UNIMORE
UNIVERSITÀ DEGLI STUDI DI
MODENA E REGGIO EMILIA

HiPeRT Lab
High-Performance Real-Time Lab

Programming Graphic Processing Units with CUDA

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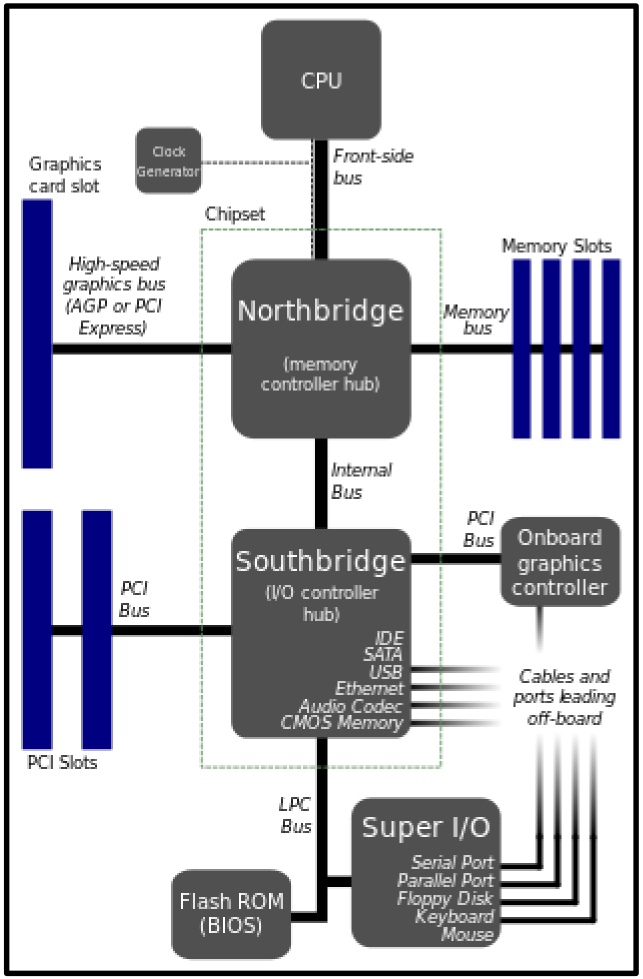
Graphics Processing Units

- ✓ (Co-)processor devoted to graphics
  - Built as "monolithical" chip
  - Integrated as co-processor
  - Recently, SoCs
- ✓ Main providers
  - NVIDIA
  - ATI
  - AMD
  - Intel…
- ✓ We will focus on NVIDIA
  - Widely adopted
  - Adopted by us



A bit of history…

- 70s: first "known" graphic card on a board package
- Early 90s: 3D graphics popular in games
- 1992: OpenGL
- 1999: NVIDIA GeForce 256 "World's first GPU"
- 2001: NVIDIA GeForce 3, w/programmable shaders (First GP-GPU)
- 2008: NVIDIA GeForce 8800 GTX w/CUDA capabilities - Tesla arch.
- 2009: OpenCL 1.0 inside MAC OS X Snow Leopard
- 2010: NVIDIA GeForce 400 Series - Fermi arch.
- 2010-1: OpenCL 1.1, 1.2
- 2012: NVIDIA GeForce 600 Series - Kepler arch.
- 2013: OpenCL 2.0
- 2014: NVIDIA GeForce 745 OEM - Maxwell arch.
- 2015 Q4: NVIDIA and HiPeRT Lab start cooperation ;)
- 2017 Q1: NVIDIA Drive Px2 for Self-Driving Cars

…a bit of confusion!

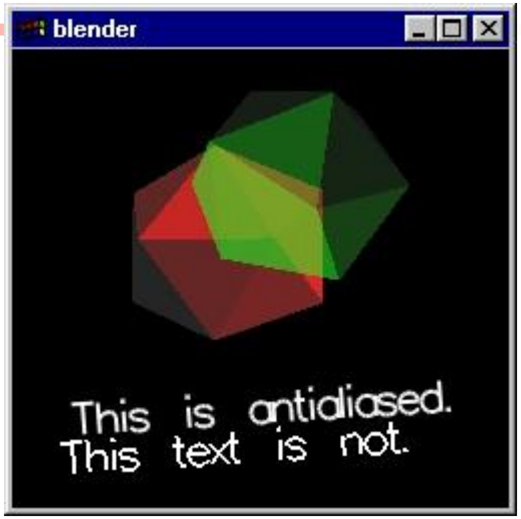
- Many architectures
  - Tesla, Fermi, Maxwell, Pascal, (soon) Volta..

- Many programming ~~librar~~… ~~languag~~… frameworks
  - OpenGL
  - CUDA
  - OpenCL
  - …

- Many application domains!
  - Graphics
  - GP-GPUs?
  - Automotive!??!?!??!

- Let's start from scratch…

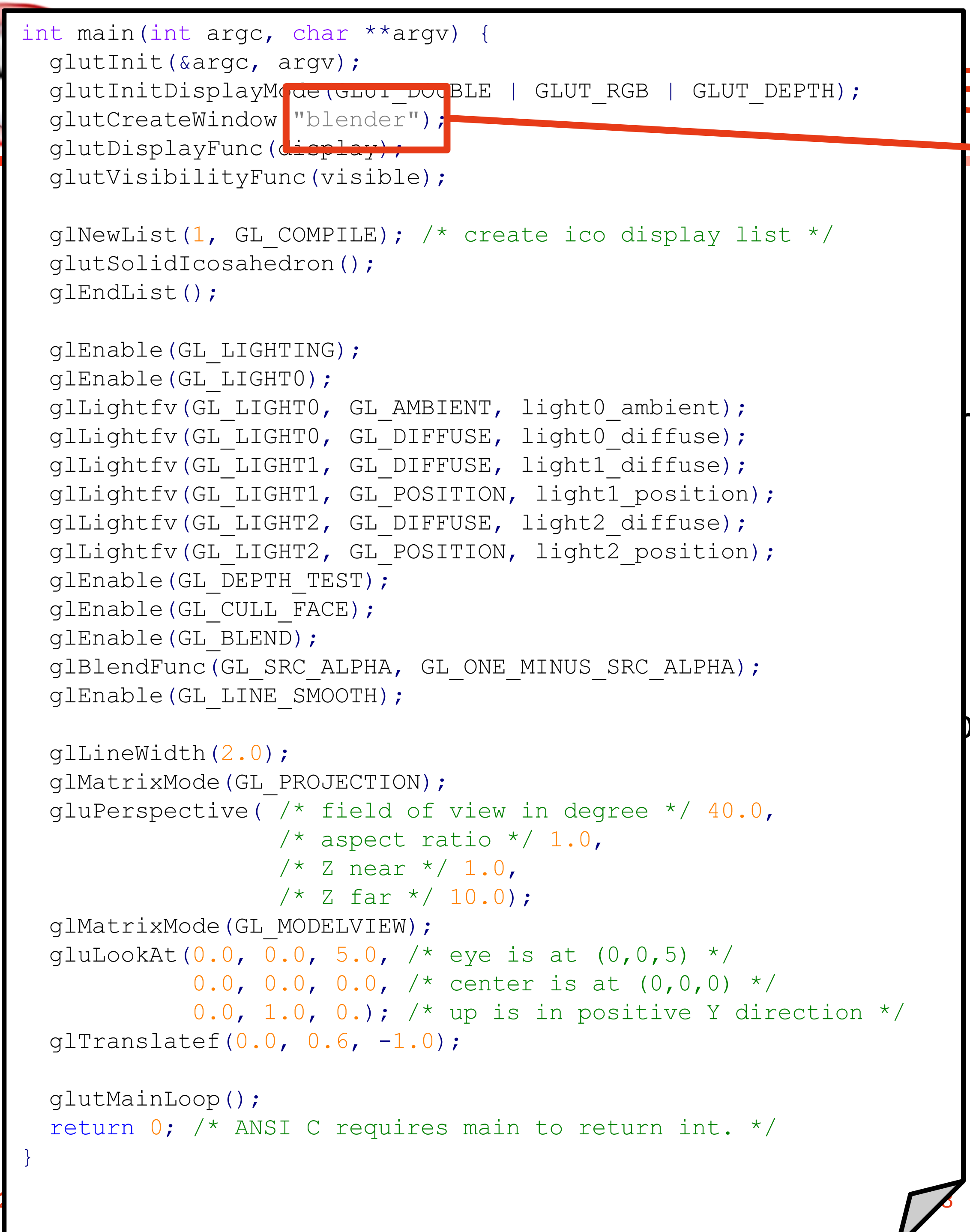
GPU for graphics - OpenGL



This is antialiased.
This text is not.

- ✓ Use GPUs for rendering of graphics
  - – A library of functions and datatypes
  - – Use directly in the code
  - – High-level operations on lights, shapes, shaders…

- ✓ Tailored for the specific domain and programmer skills
  - – Hides away the complexity of the machine
  - – Takes care of "low" level optimizations/operations



```
int main(int argc, char **argv) {
  glutInit(&argc, argv);
  glutInitDisplayMode(GLUT_DOUBLE | GLUT_RGB | GLUT_DEPTH);
  glutCreateWindow("blender");
  glutDisplayFunc(display);
  glutVisibilityFunc(visible);

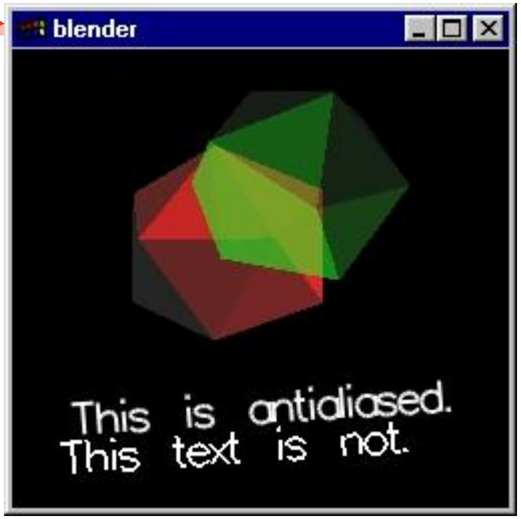
  glNewList(1, GL_COMPILE); /* create ico display list */
  glutSolidIcosahedron();
  glEndList();

  glEnable(GL_LIGHTING);
  glEnable(GL_LIGHT0);
  glLightfv(GL_LIGHT0, GL_AMBIENT, light0_ambient);
  glLightfv(GL_LIGHT0, GL_DIFFUSE, light0_diffuse);
  glLightfv(GL_LIGHT1, GL_DIFFUSE, light1_diffuse);
  glLightfv(GL_LIGHT1, GL_POSITION, light1_position);
  glLightfv(GL_LIGHT2, GL_DIFFUSE, light2_diffuse);
  glLightfv(GL_LIGHT2, GL_POSITION, light2_position);
  glEnable(GL_DEPTH_TEST);
  glEnable(GL_CULL_FACE);
  glEnable(GL_BLEND);
  glBlendFunc(GL_SRC_ALPHA, GL_ONE_MINUS_SRC_ALPHA);
  glEnable(GL_LINE_SMOOTH);

  glLineWidth(2.0);
  glMatrixMode(GL_PROJECTION);
  gluPerspective( /* field of view in degree */ 40.0,
                  /* aspect ratio */ 1.0,
                  /* Z near */ 1.0,
                  /* Z far */ 10.0);
  glMatrixMode(GL_MODELVIEW);
  gluLookAt(0.0, 0.0, 5.0, /* eye is at (0,0,5) */
            0.0, 0.0, 0.0, /* center is at (0,0,0) */
            0.0, 1.0, 0.); /* up is in positive Y direction */
  glTranslatef(0.0, 0.6, -1.0);

  glutMainLoop();
  return 0; /* ANSI C requires main to return int. */
}
```

enGL



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rs...

mer skills

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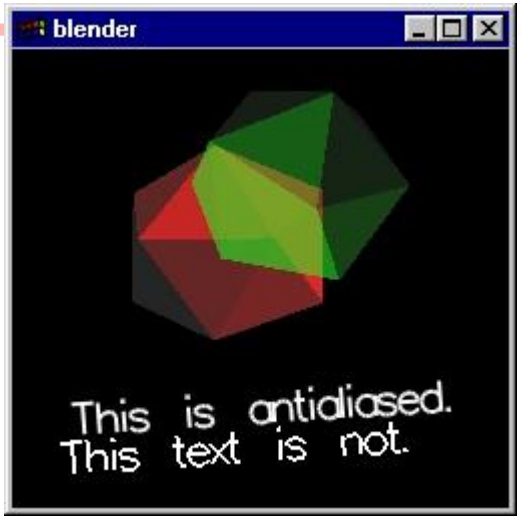
```

```
GLfloat light0_ambient[] = {0.2, 0.2, 0.2, 1.0};
GLfloat light0_diffuse[] = {0.0, 0.0, 0.0, 1.0};
GLfloat light1_diffuse[] = {1.0, 0.0, 0.0, 1.0};
GLfloat light1_position[] = {1.0, 1.0, 1.0, 0.0};
GLfloat light2_diffuse[] = {0.0, 1.0, 0.0, 1.0};
GLfloat light2_position[] = {-1.0, -1.0, 1.0, 0.0};
```



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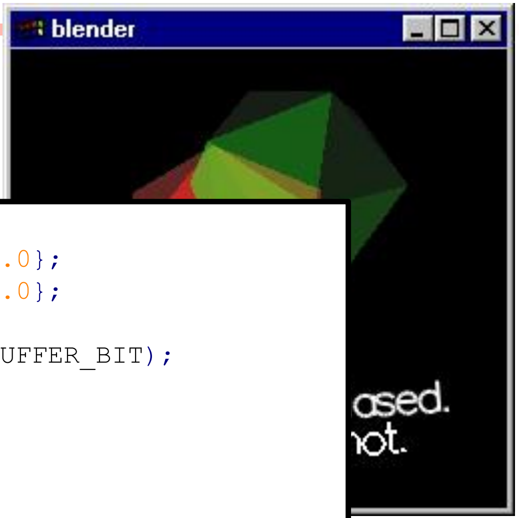

```c
void display(void) {
  static GLfloat amb[] = {0.4, 0.4, 0.4, 0.0};
  static GLfloat dif[] = {1.0, 1.0, 1.0, 0.0};

  glClear(GL_COLOR_BUFFER_BIT | GL_DEPTH_BUFFER_BIT);
  glEnable(GL_LIGHT1);
  glDisable(GL_LIGHT2);
  amb[3] = dif[3] = cos(s) / 2.0 + 0.5;
  glMaterialfv(GL_FRONT, GL_AMBIENT, amb);
  glMaterialfv(GL_FRONT, GL_DIFFUSE, dif);

  glPushMatrix();
  glTranslatef(-0.3, -0.3, 0.0);
  glRotatef(angle1, 1.0, 5.0, 0.0);
  glCallList(1); /* render ico display list */
  glPopMatrix();

  glClear(GL_DEPTH_BUFFER_BIT);
  glEnable(GL_LIGHT2);
  glDisable(GL_LIGHT1);
  amb[3] = dif[3] = 0.5 - cos(s * .95) / 2.0;
  glMaterialfv(GL_FRONT, GL_AMBIENT, amb);
  glMaterialfv(GL_FRONT, GL_DIFFUSE, dif);

  glPushMatrix();
  glTranslatef(0.3, 0.3, 0.0);
  glRotatef(angle2, 1.0, 0.0, 5.0);
  glCallList(1); /* render ico display list */
  glPopMatrix();

