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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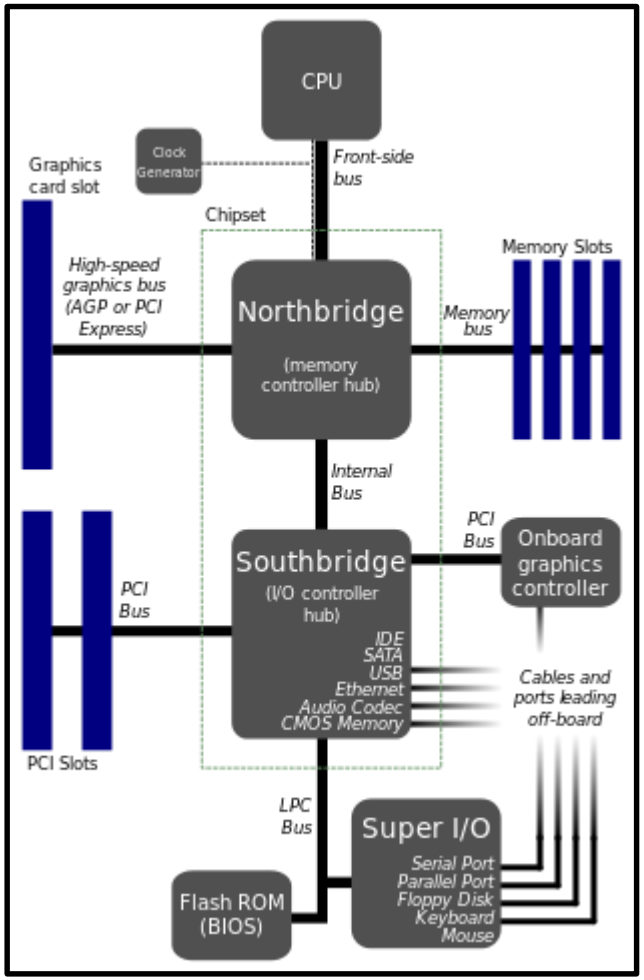
Graphics Processing Units

- (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, (soon) Parker..
- ✓ Many programming ~~librar~~… ~~languag~~… frameworks
  - OpenGL
  - CUDA
  - OpenCL
  - …
- ✓ Many application domains!
  - Graphics
  - GP-GPUs?
  - Automotive!??!?!??!
- ✓ Let's start from scratch…

GPU for graphics - OpenGL

- ✓ 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

enGL

```
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. */
}
```

rs...

mer skills

ons

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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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```
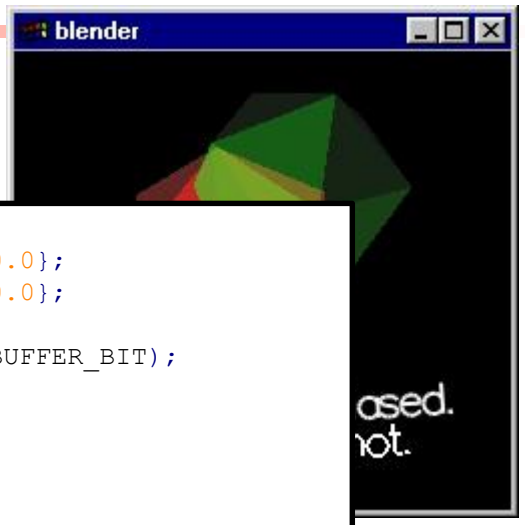

```
void display(void) {
  static GLfloat amb[] = {0.4, 0.4, 0.4, 0.0};
  static GLfloat dif[] = {1.0, 1.0, 1.0, 0.0};

  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();

 /* ... */
```



GPU for graphics - OpenGL

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- ✓ Tailored for the specific domain and programmer skills
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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

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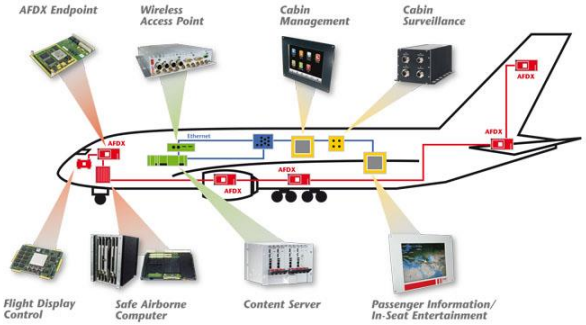
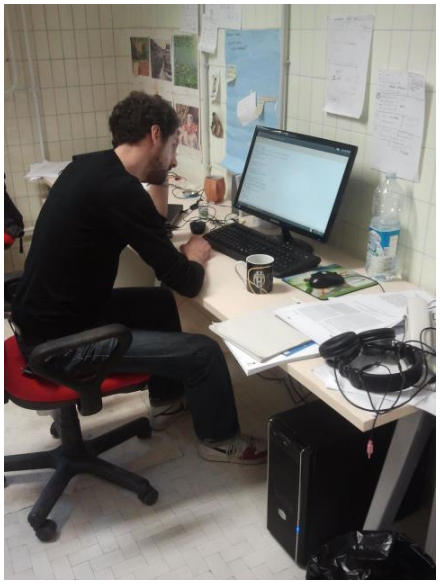
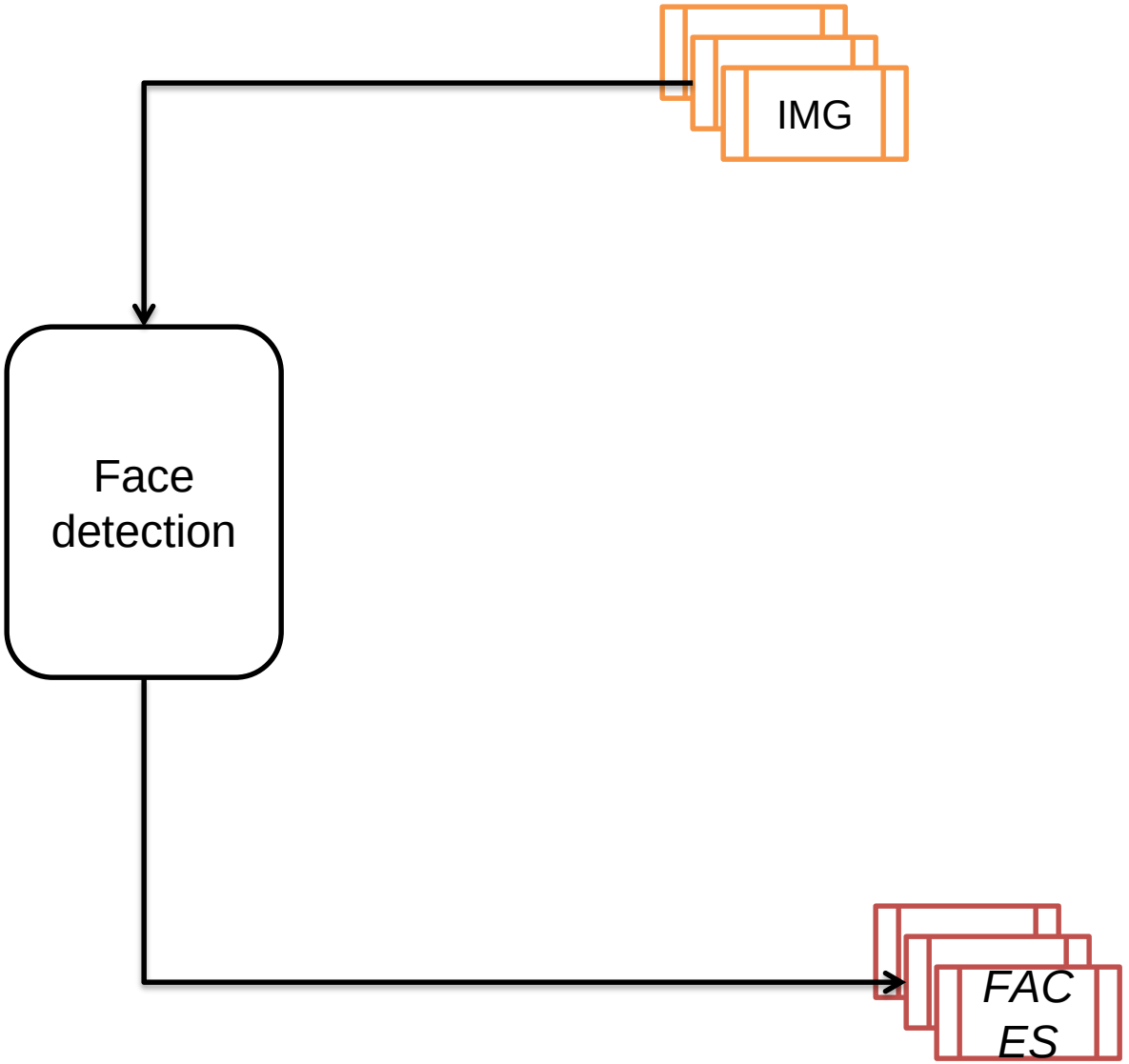
- …



Under the hood: face detection

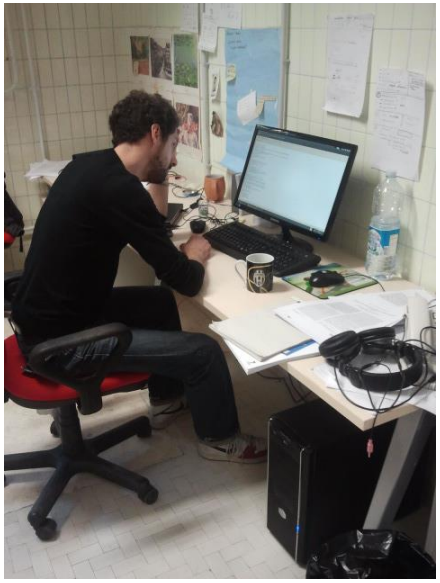




Under the hood: face detection

IMG

Face detection



FAC ES

Under the hood: face detection

IMG

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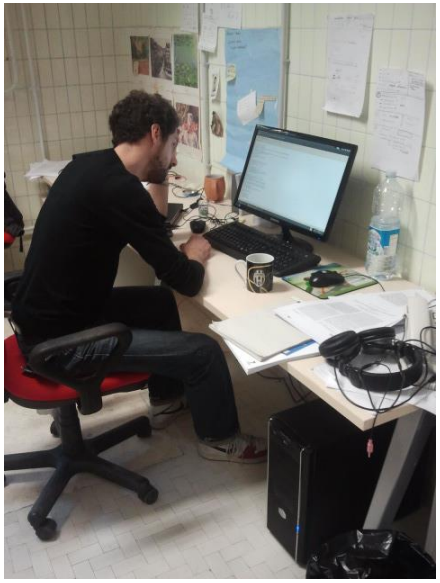


FACES

Under the hood: face detection

IMG

Color img -> Gray img

Histogram equalization

Smooting

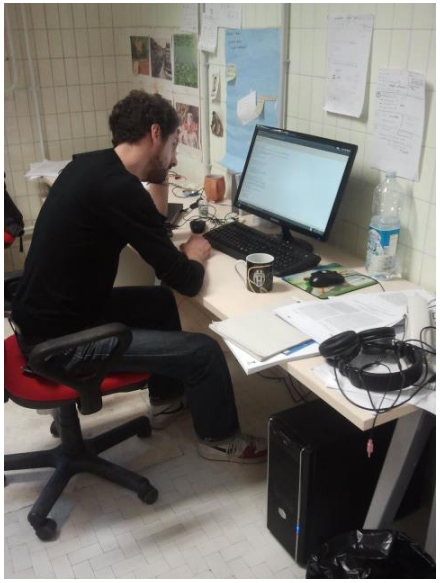
Sobel filter + Detection

Canny filter

Detection

FACES

Face detection



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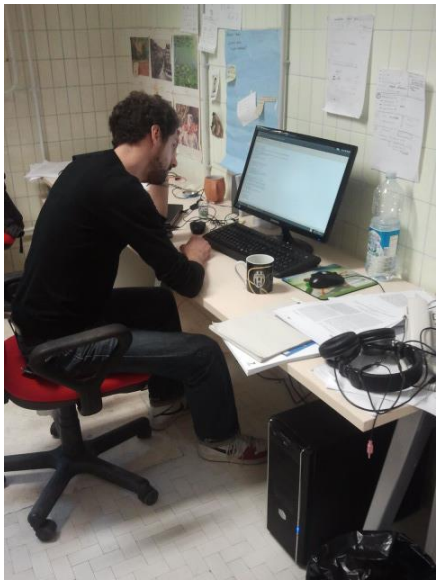

