Introduction to Parallel & Distributed Computing

OpenCL Basics

Lecture 11, Spring 2014

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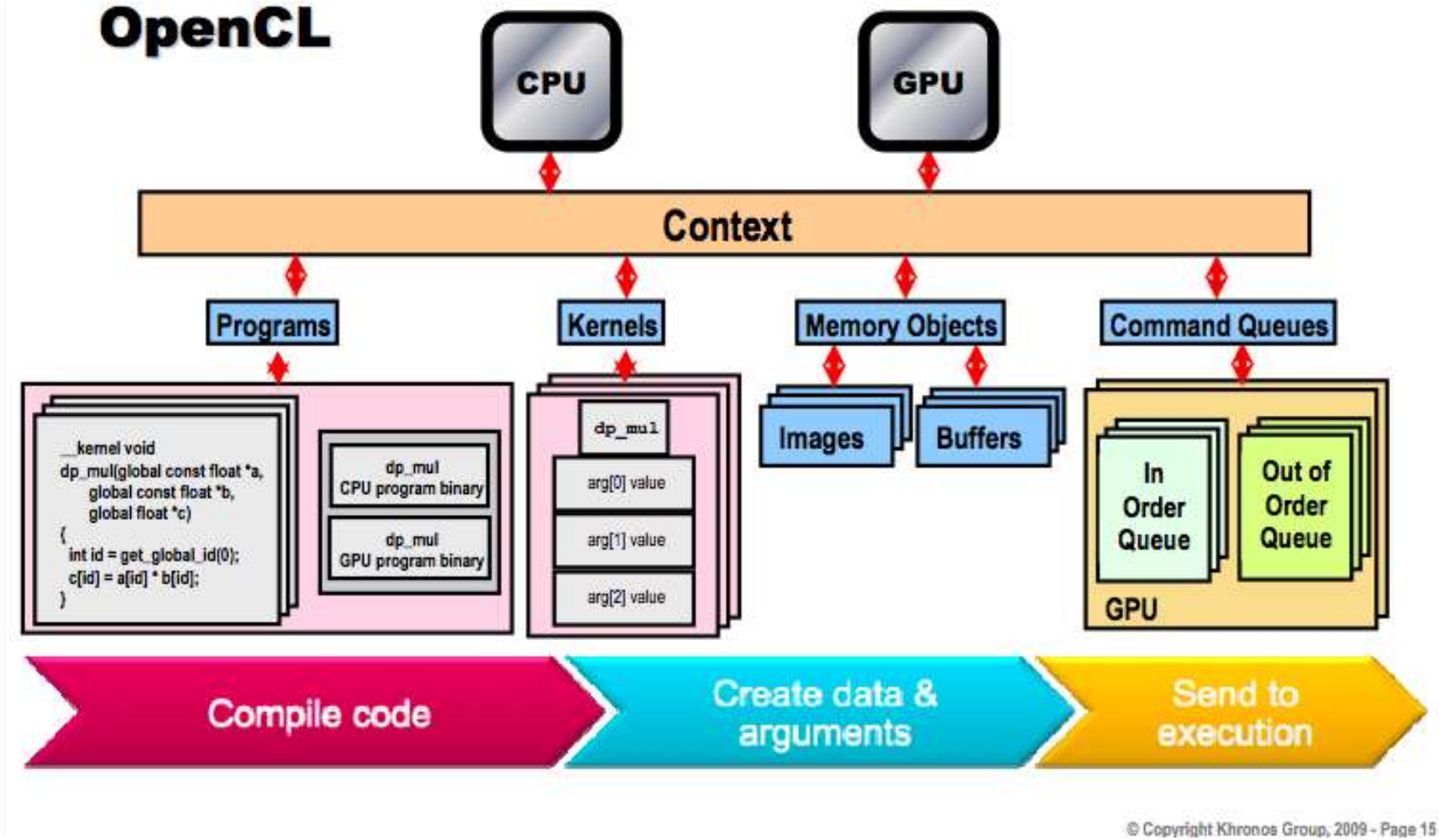
Lecture Previews

- **We shall talk about OpenCL in the next a few lectures**
  - **So that you can start early in your class projects**
- **Parallel programming paradigms**
  - **Shared memory**
    - **(CPU) An OpenMP program**
    - **(GPU) An OpenCL program**
      - small overhead in thread creation
      - great overhead in synchronization & global memory access
  - **Message passing**
    - **An MPI program**
- **Parallel algorithms will be mentioned after OpenCL**
  - **Parallel discrete search algorithms**
  - **Parallel graph algorithms**

In this Lecture …

- **OpenCL allows parallel computing on heterogeneous devices**
  - **CPUs, GPUs, other processors (Cell, DSPs, FPGAs, etc.)**
  - **Provides portable accelerated code**
- **Basic concepts in OpenCL**
  - **Platform model**
  - **Execution model**
  - **Memory model**
  - **Programming model**

Big Picture


OpenCL
CPU
GPU
Context
Programs
Kernels
Memory Objects
Command Queues
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Images
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In Order Queue
Out of Order Queue
GPU
Compile code
Create data & arguments
Send to execution
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Parallel Software – SPMD

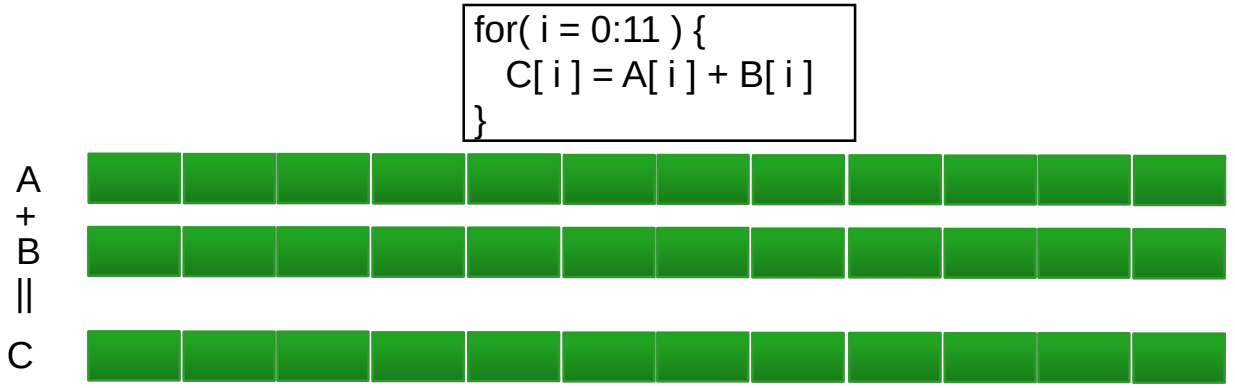
- **GPU programs (*kernels*) written using the Single Program Multiple Data (SPMD) programming model**
  - **SPMD executes multiple instances of the same program independently, where each program works on a different portion of the data**
- **For data-parallel scientific and engineering applications, combining SPMD with loop strip mining is a very common parallel programming technique**
  - **Message Passing Interface (MPI) is used to run SPMD on a distributed cluster**
  - **POSIX threads (pthreads) are used to run SPMD on a shared-memory system**
  - **Kernels run SPMD within a GPU**

Parallel Software – SPMD

- **Consider the following vector addition example**

Serial program:

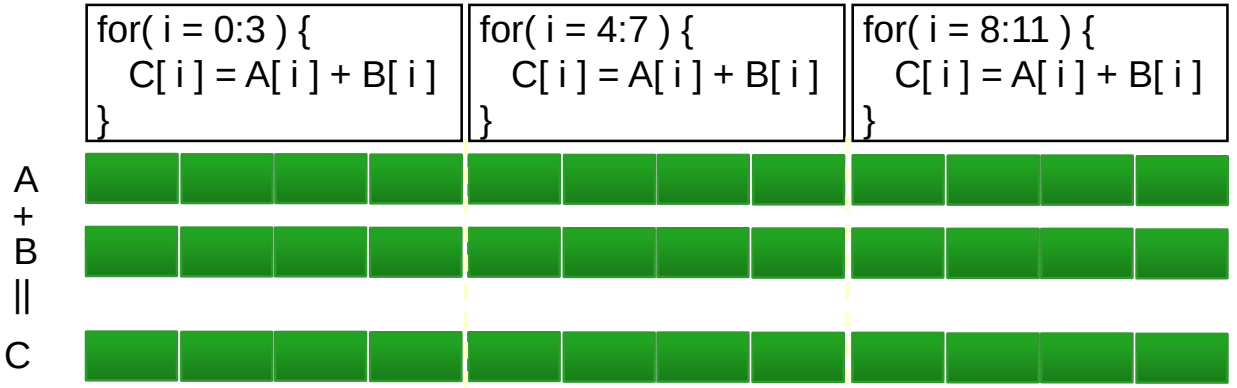
one program completes the entire task



- **Combining SPMD with loop strip mining allows multiple copies of the same program execute on different data in parallel**

SPMD program:

multiple copies of the same program run on different chunks of the data



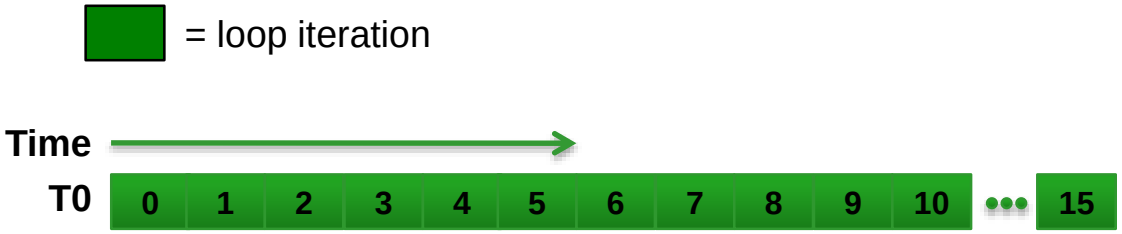
Parallel Software – SPMD

- In the vector addition example, each chunk of data could be executed as an independent thread
- On modern CPUs, the overhead of creating threads is so high that the chunks need to be large
  - In practice, usually a few threads (about as many as the number of CPU cores) and each is given a large amount of work to do
- For GPU programming, there is low overhead for thread creation, so we can create one thread per loop iteration

Parallel Software – SPMD

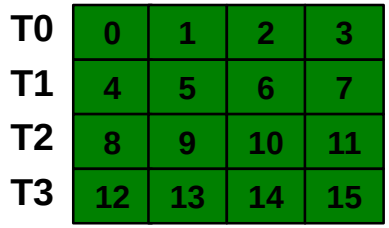
Single-threaded (CPU)

```
// there are N elements
for(i = 0; i < N; i++)
  C[i] = A[i] + B[i]
```



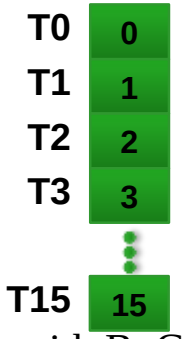
Multi-threaded (CPU)

```
// tid is the thread id
// P is the number of cores
for(i = 0; i < tid*N/P; i++)
  C[i] = A[i] + B[i]
```



Massively Multi-threaded (GPU)

```
// tid is the thread id
C[tid] = A[tid] + B[tid]
```

