Writing Your First OpenCL Application

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Agenda

- OpenCL models and objects (65 min.)
  - Lecture (35 min.)
  - Exercises (30 min.)

- Profiling and debugging (25 min.)
  - Lecture (15 min.)
  - Exercise (10 min.)

OpenCL Architecture

- Portable parallel computing programming model
  - CPUs, GPUs, FPGAs, DSPs, etc.
- 4 models
  - Platform model
  - Execution model
  - Memory model
  - Programming model

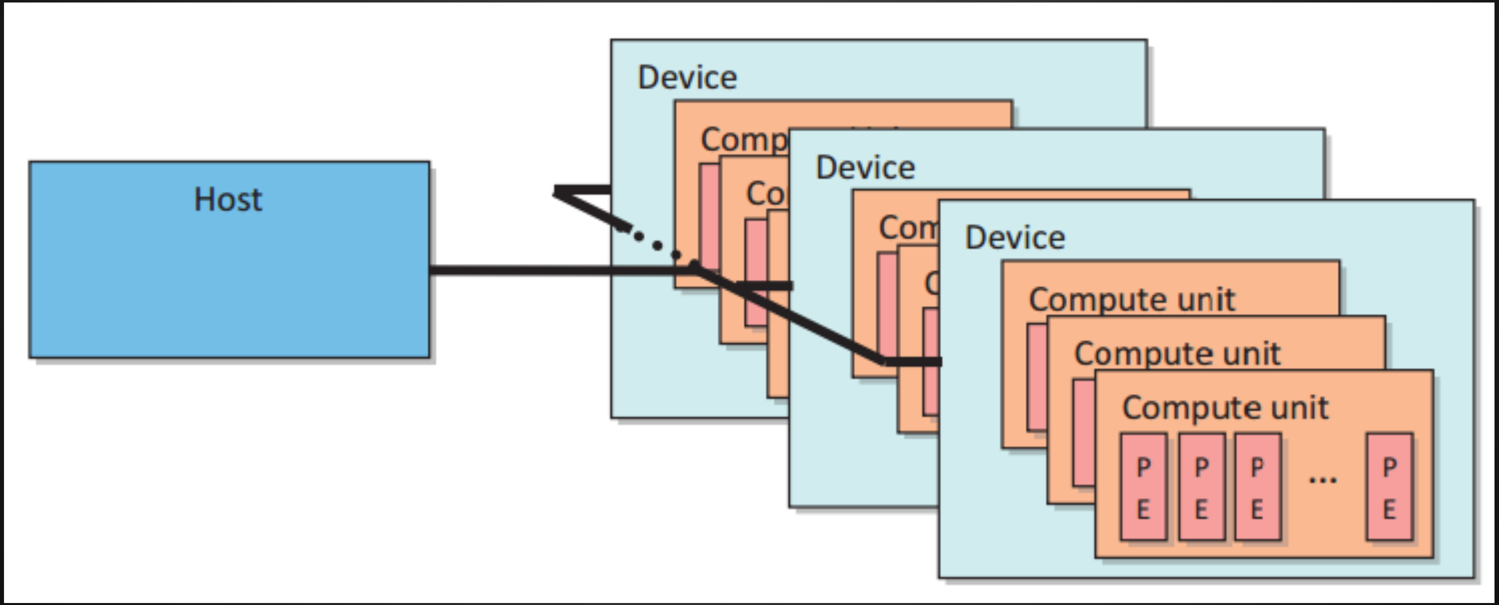
OpenCL Architecture

- 7 common objects
  - Platform
  - Context
  - Device
  - Command queue
  - Program
  - Kernel
  - Memory object

Platform Model

- Defined in OpenCL implementation, i.e., an OpenCL library
- Enables the host to interact with devices
- Currently each vendor provides only a single platform per implementation.

Platform Model



Platform Model

- Host
  - Processors an OpenCL library runs on
- Device
  - Processors an OpenCL library talks to
  - CPU: all cores are combined into a single device.
  - GPU: a GPU is a single device.