 /* ... */
```

General Purpose - GPUs

- ✓ We have a machine with thousand of cores
  - – why should we use it only for graphics?

- ✓ Use it for General Purpose Computing!
  - – GP-GPU
  - – ~yr 2000

NdA: Computing modes

– General Purpose Computing

General Purpose - GPUs

- ✓ We have a m
  - why should
- ✓ Use it for Ge
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NdA: Computing modes

- General Purpose Computing
- High-Performance Computing

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NdA: Computing modes

- – General Purpose Computing
- – High-Performance Computing
- – Embedded Computing

General Purpose - GPUs

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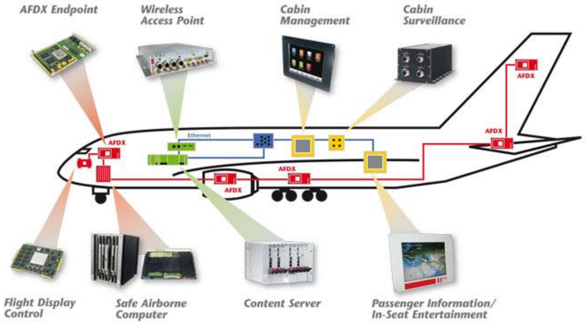
NdA: Computing modes

- – General Purpose Computing
- – High-Performance Computing
- – Embedded Computing
- – Real-Time Computing



General Purpose - GPUs

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  - why should we use it only for graphics?

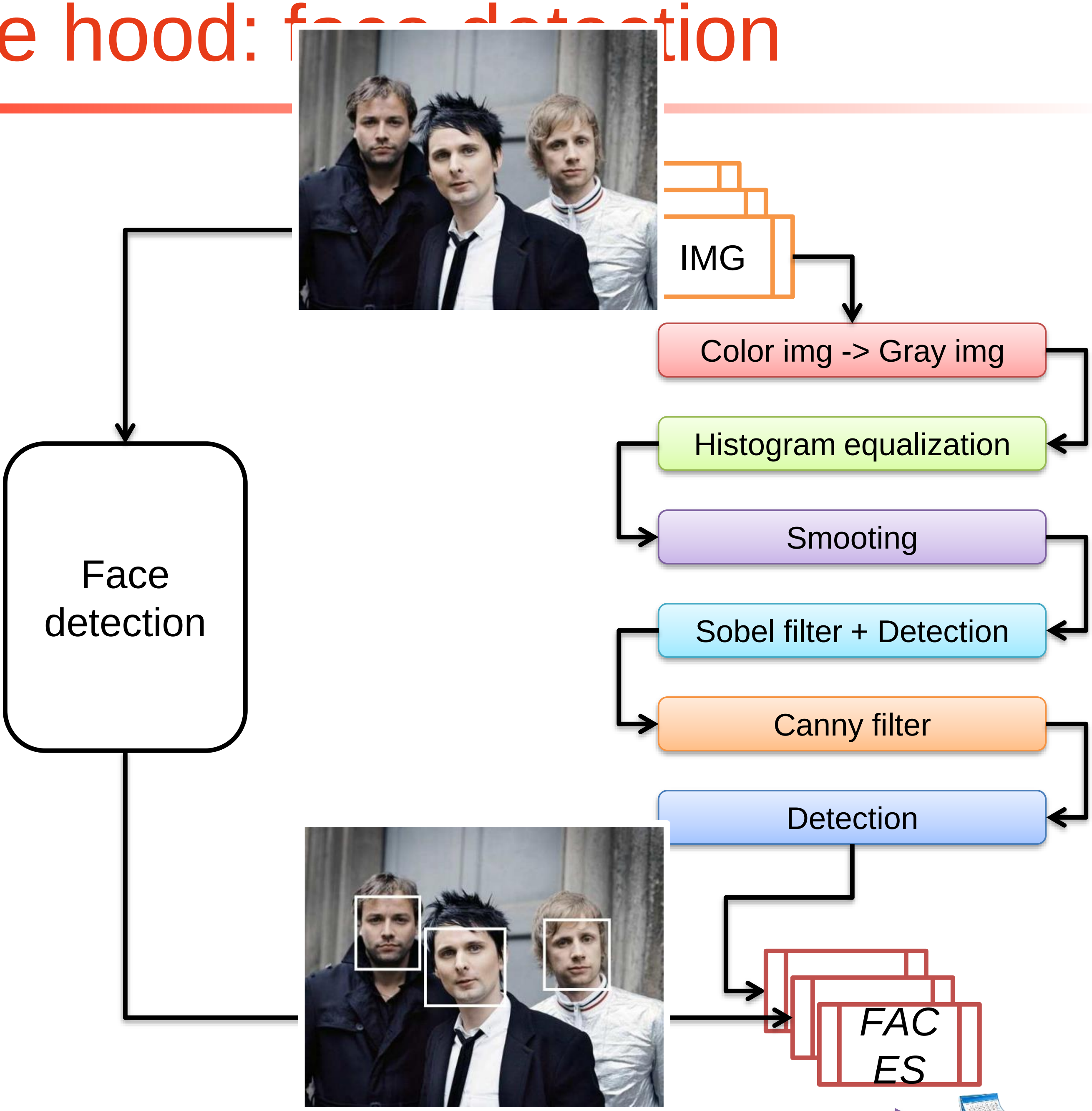
- ✓ Use it for General Purpose Computing!
  - GP-GPU
  - ~yr 2000

NdA: Computing modes
- General Purpose Computing
- High-Performance Computing
- Embedded Computing
- Real-Time Computing
- …

HiPeRT Lab

High-Performance Real-Time Lab

Under the hood: face detection



IMG

Color img -> Gray img

Histogram equalization

Smooting

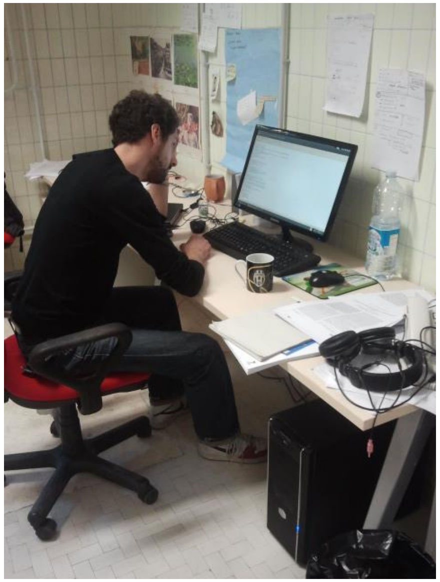
Sobel filter + Detection

Canny filter

Detection

FACES

Face detection



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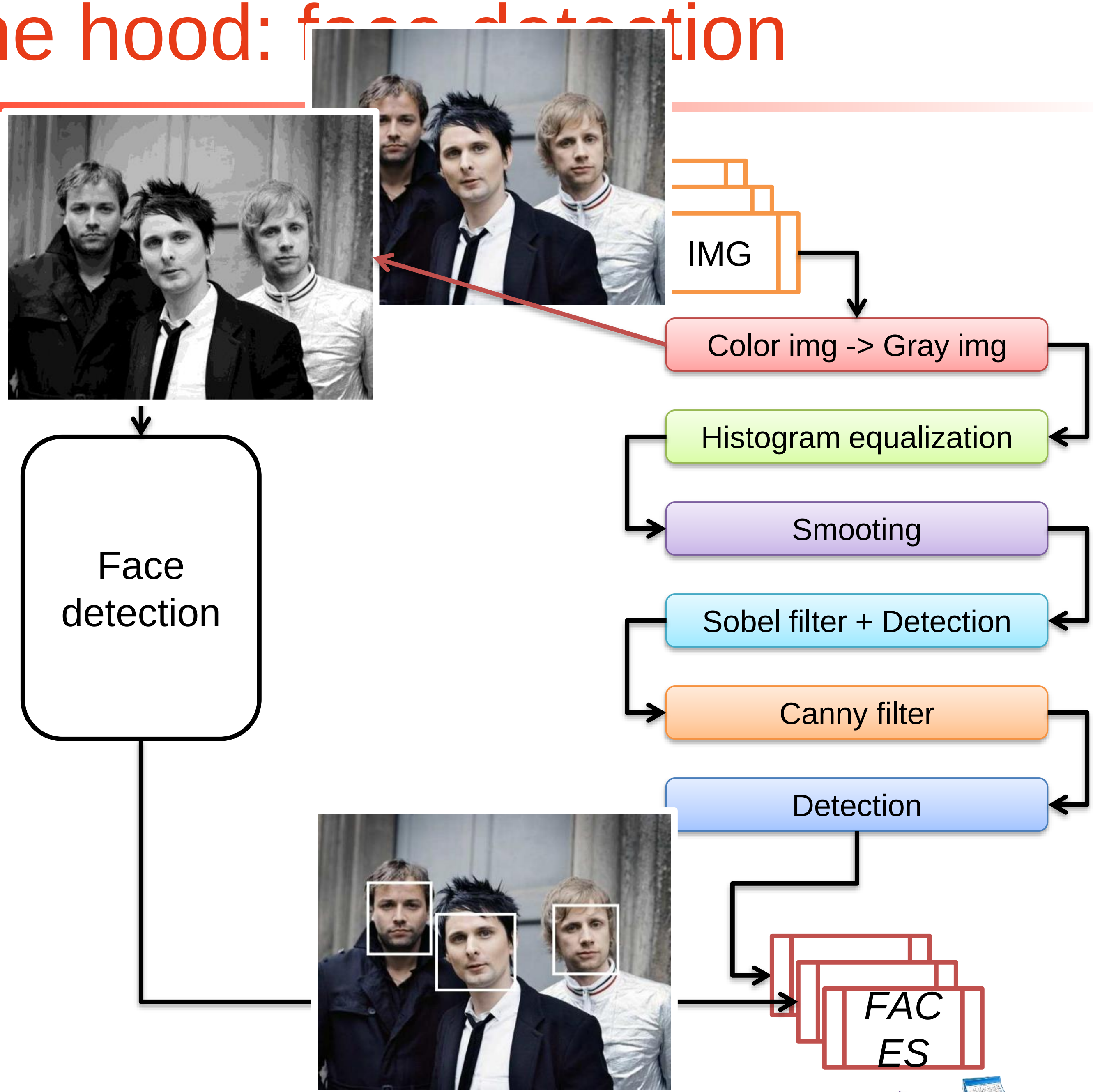

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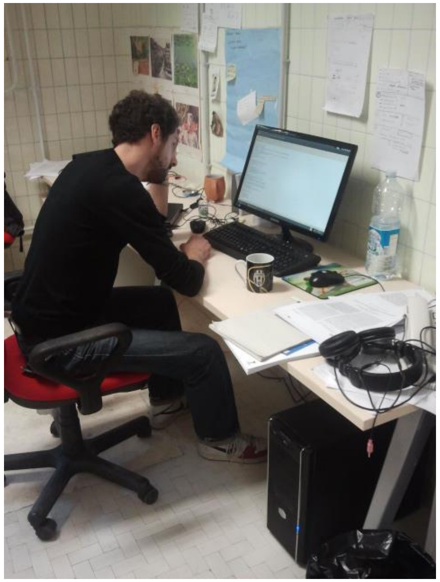

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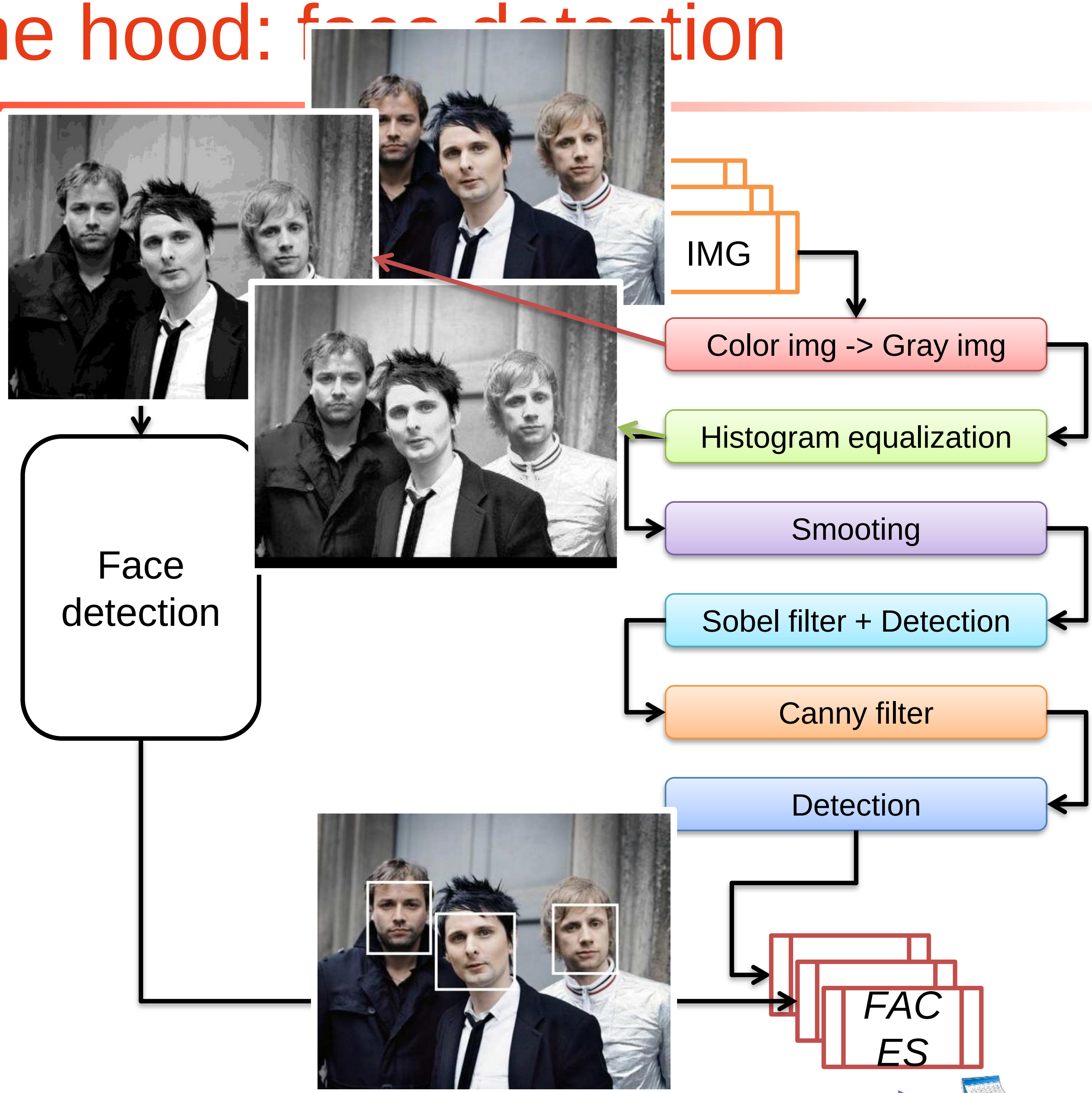

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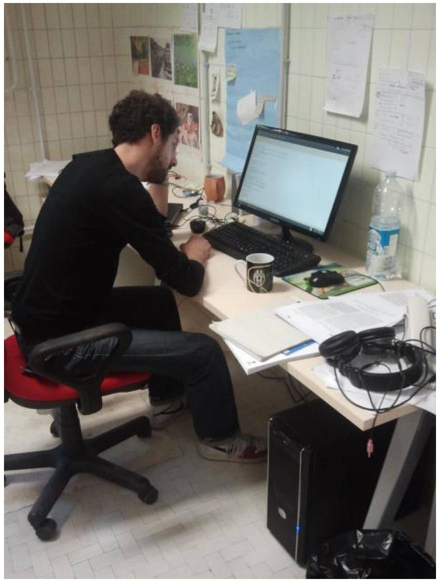

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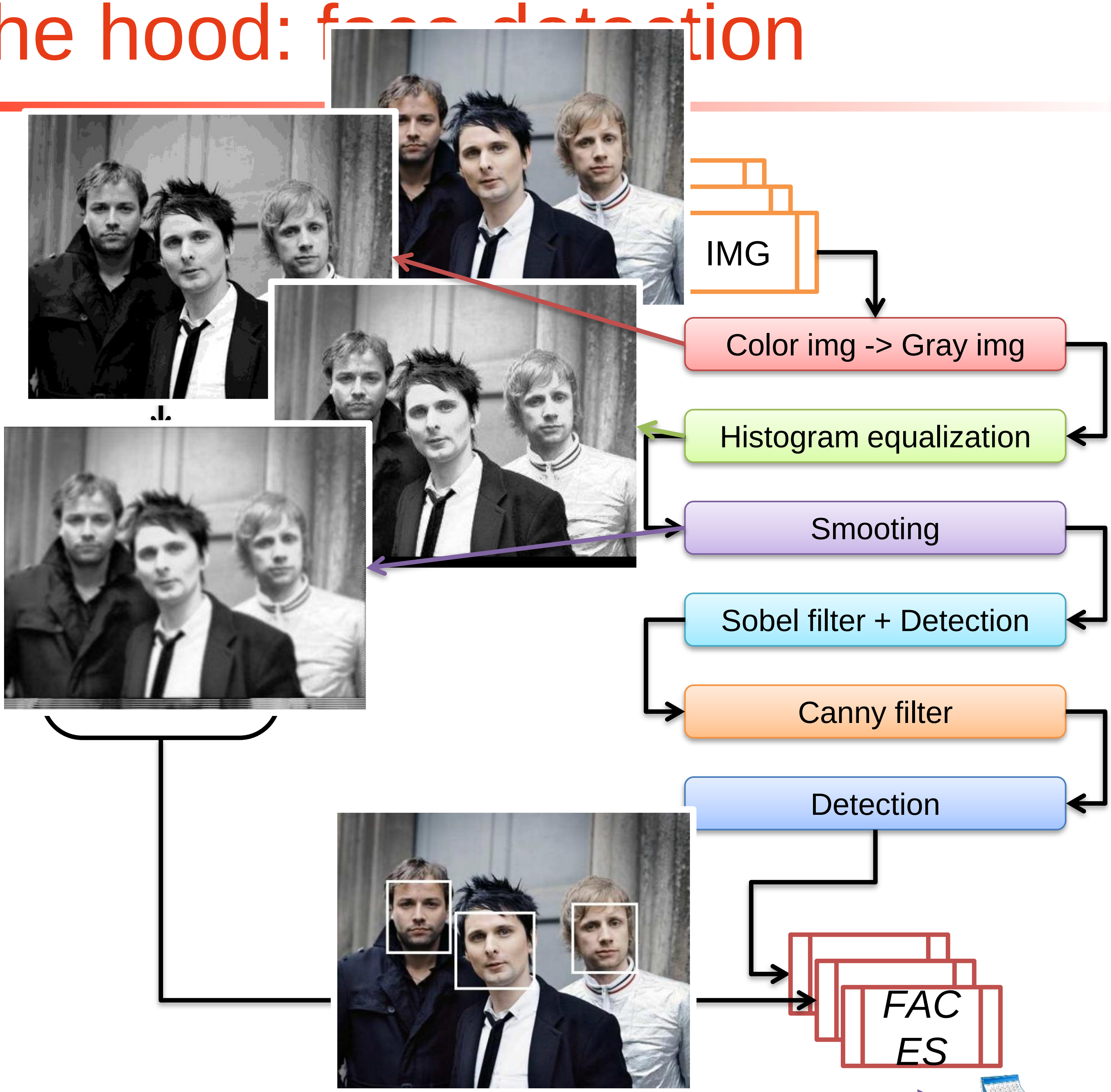

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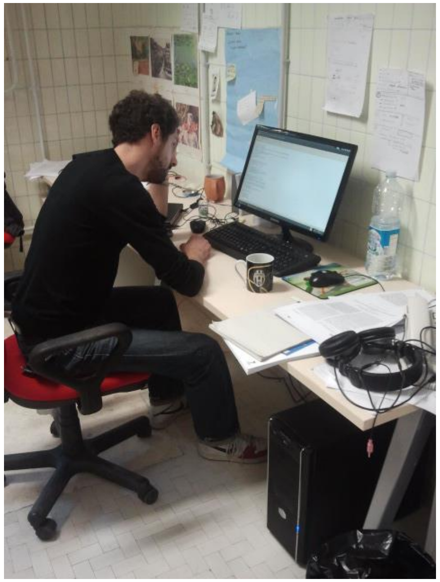

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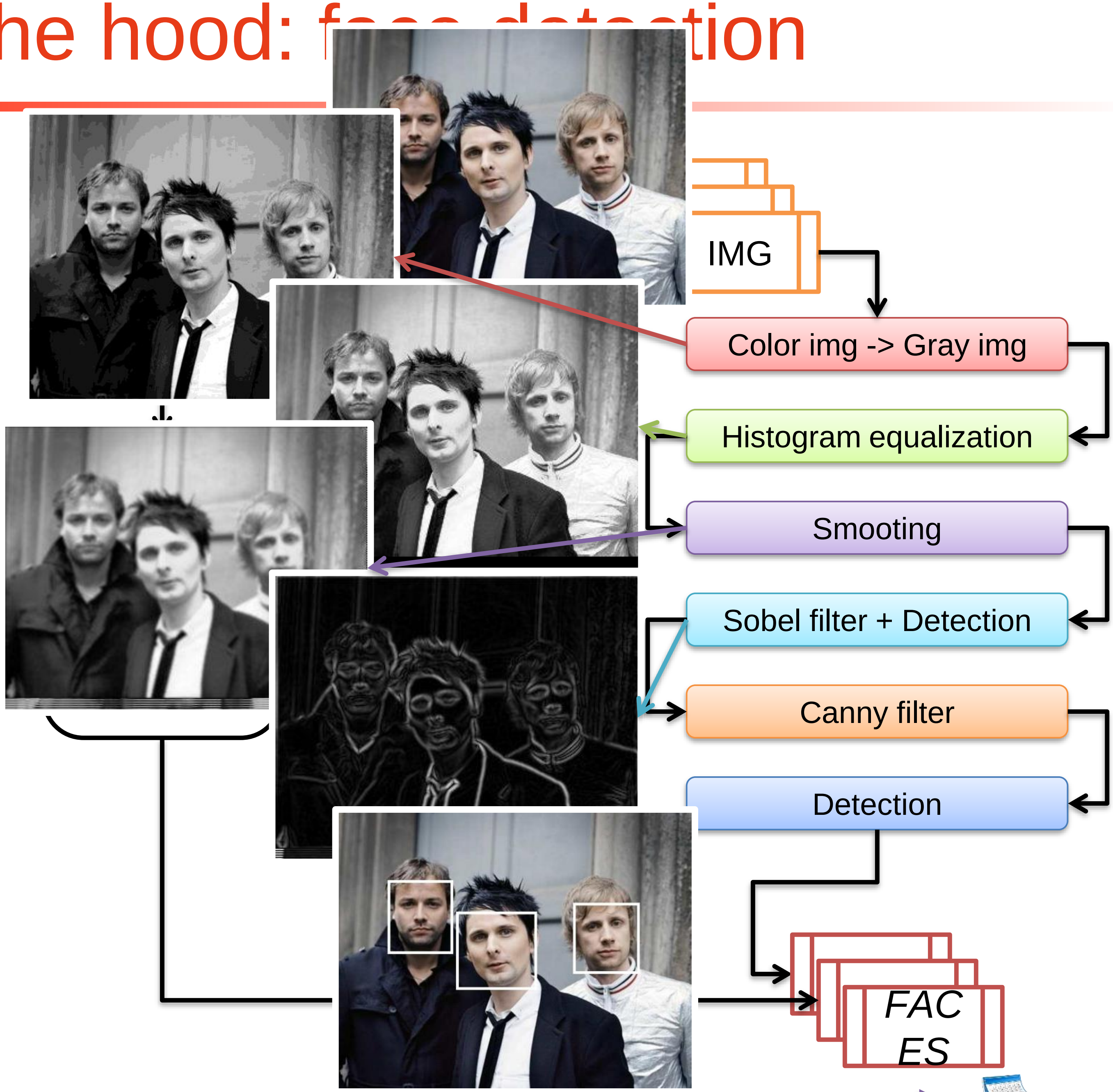

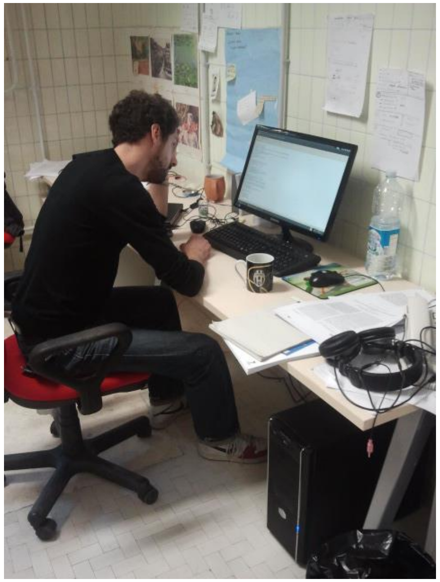

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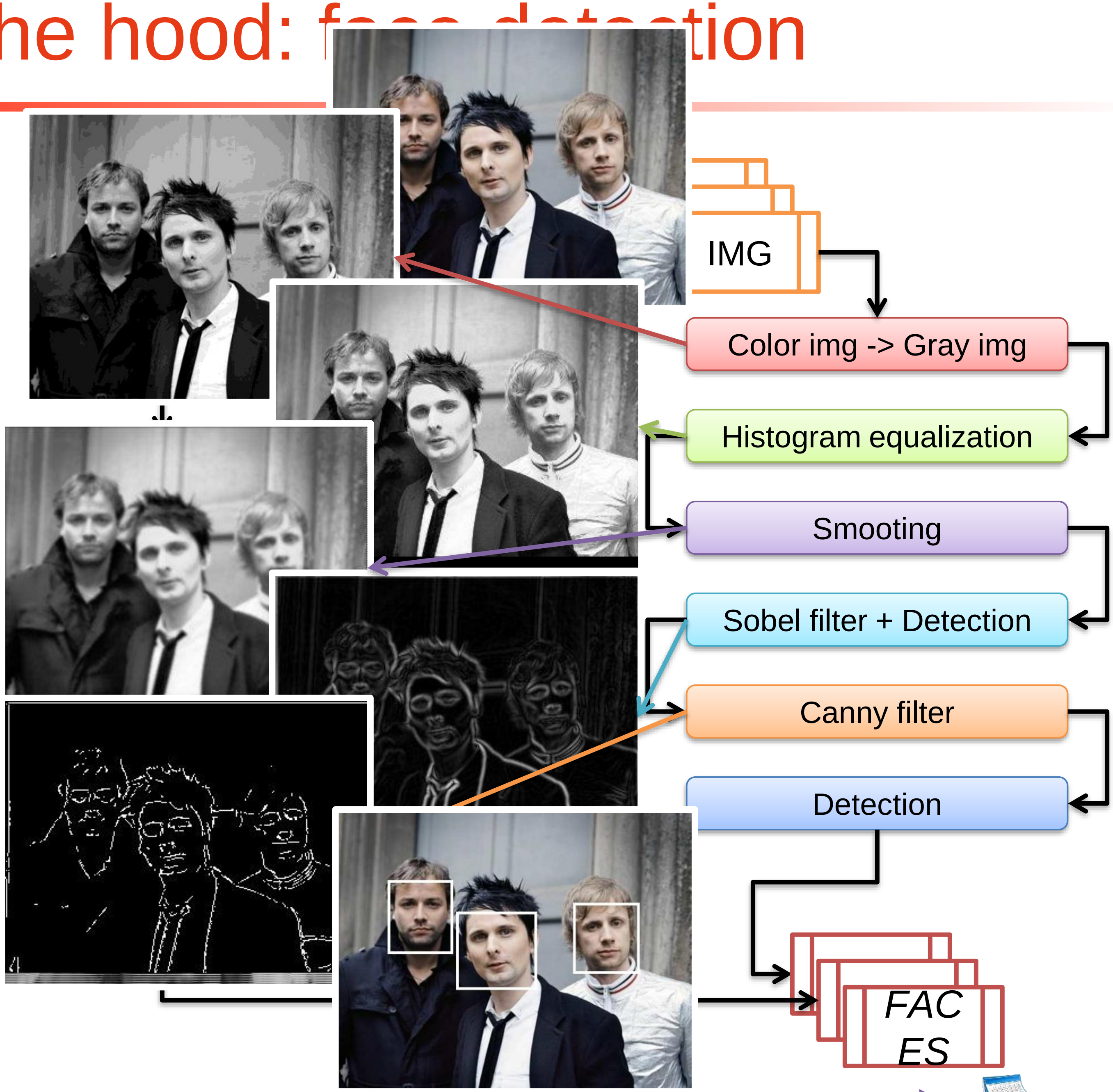

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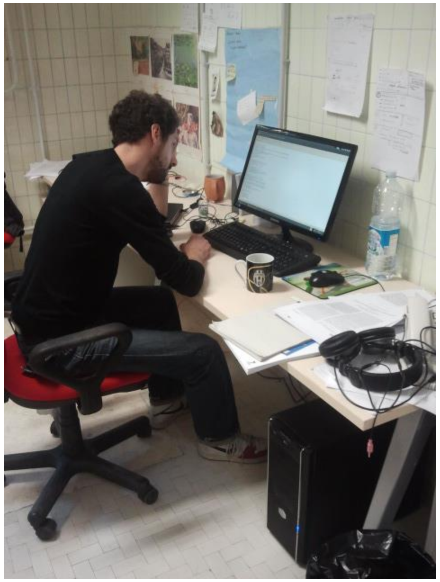
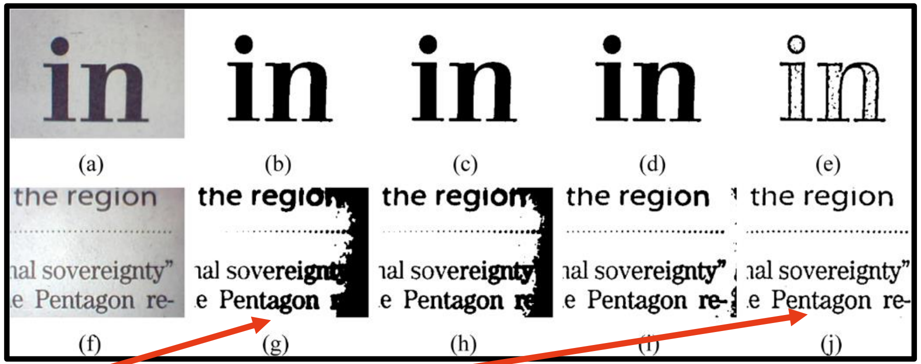


Image binarization

- ✓ Graylevel image => B/W image
- ✓ Pixel: 256 shades of gray
  - `unsigned char`s
  - 255 => white
  - 0 => black



