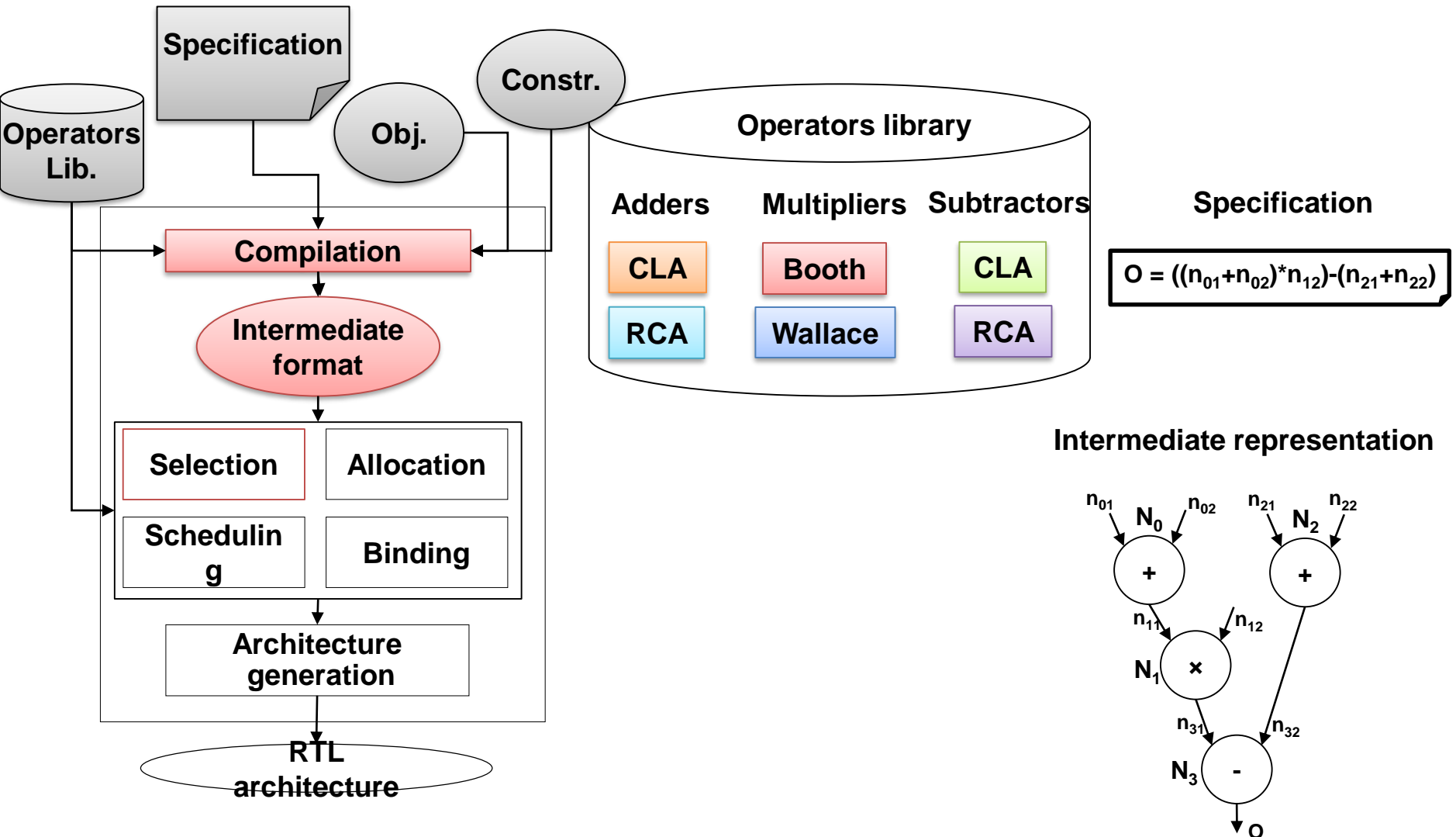


HLS steps: Inputs



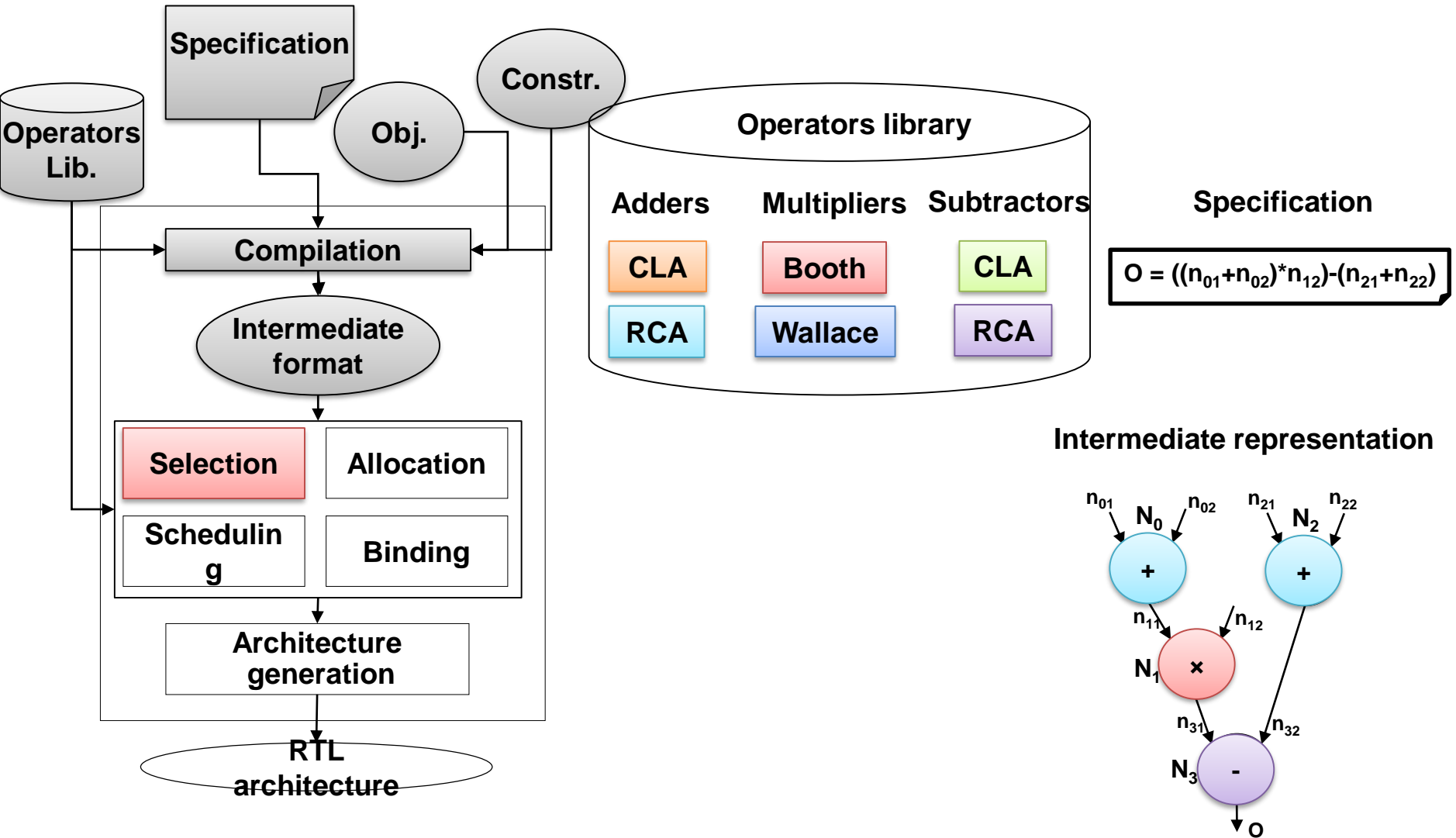


HLS steps: Compilation



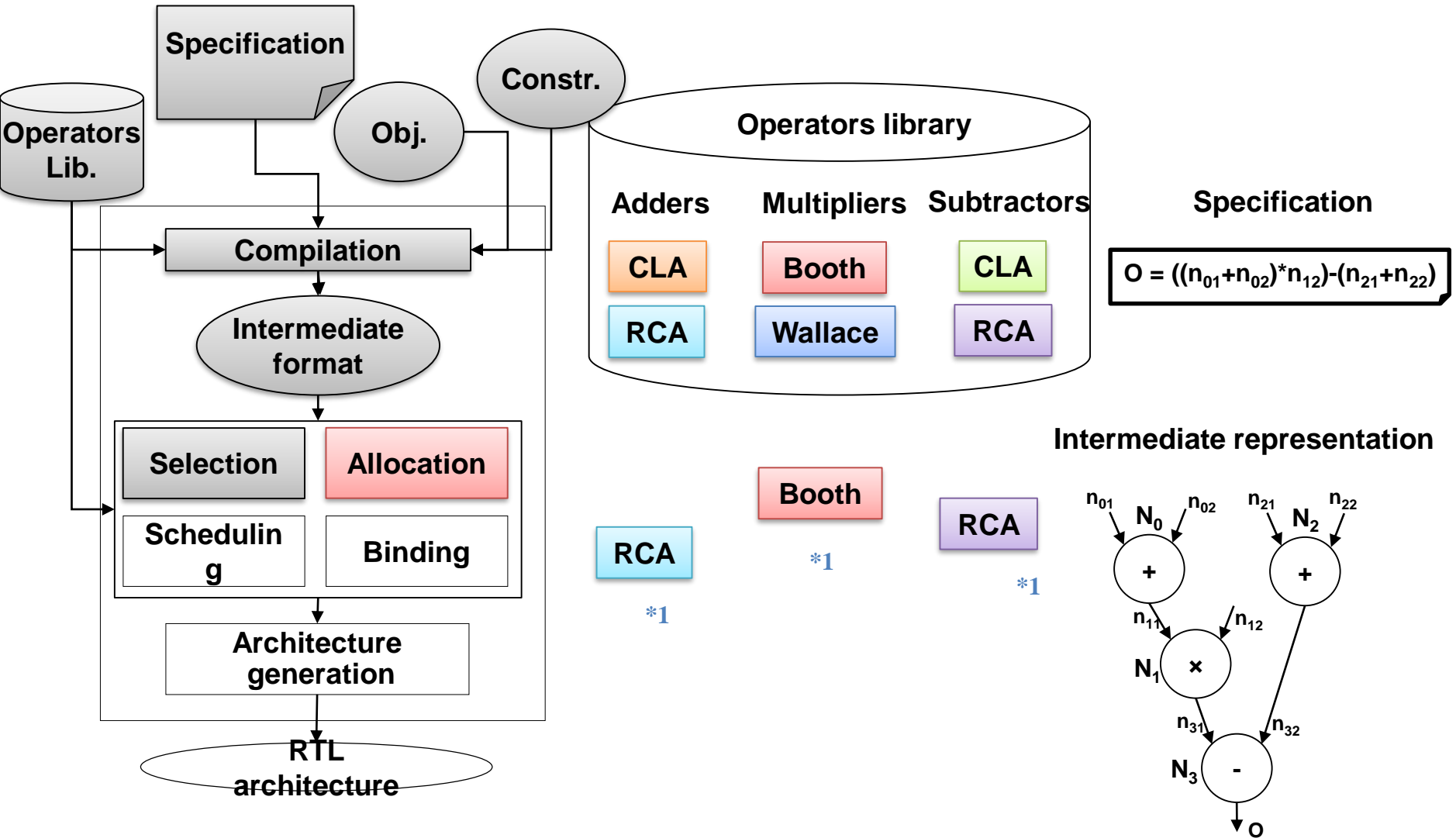


HLS steps: Selection



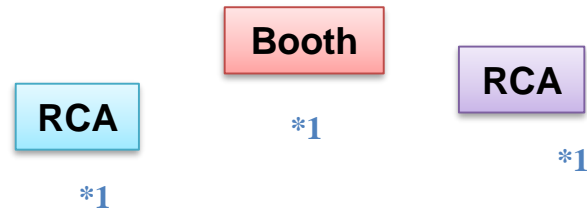