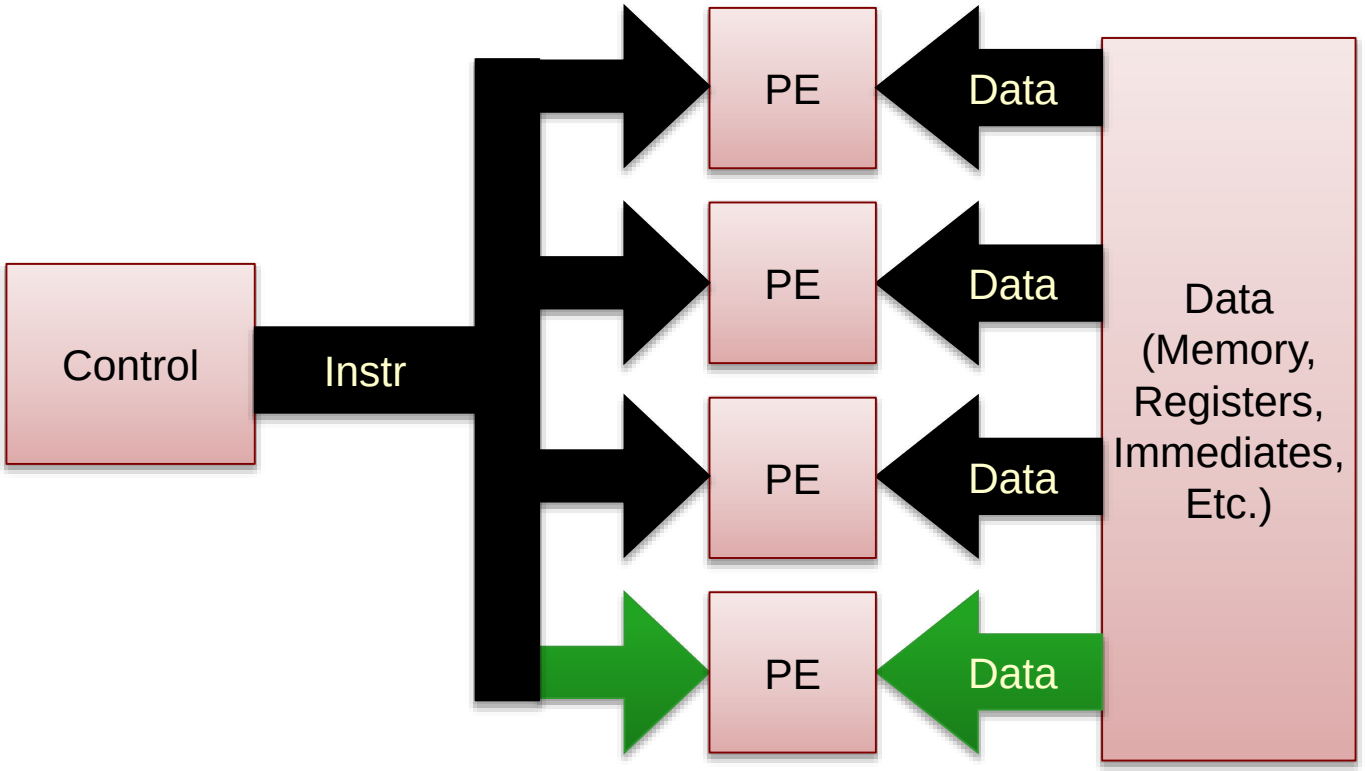


Parallel Hardware – SIMD

- **Each processing element of a Single Instruction Multiple Data (SIMD) processor executes the same instruction with different data at the same time**
  - **A single instruction is issued to be executed simultaneously on many ALU units**
  - **We say that the number of ALU units is the *width* of the SIMD unit**
- **SIMD processors are efficient for data parallel algorithms**
  - **They reduce the amount of control flow and instruction hardware in favor of ALU hardware**

Parallel Hardware – SIMD

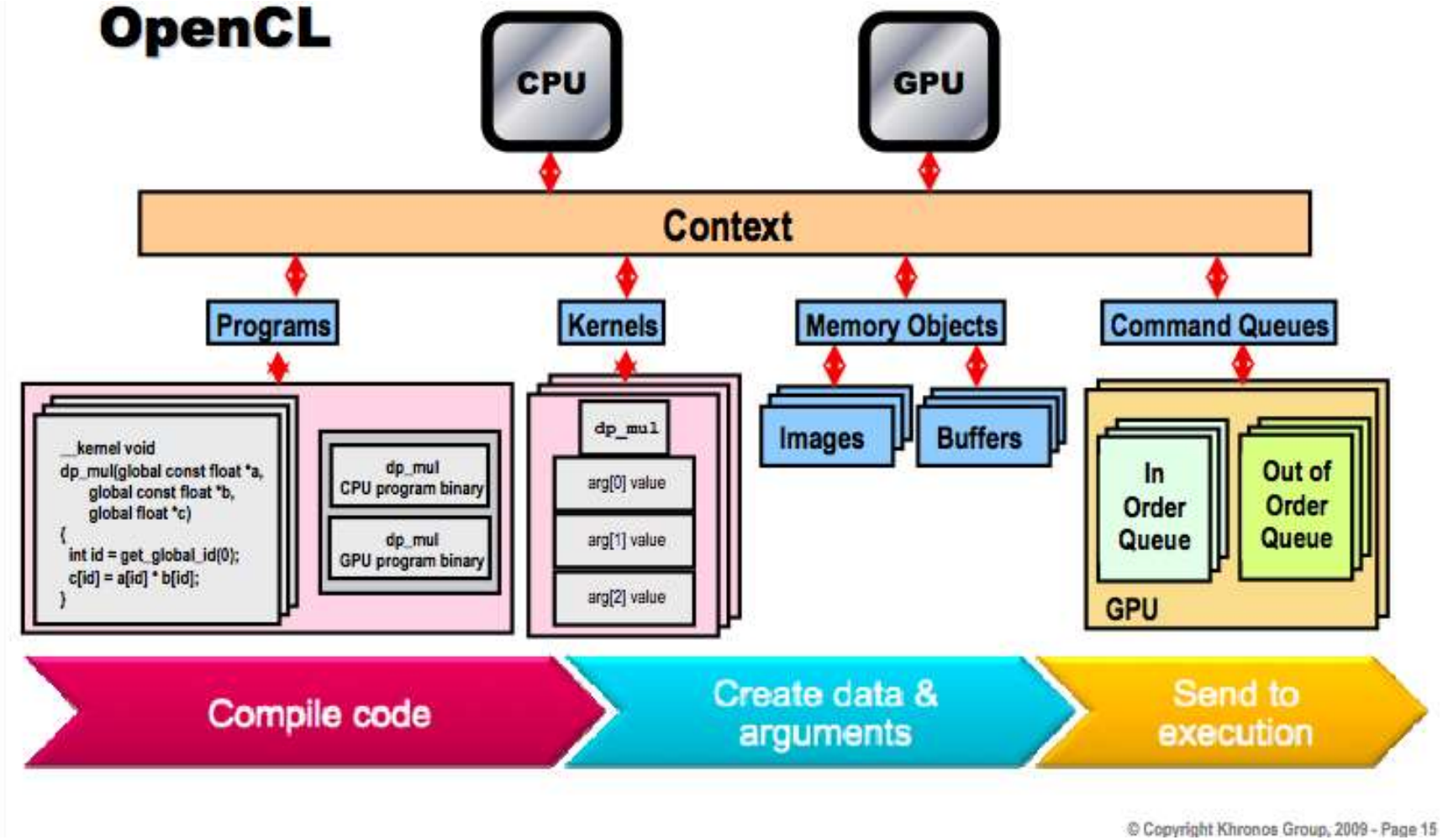
- **A SIMD hardware unit**



Parallel Hardware – SIMD

- In the vector addition example, a SIMD unit with a width of four could execute four iterations of the loop at once
- Relating to the apple-picking example, a worker picking apples with both hands would be analogous to a SIMD unit of width 2
- All current GPUs are based on SIMD hardware
  - The GPU hardware implicitly maps each SPMD thread to a SIMD "core"
    - The programmer does not need to consider the SIMD hardware for correctness, just for performance
  - This model of running threads on SIMD hardware is referred to as Single Instruction Multiple Threads (SIMT)

Big Picture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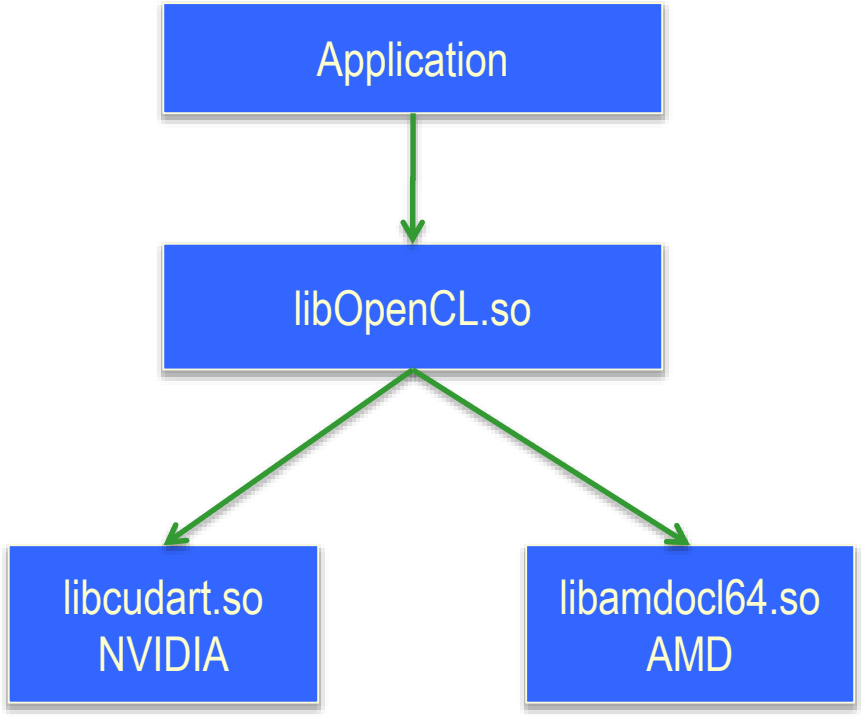
Platform Model

- **Each OpenCL implementation (i.e. an OpenCL library from AMD, NVIDIA, etc.) defines *platforms* which enable the host system to interact with OpenCL-capable devices**
  - **Currently each vendor supplies only a single platform per implementation**
- **OpenCL uses an "Installable Client Driver" model**
  - **The goal is to allow platforms from different vendors to co-exist**
  - **Current systems' device driver model will not allow different vendors' GPUs to run at the same time**