```
#define GRAY_THRESHOLD 100
#define WHITE 255
#define BLACK 0
void binarizeImage(const unsigned char inputImg[],
                   unsigned char outputImg[],
                   unsigned int imgDim)
{
  for(int i=0; i<imgDim; i++)
    if(inputImg[i] >= GRAY_THRESHOLD)
      outputImg[i] = WHITE;
    else
      outputImg[i] = BLACK;
}
```

Image binarization

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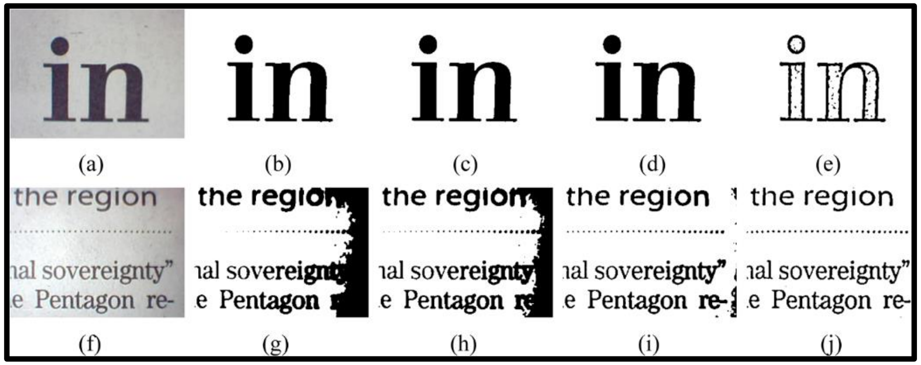

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Multiple Data

Image binarization

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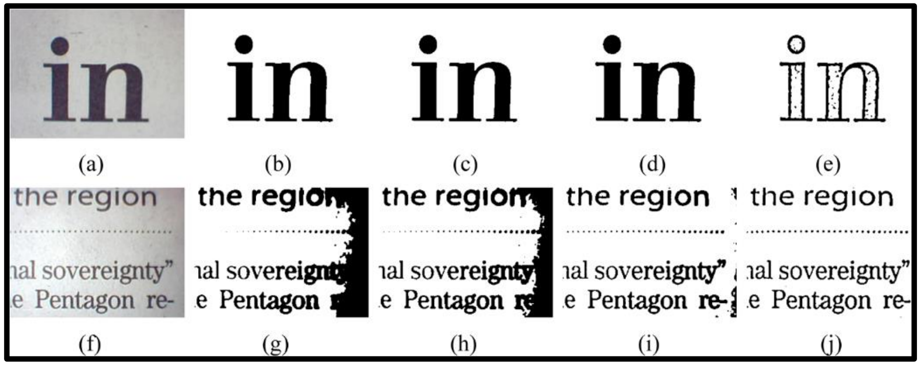

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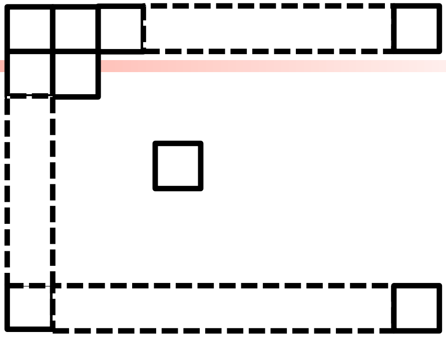
Single Program

GPUs



- ✓ Let's (re)design them!
- ✓ We want to perform graphics
  - – E.g., filters, shaders…

- ✓ Ultimately, operations on pixels!
  - – Same algorithm repeated for each (subset of) pixels

- ✓ Algorithm => program
- ✓ (subset of) pixels => data

- ✓ Same (single) Program, Multiple Data – SPMD
  - – Not SIMD!

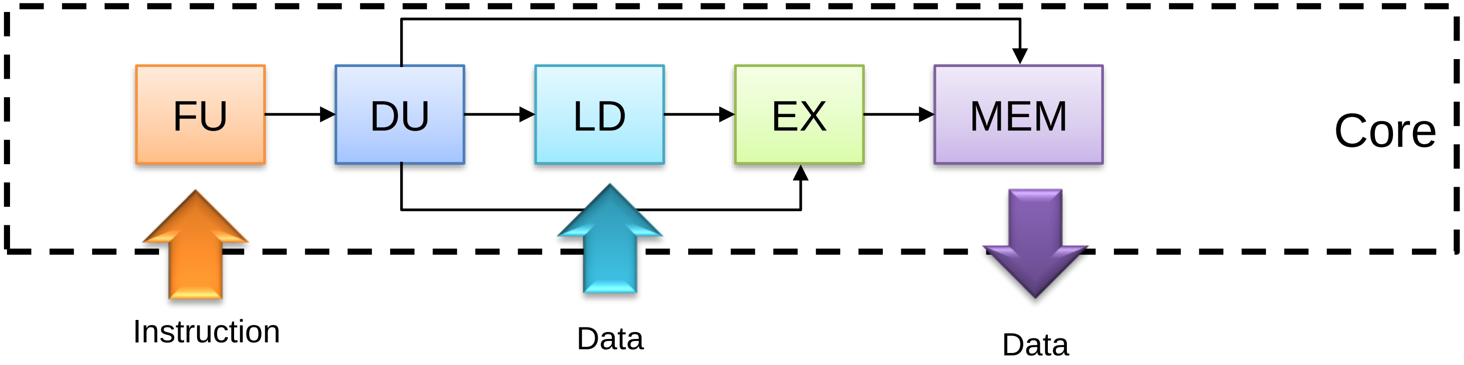
A (programmable) machine

- ✓ Algorithms for image processing are
  - – Highly regular (loop-based, with well known boundaries at image rows/columns)
  - – Massively parallel (thousands of threads)
- ✓ Regular, "big" loops
  - – Single Program (Loop Iteration) Multiple Data - SPMD
  - – Parallel threads perform the very same operation on adjacent data

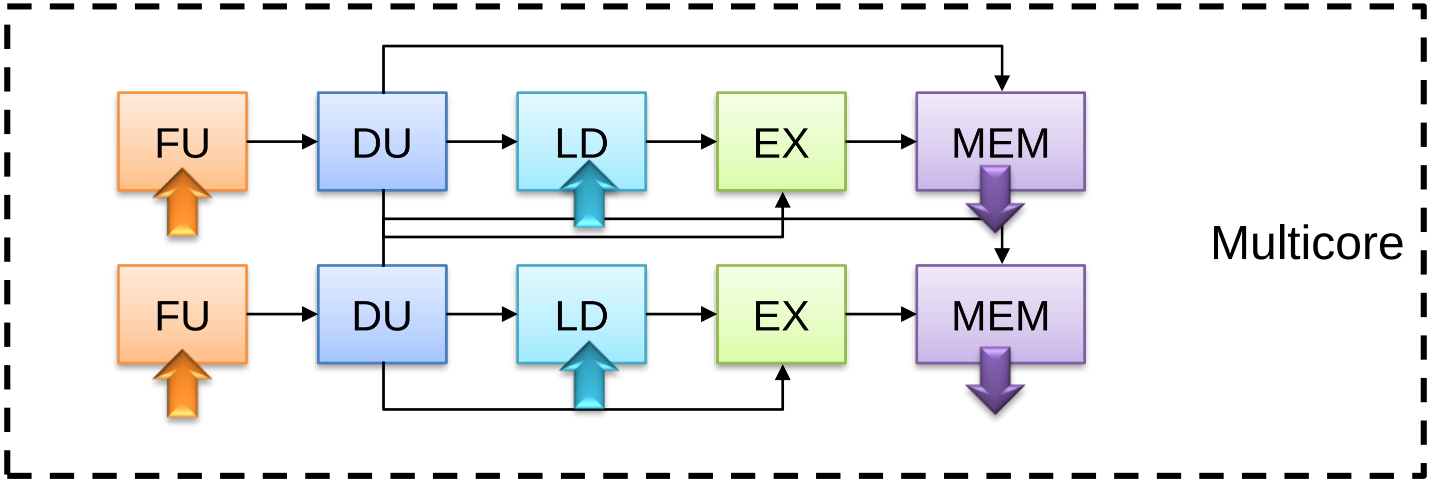
- ✓ We need a massively parallel machine
  - – Thousands of cores
- ✓ With simple cores
  - – FP Support
- ✓ To perform the very same instruction!
  - – Same Fetch Unit and Decode Unit

Fetch and decode units

- ✓ Traditional pipeline

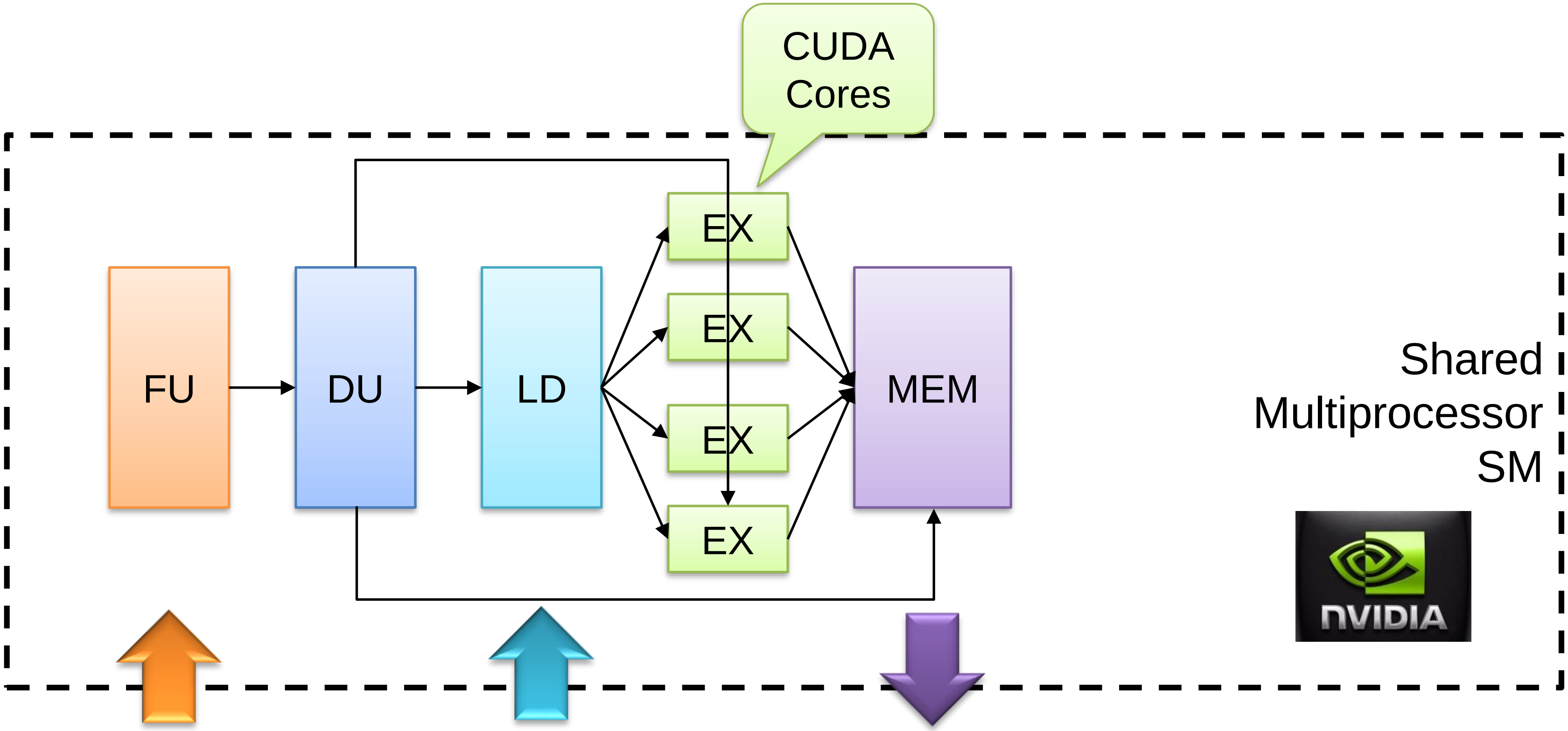


- ✓ Traditional parallel pipeline



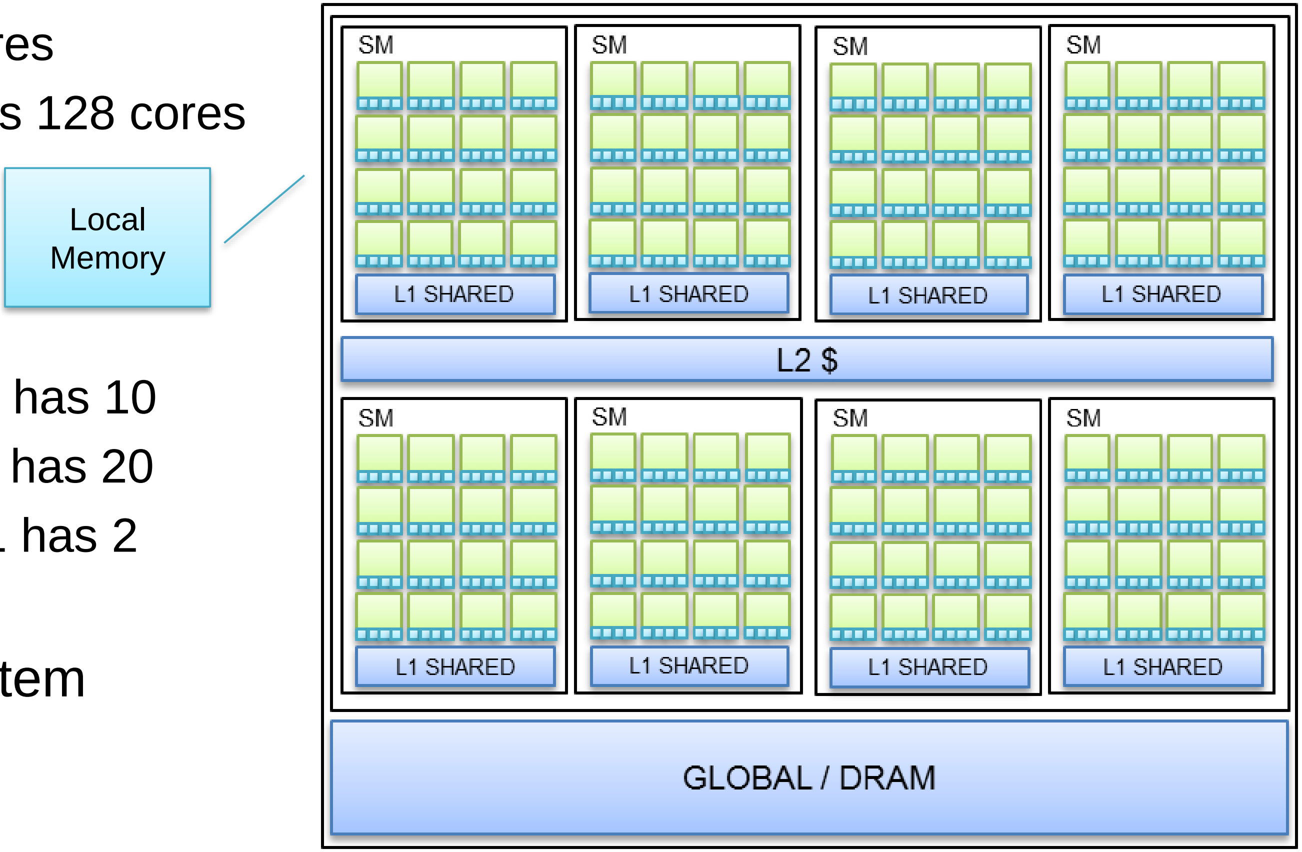
GPU multi-core

- ✓ Share FU, DU, MEM units
  - – Approximate scheme!



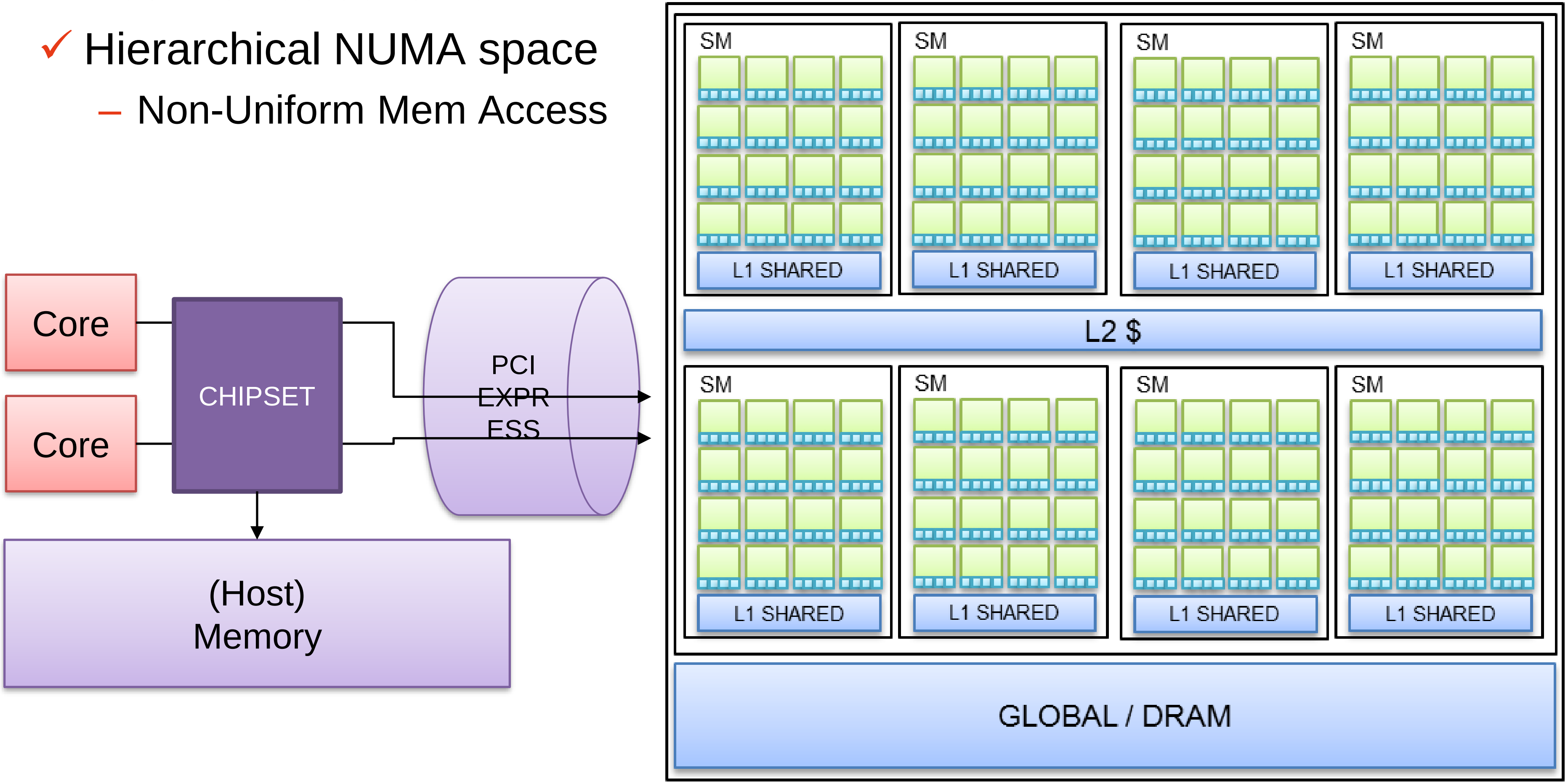
SMs as building block

- ✓ Architecture of the SM
  - GPU "class"
  - Kepler has 192 cores
  - Maxwell/Pascal has 128 cores
- ✓ Number of SMs
  - GPU model
  - Maxwell's GTX980 has 10
  - Pascal's GTX1080 has 20
  - Pascal's Drive PX1 has 2
- ✓ NUMA memory system



GPU as a device

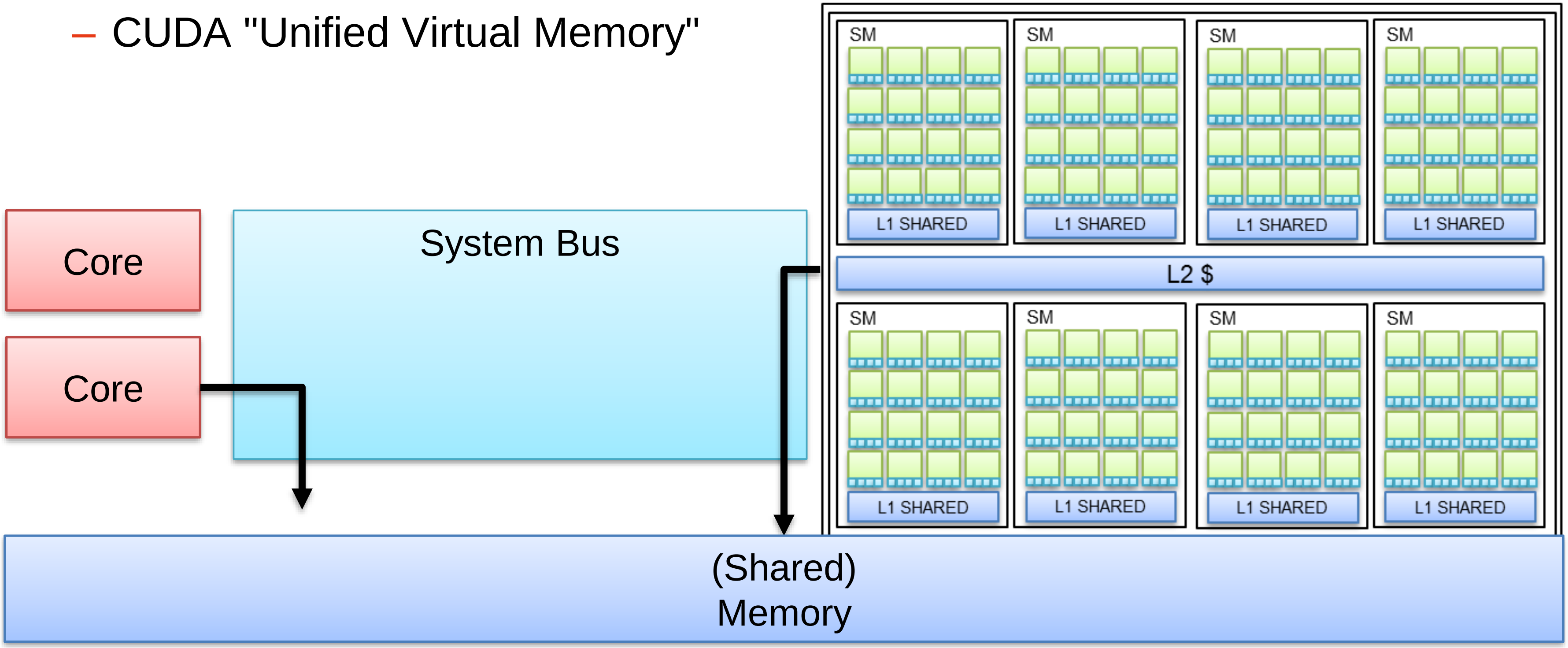
- ✓ Host-device scheme
- ✓ Hierarchical NUMA space
  - – Non-Uniform Mem Access



Integrated GP-GPUs

GP-GPU based embedded platforms

- ✓ As opposite to, traditional "discrete" GP-GPUs
- ✓ Still, host + accelerator model
- ✓ Communicate via shared memory
  - – No PCI-express
  - – CUDA "Unified Virtual Memory"



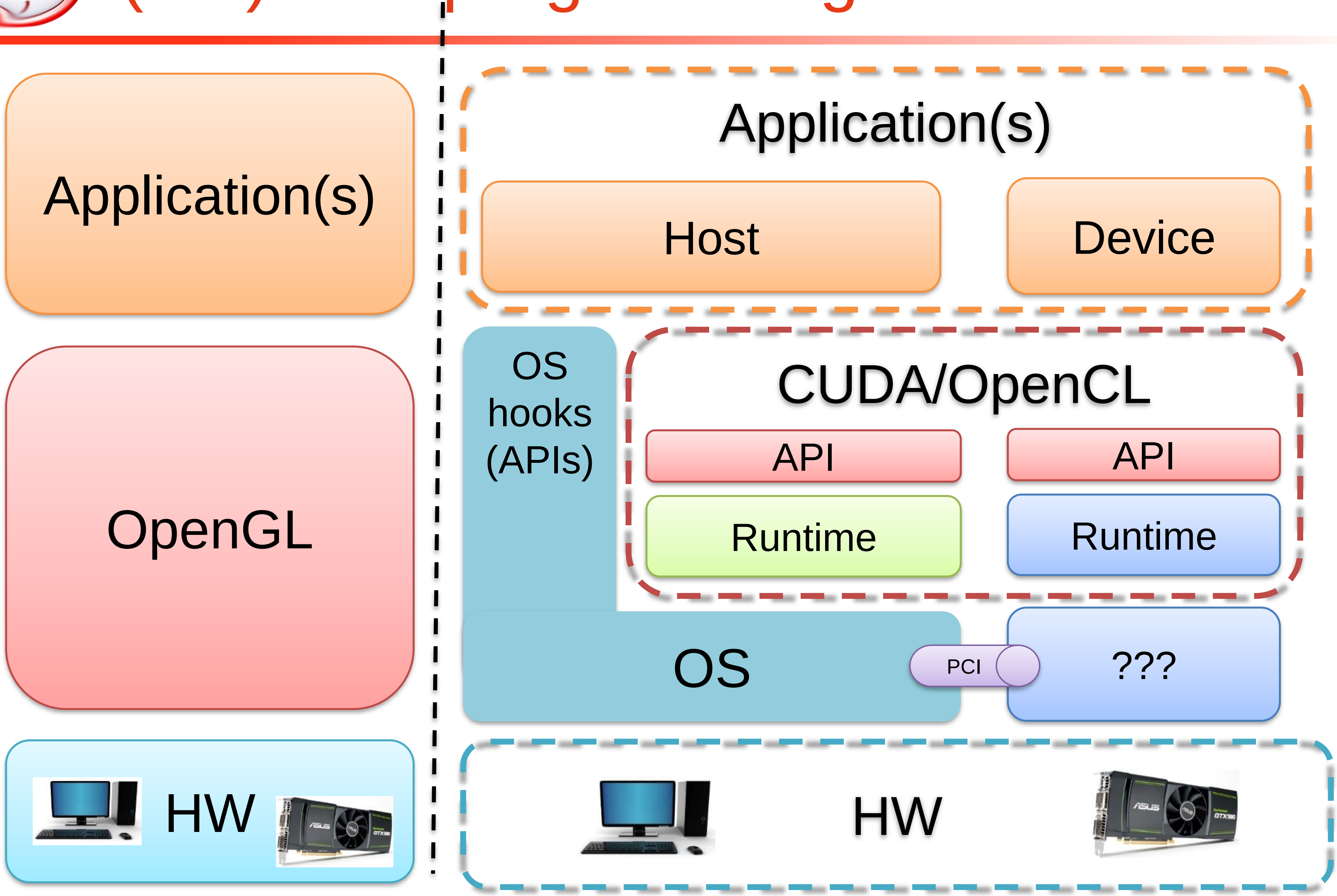
To summarize…

- ✓ Tightly-coupled SMs
  - Multiple cores sharing HW resources: L1 cache, Fetch+Decode Unit, (maybe even) Memory controller
  - GPU "Class" (NVIDIA Kepler, Maxwell, Parker..)
  - ~100s cores

- ✓ Multiple SMs integrated onto one chip
  - GPU "name" (NVIDIA GTX980, GT640…)
  - 1000s cores
  - NUMA hiearchy

- ✓ Typically (but not only) used as co-processor/accelerator
  - PCIEXPRESS connectivity

(GP)GPU programming stack



Application(s)

OpenGL

HW

Application(s)

Host

Device

OS hooks (APIs)

CUDA/OpenCL

API

API

Runtime

Runtime

OS

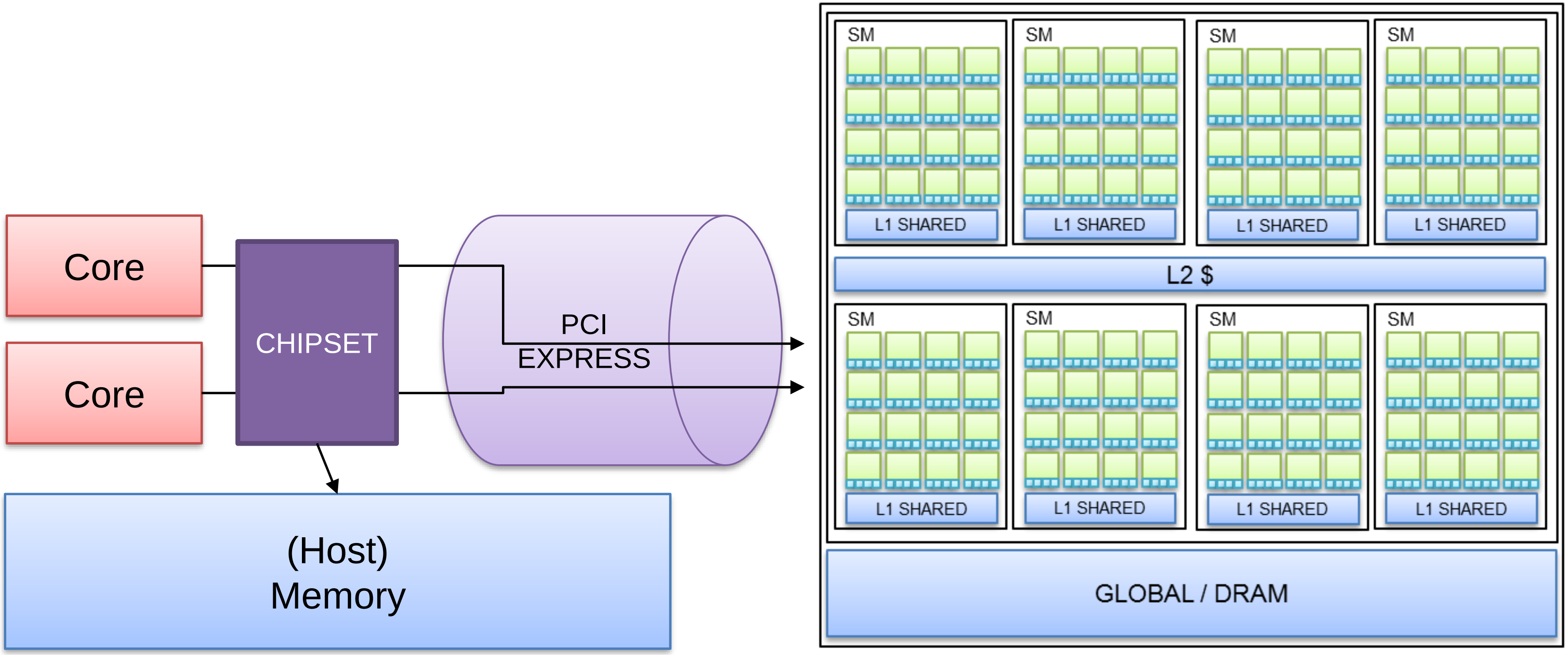
PCI

???

HW

GPU programming

- ✓ We need a programming model that provides
  1. Simple offloading subroutines
  2. An easy way to write code which runs on thousand threads
  3. A way to exploit the NUMA hierarchy



1) Offload-based programming

- ✓ Offload-based programming models
  - – CUDA
  - – OpenCL
  - – OpenMP 4.5

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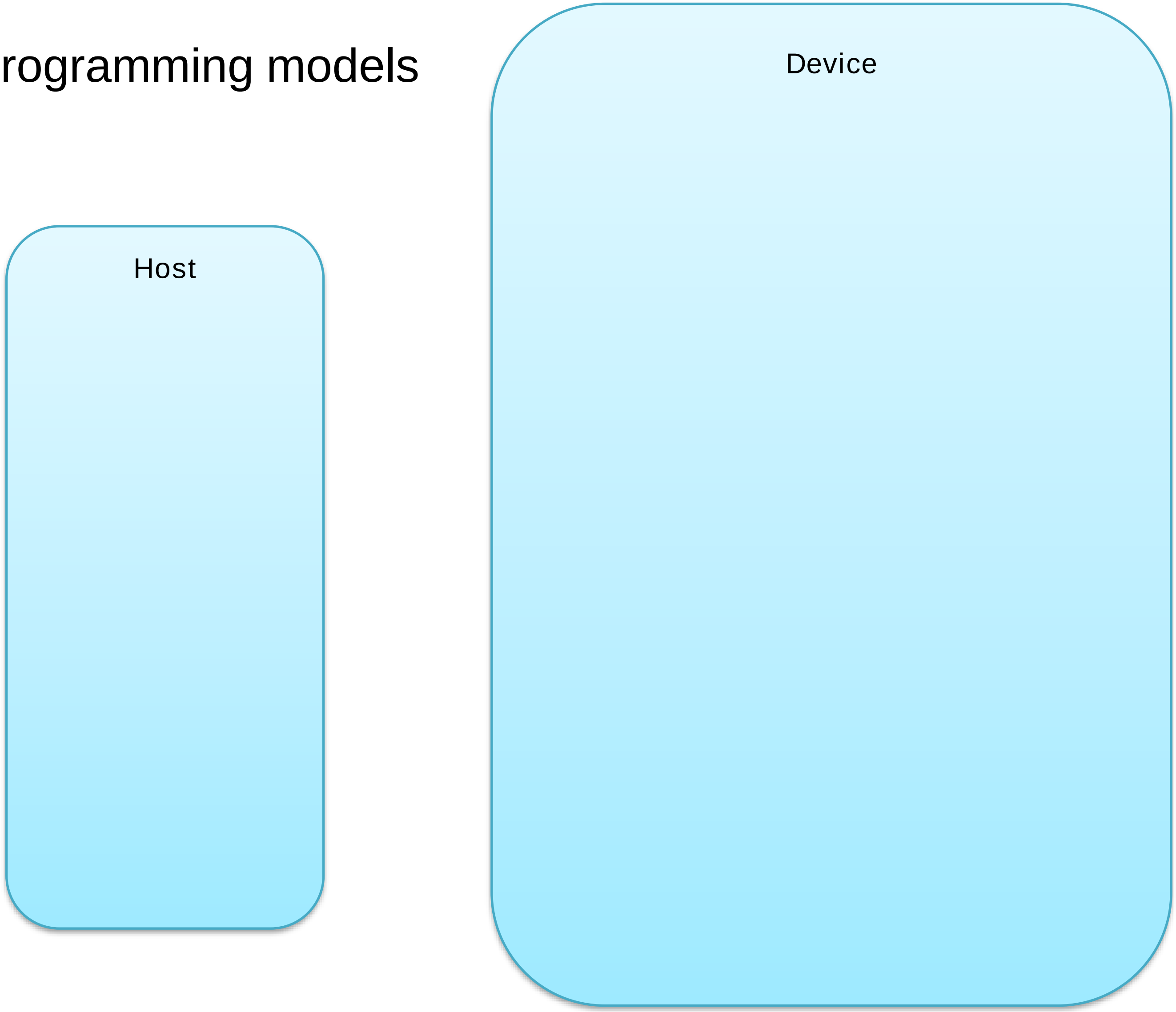
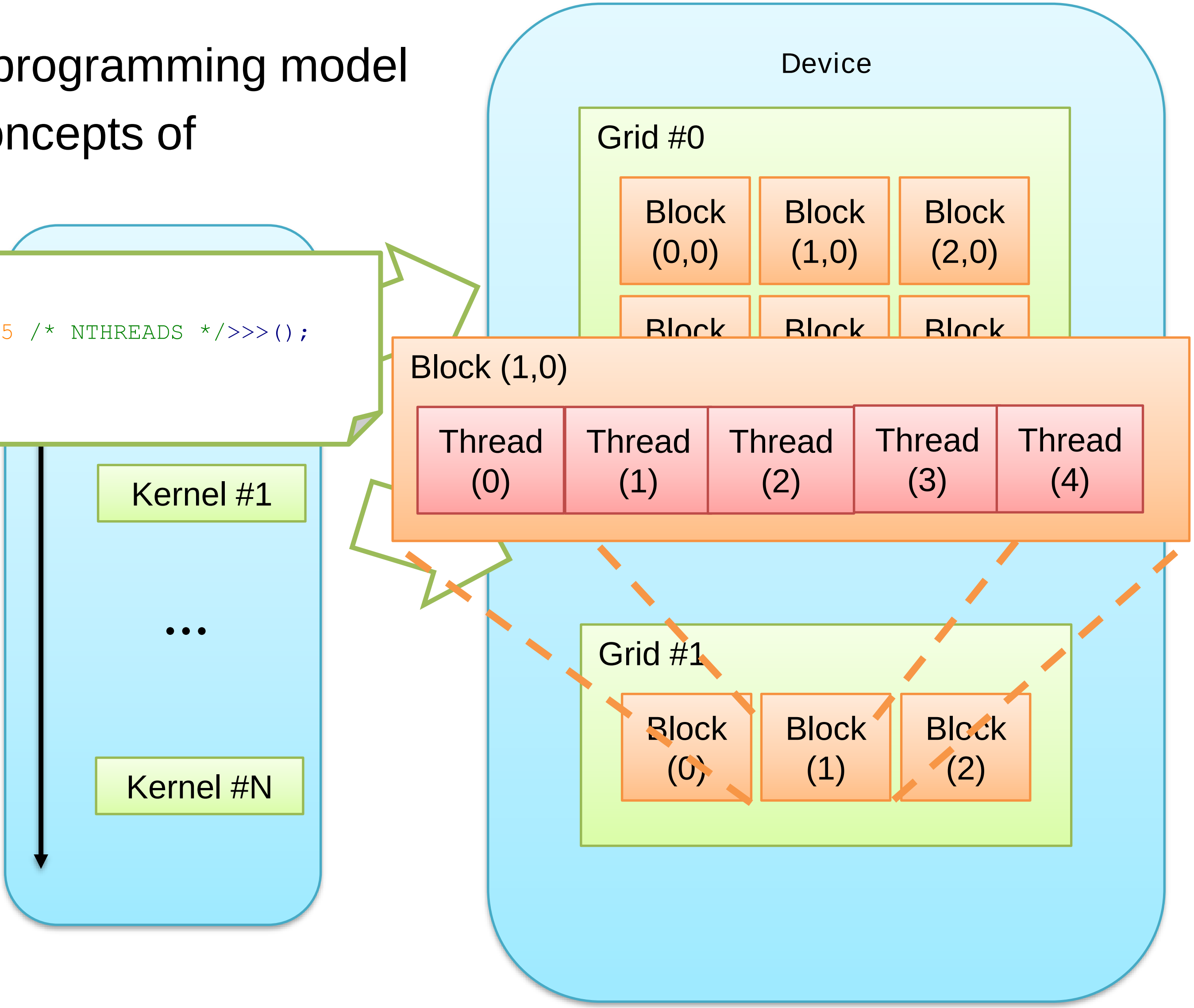
  - OpenMP 4.5



2) Parallelism in CUDA

- ✓ Esposed in the programming model
- ✓ Based on the concepts of
  - Grid(s)
  - Block(s)