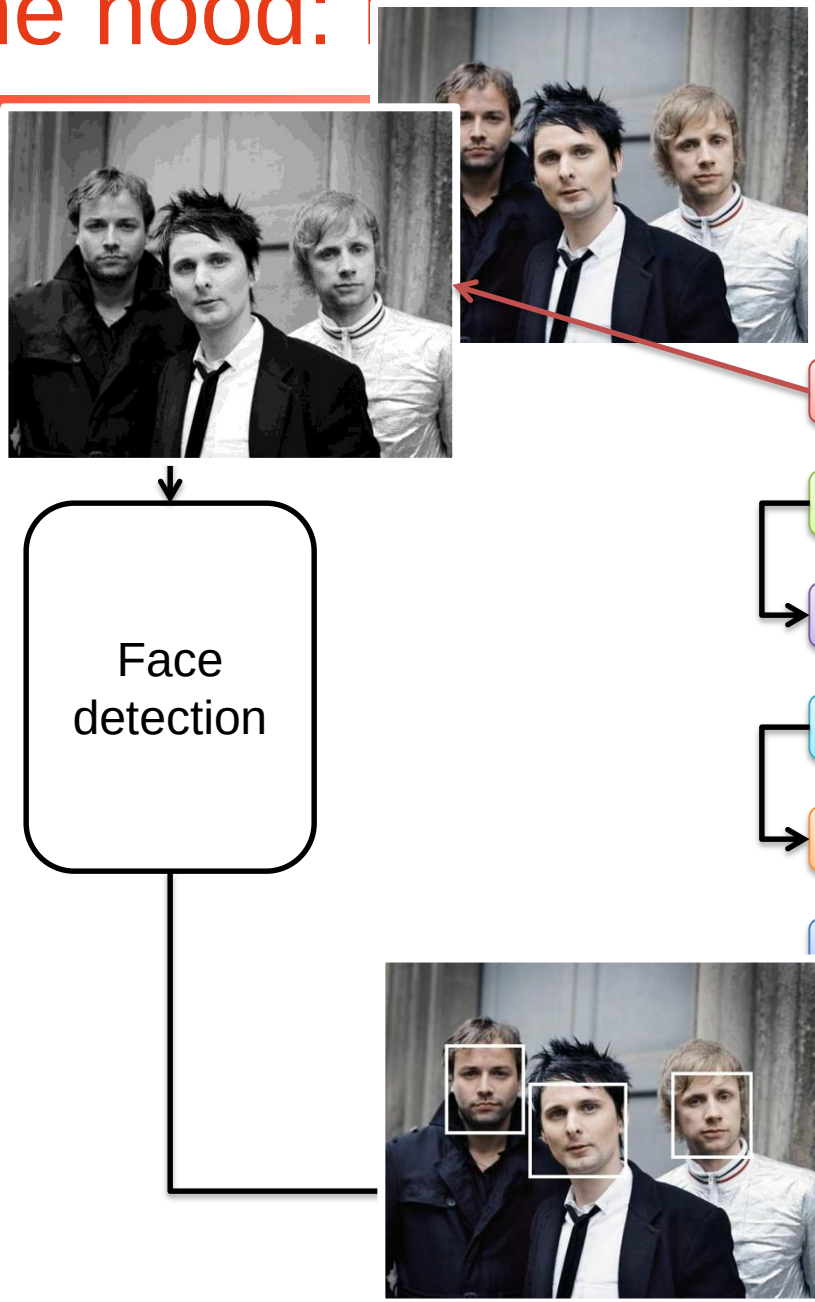

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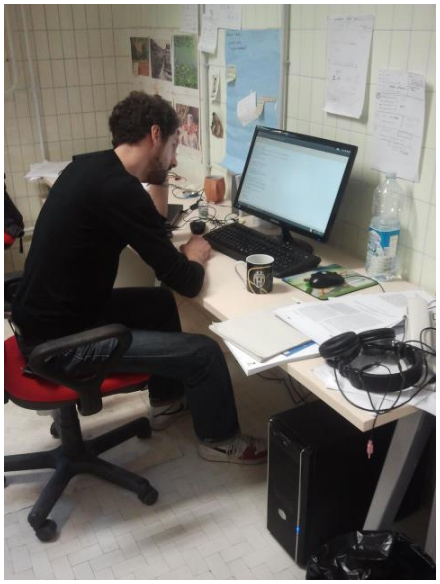

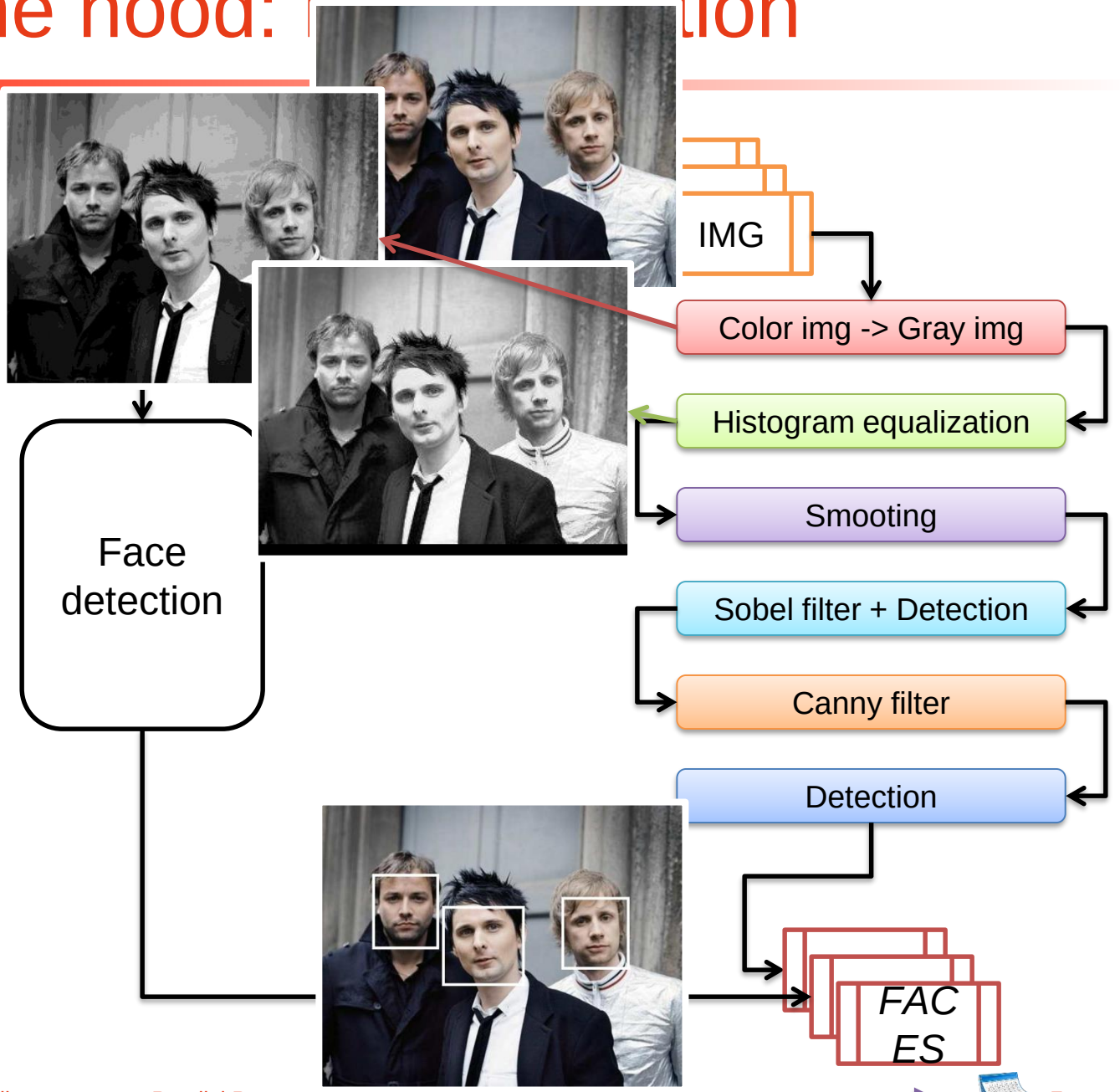

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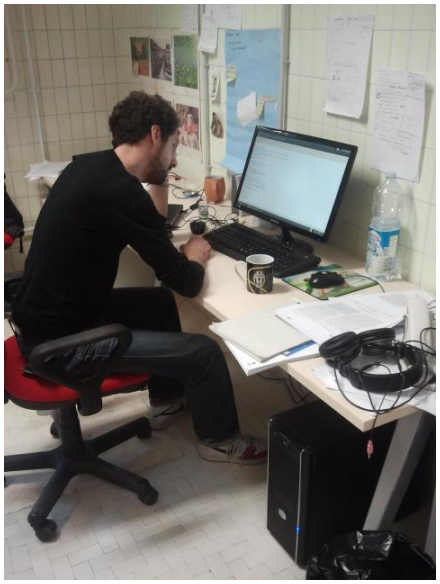

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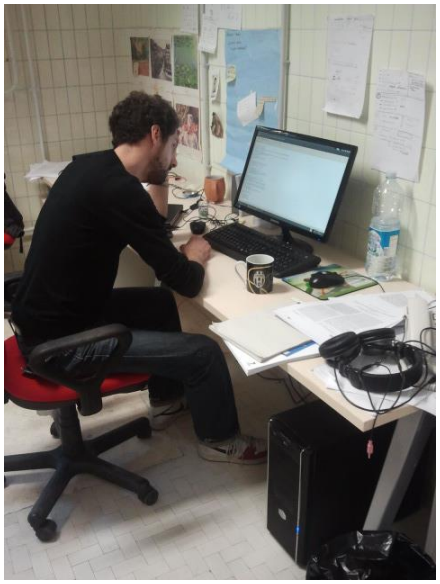

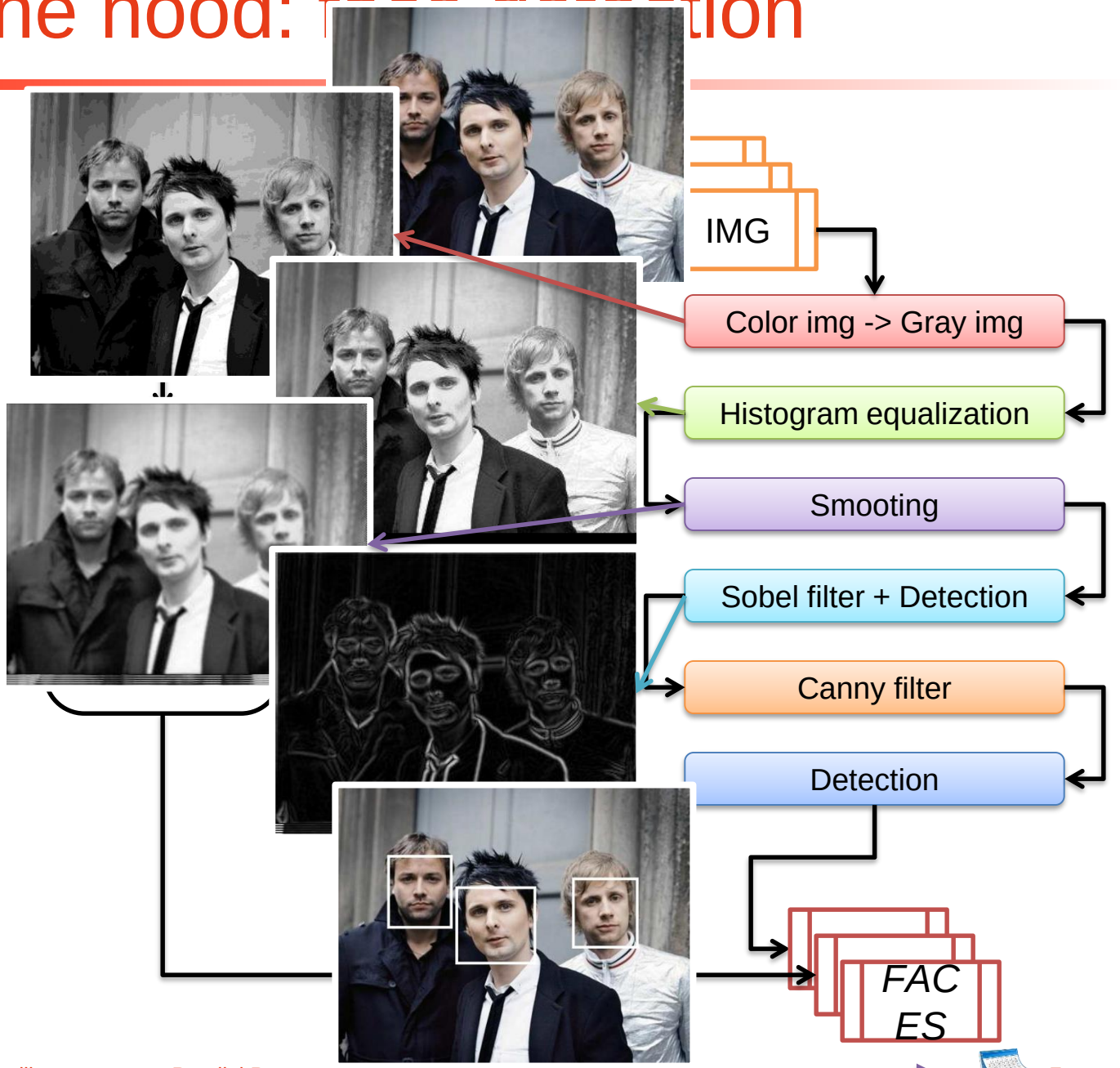

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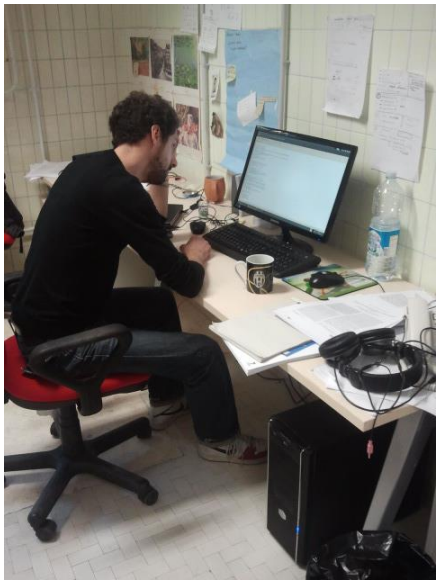

