

Introduction to OpenCL

Cliff Woolley, NVIDIA

Developer Technology Group



Welcome to the OpenCL Tutorial!

- OpenCL Platform Model
- OpenCL Execution Model
- Mapping the Execution Model onto the Platform Model
- Introduction to OpenCL Programming
- Additional Information and Resources

Design Goals of OpenCL

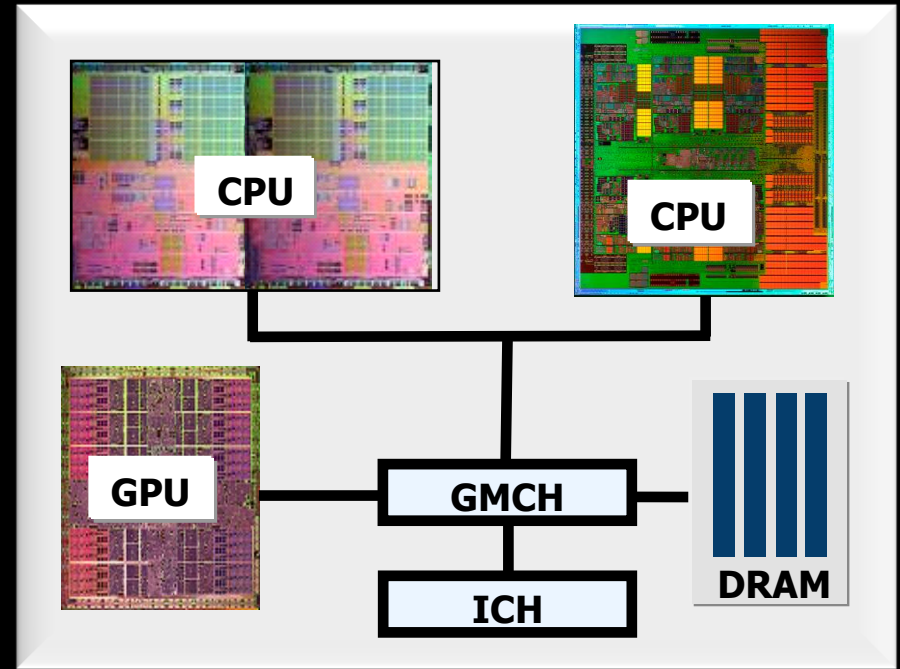
- Use all computational resources in the system
 - CPUs, GPUs and other processors as peers
- Efficient parallel programming model
 - Based on C99
 - Data- and task- parallel computational model
 - Abstract the specifics of underlying hardware
 - Specify accuracy of floating-point computations
- Desktop and Handheld Profiles



OPENCL PLATFORM MODEL

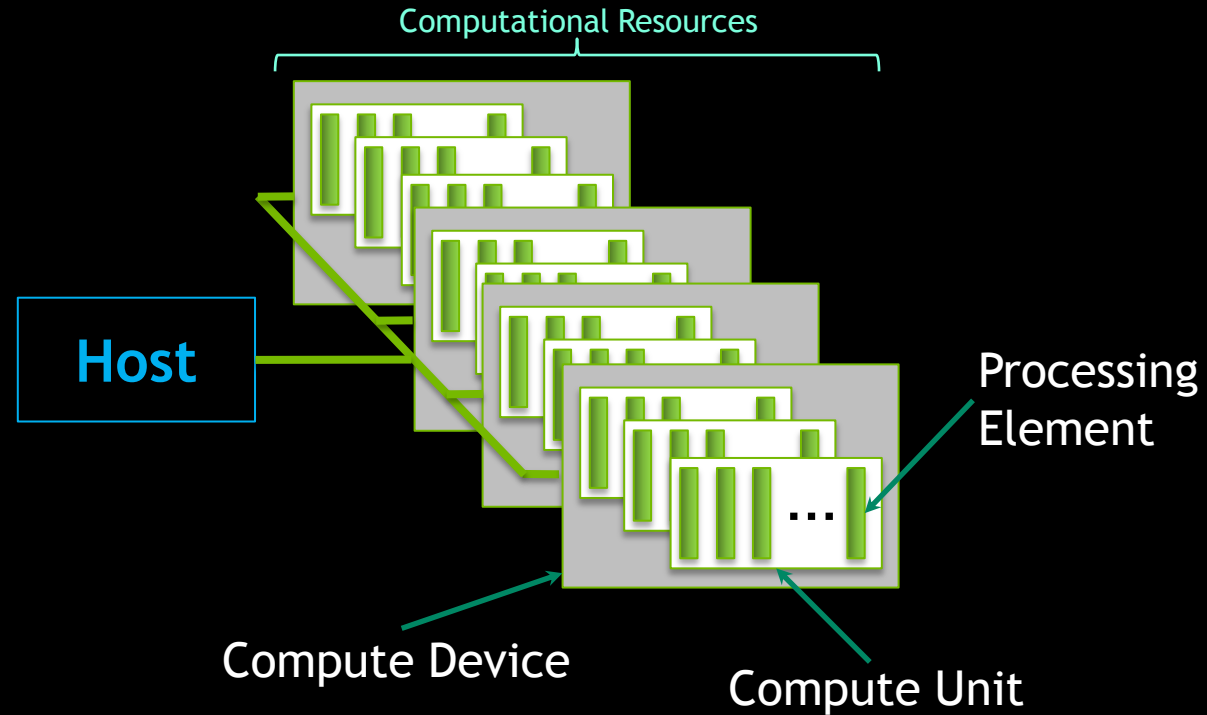
It's a Heterogeneous World

- A modern platform includes:
 - One or more CPUs
 - One or more GPUs
 - Optional accelerators (e.g., DSPs)