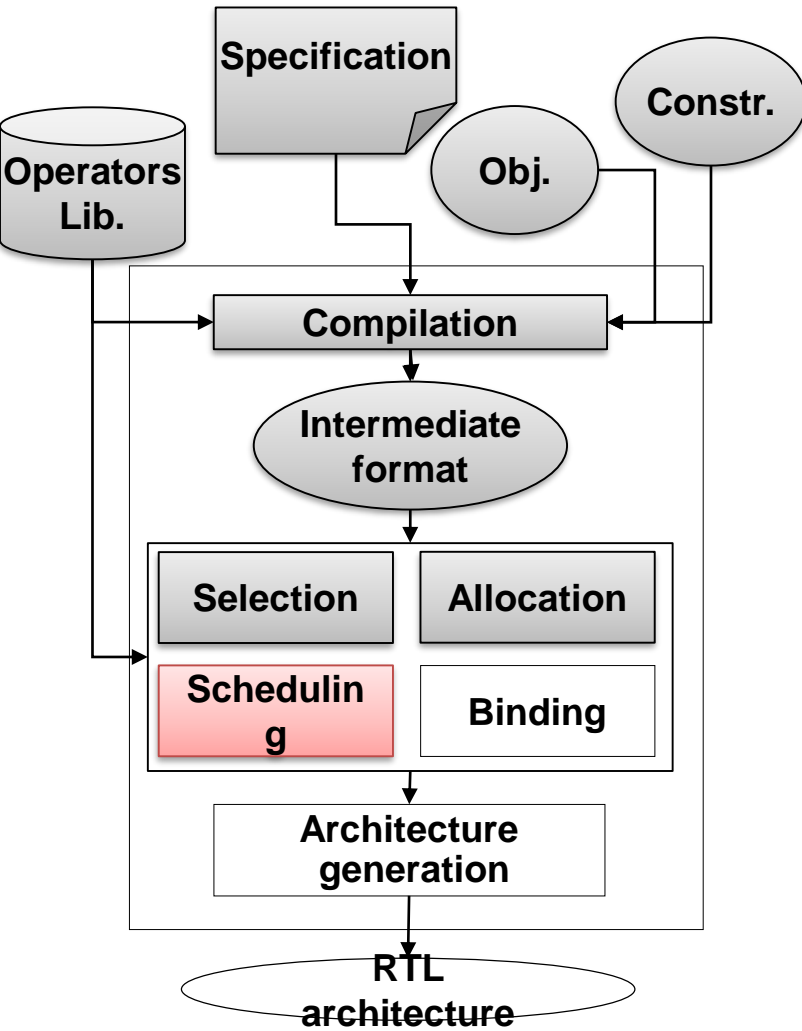


HLS steps: Allocation

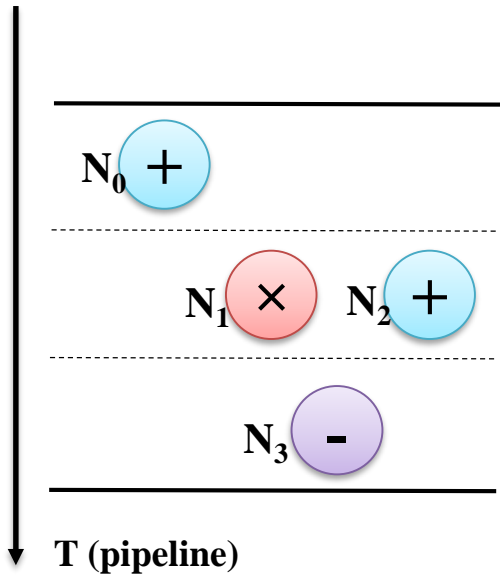
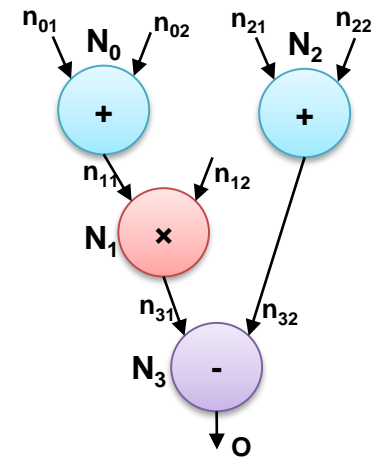




HLS steps: Scheduling

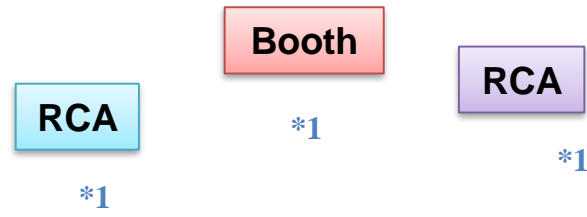
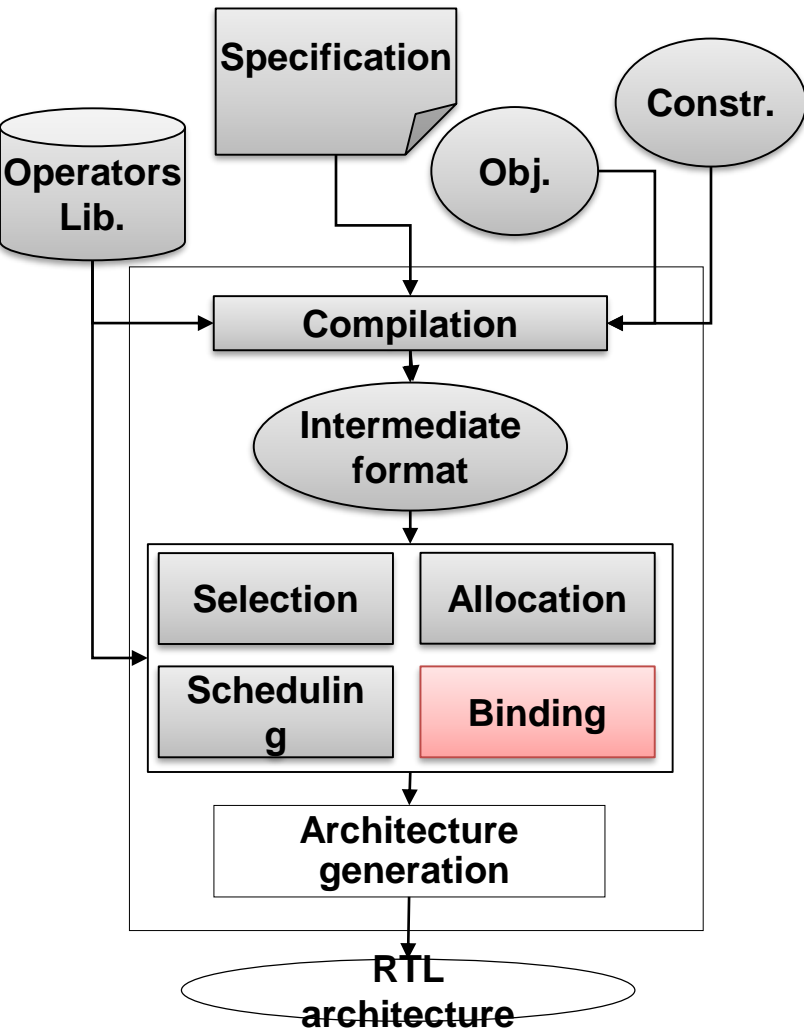