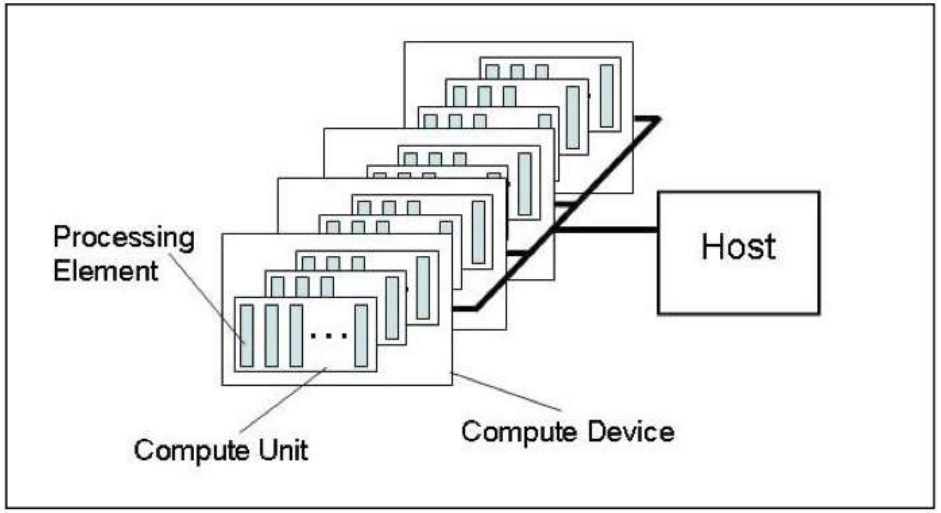
Installable Client Driver

- ICD allows multiple implementations to co-exist
- Code only links to libOpenCL.so
- Application selects implementation at runtime
  - clGetPlatformIDs() and clGetPlatformInfo() examine the list of available implementations and select a suitable one
- Current GPU driver model does not easily allow devices from different vendors in same platform



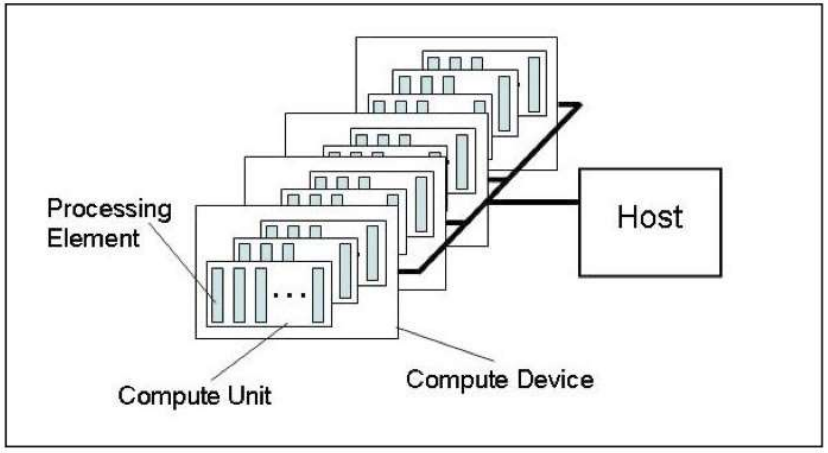
Platform Model

- The model consists of a host connected to one or more OpenCL devices
- A device is divided into one or more compute units
- Compute units are divided into one or more processing elements
  - Each processing element maintains its own program counter



Host/Devices

- **The host is whatever the OpenCL library runs on**
  - **x86 CPUs for both NVIDIA and AMD**
- **Devices are processors that the library can talk to**
  - **CPUs, GPUs, and generic accelerators**
- **For AMD**
  - **All CPUs are combined into a single device (each core is a compute unit and processing element)**
  - **Each GPU is a separate device**



Selecting a Platform

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

- **This function is usually called twice**
  - **The first call is used to get the number of platforms available to the implementation**
  - **Space is then allocated for the platform objects**
  - **The second call is used to retrieve the platform objects**

Selecting Devices

- **Once a platform is selected, we can then query for the devices that it knows how to interact with**

```
clGetDeviceIDs[4] (cl_platform_id platform,
                   cl_device_type device_type,
                   cl_uint num_entries,
                   cl_device_id *devices,
                   cl_uint *num_devices)
```

- **We can specify which types of devices we are interested in (e.g. all devices, CPUs only, GPUs only)**
- **This call is performed twice as with clGetPlatformIDs**
  - **The first call is to determine the number of devices, the second retrieves the device objects**

Contexts

- A context refers to the environment for managing OpenCL objects and resources
- To manage OpenCL programs, the following are associated with a context
  - Devices: the things doing the execution
  - Program objects: the program source that implements the kernels
  - Kernels: functions that run on OpenCL devices
  - Memory objects: data that are operated on by the device
  - Command queues: mechanisms for interaction with the devices
    - Memory commands (data transfers)
    - Kernel execution
    - Synchronization

Contexts

- **When you create a context, you will provide a list of devices to associate with it**
  - **For the rest of the OpenCL resources, you will associate them with the context as they are created**

Contexts

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

- **This function creates a context given a list of devices**
- **The properties argument specifies which platform to use (if NULL, the default chosen by the vendor will be used)**
- **The function also provides a callback mechanism for reporting errors to the user**

Command Queues

- **A *command queue* is the mechanism for the host to request that an action be performed by the device**
  - **Perform a memory transfer, begin executing, etc.**
- **A separate command queue is required for each device**
- **Commands within the queue can be synchronous or asynchronous**
- **Commands can execute in-order or out-of-order**

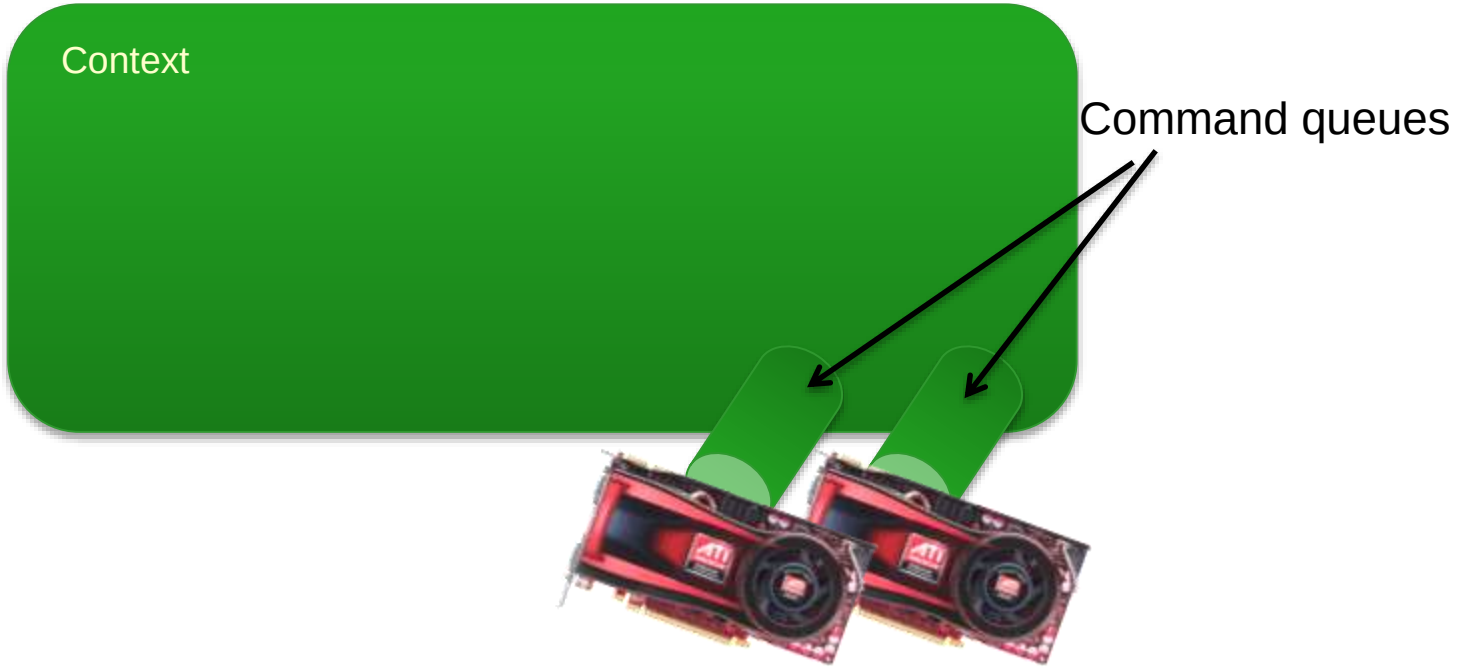
Command Queues

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

- A command queue establishes a relationship between a context and a device
- The command queue properties specify:
  - If out-of-order execution of commands is allowed
  - If profiling is enabled
    - Profiling is done using *events* (discussed in a later lecture) and will create some overhead

Command Queues

- **Command queues associate a context with a device**
  - **Despite the figure below, they are not a physical connection**



Memory Objects

- **Memory objects are OpenCL data that can be moved on and off devices**
  - **Objects are classified as either buffers or images**
- **Buffers**
  - **Contiguous chunks of memory – stored sequentially and can be accessed directly (arrays, pointers, structs)**
  - **Read/write capable**
- **Images**
  - **Opaque objects (2D or 3D)**
  - **Can only be accessed via read_image() and write_image()**
  - **Can either be read or written in a kernel, but not both**