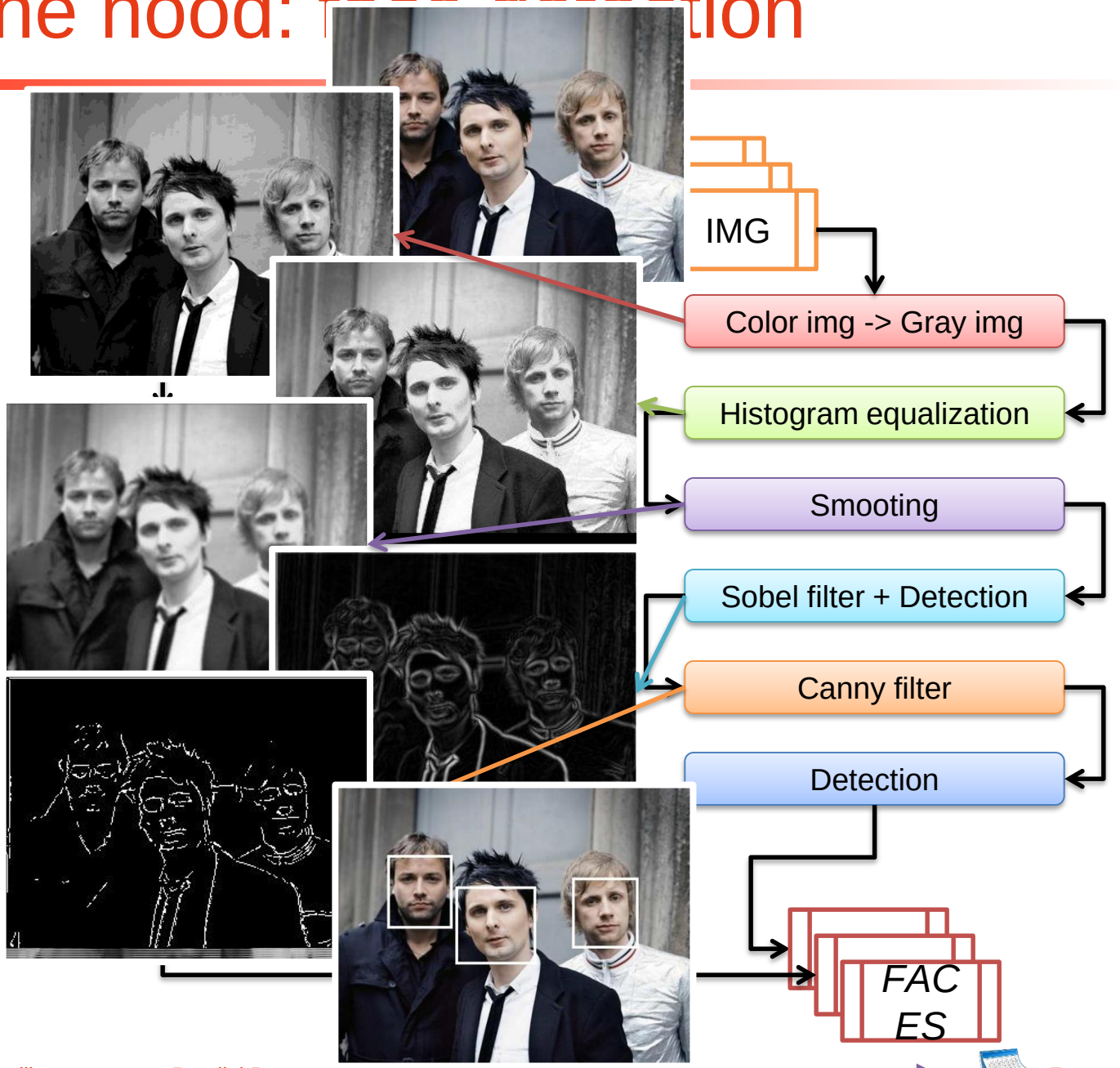

Image binarization

- ✓ Graylevel image => B/W image
- ✓ Pixel: 256 shades of gray
  - `unsigned chars`
  - 255 => white
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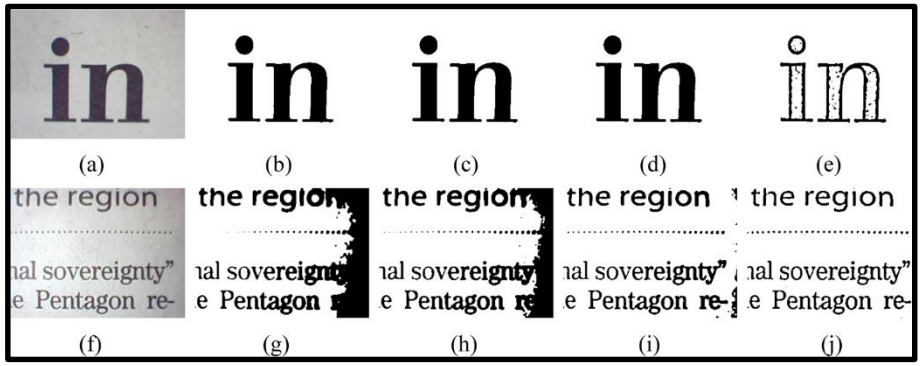