Get a Platform

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

- Usually called twice
  - First call to get the number of platforms
  - Then space is allocated for the platform objects.
  - Second call to get a platform

Exercise

Implement GetPlatform()

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

Context

- Environment for managing OpenCL objects and resources
- All OpenCL objects except platforms are managed by a context.
    - Devices
    - Programs
    - Kernels
    - Memory objects
    - Command queues

Create a Context

- Created with a type of devices

```
cl_context clCreateContextFromType (const cl_context_properties  *properties,
                                    cl_device_type  device_type,
                                    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)
```

Create a Context

- Created with one or more devices

```
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)
```

Exercise

Implement CreateContext()

```
cl_context clCreateContextFromType (const cl_context_properties  *properties,
                                    cl_device_type  device_type,
                                    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)
```

Get Devices

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

- Usually called twice
  - First call to get the number of devices
  - Then space is allocated for the device objects.
  - Second call to get one or more devices

Exercise

Implement GetDevice()

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

Command Queues

- Connecting host and device
- Each device has its own command queue.
- Commands
    - Synchronous
    - **Asynchronous**
    - **In-order execution**
    - Out-of-order execution

Command Queues

- In-order execution
  - Each command is executed after the previous one has finished.
- Out-of-order execution
  - Commands are executed as soon as they are ready with no guarantees of their ordering
  - Events are commonly used for synchronization.

Command Queues (v1.2)

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

Command-Queue Properties	Description
CL_QUEUE_OUT_OF_ORDER_EXEC_MODE_ENABLE	Determines whether the commands queued in the command-queue are executed in-order or out-of-order. If set, the commands in the command-queue are executed out-of-order. Otherwise, commands are executed in-order. See note below for more information.
CL_QUEUE_PROFILING_ENABLE	Enable or disable profiling of commands in the command-queue. If set, the profiling of commands is enabled. Otherwise profiling of commands is disabled. See clGetEventProfilingInfo for more information.

Exercise

Implement CreateCommandQueue()

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

Programs

- A collection of OpenCL kernels
  - Source code or pre-compiled binary
  - Can contain constant data and auxiliary functions
- To create a program object
  - Read in a source code string or a binary

Programs

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

```
cl_program clCreateProgramWithBinary ( cl_context context,
                                       cl_uint num_devices,
                                       const cl_device_id *device_list,
                                       const size_t *lengths,
                                       const unsigned char **binaries,
                                       cl_int *binary_status,
                                       cl_int *errcode_ret)
```

Programs

- To build a program
  - Specify target devices.
  - Pass in compiler flags.
  - Check for compilation errors.

```
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)
```

Programs

- If a program fails to compile, OpenCL requires programmers to explicitly ask for compiler output

```
cl_int clGetProgramBuildInfo (cl_program  program,
                              cl_device_id  device,
                              cl_program_build_info  param_name,
                              size_t  param_value_size,
                              void  *param_value,
                              size_t  *param_value_size_ret)
```

Exercise

Implement CreateProgram()

```
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 (CL_CALLBACK *pfn_notify)(cl_program program, void *user_data),
                        void *user_data)
```

Kernels

- Functions declared in a program and running on a device
- Created from a compiled program

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

Kernels

- Arguments are explicitly associated with a kernel.
- Arguments can be memory objects or individual values.

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

Exercise

Implement CreateKernel() and SetKernelArg()