Intermediate representation

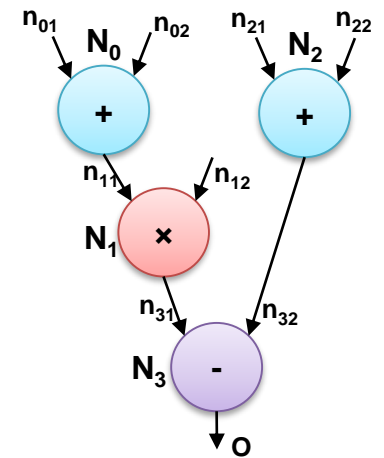




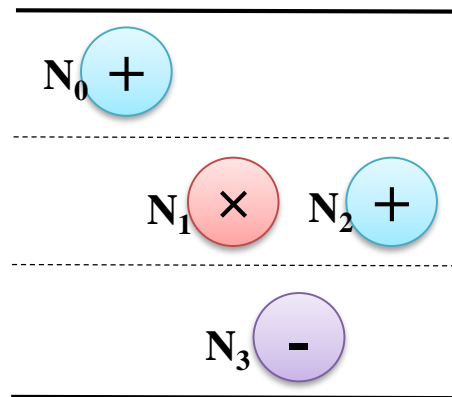
HLS steps: Binding



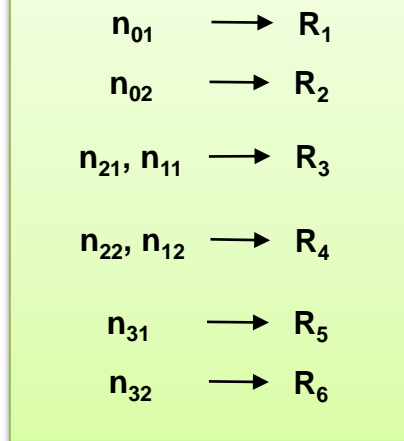
Intermediate representation



Operation Binding

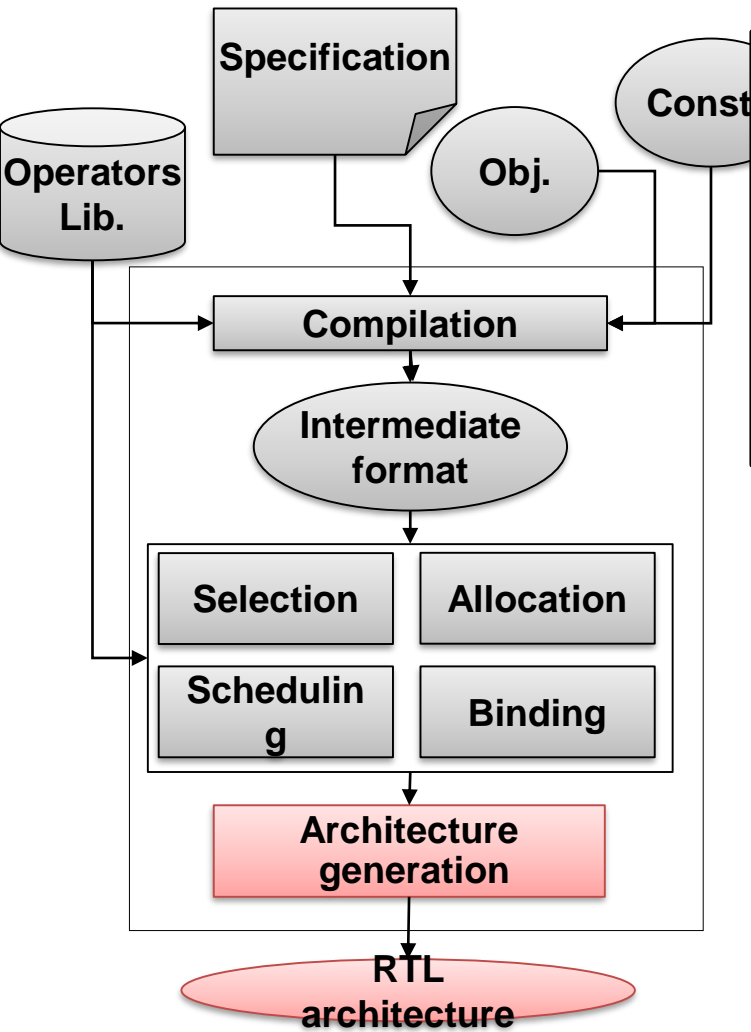


Data Binding

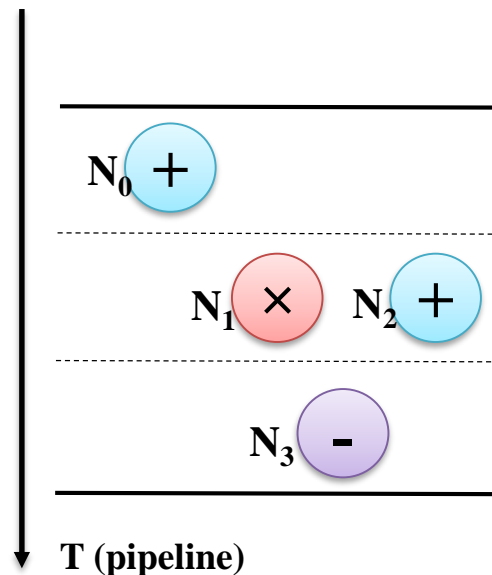
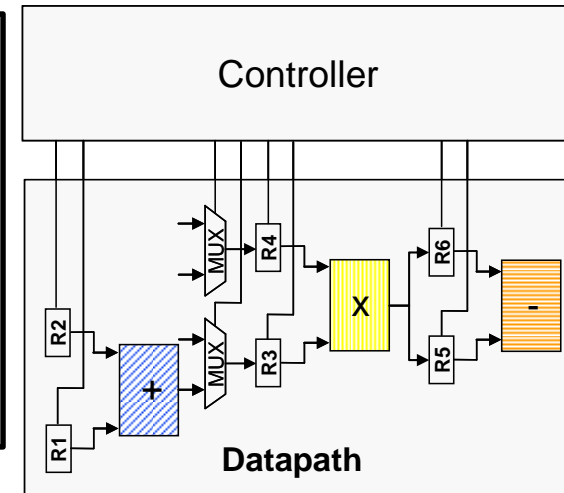




HLS steps: Binding



- Controller**
- **FSM controller**
 - **Programmable controller**
- Datapath components**
- **Storage components**
 - **Functional units**
 - **Connection components**



Data Binding

n_{01}	→	R_1
n_{02}	→	R_2
n_{21}, n_{11}	→	R_3
n_{22}, n_{12}	→	R_4
n_{31}	→	R_5
n_{32}	→	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)
-
- ✓ Let's see it in action!

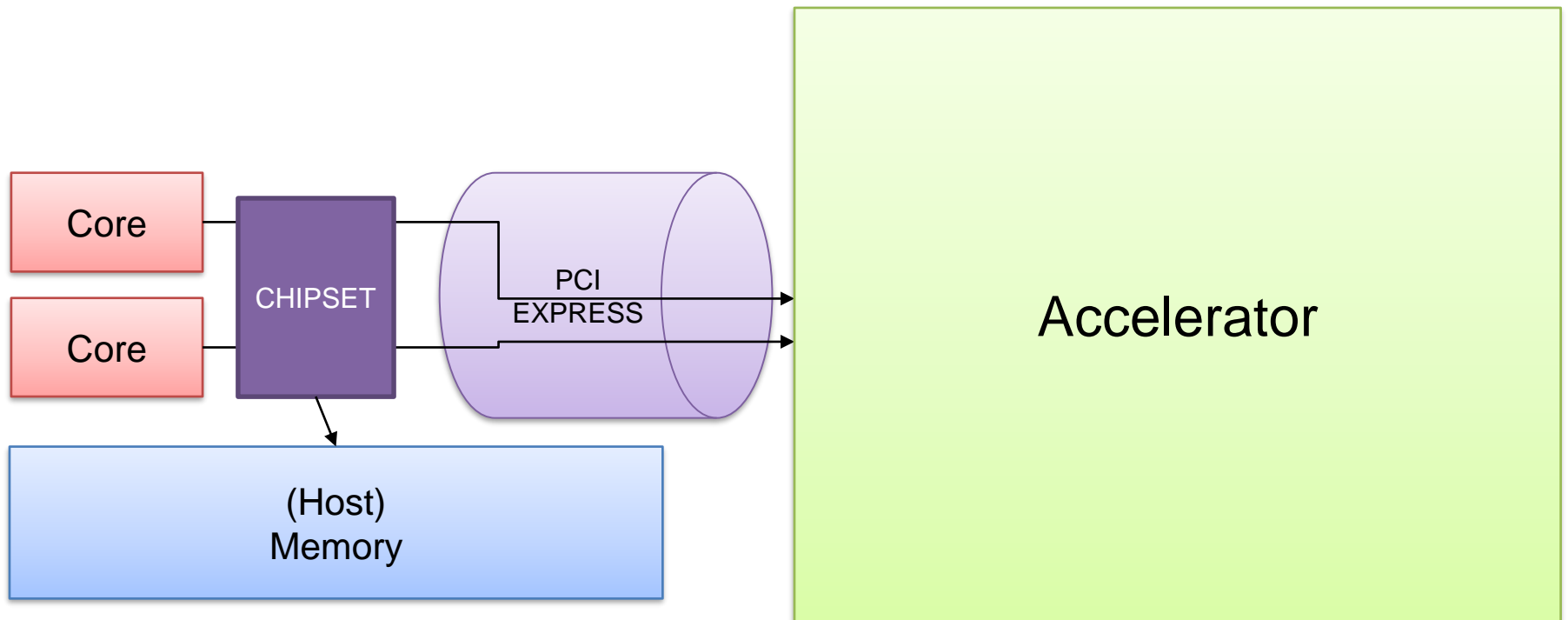


Heterogeneous systems



Host-accelerator model

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

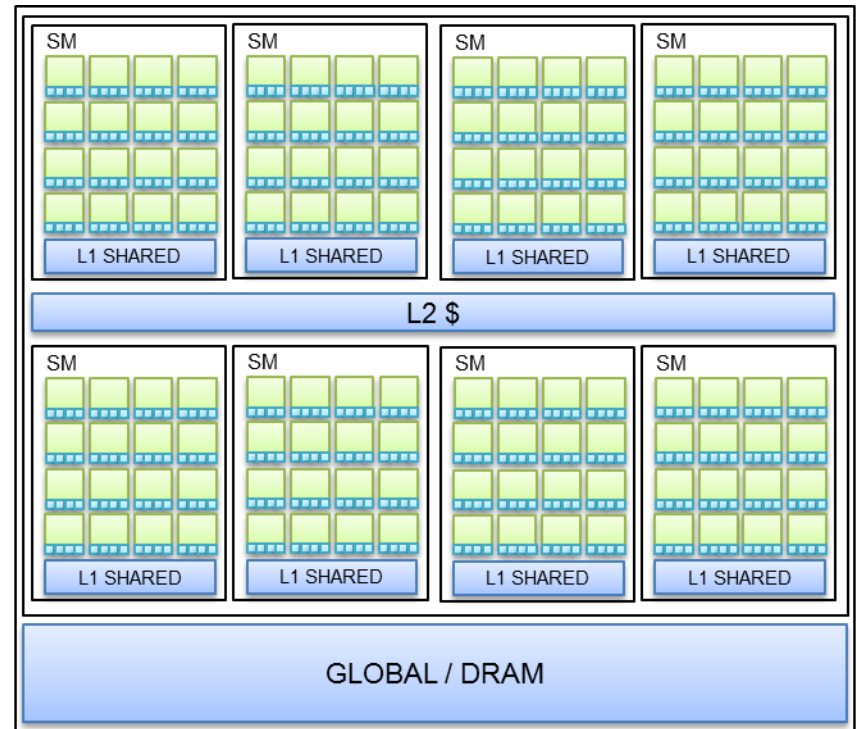
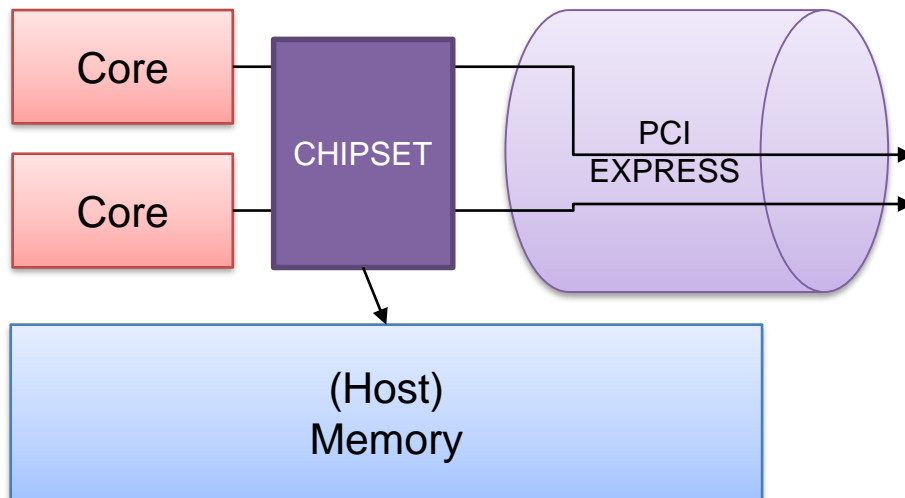




Something you are used to

GP-GPU based systems

- ✓ As in your laptop
 - ...yes, the one under your nose....
- ✓ Host => control-based code
- ✓ GPU => regular, highly-parallel code