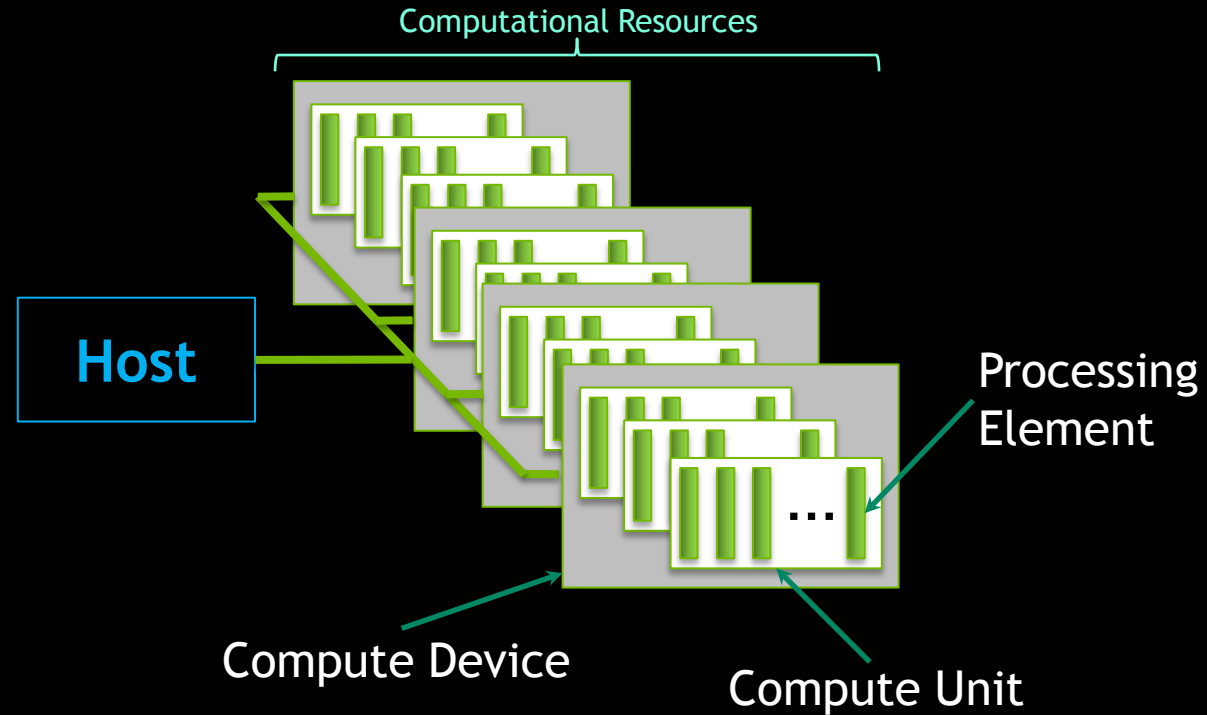


GMCH = graphics memory control hub
ICH = Input/output control hub

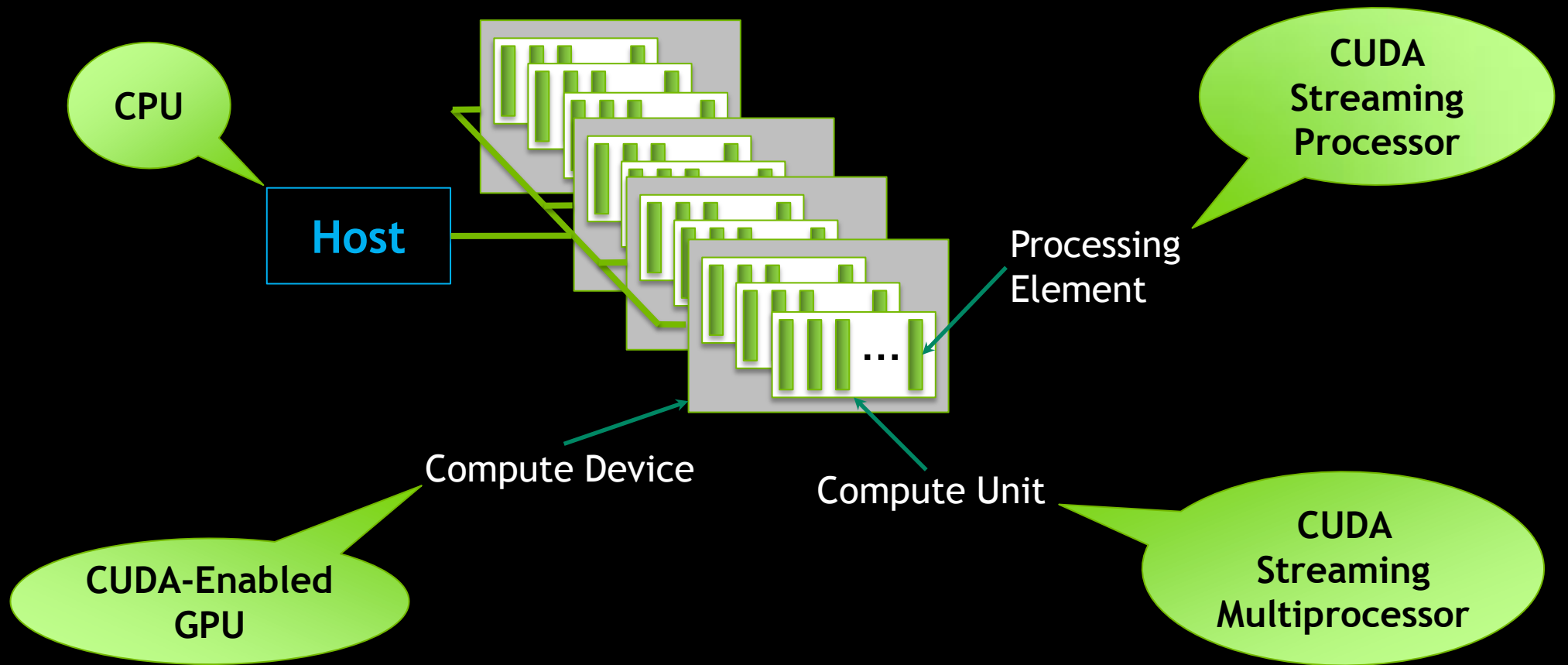
OpenCL Platform Model



OpenCL Platform Model

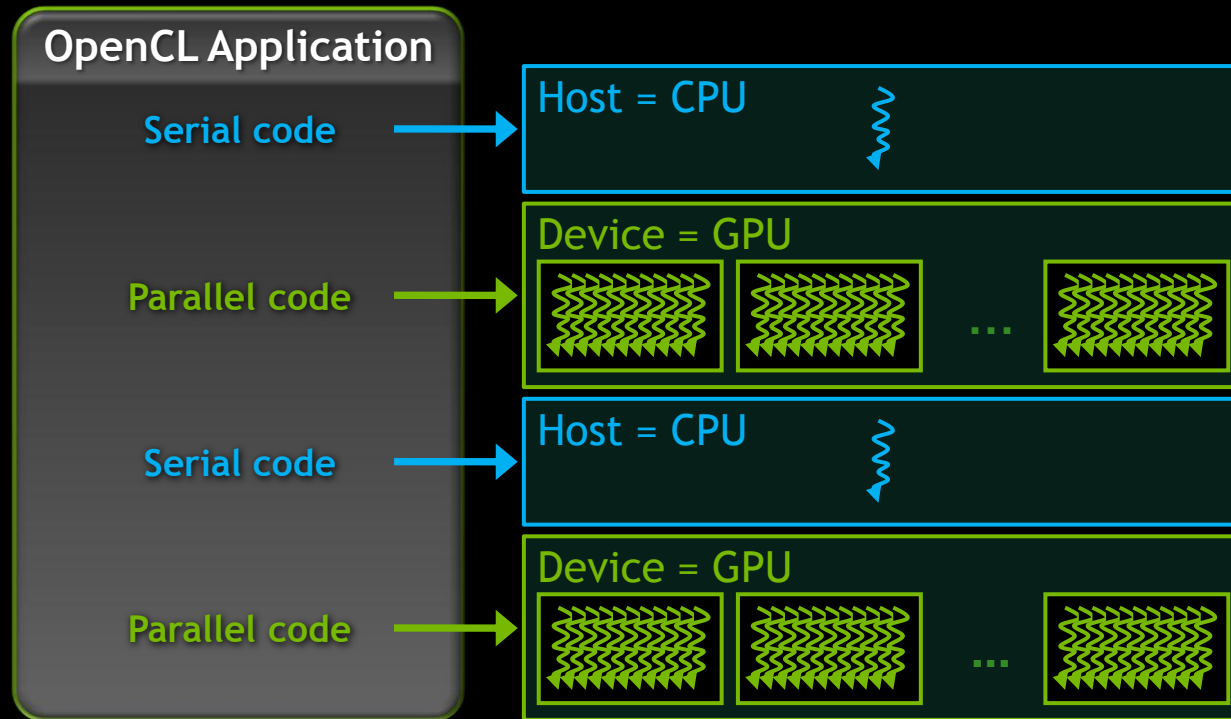


OpenCL Platform Model on CUDA Compute Architecture



Anatomy of an OpenCL Application

- **Serial** code executes in a **Host** (CPU) thread
- **Parallel** code executes in many **Device** (GPU) threads across multiple processing elements





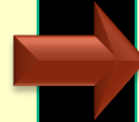
OPENCL EXECUTION MODEL

Decompose task into *work-items*

- Define N-dimensional computation domain
- Execute a *kernel* at each point in computation domain

Traditional loop as a function in C

```
void
trad_mul(int n,
         const float *a,
         const float *b,
         float *c)
{
    int i;
    for (i=0; i<n; i++)
        c[i] = a[i] * b[i];
}
```



OpenCL C kernel

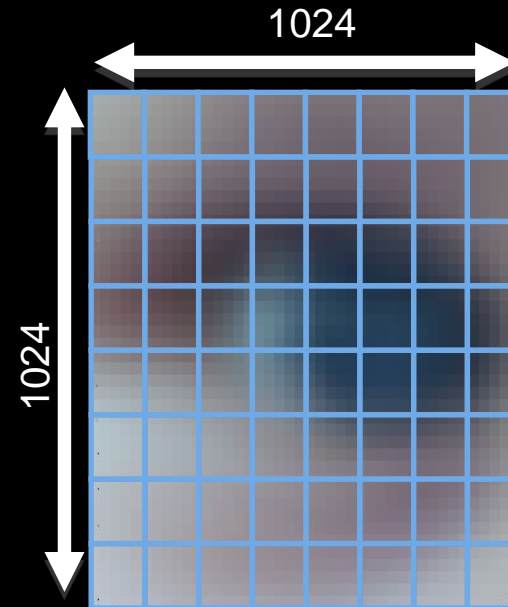
```
__kernel void
dp_mul(__global const float *a,
       __global const float *b,
       __global float *c)
{
    int id = get_global_id(0);

    c[id] = a[id] * b[id];
} // execute over n "work items"
```

An N-dimension domain of work-items

Define the “best” N-dimensioned index space for your algorithm

- Kernels are executed across a global domain of *work-items*
- Work-items are grouped into local *work-groups*
 - Global Dimensions: 1024 x 1024
(whole problem space)
 - Local Dimensions: 32 x 32
(work-group ... executes together)



OpenCL Execution Model

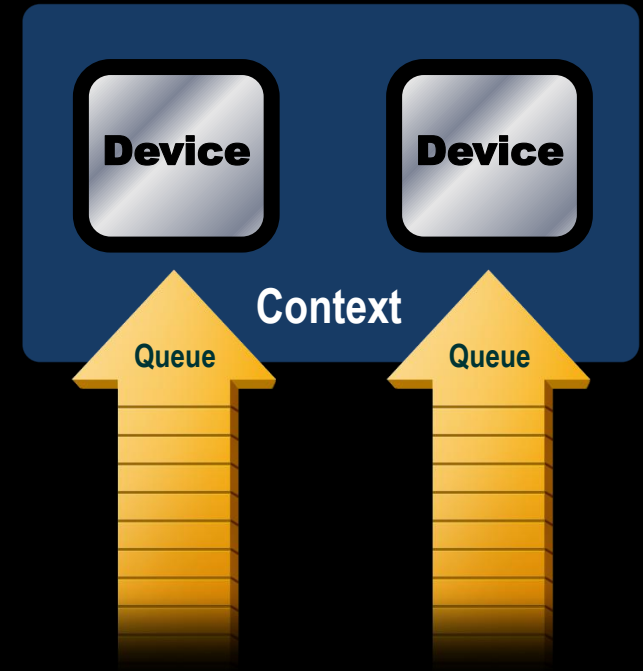
The application runs on a **Host** which submits work to the **Devices**

