OpenCL Base Course

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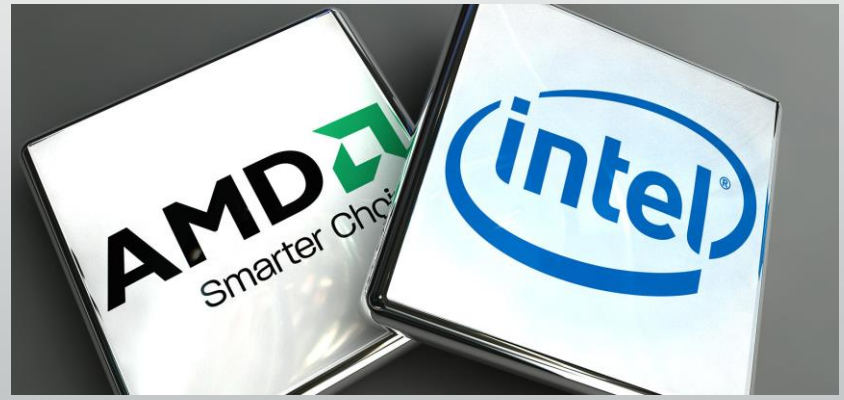
Course Overview

This OpenCL base course is structured as follows:

- Introduction
  - GPGPU programming
  - Parallel programming
  - Heterogeneous programming
- The OpenCL framework
  - The OpenCL Models
  - OpenCL API
- OpenCL programming
  - Guidelines through examples
  - Students hands-on

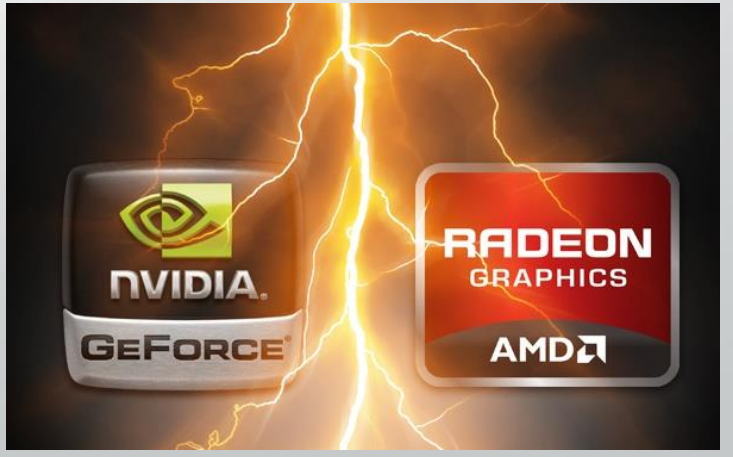
Central Processing Unit (CPU)

- Fundamental component of a modern computer
- Constantly in evolution in term of performance
- Better CPU performance = greater core clock frequency.
  - Reached the clock frequency limit due to power requirements.
- Solution: increase numbers of cores per chip.

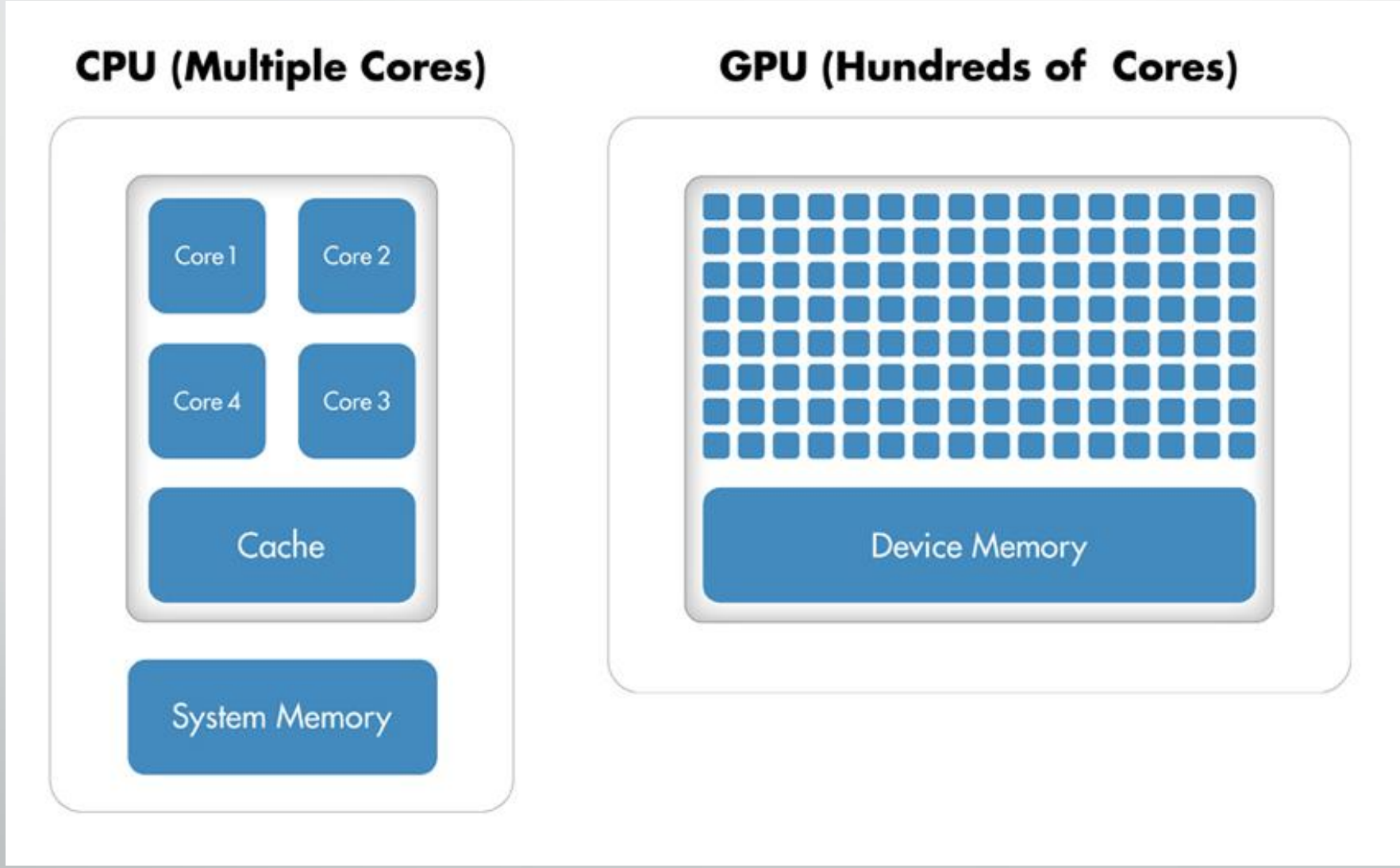


Graphics Processing Unit (GPU)

- Primarily used to manage and boost the performance of video and graphics
- Main feature: high number (hundreds) of simplistic cores
- GPUs work in tandem with a CPU, and are responsible for generating the graphical output display (computing pixel values)
- Inherently parallel - each core computes a certain set of pixels
  - Architecture has evolved for this purpose



CPU vs GPU

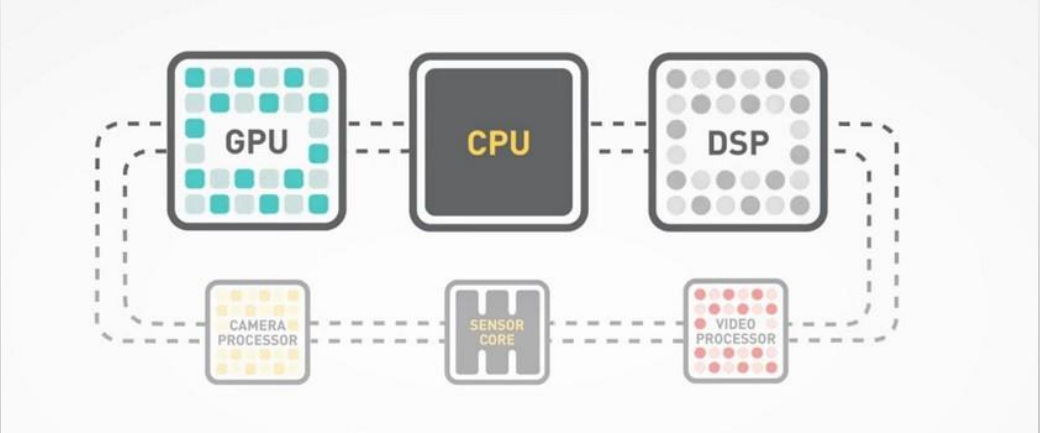

CPU (Multiple Cores)
Core 1
Core 2
Core 4
Core 3
Cache
System Memory
GPU (Hundreds of Cores)
Device Memory