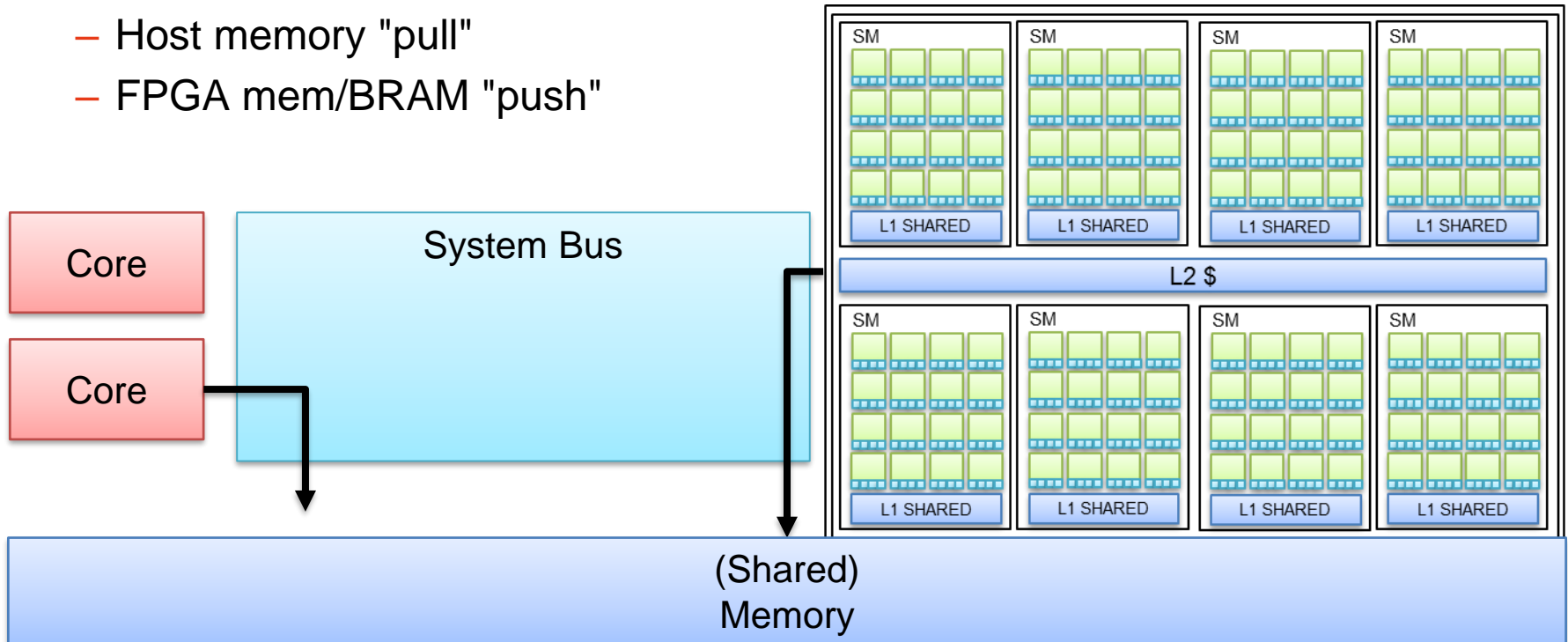




Something you are less used to

GP-GPU based embedded platforms

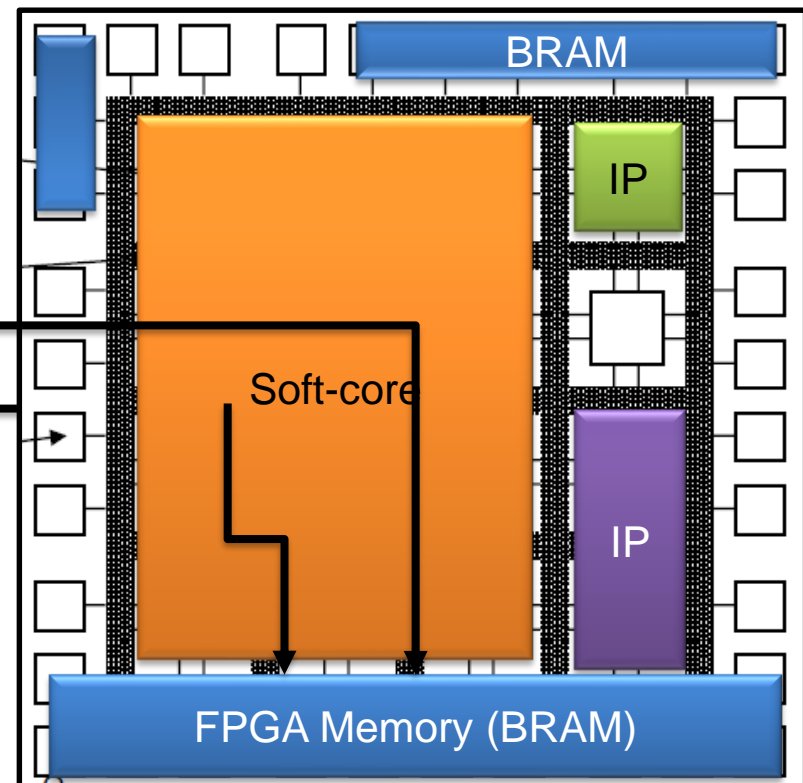
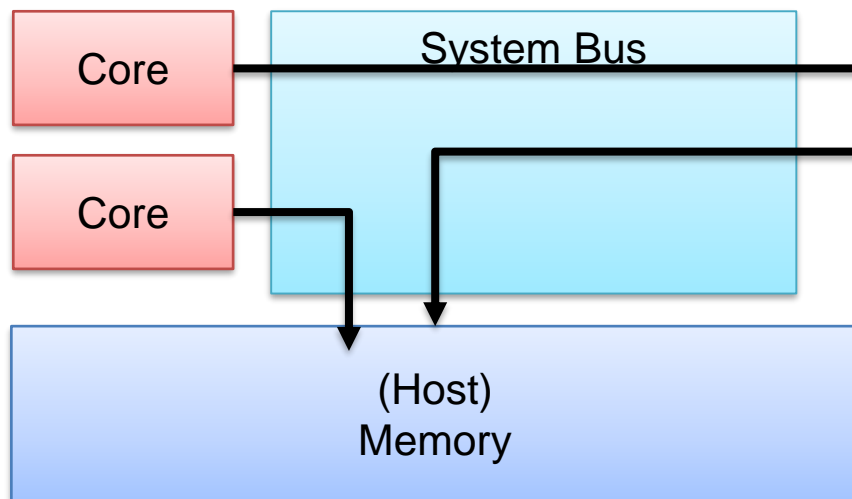
- ✓ ...this is not under your nose....
- ✓ Still, host + accelerator model
- ✓ Communicate via shared memory
 - No PCI-express
 - Host memory "pull"
 - FPGA mem/BRAM "push"





FPGA-based accelerators

- ✓ Can create hundreds of small HW accelerators (de/crypt, 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

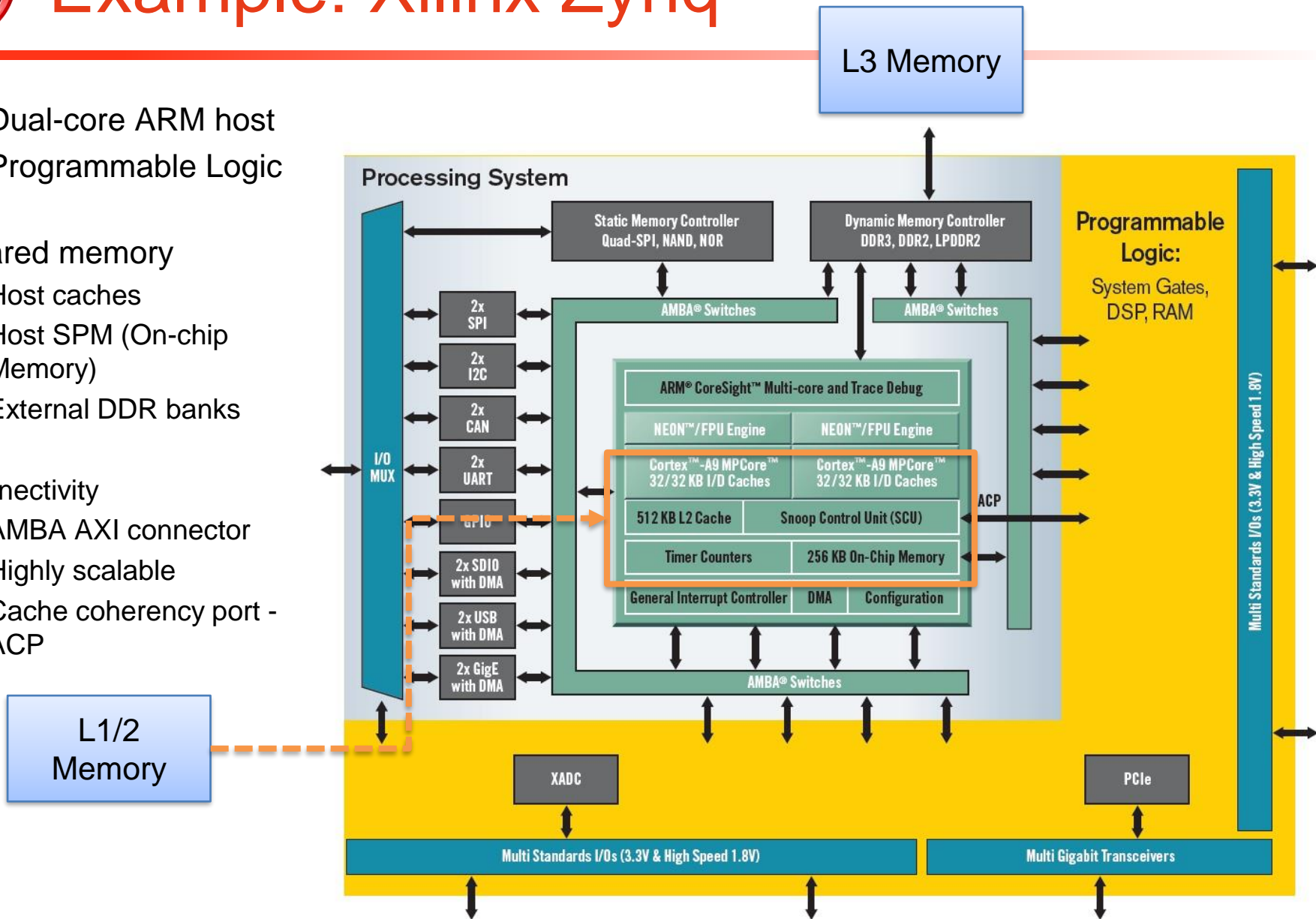
- ✓ Dual-core ARM host
- ✓ Programmable Logic