- **Work-item:** the basic unit of work on an OpenCL device
- **Kernel:** the code for a work-item (basically a C function)
- **Program:** Collection of kernels and other functions (analogous to a dynamic library)

OpenCL Execution Model

The application runs on a **Host** which submits work to the **Devices**

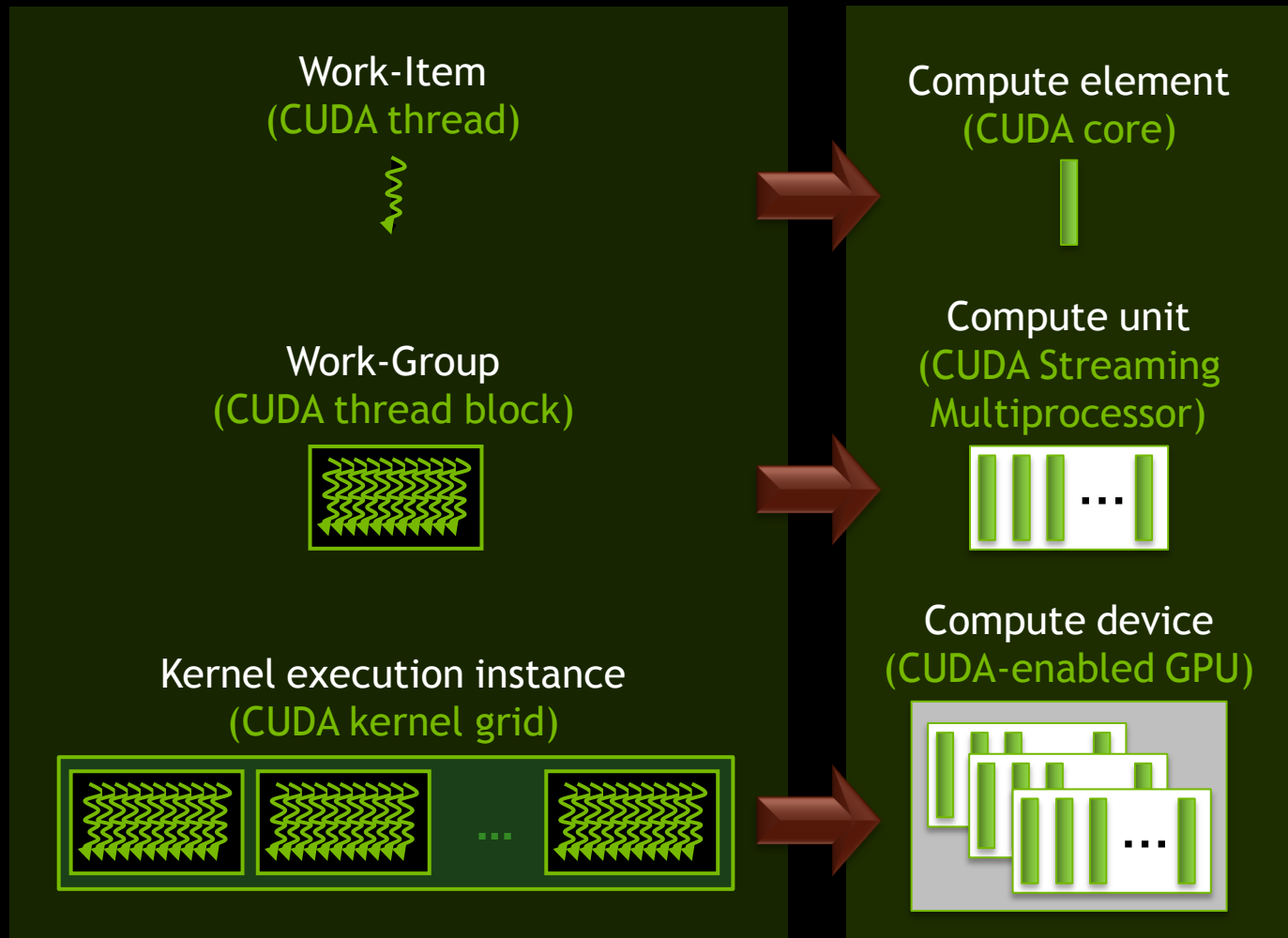
- **Context:** The environment within which work-items execute; includes devices and their memories and command queues
- **Command Queue:** A queue used by the Host application to submit work to a Device (e.g., kernel execution instances)
 - Work is queued in-order, one queue per device
 - Work can be executed in-order *or* out-of-order





MAPPING THE EXECUTION MODEL ONTO THE PLATFORM MODEL

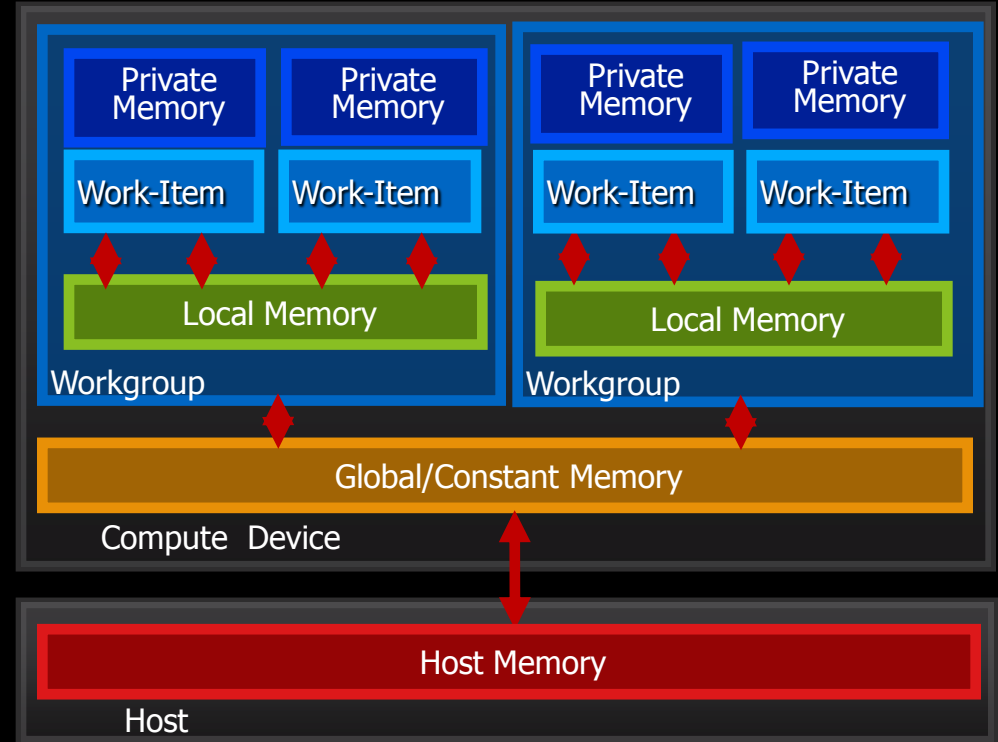
Kernel Execution on Platform Model



- Each work-item is executed by a compute element
- Each work-group is executed on a compute unit
- Several concurrent work-groups can reside on one compute unit depending on work-group's memory requirements and compute unit's memory resources
- Each kernel is executed on a compute device

OpenCL Memory Model

- **Private Memory**
 - Per work-item
- **Local Memory**
 - Shared within a workgroup
- **Global/Constant Memory**
 - Visible to all workgroups
- **Host Memory**
 - On the CPU