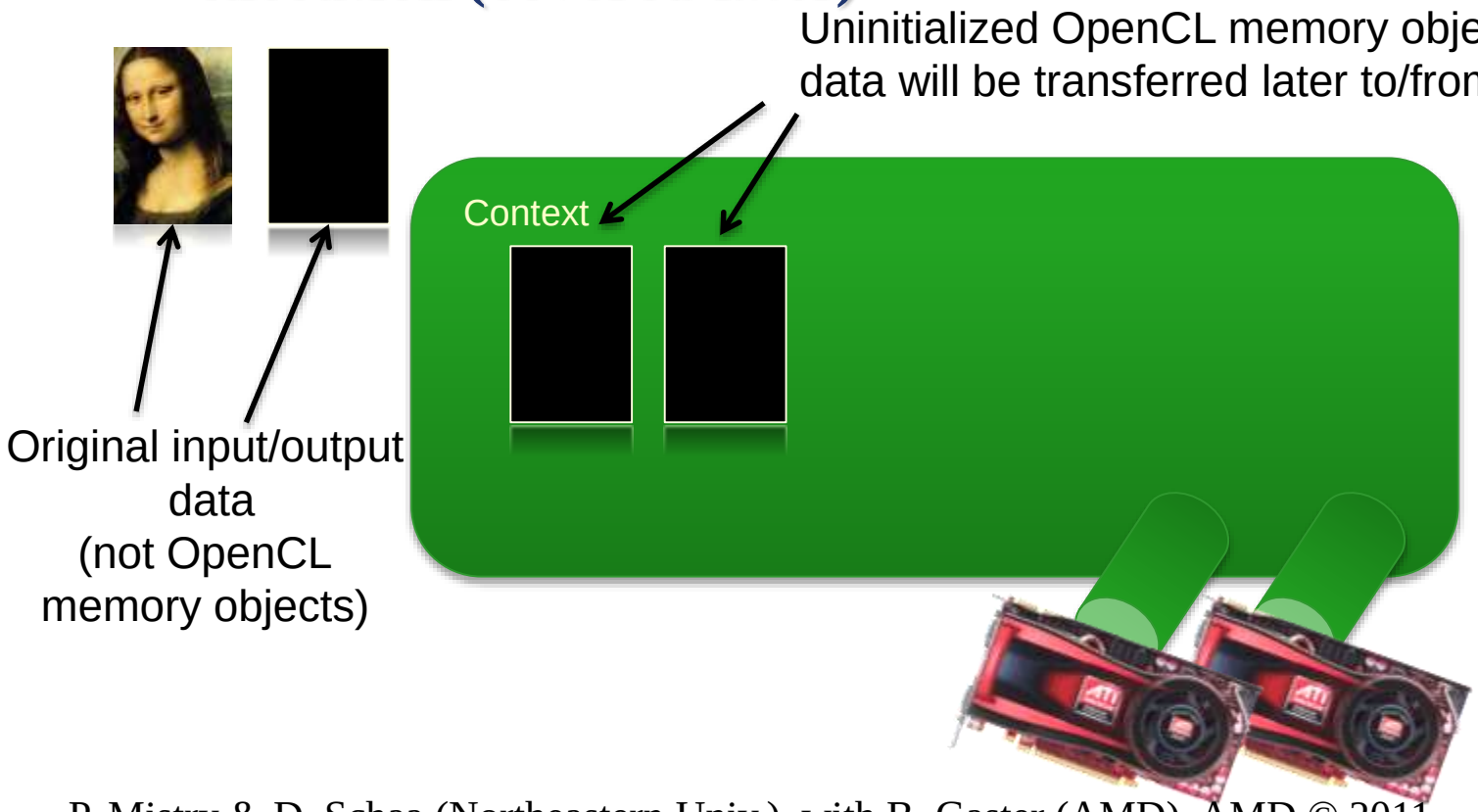
Creating buffers

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

- **This function creates a buffer (cl_mem object) for the given context**
  - **Images are more complex and will be covered in a later lecture**
- **The flags specify:**
  - **the combination of reading and writing allowed on the data**
  - **if the host pointer itself should be used to store the data**
  - **if the data should be copied from the host pointer**

Memory Objects

- **Memory objects are associated with a context**
  - **They must be explicitly transferred to devices prior to execution (covered later)**



Transferring Data

- **OpenCL provides commands to transfer data to and from devices**
  - **clEnqueue{Read|Write}{Buffer|Image}**
  - **Copying from the host to a device is considered *writing***
  - **Copying from a device to the host is *reading***
- **The write command both initializes the memory object with data and places it on a device**
  - **The validity of memory objects that are present on multiple devices is undefined by the OpenCL spec (i.e. are vendor specific)**
- **OpenCL calls also exist to directly map part of a memory object to a host pointer**

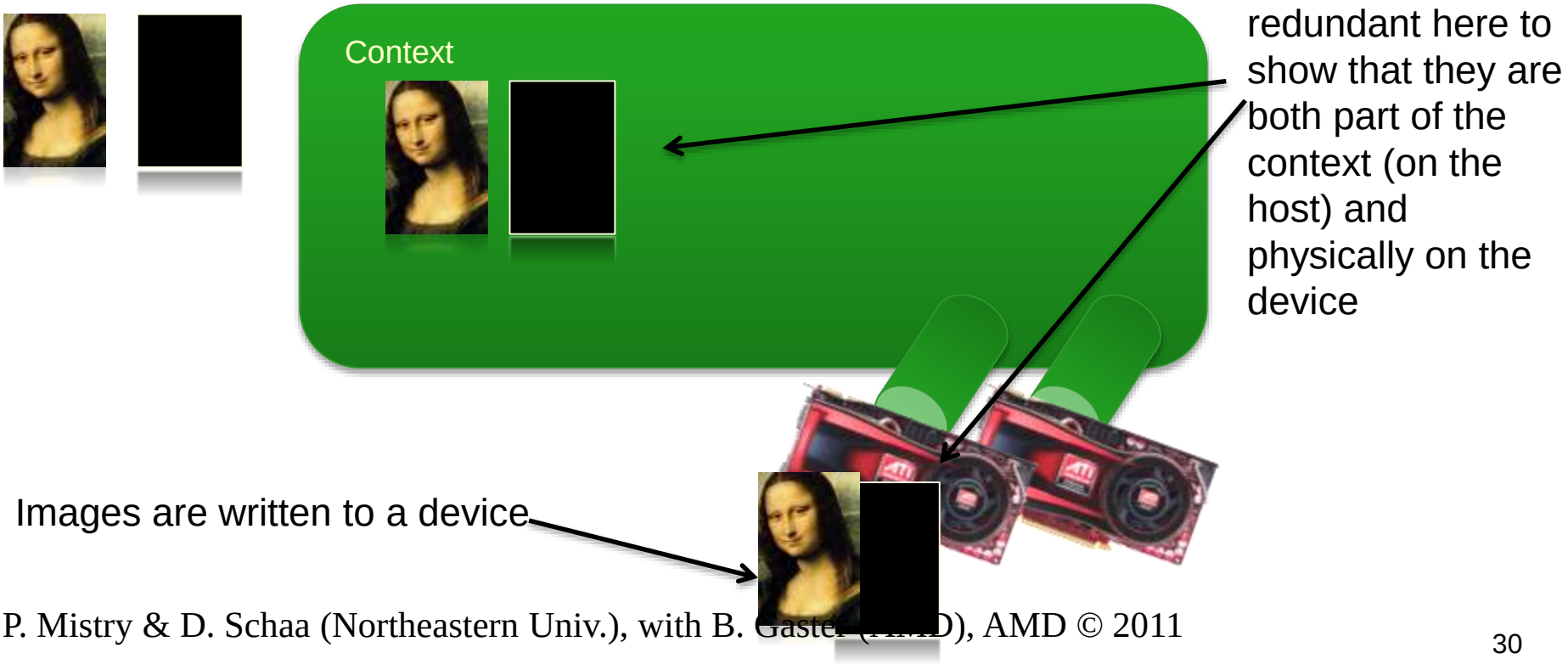
Transferring Data

```
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)
```

- **This command initializes the OpenCL memory object and writes data to the device associated with the command queue**
  - **The command will write data from a host pointer (*ptr*) to the device**
- **The *blocking_write* parameter specifies whether or not the command should return before the data transfer is complete**
- **Events (discussed in another lecture) can specify which commands should be completed before this one runs**

Transferring Data

- **Memory objects are transferred to devices by specifying an action (read or write) and a command queue**
  - **The validity of memory objects that are present on multiple devices is undefined by the OpenCL spec (i.e. is vendor specific)**

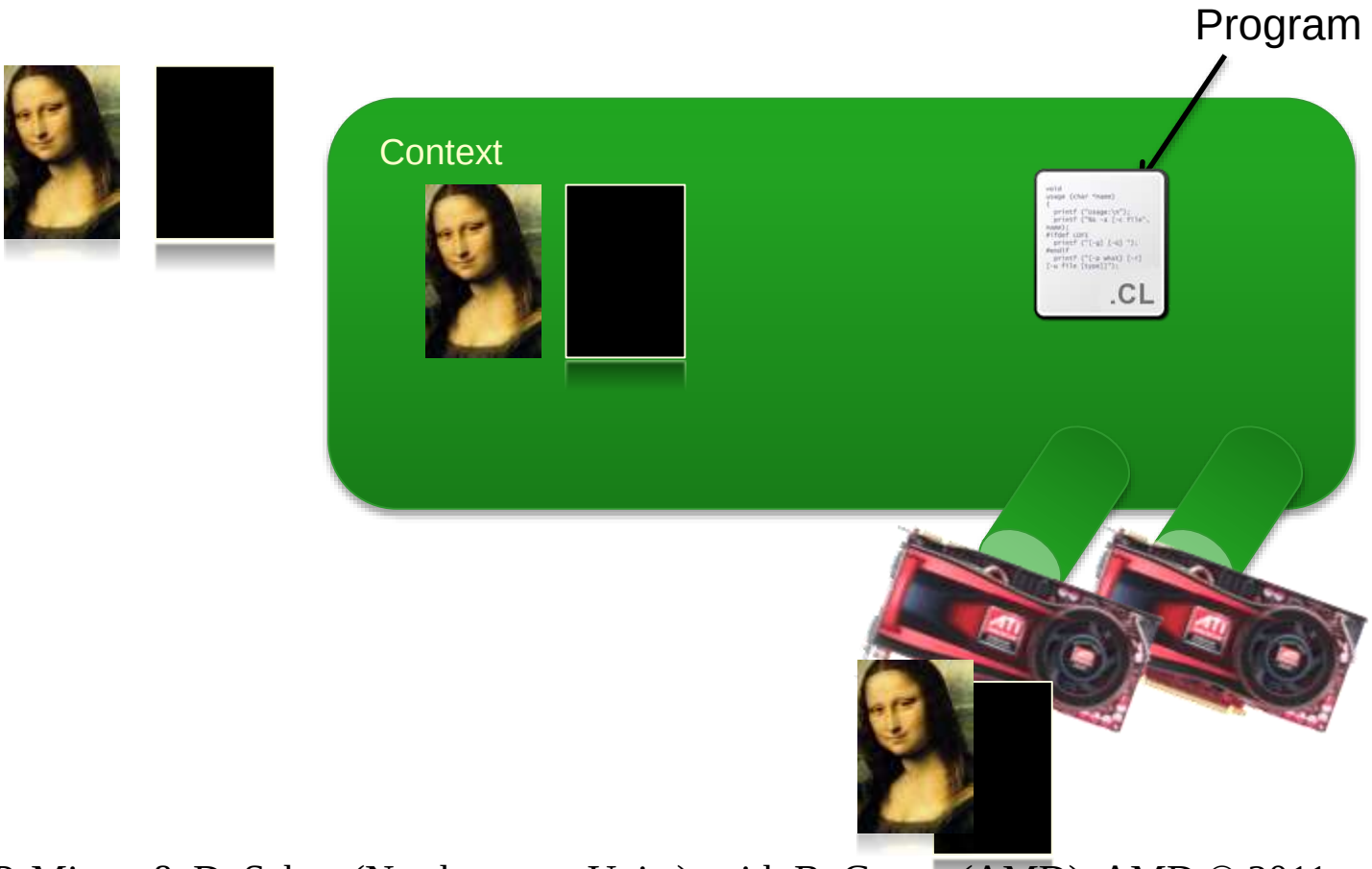


Programs

- **A program object is basically a collection of OpenCL kernels**
  - **Can be source code (text) or precompiled binary**
  - **Can also contain constant data and auxiliary functions**
- **Creating a program object requires either reading in a string (source code) or a precompiled binary**
- **To compile the program**
  - **Specify which devices are targeted**
    - Program is compiled for each device
  - **Pass in compiler flags (optional)**
  - **Check for compilation errors (optional, output to screen)**

Programs

- **A program object is created and compiled by providing source code or a binary file and selecting which devices to target**



Creating Programs

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

- **This function creates a program object from strings of source code**
  - ***count* specifies the number of strings**
  - **The user must create a function to read in the source code to a string**
- **If the strings are not NULL-terminated, the *lengths* fields are used to specify the string lengths**

Compiling Programs

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

- **This function compiles and links an executable from the program object for each device in the context**
  - **If *device_list* is supplied, then only those devices are targeted**
- **Optional preprocessor, optimization, and other options can be supplied by the *options* argument**