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

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

Runtime Compilation

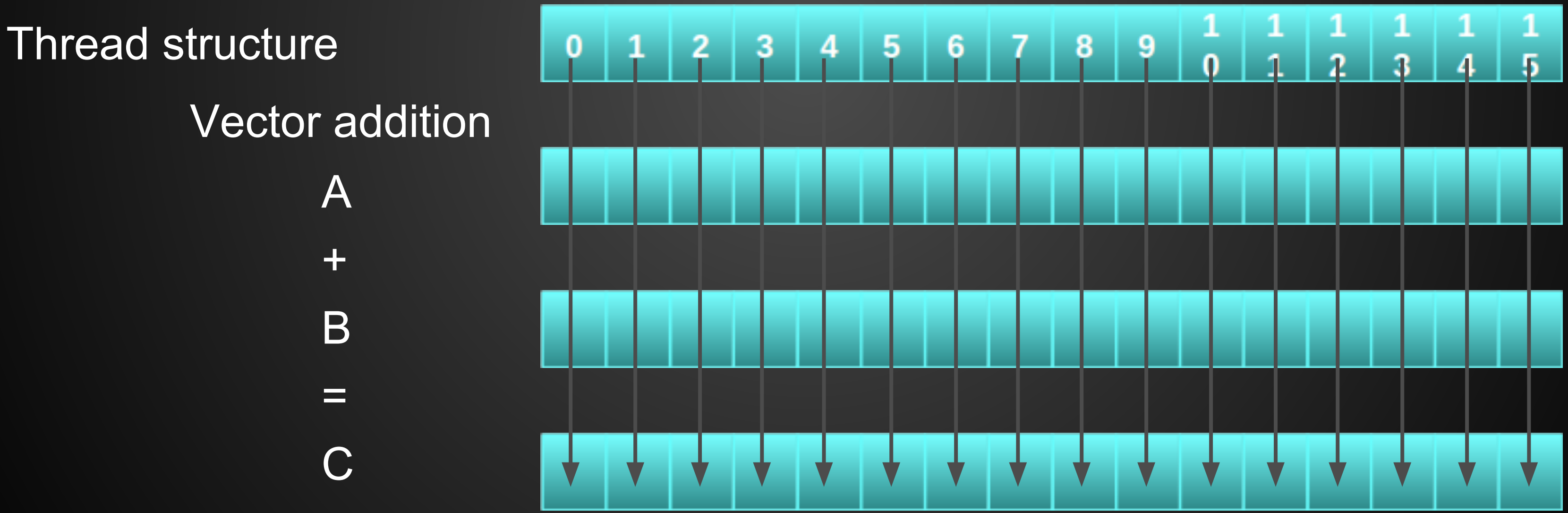
- OpenCL compiles programs and creates kernels at run time, which may incur high overhead. So each operation has to be performed only once.

What Are Left?

- Execute a kernel
  - Execution model
- Create memory objects and transfer data between host and device
  - Memory model

Execution Model

- Thread structure in SIMD
  - Each work-item works on one part of a problem.