Memory management is Explicit

You must move data from host -> global -> local ... and back

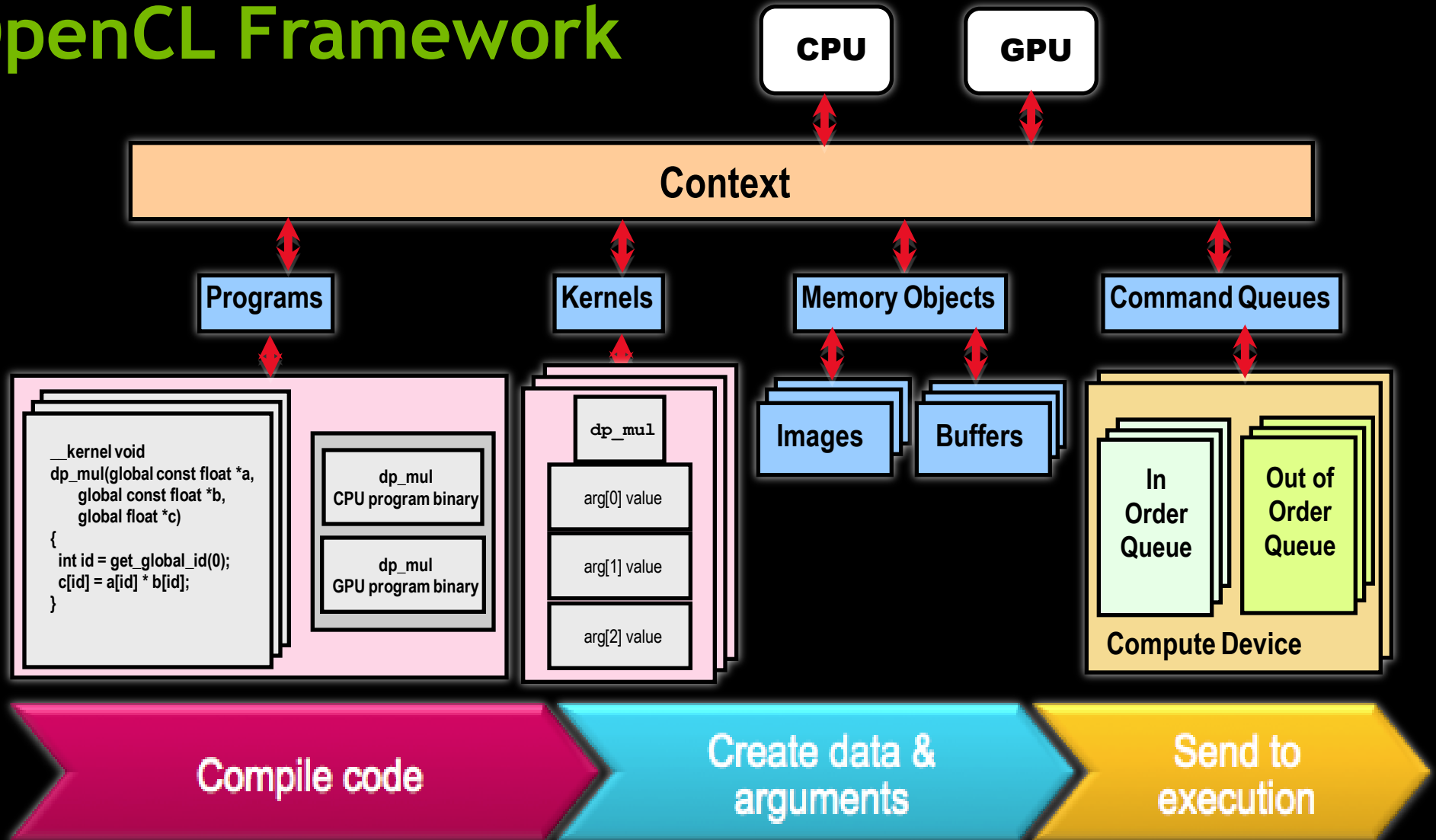


INTRODUCTION TO OPENCL PROGRAMMING

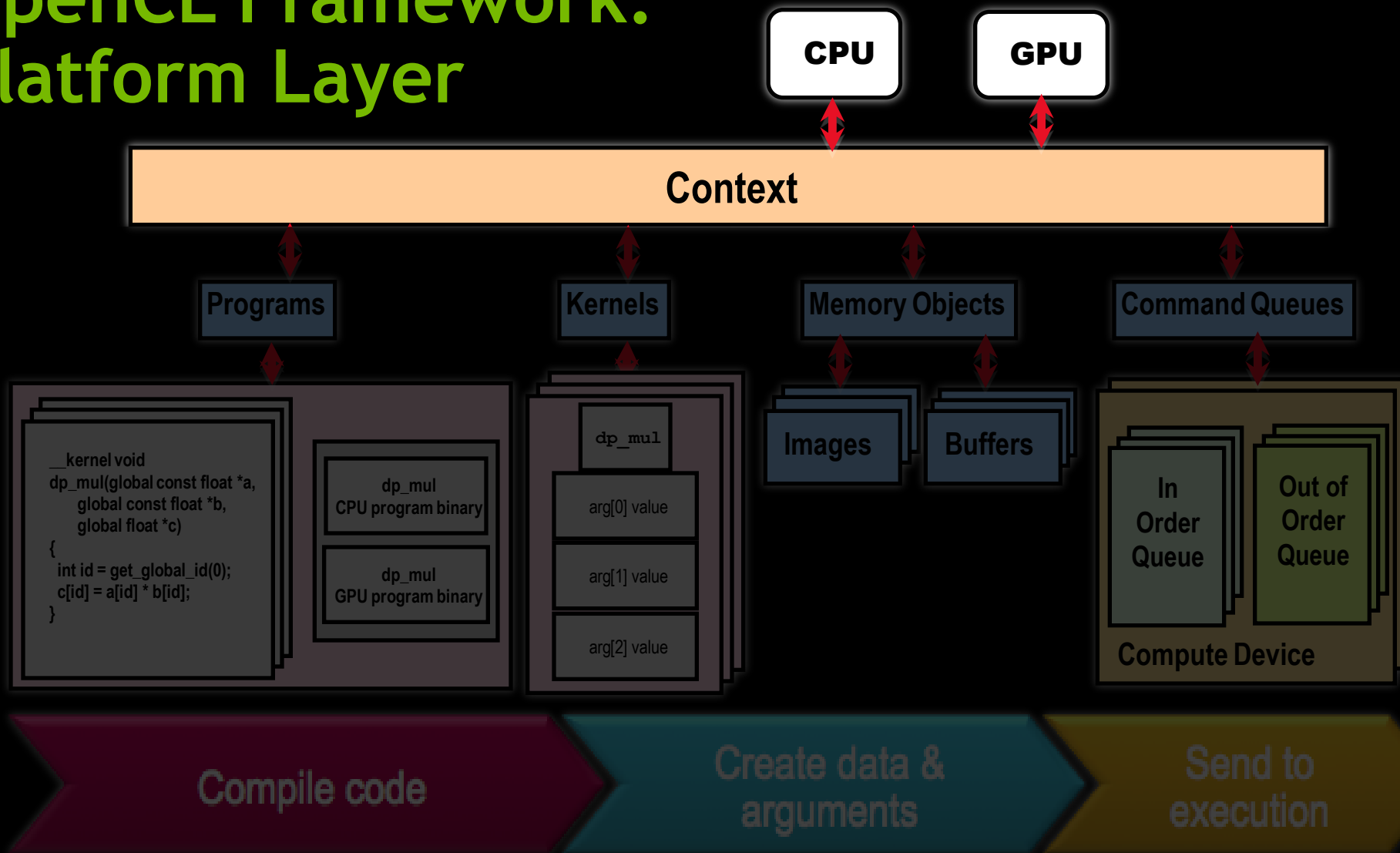
OpenCL Framework

- Platform layer
 - Platform query and context creation
- Compiler for OpenCL C
- Runtime
 - Memory management and command execution within a context

OpenCL Framework

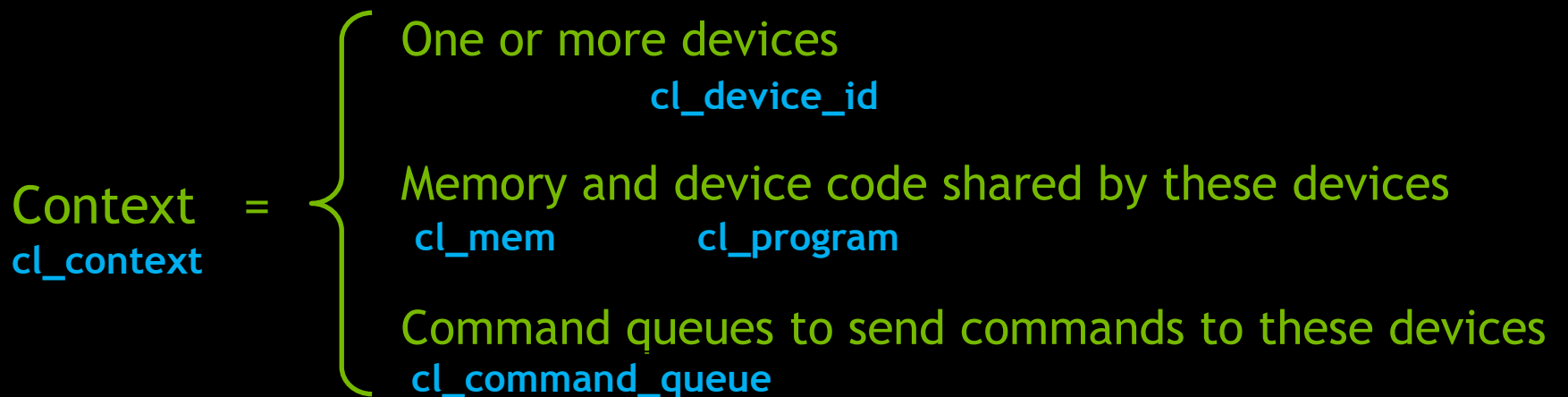


OpenCL Framework: Platform Layer



OpenCL Framework: Platform Layer

- Query platform information
 - `clGetPlatformInfo()`: profile, version, vendor, extensions
 - `clGetDeviceIDs()`: list of devices
 - `clGetDeviceInfo()`: type, capabilities
- Create an OpenCL context for one or more devices