GPGPU

- GPGPU: **General Purpose computation on Graphics Processing Units**.
- Idea: using GPU for generic computations
- GPU acts as an “accelerator” to the CPU (Heterogeneous System)
  - Most lines of code are executed on the CPU
  - Key computational kernels are executed on the GPU
    - Taking advantage of the large number of cores and high graphics memory bandwidth
  - AIM: code performs better than use of CPU alone.
- Nvidia was the pioneer for GPGPU.
  - It created CUDA Language (based on C) and the guidelines to follow

Heterogeneous Computing

- Heterogeneous computing exploits the capabilities of different computing resources in a system like
  - CPU
  - GPU
  - Multicore Microprocessor
  - Digital Signal Processor



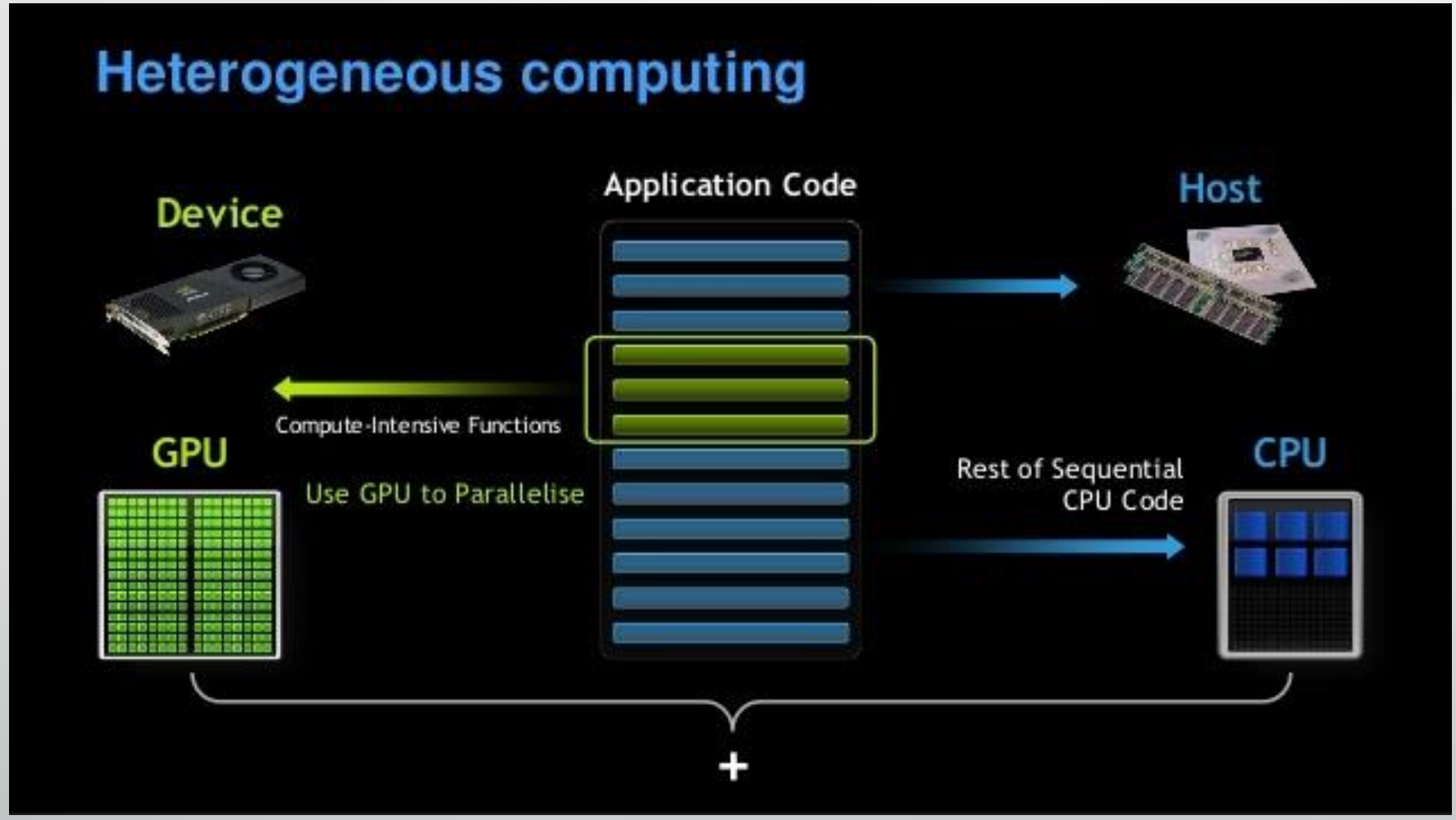
Heterogeneous Computing

- Heterogeneous applications commonly include a mix of workload behaviors:
  - *control intensive* (e.g. searching, sorting, and parsing)
  - *data intensive* (e.g. image processing, simulation and modeling, and data mining)
  - *compute intensive* (e.g. iterative methods, numerical methods, and financial modeling)
- Each of these workload classes executes most efficiently on a specific style of hardware architecture and no single device is best for running all classes of workloads. For example:
  - Control-intensive applications tend to run faster on superscalar CPUs
    - They use branch prediction mechanism that are very powerful on this hardware
  - Data-intensive applications tend to run faster on vector architectures
    - In this kind of application the same operation is applied to multiple data items, and on vector architecturs multiple operations can be executed in parallel

Heterogeneous Computing

- Usually used to obtain a high level of parallelization
- Course focus: GPU – CPU
- The use of a graphics processing unit (GPU) together with a CPU to accelerate scientific, analytics, engineering, consumer, and enterprise applications is a simple and common scenario of the heterogeneous programming