Reporting Compile Errors

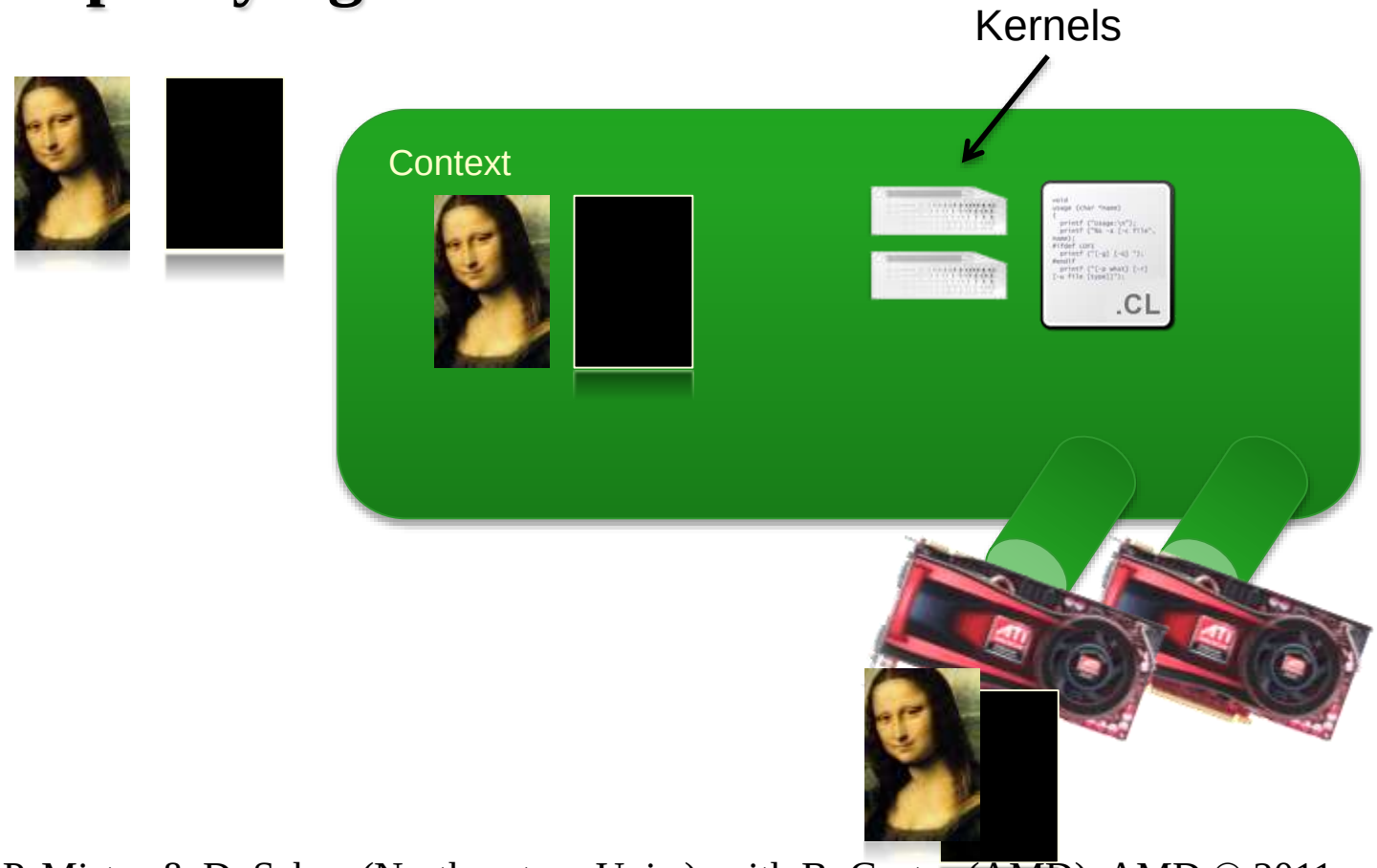
- **If a program fails to compile, OpenCL requires the programmer to explicitly ask for compiler output**
  - **A compilation failure is determined by an error value returned from clBuildProgram()**
  - **Calling clGetProgramBuildInfo() with the program object and the parameter CL_PROGRAM_BUILD_STATUS returns a string with the compiler output**

Kernels

- A kernel is a function declared in a program that is executed on an OpenCL device
  - A kernel object is a kernel function along with its associated arguments
- A kernel object is created from a compiled program
- Must explicitly associate arguments (memory objects, primitives, etc) with the kernel object

Kernels

- **Kernel objects are created from a program object by specifying the name of the kernel function**



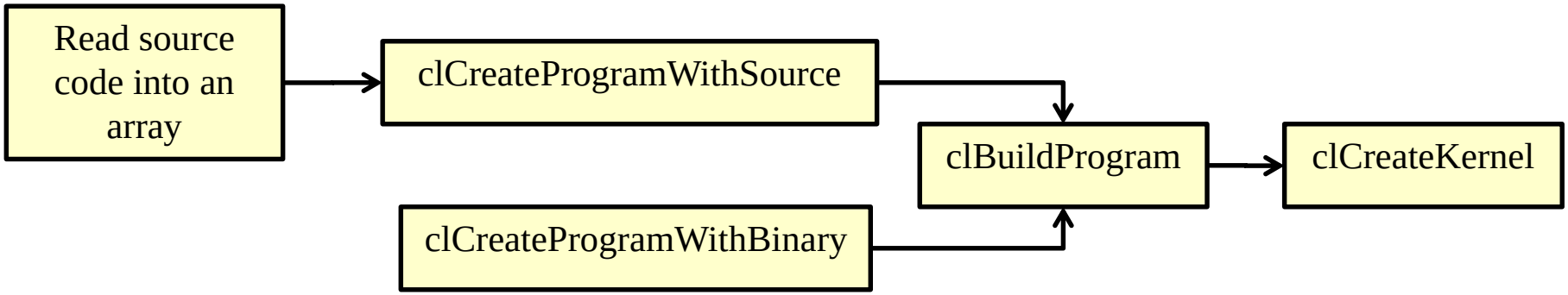
Kernels

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

- **Creates a kernel from the given program**
  - **The kernel that is created is specified by a string that matches the name of the function within the program**

Runtime Compilation

- **There is a high overhead for compiling programs and creating kernels**
  - **Each operation only has to be performed once (at the beginning of the program)**
    - **The kernel objects can be reused any number of times by setting different arguments**



Setting Kernel Arguments

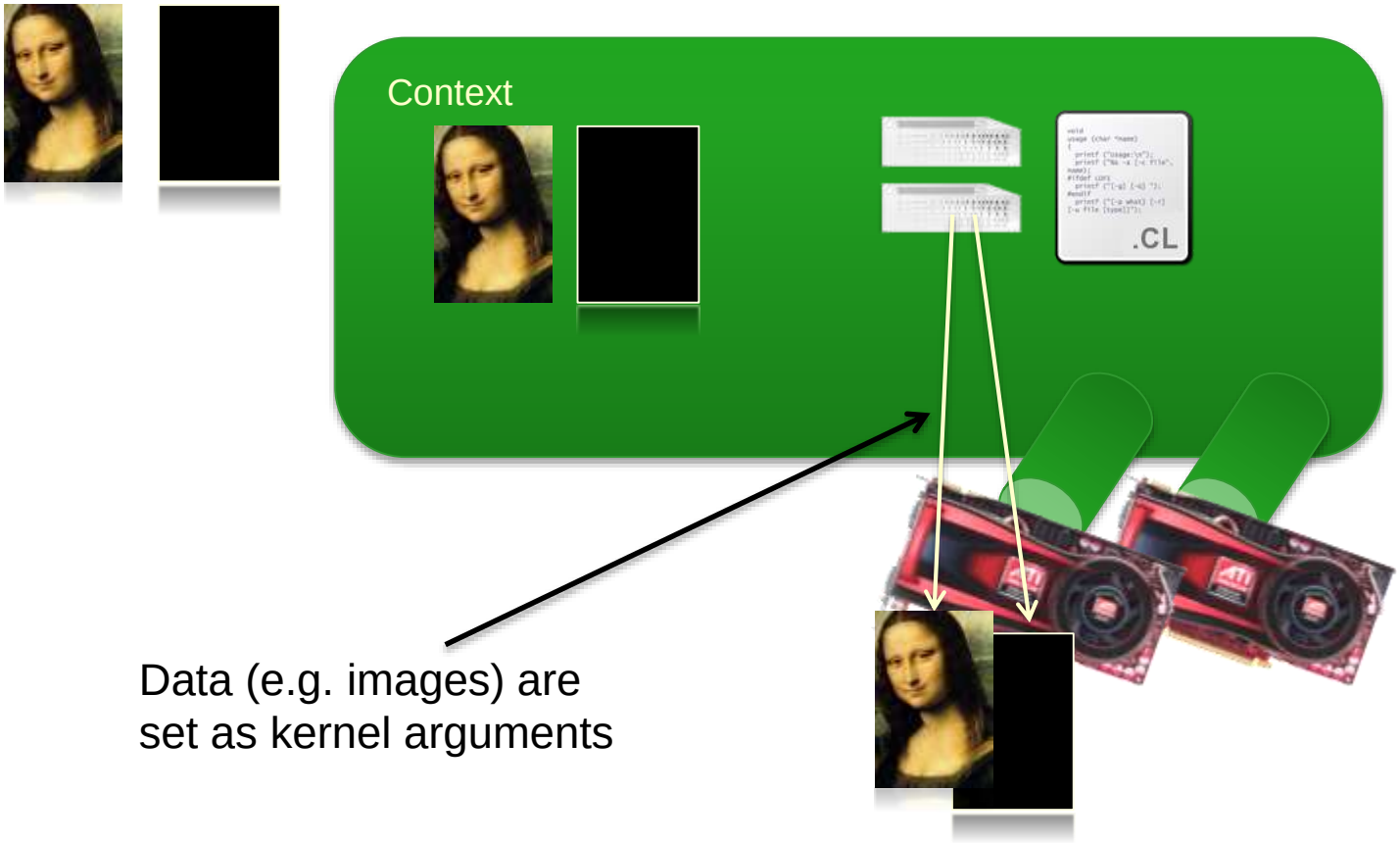
- **Kernel arguments are set by repeated calls to clSetKernelArgs**

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

  - Each call must specify:
    - The index of the argument as it appears in the function signature, the size, and a pointer to the data
  - Examples:
    - `clSetKernelArg(kernel, 0, sizeof(cl_mem), (void*)&d_iImage);`
    - `clSetKernelArg(kernel, 1, sizeof(int), (void*)&a);`