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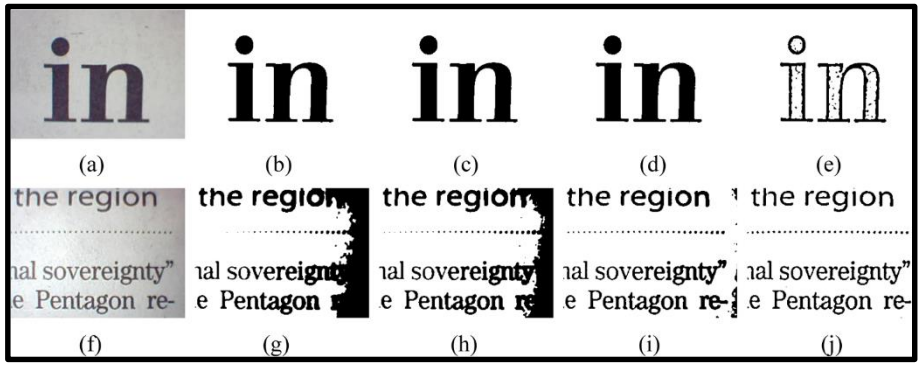


```
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#define WHITE 255
#define BLACK 0
void binarizeImage(const unsigned char inputImg[],
                   unsigned char outputImg[],
                   unsigned int imgDim)
{
  for(int i=0; i<imgDim; i++)
    if(inputImg[i] >= GRAY_THRESHOLD)
  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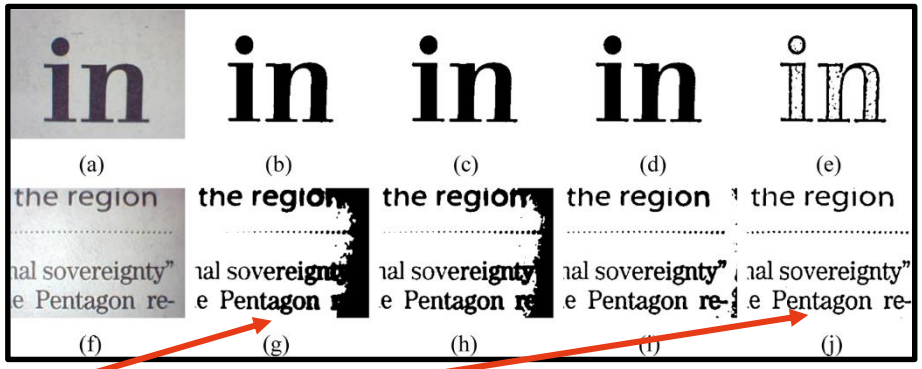


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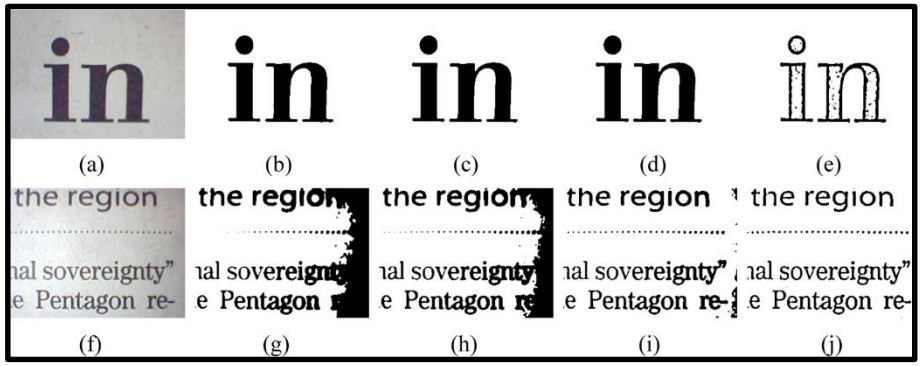


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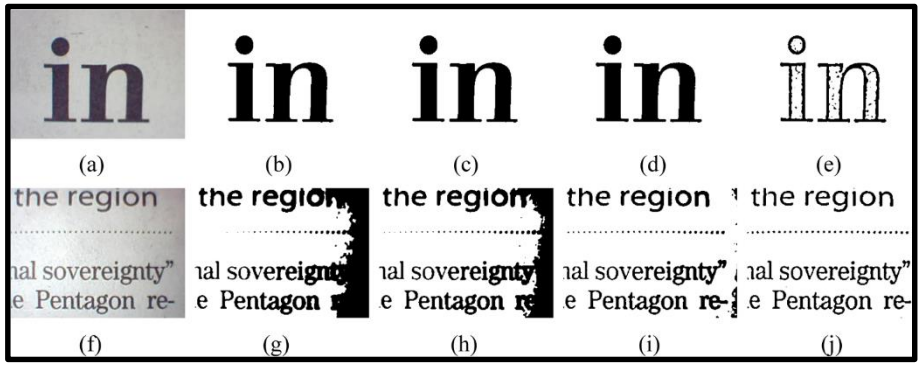


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Multiple Data

Image binarization

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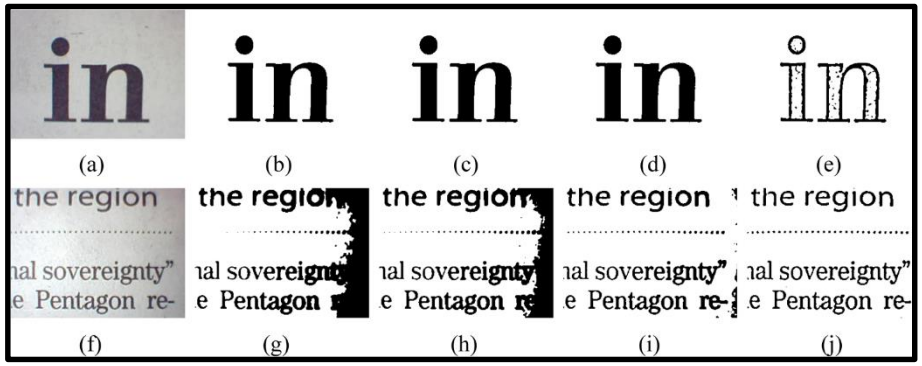


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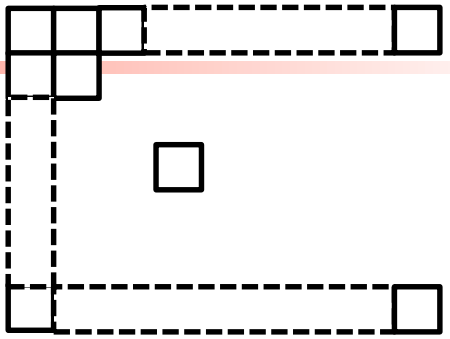