Platform Layer: Context Creation (simplified)

```
// Get the platform ID
cl_platform_id platform;
clGetPlatformIDs(1, &platform, NULL);

// Get the first GPU device associated with the platform
cl_device_id device;
clGetDeviceIDs(platform, CL_DEVICE_TYPE_GPU, 1, &device, NULL);

// Create an OpenCL context for the GPU device
cl_context context;
context = clCreateContext(NULL, 1, &device, NULL, NULL, NULL);
```

Number
returned

Context
properties

Error
callback

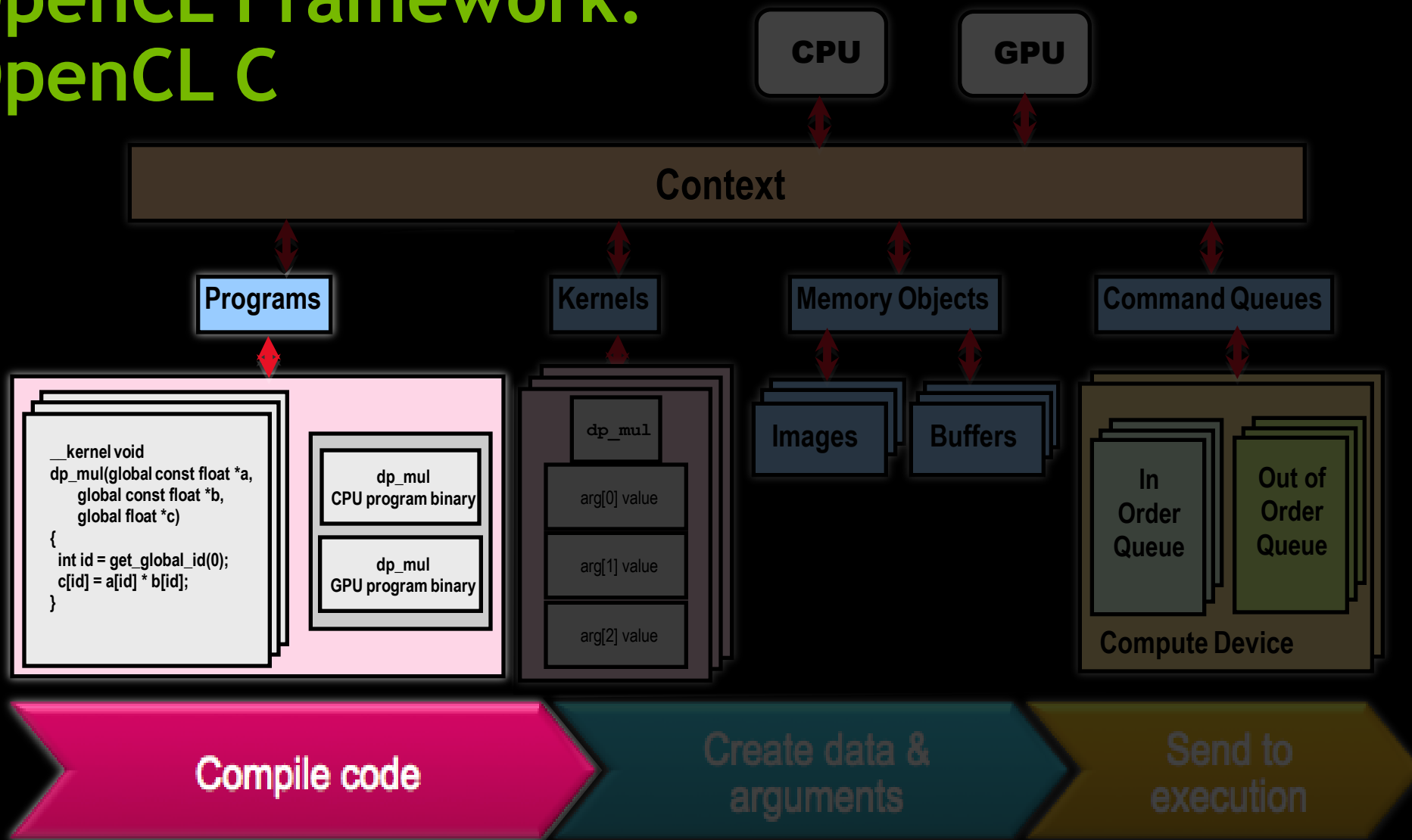
User
data

Error
code

Platform Layer: Error Handling, Resource Deallocation

- Error handling:
 - All host functions return an error code
 - Context error callback
- Resource deallocation
 - Reference counting API: `clRetain*()`, `clRelease*()`
- Both are removed from code samples for clarity
 - Please see SDK samples for complete code

OpenCL Framework: OpenCL C



OpenCL C

- Derived from ISO C99 (with some restrictions)
- Language Features Added
 - Work-items and work-groups
 - Vector types
 - Synchronization
 - Address space qualifiers
- Also includes a large set of built-in functions
 - Image manipulation
 - Work-item manipulation
 - Math functions

OpenCL C Language Restrictions

- Pointers to functions are not allowed
- Pointers to pointers allowed within a kernel, but not as an argument
- Bit-fields are not supported
- Variable-length arrays and structures are not supported
- Recursion is not supported
- Writes to a pointer to a type less than 32 bits are not supported*
- Double types are not supported, but reserved
- 3D Image writes are not supported

Some restrictions are addressed through extensions

OpenCL C Optional Extensions

- Extensions are optional features exposed through OpenCL
- The OpenCL working group has already approved many extensions to the OpenCL specification:
 - Double precision floating-point types (Section 9.3)
 - Built-in functions to support doubles
 - Atomic functions (Section 9.5, 9.6, 9.7)
 - Byte-addressable stores (write to pointers to types < 32-bits) (Section 9.9)
 - 3D Image writes (Section 9.8)
 - Built-in functions to support half types (Section 9.10)

Now core features
in OpenCL 1.1

Work-items and work-groups

- A *kernel* is a function executed for each work-item

```
__kernel void square(__global float* input, __global float* output)  
{  
    int i = get_global_id(0);  
    output[i] = input[i] * input[i];  
}
```