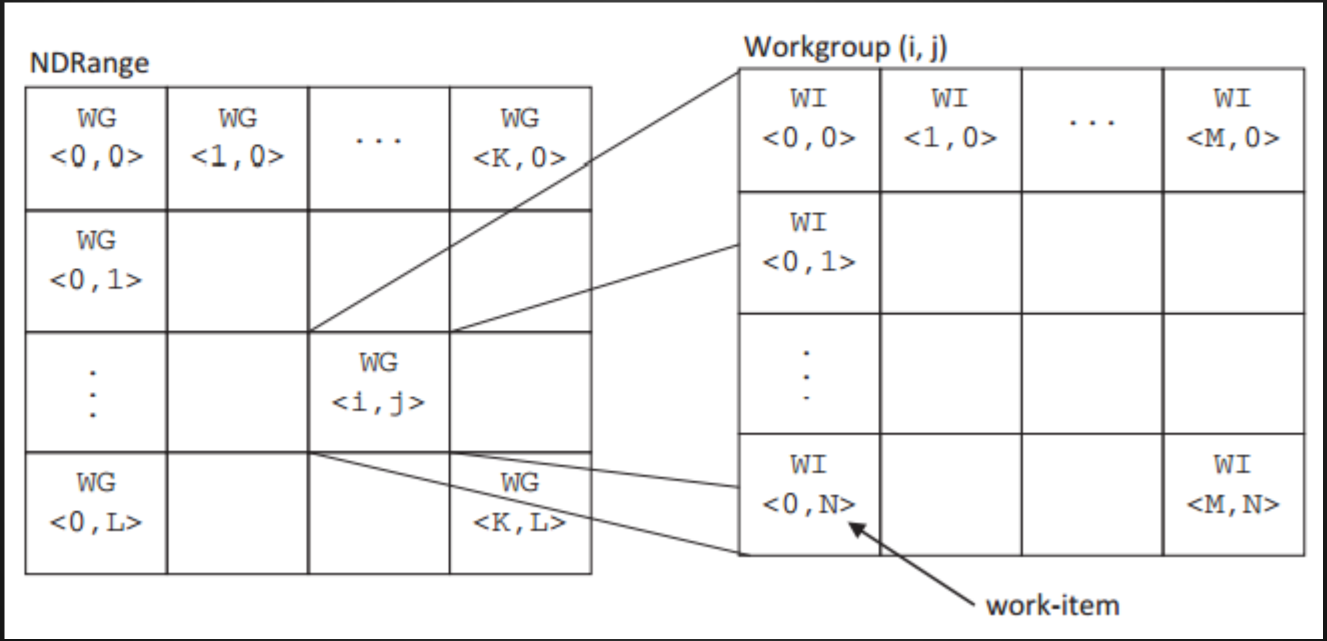
Execution Model

- Work-item: an instance of a kernel
- Work-group
  - Work-groups are independent of each other to guarantee scalability.
  - Scheduled to compute units and no guaranteed execution order
- Index space
  - A hierarchy of work-groups and work-items

Execution Model

- Work-items' IDs
  - Global ID, unique in the index space
  - Local ID in the work-group
  - GID = WG_ID * WG_SIZE + LID

Execution Model



Execution Model

get_work_dim	Number of dimensions in use
get_global_size	Number of global work items
get_global_id	Global work item ID value
get_local_size	Number of local work items
get_local_id	Local work item ID
get_num_groups	Number of work groups
get_group_id	Work group ID
get_global_offset	Work offset

Execution Model

```
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)
```

```
cl_int clFinish ( cl_command_queue command_queue)
```

- Asynchronous execution
- A list of events can be used to specify prerequisite operations that must be completed before execution

Exercise

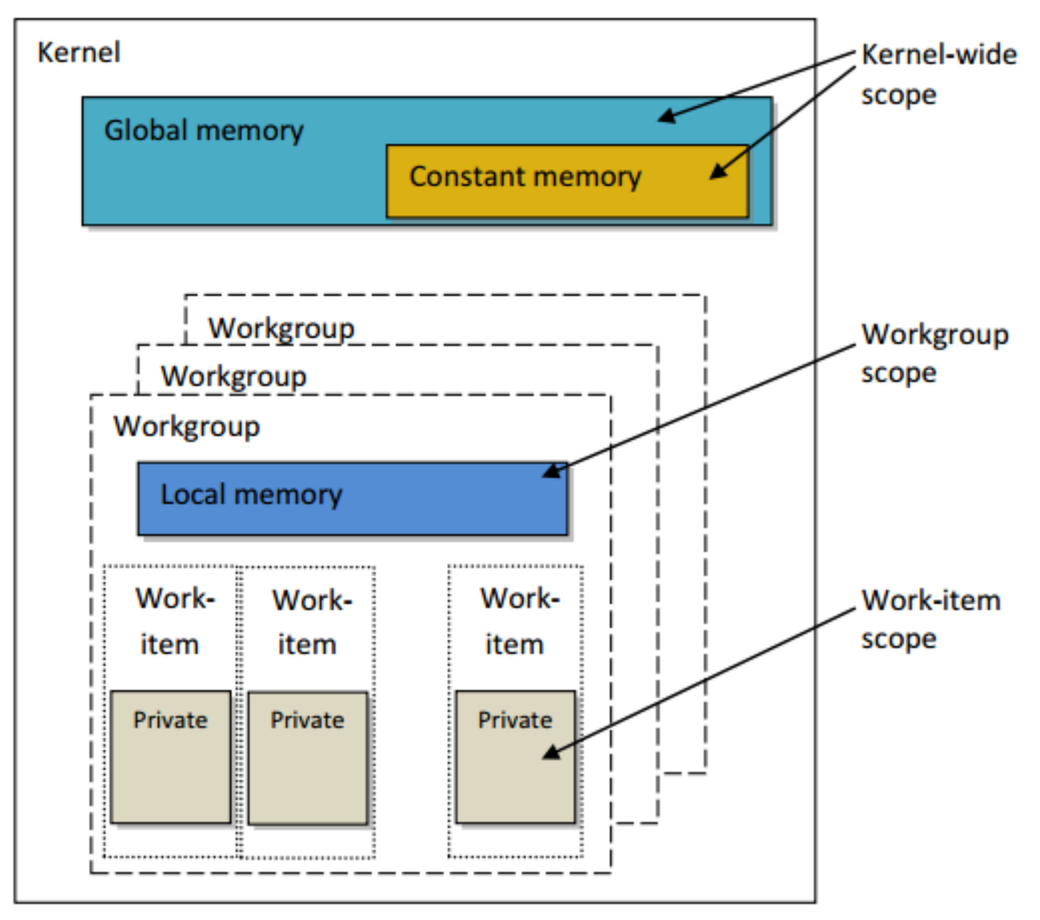
Implement RunKernel()

```
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)
```