Shared memory

- ✓ Host caches
- ✓ Host SPM (On-chip Memory)
- ✓ External DDR banks

Connectivity

- ✓ AMBA AXI connector
- ✓ Highly scalable
- ✓ Cache coherency port - ACP



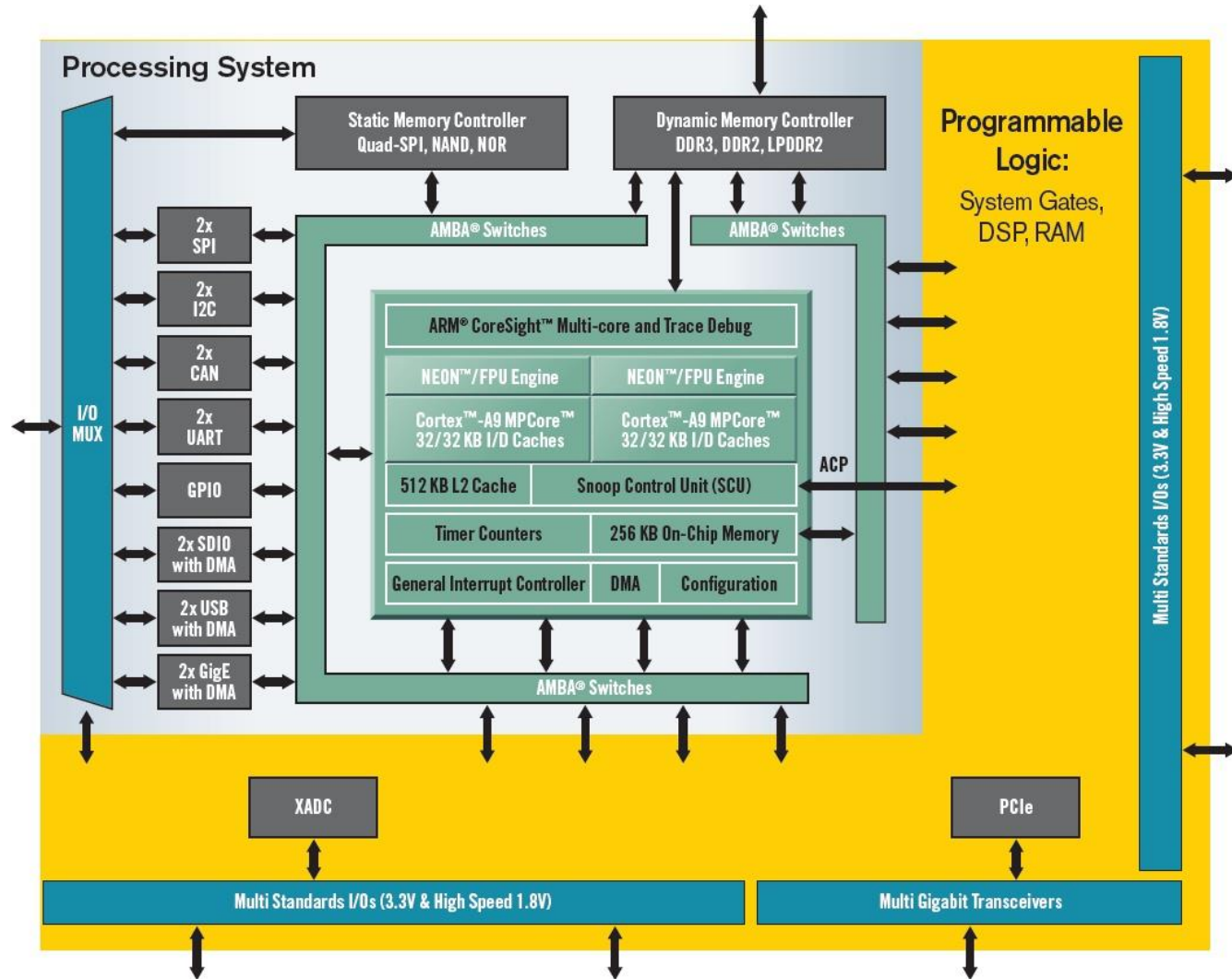


Xilinx FPGA SoCs



Xilinx Zynq-7000

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



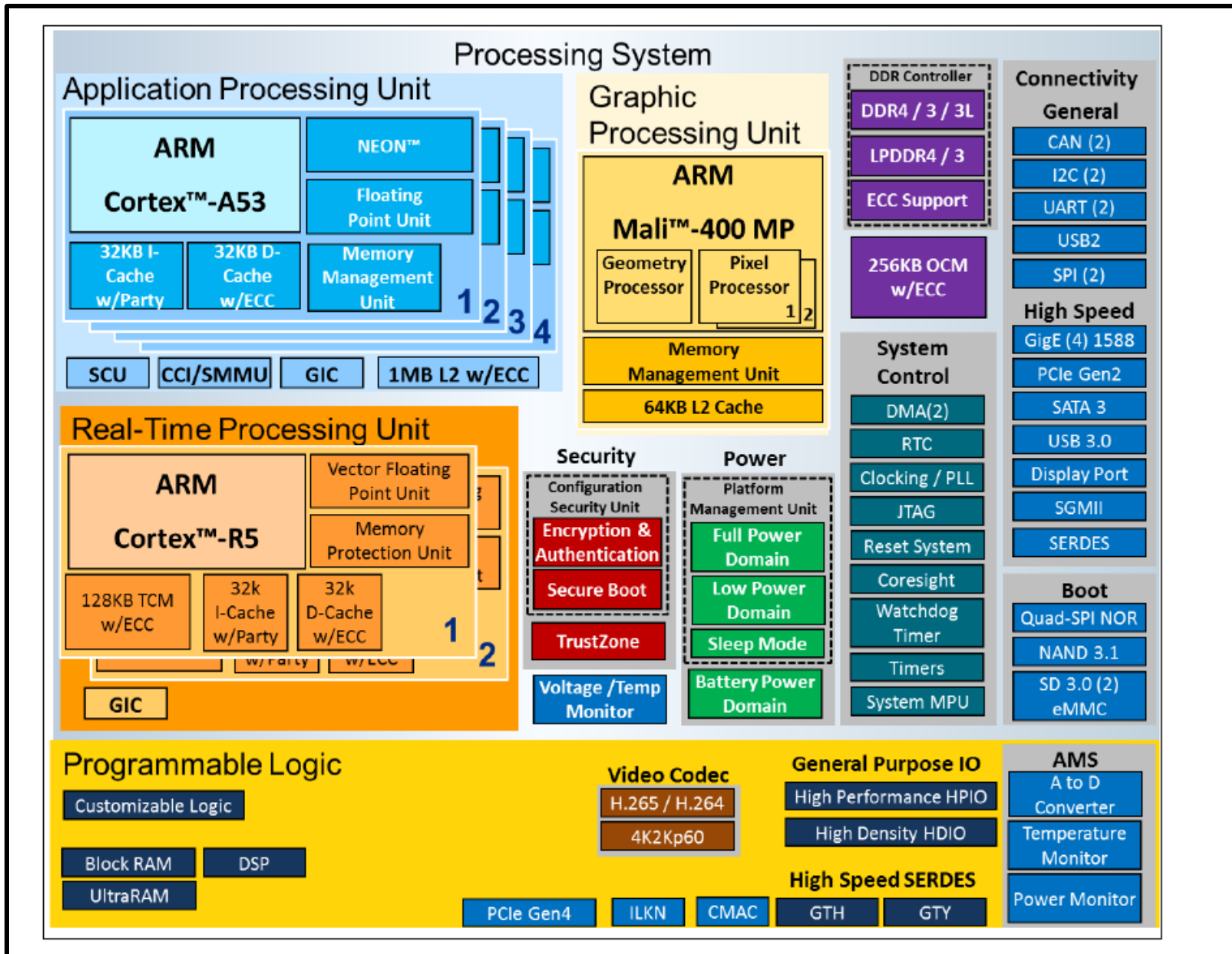


Xilinx Zynq-7000

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



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 (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



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

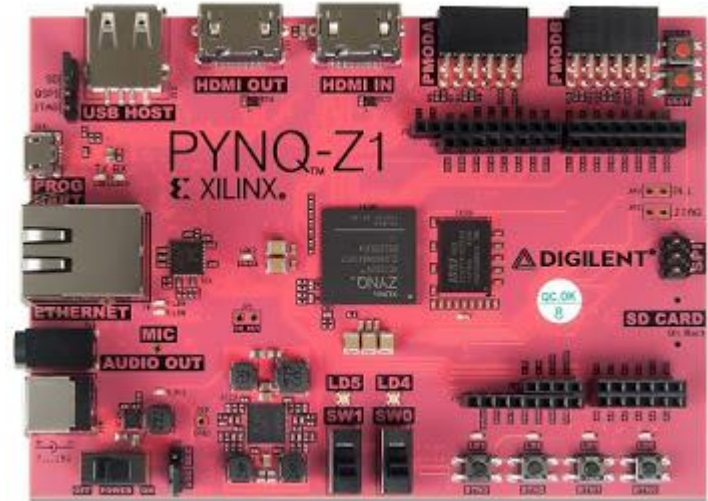
Expansion: USB Host connected to ARM PS

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)





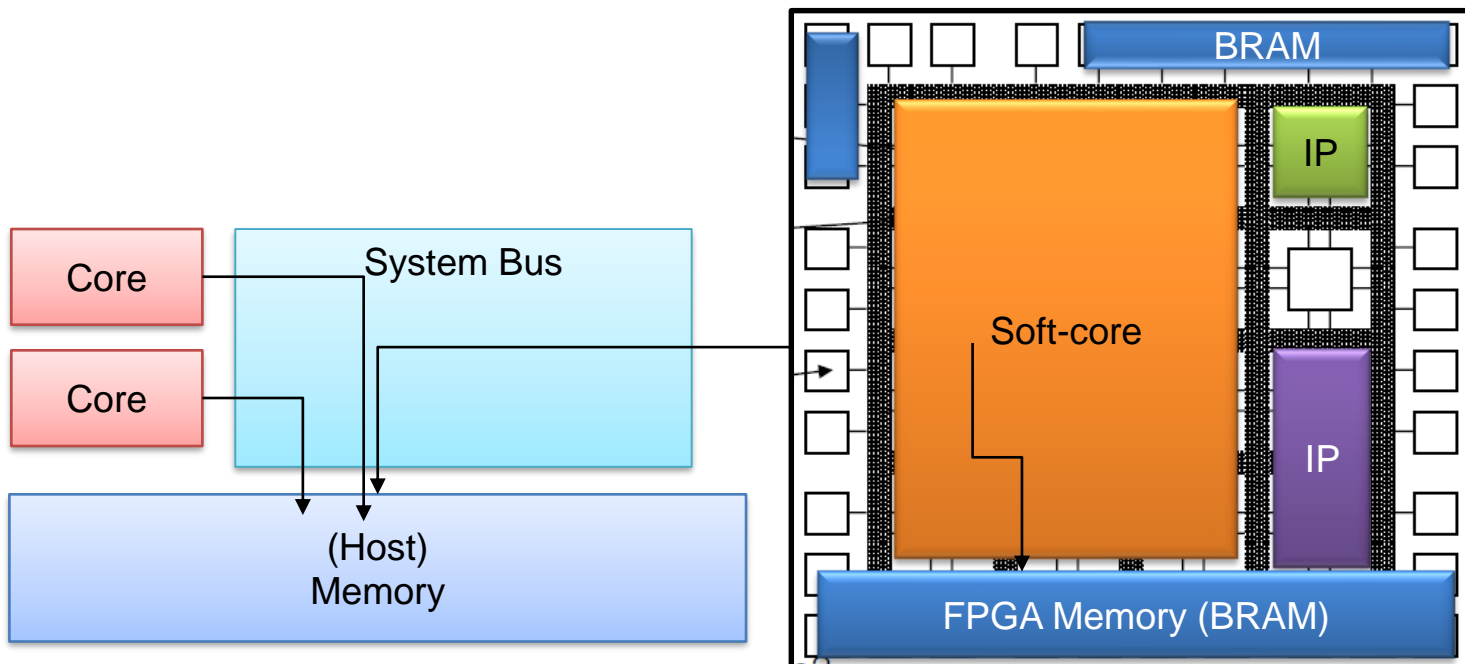
Programming heterogeneous systems



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 SW 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