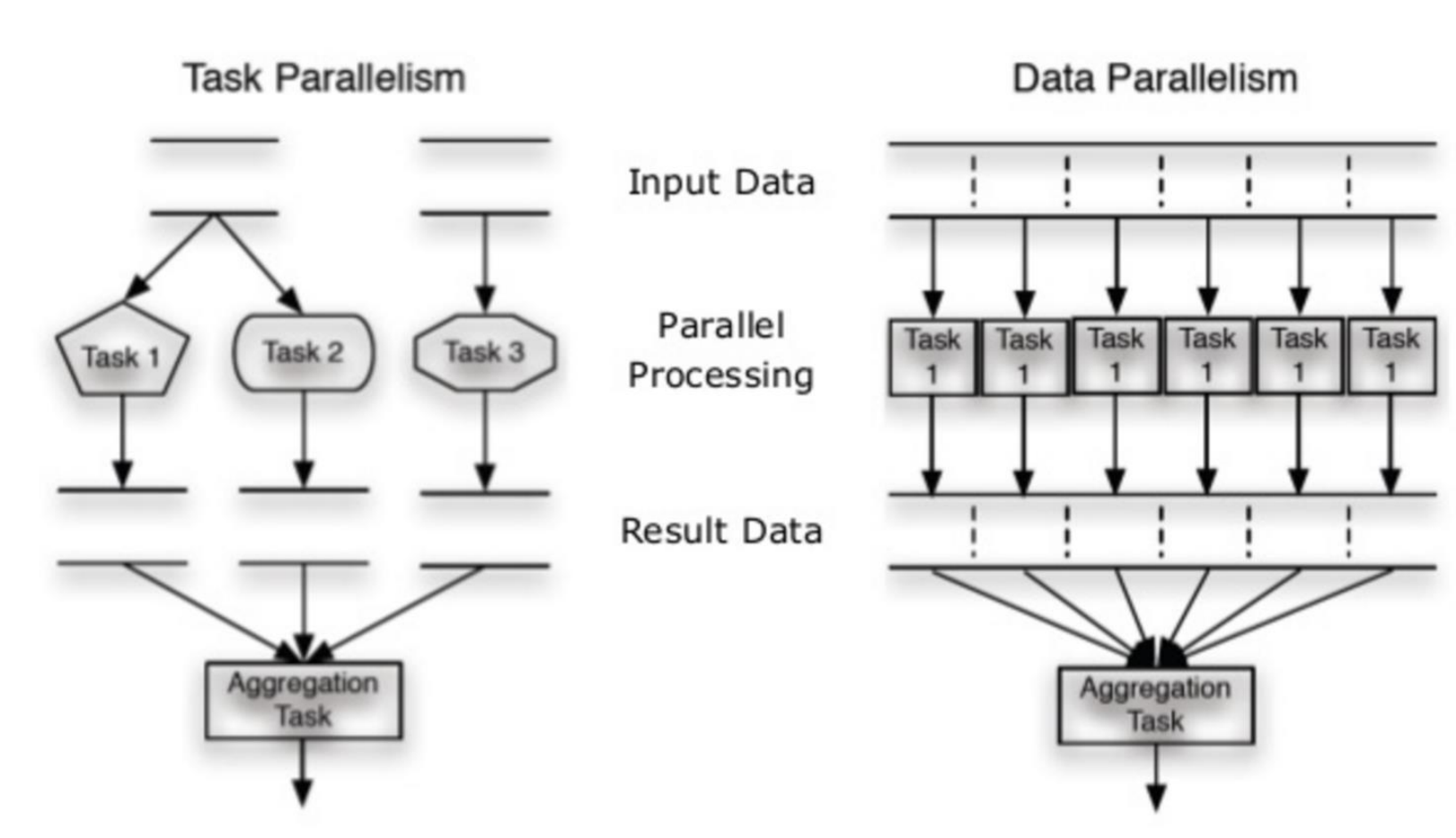
Heterogeneous Computing



Parallel Programming

- The parallel programming is the ability to use multiple computing resources to speed up the computation
- Two kinds of parallelism:
  - *Task-based*: each unit carries out a different job.
  - *Data-based*: all units do the same work on different subsets of the data

Parallel Programming



Parallel Programming

- ***A problem can be parallelized only if it can be divided into independent subproblems***
- If the problem can be divided, it's possible to use a decomposition method
- Two main decomposition methods:
  - Divide-and-conquer
    - iteratively break a problem into smaller subproblems until the subproblems fit well on the computational resources provided
  - Scatter-gather
    - send a subset of the input data to each parallel resource, and then collect the results of the computation and combine them into a result data set

Parallel Programming

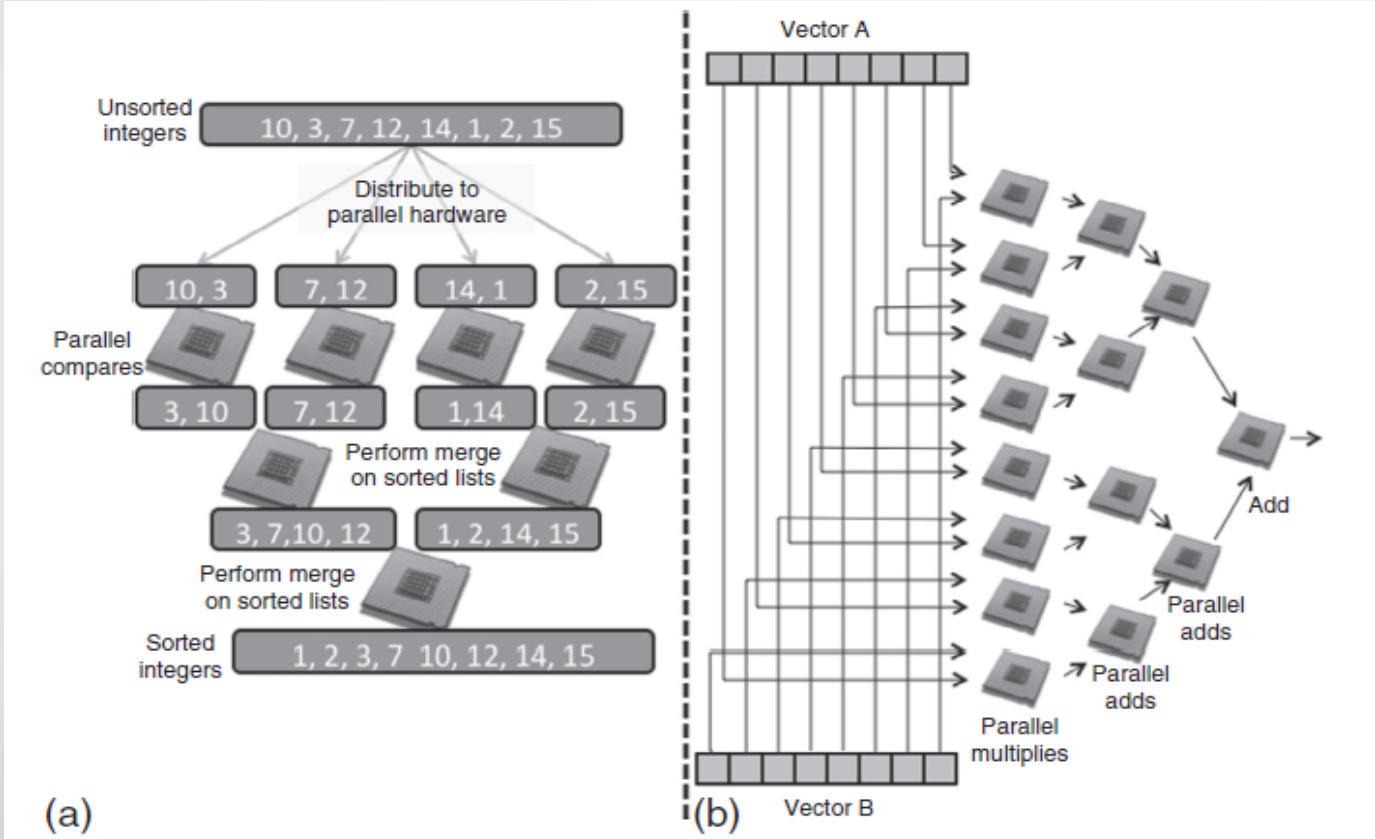


FIGURE 1.1

(a) Simple sorting: a divide-and-conquer implementation, breaking the list into shorter lists, sorting them, and then merging the shorter sorted lists. (b) Vector-scalar multiply: scattering the multiplies and then gathering the results to be summed up in a series of steps.

Parallelism Sample

- Classic Sample: multiplication of the elements of two arrays A and B (each array has N elements) storing the result of each multiply in the corresponding element of array C
- The standard way to develop this sample is implementing a sequential solution