Single Program

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!

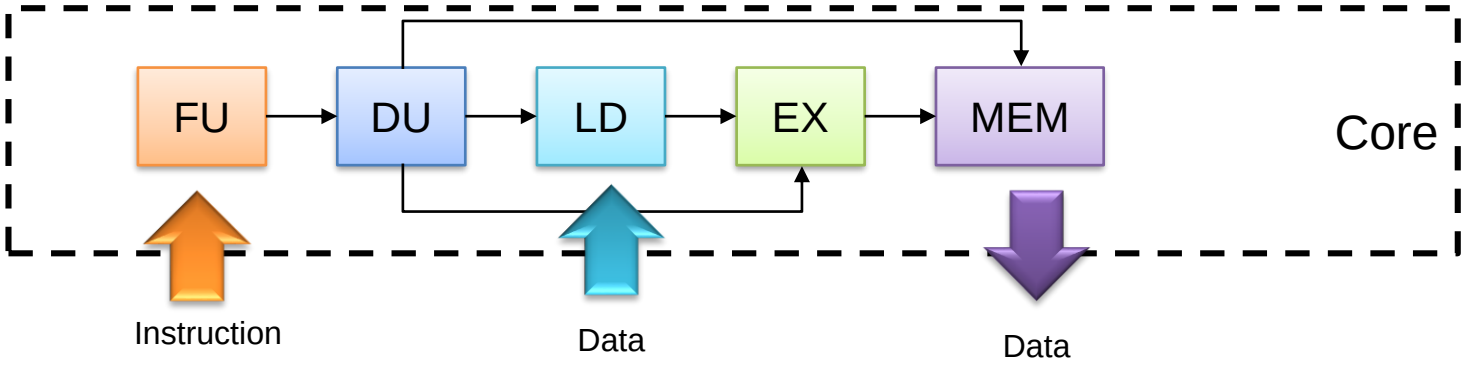
A (programmable) machine

- ✓ 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

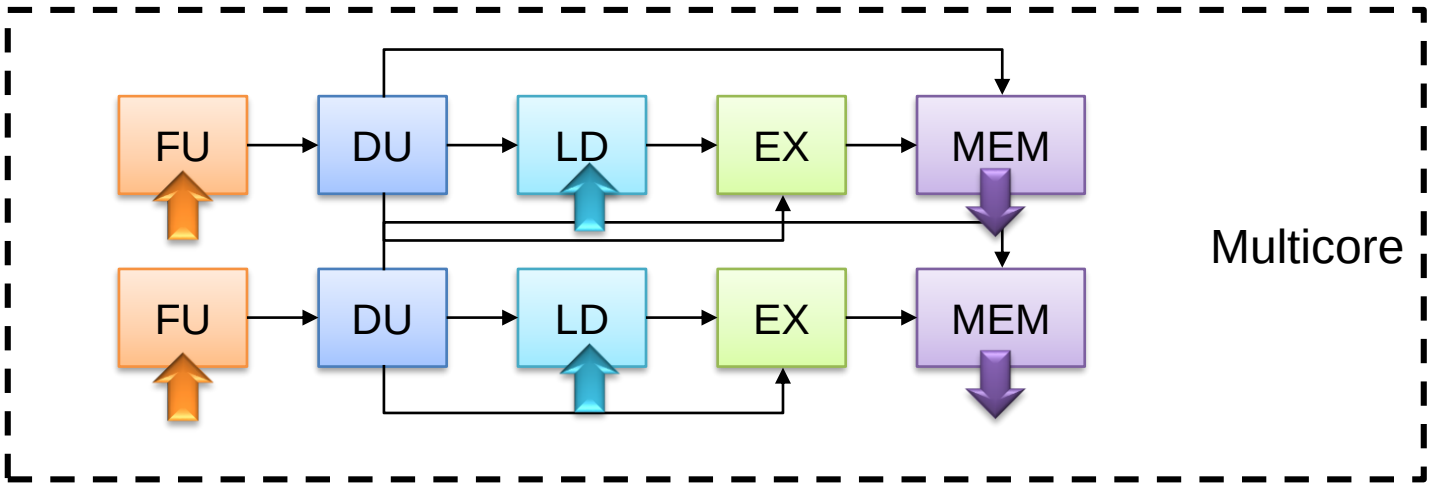
- ✓ We need a massively parallel machine
  - Thousands of cores
- ✓ With simple cores
  - FP Support
- ✓ To perform the very same instruction!
  - Same Fetch Unit and Decode Unit

Fetch and decode units

- ✓ Traditional pipeline

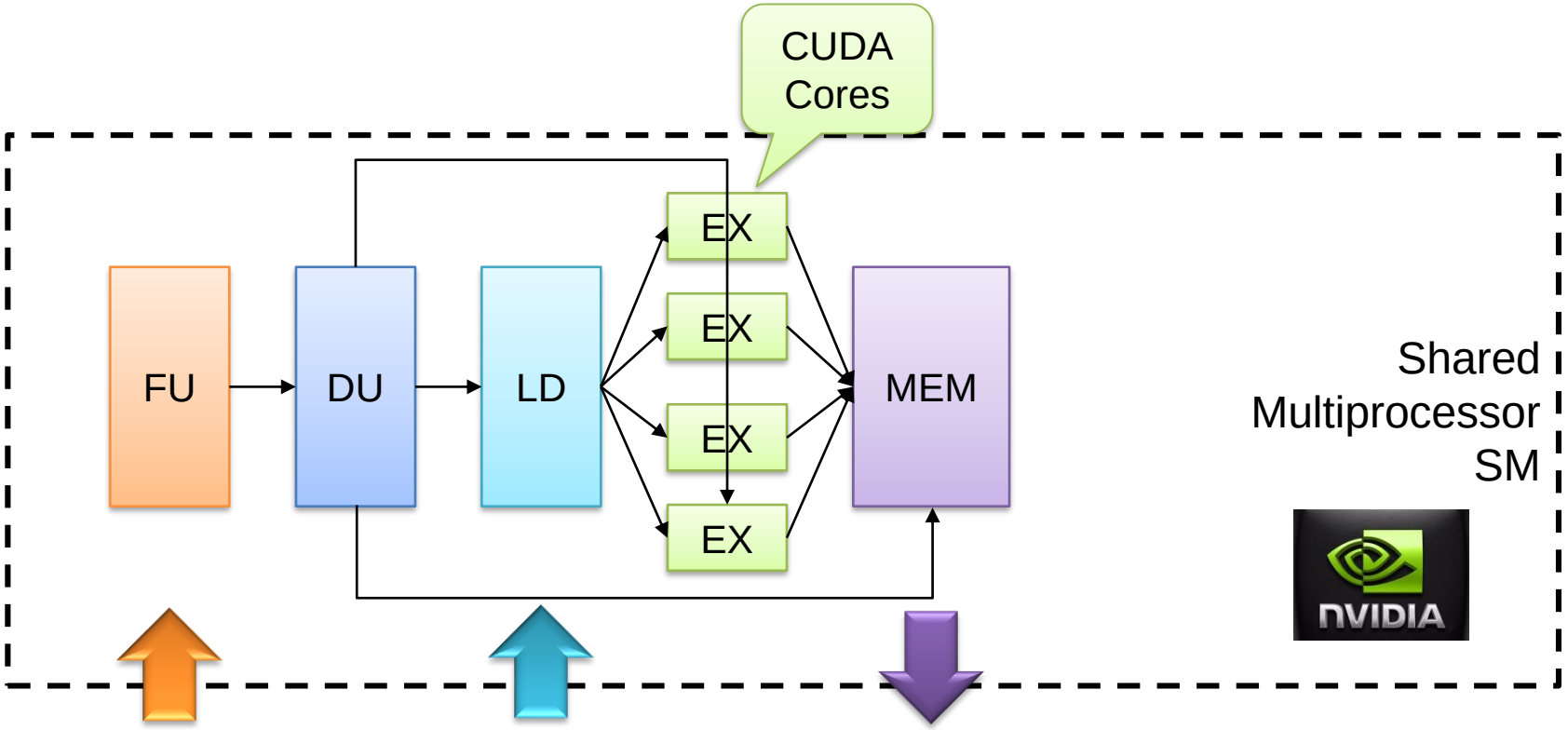


- ✓ Traditional parallel pipeline



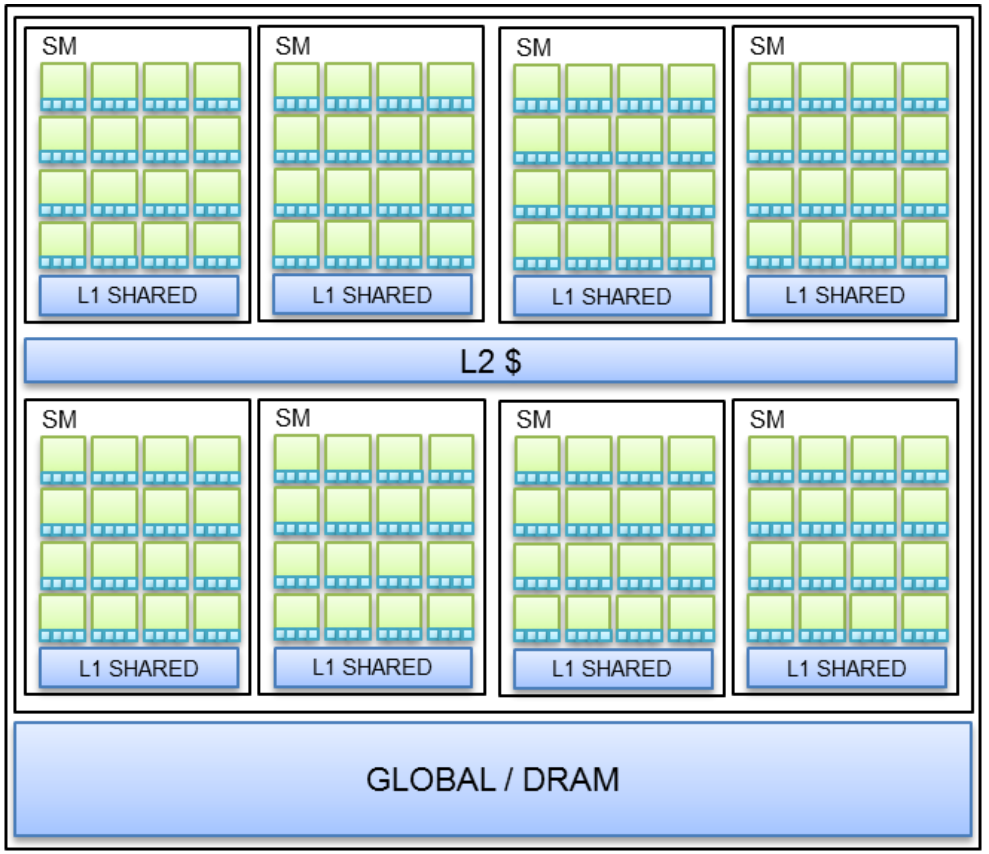
GPU multi-core

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



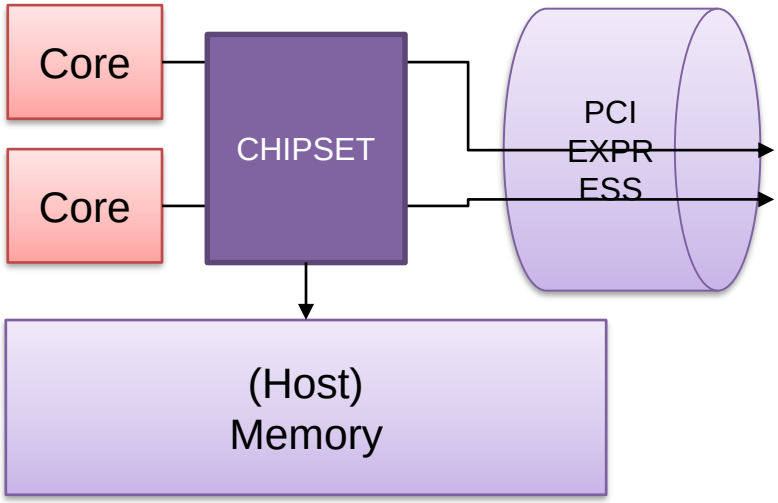
SMs as building block

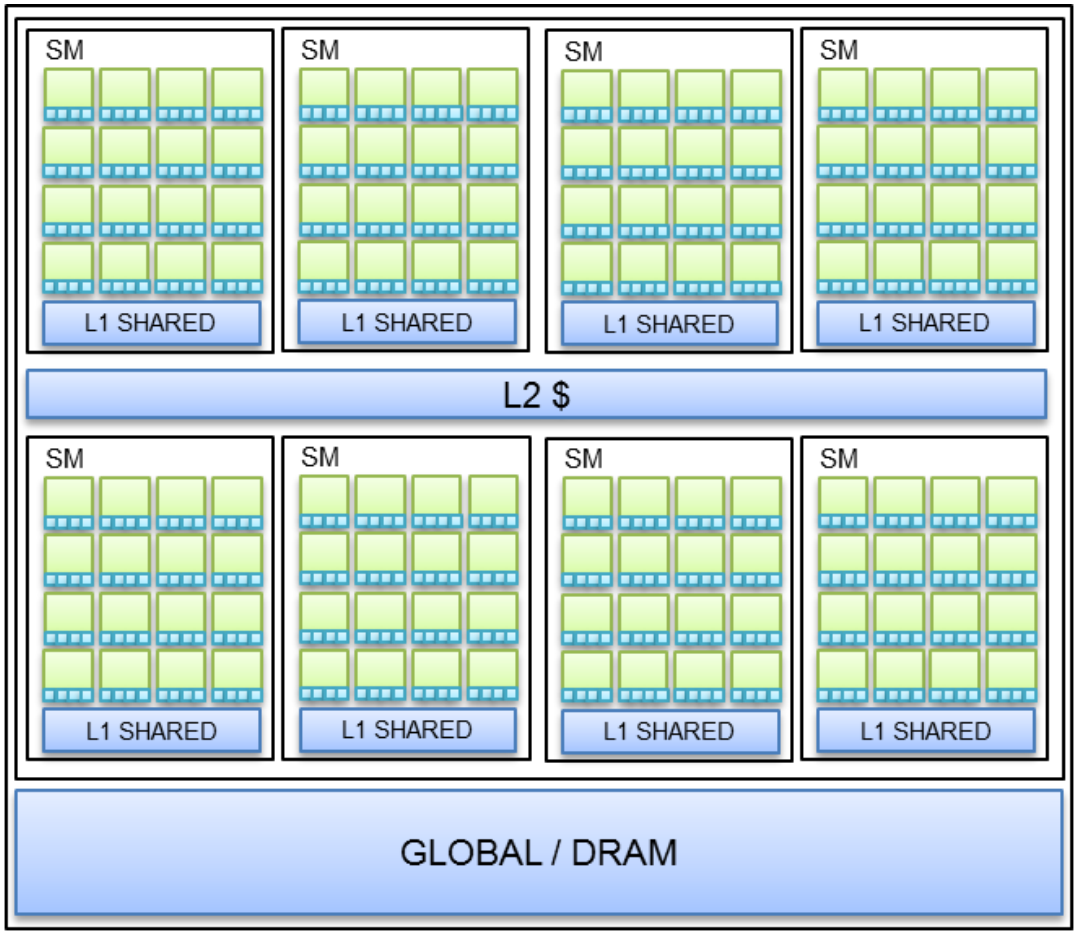
- ✓ Architecture of the SM
  - GPU "class"
  - Kepler has 192 cores
  - Maxwell/Pascal has 128 cores
- ✓ Number of SMs
  - GPU model
  - Maxwell's GTX980 has 10