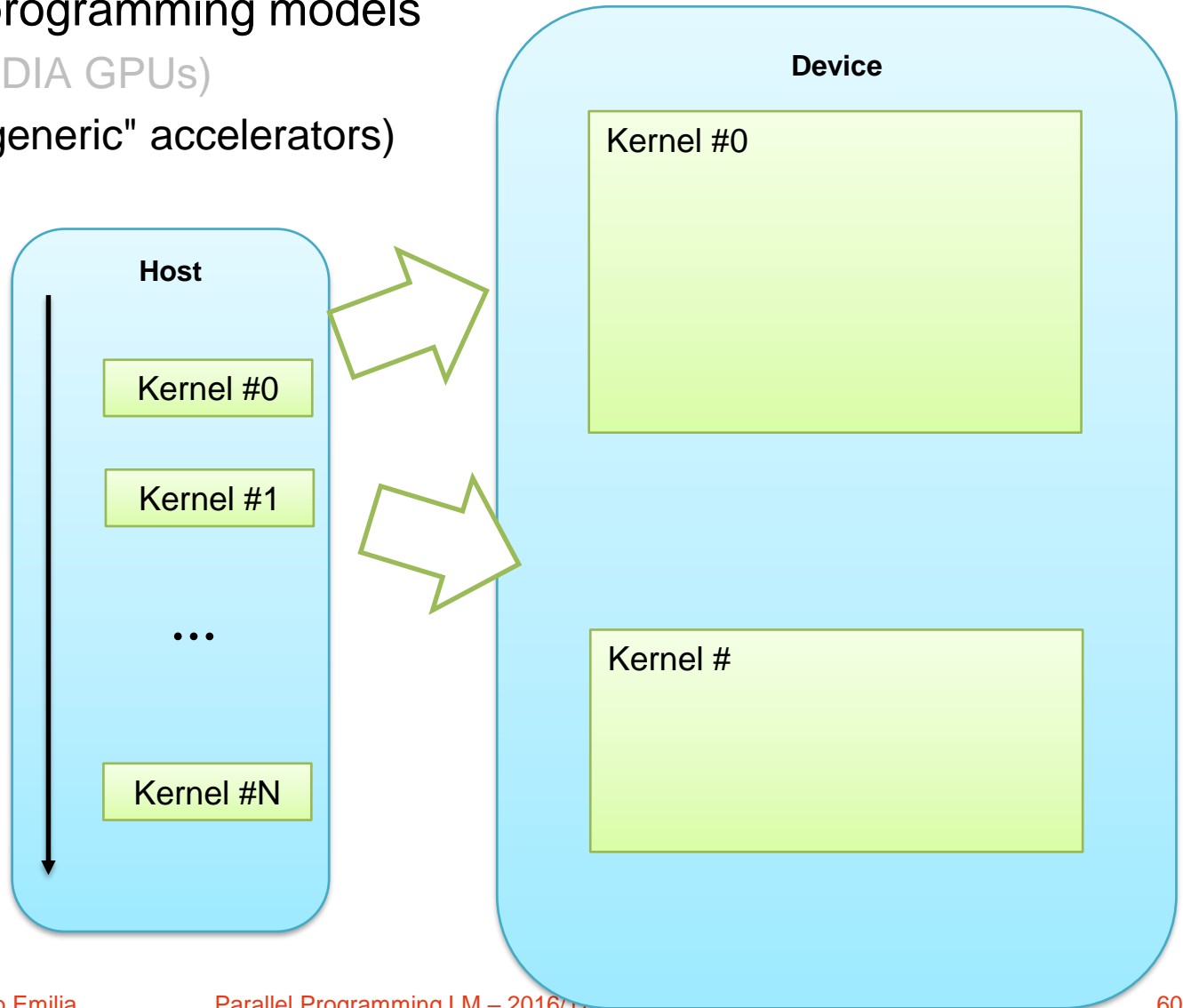
Let's see this in action!



2) offload-based programming

✓ Offload-based programming models

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





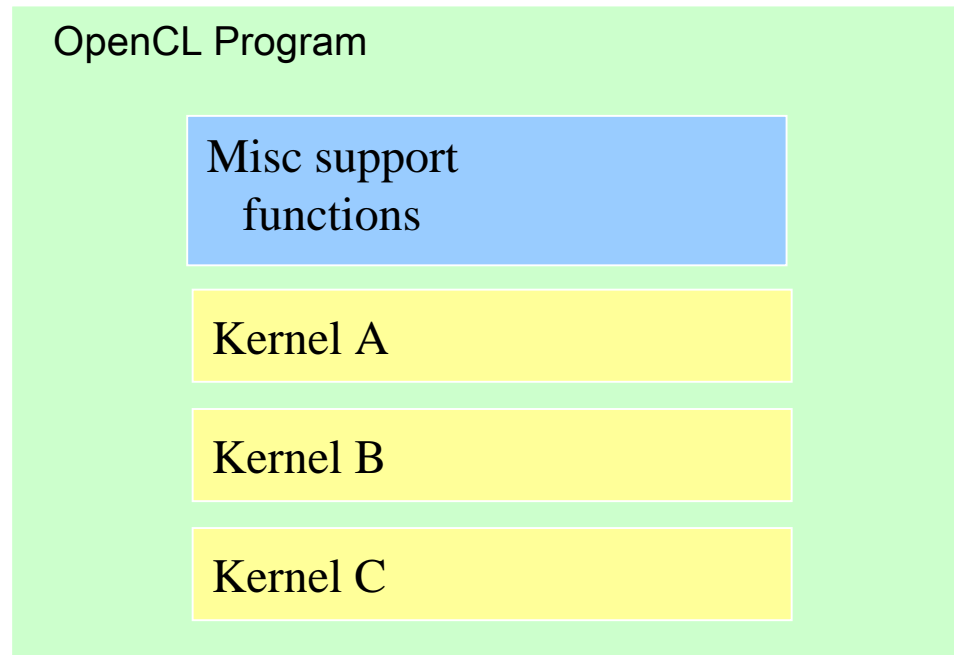
OpenCL

- ✓ 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

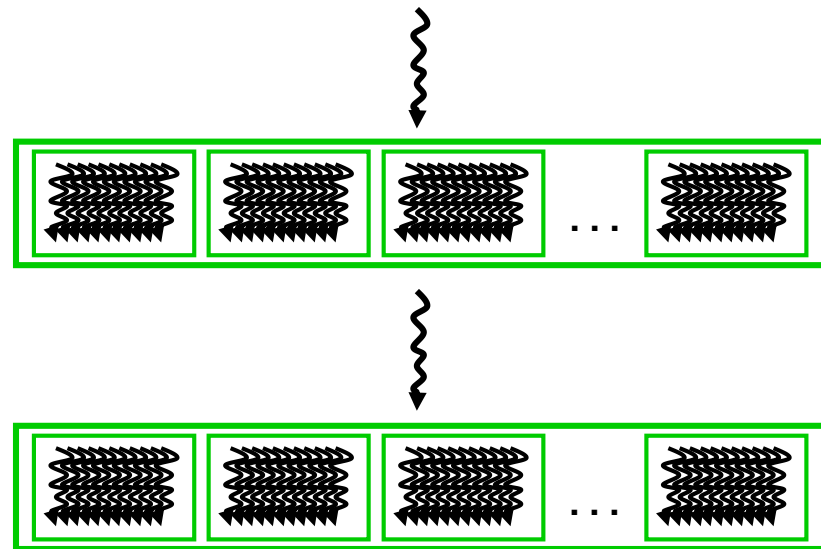
- ✓ An OpenCL “program” is a C program that contains one or more “**kernels**” and any supporting routines that run on a target device
- ✓ An OpenCL kernel is the basic unit of parallel code that can be executed on a target **device**
- ✓ In our case, an FPGA





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);
}
```



OpenMP 4.5 (yr 2011)

```
#pragma omp target [clause [[,]clause]...] new-line  
    structured-block
```

Where clauses can be:

```
if([ target :] scalar-expression)  
device(integer-expression)  
private(list)  
firstprivate(list)  
map([[map-type-modifier[,]] map-type: ] list)  
is_device_ptr(list)  
defaultmap(tofrom:scalar)  
nowait  
depend(dependence-type: list)
```

- ✓ Introduces the concept of **device**
 - Execute structured block onto device
 - map clause to move data to-from the device
 - `nowait` for asynch execution



OpenMP 4.5 in action

- ✓ ESA application for infrared signal processing
 - Here, runs on a Kalray MPPA manycore

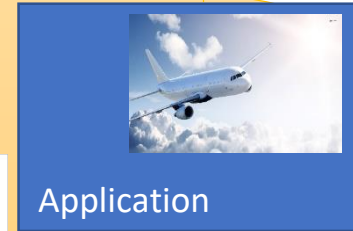
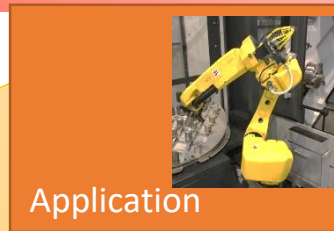
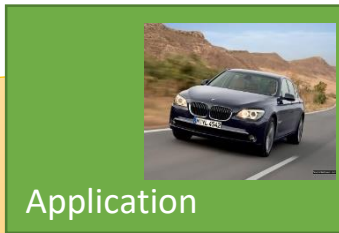
```
for (i = 0; i < DIM_Y; i++)
{
  for (j = 0; j < DIM_X; j=j+4)
  {
    UINT16BIT (*p_currentFrame1) [BS] = currentFrame[i][j];
    UINT16BIT (*p_currentFrame2) [BS] = currentFrame[i][j+1]