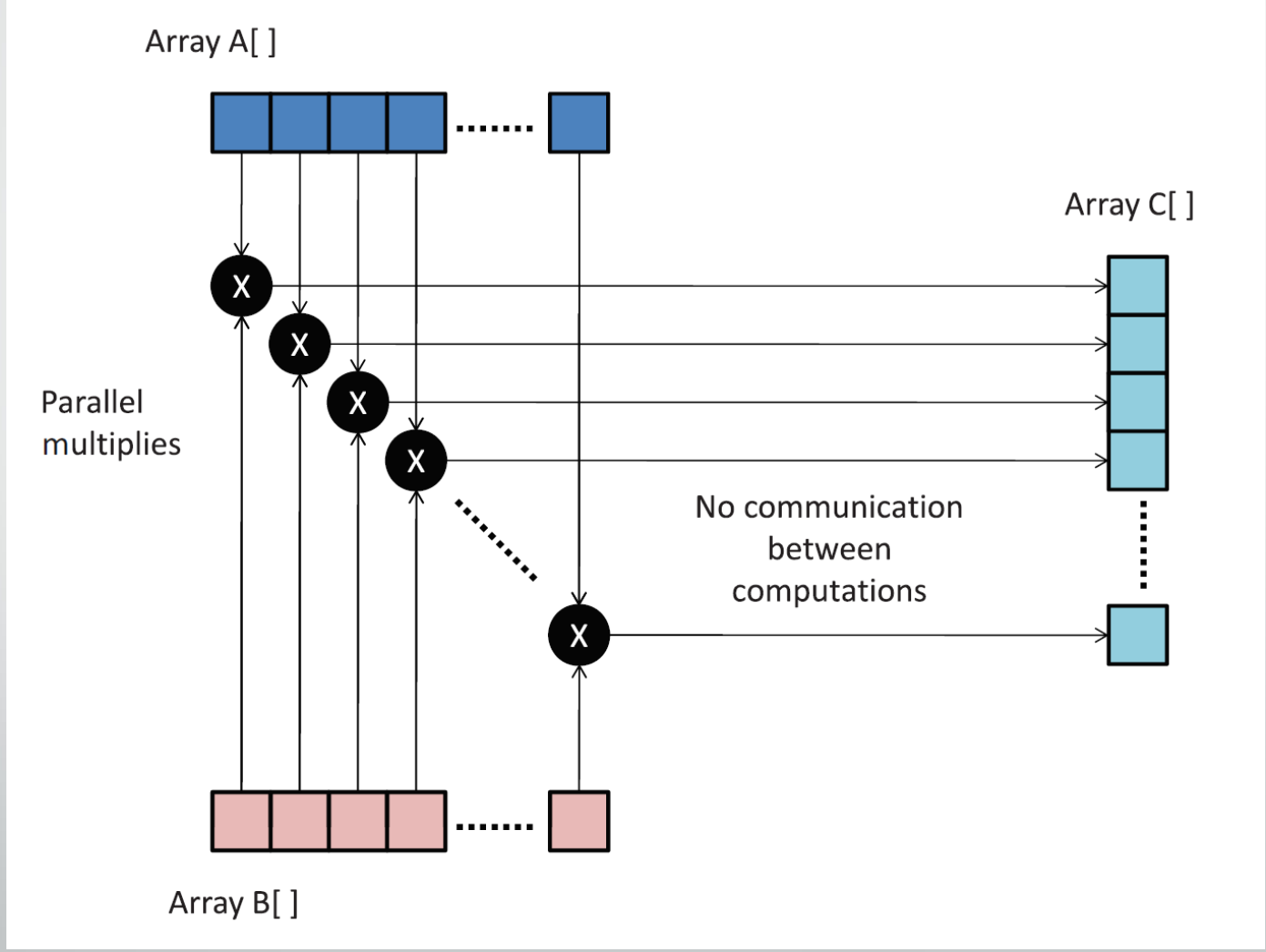
```
1    for (i=0; i<N; i++)
2        C[i] = A[i] * B[i];
```

- Problem: this solution execute N-times line 2 (one for each element in the array) without parallelism

Parallelism Sample

- **Question**: Is the sample parrallelizable? And why?
- **Answer**: Yes!!!!! The sample is parallelizable because the multiplication of each element in A and B is ***indipendent***.
  - And then it's possible to create indipendent subproblems.
- **Solution**: Generate a separate execution instance to perform the computation of each element of C. This code possesses significant data-level parallelism because it's possible to ***perform the same operation in parallel***.

Parallelism Sample – Parallel Solution



Heterogeneous Computing - Problem

- For a class of algorithms developers write code in C or C++ and run it on a CPU.
- For another class of algorithms developers often write code in CUDA and use a GPU
- Two related approaches, but each works on only one kind of processor
  - Developers has to specialize in one and ignore the other.

how do you program such machines?

OpenCL

- The solution is **Open Computing Language** or **OpenCL**, a programming language developed specifically to support heterogeneous computing environments.

OpenCL

- OpenCL is managed by the no-profit technology consortium Khronos Group (Apple, IBM, NVIDIA, AMD, Intel, ARM, etc).
- The aim of OpenCL is enable the development of applications that can be executed across a range of different devices made by different vendors.
  - Using the core language and correctly following the specification, any program designed for one vendor can execute on another vendor's hardware.

OpenCL

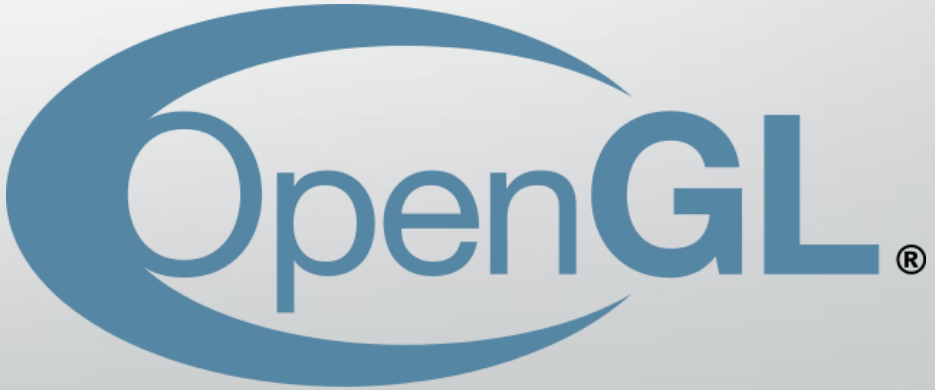
- Version 1.0 (2008) on Apple's Mac OSX Snow Leopard.
  - AMD announced support for OpenCL in the same timeframe, and in 2009 IBM announced support for OpenCL in its XL compilers for the Power architecture.
- In 2010 released version 1.1
- In 2011 released version 1.2
- In 2013 released version 2.0 (actual version).

OpenCL

- OpenCL supports different levels of parallelism.
- It efficiently maps to
  - homogeneous systems
  - heterogeneous systems.
  - single- or multiple-device systems consisting of CPUs, GPUs, and other types of devices limited only by the imagination of vendors.
- OpenCL code is written in OpenCL C, a restricted version of the C99 language with extensions appropriate for executing data-parallel code on a variety of heterogeneous devices.

OpenCL vs OpenGL

- OpenCL is similar to OpenGL but **THEY ARE NOT THE SAME**!!!!!!!
- OpenCL is specifically crafted to increase computing efficiency across platforms and it is typically used for image processing algorithms, physical simulations. It returns numerical results (**NO IMAGE RESULTS**).
- OpenGL is a graphical API that allows you to send rendering commands to the GPU. Typically, the goal is to show the rendering on screen.



OpenCL - Specification

The OpenCL specification is defined in 4 parts called *models*.

1. **Platform model**:
   - Specifies two kinds of processors:
     - Host processor: coordinates the execution. Only one.
     - Device processors: execute OpenCL C kernels. One or more
   - Defines an abstract hardware model for Devices.
2. **Execution model**: Defines how the OpenCL environment is configured by the host, and how the host may direct the devices to perform work. This includes the definitions of:
   - Host execution environment
   - Mechanisms for Host-Device interaction
   - Concurrency model used for the configuration of kernels.
     - Fundamental elements: OpenCL work-items and work-groups.

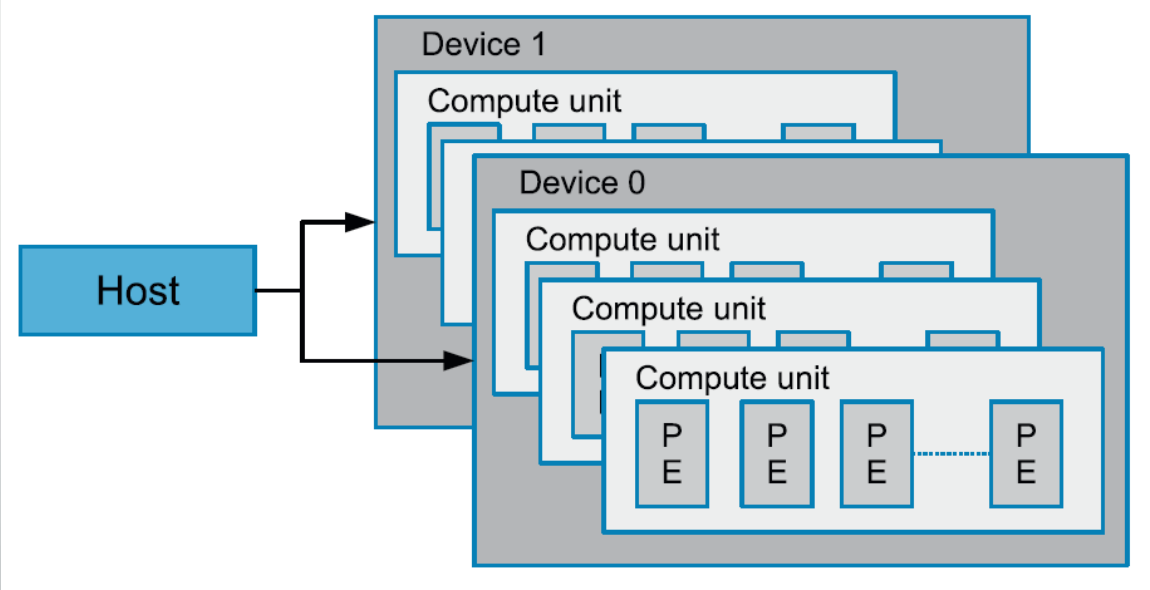
OpenCL - Specification

3. **Kernel programming model**: Defines how the concurrency model is mapped to physical hardware.