```
myKernel<<<3 /* NBLOCKS */, 5 /* NTHREADS */>>>();
```



2) Parallelism in CUDA

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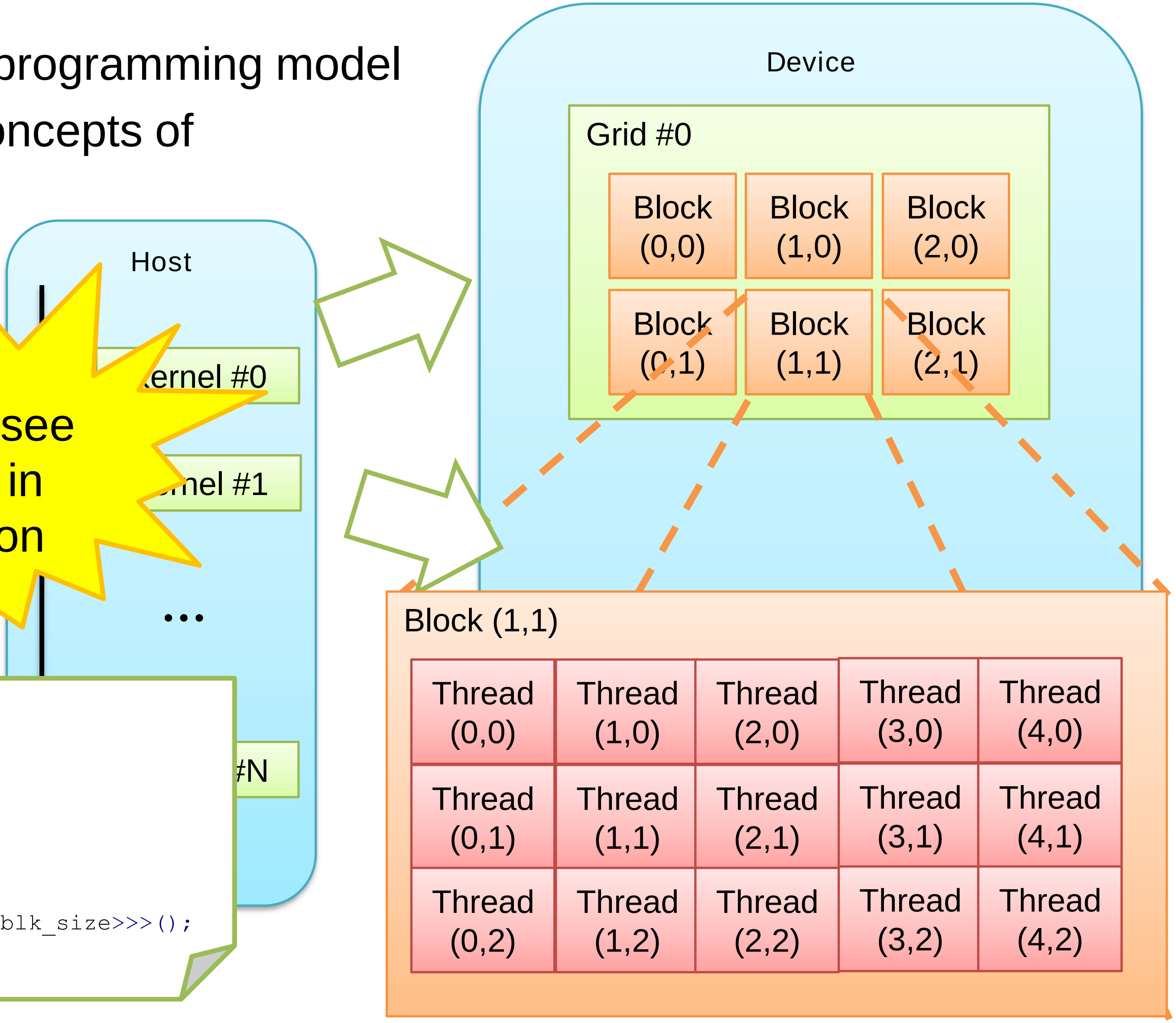
  - – Grid(s)
  - – Block(s)
  - – Thread(s)

Let's see this in action



Block (0,0)	Block (1,0)	Block (2,0)
Block (0,1)	Block (1,1)	Block (2,1)

Block (1,1)

Thread (0,0)	Thread (1,0)	Thread (2,0)	Thread (3,0)	Thread (4,0)
Thread (0,1)	Thread (1,1)	Thread (2,1)	Thread (3,1)	Thread (4,1)
Thread (0,2)	Thread (1,2)	Thread (2,2)	Thread (3,2)	Thread (4,2)