  - Pascal's GTX1080 has 20
  - Pascal's Drive PX1 has 2
- ✓ NUMA memory system



GPU as a device

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

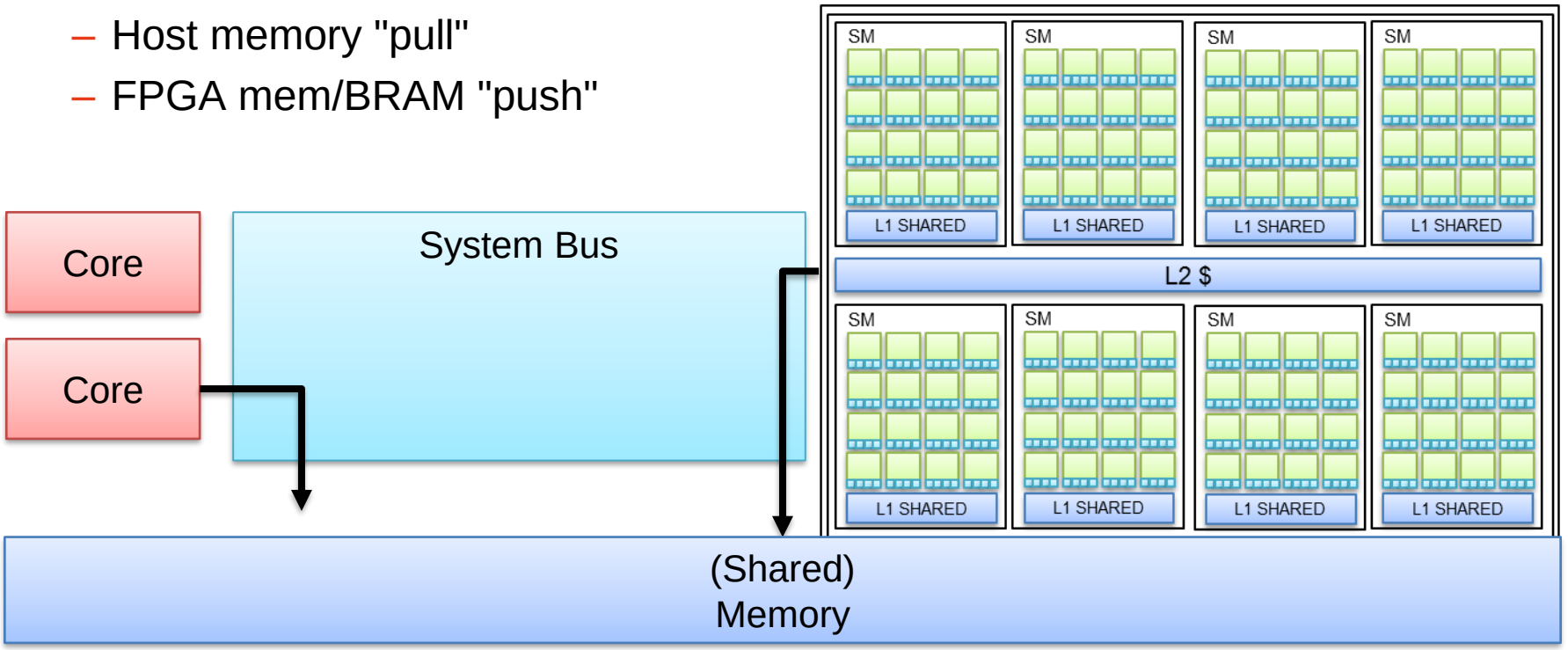




Something you are less used to

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"



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

(GP)GPU programming stack

Application(s)

OpenGL


HW


(GP)GPU programming stack

Application(s)

OpenGL

HW

Application(s)

Host

Device

OS hooks (APIs)

CUDA/OpenCL

API

Runtime

API

Runtime

OS

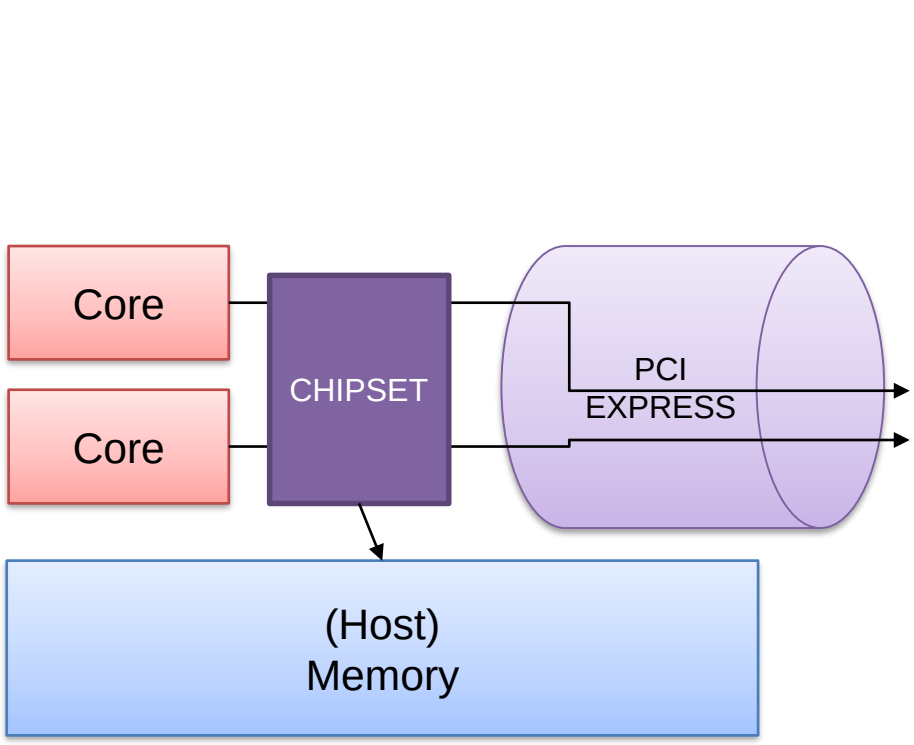
PCI

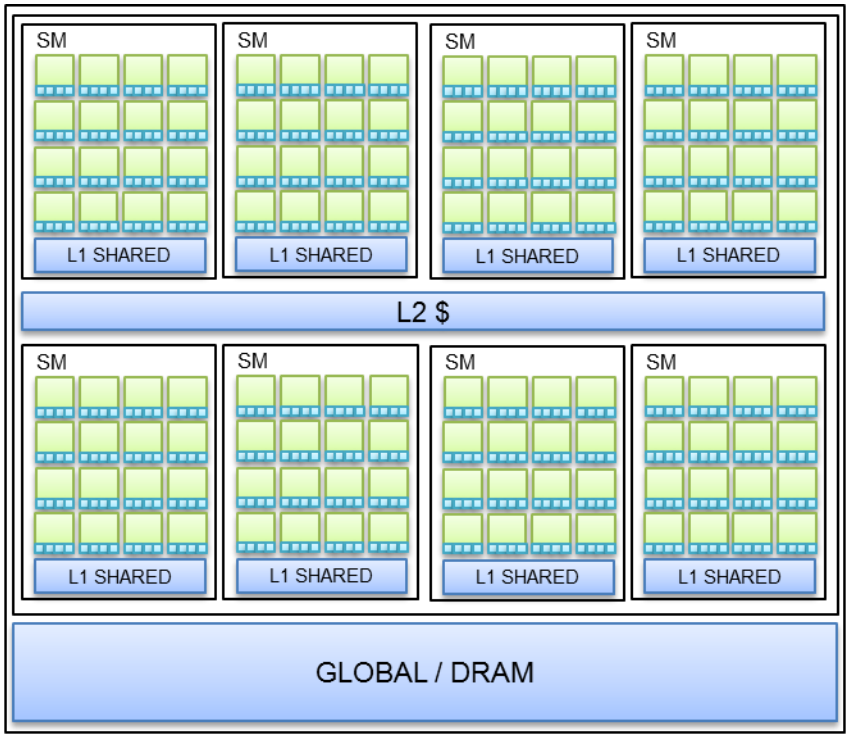
???

HW

GPU programming

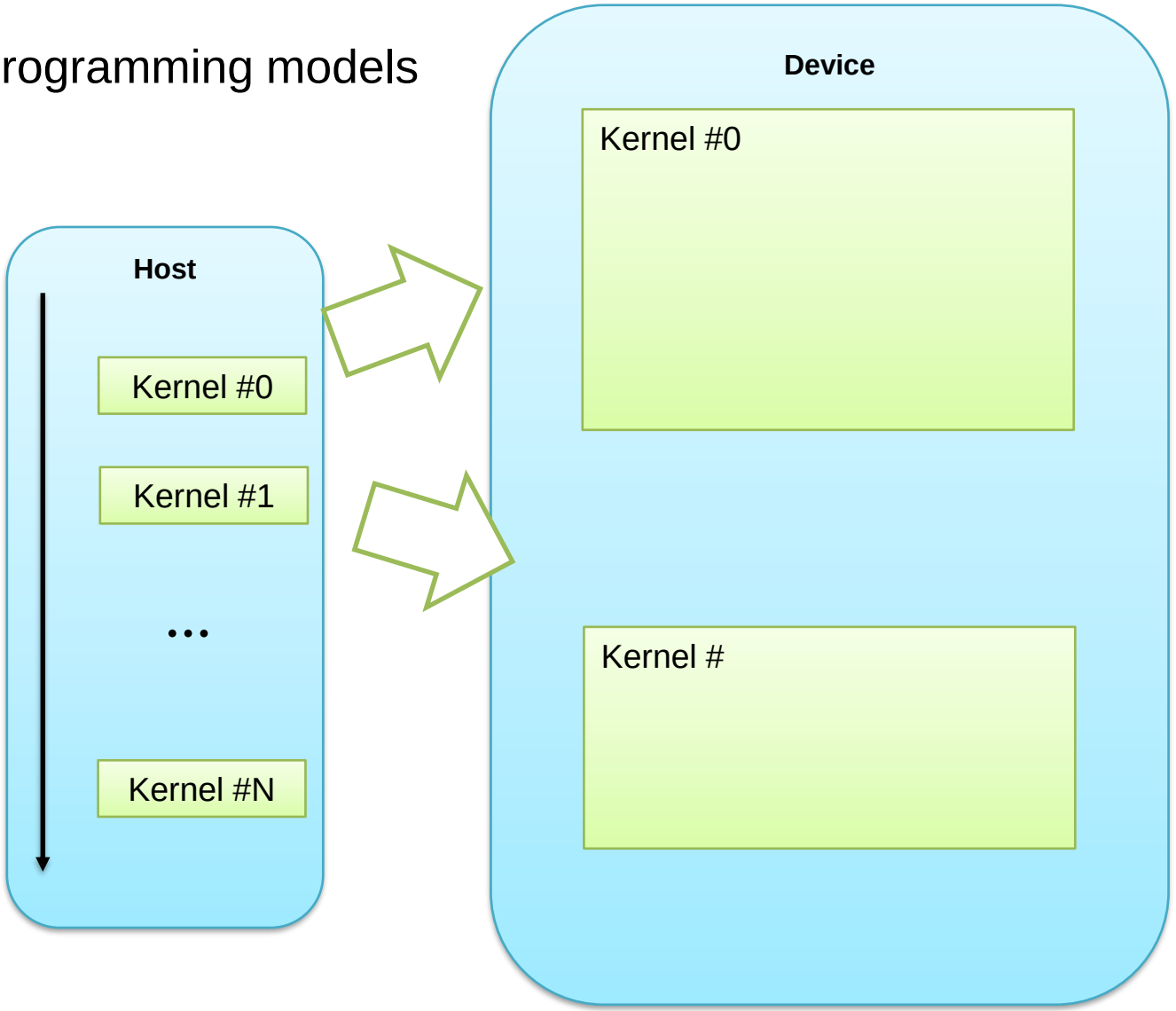
- ✓ We need a programming model that provides
  1. Simple offloading subroutines
  2. An easy way to write code which runs on thousand threads
  3. A way to exploit the NUMA hierarchy





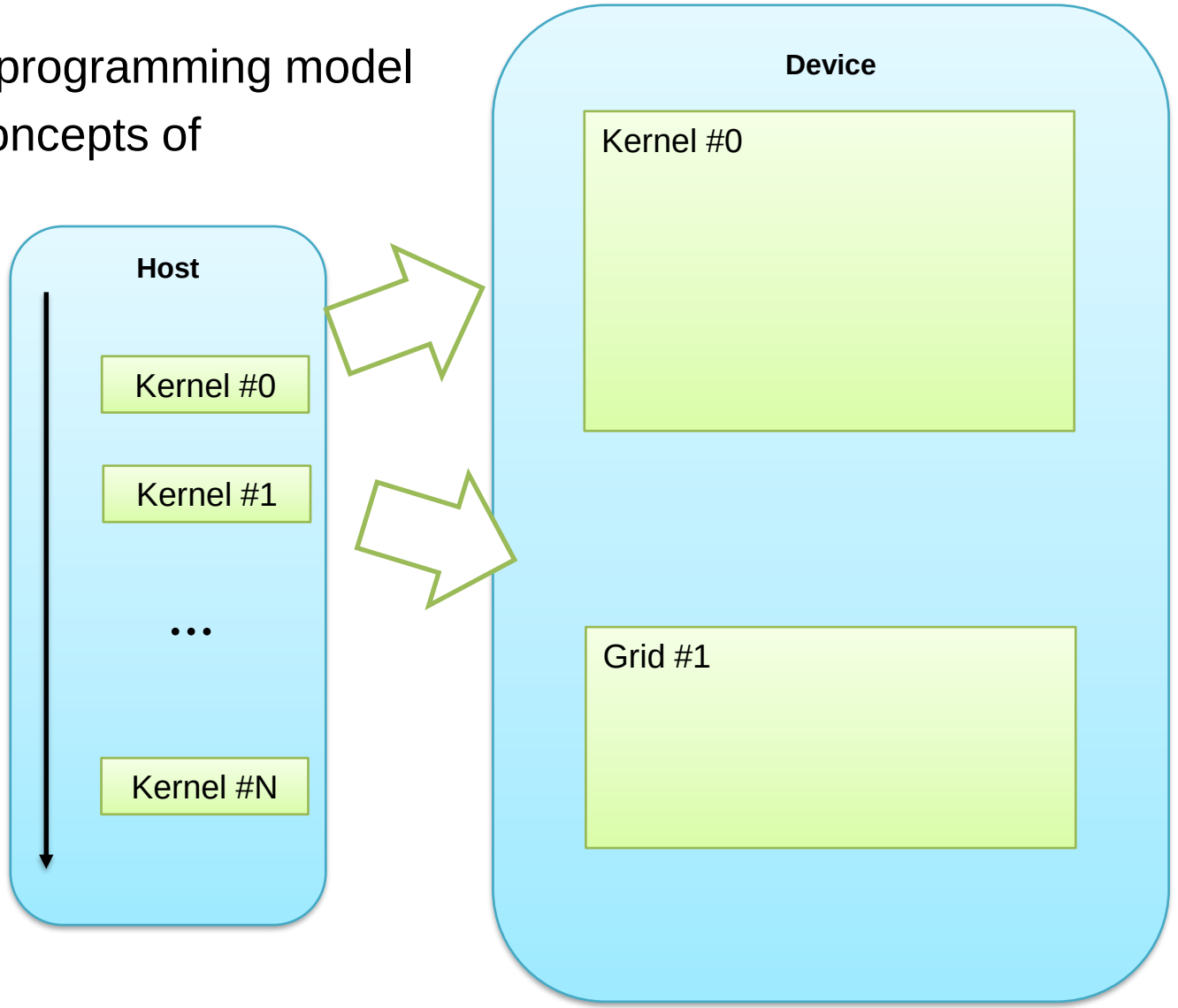