Function
qualifier

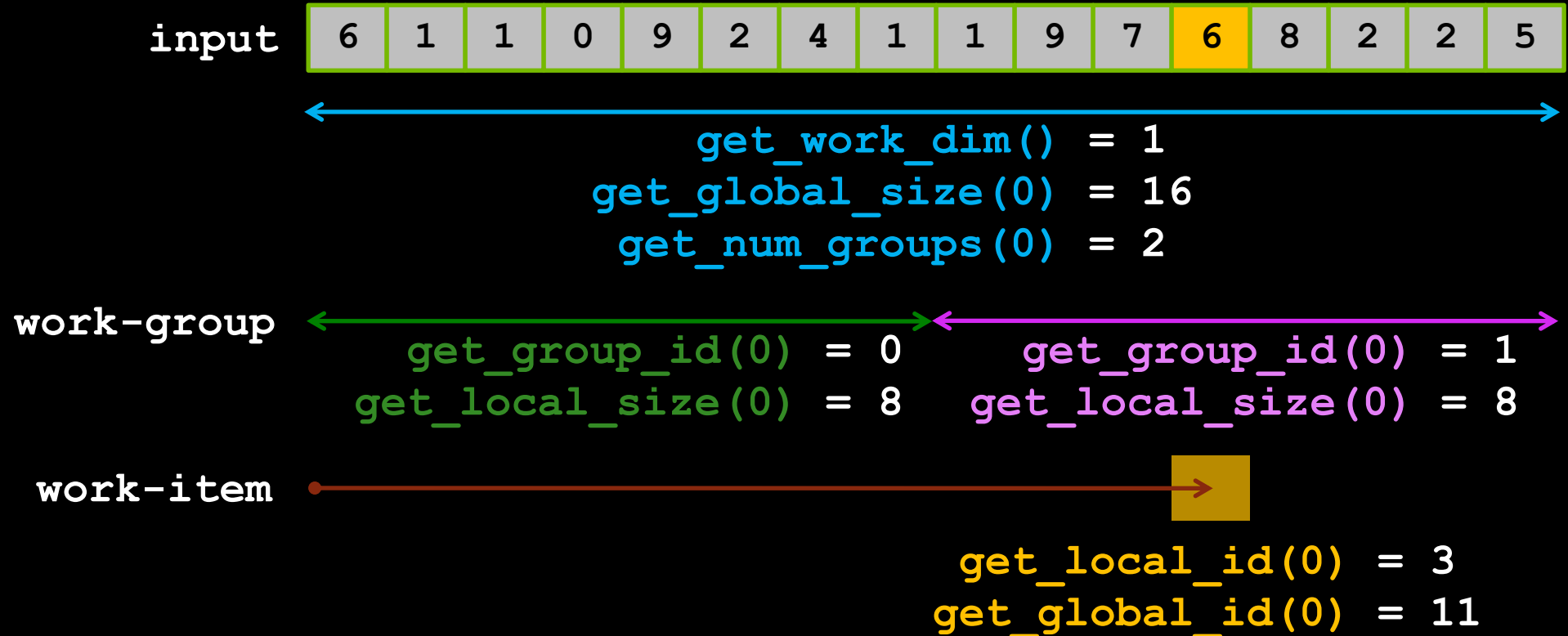
Built-in
function

Address space
qualifier

`get_global_id(0) = 7`

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
input	6	1	1	0	9	2	4	1	1	9	7	6	8	2	2	5
output	36	1	1	0	81	4	16	1	1	81	49	36	64	4	4	25

Work-items and work-groups



OpenCL C Data Types

- Scalar data types

- char, uchar, short, ushort, int, uint, long, ulong, float
- bool, intptr_t, ptrdiff_t, size_t, uintptr_t, void, half (storage)

- Image types

- image2d_t, image3d_t, sampler_t

- Vector data types

- Vector lengths 2, 3, 4, 8, 16 (char2, ushort4, int8, float16, double2, ...)
- Endian safe
- Aligned at vector length
- Vector operations

3-vectors new
in OpenCL 1.1

double is an optional
type in OpenCL

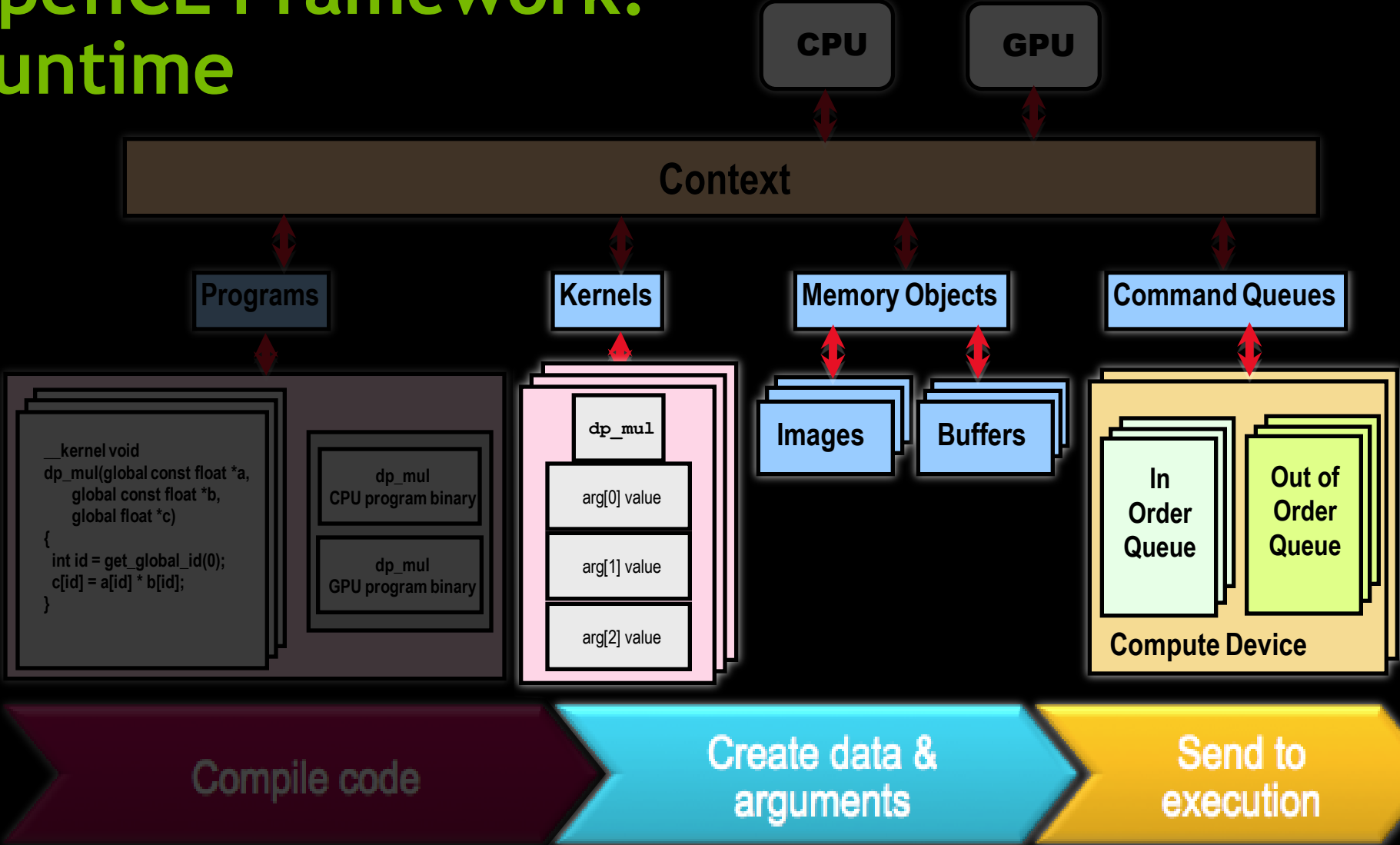
OpenCL C Synchronization Primitives

- Built-in functions to order memory operations and synchronize execution:
 - `mem_fence(CLK_LOCAL_MEM_FENCE and/or CLK_GLOBAL_MEM_FENCE)`
 - waits until all reads/writes to local and/or global memory made by the calling work-item prior to `mem_fence()` are visible to all threads in the work-group
 - `barrier(CLK_LOCAL_MEM_FENCE and/or CLK_GLOBAL_MEM_FENCE)`
 - waits until all work-items in the work-group have reached this point and calls `mem_fence(CLK_LOCAL_MEM_FENCE and/or CLK_GLOBAL_MEM_FENCE)`
- Used to coordinate accesses to local or global memory shared among work-items

OpenCL C Kernel Example

```
__kernel void dp_mul(__global const float *a,  
                    __global const float *b,  
                    __global float *c,  
                    int N)  
{  
    int id = get_global_id (0);  
    if (id < N)  
        c[id] = a[id] * b[id];  
}
```