Kernel Arguments

- **Memory objects and individual data values can be set as kernel arguments**

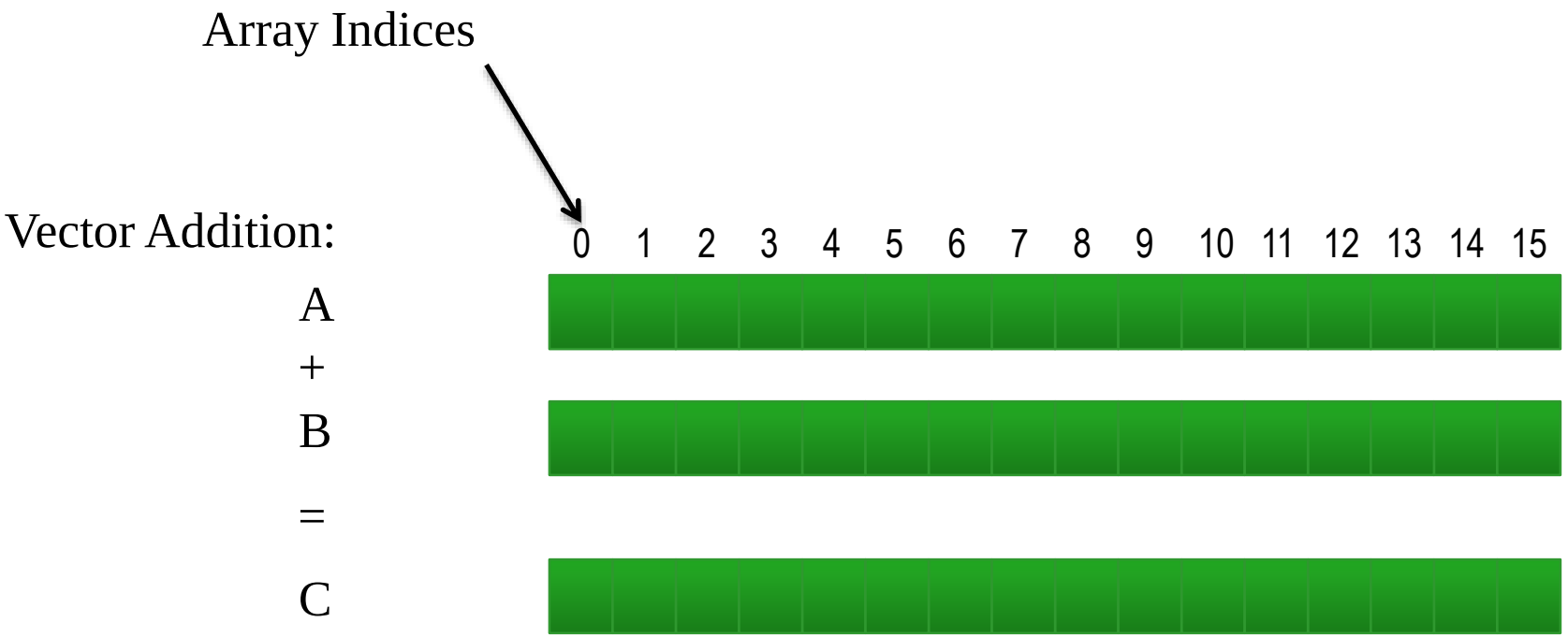


Thread Structure

- **Massively parallel programs are usually written so that each thread computes one part of a problem**
  - **For vector addition, we will add corresponding elements from two arrays, so each thread will perform one addition**
  - **If we think about the thread structure visually, the threads will usually be arranged in the same shape as the data**

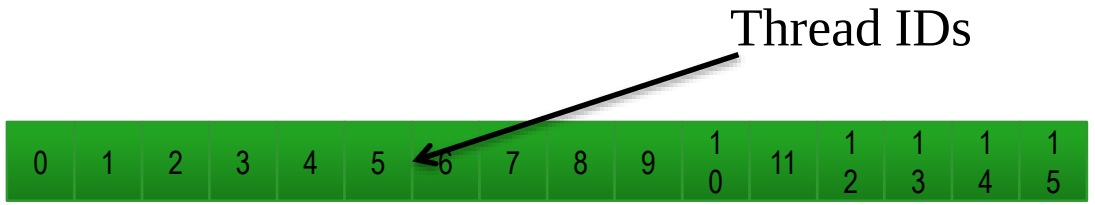
Thread Structure

- **Consider a simple vector addition of 16 elements**
  - **2 input buffers (A, B) and 1 output buffer (C) are required**

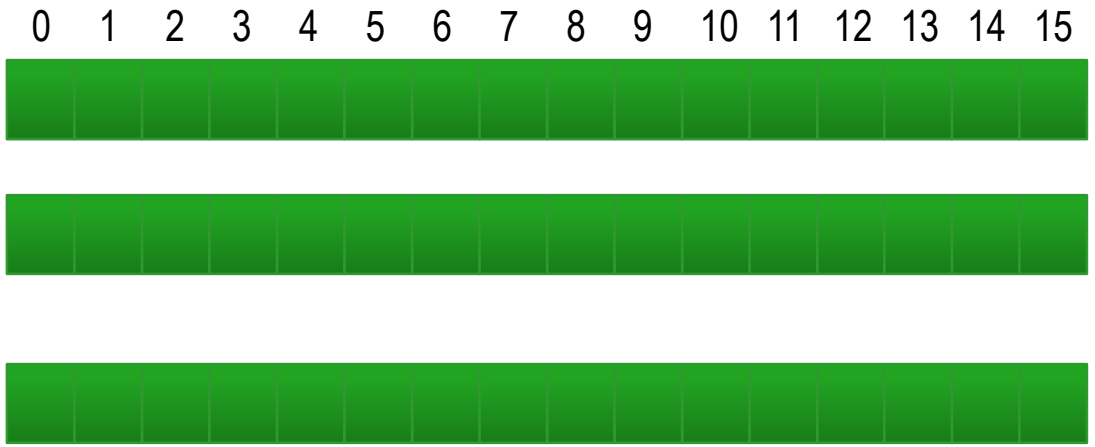


Thread Structure

- **Create thread structure to match the problem**
  - **1-dimensional problem in this case**



Vector Addition:



Thread Structure

- **Each thread is responsible for adding the indices corresponding to its ID**

Vector Addition:

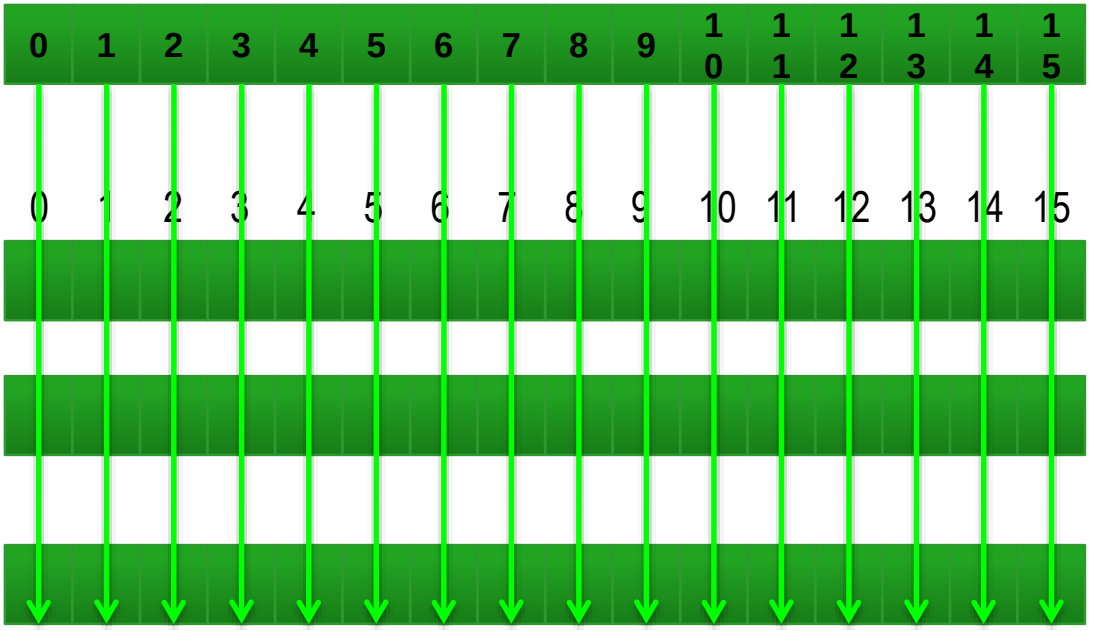
A

+

B

=

C

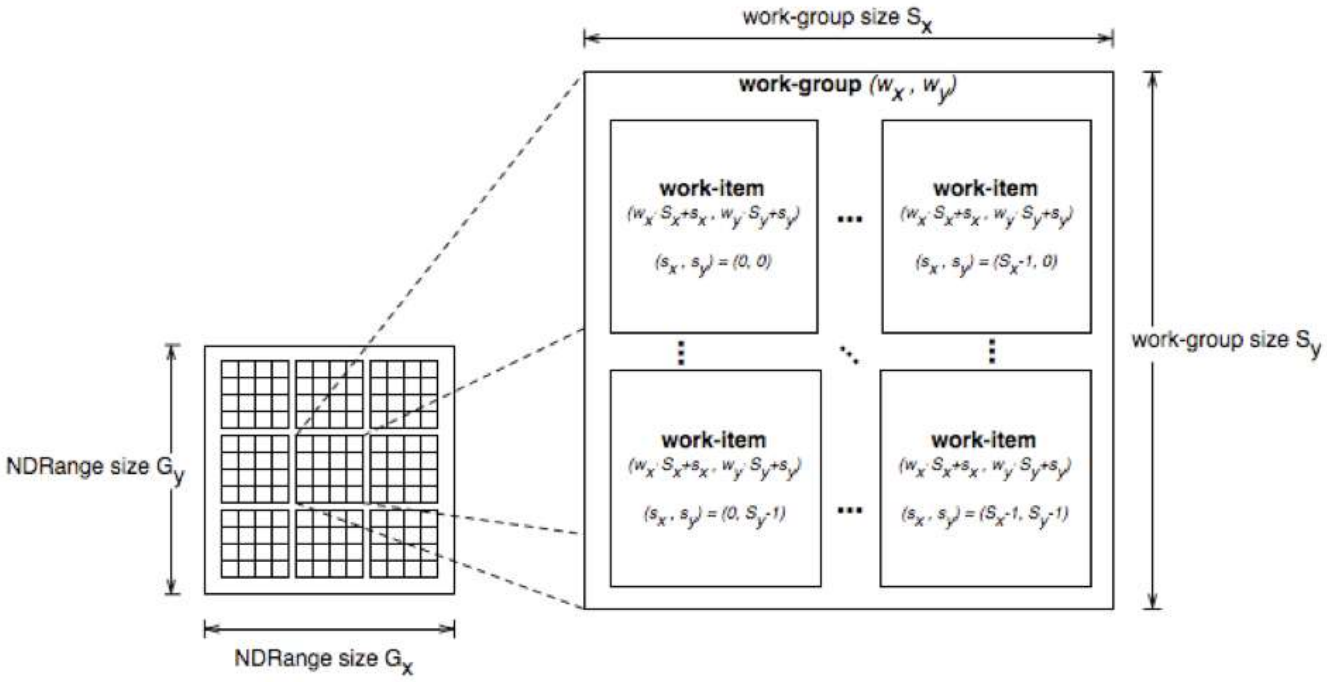


Thread Structure

- OpenCL's thread structure is designed to be scalable
- Each instance of a kernel is called a work-item (though "thread" is commonly used as well)
- Work-items are organized as work-groups
  - Work-groups are independent from one-another (this is where scalability comes from)
- An index space defines a hierarchy of work-groups and work-items