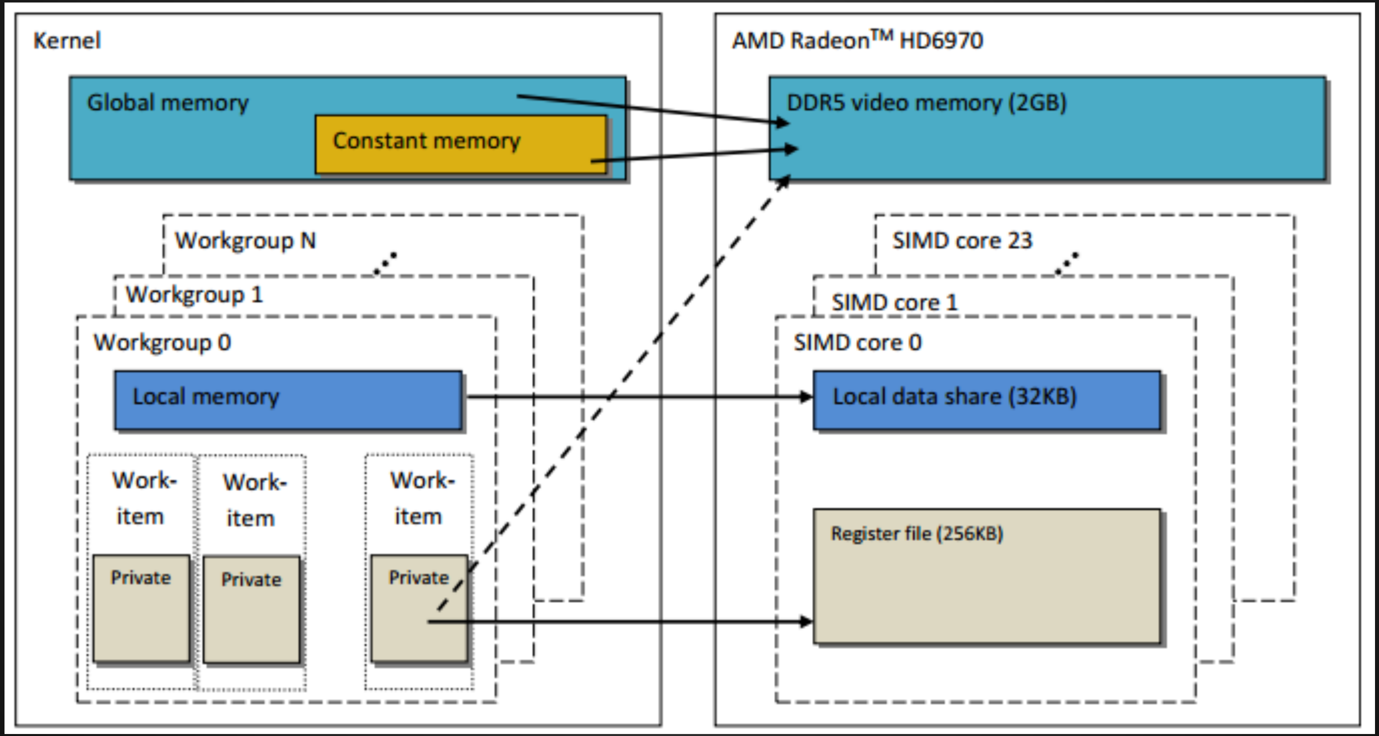
```
cl_int clFinish ( cl_command_queue command_queue)
```