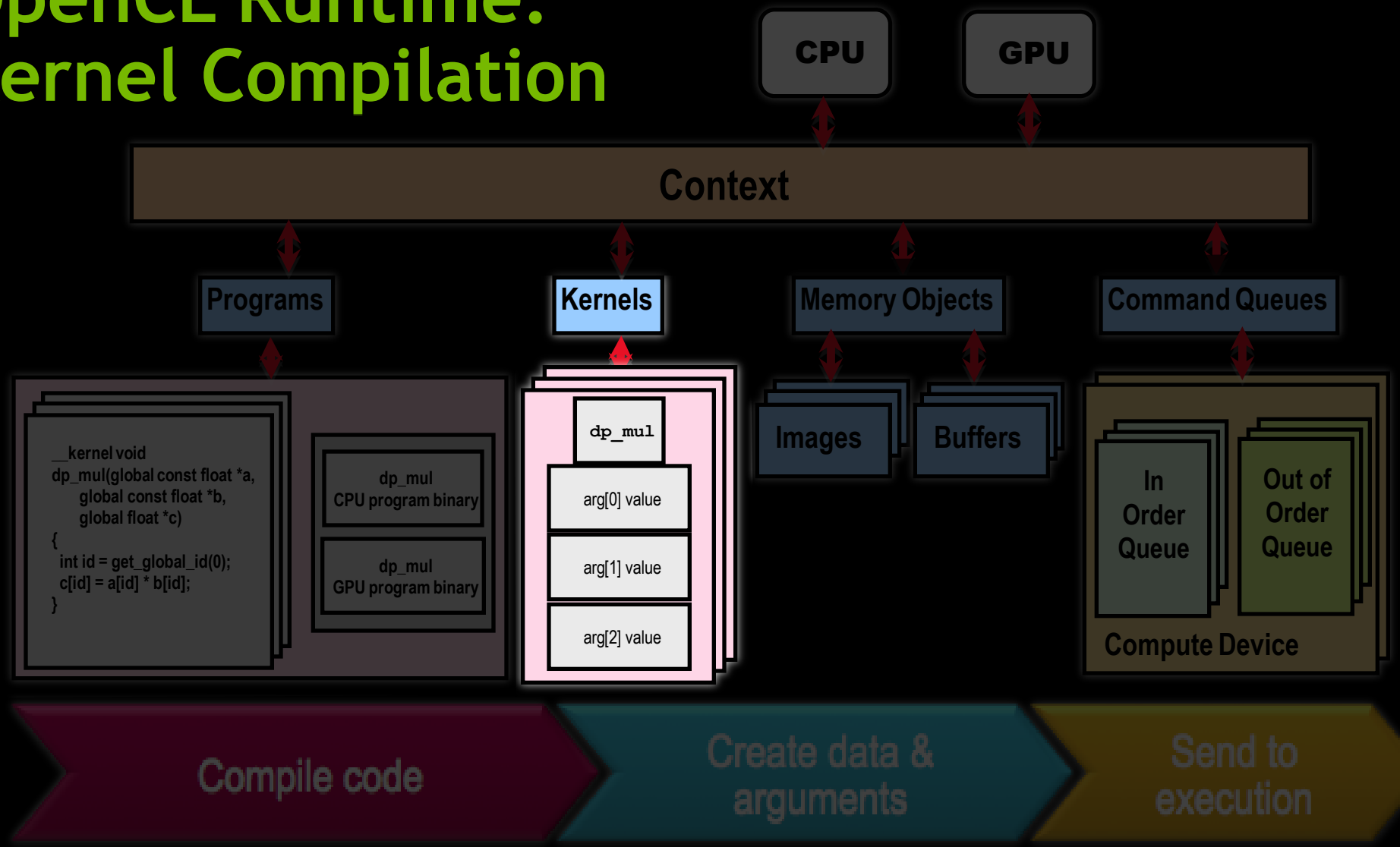
OpenCL Framework: Runtime



OpenCL Framework: Runtime

- Command queues creation and management
- Device memory allocation and management
- Device code compilation and execution
- Event creation and management (synchronization, profiling)

OpenCL Runtime: Kernel Compilation



Kernel Compilation

- A `cl_program` object encapsulates some source code (with potentially several kernel functions) and its last successful build
 - `clCreateProgramWithSource()` // Create program from source
 - `clBuildProgram()` // Compile program
- A `cl_kernel` object encapsulates the values of the kernel's arguments used when the kernel is executed
 - `clCreateKernel()` // Create kernel from successfully compiled program
 - `clSetKernelArg()` // Set values of kernel's arguments

Kernel Compilation

// Build program object and set up kernel arguments

```
const char* source = "__kernel void dp_mul(__global const float *a, \n"
                    "                    __global const float *b, \n"
                    "                    __global float *c, \n"
                    "                    int N) \n"
                    "{ \n"
                    "    int id = get_global_id (0); \n"
                    "    if (id < N) \n"
                    "        c[id] = a[id] * b[id]; \n"
                    "} \n";
```

```
cl_program program = clCreateProgramWithSource(context, 1, &source, NULL, NULL);
```

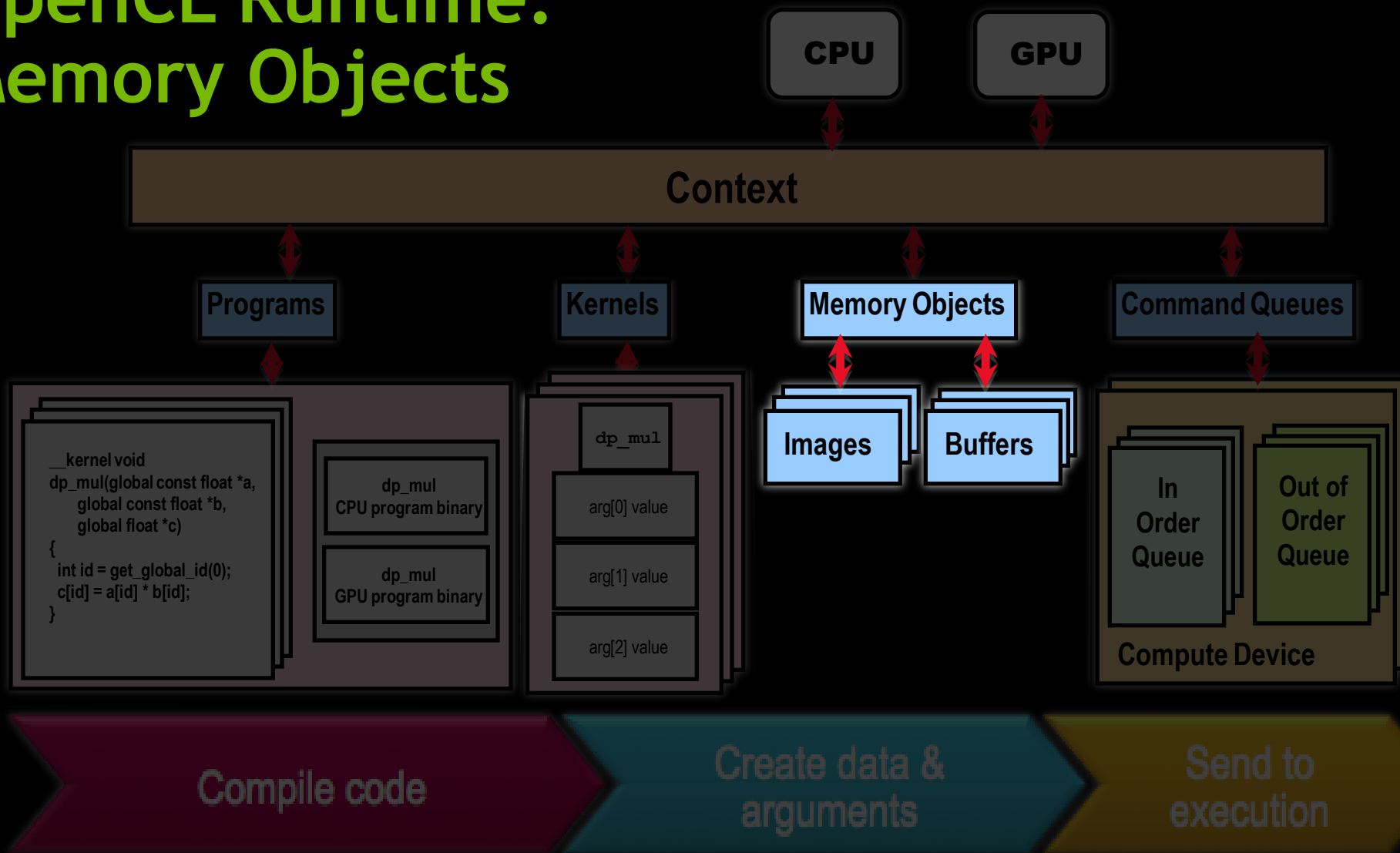
```
clBuildProgram(program, 0, NULL, NULL, NULL, NULL);
```

```
cl_kernel kernel = clCreateKernel(program, "dp_mul", NULL);
```

```
clSetKernelArg(kernel, 0, sizeof(cl_mem), (void*)&d_buffer);
```

```
clSetKernelArg(kernel, 1, sizeof(int), (void*)&N);
```

OpenCL Runtime: Memory Objects



Memory Objects

- Two types of memory objects (`cl_mem`):
 - Buffer objects
 - Image objects
- Memory objects can be copied to host memory, from host memory, or to other memory objects
- Regions of a memory object can be accessed from host by mapping them into the host address space