Thread Structure

- **Work-items can uniquely identify themselves based on:**
  - **A global id (unique within the index space)**
  - **A work-group ID and a local ID within the work-group**



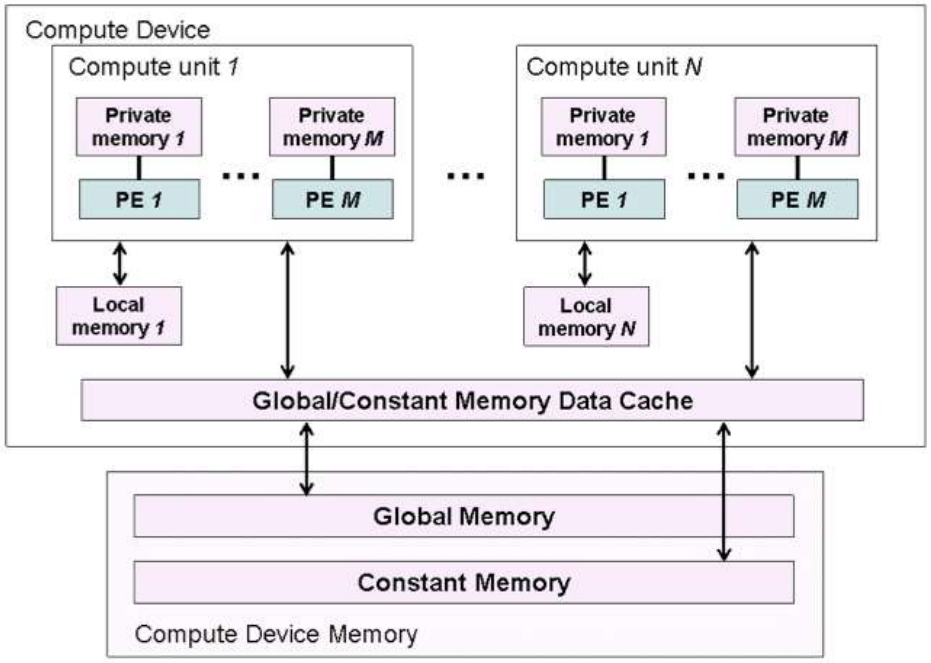
Thread Structure

- API calls allow threads to identify themselves and their data
- Threads can determine their global ID in each dimension
  - get_global_id(dim)
  - get_global_size(dim)
- Or they can determine their work-group ID and ID within the workgroup
  - get_group_id(dim)
  - get_num_groups(dim)
  - get_local_id(dim)
  - get_local_size(dim)
- get_global_id(0) = column, get_global_id(1) = row
- get_num_groups(0) * get_local_size(0) == get_global_size(0)

Memory Model

- **The OpenCL memory model defines the various types of memories (closely related to GPU memory hierarchy)**

Memory	Description
Global	Accessible by all work-items
Constant	Read-only, global
Local	Local to a work-group
Private	Private to a work-item



Memory Model

- **Memory management is explicit**
  - **Must move data from host memory to device global memory, from global memory to local memory, and back**
- **Work-groups are assigned to execute on compute-units**
  - **No guaranteed communication/coherency between different work-groups (no software mechanism in the OpenCL specification)**

Writing a Kernel

- One instance of the kernel is created for each thread

- **Kernels:**
  - Must begin with keyword __kernel
  - Must have return type void
  - Must declare the address space of each argument that is a memory object (next slide)
  - Use API calls (such as get_global_id()) to determine which data a thread will work on

Address Space Identifiers

- __global – memory allocated from global address space
- __constant – a special type of read-only memory
- __local – memory shared by a work-group
- __private – private per work-item memory
- __read_only/__write_only – used for images
- Kernel arguments that are memory objects must be global, local, or constant

Example Kernel

- **Simple vector addition kernel:**

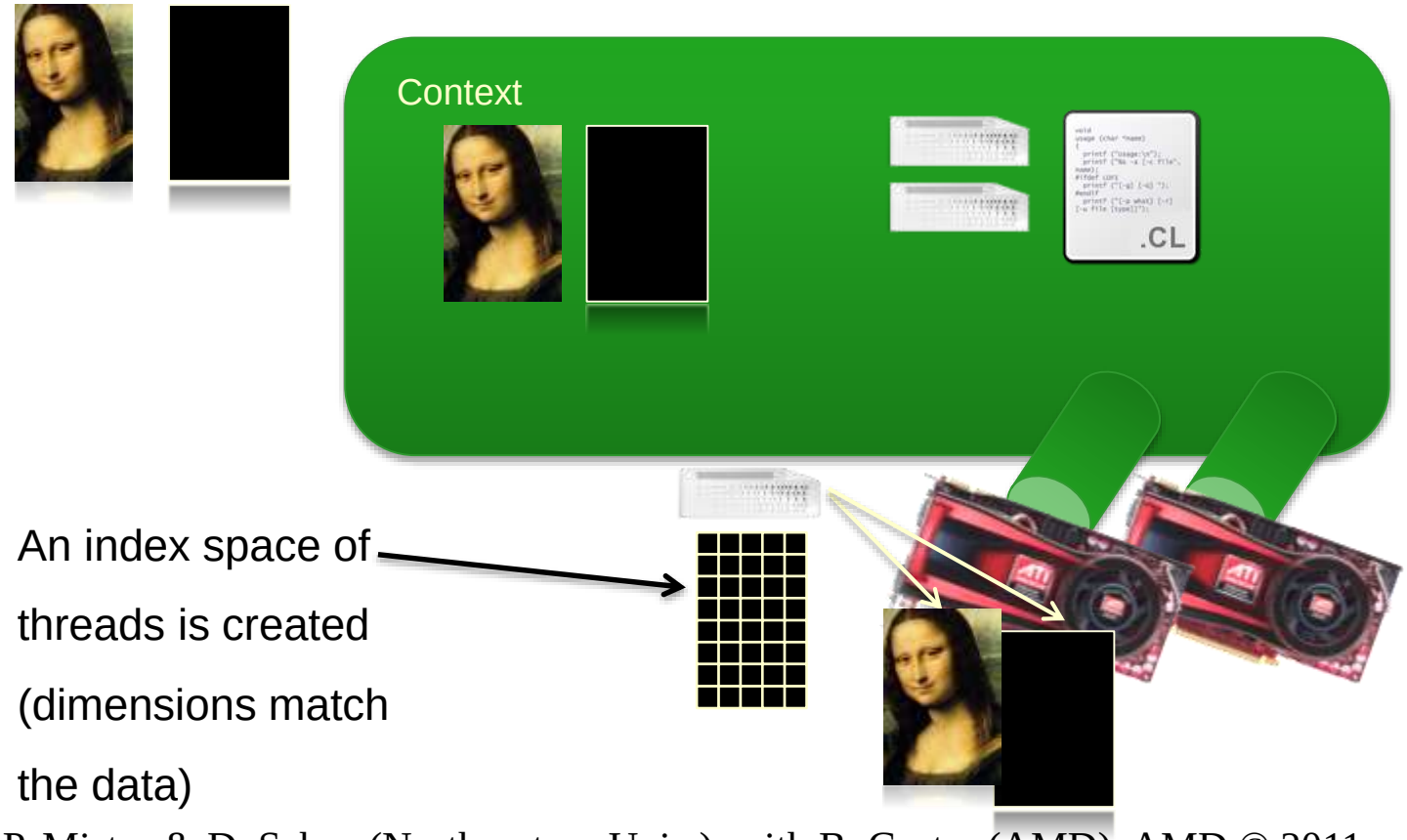
```
__kernel
void vecadd(__global int* A,
            __global int* B,
            __global int* C) {
   int tid = get_global_id(0);
   C[tid] = A[tid] + B[tid];
}
```

Executing the Kernel

- **Need to set the dimensions of the index space, and (optionally) of the work-group sizes**
- **Kernels execute asynchronously from the host**
  - **clEnqueueNDRangeKernel just adds is to the queue, but doesn't guarantee that it will start executing**

Executing the Kernel

- **A thread structure defined by the index-space that is created**
  - **Each thread executes the same kernel on different data**



Executing the Kernel

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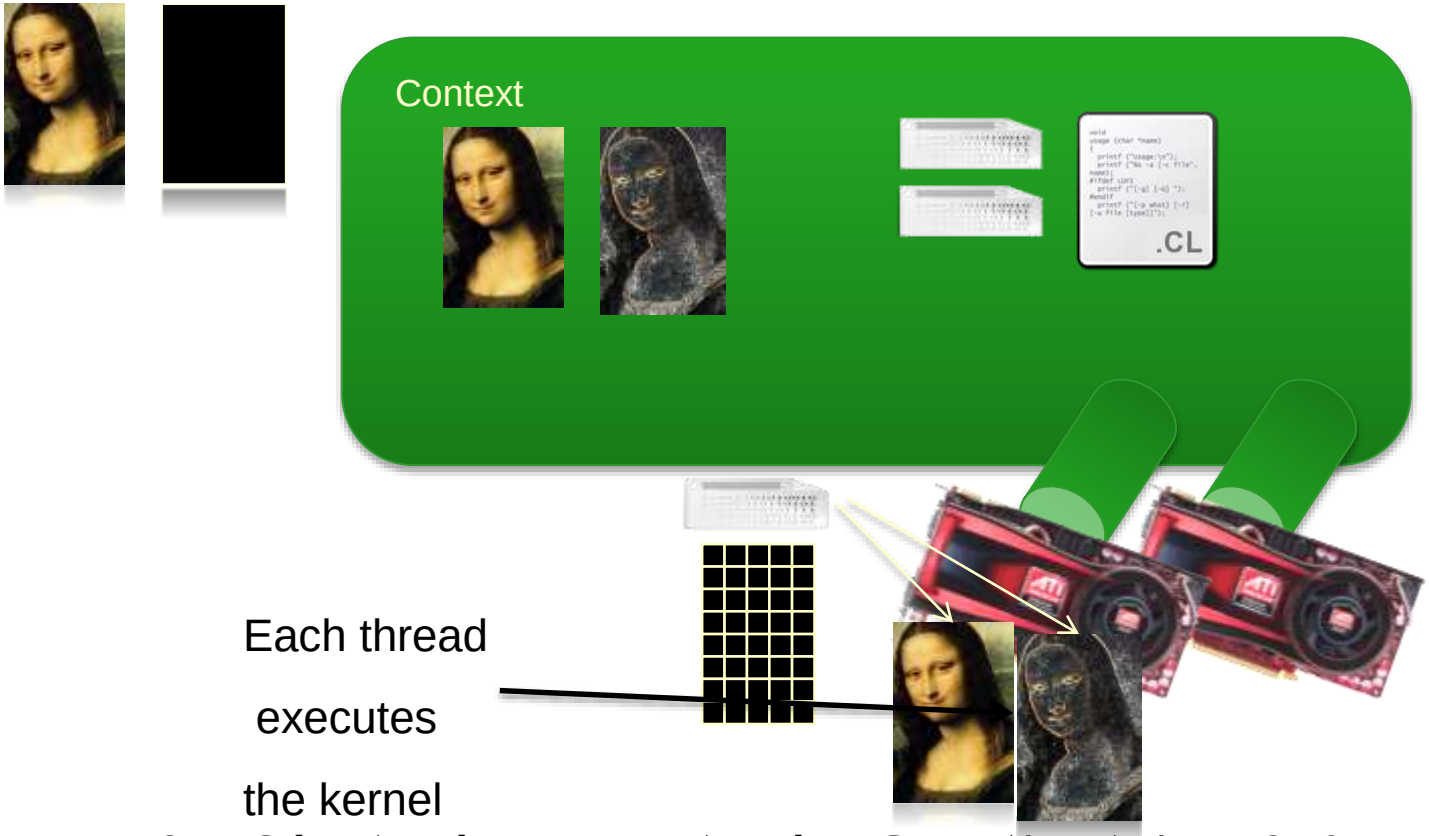