4. **Memory model**: Defines memory object types, and the abstract memory hierarchy that kernels use regardless of the actual underlying memory architecture. It also contains requirements for memory ordering and optional shared virtual memory between the host and devices.

OpenCL – Platform Model

- An *OpenCL platform* consists of a *Host* (CPU) connected to one or more *OpenCL Devices* (GPU).
- A *Device* is divided into one or more *compute units* (functionally independent)
- Each *compute unit* is divided into one or more *processing elements*.



OpenCL – Platform Model

The AMD Radeon R9 290X graphics card (Device) comprises 44 vector processors (compute units)

Each compute unit has four 16-lane SIMD (Single Instrunction Multiple Data) engines, for a total of 64 lanes (processing elements).

Each SIMD lane on the Radeon R9 290X executes a scalar instruction.

This allows the GPU device to execute a total of $44 \times 16 \times 4 = 2816$ instructions at a time.

OpenCL – Platform Model API

OpenCL offers two API functions for discovering platforms and devices:

```
cl_int clGetPlatformIDs(cl_uint num_entries,
                        cl_platform_id *platforms,
                        cl_uint *num_platforms)
```

```
cl_int clGetDeviceIDs(cl_platform_id platform,
                      cl_device_type device_type,
                      cl_uint num_entries,
                      cl_device_id *devices,
                      cl_uint *num_devices)
```

Let's analyze their behavior in a example: clInfoProgram.c

Instructions for connecting to Cometa GPU Server

SSH client to connect to our server.

Linux or MacOS: it is installed by default.

Windows: download SSH client (putty or openssh).

Step for connection:

1. ssh –l gpu 212.189.144.28
   - Enter ‘bnd3espue’ as password
2. ssh –l *username* gpu
   - ‘username’ is the login name you should have received from Cometa
   - Enter the password you received

OpenCL – Platform Model API

Remember:

- 3 step to get the *platforms/devices*
  - STEP 1: discovery quantity of platforms/devices
  - STEP 2: allocation of enough space
  - STEP 3: retrieval of the desired number of platforms/devices
- You can choose what device retrieve with *device_type* argument:
  - *CL_DEVICE_TYPE_CPU*
  - *CL_DEVICE_TYPE_GPU*
  - *CL_DEVICE_TYPE_ALL*

OpenCL – Execution and Programming Model

The Execution model defines two main components:

- **Host program**: written in C or C++, it runs on the OpenCL host.
  - creates and queries the platform and the device attributes
  - defines a context for the kernels
  - builds the kernels and manages their executions.
- **Kernels**: written in OpenCL C, they are the basic units of executable code that run on the OpenCL device.
  - Each instance of a OpenCL kernel is executed by a Compute Units.

OpenCL – Execution and Programming Model

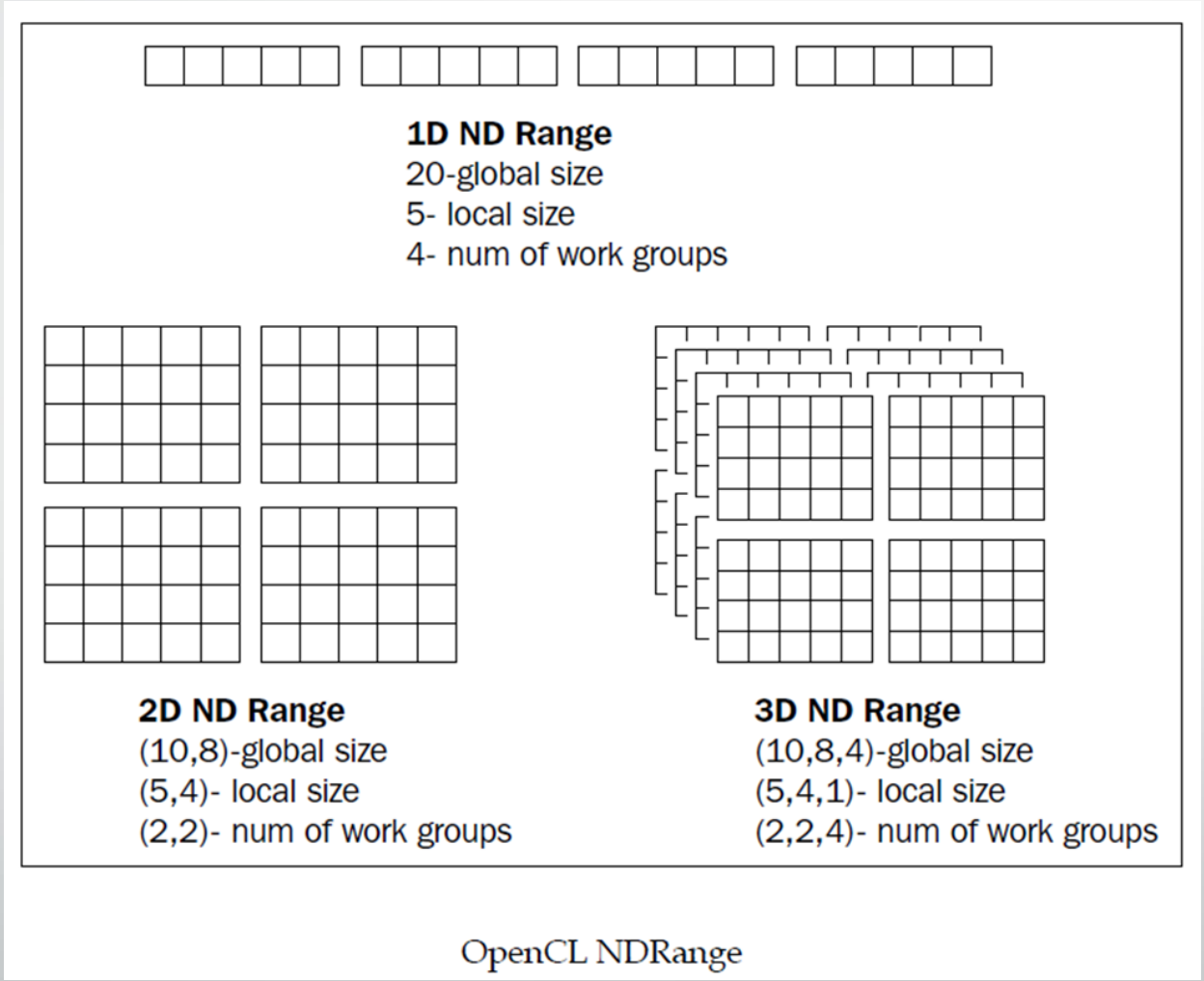
On submission of the *kernel* by the *Host* to the *Device*, an N dimensional index space is defined (N = 1 2 or 3).

The number of kernel instances is equal to the size of the index space and each kernel instance is created at each of the coordinates of this index space.

This instance is called as the "**work item**" and the index space is called as the **NDRange.** The work-items are performed by the compute units.