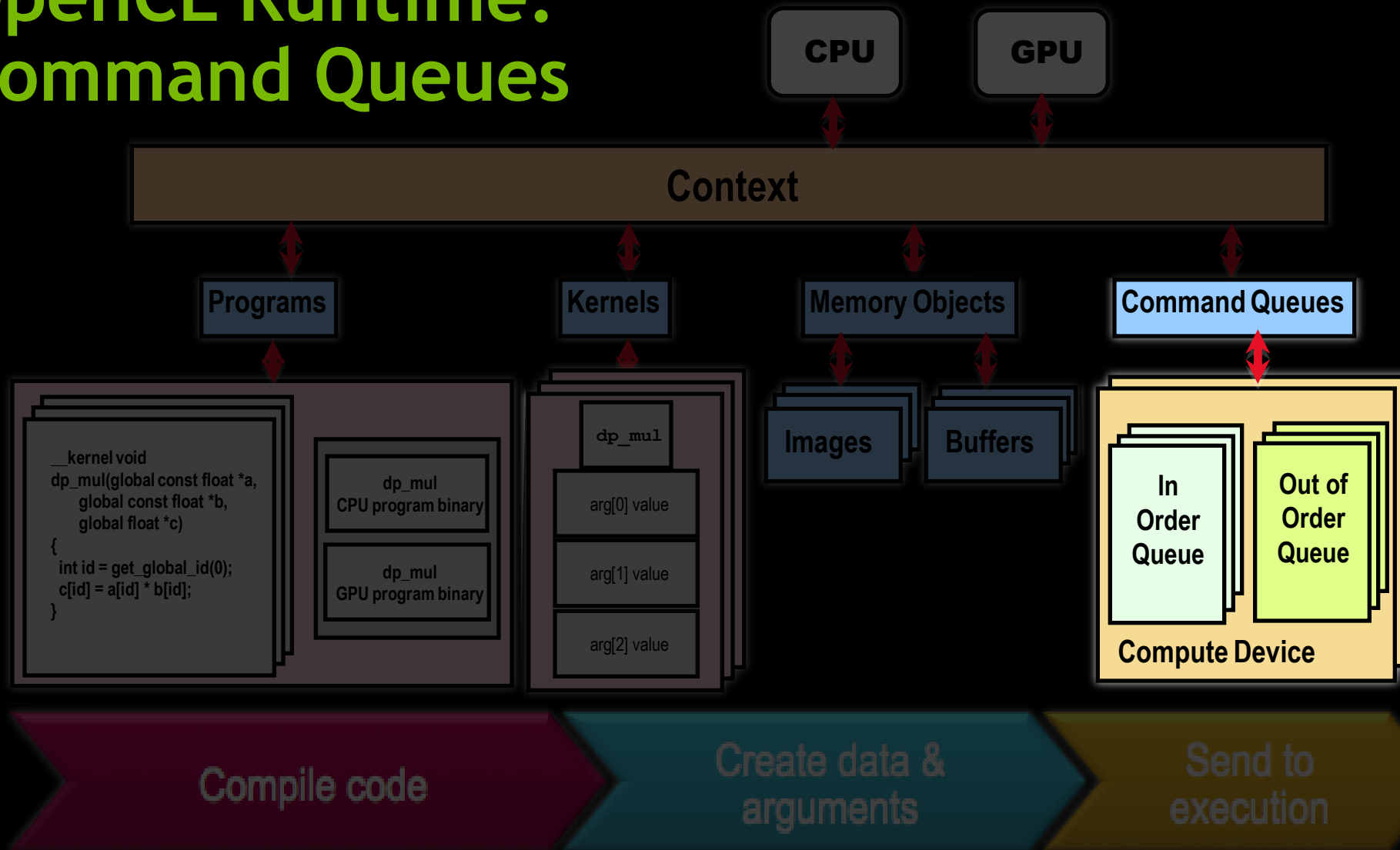
Buffer Object

- One-dimensional array
- Elements are scalars, vectors, or any user-defined structures
- Accessed within device code through pointers

Image Object

- Two- or three-dimensional array
- Elements are 4-component vectors from a list of predefined formats
- Accessed within device code via built-in functions (storage format not exposed to application)
 - Sampler objects are used to configure how built-in functions sample images (addressing modes, filtering modes)
- Can be created from OpenGL texture or renderbuffer

OpenCL Runtime: Command Queues



Commands

- Memory copy or mapping
- Device code execution
- Synchronization point

Command Queue

- Sequence of commands scheduled for execution on a specific device
 - Enqueuing functions: `clEnqueue*`()
 - Multiple queues can execute on the same device
- Two modes of execution:
 - In-order: Each command in the queue executes only when the preceding command has completed (including memory writes)
 - Out-of-order: No guaranteed order of completion for commands

```
// Create a command-queue for a specific device  
cl_command_queue cmd_queue = clCreateCommandQueue(context, device_id, 0, NULL);
```

Error
code

Properties

Data Transfer between Host and Device

```
// Create buffers on host and device
size_t size = 100000 * sizeof(int);
int* h_buffer = (int*)malloc(size);
cl_mem d_buffer = clCreateBuffer(context, CL_MEM_READ_WRITE, size, NULL, NULL);
...
// Write to buffer object from host memory
clEnqueueWriteBuffer(cmd_queue, d_buffer, CL_FALSE, 0, size, h_buffer, 0, NULL, NULL);
...
// Read from buffer object to host memory
clEnqueueReadBuffer(cmd_queue, d_buffer, CL_TRUE, 0, size, h_buffer, 0, NULL, NULL);
```



Kernel Execution: NDRange

- Host code invokes a kernel over an index space called an *NDRange*
 - NDRange = “N-Dimensional Range” of work-items
 - NDRange can be a 1-, 2-, or 3-dimensional space
 - Work-group dimensionality matches work-item dimensionality

Kernel Invocation

```
// Set number of work-items in a work-group  
size_t localWorkSize = 256;  
int numWorkGroups = (N + localWorkSize - 1) / localWorkSize; // round up  
size_t globalWorkSize = numWorkGroups * localWorkSize; // must be evenly divisible by localWorkSize  
clEnqueueNDRangeKernel(cmd_queue, kernel, 1, NULL, &globalWorkSize, &localWorkSize, 0, NULL, NULL);
```



NDRange

Command Synchronization

- Queue barrier command: `clEnqueueBarrier()`
 - Commands after the barrier start executing only after all commands before the barrier have completed
- Events: a `cl_event` object can be associated with each command
 - Commands return events and obey event waitlists
 - `clEnqueue*(..., num_events_in_waitlist, *event_waitlist, *event);`
 - Any commands (or `clWaitForEvents()`) can wait on events before executing
 - Event object can be queried to track execution status of associated command and get profiling information
- Some `clEnqueue*()` calls can be optionally blocking
 - `clEnqueueReadBuffer(..., CL_TRUE, ...);`

Synchronization: Queues & Events

- You must explicitly synchronize between queues
 - Multiple devices each have their own queue
 - Possibly multiple queues per device
 - Use events to synchronize



ADDITIONAL INFORMATION AND RESOURCES

Next Steps

- Begin hands-on development with our publicly available OpenCL driver and GPU Computing SDK
- Read the OpenCL Specification and the extensive documentation provided with the SDK
- Read and contribute to OpenCL forums at Khronos and NVIDIA

NVIDIA OpenCL Resources

- NVIDIA OpenCL Web Page:
 - http://www.nvidia.com/object/cuda_opencl.html
- NVIDIA OpenCL Forum:
 - <http://forums.nvidia.com/index.php?showforum=134>
- NVIDIA driver, profiler, code samples for Windows and Linux:
 - <http://developer.nvidia.com/object/opencl.html>

Khronos OpenCL Resources

- OpenCL Specification

 - <http://www.khronos.org/registry/cl/specs/opencl-1.1.pdf>

- OpenCL Registry

 - <http://www.khronos.org/registry/cl/>

- OpenCL Developer Forums

 - http://www.khronos.org/message_boards/

- OpenCL Quick Reference Card

 - <http://www.khronos.org/files/opencl-1-1-quick-reference-card.pdf>

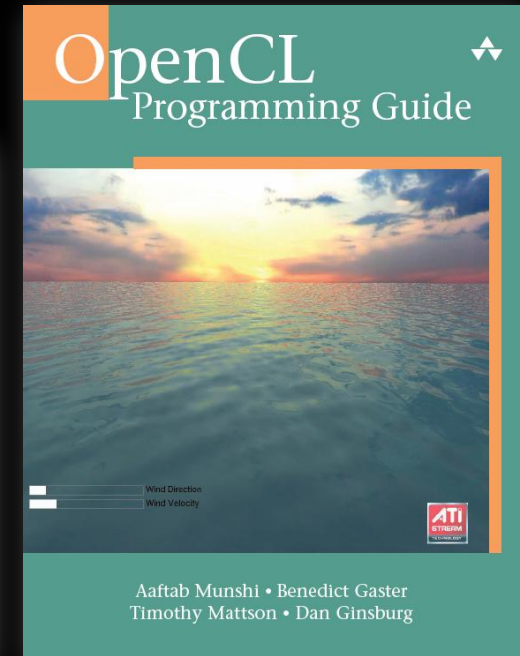
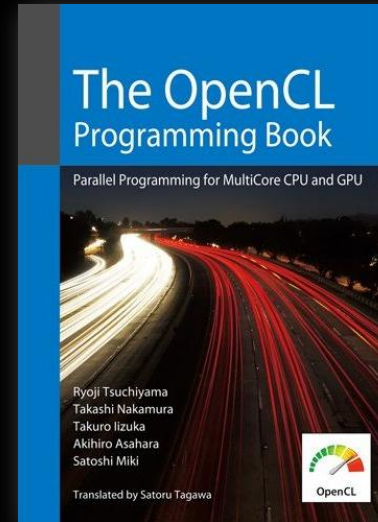
- OpenCL Online Man pages

 - <http://www.khronos.org/registry/cl/sdk/1.1/docs/man/xhtml/>



OpenCL Books

- The OpenCL Programming Book
 - Available now: search for OpenCL on Amazon
- OpenCL Programming Guide - The “Red Book” of OpenCL
 - Coming in July 2011; rough cut available on Safaribooks
 - <http://my.safaribooksonline.com/9780132488006>



Questions?