1) Offload-based programming

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



2) Parallelism in CUDA

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



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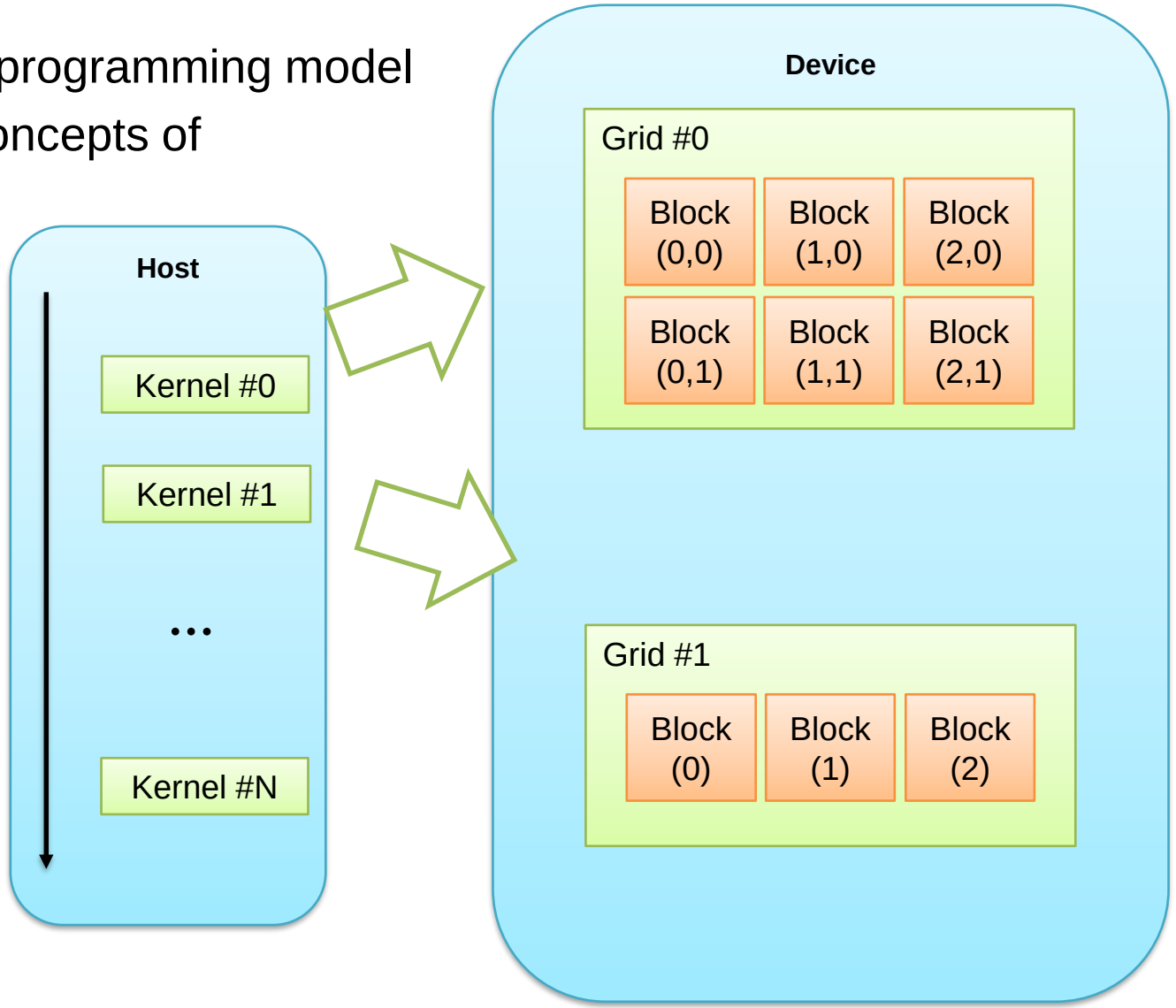

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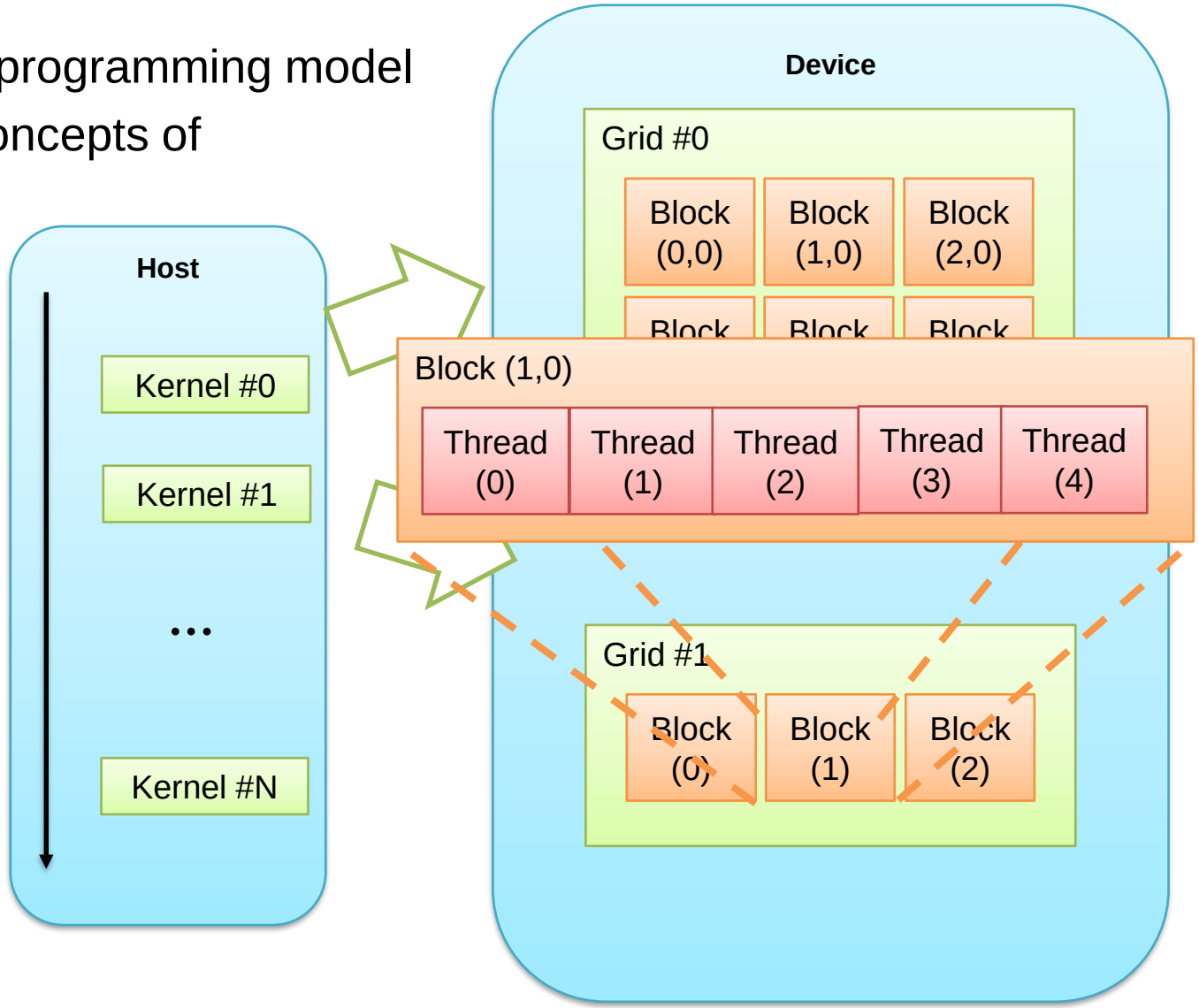

2) Parallelism in CUDA

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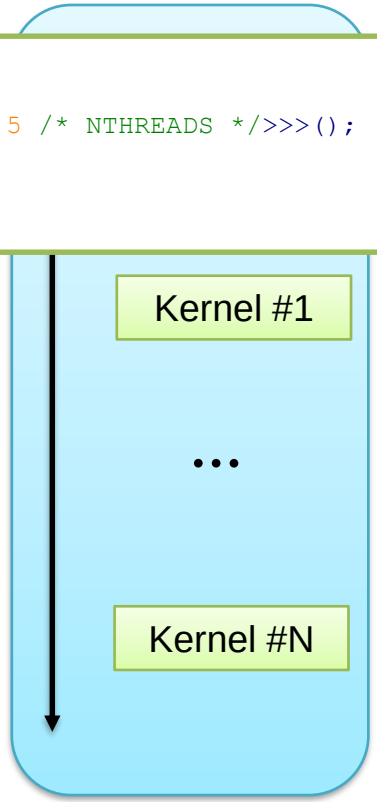
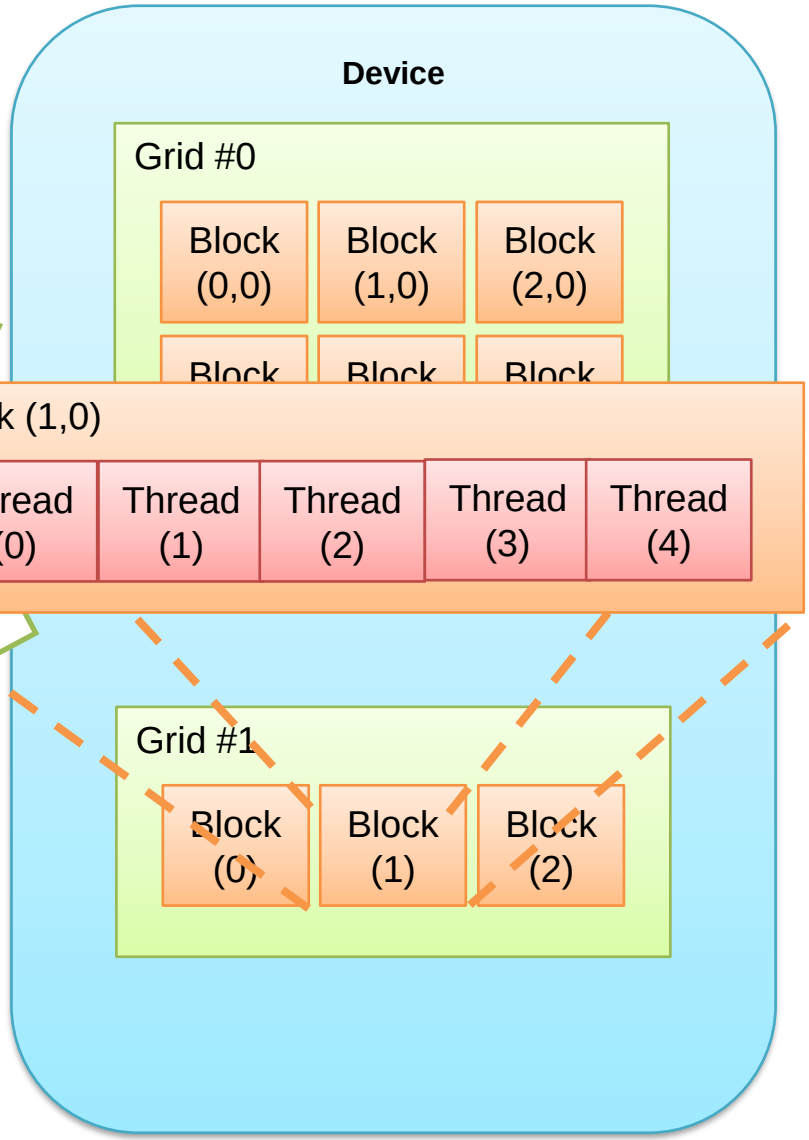
```
myKernel<<<3 /* NBLOCKS */, 5 /* NTHREADS */>>>();
```





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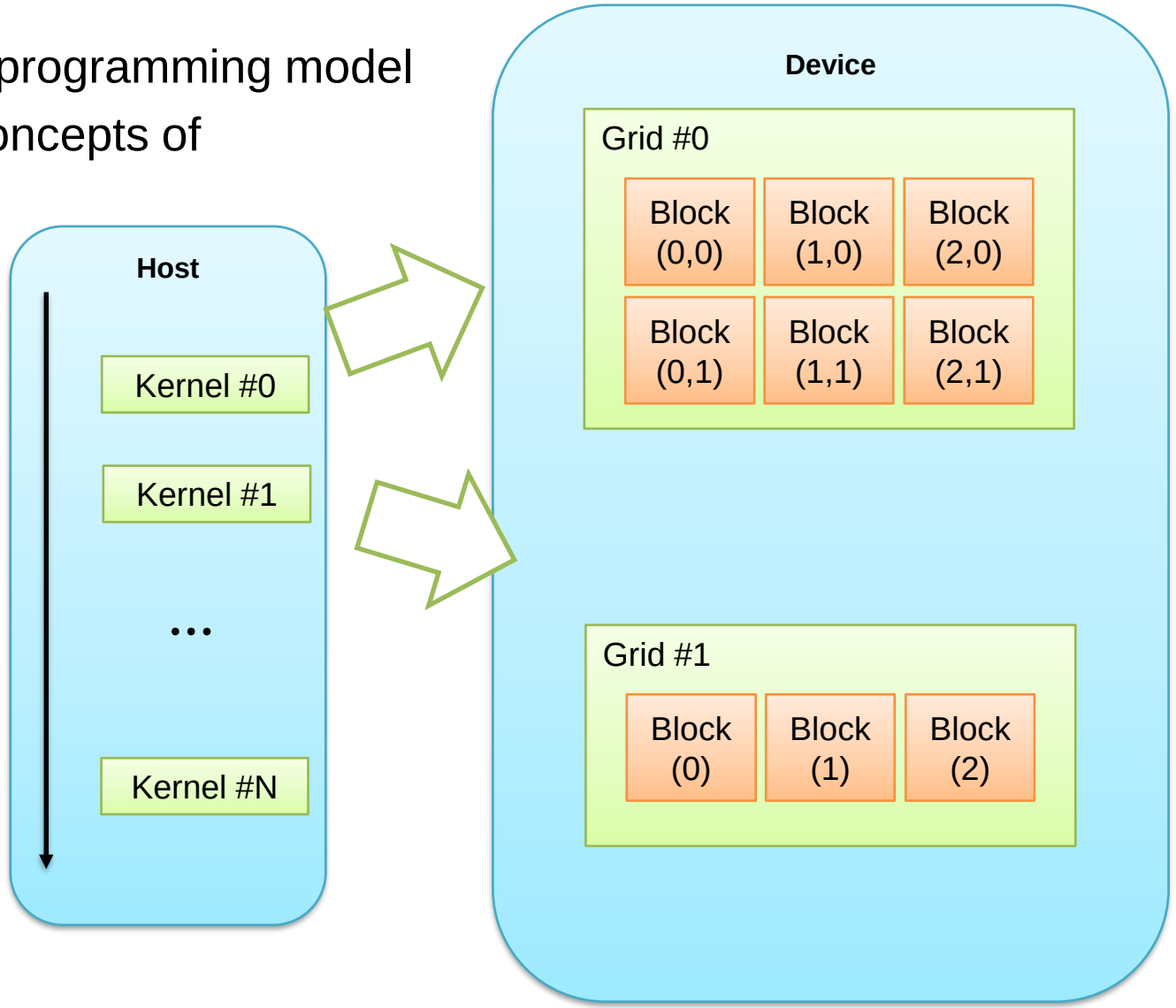

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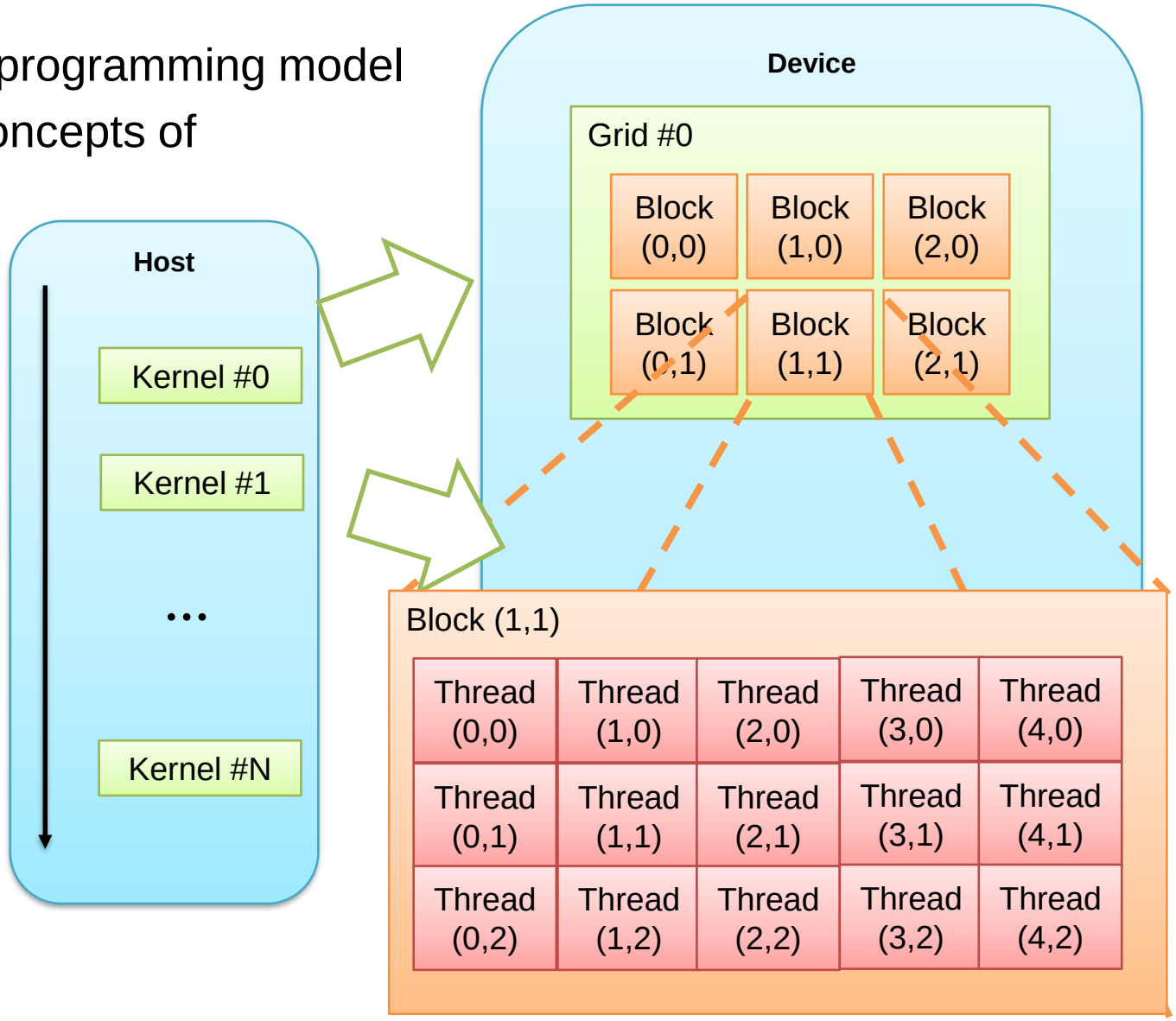

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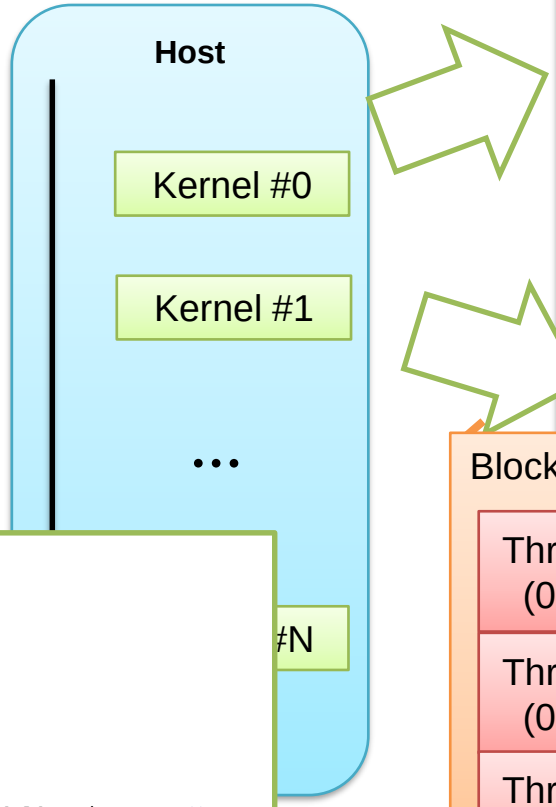

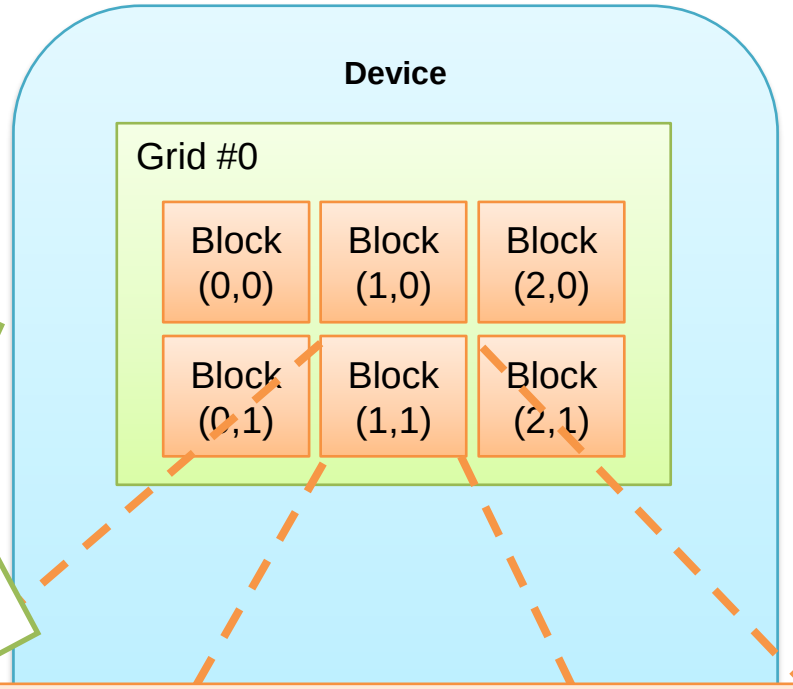

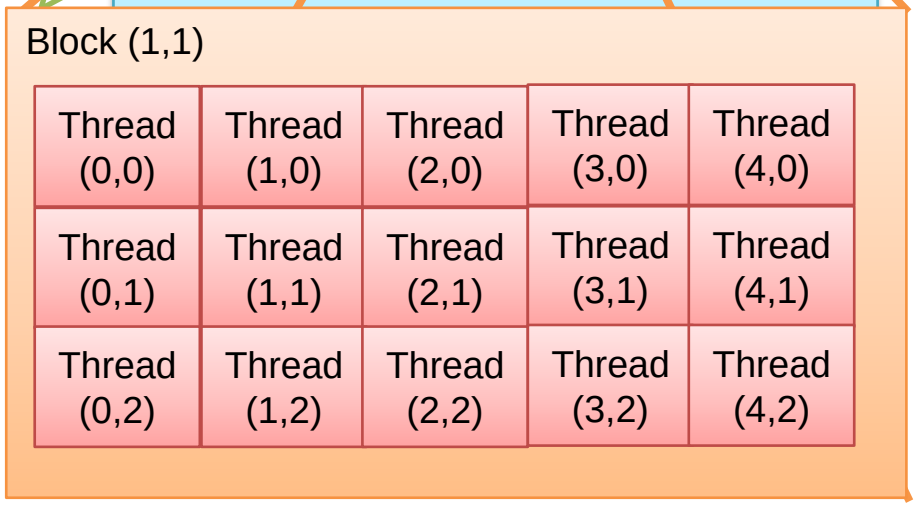