```
dim3 grid_size;
grid_size.x = 3;
grid_size.y = 2;

dim3 blk_size;
blk_size.x = 5;
blk_size.y = 3;

myKernel<<<grid_size,blk_size>>>();
```

Complexity of GPUs

- ✓ Grids ➔ kernels
- ✓ Blocks X Threads represent a "work-space"
  - Synchronization is possible only within the same CUDA Block
    - `__syncthreads()`
  - Each thread retrieves its "point" inside this space, and maps it on a specific
    - Data item, such as array element, matrix element, matrix row…
    - "Job item", such as a function
    - Can be 2x1D, 2x2D, 2x3D: extremely (too much) flexible and scalable

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```
#define GRAY_THRESHOLD 100
#define WHITE 255
#define BLACK 0
void binarizeImage(const unsigned char inputImg[],
                   unsigned char outputImg[],
                   unsigned int imgDim)
{
  for(int i=0; i<imgDim; i++)
    if(inputImg[i] >= GRAY_THRESHOLD)
      outputImg[i] = WHITE;
    else
      outputImg[i] = BLACK;
}
```

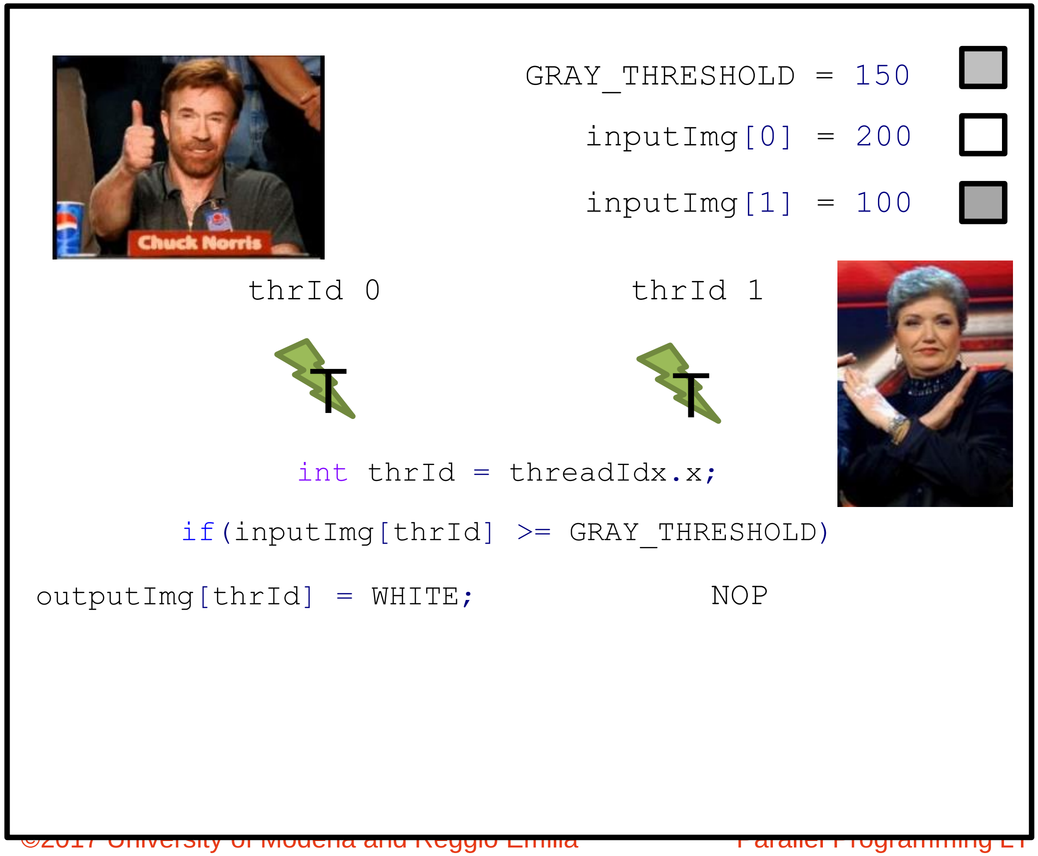
```
/* ... */

// 1 => # Blocks
// imgDim => #Threads
// 1 thread works on each pixel
int thrId = threadIdx.x;
if(inputImg[thrId] >= GRAY_THRESHOLD)
  outputImg[thrId] = WHITE;
else
  outputImg[thrId] = BLACK;

/* ... */
```

Lockstep

- ✓ (Groups of) cores share the same instruction Fetch/Decode Units
  - – Ultimately, the same Program Counter!!!
  - – Threads cannot do branches - LOCKSTEP



GRAY_THRESHOLD = 150 ▨

inputImg[0] = 200 □

inputImg[1] = 100 ▨

thrId 0

thrId 1

```
int thrId = threadIdx.x;

if(inputImg[thrId] >= GRAY_THRESHOLD)

outputImg[thrId] = WHITE;          NOP
```

```
/* ... */

// 1 => # Blocks
// imgDim => #Threads
// 1 thread works on each pixel
int thrId = threadIdx.x;
if(inputImg[thrId] >= GRAY_THRESHOLD)
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```

Lockstep

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```
GRAY_THRESHOLD = 150   ▨
   inputImg[0] = 200   □
   inputImg[1] = 100   ■

      thrId 0              thrId 1

            int thrId = threadIdx.x;

     if(inputImg[thrId] >= GRAY_THRESHOLD)

outputImg[thrId] = WHITE;          NOP

                   else

         NOP             outputImg[thrId] = BLACK;
```