    #pragma omp target firstprivate(j) \
      map(to: saturationLimit[0:32]) \
      map(to: coeffOfNonLinearityPolynomial[0:32][0:4]) \
      map(tofrom: p_currentFrame1[0:bs][0:bs]) \
      map(tofrom: p_currentFrame2[0:bs][0:bs] \
        device(device_id) priority_id(0) nowait
    {
      phase1 (p_currentFrame1,p_currentFrame2
        saturationLimit, coeffOfNonLinearityPolynomial, j);
    }
  }
}
```



The Hercules framework

HERCULES

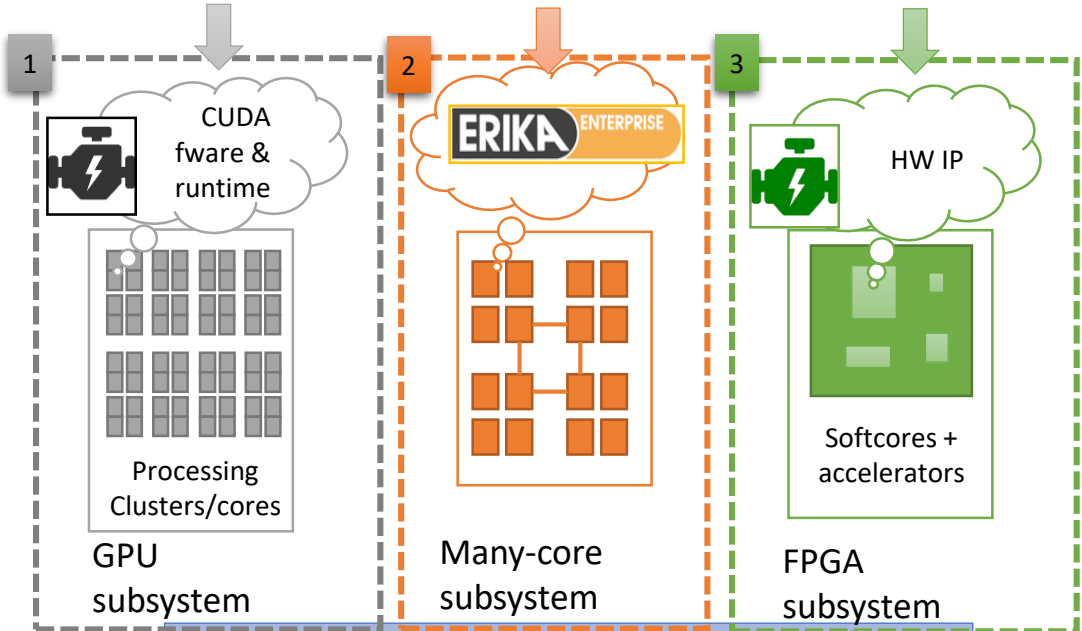
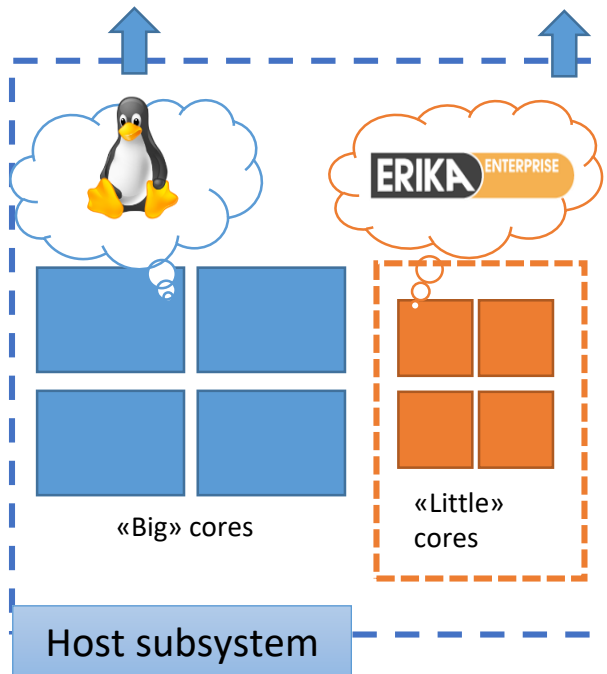


Programming model



Platform Abstraction

Offloading mechanism and communication API



Several accelerators «flavours»

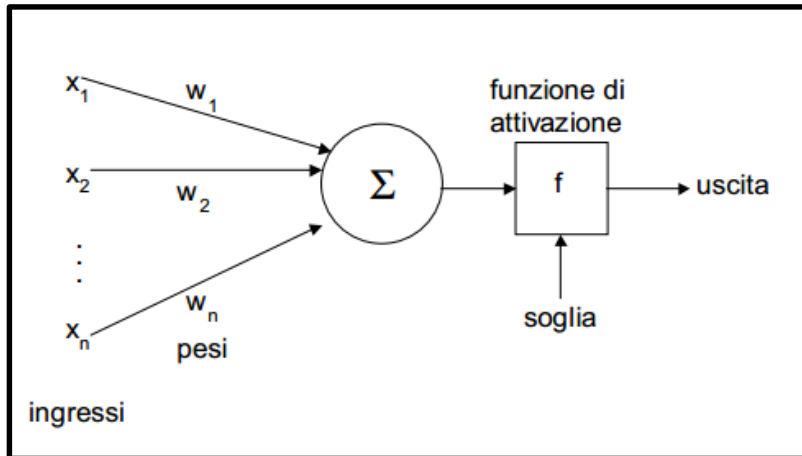
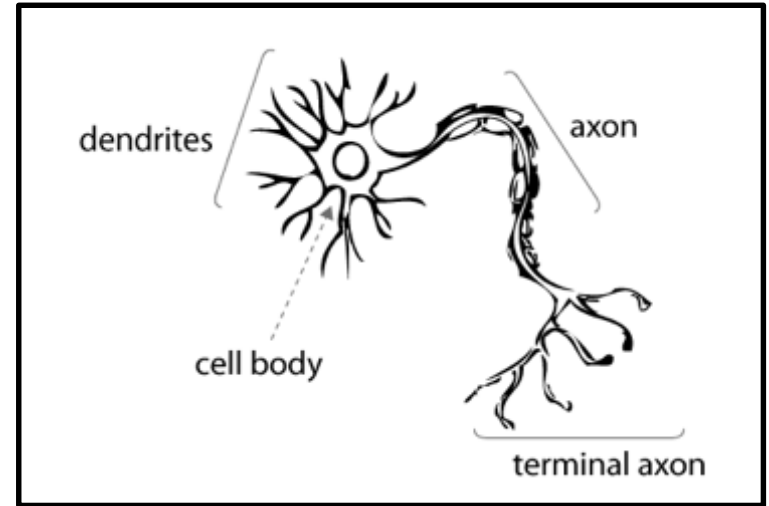


Neural Networks on FPGA accelerators



Neural networks

- ✓ Bio-inspired
- ✓ Based on neurons arranged in layers
 - And sub-layers
- ✓ Convolutional neural network
 - Neurons perform Convolutions

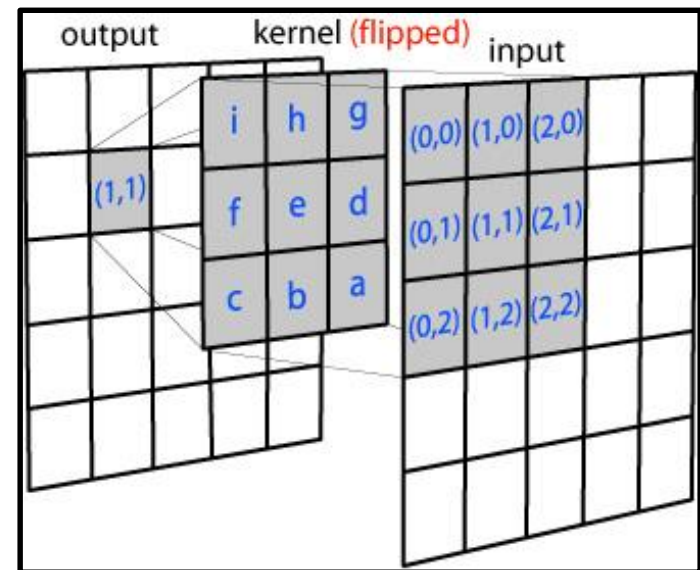




Convolution

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

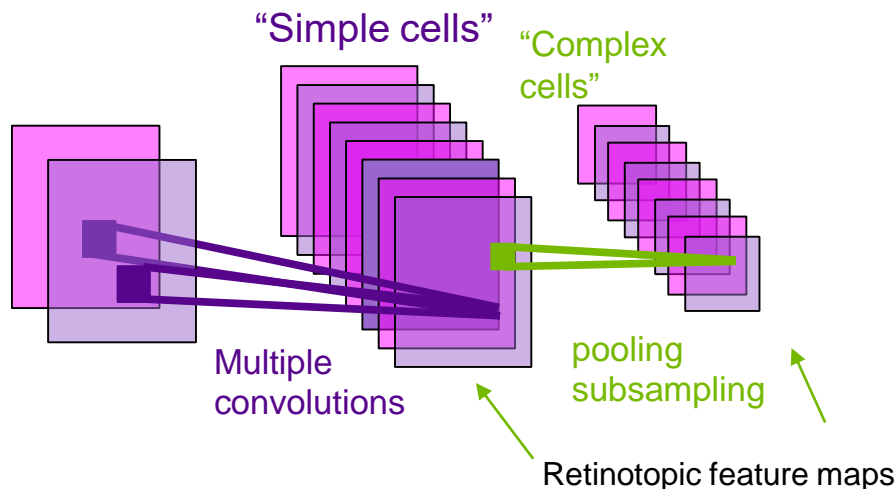
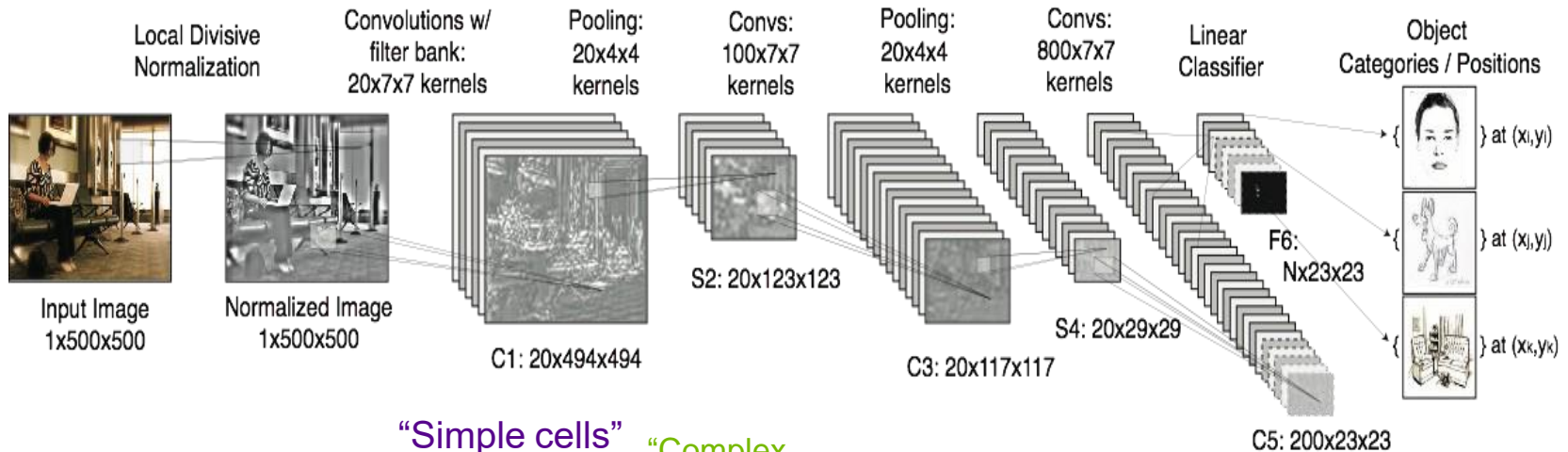
$$\begin{aligned}(f * g)(t) &\stackrel{\text{def}}{=} \int_{-\infty}^{\infty} f(\tau)g(t - \tau) d\tau \\ &= \int_{-\infty}^{\infty} f(t - \tau)g(\tau) d\tau.\end{aligned}$$





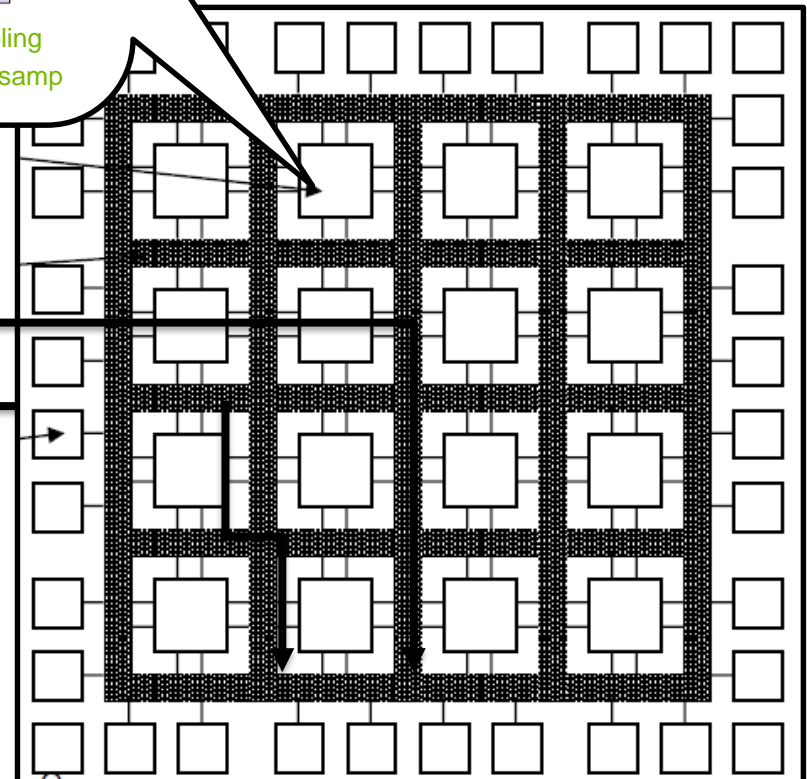
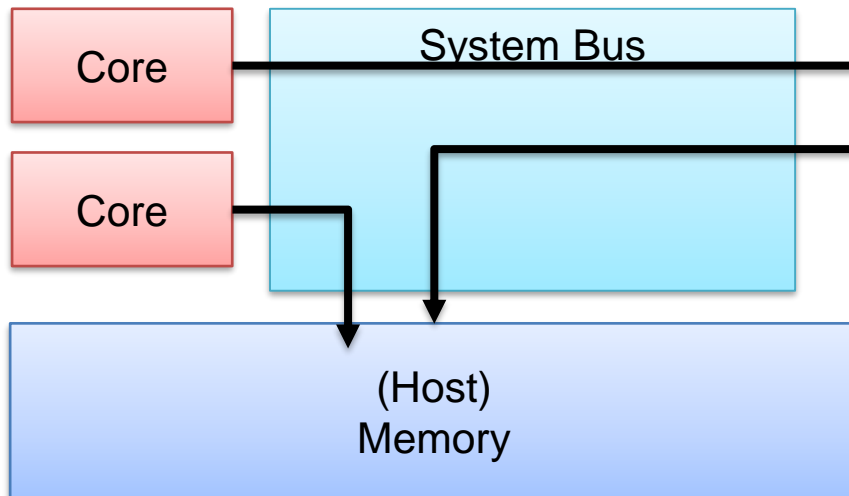
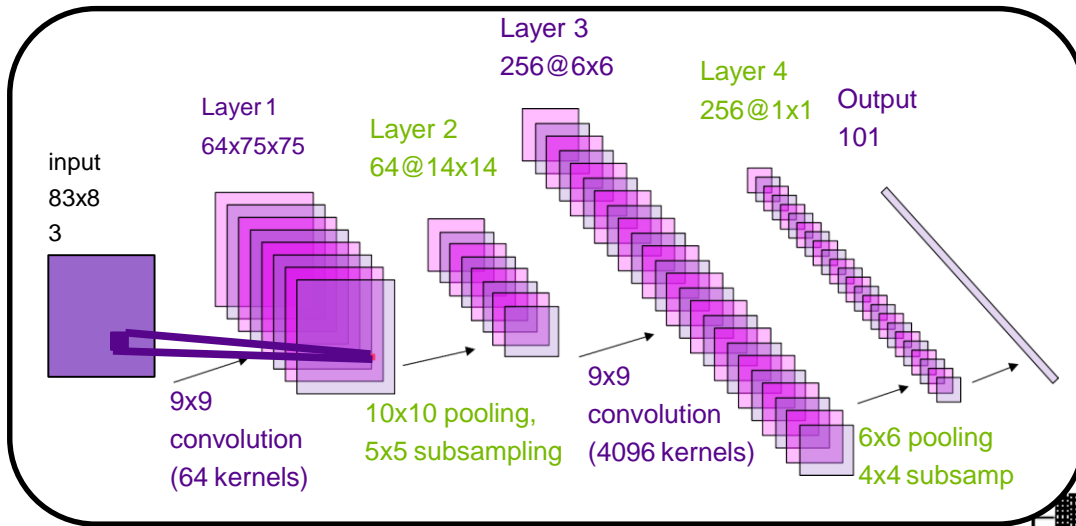