```
dim3 grid_size;
grid_size.x = 3;
grid_size.y = 2;

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

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

Lockstep

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

```
/* ... */

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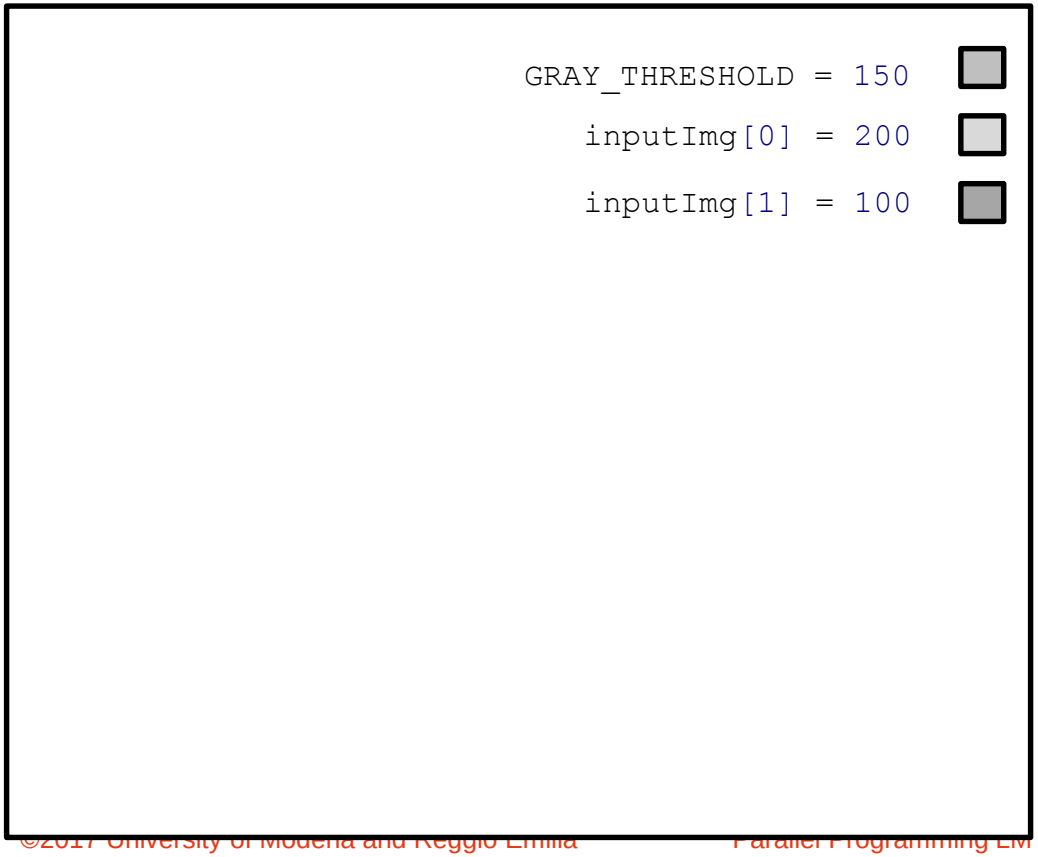


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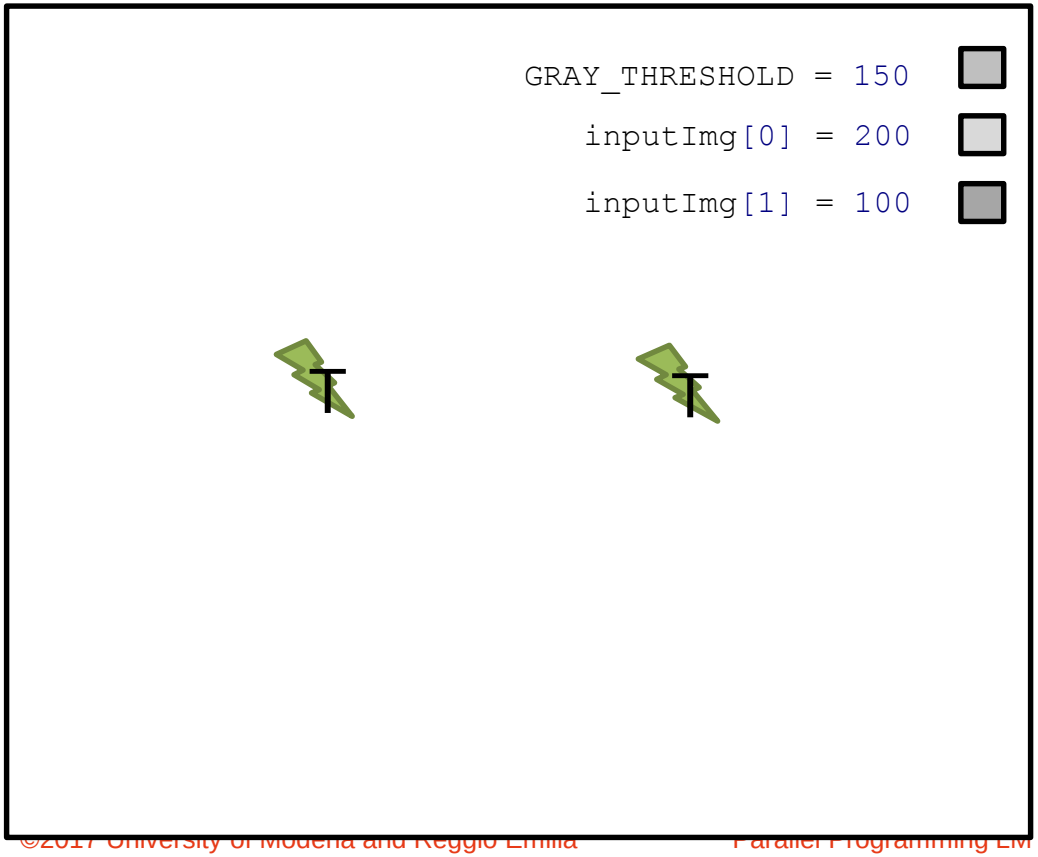


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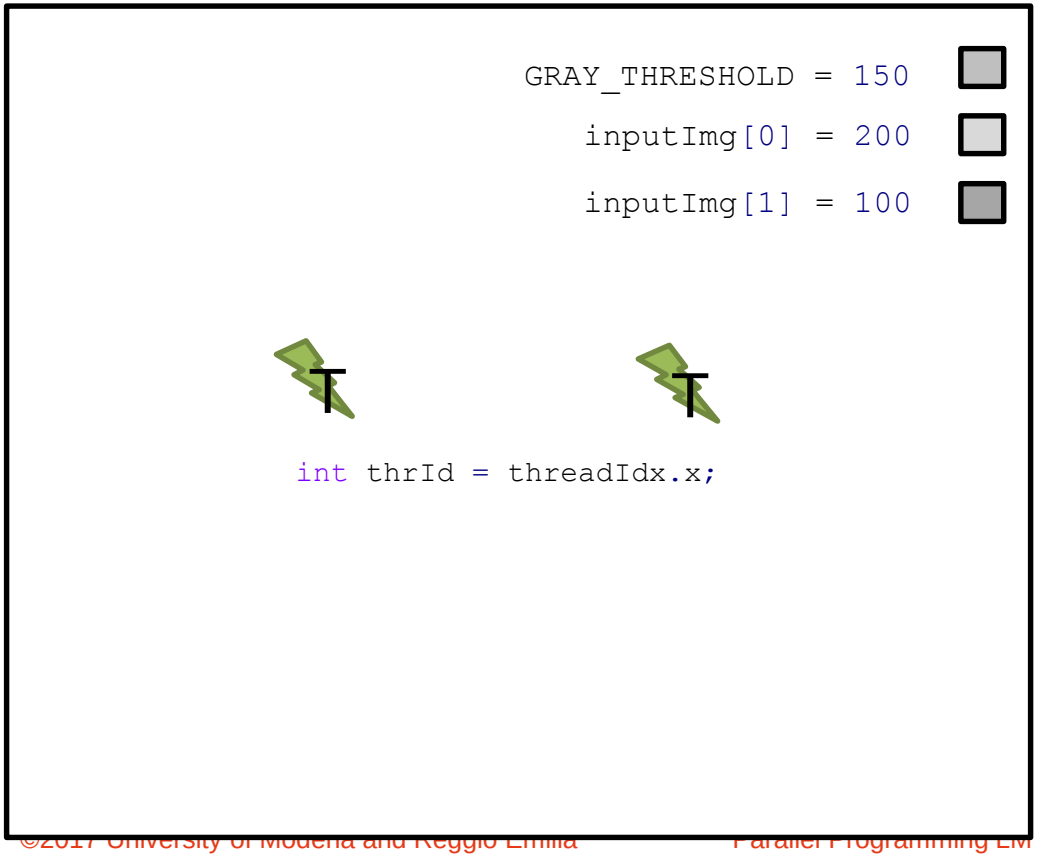


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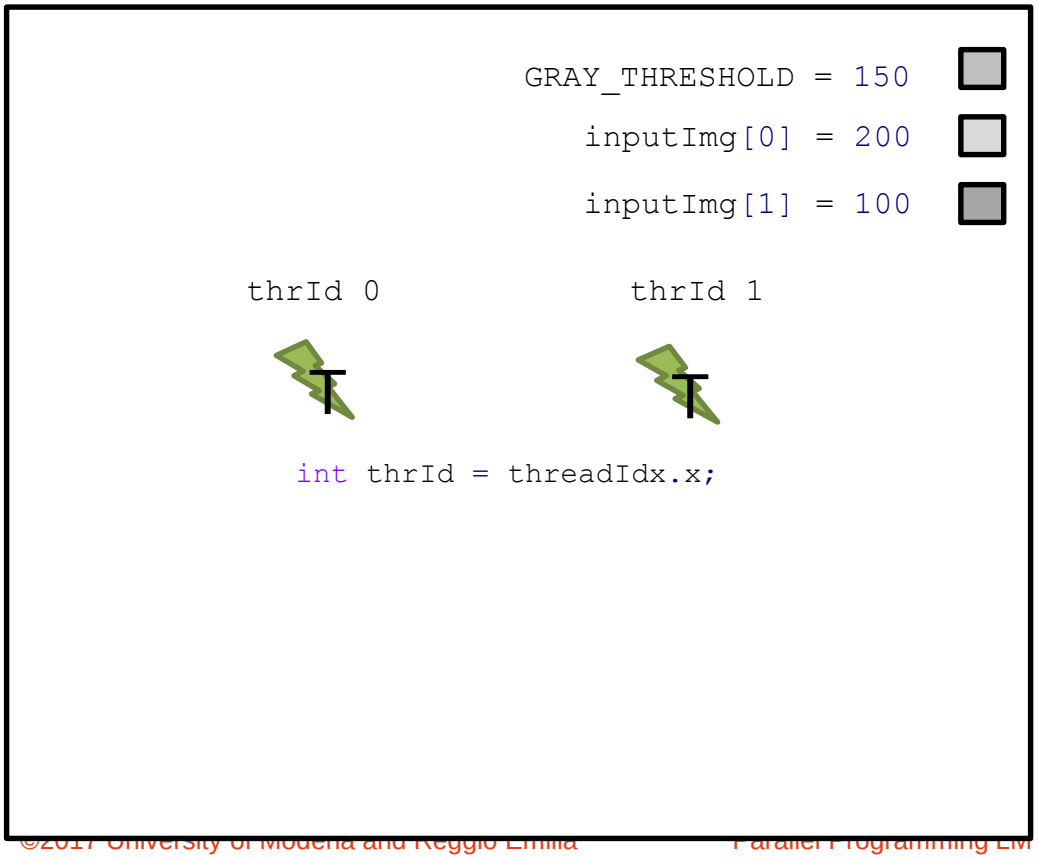


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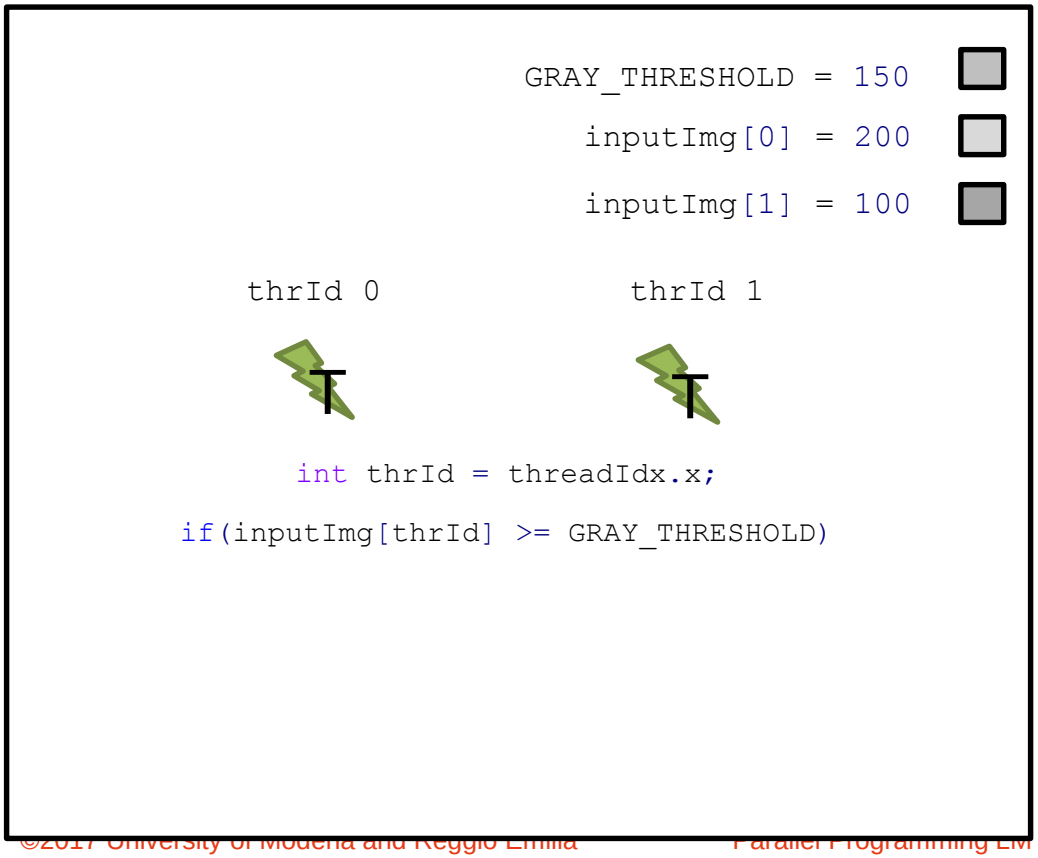


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GRAY_THRESHOLD = 150
inputImg[0] = 200
inputImg[1] = 100
```

thrId 0 thrId 1

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if(inputImg[thrId] >= GRAY_THRESHOLD)
outputImg[thrId] = WHITE;        NOP
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/* ... */
```

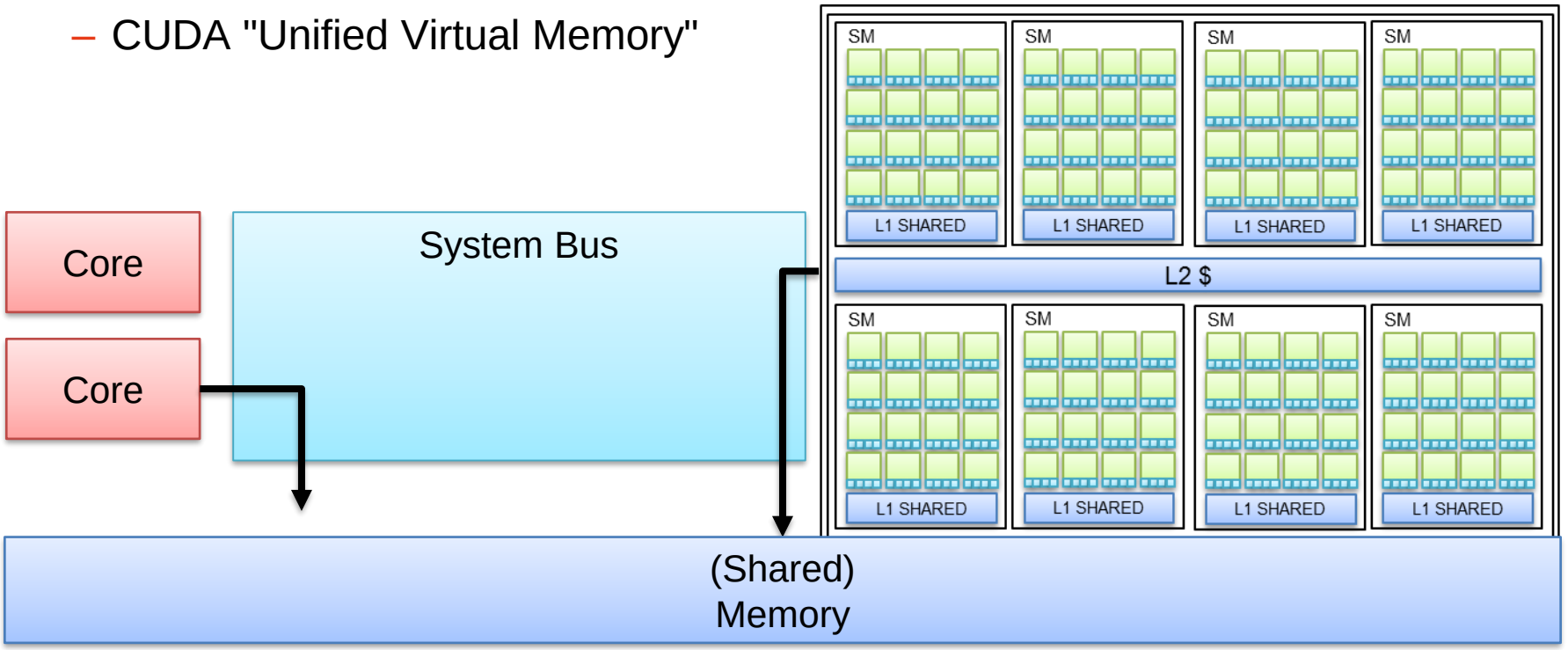
Warps, and lockstep

- ✓ 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

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"



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/
- Some pointers
  - 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