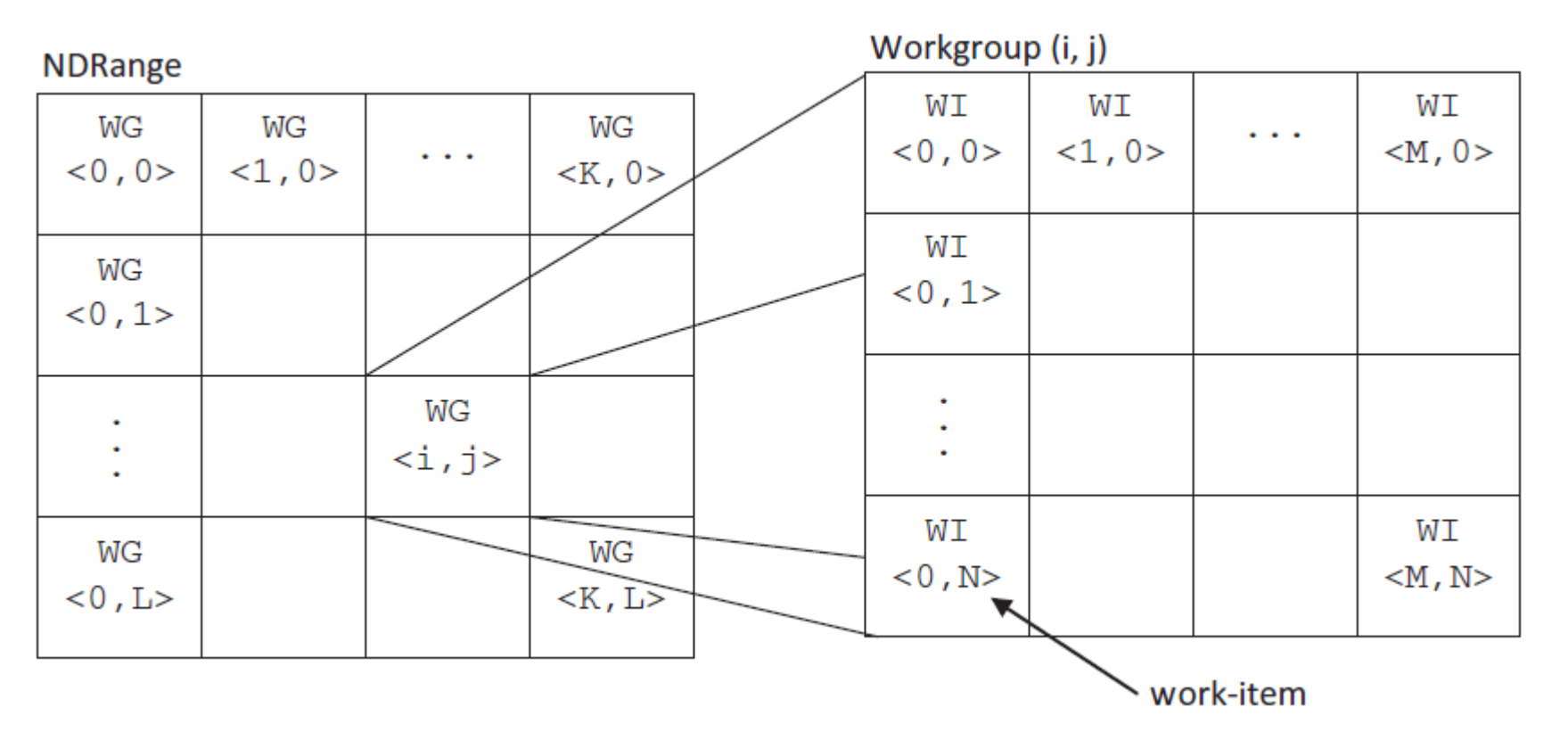
Work-items can be divided into smaller equally sized "**work-groups**"

OpenCL – Execution and Programming Model



OpenCL NDRange

OpenCL – Execution and Programming Model



OpenCL – Execution and Programming Model

- So for each work-item we can define two types of identifier:
  - **global-id**: A unique global ID given to each work item in the global NDRange
  - **local-id**: A unique local ID given to each work item within a work group

The ID is fundamental for the execution of the kernels in OpenCL

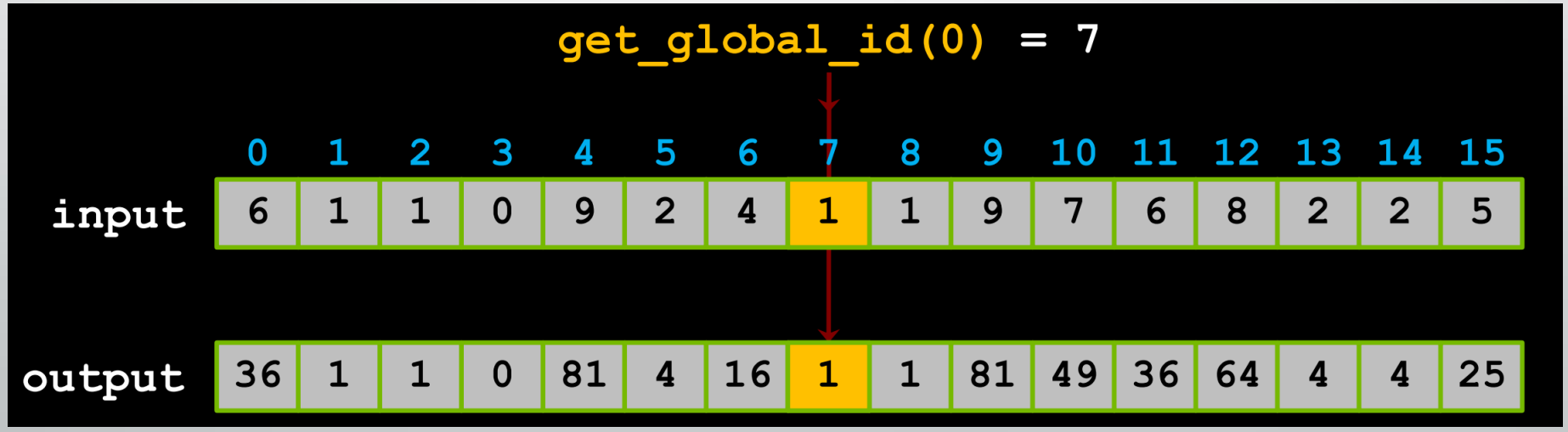
Scalar C Function	Data-Parallel Function

`void square(int n, const float *a, float *result)`
`{`
`  int i;`
`  for (i=0; i<n; i++)`
`  result[i] = a[i]*a[i];`
`}`
	`kernel void dp_square`
	`  (global const float *a, global float *result)`
	`{`
	`  int id= get_global_id(0);`
	`  result[id] = a[id]*a[id];`
	`}`
	`// dp_square execute over "n" work-items`

OpenCL – Execution and Programming Model

Data-Parallel Function

```
kernel void dp_square
   (global const float *a, global float *result)
{
  int id= get_global_id(0);
  result[id] = a[id]*a[id];
}
// dp_square execute over "n" work-items
```



OpenCL – Execution e Programming Model

- The API functions used to get information about the ID are the following:

```
• get_global_id(int dim);
• get_local_id(int dim);
• get_num_groups(int dim);
• get_group_size(int dim);
• get_group_id(int dim);
```

OpenCL – Execution and Programming Model

In order for the host to request that a kernel is executed on a device, a **context** must be configured.

It enables the host to pass commands and data to the device.

The API function to create a context is *clCreateContext()*.

```
cl_context clCreateContext( cl_context_properties *properties,
                            cl_uint num_devices,
                            const cl_device_id *devices,
                            void *pfn_notify (
                            const char *errinfo,
                            const void *private_info,
                            size_t cb,
                            void *user_data

                            ),
                            void *user_data,
                            cl_int *errcode_ret)
```

OpenCL – Execution and Programming Model

Execution model specifies that *devices* perform tasks based on *commands* which are sent from the host to the device.

A **command-queue** is the communication mechanism that the host uses to request action by a device.

One command-queue needs to be created per device.

The API function *clCreateCommandQueue()* (deprecated in OpenCL 2.0 and substituted by *clCreateCommandQueueWithProprierties*) is used to create a command-queue.

```
cl_command_queue clCreateCommandQueue( cl_context context,
                                       cl_device_id device,
                                       cl_command_queue_properties properties,
                                       cl_int *errcode_ret)
```

OpenCL – Execution and Programming Model

Any API call that submits a command to a command-queue will begin with ***clEnqueue*** and require a command-queue as a parameter.

For example:

- *clEnqueueReadBuffer*() call requests that the device send data to the host
- *clEnqueueNDRangeKernel*() requests that a kernel is executed on the device.