Executing the Kernel

```
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)
```

- **Tells the device associated with a command queue to begin executing the specified kernel**
- **The global (index space) must be specified and the local (work-group) sizes are optionally specified**
- **A list of events can be used to specify prerequisite operations that must be complete before executing**

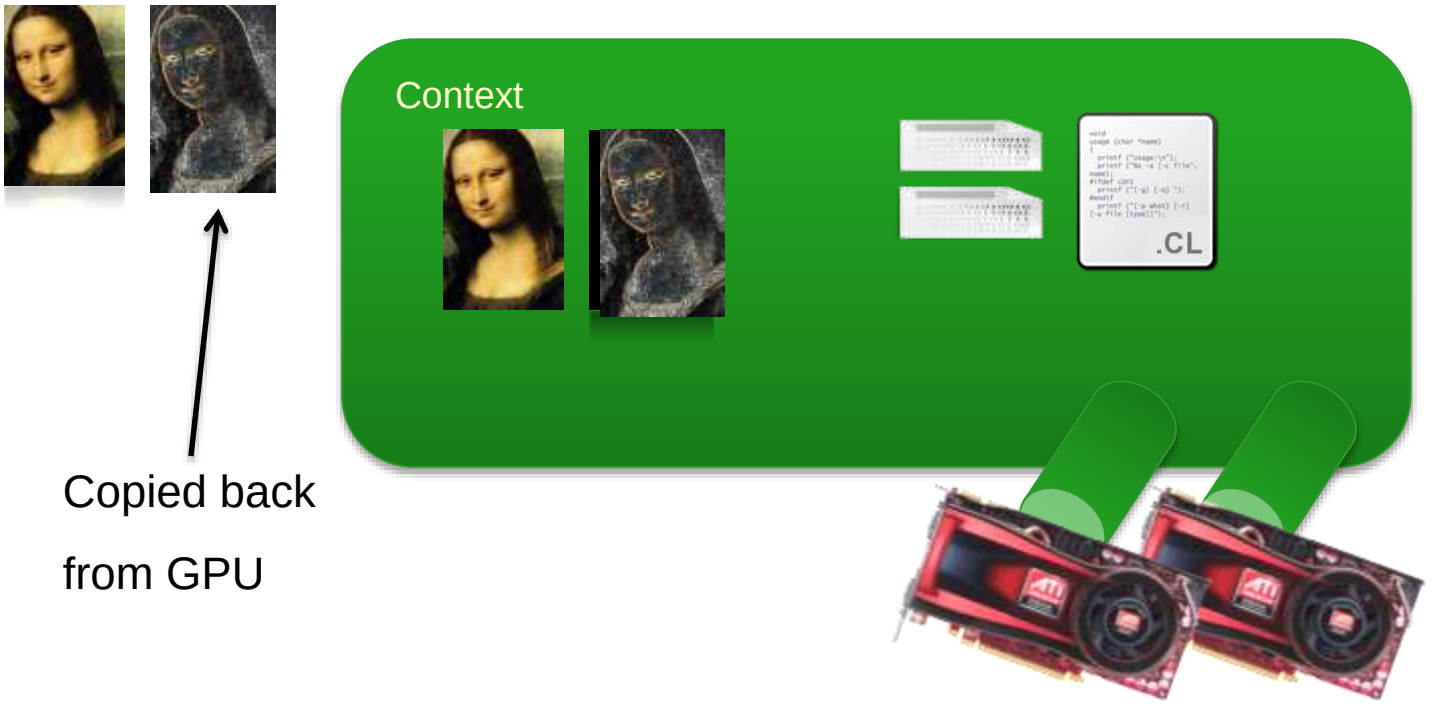
Copying Data Back

- **The last step is to copy the data back from the device to the host**
- **Similar call as writing a buffer to a device, but data will be transferred back to the host**

```
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)
```

Copying Data Back

- **The output data is read from the device back to the host**



Releasing Resources

- Most OpenCL resources/objects are pointers that should be freed after they are done being used
- There is a clRelase{Resource} command for most OpenCL types
  - Ex: clReleaseProgram(), clReleaseMemObject()

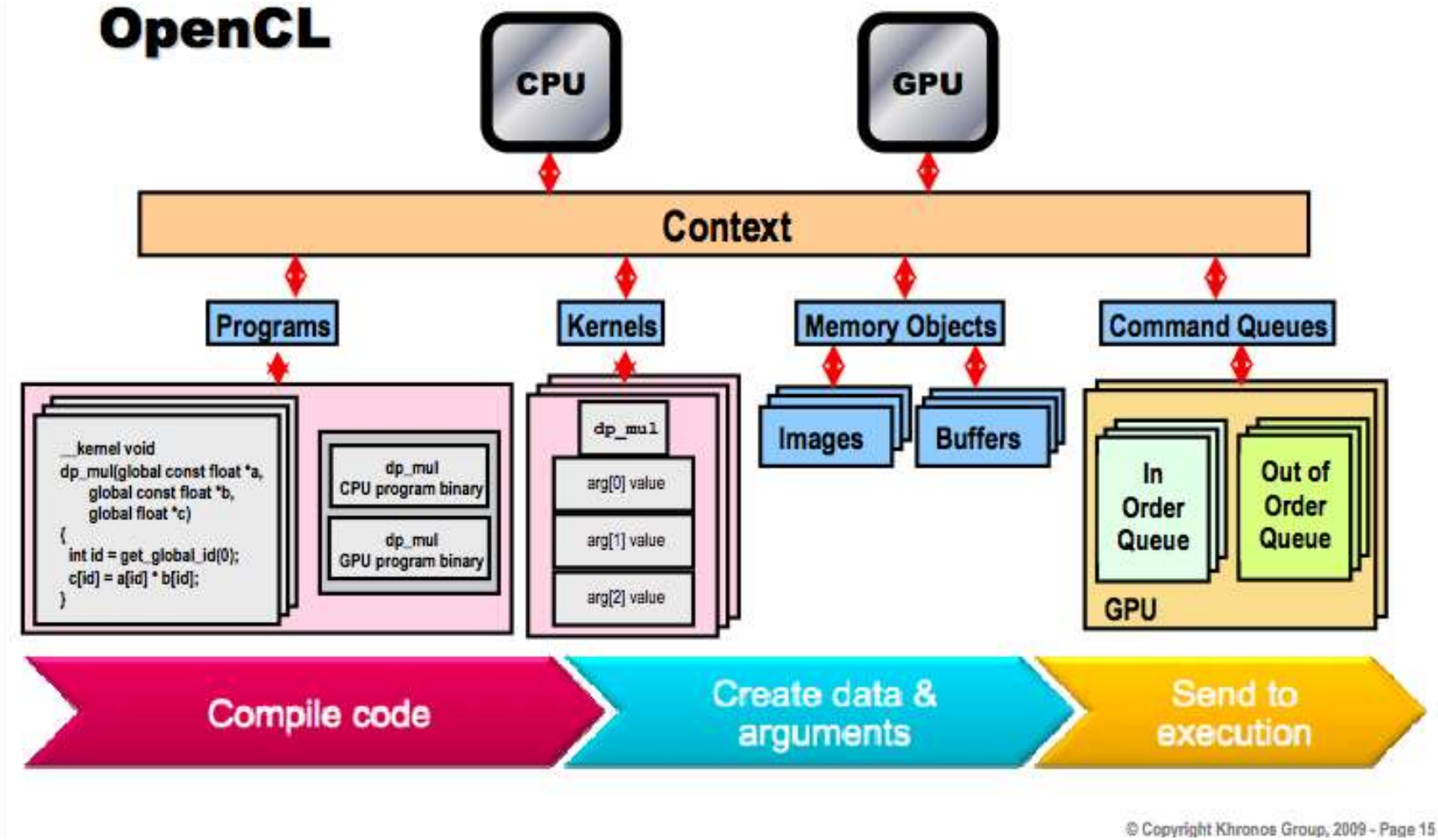
Error Checking

- **OpenCL commands return error codes as negative integer values**
  - **Return value of 0 indicates CL_SUCCESS**
  - **Negative values indicates an error**
    - **cl.h defines meaning of each return value**

CL_DEVICE_NOT_FOUND	-1
CL_DEVICE_NOT_AVAILABLE	-2
CL_COMPILER_NOT_AVAILABLE	-3
CL_MEM_OBJECT_ALLOCATION_FAILURE	-4
CL_OUT_OF_RESOURCES	-5

- **Note: Errors are sometimes reported asynchronously**

Big Picture


OpenCL
CPU
GPU
Context
Programs
Kernels
Memory Objects
Command Queues
__kernel void
dp_mul(global const float *a,
global const float *b,
global float *c)
{
int id = get_global_id(0);
c[id] = a[id] * b[id];
}
dp_mul
CPU program binary
dp_mul
GPU program binary
dp_mul
arg[0] value
arg[1] value
arg[2] value
Images
Buffers
In Order Queue
Out of Order Queue
GPU
Compile code
Create data & arguments
Send to execution
© Copyright Khronos Group, 2009 - Page 15

Programming Model

- **Data parallel**
  - **One-to-one mapping between work-items and elements in a memory object**
  - **Work-groups can be defined explicitly (like CUDA) or implicitly (specify the number of work-items and OpenCL creates the work-groups)**
- **Task parallel**
  - **Kernel is executed independent of an index space**
  - **Other ways to express parallelism: enqueueing multiple tasks, using device-specific vector types, etc.**
- **Synchronization**
  - **Possible between items in a work-group**
  - **Possible between commands in a context command queue**

Running the Example Code

- For example, a simple vector addition OpenCL program
- Before running, the following should appear in your .bashrc file:
  - export LD_LIBRARY_PATH=/opt/AMDAPP/lib/x86_64
- To compile:
  - Make sure that vecadd.c and vecadd.cl are in the current working directory
  - gcc -o vecadd vecadd.c –I/opt/AMDAPP/include –L/opt/AMDAPP/lib/x86_64 -lOpenCL

Summary

- OpenCL provides an interface for the interaction of hosts with accelerator devices
- A context is created that contains all of the information and data required to execute an OpenCL program
  - Memory objects are created that can be moved on and off devices
  - Command queues allow the host to request operations to be performed by the device
  - Programs and kernels contain the code that devices need to execute