The convolutional net model

✓ (Multistage Hubel-Wiesel system)





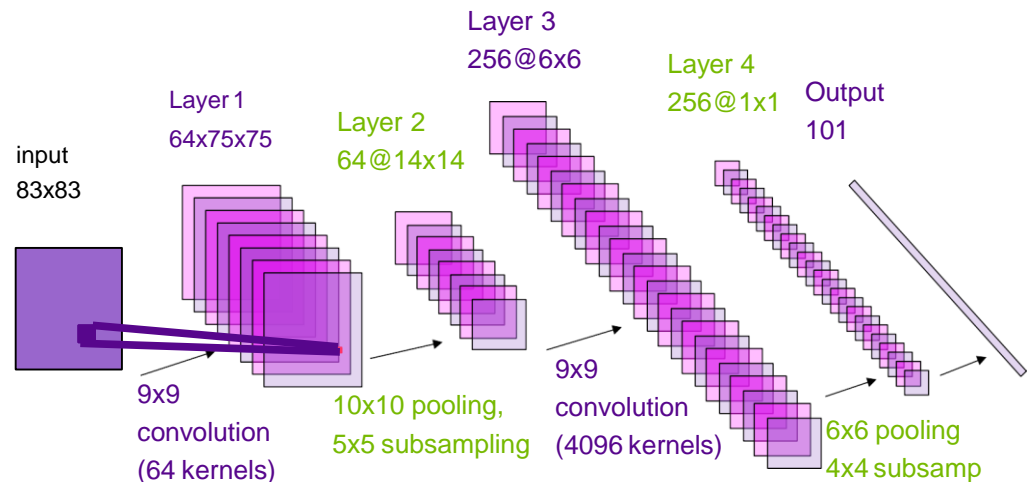
The convolutional net model (cont'd)





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?





Training a network



"The training problem"

- ✓ To set the weights/CNN kernels
- ✓ Training set must be huge

A "big data" problem

- ✓ Why do you think Google does self-driving cars?
- ✓ Why do you think big cloud players want our data?



CNN on FPGA

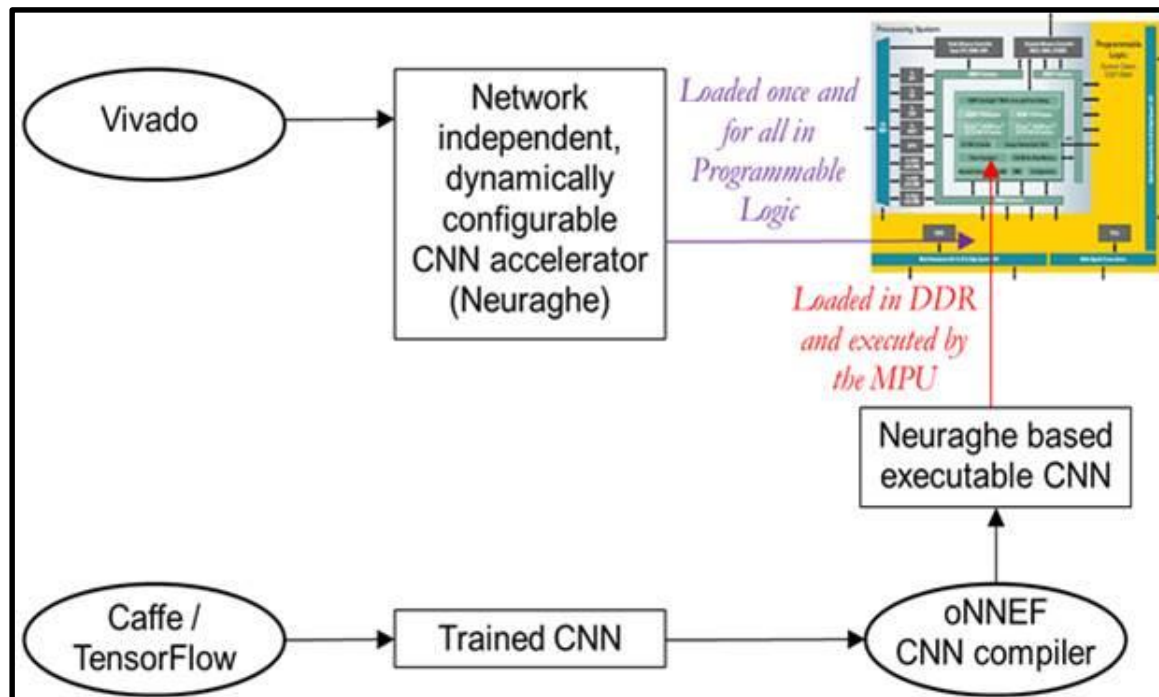
- ✓ We can implement one or more complete CNN layers on FPGA
 - How many?
- ✓ We can use float, int, datatypes
 - Int are smaller, but still efficient
- ✓ Binaries NN, where input weights are +-1
 - Smaller, more suitable for area-constrained

Name	Supported Architecture
ZynqNet	XC-7Z045
BNN	Z-7020
GraphGen-based CNN	
Pre-Trained CNN based on LeNet5	
GoogLeNet	ZCU102
AlexNet	
VGG-16	
SSD-300	
FCN-AlexNet	



Nuraghe NN on FPGA

- ✓ Trained with ML frameworks Caffè and TensorFlow
- ✓ Nuraghe accelerator, configurable for specific CNN
- ✓ CNN compiler, which translates the CNN description from Caffè or TF in a program which runs on Nuraghe/Zynq





References



- ✓ "Calcolo parallelo" website
 - http://hipert.unimore.it/people/marko/courses/programmazione_parallela/

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

- ✓ 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>