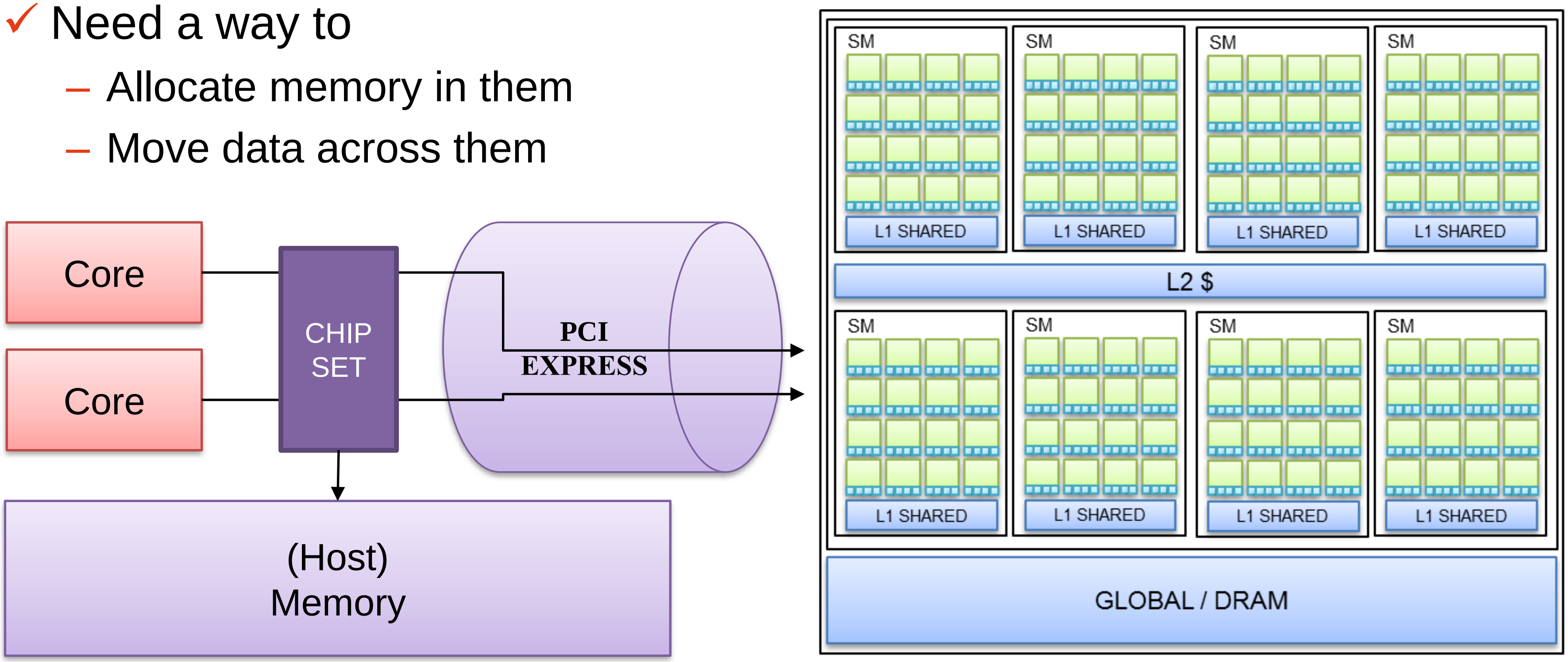
```
/* ... */

// 1 => # Blocks
// imgDim => #Threads
// 1 thread works on each pixel
int thrId = threadIdx.x;
if(inputImg[thrId] >= GRAY_THRESHOLD)
  outputImg[thrId] = WHITE;
else
  outputImg[thrId] = BLACK;

/* ... */
```

Warps, and lockstep

- ✓ Threads are grouped in warps
  - – 1 warp <-> 32 CUDA threads
  - – Units of scheduling
  - – Threads of a single blocks are scheduled and de-scheduled 32 by 32
- ✓ Threads within the same warp run in LOCKSTEP
- ✓ Memory accesses within the single warp are coalesced

3) Exploit NUMA in CUDA

- ✓ Four memory spaces
  - Host
  - Device Global
  - Device Shared
  - Device Local
- ✓ Need a way to
  - Allocate memory in them
  - Move data across them



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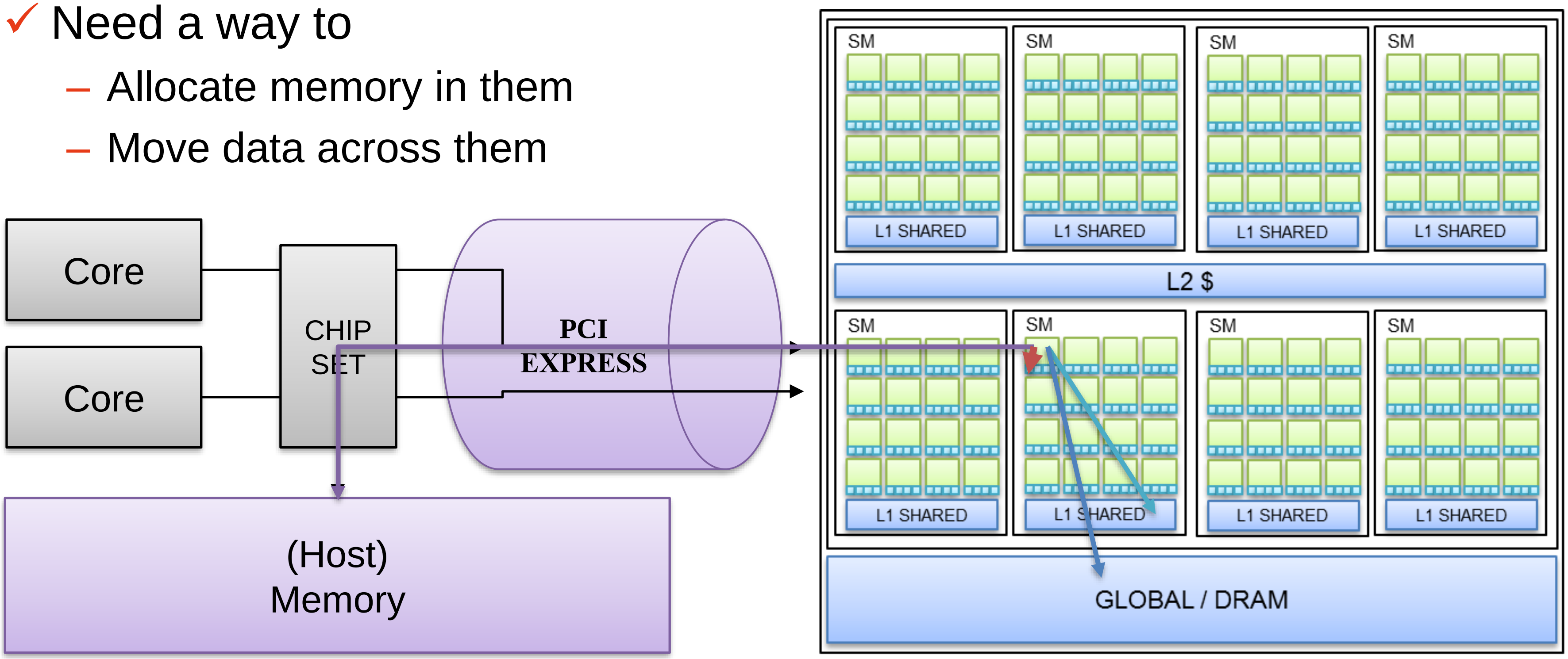
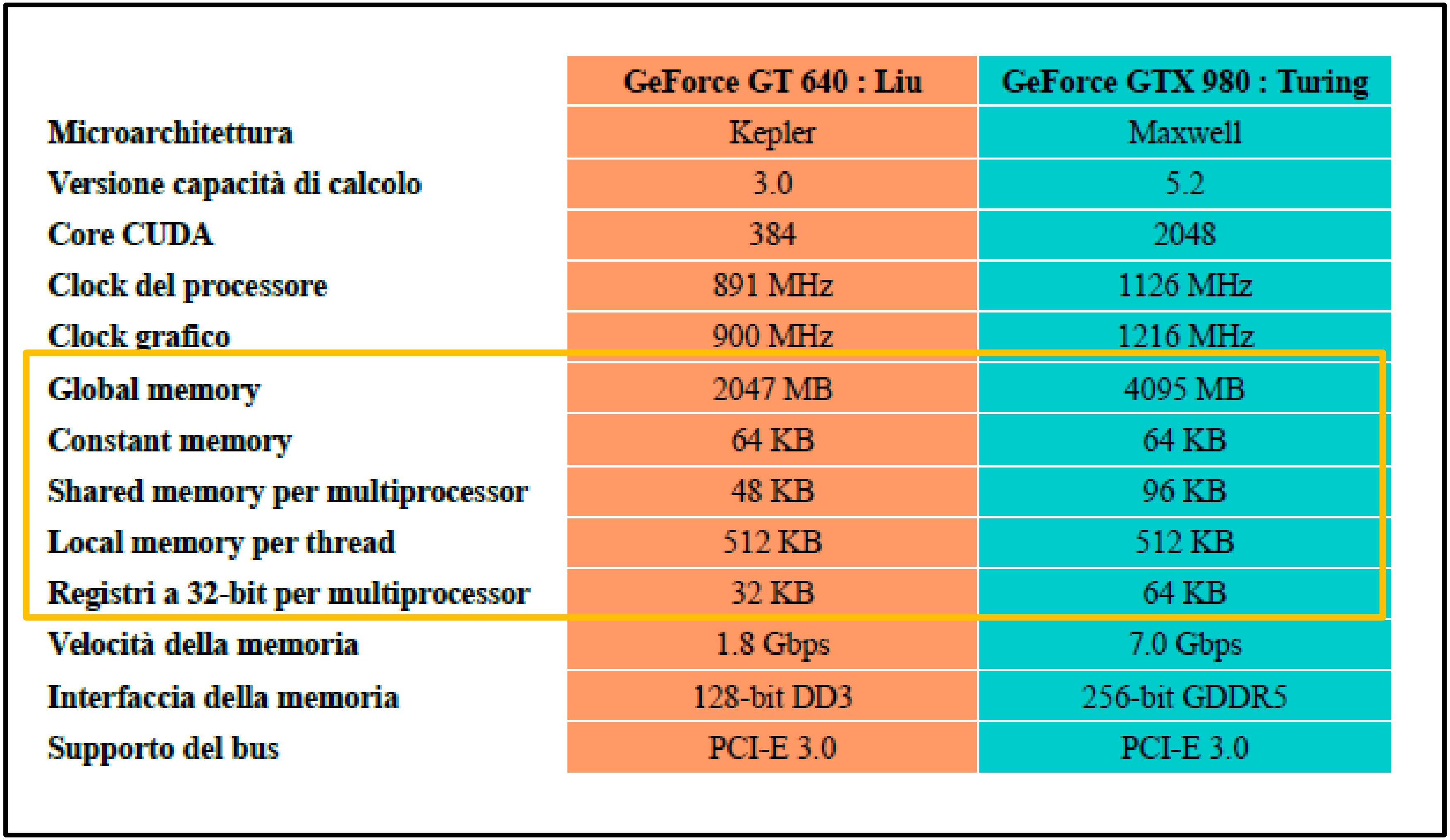
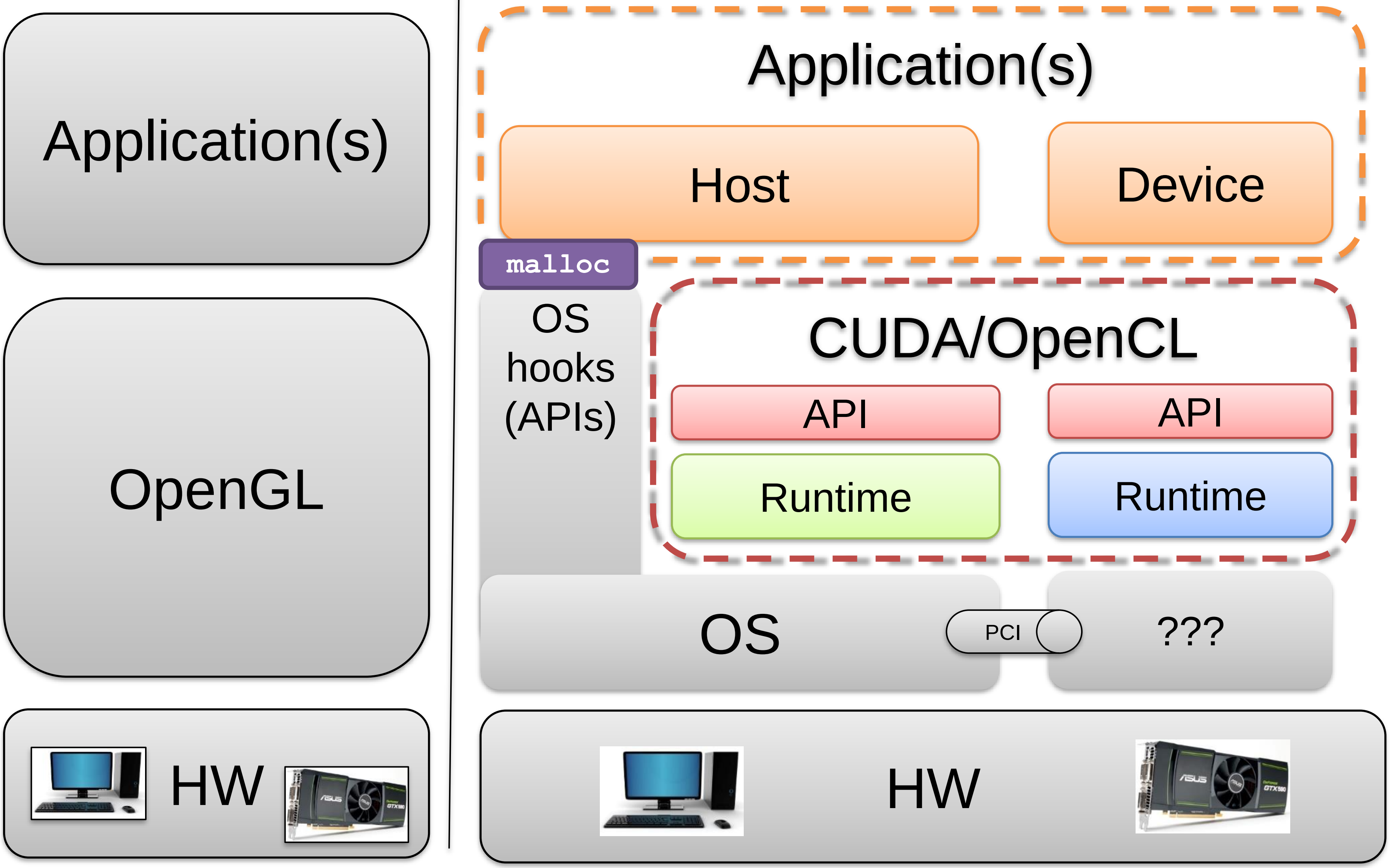


GPU memory size



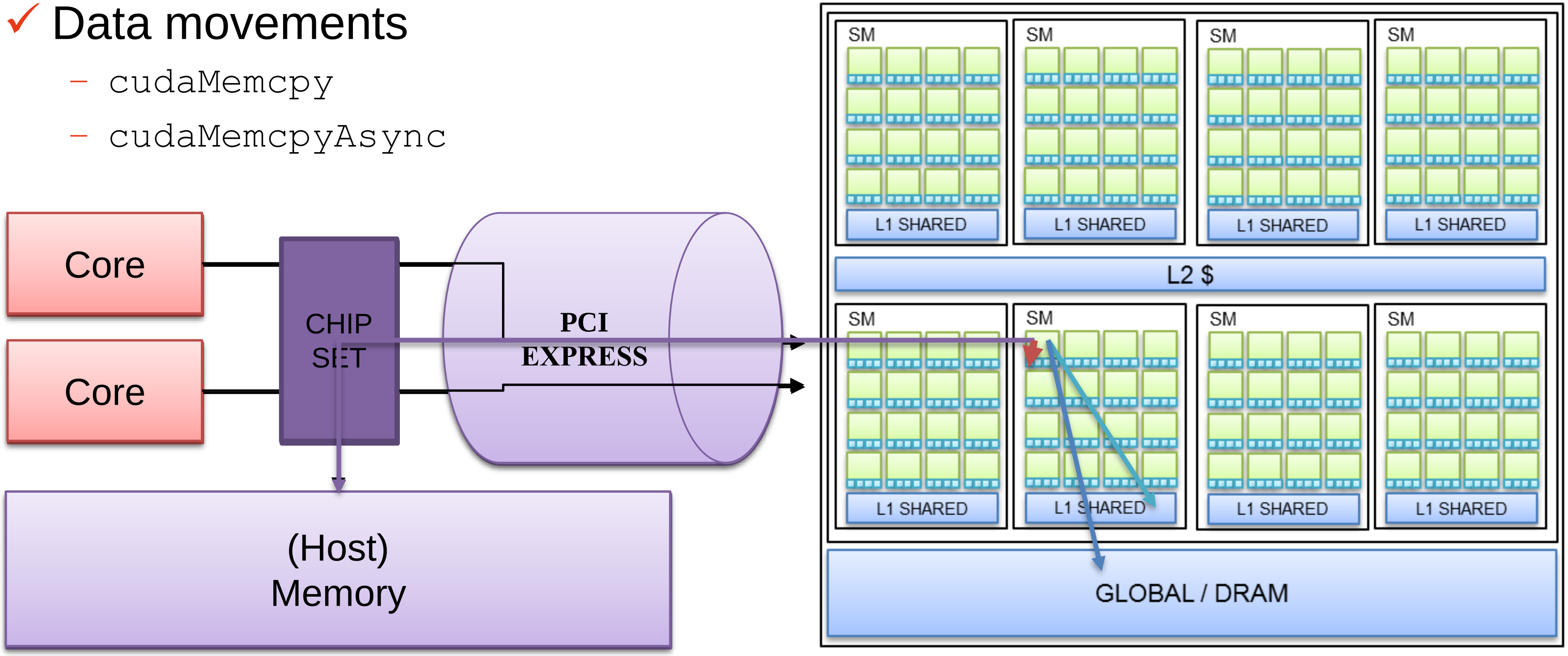
	GeForce GT 640 : Liu	GeForce GTX 980 : Turing
Microarchitettura	Kepler	Maxwell
Versione capacità di calcolo	3.0	5.2
Core CUDA	384	2048
Clock del processore	891 MHz	1126 MHz
Clock grafico	900 MHz	1216 MHz
Global memory	2047 MB	4095 MB
Constant memory	64 KB	64 KB
Shared memory per multiprocessor	48 KB	96 KB
Local memory per thread	512 KB	512 KB
Registri a 32-bit per multiprocessor	32 KB	64 KB
Velocità della memoria	1.8 Gbps	7.0 Gbps
Interfaccia della memoria	128-bit DD3	256-bit GDDR5
Supporto del bus	PCI-E 3.0	PCI-E 3.0