Memory Model

- Global mem
- Constant mem
- Local mem
- Private mem



Memory Model



Memory Model

- Memory objects are explicitly managed.
    - Between host memory and device memory
    - Between global memory and local memory

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

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

Exercise

Implement WriteToGPU() and ReadFromGPU()

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

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

Writing a Kernel

- One instance of a kernel is created for each work-item.
- Kernels
  - Must begin with keyword __kernel
  - Must have return type void
  - Must declare the address space of each memory object argument
  - Use built-in work-item functions to get IDs, sizes, etc.

Exercise

Write VectorAddKernel

- Arguments: c, a, b, n
  - c: buffer, __global
  - a: buffer, __global
  - b: buffer, __global
  - n: unsigned int
- Functionality: vector addition c = a + b

Programming Model

- Data parallel
  - One-to-one mapping between work-items and elements in a memory object
  - Work-group defined explicitly or implicitly
- Task parallel
  - Kernel executed independent of an index space
- Synchronization
  - Between work-items in a work-group
  - Between command queues in a context

Wrap-Up

- 4 models
  - Platform, Execution, Memory, Programming
- 7 common objects
  - Platform, Context, Device
  - Command Queue, Program, Kernel, Memory Objects

Exercise

Make VectorAdd example work.

Agenda

- OpenCL models and objects (65 min.)
  - Lecture (35 min.)
  - Exercises (30 min.)

- Profiling and debugging (25 min.)
  - Lecture (15 min.)
  - Exercise (10 min.)

Command Queues With Profiling Enabled

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

Command-Queue Properties	Description
CL_QUEUE_OUT_OF_ORDER_EXEC_MODE_ENABLE	Determines whether the commands queued in the command-queue are executed in-order or out-of-order. If set, the commands in the command-queue are executed out-of-order. Otherwise, commands are executed in-order. See note below for more information.
CL_QUEUE_PROFILING_ENABLE	Enable or disable profiling of commands in the command-queue. If set, the profiling of commands is enabled. Otherwise profiling of commands is disabled. See clGetEventProfilingInfo for more information.

Events For Profiling

```
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)
```

Profiling API

```
cl_int clGetEventProfilingInfo ( cl_event event,
                                 cl_profiling_info param_name,
                                 size_t param_value_size,
                                 void *param_value,
                                 size_t *param_value_size_ret )
```

cl_profiling_info	**Return Type**	**Info. returned in** *param_value*
CL_PROFILING_COMMAND_QUEUED	cl_ulong	A 64-bit value that describes the current device time counter in nanoseconds when the command identified by *event* is enqueued in a command-queue by the host.
CL_PROFILING_COMMAND_SUBMIT	cl_ulong	A 64-bit value that describes the current device time counter in nanoseconds when the command identified by *event* that has been enqueued is submitted by the host to the device associated with the command-queue.
CL_PROFILING_COMMAND_START	cl_ulong	A 64-bit value that describes the current device time counter in nanoseconds when the command identified by *event* starts execution on the device.
CL_PROFILING_COMMAND_END	cl_ulong	A 64-bit value that describes the current device time counter in nanoseconds when the command identified by *event* has finished execution on the device.

Exercise

Profile the kernel execution time

Demo

See how much a GPU is faster than a CPU.