OpenCL – Execution and Programming Model

The command put in a queue are handled through the use of **events**. Each command of *clEnqueue* type has three parameters in common:

- a pointer to a list of events that specify dependencies for the current command called ***wait-list***. It is used to specify dependencies for a command
- the number of events in the wait list
- a pointer to an event that will represent the execution of the current command

```
cl_uint num_events_in_wait_list,
const cl_event *event_wait_list,
cl_event *event)
```

OpenCL – Execution e Programming Model

In addition, OpenCL includes barrier operations that can be used to synchronize execution of command-queues.

- *clFlush*() issues all previously queued OpenCL commands in a command-queue to the device associated with the command-queue
- *clFinish*() blocks until all previously queued OpenCL commands in a command-queue are issued to the associated device and have completed

OpenCL – Execution and Programming Model

The OpenCL API also includes the function *clWaitForEvents()*, which causes the host to wait for all events specified in the wait list to complete execution.

```
cl_int clWaitForEvents (cl_uint num_events,
                        const cl_event *event_list)
```

OpenCL – Execution and Programming Model

OpenCL source code **is compiled at runtime** through a series of API calls.

The process of creating a kernel from source code is as follows:

1. Store the OpenCL C source code in a character array.
   - If the source code is stored in a file, it must be read into memory and stored as a character array.
   - Each kernel in a program source string or file is identified by a ***__kernel*** qualifier
2. Turn the source code into a program object, *cl_program*, by calling *clCreateProgramWithSource()*.
   - It's possible to create a program from binary source with *clCreateProgramWithBinary()*

OpenCL – Execution and Programming Model

3. Compile the program object, for one or more OpenCL devices, with *clBuildProgram()*.
   - In case of compile errors, they will be reported here.
4. Create a kernel object of type *cl_kernel* calling *clCreateKernel* and specifying the program object and kernel name.
   - The final step of obtaining a *cl_kernel* object is similar to obtaining an exported function from a dynamic library.

OpenCL – Execution and Programming Model

```
cl_program clCreateProgramWithSource (cl_context context,
                                      cl_uint count,
                                      const char **strings,
                                      const size_t *lengths,
                                      cl_int *errcode_ret)
```

```
cl_int clBuildProgram (cl_program program,
                       cl_uint num_devices,
                       const cl_device_id *device_list,
                       const char *options,
                       void (*pfn_notify)(cl_program, void *user_data),
                       void *user_data)
```

```
cl_kernel clCreateKernel (cl_program  program,
                          const char *kernel_name,
                          cl_int *errcode_ret)
```

OpenCL – Execution and Programming Model

Unlike invoking functions in C programs, we cannot simply call a *kernel* with a list of arguments.

Before enqueue the *kernel*, we have to specify each kernel argument individually using *clSetKernelArg().*

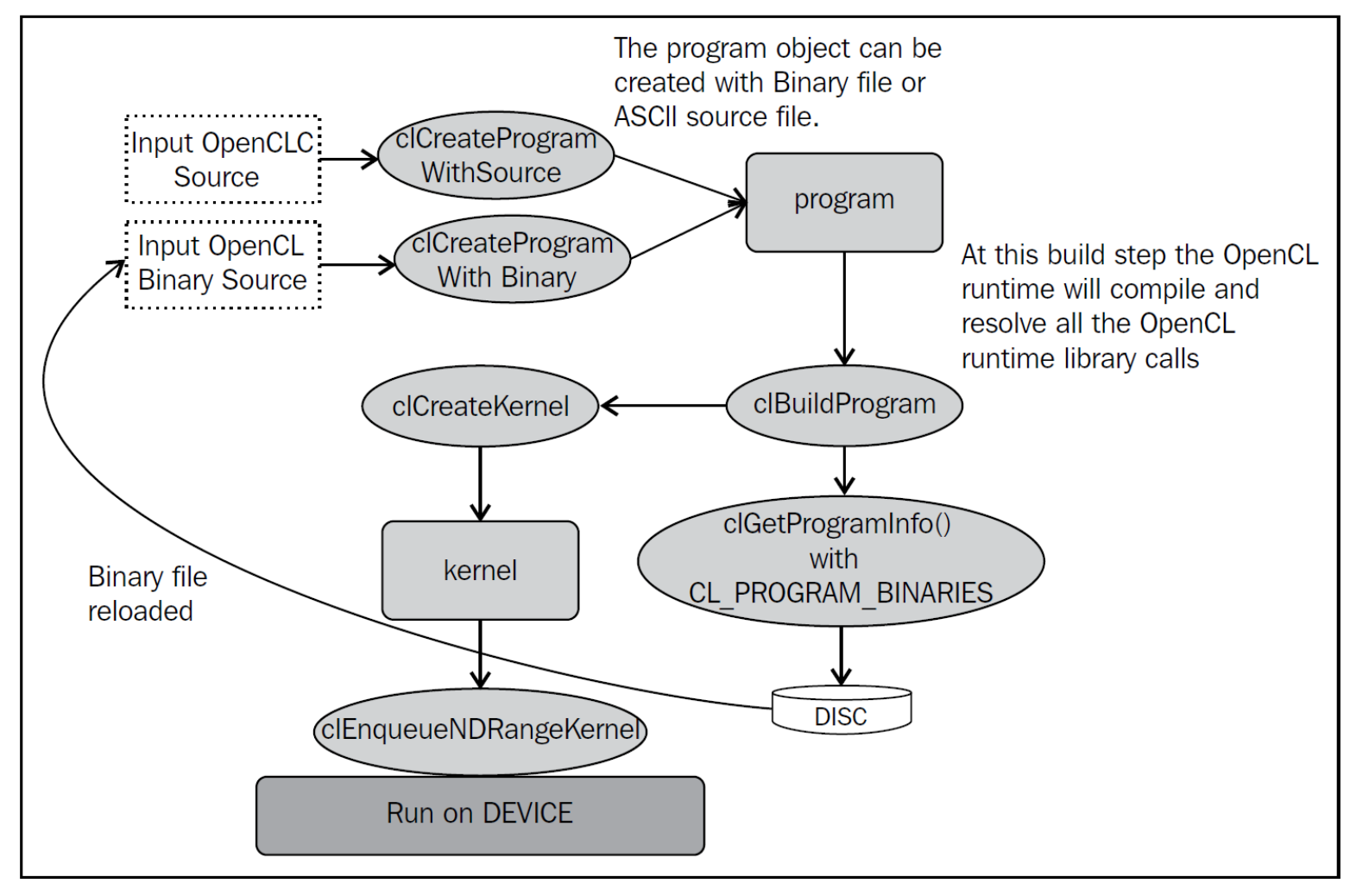
```
cl_int clSetKernelArg (cl_kernel kernel,
                       cl_uint arg_index,
                       size_t arg_size,
                       const void *arg_value)
```

OpenCL – Execution and Programming Model

Enqueuing a command to a device to begin kernel execution is done with a call to *clEnqueueNDRangeKernel()*.

```
cl_int clEnqueueNDRangeKernel (cl_command_queue command_queue,
                               cl_kernel kernel,
                               cl_uint work_dim,
                               const size_t *global_work_offset,
                               const size_t *global_work_size,
                               const size_t *local_work_size,
                               cl_uint num_events_in_wait_list,
                               const cl_event *event_wait_list,
                               cl_event *event)
```

OpenCL – Execution and Programming Model



OpenCL – Memory Model

To support portability, OpenCL defines an abstract *memory model* that programmers can target when writing code and vendors can map to their actual memory hardware.

OpenCL defines three types of memory objects: b*uffers*, *images* and *pipes*.

```
cl_mem clCreateBuffer (cl_context context,
                       cl_mem_flags flags,
                       size_t size,
                       void *host_ptr,
                       cl_int *errcode_ret)
```

OpenCL – Memory Model

```
cl_int clEnqueueReadBuffer (cl_command_queue command_queue,
                            cl_mem buffer,
                            cl_bool blocking_read,
                            size_t offset,
                            size_t cb,
                            void *ptr,
                            cl_uint num_events_in_wait_list,
                            const cl_event *event_wait_list,
                            cl_event *event)
```

```
cl_int clEnqueueWriteBuffer (cl_command_queue command_queue,
                             cl_mem buffer,
                             cl_bool blocking_write,
                             size_t offset,
                             size_t cb,
                             const void *ptr,
                             cl_uint num_events_in_wait_list,
                             const cl_event *event_wait_list,
                             cl_event *event)
```

OpenCL – Memory Model

OpenCL classifies memory as either *host memory* or *device memory*.