(GP)GPU programming stack



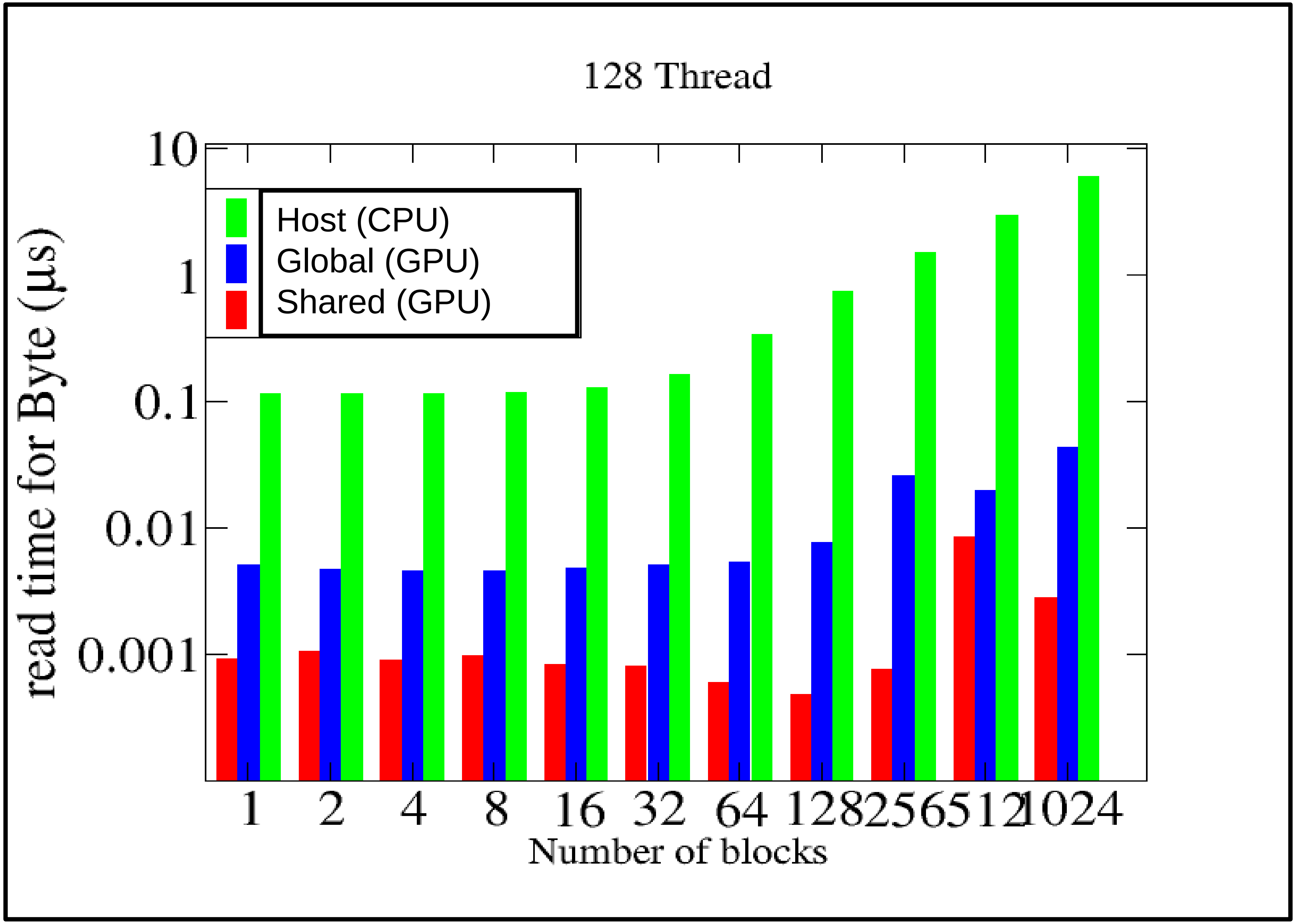
3) Exploit NUMA in CUDA

- ✓ Runtime must be aware of all
- ✓ Memory allocations
  - `cudaHostAlloc` ➔ Host mem
  - `cudaMalloc` ➔ Global mem
  - `__shared__` keyword ➔ Shared mem
- ✓ Data movements
  - `cudaMemcpy`
  - `cudaMemcpyAsync`



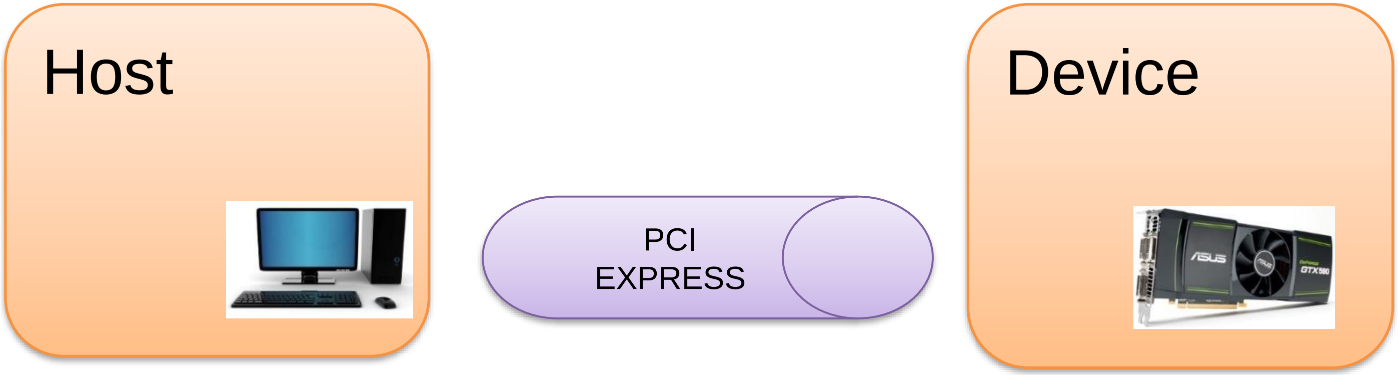
Non-Uniform Access Time

Serena's thesis 110/110



OpenCL

- Open Computing Language
  - More verbose than CUDA
- More "library-based" approach
- Different artifacts for managing parallelism
  - CUDA blocks, Threads
  - OpenCL Work Groups, work items



Host

PCI EXPRESS

Device

CUDA vs. OpenCL - Offload code

OpenCL

```
/* Create Command Queue */
command_queue = clCreateCommandQueue(context, device_id, 0, &ret);

/* Create Kernel Program from the source */
program = clCreateProgramWithSource(context, 1, (const char **)&source_str,
                                     (const size_t *) &source_size, &ret);

/* Build Kernel Program */
ret = clBuildProgram(program, 1, &device_id, NULL, NULL, NULL);

/* Create OpenCL Kernel */
kernel = clCreateKernel(program, "hello", &ret);

/* Execute OpenCL Kernel */
ret = clEnqueueTask(command_queue, kernel, 0, NULL,NULL);
```

NVIDIA CUDA

```
helloworld<<<3,5>>>();

cudaDeviceSynchronize()
```

CUDA vs. OpenCL - Kernel code

OpenCL

```
__kernel void helloworld()
{
  int wiId = get_local_id(0);
  int wgId = get_group_id(0);
  int wiMum = get_local_size(0);
  int wgNum = get_num_groups(0);

  printf("\t\t\t\t\t[DEVICE] Hello World! \
         I am Work Item #%d out of %d, \
         and I belong to Work Group #%d out of %d\n",
         wiId, wiNum, wgId, wgNum);
  return;
}
```

NVIDIA CUDA

```
__global__ void helloworld()
{
  int thrId = threadIdx.x;
  int blkId = blockIdx.x;
  int thrNum = blockDim.x;
  int blkNum = gridDim.x;

  printf("\t\t\t\t\t[DEVICE] Hello World! \
         I am thread #%d out of %d, \
         and I belong to block #%d out of %d\n",
         thrId, thrNum, blkId, blkNum);

  return;
}
```

..and OpenMP? Threads, tasks, devices

```
#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)
```

- ✓ OpenMP 4.5 introduces the concept of device
  - Execute `structured` block onto `device`
  - `map` clause to move data to-from the device

What do we do?

- Semantic Intelligence
  - Micaela's
- LightKer
  - Serena's
  - Genetic Algorithms (Nico and Me ☺)
- GPUs for automotive

Semantic web

- ✓ Web 3.0

The Semantic Web provides a common framework that allows data to be shared and reused across application, enterprise, and community boundaries (J Zeldman, 2006)

…indovina chi?

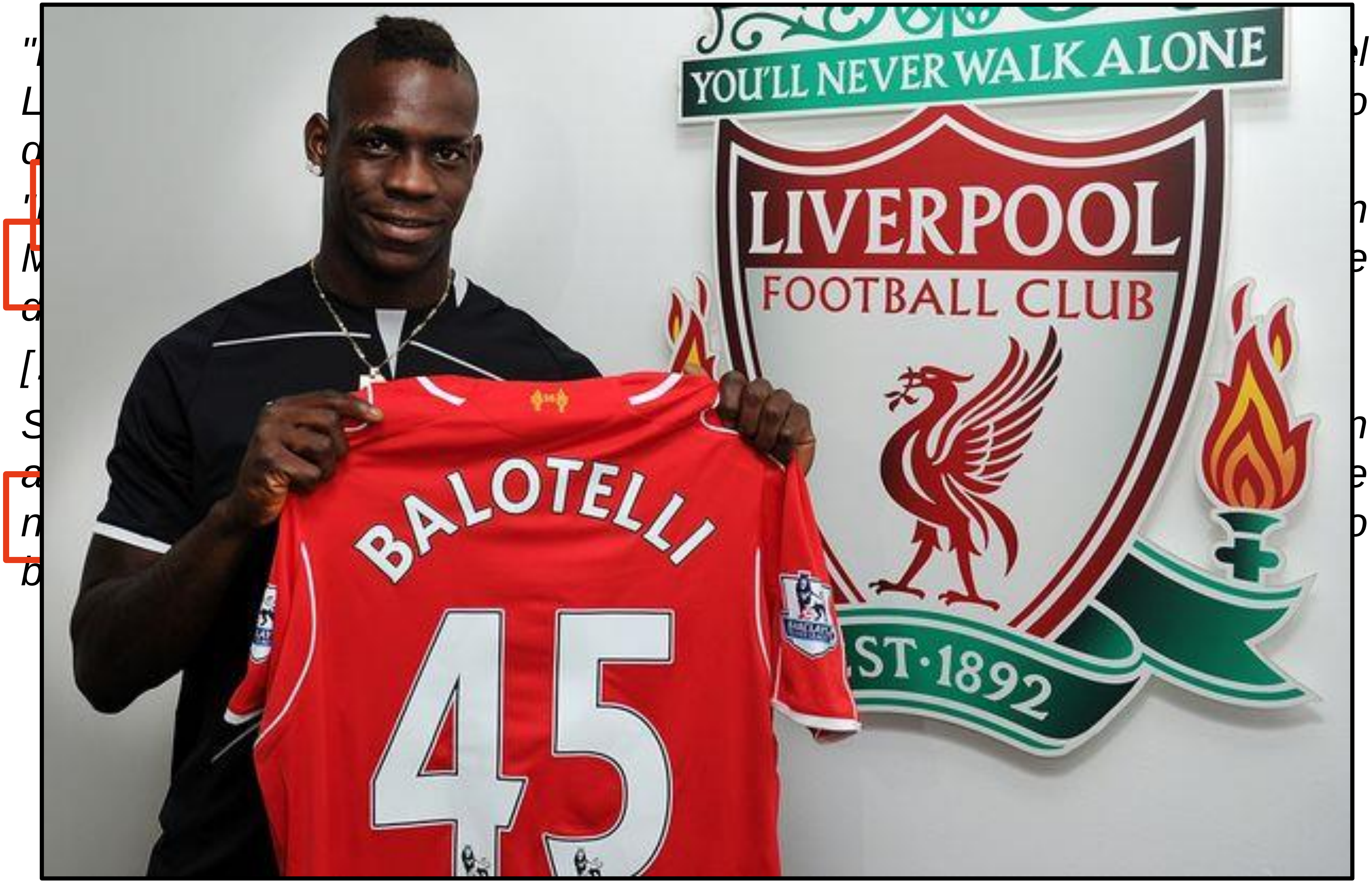
"Per lavorare con lui servirebbe lo stipendio raddoppiato". Il tecnico del Liverpool, Brendan Rodgers, in conferenza stampa ha scherzato parlando della situazione del bomber di colore.

"Mancini lo conosce molto bene - spiega -, disse che per lavorare con Mario servirebbe lo stipendio raddoppiato. Ed io non posso che essere d'accordo con lui, l'ho detto anche alla dirigenza.

[…]

Sul futuro della punta ex Inter e Milan, Rodgers ha le idee chiare: "Non andrà da nessuna parte a gennaio". Ieri ha avvertito il suo giocatore numero 45 del rischio di sprecare il suo talento. "Roberto lo conosce molto bene", si è limitato a commentare il tecnico dei Reds.

…indovina chi?



GP-GPUs in action

- ✓ Expert System
  - World leader of semantic intelligence
  - Modena

EXPERT SYSTEM
SEMANTIC INTELLIGENCE

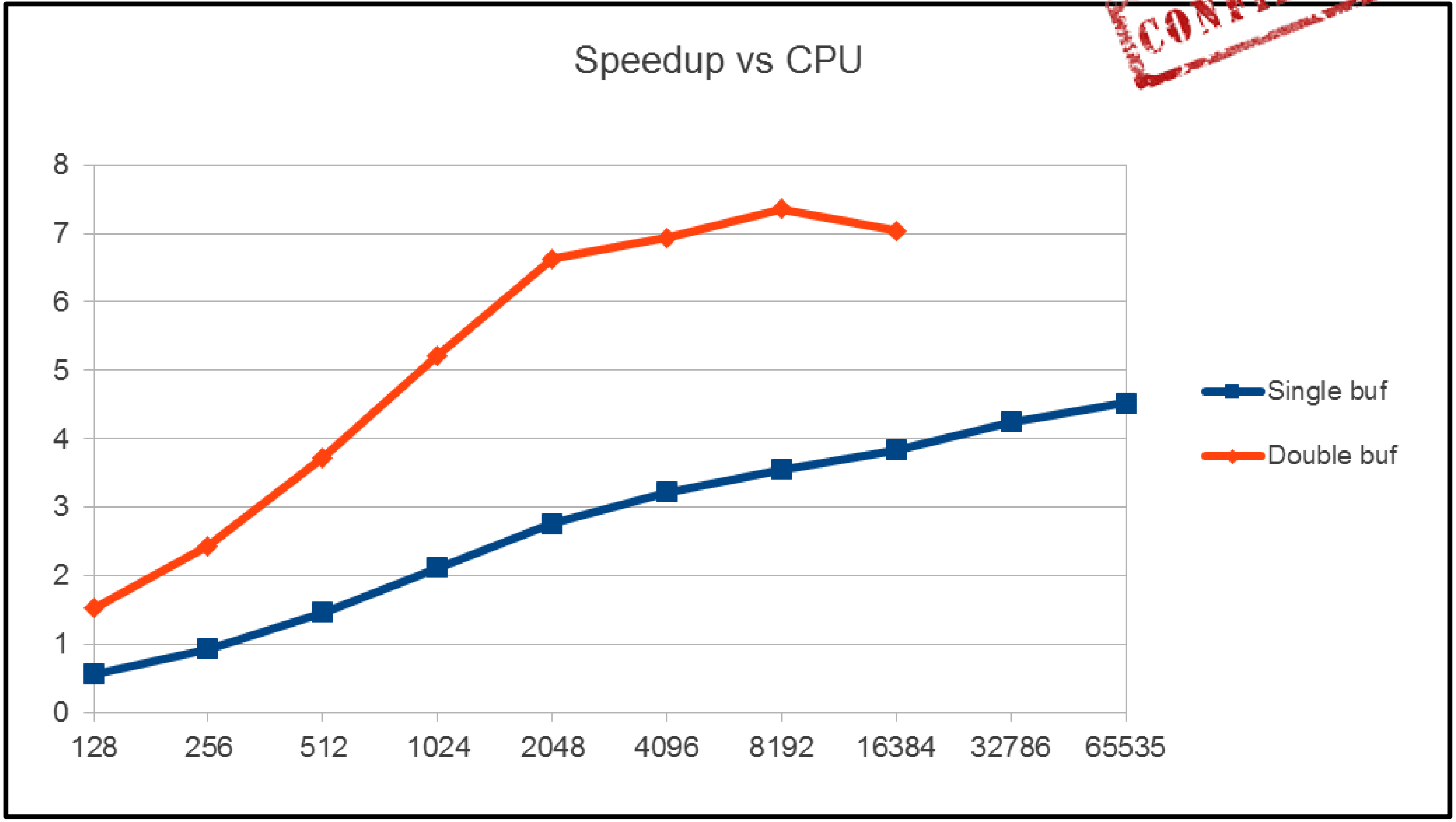
- ✓ Application
  - Search in a graph
  - 1 search <-> 1 CUDA block
  - Parallel searches on CUDA thread

- ✓ Micaela's thesis
  - 110/110 cum laude

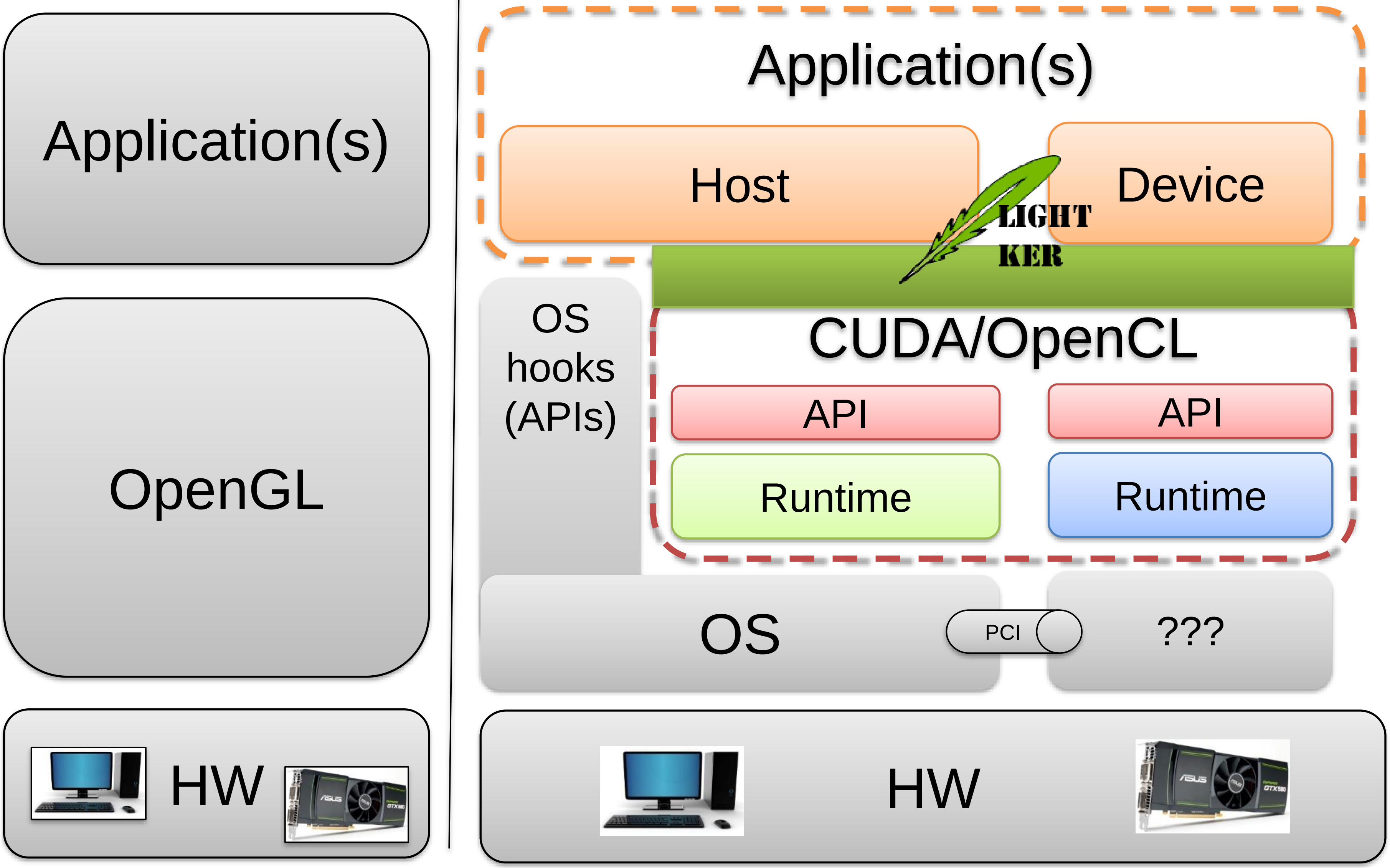
8 times faster! ☺

Micaela's thesis
110/110

CONFIDENTIAL



(GP)GPU programming stack



Application(s)