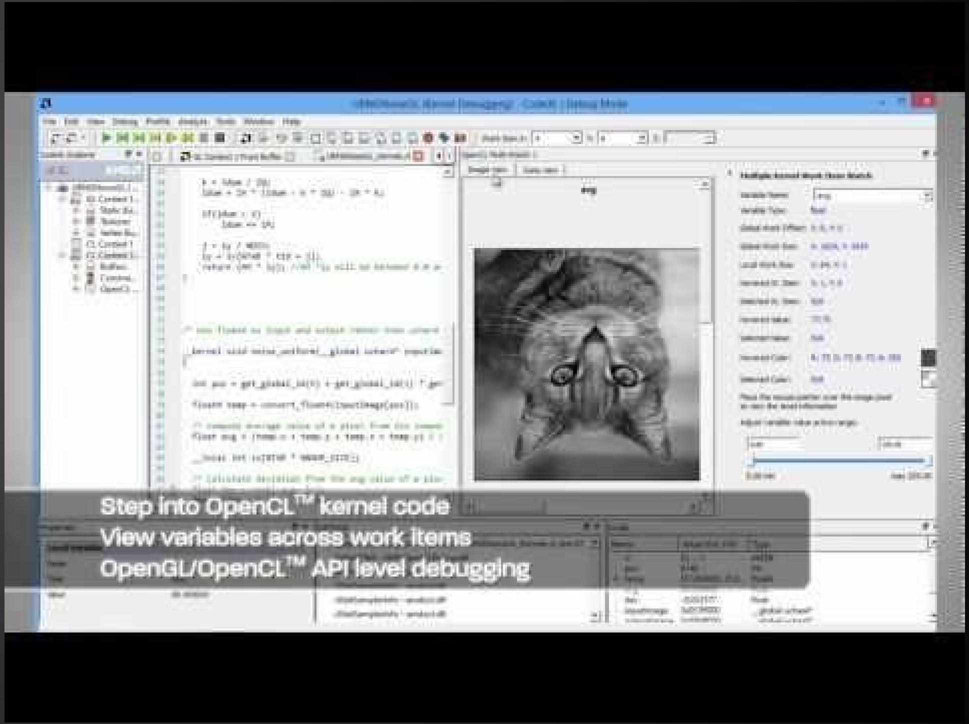
Debugging Kernels With printf()

- AMD GPUs support printing in kernels.
  - `cl_amd_printf` extension has to be enabled.
  - Remember that a kernel has many instances.

    Generally one wants to check out only a few work-items.
- Information to be printed is buffered until the kernel completes and then transferred back to the host.
  - The kernel must be finished.

AMD CodeXL

- Integrated tool for debugging and profiling



Programming Multiple Devices

- Single context, multiple devices
    - Simple
    - Memory objects are common in a context
- Multiple context, multiple devices
    - Computing on a cluster
- Considerations for CPU-GPU heterogeneous computing
    - Scheduling, load balancing

Summary

- OpenCL models
  - Platform, Execution, Memory, Programming
- OpenCL common objects
  - Platform, Context, Device
  - Command Queue, Program, Kernel, Memory Object
- Profiling and debugging

Next Session (Leiming Yu)

- Global memory is off chip and so slow, which is a very bad idea for data reuse. Local memory is on chip and much faster. How to use it?
- Vector addition is just a toy. How to write and optimize a real application?

Reference

- OpenCL university kit
  - By Perhaad Mistry and Dana Schaa
- AMD OpenCL Programming User Guide
  - rev 1.0 Beta
- Heterogeneous Computing with OpenCL
  - By Benedict Gaster, Lee Howes, David R. Kaeli, Perhaad Mistry & Dana Schaa

Thank you!

Questions?

OpenCL 2.0 Main Features

- SVM: Shared Virtual Memory
  - Pointer-containing data structures can be easily shared between host and device.
- DP: Dynamic Parallelism
  - Kernels can enqueue kernels without host interactions.
- Pipes
  - Pipes enable data transfers between kernels without host interactions.