OpenCL divides *device memory* into four *memory regions.*

These *memory regions* are relevant within OpenCL kernels.

- ***Global Memory****:* visible to all work-items
  - similar to the main memory on a CPU-based system.
- ***Costant Memory***: specifically designed for data where each element is accessed simultaneously by all work-item.
  - Part of Global Memory
- ***Local Memory****:* memory that is shared between work-items within a work-group.
- ***Private Memory****:* memory that is unique to an individual work-item.

OpenCL – Memory Model

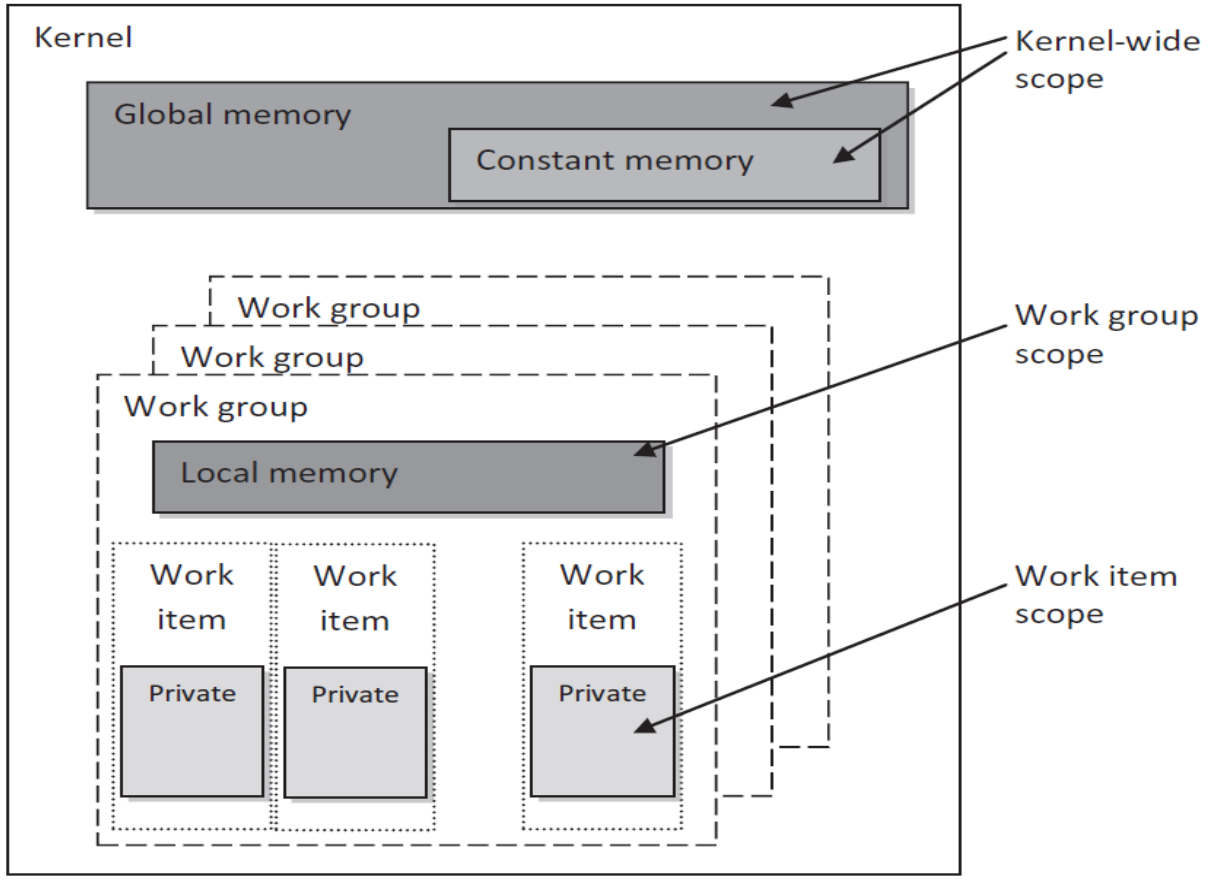


FIGURE 3.6

Memory regions and their scope in the OpenCL memory model.

OpenCL – Memory Model

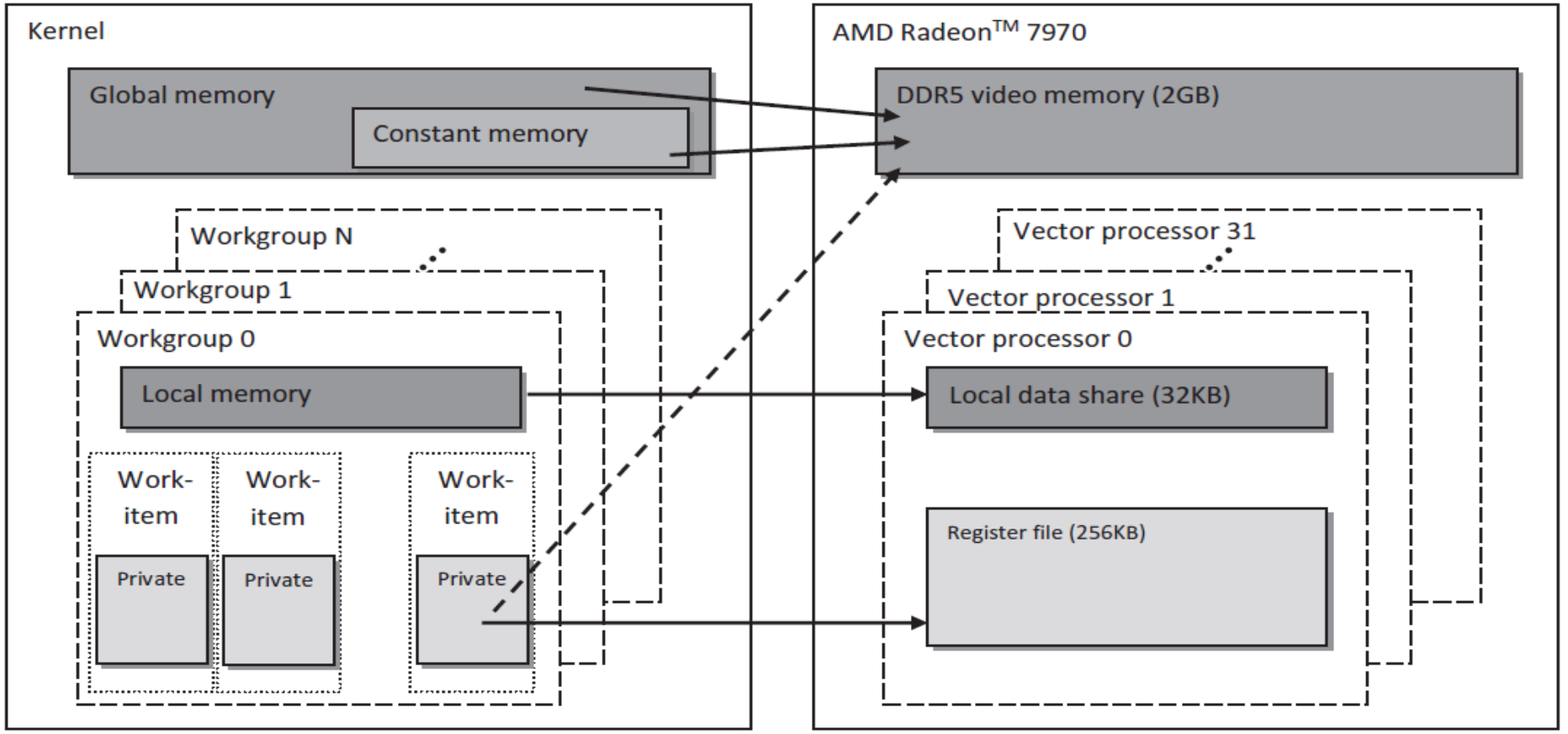


FIGURE 3.7

Mapping the OpenCL memory model to an AMD Radeon HD 7970 GPU.

THANK YOU FOR YOUR ATTENTION