OpenGL

HW

Application(s)

Host

Device

LIGHT KER

OS hooks (APIs)

CUDA/OpenCL

API

API

Runtime

Runtime

OS

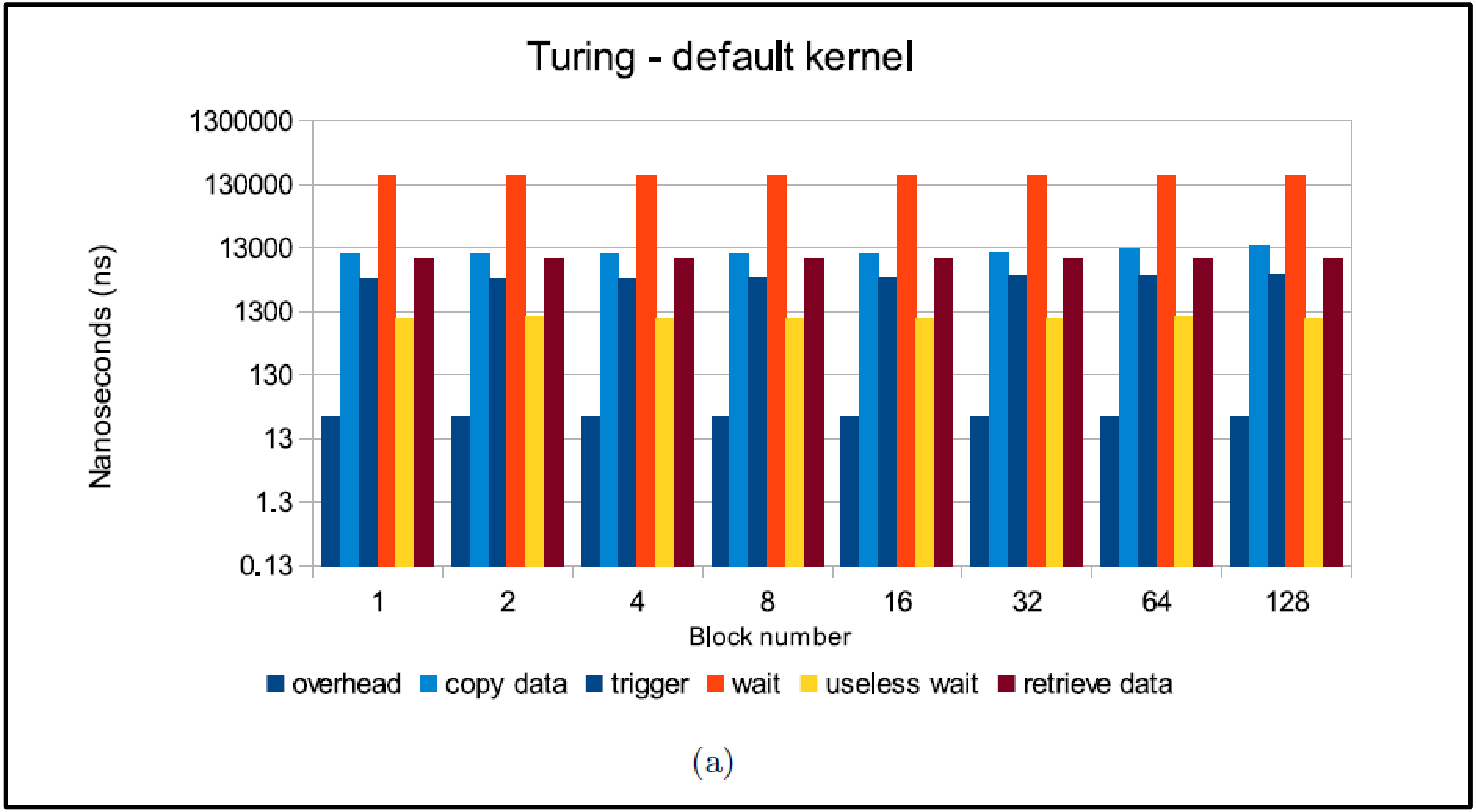
PCI

???

HW

CUDA Kernel

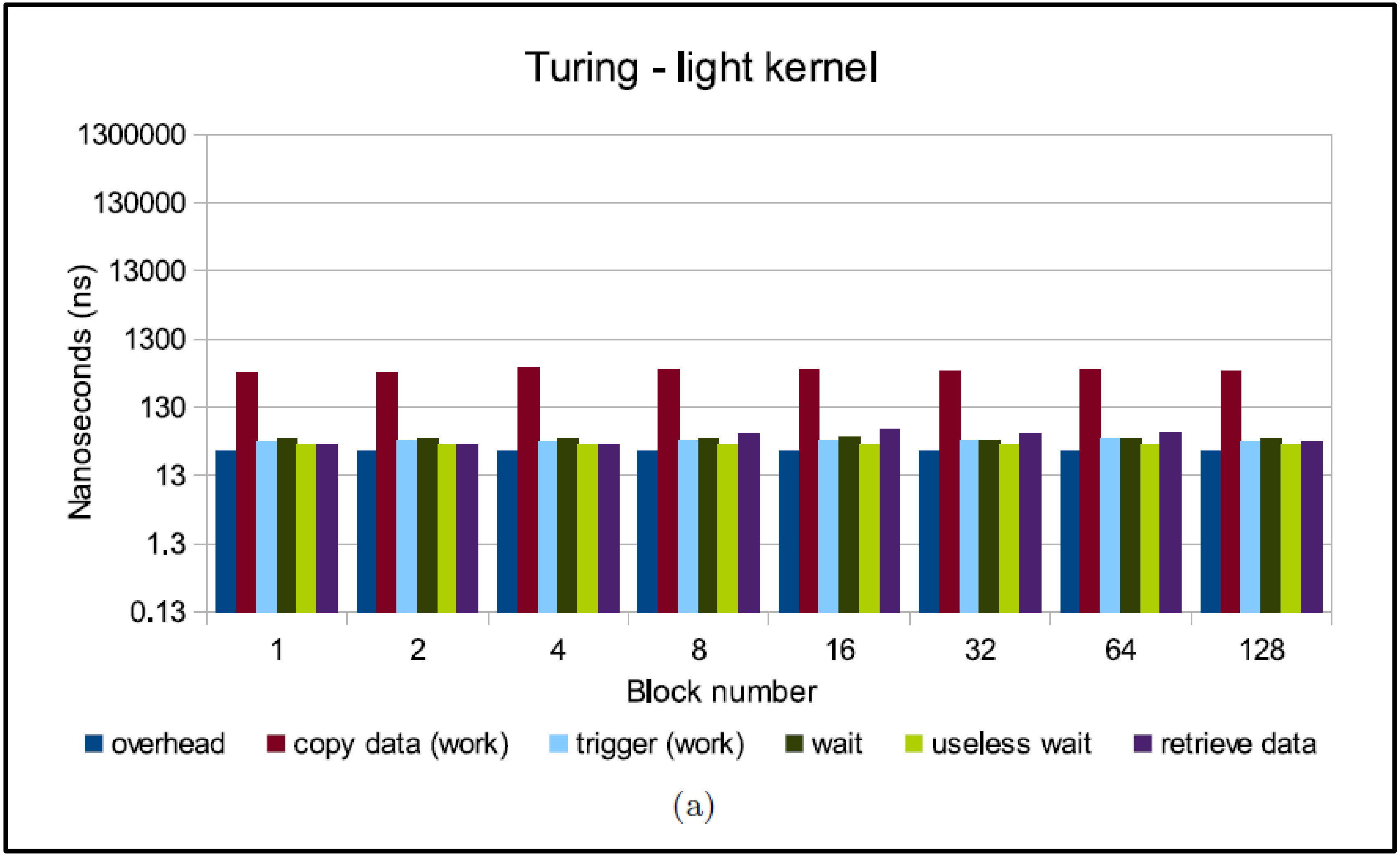
Serena thesis
110/110



(a)

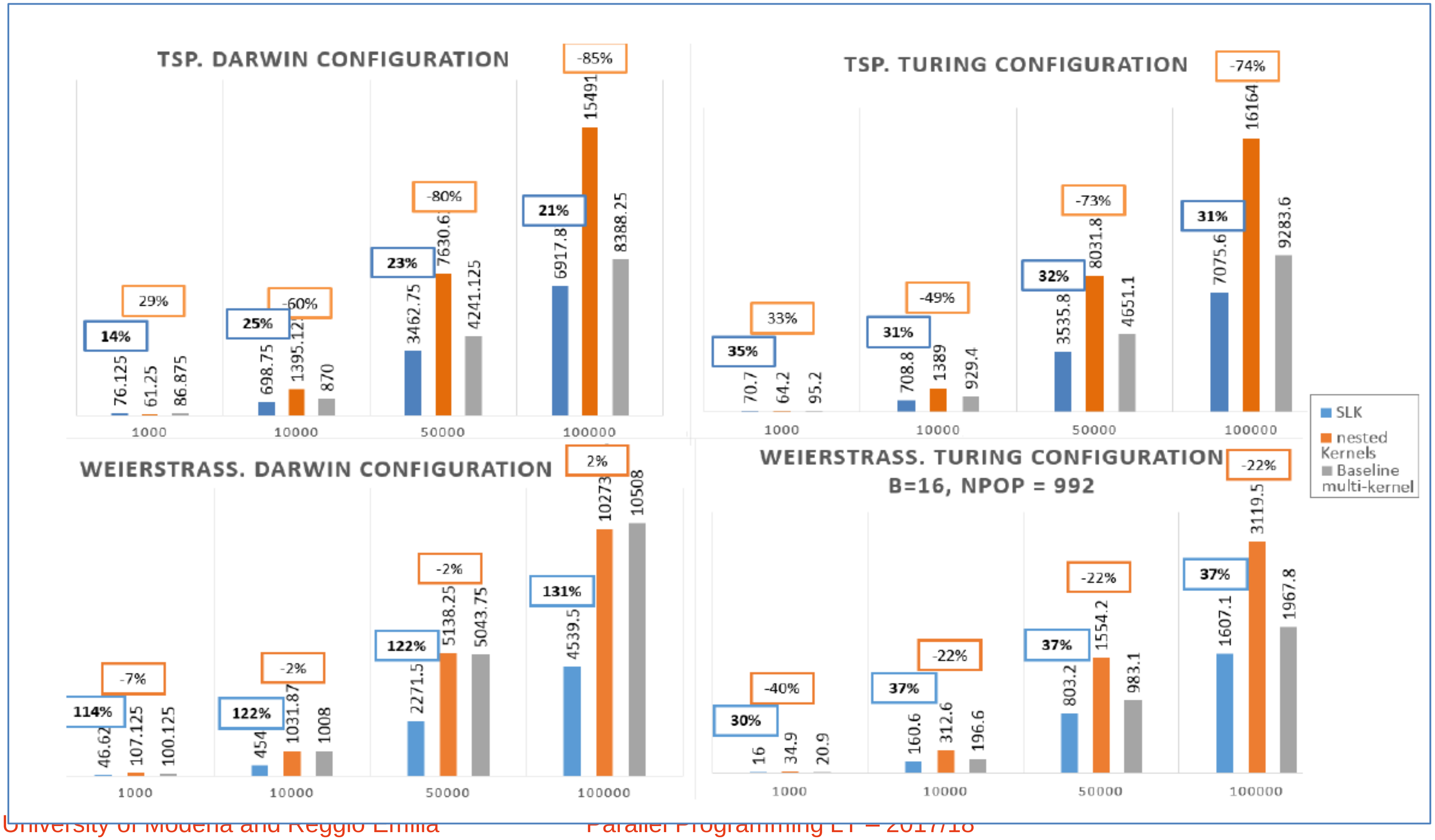
CUDA LightKer

Serena thesis 110/110



LightKer for genetic algorithms

- ✓ *"Efficient implementation of Genetic Algorithms on GP-GPU with scheduled persistent CUDA threads"*, Nicola Capodieci and Paolo Burgio, in: Proceedings of the 7th International Symposium on Parallel Architectures, Algorithms and Programming, PAAP (2015)



GPUs for automotive

- ✓ GPUs are not suitable for automotive/avionics applications
  - "Would you ever take a plane with a GPU-based control systems?"
  - ..even if they tell you so…

Hercules

"It will develop an integrated framework to allow achieving predictable performance on top of cutting-edge heterogeneous GPU-based platforms…two innovative industrial use cases: a pioneering autonomous driving system for the automotive domain, and a visual recognition system for the avionic domain"

- ✓ We are project leaders!! ☺
- ✓ Industrial Advisory Board Members:
  - BMW
  - Porsche
  - Continental Automotive
  - Nvidia
  - Tom's Hardware
  - …

Driverless systems today

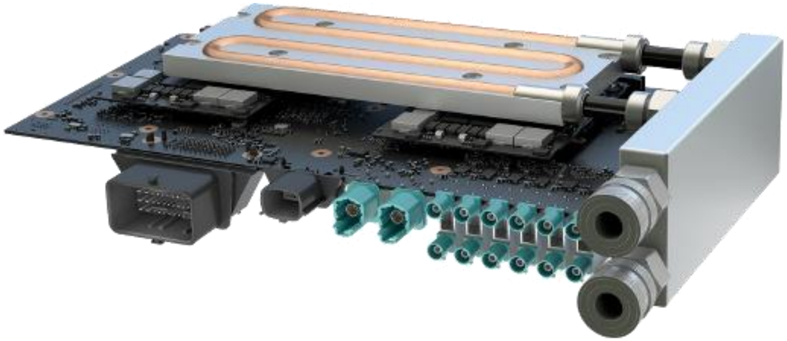
Expensive: $60k

Bulky: Multiple servers and batteries

Power hungry: up to 5kW!!!

Not marketable!

NVIDIA Drive PX2



The DriveBox

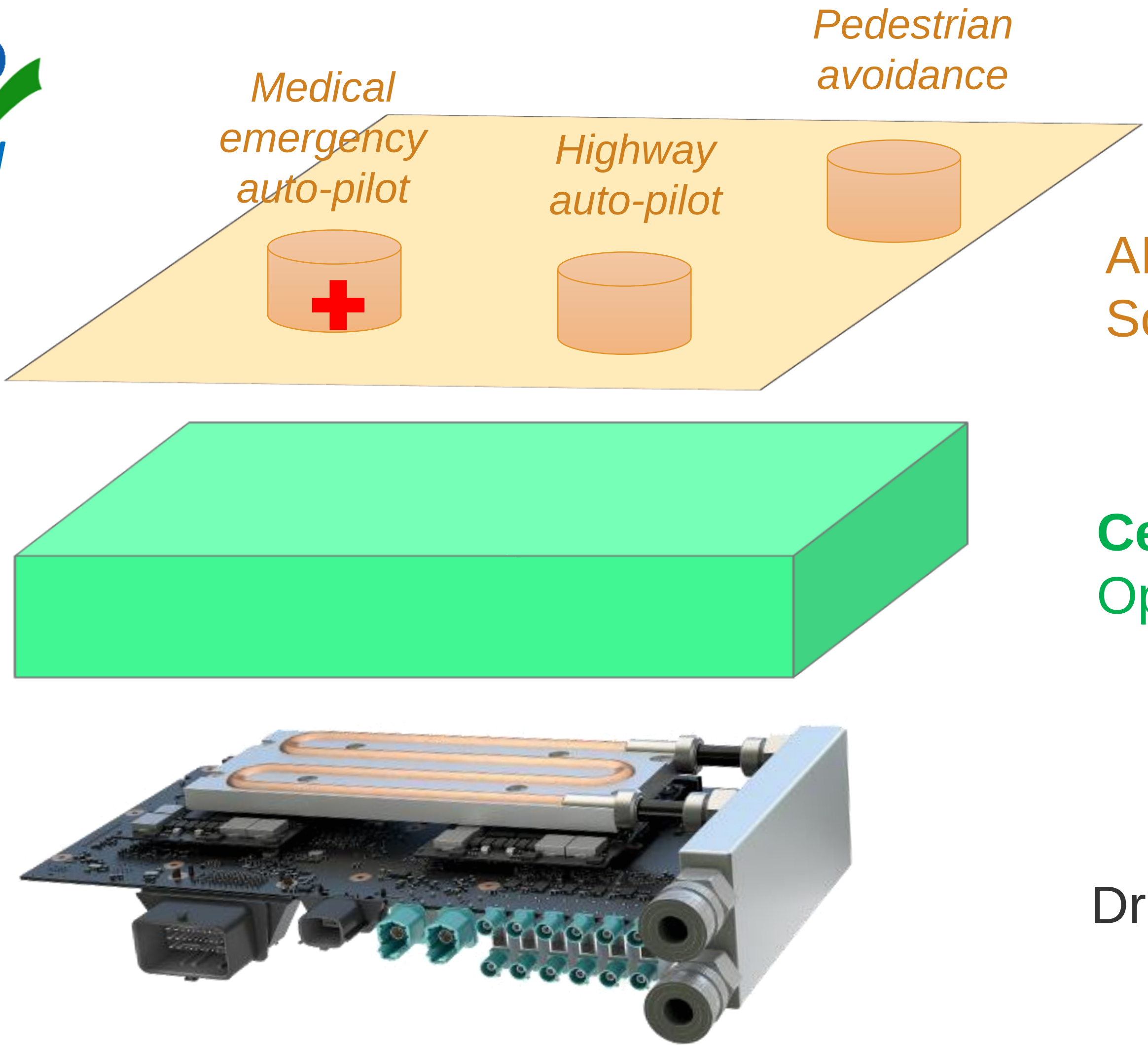
- ✓ Kit for semi-autonomous driving
  (pedestrian avoidance, highway autopilot, …)

- ✓ Optimized for power efficient platforms
  State-of-the-art industrial research
  TFLOPs w/ <10W!!

NVIDIA Drive PX2

- ✓ Huge performance
- ✓ Low-power consumption
- ✓ Unprecedented safety

Software stack



ADAS Control Software

Certifiable
Operating System

Drive PX2 board

How to run the examples

Let's
code!

- Download the `Code/` folder from the course website

- Compile

```
$ nvcc code.c
```

- Run
  - ./file.exec

References

- ✓ "Calcolo parallelo" website
  - – http://cdm.unimo.it/home/matematica/zanni.luca/calc_par_2017.html
- ✓ My contacts
  - – paolo.burgio@unimore.it
  - – http://hipert.mat.unimore.it/people/paolob/
- ✓ Useful links
  - – http://www.google.com
  - – http://www.nvidia.it/object/cuda-parallel-computing-it.html
  - – http://www.openmp.org/mp-documents/openmp-4.5.pdf
  - – https://www.khronos.org/
  - – https://www.khronos.org/opencl/
  - – https://developer.nvidia.com/opencl